

Electrically Functional Photopolymer Resins for Vat Photopolymerization

A Framework-Driven Engineering Review and Industrial Perspective

Conductivity Regimes, Dielectric Function and System-Dependent Electrical Performance

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Document genre and intended audience

This document is a framework-driven engineering review and industrial perspective on electrically functional photopolymer resins for vat photopolymerisation, written from a primary-source industrial-author viewpoint with three decades of formulation experience. It is not a pure academic review. The author is the founder and Scientific Director of the manufacturer of one of the industrial portfolios discussed at the end of §3 (§3.12) and Appendix A. The structural alignment between the route taxonomy proposed in this review and the architecture of that case-study portfolio is documented and acknowledged explicitly in §13.10. The document combines three complementary registers: (i) A scientific review of the peer-reviewed literature on conductive, dielectric and electrostatic photopolymer additive manufacturing, with 57 numbered literature references and technical monographs (30 of them in the 2022–2026 window), together with 6 international standards. The chemistry sections (§3.1–§3.7), the manufacturing-physics section (§3.5), the polymer-physics fundamentals (§3.9) and the application sections (§4–§11) consolidate the published body of work and identify cross-cutting limitations. (ii) An engineering framework — the System-Dependent Conductivity Framework (SDCF, §1.4) — that interprets the realised electrical performance of a printed part as a system-level outcome rather than as a resin-only property. The framework is supported by Tables A through E and Figure 1, and is the central interpretive contribution of the review. (iii) An industrial perspective documenting one publicly available case-study portfolio (§3.12 and Appendix A), the manufacturing alternatives that complement direct conductive VPP printing (§3.11), and the field-level gaps that constrain industrial-grade deployment (§13.11). The intended audience is: industrial formulators developing conductive and dielectric photopolymer systems; engineering R&D teams evaluating VPP-printed electrically functional components for product integration; advanced researchers seeking a consolidated field map; and journal reviewers of additive manufacturing, polymer composites and printed-electronics manuscripts. The document is targeted at publication in engineering-focused additive manufacturing journals (Additive Manufacturing, Virtual and Physical Prototyping, Advanced Engineering Materials, Materials & Design, Progress in Additive Manufacturing) rather than at fundamental polymer-science journals (Progress in Polymer Science, Polymer Reviews, Progress in Materials Science), which would require a substantially different balance between framework and fundamental polymer physics. The document is also made publicly available through the 3Dresyns engineering publications space as part of the author's commitment to open technical communication.

Abstract

Problem. Additive manufacturing of electrically functional parts has progressed from filament-based conductive thermoplastics into vat photopolymerisation (VPP) systems capable of micron-scale resolution, enabling printed electronics, electrostatic-control fixtures, bioelectronics, embedded sensors, sacrificial conductor templates, RF/microwave dielectric components and 4D electro-thermo-responsive actuators. A recurrent interpretive limitation in the literature is the reporting of surface resistivity, volume conductivity and percolation thresholds as single numerical values decoupled from the cured-system configuration. We argue that this reporting convention is the principal cause of the limited cross-study transferability of conductive-AM data: a "conductive resin" is not a stable universal entity but a system-realised conductive structure, and the realised electrical performance of a printed part is a system-level outcome — set jointly by formulation, printer optics, exposure profile, geometry, post-cure protocol and storage history — rather than an intrinsic resin-only property. The SDCF is an author-proposed conceptual framework for organising factors that can contribute to differences between constituent, formulation, printed-part and deployed-system electrical performance. It does not by itself distinguish measurement uncertainty from causal material or process effects. **Field fragmentation.** The literature on electrically functional VPP photopolymers spans seven distinct conductivity-route chemistries, three operational regimes, an orthogonal dielectric direction, and a wide envelope of application classes from electrostatic fixtures to bioelectronics R&D. The cross-route consolidation needed for engineering-grade material selection is absent from the peer-reviewed body of work, and metrology heterogeneity across studies (different sample geometries, different

post-cure histories, different ambient conditions) prevents direct comparison of reported electrical performance across publications. **Contribution.** This review proposes a unified field synthesis along two complementary axes: a taxonomy of seven electrical-function routes operating across three regimes — Regime A (static-dissipative, evaluated under an application-specific ESD control plan); Regime B (functional conductive, characterised using explicitly stated electrical quantities and methods); Regime C (author-proposed high-conductivity printed-conductor regime, characterised using bulk conductivity) — plus one orthogonal dielectric route ($\epsilon_r > 5$, $\tan \delta < 0.05$ at GHz frequencies), with two orthogonal design axes (solubility of the cured part, biological-evidence status); and a comparative manufacturing-space positioning of VPP against FDM, DIW, inkjet, aerosol-jet, LMM, Cold Fusion SLS and bulk metallic conductors. The review consolidates 57 numbered literature references and technical monographs (30 in the 2022–2026 window), 6 international standards and 18 publicly available industrial documentation sources. Bulk conductivity, volume resistivity, surface resistance and sheet resistance are distinct quantities. Values and regime boundaries are compared only when the measurement method, specimen thickness, geometry, electrode configuration and conditioning make the comparison technically valid. **Framework.** We formalise the system-level interpretation as the System-Dependent Conductivity Framework (SDCF) (§1.4, §3.9, Fig. 1, Fig. 7, Table A1), identifying the cure-state and ambient-state governing variables that translate the resin-level chemistry into the part-level realised electrical response, with quantitative anchors including crosslink density envelope 10^{-3} – 10^{-2} mol/cm³, water-driven Fickian diffusion coefficients 10^{-8} – 10^{-6} cm²/s, Tg depressions of 5–30 °C at 60–90% RH, silver-nanowire percolation at ~5 wt% loading, silver-microparticle percolation at tens of wt%, and a six-stage time-dependent trajectory from as-printed state through long-term ageing to end-of-life. **Insight.** Peer-reviewed validation is mature in electronics housings and ESD-controlled fixtures, in printed electrodes for bioelectronics R&D (three independent academic anchors documenting the photopolymer-PEDOT:PSS route for DLP-printed conductive hydrogels and ECG/EMG bioelectrodes), in sacrificial PEDOT:PSS templates for multi-material microfluidic devices, in inkjet conductive supports, and in ceramic-loaded high-permittivity photopolymer composites for microwave applications. Industrial deployment runs ahead of peer-reviewed confirmation in 4D electro-thermo-responsive actuators and in photopolymer-printed antennas. Critical limitations include percolation-threshold irreproducibility, conductivity hysteresis and humidity-driven drift in PEDOT:PSS systems, electromigration and sulfur tarnishing of silver-based systems, and the distinction between product-specific material or specimen data that may contribute to a device-level biological evaluation and medical-device approval. **Outlook.** The principal open directions are standardisation of printed-electronics resistivity metrology, expansion of 4D conductive chemistries beyond single-anchor portfolios, soluble PEDOT:PSS variant development, dielectric photopolymer formulation at higher relative permittivity, and bioprinting integration of electrically functional photopolymers at full VPP resolution.

Keywords *electrically functional photopolymer · vat photopolymerisation · printed electronics · system-dependent conductivity framework · static-dissipative photopolymer · carbon nanotube composite · graphene nanoplatelet composite · PEDOT:PSS · silver-based conductor · ferroelectric photopolymer composite · bioelectronics · sacrificial conductor · 4D printing · ESD control · 3Dresyns*

1. Introduction

1.0 Formal nomenclature

This review introduces and uses several terms that have specific meanings in the engineering-review context of this document. The terms are defined formally at first occurrence to distinguish them from broader usage in the polymer-science and printed-electronics literature. The four-level conductivity hierarchy. A central interpretive contribution of this review is the formalisation of the electrical performance reporting space into four distinct levels of measurement context. The four levels are not redundant statements of the same quantity; they correspond to measurements made under increasingly restrictive system constraints and they differ from each other by amounts that are often comparable to the reporting precision. Level 1 — Intrinsic conductivity. The conductivity of the conductive component alone, characterised as a material property independent of host matrix or processing history. Examples: bulk silver conductivity $\approx 6.3 \times 10^5$ S/cm; single-walled CNT axial conductivity 10^2 – 10^6 S/cm depending on chirality and length; graphene basal-plane conductivity 10^4 – 10^5 S/cm; PEDOT:PSS bulk conductivity 0.1– 10^3 S/cm depending on synthesis route and PSS:PEDOT ratio. Level 2 — Effective conductivity. The conductivity of the conductive-component network in a model bulk environment (typically a coupon cured under controlled conditions, characterised in a dry laboratory atmosphere at the post-cure stabilised state). This is the value typically reported in manufacturer technical datasheets and in proof-of-concept academic publications. The effective

conductivity reflects the percolation-network configuration achieved by the supplier-side cure protocol on the supplier-side reference geometry and is bounded by the intrinsic conductivity of Level 1. Level 3 — Realised conductivity. The conductivity measured on a

specific cured part produced under the user's platform, cure protocol, geometry and post-cure history. The realised conductivity reflects the System-Dependent Conductivity Framework (SDCF, below): it is the Level 2 value modified by the user-side optical, dispersion-state, orientation, geometry and post-cure factors. The SDCF is an author-proposed conceptual framework for organising factors that can contribute to differences between constituent, formulation, printed-part and deployed-system electrical performance. It does not by itself distinguish measurement uncertainty from causal material or process effects. Level 4 — Operational conductivity. The conductivity manifested during service over time, integrating environmental equilibration (Stage 3 of §3.9), service-condition cycling (Stage 4), long-term ageing (Stage 5) and end-of-life trajectory (Stage 6). Operational conductivity is history-dependent and cannot be characterised by a single value: it is a trajectory. The trajectory may rise (silver routes during initial sintering), fall (humidity-driven PEDOT:PSS drift recovery after de-humidification cycle), oscillate (cyclic-humidity service environments) or progressively degrade (electromigration, sulfur tarnishing). Operational conductivity is the engineering-relevant quantity for parts deployed in service. The four-level hierarchy resolves a recurrent ambiguity in the conductive-AM literature: a "single-value conductivity" reported in a publication can correspond to any one of the four levels depending on the measurement protocol, and the discrepancy between two studies reporting nominally similar conductivities is often a Level 2 vs Level 3 mismatch rather than a chemistry-route disagreement. The remainder of this review uses intrinsic, effective, realised and operational as defined here; where the literature reports values without specifying the level, the present review interprets the value at the level most consistent with the reported measurement protocol.

Realised electrical performance. The set of measured electrical properties (surface resistivity, volume conductivity, percolation threshold, relative permittivity, dielectric loss tangent, dielectric breakdown strength) of a specific cured photopolymer part, measured on a specific user platform under specific cure-state, post-cure-state, geometry and ambient-condition history — i.e. Level 3 of the four-level hierarchy above. The realised electrical performance is contrasted with the nominal electrical performance reported in manufacturer technical datasheets and in proof-of-concept publications (typically Level 2 effective conductivity), which is the value measured by the supplier under the supplier's reference conditions and on the supplier's reference geometry. The two values are typically related but not identical, and the discrepancy is the central interpretive object of the System-Dependent Conductivity Framework. System-Dependent Conductivity Framework (SDCF). A seven-stage process chain (Fig. 1, Table A1, §1.4) that links the intrinsic chemistry of the resin and the conductive component (stage 1), the dispersion state of the uncured formulation (stage 2), the printer optical and exposure parameters (stages 3-4), the cured-part geometry (stage 5), the post-cure protocol (stage 6), and the storage and service environment (stage 7) to the realised electrical performance of the cured part. The SDCF is the central interpretive contribution of the review and reappears as the organising principle of §3, §13 and the application sections §4-§11. The SDCF is a descriptive-and-predictive framework, not a quantitative model: it identifies the governing variables and the typical influence rankings (Table A1), and it predicts the qualitative scaling of the realised performance with each variable, but it does not provide a closed-form relationship between cured-system configuration and measured electrical property. Closed-form models exist for individual sub-stages (e.g. percolation theory for stage 1-2, Beer-Lambert attenuation for stage 3) and are cited where applicable. Operational regime. An author-proposed engineering grouping used to organise applications. Each regime must be defined using the relevant electrical quantity, test method, specimen geometry and conditioning. Packaging-derived IEC 61340-5-3 ranges are references only and do not create universal printed-part classes.

IEC 61340-5-3:2022 standard [S3], typically targeted for ESD-controlled fixtures and electronics-handling tools; Regime B (functional conductive) with surface resistivity below $10^4 \Omega/\text{sq}$, typically targeted for printed electrodes, sensor traces, sacrificial conductive templates and low-current functional conductors; Regime C (high-conductivity printed-conductor regime) with bulk conductivity above 10^2 S/cm , typically targeted for antennas, radiating elements, RFID/NFC tags and high-current paths. The high-conductivity printed-conductor regime designation refers to the printed-electronics operational context, not to equivalence with bulk metallic conductors (which sit approximately five orders of magnitude higher in bulk conductivity); the distinction is developed explicitly in §3.7. An orthogonal route delivers

dielectric function with high relative permittivity ϵ_r (typically above 5 at GHz frequencies) and low loss tangent (typically below 0.05) for RF/microwave applications; the dielectric route operates outside the conductive-regime classification and is treated separately throughout the review. Conductivity-Resolution-Printability Triad. The three coupled engineering objectives that any conductive VPP photopolymer formulation must simultaneously satisfy (§3.5): target electrical conductivity in the cured part, target print resolution (set by feature scale and surface finish), and target printability (set by the operating viscosity envelope of the platform, the recoating dynamics and the inter-layer cure cycle). The three objectives are coupled through the filler-loading variable:

raising the conductive-phase loading improves the realised conductivity, degrades the optical-attenuation-limited resolution, and degrades the rheology-limited printability simultaneously.

The triad sets a system-level ceiling on the conductivity achievable at a given platform-and-resolution target, independent of the chemistry-route choice, and is one of the central trade-offs that the SDCF formalises. Electrical-function route. A coherent combination of (i) a conductive-or-dielectric component class, (ii) a host photopolymer matrix family, and (iii) a documented engineering deployment pattern that delivers a specific subset of the operational-regime space. The review identifies seven principal routes (§1.3, §3.2) plus the orthogonal dielectric route, and uses the term "route" to designate this composite design unit rather than the narrower meaning (a specific chemical pathway) that the term carries in synthetic chemistry contexts.

Design axes. Two orthogonal binary choices that cross all seven electrical-function routes (§1.3): the solubility axis (cured-part soluble or non-soluble after cure, relevant for sacrificial-template workflows) and the biological-evidence axis (Bio-designated or non-Bio variants of the route, relevant for bioelectronics R&D and medical-device-adjacent applications). The design axes operate independently of the route classification and combine multiplicatively with it to define the formulation design space. Cure-state effects. The set of variations in the realised electrical performance attributable to differences in the cure history of the cured part, holding the resin formulation constant. Cure-state effects include cure conversion, crosslink density, filler orientation during cure, post-cure thermal-cycle history and oxygen-inhibition history. The cure-state effects are SDCF stages 3-6 and are developed in §3.9.

1.1 The functional-electronics transition in additive manufacturing

The interpretation of additive manufacturing as a technology for the production of inert mechanical parts is increasingly complemented by functional additive manufacturing — the production of parts that hold an active electrical, optical, biological or actuator function [1–2,8]. Within functional additive manufacturing, the electrically functional segment occupies a particularly demanding position. The printed part must hold a defined electrical function across its service life, retain dimensional stability under thermal cycling, deliver reproducible electrical performance within engineering tolerances, and where applicable comply with regulatory frameworks for electrostatic control (IEC 61340-5-1, IEC 61340-5-3), biological contact (ISO 10993-1), device classification (EU MDR 2017/745) or RF/microwave specification. These requirements are not addressed by a single resin chemistry. The electrical function delivered by the cured part — whether static-dissipative protection of sensitive electronics, intrinsic or filler-mediated active conduction, conducting-polymer transport, metallic-particle conduction, or dielectric response in high-permittivity ceramic composites — sets the response of the system to operating

temperature, humidity history, geometry, dispersion quality and long-term ageing. Two routes that deliver the same numerical value of a chosen electrical figure of merit can correspond to qualitatively different long-term behaviour, and a route that performs favourably on one parameter may underperform on another [7,11,18]. Background technical references on the underlying conducting-polymer chemistry [B1], printed-electronics ink design [B2], photopolymer lithography fundamentals [B3] and conductive 3D composite formulation [B4] consolidate the chemistry context that the present review builds on for the additive manufacturing application space. IEC 61340-5-3:2022 specifies properties and requirements for packaging intended to protect electrostatic-discharge-sensitive devices. Its resistance ranges are used here only as packaging-derived engineering references and are not universal material classes or acceptance criteria for additively manufactured fixtures or parts. Where such ranges are used, the item type, measured electrical property, test method, electrode configuration, conditioning, geometry and application-specific ESD control plan must be stated. IEC 61340-5-1:2024 defines requirements for establishing, implementing and maintaining an organisational ESD control program. Compliance cannot be inferred from resin identity or one electrical measurement alone.

1.2 The triple constraint of vat photopolymerisation for electrically functional systems

Definition. For the purposes of this review, electrically functional photopolymers are defined as photopolymer systems designed to deliver controlled electrical behaviour — including conductive (Regime C, high-conductivity printed-conductor regime), functional-conductive (Regime B, 10^{-3} – 10^4 Ω/sq), static-dissipative (Regime A, 10^4 – 10^{11} Ω/sq), dielectric-orthogonal (high ϵ_r , low $\tan \delta$ at GHz frequencies), and field-responsive (4D electro-thermo-responsive) behaviour — rather than purely structural performance. The class includes filler-based percolation composites (carbon nanotube, graphene

nanoplatelet, silver-based, ceramic-loaded), intrinsic conductive photopolymer backbones, conducting-polymer-loaded systems (PEDOT:PSS-based), conductive surface coatings on cured photopolymer substrates and stimulus-responsive hydrogel-based photopolymer systems. Excluded from the class are photopolymer systems whose electrical response is incidental rather than designed (typical insulating engineering photopolymers with parasitic conductivity below 10^{-12} S/cm) and conductive inks not transferable to VPP processing (high-temperature sintered metallic inks, conductive thermoplastics for FDM). Vat photopolymerisation imposes a triple constraint on the formulation of electrically functional systems. The matrix must be photocurable through radical polymerisation at viscosities compatible with the platform [5–6] — typically below approximately 2,000 mPa·s for desktop MSLA and DLP

platforms, with industrial laser-SLA accepting higher values. The electrically active component must not absorb the curing wavelength to an extent that prevents through-depth cure: a system in which the conductive filler, the conducting polymer or the high-permittivity ceramic absorbs strongly in the 365–405 nm window propagates a cure-depth limitation that compromises layer adhesion and dimensional stability [5,18,30]. The electrically active component must remain stably dispersed in the matrix during printing — agglomeration or sedimentation during cure produces a part whose electrical response is geometry-anisotropic in ways the CAD did not anticipate, and storage shelf-life of the uncured formulation determines whether the same response is reproducible from one print to the next [7,31]. Filler-based percolation composites address the first two constraints through control of filler loading and dispersion chemistry but face the third constraint as an ongoing engineering problem [2–3,7,32–33]. Recent peer-reviewed work has revealed that the rheological percolation threshold (the loading at which the suspension transitions from Newtonian to non-Newtonian behaviour) and the electrical percolation threshold (the loading at which conduction emerges) are decoupled in VPP photopolymer matrices, with the matrix chemistry and the dispersion protocol controlling the size of the gap between the two [32]. The strategic implication is that the lowest filler loading compatible with VPP printability and the lowest filler loading delivering target conductivity do not coincide; the formulation must navigate the gap explicitly. Conducting-polymer matrices address the first and third constraints through covalent integration of the conducting polymer into the photopolymer system but face the second constraint as a wavelength-management problem because the conducting polymer typically has its own absorption profile that overlaps with the

curing wavelength range [4,12,17,28]. Metallic-particle systems based on silver address the first and third constraints with established formulation chemistry but face long-term ageing under humid and oxidative environments [11,19,29]. Ceramic-loaded dielectric composites address the first constraint at low-to-moderate filler loading but face severe printability and wavelength-attenuation constraints at the high loadings required for engineering-grade permittivity [18,34]. The four constraint patterns together imply that no single formulation strategy spans the electrically functional design space of VPP printed electronics. The portfolio response — multiple chemistry routes addressing different combinations of electrical function, biocompatibility, solubility and matrix viscosity — is therefore an engineering necessity rather than a marketing artefact.

1.3 Seven electrical-function routes, three operational regimes, two orthogonal design axes

This review organises the electrically functional VPP photopolymer field around seven electrical-function routes operating across three operational regimes of electrical behaviour. The

Regime A — Static-dissipative: Route 1 covers ESD-focused photopolymers evaluated under an application-specific ESD control plan. IEC 61340-5-3:2022 packaging ranges may be cited only as engineering references, with the measured electrical property, method, electrode configuration, conditioning and geometry stated. Regime B — Functional active conduction: Routes 2–5 cover intrinsic, CNT, GNP and PEDOT:PSS systems. Bulk conductivity, volume resistivity, surface resistance and sheet resistance must be reported as distinct quantities; no universal boundary is proposed. Regime C — High-conductivity printed-conductor regime: Route 6 covers silver-based systems described using measured bulk conductivity and a stated method. Route 7 is an orthogonal dielectric route evaluated using relative permittivity and loss tangent.

- Route 5: Intrinsically conducting polymer (ICP) — delocalised conduction along the conducting-polymer backbone of poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS).

Regime C — High-conductivity printed-conductor regime conduction (bulk conductivity $>10^2$ S/cm):

- Route 6: Silver-based metallic systems — conduction through dispersed silver-particle networks at high loading.

Orthogonal regime — Dielectric response (relative permittivity ϵ_r at GHz frequencies):

- Route 7: Ferroelectric and high-permittivity composites — non-conductive high- ϵ_r behaviour through ceramic filler (BaTiO_3 , TiO_2 , $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$) dispersion in a photopolymer host.

Two orthogonal design axes cross each conductive route: the solubility of the cured part (non-soluble permanent conductor vs water-soluble or water-swellaible sacrificial conductor) and the biological-evidence status (resin-level

alignment with ISO 10993-1 for bioelectronics R&D applications). A separate 4D electro-thermo-responsive direction (4D-ETR) operates as a stimuli-responsive hydrogel platform shared with bio-scaffold workflows. The taxonomy is intended as a structural map of the electrically functional VPP photopolymer field as it has consolidated in the peer-reviewed literature over the 2015–2026 period [2–4,7–8,10–14,17–19,28,30,32–38]. It is not derived from any single commercial portfolio. A representative industrial implementation of the taxonomy is documented as a case study at the end of §3, after the chemistry and design principles have been developed without portfolio-specific commitments.

1.4 The System-Dependent Conductivity Framework (SDCF)

A central interpretive position of this review can be stated at the outset. The surface resistivity, volume conductivity, percolation-threshold values, relative permittivity and loss tangent of an electrically functional photopolymer part should be interpreted as system-level outcomes rather than as intrinsic resin-only properties. We refer to this position as the System-Dependent Conductivity Framework (SDCF) and formalise it as a seven-stage process chain in Fig. 1. The SDCF identifies seven stages that jointly determine the realised electrical performance of a cured part: (1)

the intrinsic chemistry of the resin and the conductive component, (2) the dispersion quality and the as-mixed filler loading, (3) the printer optics (wavelength, peak irradiance, beam profile), (4) the power-time decomposition of the cumulative cure dose, (5) the geometry and build orientation, (6) the post-cure protocol (UV dose, thermal cycle, dwell time), and (7) the storage and service environment (humidity, atmosphere, ageing). The output of the chain is not a single conductivity value but a distribution: prints from nominally identical formulations on different platforms, in different geometries or with different post-cure protocols sit at different points within this distribution.

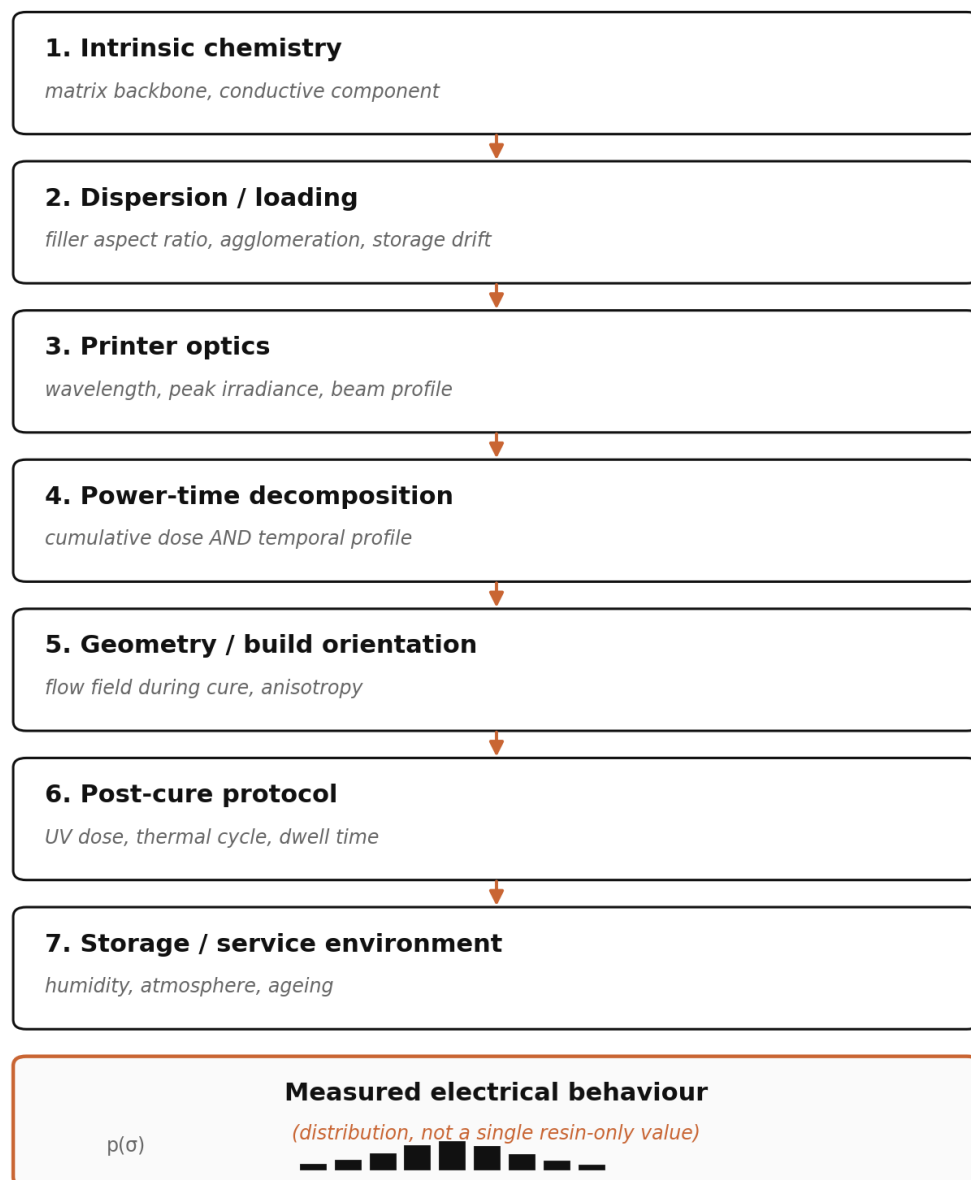


Figure 1. The System-Dependent Conductivity Framework (SDCF). Seven-stage process chain from intrinsic chemistry to measured electrical behaviour. The output is a distribution of realised values rather than a single resin-only property.

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The position is not new in the polymer-physics or printed-electronics literature, where the dependence of electrical performance on processing variables is documented for filament-based composites [8], for printed nanoparticle inks [11,29], for conducting-polymer films [12,28] and for ceramic-loaded dielectric composites [18]. Recent VPP-specific work has quantified the dependence directly: Sevriugina et al. [32] demonstrated that the disparity between the electric and rheological percolation thresholds in carbon-filled VPP photopolymers is controlled by the matrix type and the dispersion protocol, with cross-system variability of approximately one order of magnitude in the realised conductivity at fixed nominal loading. What this review identifies as an under-addressed interpretive limitation is the convention in many electrically functional VPP photopolymer manufacturer datasheets and in a subset of the peer-reviewed literature to report a single

performance value per product, decoupled from the system configuration that produced it. The convention is inherited from the bulk-polymer characterisation tradition where the cured-part geometry is sufficiently large that surface and geometric effects are negligible. For VPP additive manufacturing parts at typical resolution scales (50–200 μm layer thickness, sub-millimetre feature size), the convention propagates a mismatch between reported value and realised value that this

review aims to make explicit.

Table A1. SDCF governing variables and their influence on realised electrical performance.

SDCF stage	Governing variable	Influence on realised performance	Principal mechanism
1 — Chemistry	Resin matrix type (aromatic vs aliphatic)	High	Sets the electric-vs-rheological percolation gap [32]
1 — Chemistry	Conductive component type and aspect ratio	High	Sets the percolation threshold for filler routes [2–3,7,22]
2 — Dispersion	Dispersion quality (aggregation state)	High	Aggregated fillers behave as oversized effective particles with lower aspect ratio [7,33]
2 — Dispersion	As-mixed filler loading	High	Below-threshold loading is insulating; above-threshold loading follows power-law conductivity rise [2,22,27]
3 — Printer optics	Curing wavelength	High	Determines depth of cure with conductive-component absorption [4–5,18,28,49]
3 — Printer optics	Peak irradiance and beam profile	Moderate	Affects cure kinetics and local exotherm [1,5–6]
4 — Cure dose	Cumulative cure dose (power x time)	High	Determines crosslink density and final conversion [1,5,26]
4 — Cure dose	Layer thickness	Moderate	Sets the cure-depth gradient per layer and affects through-thickness uniformity

5 — Geometry	Build orientation relative to filler axis	Moderate-High (filler routes)	Anisotropic conductivity from flow-aligned platelets and nanotubes [3,22]
5 — Geometry	Cured-feature characteristic dimension	Moderate	Surface-to-volume ratio affects oxygen-inhibition skin and ageing kinetics
6 — Post-cure	Post-cure UV dose and atmosphere	High	Completes conversion; oxygen exposure affects surface conductivity [26]
6 — Post-cure	Post-cure thermal cycle	Moderate	Sets matrix relaxation and conductive-network sintering (silver routes) [11,19,29]
7 — Storage / service	Ambient humidity	High (PEDOT:PSS routes), moderate (filler routes)	Reversible-with-hysteresis conductivity change in PEDOT:PSS [12,17,28,38]; moderate effect on filler routes
7 — Storage / service	Operating temperature	Moderate-High (ferroelectric routes near Curie point)	Curie-point ϵ_r collapse in BaTiO ₃ -based composites [18,23,25]; moderate effect on metallic and filler routes
7 — Storage / service	Service-life environment (oxidative, sulfur-containing)	High (silver routes)	Tarnishing, electromigration [11,19,29]

Influence rankings (high / moderate / low) are qualitative consolidations from the peer-reviewed literature cited and reflect the typical order of magnitude of the effect on the realised surface resistivity, volume conductivity, percolation threshold or dielectric response. The mapping between variable and route is non-uniform: a variable that exerts high influence on one route may exert moderate or low influence on another, as detailed in §3.4–§3.10.

The table summarises the principal cure-state, processing and ambient-state variables that translate the resin-level chemistry into the part-level electrical response. Influence rankings (high / moderate /

low) are qualitative consolidations from the peer-reviewed literature cited and reflect the typical order of magnitude of the effect on the realised surface resistivity, volume conductivity, percolation threshold or dielectric response. The mapping between variable and route is non-uniform: a variable that exerts high influence on one route may exert moderate or low influence on another, as detailed in §3.4–§3.10.

SDCF stage Governing variable Influence on realised Principal mechanism performance

1 — Chemistry Resin matrix type (aromatic High Sets the vs aliphatic) electric-vs-rheological percolation gap [32]

1 — Chemistry Conductive component type High Sets the percolation threshold and aspect ratio for filler routes [2–3,7,22]

2 — Dispersion Dispersion quality High Aggregated fillers behave as (aggregation state) oversized effective particles with lower aspect ratio [7,33]

2 — Dispersion As-mixed filler loading High Below-threshold loading is insulating; above-threshold loading follows power-law conductivity rise [2,22,27]

3 — Printer optics Curing wavelength High Determines depth of cure with conductive-component absorption [4–5,18,28,49]

3 — Printer optics Peak irradiance and beam Moderate Affects cure kinetics and local profile exotherm [1,5–6]

- 4 — Cure dose Cumulative cure dose (power High Determines crosslink density x time) and final conversion [1,5,26]
- 4 — Cure dose Layer thickness Moderate Sets the cure-depth gradient per layer and affects through-thickness uniformity
- 5 — Geometry Build orientation relative to Moderate-High (filler routes) Anisotropic conductivity from filler axis flow-aligned platelets and nanotubes [3,22]
- 5 — Geometry Cured-feature characteristic Moderate Surface-to-volume ratio dimension affects oxygen-inhibition skin and ageing kinetics
- 6 — Post-cure Post-cure UV dose and High Completes conversion; atmosphere oxygen exposure affects surface conductivity [26]
- 6 — Post-cure Post-cure thermal cycle Moderate Sets matrix relaxation and conductive-network sintering (silver routes) [11,19,29]
- 7 — Storage / service Ambient humidity High (PEDOT:PSS routes), Reversible-with-hysteresis moderate (filler routes) conductivity change in PEDOT:PSS [12,17,28,38]; moderate effect on filler routes
- 7 — Storage / service Operating temperature Moderate-High (ferroelectric Curie-point ϵ_r collapse in routes near Curie point) BaTiO₃-based composites [18,23,25]; moderate effect on metallic and filler routes
- 7 — Storage / service Service-life environment High (silver routes) Tarnishing, electromigration (oxidative, sulfur-containing) [11,19,29]

The SDCF reappears throughout the review as the organising principle of the chemistry section (§3), the failure-mode framework (§3.10 and §13.10), the cure-state effects section (§3.9) and the comparative selection framework (§12). It is the central interpretive contribution of the review.

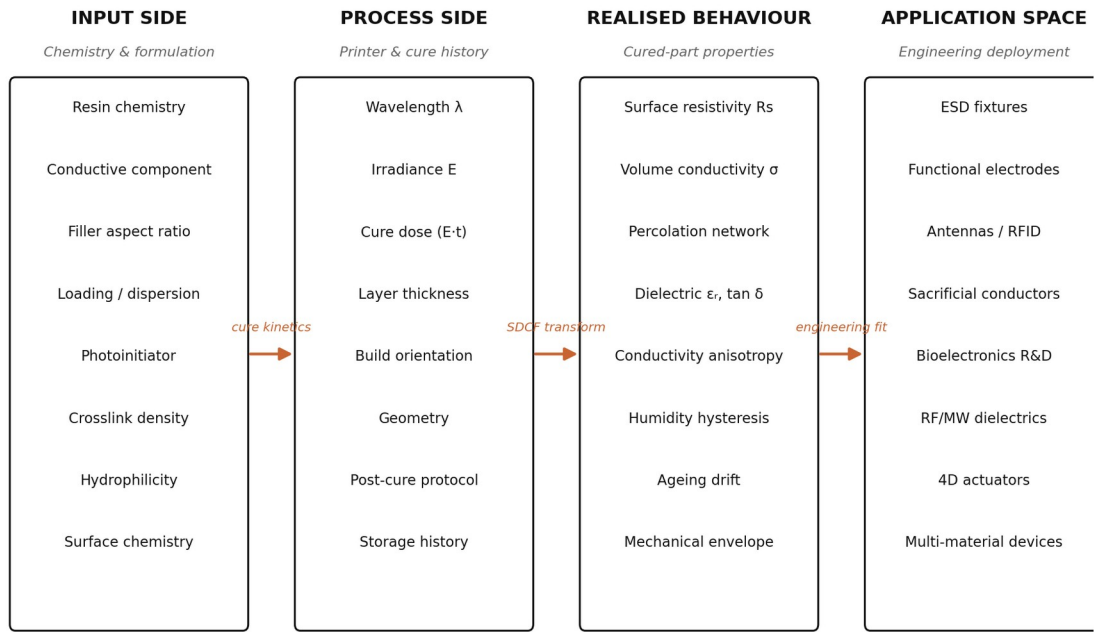


Figure 7. Conceptual framework: from input chemistry to engineering application. Four-column architecture mapping the design problem of electrically functional VPP photopolymers; the central SDCF transform links the input-and-process design space to the realised behaviour.

Four-column architecture mapping the design problem of electrically functional VPP photopolymers: the input side (chemistry, conductive component, filler aspect ratio, loading, photoinitiator, crosslink density, hydrophilicity, surface chemistry) is transformed through the process side (printer wavelength, irradiance, cure dose, layer thickness, build orientation, geometry, post-cure protocol, storage history) into the realised behaviour of the cured part (surface resistivity, volume conductivity, percolation network, dielectric properties, conductivity anisotropy, humidity hysteresis, ageing drift, mechanical envelope), which positions the part within the application space of the field. The central SDCF transform links the input-and-process design space to the realised behaviour: route selection narrows the design space, but the realised behaviour is set by the full input-process history, not by the resin chemistry alone. The figure operates as the conceptual key to the review and integrates the framework material developed in §1, §3 and §12 into a single visual map.

1.5 Scope and structure

Section 2 documents the literature search methodology and positions VPP electrically functional photopolymers within the broader printed-electronics landscape (FDM, DIW, inkjet/aerosol-jet). Section 3 develops the chemistry and design principles common to the seven routes, consolidates quantitative envelopes from the peer-reviewed literature and from publicly available manufacturer datasheets, identifies critical limitations of the field, and introduces the representative industrial portfolio as an industrial case study. Sections 4 through 11 examine eight application areas with peer-reviewed and industrial documentation. Section 12 consolidates a route-vs-application selection framework. Section 13 identifies open challenges. Section 14 concludes. The intended reader is the formulation engineer, the AM process engineer, the printed-electronics R&D lead and the advanced industrial user.

2. Literature methodology and landscape positioning

2.0 Literature search and selection methodology

Peer-reviewed publications were identified through Scopus, Web of Science and Google Scholar database searches conducted between January and April 2026, using combinations of the following keyword sets: ("vat photopolymerization" OR "stereolithography" OR "SLA" OR "DLP" OR "LCD" OR

"MSLA" OR "two-photon polymerization") combined with ("conductive resin" OR "conductive photopolymer" OR "printed electronics" OR "ESD photopolymer" OR "static dissipative photopolymer" OR "conductive composite" OR "carbon nanotube composite" OR "graphene composite" OR "PEDOT:PSS" OR "conductive hydrogel" OR "silver nanoparticle" OR "sacrificial conductor" OR "ferroelectric photopolymer" OR "high permittivity photopolymer" OR "dielectric photopolymer composite" OR "piezoresistive photopolymer"). Searches were further filtered by year (2014–2026), language (English), and document type (peer-reviewed articles, peer-reviewed reviews, peer-reviewed conference proceedings). The 2014 lower bound reflects the commercial availability boundary of high-resolution desktop VPP hardware on which electrically functional resin formulations subsequently developed; pre-2014 literature is referenced selectively where it provides foundational percolation theory, conducting-polymer chemistry, dielectric composite theory or printed-electronics methodology that remains current. Particular emphasis was placed on identifying 2022–2026 primary studies on VPP-specific electrically functional composites, with approximately one-third of the peer-reviewed bibliography drawn from this most-recent window

[13,15,18,20,28,30,32–40]. Inclusion criteria: studies reporting either characterisation or application of electrically functional photopolymer resin systems printable on vat photopolymerisation platforms; studies on conducting-polymer, filler-composite or dielectric-composite chemistry directly relevant to VPP processability; standards and regulatory documents directly cited in the application sections (§4–§11). Exclusion criteria: studies on conductive inks not transferable to VPP (e.g. high-temperature sintered metallic inks for screen printing); studies on conductive bulk thermoplastics

for FDM that do not generalise to photocurable systems; studies on conductive coatings rather than bulk-cured parts (with the exception of conductive coatings applied to VPP-printed substrates, noted in §3.12). Industrial documentation, technical datasheets and manufacturer publications are cited where they provide engineering parameters not available in the peer-reviewed literature; these references carry the prefix [PR] (product reference) and are flagged as manufacturer documentation in the reference list. Where publicly available technical datasheets report quantitative TDS values (e.g. hardness, modulus, surface resistivity, relative permittivity), those values are cited with explicit acknowledgement of the SDCF (§1.4) and with the publicly available TDS as the source. The single-author industrial-academic origin of this review is declared in the Disclosure note; the consequences for interpretive scope are made explicit in §13.10 (Limitations). Selection accountability and study flow. The initial database searches returned approximately 1,400 records across the keyword combinations and date windows specified above. Duplicate-removal across the three databases reduced the pool to approximately 920 unique records. Title-and-abstract screening against the inclusion criteria reduced the pool to approximately 180 records eligible for full-text review. Full-text review against the inclusion-exclusion criteria —with the principal exclusion reasons being non-VPP printing technology (FDM-only, DIW-only, inkjet-only without VPP transferability), studies of insulating engineering photopolymers with parasitic conductivity below 10^{-12} S/cm, and studies on conductive coatings without bulk-cured photopolymer substrate context — produced the 56 peer-reviewed references and technical monographs cited in this review. The 6 international standards were selected by direct reference from the regulatory and metrology sections of the cited peer-reviewed literature (IEC 61340 family, ISO 10993 family, ASTM D257, ASTM D6866). The 4 background technical references (Sigma-Aldrich Material Matters volumes covering conducting polymers, printed-electronics inks, photopolymer lithography fundamentals and

conductive 3D composites) were selected for chemistry-foundation context. The 18 product references ([PR] prefix) are publicly available technical datasheets or instructions-for-use that document engineering parameters not present in the peer-reviewed sources; they are flagged as manufacturer documentation in the reference list and are not used as primary evidence for cross-route claims. The 85-reference final count comprises 57 numbered literature references and technical monographs (30 of them in the 2022–2026 window), 6 standards, 4 background technical references and 18 product references. A formal PRISMA-style flow diagram is not provided because the review is not a systematic review

under the PRISMA framework; it is a framework-driven engineering review with descriptive synthesis, and the numerical flow above is provided for selection-accountability rather than systematic-review compliance.

2.1 By printing technology

Along the printing-technology axis, four families currently address the electrically functional additive manufacturing space. Fused deposition modelling (FDM) of conductive thermoplastic filaments has the longest commercial history. Polylactic acid, polycaprolactone and thermoplastic polyurethane filaments loaded with carbon black, carbon nanotubes or graphene are commercially available, with peer-reviewed validation in printed circuit prototyping, sensor fabrication and educational electronics [8,36]. The achievable resolution is typically 200–500 μm at the line scale, which limits the technology to coarser printed-electronics geometries. Direct-ink writing (DIW) of conductive inks based on silver nanoparticles, copper nanoparticles, eutectic gallium-indium liquid metal or carbon-based fillers extends the resolution envelope downward, with sub-100 μm line widths achievable on industrial platforms [10,20,29]. The Lewis laboratory at Harvard and several adjacent research groups have established DIW as the dominant academic route for high-resolution printed electronics, with applications spanning stretchable electronics, neural interfaces and embedded sensors [10,20]. DIW typically operates with inks rather than with cured-network materials, and the printed part

requires a post-print sintering or curing step that fixes the conductive network. Inkjet and aerosol-jet printing of conductive nanoparticle inks target the sub-50 μm resolution envelope with droplet-based deposition. Commercial platforms have established this route for printed-circuit prototyping with through-hole and via-level resolution comparable to conventional PCB manufacturing [11,21,29]. The materials are typically silver nanoparticle inks with thermal-sintering post-processing. Vat photopolymerisation (VPP) of electrically functional photopolymer resins — SLA, DLP and LCD masked stereolithography — is the most recent commercial entrant. The historical bottleneck was the triple constraint identified in §1.2: a photopolymer matrix is by default electrically insulating, and the strategies for delivering electrical function through the matrix without compromising photocurability are non-trivial [4,7,18,30]. The development of photopolymer chemistries that print with full VPP fidelity and deliver electrical function across the seven routes mapped in §1.3 has progressed substantially over the past 5–7 years, opening the resolution and surface-quality envelope of SLA, DLP and LCD to printed-electronics workflows that previously belonged to FDM, DIW or inkjet platforms. Recent peer-reviewed reviews [33–35] have consolidated the VPP conductive-nanocomposite state of the art and identified the three open methodological questions that continue to constrain the field: how to maintain cure depth at conductive loading, how to manage anisotropic conductivity from build-orientation effects, and how to standardise reporting metrology across studies. The resolution and surface-quality position of VPP is not absolute. Inkjet and aerosol-jet platforms remain advantaged in throughput for large-area printed electronics with sub-50 μm features; recent advances in acoustic-focused aerosol-jet printing have pushed aerosol-jet line widths below 6 μm with overspray below 0.1 μm and printing stability over 8-hour runs [52]. Comparative direct-write analysis [53] further benchmarks aerosol-jet printing against alternative direct-write deposition

techniques for flexible electronics, with the trade-off between resolution, throughput and ink versatility determining the optimal route per application class. DIW remains advantaged in materials flexibility and in geometries that benefit from controlled rheological deposition or the integration of soft and stretchable matrices [20]. FDM remains advantaged in cost per part for educational and prototyping applications where resolution above 200 μm is sufficient. VPP electrically functional photopolymers occupy the application space where the electrical function and the structural function of the part must be delivered by a single cured material at sub-100 μm resolution without substantial loss of dimensional fidelity.

Table B. Comparative manufacturing-space positioning of VPP electrically functional photopolymers against alternative additive manufacturing technologies.

Technology	Conductivity range (bulk, S/cm)	Feature resolution	Multi-material capability	Typical throughput	Mechanical compliance	Mature application areas
FDM conductive thermoplastic filaments	10^{-3} – 10^1	200–500 μm	manual (filament swap)	low–medium	rigid to elastomeric (Shore A–D)	educational electronics, sensor prototypes, low-cost prototyping [8,36]
DIW conductive inks (Ag NP, EGaln, CNT, PEDOT)	10^{-2} – 10^4 (Ag); 10^{-2} – 10^2 (PEDOT, EGaln)	50–200 μm	high (multi-nozzle)	low	wide range incl. stretchable	research bioelectronics, soft robotics, stretchable antennas [10,20,29]

Inkjet conductive nanoparticle inks	10^2 – 10^4 (Ag post- sintering)	20–50 μm	medium	high (large- area)	rigid substrate dependent	printed circuit prototyping, large-area printed electronics, RFID/NFC [11,21,29,46]. Limitation: viscosity ceiling <50 mPa·s sets a hard ceiling on filler loading; high-loading inkjet feedstocks produce nozzle clogging.
Aerosol-jet conductive nanoparticle inks	10^2 – 10^4	<6–50 μm [52]	medium	high (controlled deposition)	rigid substrate dependent	high- resolution printed circuits, large-area printed electronics, sensors [52– 53]
VPP electrically functional photopolym ers	10^{-5} – 10^4 (full route span Tables 1–2)	25–100 μm	medium (rotating-vat or sequential, [13–14,44])	medium (batch)	wide range (Shore A10–D90 per route, §A.2)	ESD fixtures, bioelectronics R&D, sacrificial microfluidic templates, RF/microwave dielectric [13,18,32– 33,36,48–49]
LMM (lithography- based metal manufacturing)	metallic equivalent (post- sinter)	30–100 μm	low (single-feed stock typically)	medium	rigid post-sinter; metal envelope	high-loading conductive metal parts at intermediate resolution; expanding to engineering metals beyond stainless and copper [PR1,PR2]. Rheological regime: high- loading paste feedstock (50– 60 vol% metal); requires LMM-specific hardware.
Cold Fusion SLS (binder- mediated metal sintering)	metallic equivalent (post- sinter)	50–150 μm	low–medium	medium	rigid post-sinter; metal envelope	low-cost low- power SLS hardware accessing conductive metallic parts; widens AM platform palette to

						desktop-scale units [PR1,PR2]
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Technology	Conductivity range (bulk, S/cm)	Feature resolution	Multi-material capability	Typical throughput	Mechanical compliance	Mature application areas
Indirect AM (VPP mold + slurry casting + debinding + sintering)	metallic equivalent (post-sinter)	mold-limited (typically VPP resolution + slurry shrinkage)	high (multi-slurry hybrid)	medium-low	rigid post-sinter; metal/ceramic envelope	high-loading conductive parts requiring mechanical envelope unreachable by direct VPP; bypasses VPP photopolymer-printability ceilings
Conductive surface coating on cured photopolymer	10 ⁰ -10 ² (paint-thickness dependent)	substrate-limited	high (selective area painting)	high (post-print step)	hydrophobic structural matrix + surface coating	localised conductive function on parts otherwise optimised for mechanical performance [PR8]
Reference: bulk metallic conductors (Cu, Al)	10 ⁵ -10 ⁶	not AM-direct	not applicable	n/a	rigid	not AM-direct (subtractive or cold spray)

Values are indicative ranges from the cited literature [8,10-11,13,18,20-21,29-30,32-36,41,46] and from manufacturer documentation; specific values within each cell depend on the platform, the material system and the operating conditions.

photopolymers against alternative additive manufacturing technologies. Values are indicative ranges from the cited literature [8,10-11,13,18,20-21,29-30,32-36,41,46] and from manufacturer documentation; specific values within each cell depend on the platform, the material system and the operating conditions.

Technology Conductivity Feature Multi-material Typical Mechanical Mature range (bulk, resolution capability throughput compliance application S/cm) areas

FDM conductive 10⁻³-10¹ 200-500 μm manual low-medium rigid to educational thermoplastic (filament swap) elastomeric electronics, filaments (Shore A-D) sensor prototypes, low-cost prototyping [8,36]

DIW conductive 10⁻²-10⁴ (Ag); 50-200 μm high low wide range incl. research inks (Ag NP, 10⁻²-10²(multi-nozzle) stretchable bioelectronics, EGAIn, CNT, (PEDOT, EGAIn) soft robotics, PEDOT) stretchable antennas [10,20,29]

Inkjet 10²-10⁴ (Ag 20-50 μm medium high rigid substrate printed circuit conductive post-sintering) (large-area) dependent prototyping, nanoparticle large-area inks printed electronics, RFID/NFC [11,21,29,46]. Limitation: viscosity ceiling <50 mPa·s sets a hard ceiling on filler loading; high-loading inkjet feedstocks produce nozzle clogging.

Aerosol-jet 10^2 – 10^4 <6–50 μm [52] medium high (controlled rigid substrate high-resolution conductive deposition) dependent printed circuits, nanoparticle large-area inks printed electronics, sensors [52–53]

VPP electrically 10^{-5} – 10^4 (full 25–100 μm medium medium (batch) wide range ESD fixtures, functional route span (rotating-vat or (Shore A10–D90 bioelectronics photopolymers Tables 1–2) sequential, per route, §A.2) R&D, sacrificial [13–14,44]) microfluidic templates, RF/microwave dielectric [13,18,32–33,36,48–49]

Technology Conductivity Feature Multi-material Typical Mechanical Mature range (bulk, resolution capability throughput compliance application S/cm) areas

LMM (lithograph metallic 30–100 μm low (single-feed medium rigid post-sinter; high-loading y-based metal equivalent stock typically) metal envelope conductive manufacturing) (post-sinter) metal parts at intermediate resolution; expanding to engineering metals beyond stainless and copper [PR1,PR2].

Rheological regime: high-loading paste feedstock (50–60 vol% metal); requires LMM-specific hardware.

Cold Fusion SLS metallic 50–150 μm low-medium medium rigid post-sinter; low-cost (binder-mediate equivalent metal envelope low-power SLS d metal (post-sinter) hardware sintering) accessing conductive metallic parts; widens AM platform palette to desktop-scale units [PR1,PR2]

Indirect AM (VPP metallic mold-limited high medium-low rigid post-sinter; high-loading mold + slurry equivalent (typically VPP (multi-slurry metal/ceramic conductive parts casting + (post-sinter) resolution + hybrid) envelope requiring debinding + slurry mechanical sintering) shrinkage) envelope unreachable by direct VPP; bypasses VPP photopolymer-printability ceilings

Conductive 10^0 – 10^2 substrate-limited high (selective high (post-print hydrophobic localised surface coating (paint-thickness d area painting) step) structural conductive on cured dependent) matrix + function on photopolymer surface coating parts otherwise optimised for mechanical performance [PR8]

Reference: bulk 10^5 – 10^6 not AM-direct not applicable n/a rigid not AM-direct metallic (subtractive or conductors (Cu, cold spray) Al)

Three observations follow from Table B. First, the conductivity envelopes overlap substantially across FDM, DIW, inkjet and VPP technologies; technology selection is rarely determined by conductivity alone. Second, VPP electrically functional photopolymers sit in the middle of the resolution-vs-throughput trade-off, with feature resolution comparable to inkjet/aerosol-jet but throughput lower than the high-volume printed-electronics routes. Third, the most distinctive characteristic of VPP electrically functional photopolymers is the combination of sub-100 μm resolution with the wide mechanical-compliance envelope available per route (Shore A10 super-elastic to Shore D90 high-temperature within a single ESD chemistry family, §A.2), supporting application classes that require the electrical function and the structural function in a single cured material. The high-conductivity printed-conductor regime regime (Regime C) of Route 6 reaches 10^4 S/cm, approximately one order of magnitude below the bulk copper/aluminium reference; closing this gap is identified as

an open challenge in §13.1.

2.2 By electrical-function regime — overview

Three operational regimes structure the electrically functional photopolymer landscape along the surface resistivity / volume conductivity axis, with a fourth orthogonal axis covering dielectric

response. Table A2 summarises the regime structure as it applies to printed-electronics applications. Figure 2 maps the route positions in the resistivity-printability space.

Table A2. Three operational regimes of electrically functional VPP photopolymers, plus one orthogonal dielectric regime.

Regime	Surface resistivity	Typical figure of merit	Engineering target	Routes addressing the regime
A. Static-dissipative (ESD)	$10^4 \leq R_s \leq 10^{11} \Omega/\text{sq}$	Surface resistivity	Electronics handling, ESD-safe workflows under IEC 61340-5-1	Route 1 (ESD-focused photopolymers)
B. Functional conductive	Application-specific target; state the electrical quantity, method and geometry	Volume conductivity, sheet resistance	Printed electrodes, embedded sensors, traces, bioelectronics R&D	Routes 2 (intrinsic), 3 (CNT), 4 (GNP), 5 (PEDOT:PSS)
C. High-conductivity printed-conductor regime	$\leq 10^{-1} \Omega/\text{sq}$	Volume conductivity	Printed antennas, RFID/NFC tags, high-current paths	Route 6 (silver-based metallic)
Orthogonal: Dielectric	(non-conductive)	Relative permittivity ϵ_r , loss tangent $\tan \delta$ at GHz	RF/microwave components, capacitors, resonators	Route 7 (ferroelectric / high-permittivity composites)

Packaging-derived resistance ranges from IEC 61340-5-3:2022 [S3] are shown only as engineering references and not as universal printed-part classes; the high-conductivity printed-conductor regime threshold follows the conventional printed-electronics literature.

orthogonal dielectric regime. Packaging-derived resistance ranges from IEC 61340-5-3:2022 [S3] are shown only as engineering references and not as universal printed-part classes; the high-conductivity printed-conductor regime threshold follows the conventional printed-electronics literature.

Regime | Electrical quantity and engineering interpretation | Engineering target | Routes addressing the regime

A. Static-dissipative | Electrical property, method, geometry, conditioning and application-specific ESD criterion must be stated; packaging-derived ranges are engineering references only | Electronics handling and ESD-control workflows | Route 1

B. Functional conductive | Bulk conductivity, volume resistivity, surface resistance or sheet resistance reported only with the relevant method and geometry; no universal boundary is proposed | Printed electrodes, embedded sensors, traces and bioelectronics R&D | Routes 2–5

C. High-conductivity printed-conductor regime | Author-proposed screening regime described using measured bulk conductivity and a stated method | Printed antennas, RFID/NFC tags and high-current paths | Route 6

Orthogonal: Dielectric (non-conductive) Relative permittivity ϵ_r , RF/microwave Route 7 (ferroelectric / loss tangent $\tan \delta$ at components, high-permittivity GHz capacitors, resonators composites)

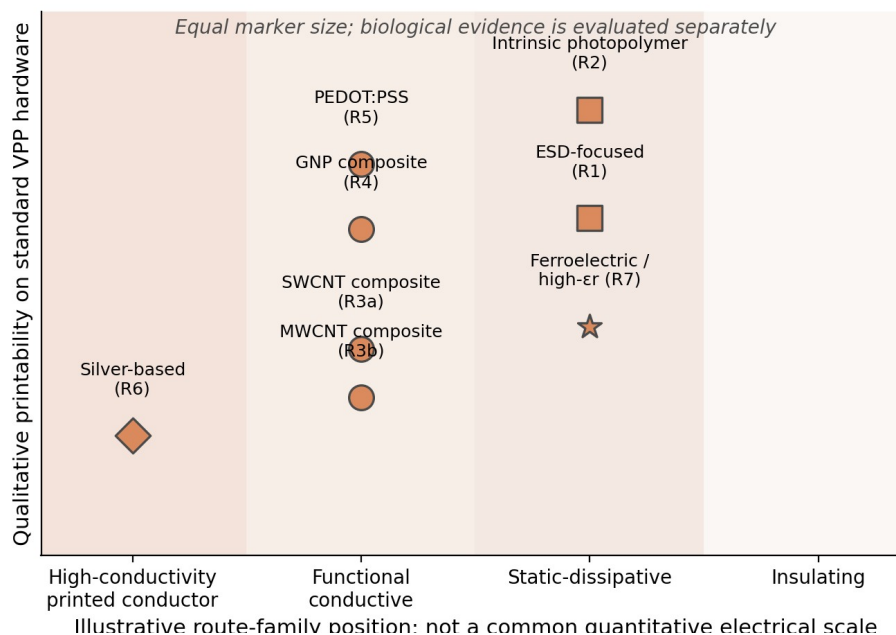


Figure 2. Qualitative route-space map of electrically functional VPP photopolymers. The horizontal position is an illustrative route-family position rather than a common quantitative electrical scale; printability on standard VPP hardware is shown on the vertical axis. All markers have equal size and carry no biological-suitability meaning. Marker shape distinguishes mechanism class. Biological-evidence status must be reported separately using product-specific, test-defined evidence categories.

Figure 2 compares route families qualitatively against printability on standard VPP hardware. It deliberately does not place bulk conductivity, volume resistivity, surface resistance and sheet resistance on one quantitative axis, because those quantities are not interchangeable without defined geometry and test conditions. All markers have equal size and no biological-suitability meaning; product-specific biological evidence is evaluated separately.

The three author-proposed conductive regimes are not interchangeable. Bulk conductivity, volume resistivity, surface resistance and sheet resistance must not be placed on one common quantitative scale unless the measurement method, specimen geometry and valid conversion are supplied. The orthogonal dielectric route addresses relative permittivity and loss tangent and is therefore evaluated separately. Route chemistry and application constraints are developed in the following sections.

percolation-theory background for filler-based composites is developed in §3.4; the ceramic-composite background for the dielectric route is developed in §3.6; the critical limitations of

each regime are developed in §3.8; the cure-state effects that govern process-dependent electrical performance are developed in §3.9.

3. Chemistry and design principles

3.1 Terminology

The electrically functional photopolymer literature uses several terms with definitions that vary across publications. To avoid ambiguity, the following operational definitions are used consistently throughout this review.

Term Operational definition

Insulating. Cured material described using a measured electrical property, test method, geometry, conditioning and application-specific acceptance criterion; no universal printed-part class is inferred from IEC 61340-5-3:2022.

Static-dissipative. Cured material evaluated under a stated electrical test method and application-specific ESD control plan. Packaging-derived resistance ranges may be used as engineering references but are not universal acceptance criteria for printed fixtures or parts.

Functional conductive Cured material with surface resistivity between approximately 10^{-1} and $10^4 \Omega/\text{sq}$, the range for printed electrodes, embedded sensors and bioelectronics.

Term Operational definition

High-conductivity printed-conductor regime Cured material with surface resistivity below approximately $10^{-1} \Omega/\text{sq}$, the range for printed antennas and high-current paths.

Dielectric (high-permittivity) Cured material characterised by its relative permittivity ϵ_r and loss tangent $\tan \delta$ at the application frequency, with ϵ_r typically above 5 for engineering-grade RF/microwave applications.

Percolation threshold Minimum filler loading at which a connected conductive network spans the cured part. Defined statistically; sharpness of the transition depends on dispersion quality and filler aspect ratio. The electric percolation threshold and the rheological percolation threshold can differ substantially in VPP matrices (§3.4) [32].

Conducting polymer A polymer whose backbone supports delocalised electronic states giving rise to intrinsic conductivity, typically through doping.

Conductive composite A photopolymer matrix loaded with a discrete conductive filler component above the percolation threshold.

Dielectric composite A photopolymer matrix loaded with a high-permittivity ceramic filler that increases the composite ϵ_r without rendering it conductive.

Sacrificial conductor A printed conductive part intended to be removed after the manufacturing step, typically by water dissolution or swelling-assisted disintegration.

Bioelectronics research formulation A conductive or dielectric cured material formulated to support biological-contact applications under ISO 10993-1 risk-management framework.

ISO 10993-1:2025 provides requirements and general principles for evaluating the biological safety of a medical device within a risk-management process. It does not certify a liquid resin or create an intrinsic formulation-level biological-safety designation. Product-specific material or specimen data may contribute to device-level evaluation only when the tested specimen, workflow, endpoints and intended contact are defined. Medical-device approval remains a separate device-level regulatory outcome.

4D electro-thermo-responsive A cured material whose shape, volume or property changes reversibly under electrical or thermal stimulus, typically based on a hydrogel platform.

SDCF System-Dependent Conductivity Framework — the interpretive position that the realised electrical performance of a cured part is a system-level outcome of the seven-stage process chain in Fig. 1, not an intrinsic resin property (§1.4).

The framework that follows distinguishes between the design target (set by formulation intent) and the realised behaviour (modulated by cure kinetics, post-cure protocol, geometry and service environment), in parallel with the design-target-vs-realised-behaviour framework developed in the companion review on water-soluble sacrificial photopolymers [16].

3.2 The seven electrical-function routes

The seven routes differ in their physical mechanism, in their response to filler loading or conducting-polymer content, in their interaction with the curing wavelength and in their long-term ageing under service conditions. Each route delivers a distinct combination of advantages and limitations that determine which application classes and operational regimes it serves. Route 1 —ESD-focused photopolymers (Regime A). Designed to deliver an application-specific static-dissipative response across a broad mechanical envelope from ultra-rigid high-temperature grades to super-elastic compliant grades. The mechanism is typically a controlled-low-loading dispersion of a conductive component (carbon-based or metallic) below the active-conduction percolation threshold, such that the surface resistivity falls in the static-dissipative band without entering the functional-conductive regime [PR5]. The advantage of dedicated ESD-focused formulations over filler-loaded conductive composites operated at sub-percolation loading is engineering reproducibility: the static-dissipative behaviour is the design target rather

than a transient state on the percolation curve. The route is positioned for electronics-safe fixtures, handling tools, workstation accessories and antistatic functional parts; it is not intended for active electrical conduction. Route 2 — Intrinsic conductive photopolymer backbone (Regime B). Produces a cured polymer in which the conduction is delivered by the photopolymer backbone itself, without a separate filler or conducting-polymer component. The conductivity envelope is bounded by the chemistry of the matrix and typically falls below the filler-based composite envelope at equivalent matrix viscosity. The advantage of the intrinsic route is that the absence of a discrete filler eliminates dispersion-quality variability, sedimentation during storage and filler-orientation anisotropy in printed parts. The intrinsic route is positioned as the structural conductor for functional prototypes where the absence of filler-related variability simplifies process validation. Route 3 — 1D filler percolation composites: SWCNT and MWCNT (Regime B). Deliver conduction through electron transport along the 1D nanotube backbone and across nanotube-nanotube contacts in the percolation network. The percolation threshold for SWCNTs is typically lower than for MWCNTs at equivalent dispersion quality, reflecting the higher aspect ratio of single-walled tubes [2,7,32]. Recent VPP-specific work has demonstrated that high-aspect-ratio SWCNTs can percolate at filler loadings below 0.01 vol%, where UV interference with cure is negligible, but at the cost of surfactant-assisted dispersion that introduces contact resistance limiting the realised conductivity [33]. The advantage of the SWCNT variant is the lower filler loading required to achieve a given conductivity, with corresponding benefits in matrix viscosity and printability. The disadvantages are dispersion quality (SWCNTs aggregate more readily than MWCNTs under typical processing) and cost (high-quality SWCNT is materially more expensive than MWCNT). The MWCNT variant addresses the same conduction mechanism through multi-walled tubes with lower aspect ratio and lower cost. The percolation threshold is typically higher than for SWCNTs, requiring proportionally higher filler loading to achieve equivalent conductivity [2,7,32]. The MWCNT advantage is cost, dispersion stability and storage shelf-life of the uncured formulation; the disadvantage is that the higher filler loading produces a higher matrix viscosity and a darker visual appearance that constrains aesthetic applications. Route 4 — 2D filler percolation composites: GNP (Regime B). Deliver conduction through 2D platelet overlap rather than 1D nanotube contact, with percolation geometry that differs in two respects [3,22,35]. The percolation threshold for 2D fillers depends on the in-plane orientation distribution of the platelets, with aligned platelets producing percolation at lower loading than randomly oriented platelets at equivalent platelet aspect ratio. The cured part typically exhibits measurable conduction anisotropy if the platelets align with the build flow during printing. Recent peer-reviewed reviews of VPP graphene composites [35] have consolidated the field around three formulation strategies: as-mixed graphene nanoplatelet dispersion (with the trade-off identified

here), UV-transparent graphene oxide (GO) with post-cure thermal reduction to rGO [33], and chemically functionalised graphene for improved dispersion. The GO/rGO route addresses the UV-absorption limitation at the cost of an additional thermal post-processing step. The GNP route is

positioned for applications where planar conduction is the intended function and where the anisotropy can be exploited as a design parameter rather than mitigated as a limitation. Route 5 — Intrinsically conducting polymer: PEDOT:PSS (Regime B). Delivers conduction through delocalised electronic states along the conducting-polymer backbone, with no discrete filler component [4,12,17,28]. The conductivity envelope is intrinsically lower than the metallic route but offers two specific advantages relevant to the printed-electronics field: optical transparency in thin-film configurations (suitable for transparent electrodes and electrochromic devices) and reported use in hydrated bioelectronics research, subject to grade-, specimen- and workflow-specific biological evaluation [37–38]. Recent peer-reviewed work has demonstrated 3D-printed PEDOT:PSS hydrogel bioelectronic interfaces with bulk conductivity above 100 S m^{-1} , charge-injection capacity above 13 mC cm^{-2} and porcine-skin adhesion above 30 kPa [39]. Two-photon polymerisation has been used to fabricate PEDOT:PSS 3D microstructures with submicron resolution for neural-interface applications [40]. The PEDOT:PSS conductivity is sensitive to humidity history and to the post-cure atmosphere,

with measurable drift over weeks to months under uncontrolled storage [12,28] — a critical limitation developed in §3.8. Route 6 — Silver-based metallic systems (Regime C). Deliver metallic conduction through dispersed silver particles in the cured matrix, with conductivity at the upper end of the printed-electronics envelope [11,19,29]. The route is positioned for applications where conductivity is the dominant engineering parameter and where the cost, density and long-term oxidative stability of silver are acceptable. The silver route faces several specific limitations beyond simple oxidation — electromigration, sulfur tarnishing, galvanic incompatibility with adjacent metallic interconnects, and cyclic fatigue — developed in §3.8. Route 7 — Ferroelectric and high-permittivity composites (Orthogonal dielectric regime). Deliver high relative permittivity (ϵ_r above 5–10 at GHz frequencies) through dispersion of high-permittivity ceramic fillers — barium titanate (BaTiO_3 , BTO), titanium dioxide (TiO_2), calcium copper titanate ($\text{CaCu}_3\text{Ti}_4\text{O}_{12}$, CCTO) — in a photopolymer host [18,34]. The route is positioned for RF and microwave applications: high-permittivity dielectric components, antennas, capacitors, resonators, microwave devices and electro-optic devices. The ferroelectric, pyroelectric and piezoelectric properties of the BaTiO_3 filler propagate into the composite, enabling sensor and energy-harvesting functions beyond static dielectric response [18,23]. The dielectric route is orthogonal to the conductive routes: high-permittivity composites are not conductive (the ceramic fillers are themselves insulating) and the engineering figures of merit are ϵ_r and $\tan \delta$ at the application frequency rather than surface resistivity. The route faces severe printability constraints at the high filler loadings (typically 50–70 wt%) required for engineering-grade permittivity [18]. Auxiliary: 4D electro-thermo-responsive direction. A separate stimuli-responsive direction operates as a hydrogel platform sharing chemistry with bio-scaffold workflows. Reversible shape, volume or property change is driven by electrical or thermal stimulus rather than by static conduction or dielectric response [9,15,24]. The 4D-ETR direction is positioned for soft-actuator R&D, smart-electronics prototypes and hydrogel bioelectronics; commercial portfolios across the field currently anchor on a small number of products in this direction (§3.12), reflecting the early-maturity stage of 4D conductive chemistry.

3.3 Author-proposed electrical-performance-printability-biological-evidence map.

These dimensions are not interchangeable performance metrics. Electrical performance and printability are engineering attributes; biological-evidence maturity describes the availability and relevance of product-specific evidence under defined conditions and does not establish final-device suitability.

High functional-component loading can increase viscosity, optical attenuation and cure-depth constraints. Biological response cannot be ranked generically by route: it depends on the specific grade, additives, processing, residual species, specimen, test model, endpoint and intended contact. The map therefore treats biological-evidence maturity as a separate evidence dimension rather than an intrinsic material property. Achieving desktop-platform viscosity can require lower functional-component loading, which may reduce electrical performance. Figure 3 visualises this qualitative

trade-off. Achieving desktop-platform viscosity can require lower functional-component loading, which may reduce electrical performance. Figure 3 visualises this qualitative trade-off.

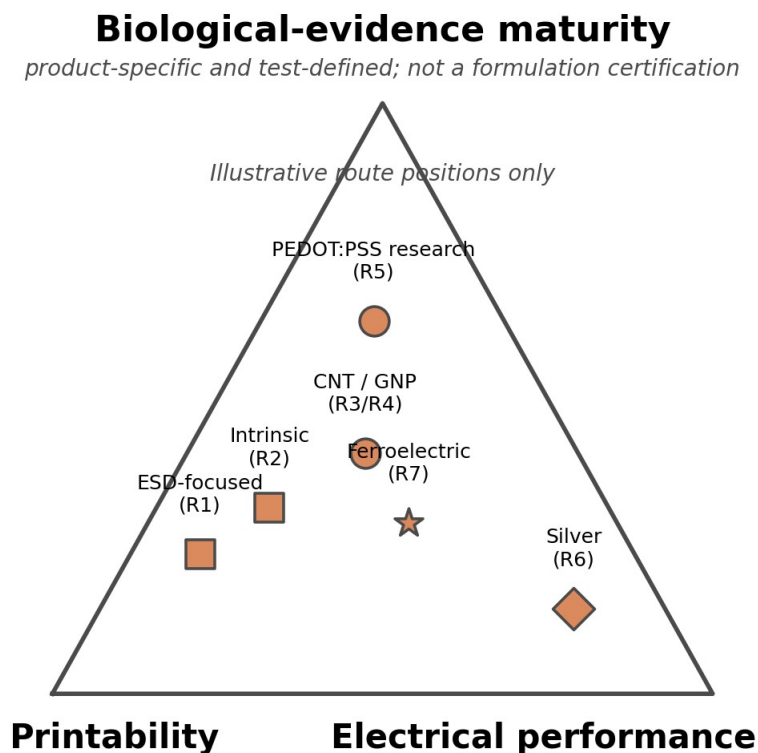


Figure 3. Author-proposed qualitative trade-off space: electrical performance, printability and biological-evidence maturity. Route positions are illustrative and do not establish biological suitability or device-level acceptance.

Figure 3 is an author-proposed qualitative map, not a ranking or suitability determination. Electrical performance and printability are engineering attributes, while biological-evidence maturity describes only the availability and relevance of product-specific evidence under defined test conditions. Route position does not establish biological suitability or device-level acceptance.

The diagram should be used only to organise questions for route selection. Every candidate formulation requires application-specific electrical, printability, mechanical, ageing and biological evaluation as applicable. Evidence associated with one route, grade or specimen cannot be transferred automatically to another formulation or finished device.

Table C. Design-axis comparative matrix across the seven electrical-function routes plus the 4D-ETR direction.

Route	Conductivity ceiling	Printability constraint	Mechanical retention	Biological-evidence maturity	Long-term stability	Relative cost
1 — ESD-focused	Low (Regime A)	Low	High (full envelope A10–D90)	Route-dependent; verify product-specific evidence	High under controlled environment	Low–Moderate
2 — Intrinsic backbone	Low–Moderate	Low	High	Bio-designated variants; evidence not established here	High	Low
3 — CNT (SWCNT + MWCNT)	High	Moderate (dispersion-controlled)	Moderate (loading-dependent)	Bio-designated variants; evidence not established here	High	Moderate
4 — GNP	Moderate–High	Moderate (orientation-anisotropic)	Moderate	Bio-designated variants; evidence not established here	High	Moderate
5 — PEDOT:PSS	Moderate	High (wavelength absorption overlap [49]; flocculation; hydrophilic-host-only)	High (hydrogel-compliant)	Research/specimen evidence; grade-specific	Moderate (humidity drift [12,17,28,38])	Moderate–High
6a — Silver nanowire (AgNW)	Very high (Regime C)	Moderate (coiling-control during dispersion)	Moderate–Low	No product-specific evidence identified here	Moderate (electromigration, tarnishing)	High
6b — Silver micro particle/micro flake	Very high (Regime C)	Very high (heated printing required; 10–20 μm layers)	Low (high-loading embrittlement)	No product-specific evidence identified here	Moderate (electromigration, tarnishing)	Very high
7 — Ferroelectric / high- ϵ_r	Not applicable (dielectric route)	Very high (50–70 wt% ceramic loading)	Moderate	Filler- and specimen-dependent evidence	High (Curie-point caveat for BaTiO_3)	Moderate–High
4D-ETR	Moderate (dynamic, stimulus-dependent)	Moderate	Variable (response-amplitude trade-off)	Research/specimen evidence; system-specific	Moderate (cycle-stability constrained)	Moderate

Rankings (low, moderate, high) are qualitative consolidations from the peer-reviewed literature cited and the publicly available industrial documentation; the SDCF (§1.4 Table A1) determines the realised value within each cell on the user's specific platform.

the 4D-ETR direction. The matrix consolidates the qualitative trade-offs visualised in Fig. 3 into a structured comparison across six engineering-relevant dimensions: conductivity ceiling, printability constraint at the VPP irradiance budget, mechanical retention under high loading, biological-evidence status, long-term stability under typical service environments, and cost per cured volume.

Rankings (low, moderate, high) are qualitative consolidations from the peer-reviewed literature cited and the publicly available industrial documentation; the SDCF (§1.4 Table A1) determines the realised value within each cell on the user's specific platform.

Table C may be used only as a qualitative question-organising tool. A candidate route must be evaluated against application-specific electrical, printability, mechanical, ageing, cost and biological-evidence requirements. The low, moderate and high entries are author judgements, not validated acceptance classes, and no row establishes biological suitability or device-level acceptance.

3.4 Percolation theory for filler-based composites

The conduction in filler-based composites — SWCNT, MWCNT and GNP routes — is governed by percolation theory [2-3,7,22,27]. Below the percolation threshold, filler particles are isolated in the matrix and the cured part is insulating. At the threshold, a connected filler network spans the cured part and the conductivity transitions sharply from the insulating regime to the conductive regime. Above the threshold, conductivity rises with increasing filler loading according to a power-law dependence on loading-above-threshold, with a critical exponent that depends on the filler geometry and on the network dimensionality [2,22]. For 1D fillers (CNTs), the percolation threshold depends on the aspect ratio of the nanotubes. High-aspect-ratio SWCNTs (typically aspect ratio > 1000) percolate at filler loadings below 1 wt% under optimal dispersion; lower-aspect-ratio MWCNTs (typical aspect ratio 100-500) require proportionally higher loadings, typically 1-3 wt% [2,7]. Recent VPP-specific work has shown SWCNT percolation below 0.01 vol% in well-dispersed photopolymer hosts [33]. The dispersion quality dominates the realised percolation threshold: aggregated nanotubes behave as oversized effective particles with lower aspect ratio, producing a higher effective threshold than the dispersion-quality control case. For 2D fillers (GNPs), the percolation threshold depends on platelet aspect ratio and on the orientation distribution [3,22]. Randomly oriented platelets at typical aspect ratios percolate at filler

loadings of 1-5 wt%; aligned platelets percolate at lower loadings but produce anisotropic conduction. The platelet orientation in the cured part is set by the flow conditions during printing — build direction relative to the cured-layer plane, layer thickness and cure rate together determine the orientation distribution that the cured part inherits. Electric versus rheological percolation in VPP matrices. A VPP-specific consideration revealed by recent peer-reviewed work [32] is that the rheological percolation threshold (the loading at which the suspension transitions from Newtonian to non-Newtonian behaviour and printability begins to degrade) and the electric percolation threshold

(the loading at which conduction emerges) are decoupled in photopolymer matrices, with the size of the gap controlled by the matrix type and the dispersion protocol. In aromatic photopolymer matrices the gap can be wide, allowing operation in the percolation-conductive regime at viscosities compatible with standard VPP hardware. In non-aromatic matrices the rheological threshold can fall below the electric threshold, forcing the user to choose between conductivity and printability. The decoupling is a system-level property, not a filler property — the same filler in different matrices yields different gaps. The percolation-theory framework predicts the threshold; the realised conductivity above threshold depends on additional factors that the framework treats as parameters. Contact resistance between adjacent filler particles dominates the conductivity in the regime where inter-particle contacts are the limiting resistive elements [2,7]. Matrix-mediated tunnelling conductance across small inter-particle gaps contributes to the conductivity when gaps are below approximately 1-10 nm. Thermal expansion mismatch between filler and matrix produces a temperature-dependent conductivity not captured by the percolation framework alone. The practical consequence is that the percolation framework predicts where in the loading curve a given system transitions from insulating to conductive, but does not predict the specific conductivity at a given loading without empirical calibration on the specific resin-printer-geometry combination.

Aspect ratio, optical transparency and cure-depth budget. For VPP photopolymer applications, the filler aspect ratio interacts with the cure-depth budget through the optical-attenuation pathway. At equivalent filler chemistry and equivalent target conductivity, high-aspect-ratio fillers (nanowires, single-walled nanotubes, high-aspect-ratio platelets) deliver percolation at lower volumetric loading than low-aspect-ratio fillers (spherical particles, microparticles of the same chemistry) [2,7,22,50]. The implication for VPP cure-depth budget is direct: the curing wavelength encounters a lower volumetric obstruction per unit cured volume at the high-aspect-ratio loading, and the system retains greater optical transparency at the equivalent conductivity. The same target conductivity can therefore be reached either at low loading of high-aspect-ratio fillers (preserving cure depth) or at high loading of low-aspect-ratio particles (penalising cure depth). The trade-off explains a recurrent observation in the VPP conductive-composite literature [50]: silver nanowire systems reach the high-conductivity printed-conductor regime regime at approximately 5 wt% loading with preserved cured-part transparency, while silver microparticle and microflake systems require substantially higher loadings (typically tens of wt%) with concomitant loss of cure-depth budget and the manufacturing-process consequences detailed in §3.11. A counter-intuitive viscosity-coiling coupling for nanowires. The aspect-ratio advantage of metallic nanowires is partially offset by a specific failure mode whose viscosity dependence is opposite to naive expectation [PR17]. Silver nanowires and the broader metallic-nanowire family tend to coil on themselves during synthesis, storage and dispersion handling; the coiled configuration is entropically favourable and the uncoiled configuration is metastable. Counter to the intuition that a low-viscosity matrix would simplify maintaining the wires in an uncoiled state, the opposite holds: low-viscosity host matrices provide higher rotational and translational mobility to the nanowires, which accelerates the relaxation toward the coiled state and produces irreversible coiling on practical print-cycle timescales. Maintaining the percolation-active uncoiled configuration therefore favours a host matrix with sufficient viscosity (typically in the upper region of the standard VPP envelope, approximately 1,500–4,000 mPa·s) or a yield-stress contribution that immobilises the wires below a critical shear. This mobility-suppression requirement creates a route-specific design

constraint that is opposite to the printability-driven preference for low matrix viscosity discussed in §3.5: silver-nanowire formulations face a tighter viscosity envelope than other conductive routes, requiring a balance between low-enough viscosity for VPP recoating and high-enough viscosity to suppress nanowire re-coiling. Uncoiling during the dispersion preparation step must additionally be achieved without breaking the wires; over-aggressive dispersion fragments the wires and reduces the effective aspect ratio (and therefore the realised conductivity) at fixed nominal loading.

3.5 Rheology-governed printability and the optical-rheological coupling

The rheology of the uncured electrically functional formulation is a central process variable in VPP additive manufacturing and is often under-treated in conductivity-focused publications [8,9,36,37,PR17]. A system that achieves a target conductivity in the cured part but cannot recoat reliably between layers, sustains sedimentation across multi-hour print runs, or generates trapped bubbles at high cure speed is not a printable system at engineering scale. This subsection consolidates the rheology-printability constraints that the present review treats as orthogonal axes within the SDCF (§1.4 Table A1) and that operate alongside the chemistry, percolation and cure-state constraints of the preceding subsections. The conductivity-resolution-printability triad. Three desired outcomes in electrically functional VPP photopolymers are simultaneously constrained by the formulation viscosity envelope. Target conductivity is improved by raising the conductive-phase loading (filler-based routes) or the conducting-polymer content (Route 5), with the trade-offs documented in §3.4 and §3.8. Target print resolution is improved by minimising the optical scattering and attenuation of the uncured formulation — both increase with filler loading. Target printability requires the uncured formulation to remain within the operating viscosity envelope of

the platform (typically below 2,000–5,000 mPa·s at the operating temperature for standard MSLA/DLP/LCD platforms [5–6]), with shear-thinning and recoatability behaviour compatible with the layer-by-layer cycle. The three objectives are coupled through the filler-loading variable: raising loading improves conductivity, degrades resolution and degrades printability simultaneously. The rheology-printability envelope therefore sets a system-level ceiling on the conductivity achievable at a given platform-and-resolution target, independent of the chemistry choice. Newtonian versus non-Newtonian behaviour. Unloaded photopolymer matrices typically exhibit Newtonian flow over the shear-rate range encountered during VPP printing (approximately 1–100 s⁻¹ during recoating). The introduction of conductive fillers produces non-Newtonian behaviour whose specific signature depends on the filler geometry, loading and dispersion state [2,7,32–33]. Shear-thinning behaviour (decreasing viscosity at increasing shear) is favourable for VPP printing because it eases recoating at high shear during the recoater pass while preserving low-shear stability during the inter-layer dwell time. Yield-stress behaviour (the formulation behaves as a solid below a critical stress and flows above it) suppresses sedimentation during the inter-layer dwell time but can complicate self-levelling and produce surface texture defects. Strong viscoelasticity can produce surface instabilities, layer-tearing during peel and trapped bubbles. Engineering-grade conductive formulations are typically tuned for moderate shear-thinning behaviour with a small yield-stress contribution and minimal viscoelasticity — a combination that addresses both the dynamic (recoating) and the static (sedimentation) printability requirements. Sedimentation physics — Stokes framework. The static-state sedimentation of conductive fillers in the uncured matrix follows Stokes' law in the dilute limit: the terminal settling velocity v of a spherical particle of radius r and density ρ_p in a fluid of density ρ_f and viscosity η is $v = 2r^2(\rho_p - \rho_f)g / 9\eta$, where g is gravitational acceleration. Three scaling implications follow. First, the settling rate scales with the squared particle radius, so micron-scale particles settle approximately three orders of magnitude faster than nanometre-scale particles at equivalent density mismatch. Second, the settling rate scales linearly with the filler-to-matrix density mismatch, which is the dominant driver for metallic fillers (silver $\Delta\rho \approx 9.5$ g/cm³ relative to typical photopolymer matrices, §3.11) and a moderate driver for ceramic fillers (BaTiO₃ $\Delta\rho \approx 5$ g/cm³, TiO₂ $\Delta\rho \approx 3$ g/cm³) and a small driver for carbon-based fillers (CNT $\Delta\rho \approx 1$ g/cm³, GNP $\Delta\rho \approx 1$ g/cm³). Third, the settling rate scales inversely

with matrix viscosity, providing a formulation handle: viscosity tuning through reactive diluents, polymer-architecture choice or controlled-temperature operation directly affects the practical vat-residence time for sedimentation-prone formulations. The Stokes framework is a dilute-limit

approximation; at the concentrated loadings typical for engineering-grade conductivity,

hindered-settling and yield-stress effects modify the practical settling envelope and are the engineering rationale for dispersant-and-anti-sedimentation additives ([PR17] §3.11).

Optical-rheological coupling. A central observation from the preceding paragraphs is that optical attenuation (cure-depth budget, §3.4) and rheological constraint (viscosity envelope, recoating dynamics) are not independent variables in conductive VPP formulations; both respond to the same

filler-loading axis with the same monotonic trend. Raising the conductive-phase loading degrades both the optical-attenuation budget and the rheological-printability envelope simultaneously, and there is no formulation-level decoupling between the two. The system-level consequence is that the

conductive-VPP design problem is fundamentally three-dimensional (conductivity, optical

attenuation, rheology) rather than two-dimensional (conductivity, printability), and the optical and rheological axes can each set the binding constraint depending on the platform, the geometry and the resolution target. This coupling is documented qualitatively across the recent VPP conductive-composite literature [7,18,32–34,49] and is captured in the manufacturing-physics framing of §3.11. Filler-morphology rheological signature. The non-Newtonian rheology of the conductive formulation depends strongly on the filler geometry. Spherical particles (silver microparticles, metallic spheres, ceramic equiaxed grains) produce a moderate viscosity rise at equivalent volume fraction with a

near-Newtonian-to-mildly-shear-thinning signature. Platelets and flakes (graphene nanoplatelets, silver microflakes, ceramic flakes) produce a higher viscosity rise at equivalent loading with strong shear-thinning and measurable yield stress, reflecting platelet-platelet packing interactions. High-aspect-ratio fillers (carbon nanotubes, metallic nanowires, fibres) produce a substantial viscosity rise per unit volume fraction and a pronounced non-Newtonian signature with viscoelastic behaviour at modest loading, reflecting entanglement and network formation at sub-percolation concentrations [2,7,33].

Table E. Filler-morphology rheological signature in VPP photopolymer matrices.

Filler geometry	Percolation efficiency	Rheological viscosity penalty	Shear-thinning signature	Yield-stress contribution	Anisotropy under shear	Sedimentation tendency at typical loading
Spherical particles	Low	Moderate	Weak (near-Newtonian)	Low	Low	High (Stokes $\propto r^2 \cdot \Delta\rho$)
Microflakes/platelets	Moderate-High	High	Strong	Moderate	Moderate (flow alignment)	Moderate-High
Graphene nanoplatelets (GNP)	Moderate-High	Moderate-High	Strong	Moderate	High (flow alignment)	Moderate
Carbon nanotubes (CNT)	Very high	Severe at >0.5 wt%	Very strong	High (network entanglement)	High (flow alignment)	Low
Metallic nanowires (e.g. AgNW)	Very high	High	Strong	Moderate-High	Moderate (orientation under shear)	Moderate (mitigated by entanglement)

Qualitative consolidation of the rheology trends across the principal filler geometries. The table operates jointly with Table C (§3.3) and Table D (§3.8) to identify the rheology-printability envelope per route. Specific values depend on the matrix chemistry, the dispersion protocol and the temperature of operation.

Qualitative consolidation of the rheology trends across the principal filler geometries used in electrically functional VPP photopolymers. The table operates jointly with Table C (design-axis matrix, §3.3) and Table D (silver morphology, §3.8) to identify the rheology-printability envelope per route. Specific rheology values depend on the matrix chemistry, the dispersion protocol and the temperature of operation; the table reports the qualitative trend.

Filler Percolation Rheological Shear-thinning Yield-stress Anisotropy Sedimentation geometry
efficiency viscosity g signature contribution under shear tendency at penalty typical loading

Spherical Low Moderate Weak (near-New Low Low High (Stokes $\propto$ particles tonian) $r^2 \cdot \Delta\rho$)

Microflakes/plat Moderate-High High Strong Moderate Moderate (flow Moderate-High elets
alignment)

Graphene Moderate-High Moderate-High Strong Moderate High (flow Moderate nanoplatelets
alignment) (GNP)

Carbon Very high Severe at >0.5 Very strong High (network High (flow Low nanotubes wt%
entanglement) alignment) (CNT)

Metallic Very high High Strong Moderate-High Moderate Moderate nanowires (e.g. (orientation
(mitigated by AgNW) under shear) entanglement)

Network-damage during cure shrinkage. A rheology-adjacent effect specific to VPP-processed conductive composites is the disruption of the percolation network by polymerisation shrinkage during cure. Acrylate and methacrylate photopolymerisation produces volumetric shrinkage of

approximately 5–15% depending on the matrix chemistry and conversion. In conductive-filler composites, the matrix contraction generates differential strain at the filler-matrix interfaces and can introduce microcracks that disrupt the inter-filler contacts of the percolation network. The effect is most pronounced for brittle conductive networks (high-loading silver microparticle and microflake systems, ceramic-loaded dielectric composites) and for low-aspect-ratio fillers where the percolation network is sensitive to small relative displacements. High-aspect-ratio fillers (CNT, nanowires) tolerate shrinkage-induced network strain better because the high-aspect-ratio geometry maintains multiple contact paths per filler. The shrinkage-network-damage interaction is the physical mechanism behind the post-cure shrinkage cracking failure mode of Table 3 §3.10 and is a frequently under-reported contributor to the gap between published academic conductivity values and the conductivity realised in industrial-scale parts.

3.6 Dielectric composite theory for the ferroelectric route

The high relative permittivity of dielectric composites — Route 7 — does not follow percolation behaviour. The ceramic filler particles (BaTiO_3 , TiO_2 , CCTO) are themselves dielectric, not conductive, and the composite ϵ_r rises continuously with filler loading according to effective-medium mixing rules rather than transitioning sharply at a threshold [18,25]. The most widely applied mixing rules in the photopolymer-ceramic composite literature are the Maxwell-Garnett rule for low filler loadings and the Bruggeman effective-medium rule for higher loadings; both predict that the composite ϵ_r increases monotonically with the volume fraction of high-permittivity filler, with the specific form of the dependence depending on the filler-to-matrix permittivity ratio and on the assumed particle geometry [18,25]. The loss tangent ($\tan \delta$) of the composite depends on the loss tangent of each component and on the morphology of the dispersion. At GHz frequencies, the loss tangent of well-dispersed BaTiO_3 -photopolymer composites typically remains below 0.05 across the loading range explored in the printed-electronics literature [18]. Above approximately 70 wt% ceramic loading, the matrix viscosity rises into a regime where printability degrades severely on standard VPP hardware and where the wavelength attenuation by ceramic scattering further constrains cure depth [18]. The engineering envelope of the route is therefore set jointly by the ϵ_r -target, the printability constraint at the high ceramic loadings required, and the $\tan \delta$ tolerance of the application frequency. A second consideration specific to the ferroelectric route is the temperature dependence of ϵ_r . BaTiO_3 undergoes a tetragonal-to-cubic ferroelectric phase transition at the Curie temperature near 120 °C, with ϵ_r rising sharply toward the transition before dropping in the cubic high-temperature phase [23]. The temperature dependence is significant for any RF/microwave application operating outside narrow temperature bands and must be characterised on the cured composite rather than assumed from the bulk ceramic behaviour.

3.7 Quantitative envelopes across routes (literature and TDS consolidation) Table 1 consolidates the quantitative electrical-performance envelope across the seven routes from the peer-reviewed literature on cured photopolymer-host systems and adjacent polymer-composite systems where VPP-specific datasets remain limited. The ranges are intended as

orders-of-magnitude orientation rather than as specifications for any particular product; the published ranges span several orders of magnitude per route, and the specific position within the range depends on filler loading, dispersion quality, cure conditions, geometry and the metrology protocol of the citing study.

Table 1. Electrical-performance envelope by route — peer-reviewed literature consolidation.

Route	Regime	Typical surface resistivity (Ω/sq)	Typical bulk conductivity (S/cm)	Typical loading or content	Matrix viscosity impact	Cure wavelength attenuation	Source class
1 — ESD-focused	A (10^4 – 10^{11})	10^4 – 10^{11}	n/a	controlled low loading	low-moderate rate	low-moderate	dedicated ESD photopolymers, PR data [PR5]
2 — Intrinsic photopolymer backbone	B (10^{-1} – 10^4)	10^2 – 10^{11}	10^{-11} – 10^{-4}	n/a (no filler)	minimal	minimal	photopolymer matrix chemistry, PR data
3a — SWCNT composite	B	10^0 – 10^6	10^{-4} – 10^1	0.01–1 wt%	moderate-high	strong (broad UV-Vis absorption)	refs [2,7,13,22, 32–33], VPP and adjacent
3b — MWCNT composite	B	10^0 – 10^7	10^{-5} – 10^0	1–5 wt%	high	strong (broad UV-Vis absorption)	refs [2,7,22,26,32], VPP and adjacent
4 — GNP composite	B	10^0 – 10^5	10^{-4} – 10^0	1–10 wt%	high	moderate (wavelength-dependent)	refs [3,22,27,35], VPP and adjacent
5 — PEDOT:PSS	B	10^0 – 10^4	10^{-3} – 10^1	0.5–5 wt% PEDOT:PSS	moderate	moderate (visible-light absorption tail)	refs [4,12,17,28,37,39], cured composites
6 — Silver microflake/nanoparticle	C ($<10^{-1}$)	10^{-3} – 10^0	10^1 – 10^4	30–70 wt%	very high	strong (broad reflection/absorption)	refs [11,19,29], cured composites
7 — Ferroelectric/high-permittivity	dielectric	(insulating)	(insulating)	20–70 wt% ceramic	very high	moderate (ceramic scattering)	refs [18,25,34], cured composites

PR = manufacturer technical datasheet (publicly available product reference, §2.0). "VPP and adjacent" indicates that the cited ranges combine VPP-specific photopolymer-host studies with adjacent polymer-composite studies where VPP-specific data are limited. The conductivity envelope of any specific product depends on the full system configuration (§3.9) and should be calibrated by the user.

consolidation. Values compiled from cured photopolymer-host systems whenever available; adjacent polymer-composite literature used where VPP-specific datasets remain limited.

Route Regime Typical surface resistivity (Ω/sq) Typical bulk conductivity (S/cm) Matrix viscosity impact Cure wavelength attenuation Source class

1 — ESD-com A (10^4 – 10^{11}) 10^4 – 10^{11} n/a controlled low low-moderate low-moderate dedicated pliant loading ESD photopolymers, PR data [PR5]

2 — Intrinsic B (10^{-1} – 10^4) 10^2 – 10^{11} 10^{-11} – 10^{-4} n/a (no filler) minimal minimal photopolymer photopolymer matrix backbone chemistry, PR data

3a — SWCNT B 10^0 – 10^6 10^{-4} – 10^1 0.01–1 wt% moderate-high strong (broad refs [2,10,17, composite h UV-Vis 26,36,37], absorption) VPP and adjacent

3b — MWCNT B 10^0 – 10^7 10^{-5} – 10^0 1–5 wt% high strong (broad refs [2,10,26, composite UV-Vis 30,36], VPP absorption) and adjacent

4 — GNP B 10^0 – 10^5 10^{-4} – 10^0 1–10 wt% high moderate (wavelength-dependent) VPP and adjacent

5 — B 10^0 – 10^4 10^{-3} – 10^1 0.5–5 wt% moderate moderate refs [4,16,21, PEDOT:PSS PEDOT:PSS (visible-light 32,41,43], absorption cured tail) composites

6 — Silver mic C ($<10^{-1}$) 10^{-3} – 10^0 10^1 – 10^4 30–70 wt% very high strong (broad refs roflake/nanop reflection/abs [11,19,29], article orption) cured composites

7 — Ferroelec dielectric (insulating) (insulating) 20–70 wt% very high moderate refs tric/high-perm ceramic (ceramic [18,25,34], ittivity scattering) cured composites

Notes: PR = manufacturer technical datasheet (publicly available product reference, §2.0). "VPP and adjacent" indicates that the cited ranges combine VPP-specific photopolymer-host studies with adjacent polymer-composite studies (typically epoxy, polyurethane or thermoplastic hosts) where VPP-specific data are limited. The conductivity envelope of any specific product within these route classes depends on the full system configuration (§3.9) and should be calibrated by the user. Three observations follow from Table 1. First, the conductive routes (2–6) span approximately 14 orders of magnitude of surface resistivity, from 10^{-3} Ω/sq for engineering-grade silver composites to 10^{11} Ω/sq for the upper boundary of the static-dissipative band. Treating "conductive photopolymers" as a single material class is therefore not meaningful; the route and regime must be specified. Second, the silver route is the principal currently documented route reaching the high-conductivity printed-conductor regime regime (Regime C). The "high-conductivity printed-conductor regime" designation in this review refers to the printed-electronics operational context — the conductivity range that supports antenna radiating elements, RFID/NFC tag traces and high-current paths in printed-electronics applications — not to equivalence with bulk metallic conductors (which sit approximately five orders of magnitude lower in surface resistivity, see §13.1). The conducting-polymer and filler-composite routes typically peak in the upper end of the functional-conductive regime (Regime B). Third, the wide envelope per route reflects two contributions: the genuine sensitivity of conductivity to system configuration (the SDCF, §1.4), and the methodological heterogeneity of the published literature (different metrology protocols, different sample geometries, different post-cure histories) [32–33]. The recent Nechausov et al. Perspective in Advanced Functional Materials [50] consolidates the VPP functional-material envelope with quantitative anchor points: MWCNT-loaded VP composites at 0.6 wt% reach 0.071 S/m through solution-intercalation-assisted dispersion; SWCNT-loaded ionogels at 0.4 wt% reach 0.182 S/m through ionic-liquid-assisted dispersion; freeze-dried silver nanowire composites at 5 wt% reach

11 S/m through coplanar alignment during layer-by-layer VP cure. These specific values further illustrate the SDCF: identical filler classes deliver substantially different conductivity envelopes depending on the dispersion protocol and the cured-layer flow conditions.

Table 2. Dielectric-performance envelope for Route 7 — peer-reviewed literature consolidation for ceramic-loaded photopolymer composites at GHz frequencies.

Filler	Typical loading	ϵ_r at 2–10 GHz	$\tan \delta$ at 2–10 GHz	ϵ_r at 10–20 GHz	$\tan \delta$ at 10–20 GHz	Notes / source
TiO ₂ (TO)	20 wt% in VIS-ph otopolymer	5–7	0.02–0.05	4–6	0.03–0.06	Malas et al. 2019 [18], VPP daylight
CCTO (CaCu ₃ Ti ₄ O ₁₂)	20 wt%	6–8	0.03–0.07	5–7	0.04–0.08	Malas et al. 2019 [18], VPP daylight
BaTiO ₃ (BTO)	50–70 wt%	8–12	0.02–0.04	8–9	<0.04	broad literature [18,23,25,34]

Values are indicative ranges from cured photopolymer-host composite samples; the temperature dependence of BaTiO₃ permittivity near the Curie point (§3.6) and the loss-tangent dependence on filler dispersion morphology imply that any specific product within Route 7 should be characterised on the target geometry and operating temperature.

for ceramic-loaded photopolymer composites at GHz frequencies.

Filler Typical ϵ_r at 2–10 GHz tan δ at 2–10 GHz ϵ_r at 10–20 GHz tan δ at 10–20 GHz Notes / source loading GHz GHz

TiO₂ (TO) 20 wt% in VIS-p 5–7 0.02–0.05 4–6 0.03–0.06 Malas et al. hotopolymer 2019 [18], VPP daylight

CCTO 20 wt% 6–8 0.03–0.07 5–7 0.04–0.08 Malas et al. (CaCu₃Ti₄O₁₂) 2019 [18], VPP daylight

BaTiO₃ (BTO) 50–70 wt% 8–12 0.02–0.04 8–9 <0.04 broad literature [18,23,25,34]

Values are indicative ranges from cured photopolymer-host composite samples; the temperature dependence of BaTiO₃ permittivity near the Curie point (§3.6) and the loss-tangent dependence on filler dispersion morphology imply that any specific product within Route 7 should be characterised on the target geometry and operating temperature.

3.8 Critical limitations and inconsistencies in the field

The electrically functional VPP photopolymer literature exhibits several critical limitations and inconsistencies that affect the interpretation of reported results across studies. These are not failures of any particular research group; they reflect the early-maturity stage of the field and the absence of standardised metrology for electrically functional AM parts. Percolation-threshold irreproducibility across studies. Reported percolation thresholds for nominally equivalent filler–matrix systems vary materially across the cited published studies [2,7,22,32]. Direct quantitative comparison requires harmonised dispersion, loading and measurement protocols. The principal contributors are heterogeneity in dispersion protocols (sonication time, surfactant choice, dispersant-to-filler ratio), in nominal-versus-effective filler loading (the effective loading after agglomeration during cure can differ substantially from the nominal as-mixed loading), and in measurement geometry. The recent

demonstration that electric and rheological percolation thresholds are decoupled and matrix-dependent [32] adds a further dimension to the variability: studies using different matrix chemistries (aromatic vs non-aromatic photopolymer hosts) can report different percolation thresholds even at identical filler loading and dispersion protocol. The field lacks a standardised dispersion-and-measurement protocol that would enable cross-study comparison; consequently, percolation-threshold values from one study cannot be transferred to another resin-printer combination without empirical re-calibration. The standardisation gap is more pronounced for Route 3 (CNT) than for Route 4 (GNP) because of the broader variability in CNT supplier specifications (chirality distribution, length distribution, surface functionalisation). PEDOT:PSS conductivity drift, hysteresis and mechanical robustness. PEDOT:PSS is frequently presented in the printed-electronics literature as a stable conducting-polymer alternative to filler-based composites. The system-level reality is more nuanced. The conductivity is humidity-sensitive: increases of 1–2 orders of magnitude under high-humidity conditioning are followed by partial recovery upon drying, with hysteresis loops that depend on the conditioning history [12,17,28]. Long-term conductivity drift over months under uncontrolled storage has been documented across multiple PEDOT:PSS formulations [38]. The mechanical robustness of cured PEDOT:PSS-containing photopolymer matrices is constrained by the conducting-polymer content; high PEDOT:PSS loading reduces flexural modulus and toughness relative to the unloaded host. Recent 3D-printed PEDOT:PSS hydrogel bioelectronic interfaces have

addressed the mechanical limitation through composite formulation with poly(vinyl

alcohol-formaldehyde) (PVAf) or similar tough hydrogel hosts, with reported conductivity above 100 S m⁻¹ and adhesion above 30 kPa [39]. A complementary VPP-specific constraint has been identified in the recent peer-reviewed literature:

the absorption spectrum of PEDOT:PSS overlaps with the absorption spectrum of conventional photoinitiators at the 365–405 nm curing window, reducing crosslinking efficiency in

PEDOT:PSS-loaded photopolymer formulations and constraining the achievable PEDOT:PSS loading without compromising through-thickness cure [49]. The constraint motivates the use of photoinitiator systems with absorption profiles displaced from the PEDOT:PSS absorption band, of which the 3Dresyns Fine Tuner photoaccelerant range (used in Mantione et al. [48]; see §6) is one documented example. Studies presenting single conductivity values for PEDOT:PSS systems without humidity history, ageing data, mechanical characterisation or photoinitiator-PEDOT:PSS spectral compatibility should be read with these contextual constraints in mind. Silver systems — beyond oxidation. The conductive-AM literature on silver-based systems frequently identifies oxidation as the dominant ageing concern. The system-level reality involves several additional degradation modes that are less frequently discussed [11,19,29]. Electromigration of silver under DC bias in humid environments produces dendrite growth that can short-circuit adjacent conductors over operating timescales of months to years; this is a well-established failure mode in printed-circuit

literature but is under-reported in the AM-silver composite literature. Sulfur tarnishing under industrial-atmosphere conditions (H₂S exposure) produces non-conductive silver sulfide surface layers that progressively isolate the metallic network. Galvanic incompatibility between silver and adjacent base metals (copper, aluminium) in printed-electronics assemblies accelerates corrosion at the silver-base-metal interface under humidity. Cyclic mechanical fatigue under thermal cycling produces silver-particle delamination from the polymer matrix, with corresponding conductivity loss. The selection of silver-based VPP photopolymer routes for applications with multi-year service life should explicitly address these failure modes in the engineering specification. Silver morphology selection — nanowires versus microparticles. Within the silver route the practical engineering choice between nanowire and microparticle morphologies is governed by the aspect-ratio trade-off introduced in §3.4. Silver nanowires reach the high-conductivity printed-conductor regime conductivity regime at approximately 5 wt% loading [50] and preserve a substantial fraction of the cured-part optical transparency, leaving cure-depth budget available for VPP processing at standard layer thicknesses. The principal nanowire-specific limitation is the tendency of high-aspect-ratio metallic nanowires to coil on themselves during synthesis, storage and dispersion handling [PR17]; uncoiling without breakage requires dispersion at the lowest shear intensity that achieves the percolation-active state, and breakage of the wires during over-aggressive dispersion is documented to reduce realised conductivity at fixed nominal loading. Silver microparticles and microflakes reach the high-conductivity printed-conductor regime regime at substantially higher loading (typically tens of wt%) — a loading that produces two coupled system-level consequences. First, the high volumetric filler fraction increases the viscosity of the uncured formulation above the standard MSLA/DLP/LCD operating window (above approximately 2,000–5,000 mPa·s), requiring either temperature-controlled heated-vat printers (operating typically at 30–60 °C above ambient) or alternative formulation strategies (reactive diluents, low-viscosity matrices). Second, the high volumetric loading produces an optically opaque uncured resin that severely attenuates the curing wavelength; through-depth cure is achievable only at layer thicknesses of approximately 10–20 µm rather than the 50–200 µm typical of non-loaded photopolymers, with corresponding throughput penalty (the part-time scales inversely with layer thickness for a fixed print height). The nanowire-versus-microparticle morphology choice is therefore

a multi-axis decision involving conductivity ceiling, cure-depth budget, viscosity-driven printer-platform requirements, layer-thickness throughput trade-off, and dispersion-handling sensitivity — not a one-dimensional conductivity-versus-cost comparison.

Table D. Silver-filler morphology comparison within Route 6.

Morphology	Aspect ratio	Loading for Regime C	Uncured viscosity	Cure-depth optical	Layer thickness (typical)	Printer platform requireme	Principal handling sensitivi
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				budget		nt	ty
Nanowire (AgNW)	High (>100)	~5 wt% [50]	Compatible with standard VPP envelope	Preserved (semi-transparent uncured resin)	50–100 μm	Standard MSLA/DLP/LCD	Coiling and shear breakage during dispersion
Microparticle (Ag spherical)	Low (~1)	Tens of wt%	Above standard envelope (heated printing typically required)	Severely attenuated (opaque uncured resin)	10–20 μm	Heated-vat MSLA/DLP/LCD or industrial SLA	Sedimentation under density mismatch (§3.11)
Microflake (Ag platelet)	Moderate (10–50)	Tens of wt%	Above standard envelope (heated printing typically required)	Severely attenuated (opaque uncured resin)	10–20 μm	Heated-vat MSLA/DLP/LCD or industrial SLA	Orientation anisotropy during cure (§3.4) and sedimentation

Three principal silver-filler morphologies span the engineering envelope of the high-conductivity printed-conductor regime regime, with substantially different system-level profiles. Loadings and layer-thickness ranges are indicative; specific values are SDCF-dependent (§1.4 Table A1) and should be characterised on the user's platform.

morphologies span the engineering envelope of the high-conductivity printed-conductor regime regime, with substantially different system-level profiles. Loadings and layer-thickness ranges are indicative; specific values are SDCF-dependent (§1.4 Table A1) and should be characterised on the user's platform.

Morphology Aspect ratio Loading for Uncured Cure-depth Layer Printer Principal Regime C viscosity optical thickness platform handling budget (typical) requirement sensitivity

Nanowire High (>100) ~5 wt% [50] Compatible Preserved (se 50–100 μm Standard MSL Coiling and (AgNW) with standard mi-transparent A/DLP/LCD shear VPP envelope t uncured breakage resin) during dispersion

Microparticle Low (~1) Tens of wt% Above Severely 10–20 μm Heated-vat M Sedimentatio (Ag spherical) standard attenuated SLA/DLP/LCD n under envelope (opaque or industrial density (heated uncured SLA mismatch printing resin) (§3.11) typically required)

Microflake (Ag Moderate Tens of wt% Above Severely 10–20 μm Heated-vat M Orientation platelet) (10–50) standard attenuated SLA/DLP/LCD anisotropy envelope (opaque or industrial during cure (heated uncured SLA (§3.4) and printing resin) sedimentation typically required)

The table illustrates a recurring observation across the conductive-AM literature: morphology and loading are not independent design variables, and the choice between them propagates into a multi-axis set of platform-and-process consequences that the engineering specification must address. PEDOT:PSS dispersion stability and chemical compatibility. Beyond the conductivity-drift and spectral-overlap considerations developed above, the PEDOT:PSS route faces two additional system-level constraints relevant to VPP formulation. First, PEDOT:PSS dispersions exhibit a tendency toward flocculation during storage and during incorporation into photopolymer matrices, with cluster formation occurring on timescales of weeks at room temperature and faster under elevated temperature or shear. The flocculation reduces the suspension stability of the conducting-polymer phase and degrades the realised conductivity of the cured part through formation of "sea-

island" cluster structures (§3.11) rather than the continuous percolation network needed for engineering-grade performance. Second, commercial PEDOT:PSS is supplied as an aqueous dispersion, which constrains the host-photopolymer chemistry: the resins, oligomers and

monomers compatible with PEDOT:PSS-loaded systems must be water-soluble or strongly hydrophilic to maintain compatibility with the aqueous PEDOT:PSS phase. The constraint substantially narrows the host-monomer envelope relative to standard non-aqueous photopolymer chemistry and partially explains the predominance of PEG-acrylate and similar hydrophilic

backbones in published PEDOT:PSS-loaded photopolymer formulations [38,48–49]. The chemical-compatibility constraint also shapes the cleaning-solvent selection (§3.11): water-based cleaning, which would otherwise be the lowest-aggressivity option for cured photopolymer parts, can extract or dissolve the PEDOT:PSS phase from water-soluble-matrix variants, producing the conductivity-loss-after-washing failure mode of Table 3 §3.10. The hydrophilic-host mechanical penalty. A consequential corollary of the PEDOT:PSS host-compatibility constraint extends across the conducting-polymer route and is rarely surfaced explicitly in the academic conductive-AM literature. The photopolymer resins, oligomers and monomers commonly reported in the conductive-AM literature as effective hosts for controlled electrical conductivity in VPP printing — PEG-acrylates, hydroxyethyl-acrylate, hydroxypropyl-acrylate, polyvinyl-alcohol-based hydrogel precursors and the broader family of water-soluble and strongly hydrophilic photopolymer chemistries — typically deliver mechanical performance inferior to their hydrophobic structural counterparts. Hydrophilic chemistries tend to deliver lower glass-transition temperature, lower flexural modulus, lower yield strength, lower fatigue resistance and higher moisture uptake than aromatic and aliphatic hydrophobic engineering photopolymers at equivalent crosslinking. The system-level consequence is that the combinations of

"high electrical conductivity + high mechanical performance" pursued in the literature are constrained at the chemistry level: a photopolymer system optimised for conducting-polymer compatibility (hydrophilic backbone) cannot simultaneously deliver the mechanical envelope of an aromatic high-performance engineering photopolymer in the same cured part. The trade-off is one of the most significant under-discussed limitations of the Route 5 (PEDOT:PSS) and Route 2 (intrinsic backbone) conductive-photopolymer space and motivates the alternative manufacturing routes consolidated in §3.11 (indirect routes via molds with conductive slurries, paint-based surface deposition on cured photopolymer substrates, and alternative AM platforms — LMM, inkjet, Cold Fusion SLS — that decouple the conductive function from the structural function or relax the photopolymer-specific viscosity envelope). Ferroelectric route — temperature dependence and printability ceiling. The high-permittivity ferroelectric route (§3.6) faces two limitations that the conductive routes do not encounter [18,23,34]. First, the temperature dependence of ϵ_r near the BaTiO₃ Curie point (approximately 120 °C) produces a non-flat permittivity response across realistic service temperature ranges; applications requiring temperature-independent ϵ_r should select either a non-ferroelectric filler (TiO₂) or a Curie-point-shifted ferroelectric filler. Second, the printability ceiling at approximately 70 wt% ceramic loading sets a hard upper bound on the achievable ϵ_r at standard VPP irradiance; reaching higher permittivity requires either alternative deposition routes (direct ink writing, ceramic injection moulding of photocurable feedstocks) or post-print densification (debinding and sintering of high-loaded green parts). The Bio designator and the regulatory boundary. A commercial Bio designator is not an ISO 10993 certification, a biological-safety conclusion or a device approval. Any product-specific material or specimen data must identify the tested grade, workflow, specimen, endpoints and intended contact. Such evidence may contribute to a device-level biological evaluation but cannot be transferred automatically to another formulation or finished device. Clinical or implantable use requires the applicable device-level biological evaluation and regulatory pathway.

3.9 Process optimisation, printer dependency and cure-state effects

The seven stages of the SDCF (Fig. 1) are developed here as the cure-state effects that govern process-dependent electrical performance. The formulation chemistry, the percolation framework and the dielectric mixing rules set the intrinsic envelope; the specific printer and exposure strategy determine whether the realised performance matches the target. Irradiance dependency.

Photopolymerisation kinetics scale with optical irradiance, and the irradiance regime determines cured-network architecture and filler orientation. Laser SLA delivers high on-the-spot irradiance during scanning. DLP typically operates at 1–30 mW/cm² with whole-layer simultaneous exposure. LCD MSLA typically operates below 6 mW/cm². For filler-based composites the irradiance regime affects percolation-network formation: lower-irradiance regimes allow longer flow times during cure, with measurable consequences for filler orientation and network connectivity. Higher-irradiance regimes lock the filler distribution before flow can re-distribute particles, producing a percolation network that more closely reflects the as-mixed dispersion at the

cost of any beneficial in-print orientation [7]. For ceramic-loaded dielectric composites (Route 7), the irradiance regime additionally determines the optical-scattering-limited cure depth: at high ceramic loading the scattering shadow beneath each cured layer constrains the through-thickness cure homogeneity [18]. Power-time decomposition of cure dose. Cumulative energy dosage (mJ/cm² = mW/cm² × s) is a necessary but insufficient parameter for predicting electrically functional composite behaviour. For identical cumulative dose, lower irradiance over longer exposure allows more in-print orientation and re-dispersion than higher irradiance over briefer exposure. Two prints carrying identical total dose with different power-time decompositions can yield materially different electrically functional architectures. Calibration must therefore specify both the dose and the power-time profile. Geometry-dependent flow and orientation. Cured-part geometry sets the flow field that filler particles experience during cure. Thin-walled traces with high aspect ratio produce filler orientation along the trace direction, with corresponding conduction anisotropy. Bulk geometries with low aspect ratio produce more isotropic filler distributions. Build direction (Z vs in-plane) modulates the orientation. For 1D fillers the orientation effect is significant at aspect ratios above approximately 100; for 2D fillers it is significant at all aspect ratios. Electrical performance of a printed conductor therefore varies with print orientation chosen for the same geometric design. Post-cure performance drift. Several routes exhibit measurable post-cure performance drift over hours to weeks. PEDOT:PSS exhibits humidity-dependent drift over weeks (§3.8). Silver exhibits oxidative drift over months (§3.8). Filler-based composites exhibit shorter-timescale drift over hours to days as the cured matrix completes thermal post-cure and residual reactive species consume free filler-surface sites [7]. Ferroelectric composites exhibit temperature-cycling drift as the ferroelectric domain configuration evolves [23]. The post-cure protocol therefore determines the stabilised performance measured at the moment of release. Storage history of the uncured formulation. Filler-based electrically functional resins exhibit gradual sedimentation, agglomeration and dispersion drift over the storage shelf-life of the uncured formulation. The performance of a print made from a vat at the end of shelf-life is typically different from a print made from the same product at the beginning of shelf-life. Re-dispersion protocols restore dispersion to within formulation tolerance but cannot fully reverse advanced sedimentation [7]. Documented commercial portfolios in this segment typically guarantee a shelf-life of 6 months at controlled temperature (15–25 °C) for filler-based and conducting-polymer products [PR3,PR4]. Host polymer molecular weight and printability resolution. A documented system-level dependence specific to

conducting-polymer-based formulations is the effect of the host polymer molecular weight on the photopolymerisation kinetics and the printing resolution. Mantione et al. [48] systematically characterised three PEGDA molecular weights (M_n = 250, 575 and 700 Da) as the photocurable host for PEDOT:PSS-based DLP inks, demonstrating that the printability resolution improves monotonically with PEGDA molecular weight while the swelling ratio and the mechanical compliance shift in parallel. The molecular-weight dependence is not a free parameter for the user; it is set by

the formulation supplier. The SDCF implication is that the cured-part properties depend on the host molecular weight as much as on the conductive-component loading, and that user-side calibration

on a specific product is not transferable to a nominally similar product with a different molecular-weight host polymer. The combined practical consequence is the SDCF (§1.4 and Fig. 1): the formulation chemistry sets the electrical-performance envelope; the printer irradiance, the power-time decomposition, the build orientation, the geometry, the post-cure protocol, the ambient humidity and the storage history together determine where within the envelope a given print lands. Engineering teams adopting these materials should plan for per-platform calibration, controlled ambient conditions, and explicit specification of the electrical-performance measurement protocol used to characterise the cured part. Polymer-physics fundamentals underlying the cure-state effects. Several of the cure-state and storage-state effects above have direct polymer-physics interpretations that link the

cured-network architecture to the realised electrical performance. The crosslink density of the cured photopolymer matrix is set by the cure conversion and the host-monomer functionality; for typical multi-functional acrylate and methacrylate matrices, the crosslink density sits in the range of

10^{-3} – 10^{-2} mol/cm³ at full conversion, with the lower end corresponding to flexible

hydrogel-compliant hosts (PEG-acrylate networks at $M_n \approx 575$ – 700 Da [48]) and the upper end corresponding to glassy structural hosts. The crosslink density determines the network mesh size that the conductive component sees as the cure proceeds and the average chain mobility between crosslinks after cure. For filler-based composites, lower crosslink density permits greater filler re-arrangement during cure and post-cure (with the orientation and percolation-efficiency consequences of §3.4); for conducting-polymer composites (Route 5), lower crosslink density permits greater chain mobility of the conducting polymer phase, which improves intra-phase charge transport but increases humidity-induced swelling and the corresponding humidity-driven conductivity drift documented in §3.8. Water plasticisation of the cured network. A polymer-physics mechanism that is consistently under-discussed in the conductive-AM literature is the plasticising effect of absorbed water on the cured photopolymer network, particularly in the hydrophilic-host chemistries of Route 5 (PEDOT:PSS) and the Bio variants of Routes 2-4. Water uptake into the cured network at equilibrium with ambient humidity follows Fickian diffusion at typical service-condition temperatures, with diffusion coefficients in the range of 10^{-8} – 10^{-6} cm²/s depending on the matrix hydrophilicity and the crosslink density. The absorbed water lowers the glass-transition temperature T_g of the cured network through plasticisation — typical T_g depressions of 5–30 °C are documented in hydrogel-compliant hydrophilic photopolymers at equilibrium with 60–90% relative humidity ambient. The T_g depression increases chain mobility above the glassy threshold, alters the dielectric environment seen by the conducting polymer phase, and produces the swelling and the network mesh-size expansion that translate into the humidity-driven conductivity hysteresis of PEDOT:PSS systems documented in §3.8 and the surface-resistivity drift of ESD-focused systems under humid storage [12,17,28,38]. Network topology constraints — chain entanglement density, dangling-end fraction, crosslink junction functionality — further modulate the water-plasticisation amplitude and shape the recovery hysteresis on de-humidification. Free-volume theory provides the underlying framework: the absorbed water occupies free volume within the cured network and the additional free volume produced by plasticisation determines the chain mobility regime that the conductive component traverses. For engineering specifications targeting humid service environments, the water-plasticisation effect should be characterised at the relevant relative-humidity range rather than at the dry-state nominal condition reported in most datasheets. Flory-Huggins compatibility and the conductive-phase-host interaction. The thermodynamic compatibility between the conductive component and the photopolymer host is governed by the Flory-Huggins interaction parameter χ , which captures the enthalpic and entropic contributions to the mixing free energy. For dispersion-stable conductive-photopolymer formulations, the host-component combination should

sit close to or within the miscibility window of the Flory-Huggins phase diagram at the operating temperature, with χ values below the critical threshold for phase separation at the working concentration. PEDOT:PSS aqueous dispersions are compatible with hydrophilic photopolymer hosts (low χ) and incompatible with hydrophobic photopolymer hosts (high $\chi \rightarrow$ phase separation, as documented in the PEDOT:PSS hydrophobic-host phase-separation failure mode of Table 3 §3.10).

For filler-based composites, the analogous compatibility metric is the surface energy match between filler and matrix, which determines the wetting behaviour and the equilibrium dispersion state at fixed dispersion-protocol input. Surface-functionalisation of conductive fillers (silanisation of graphene, COOH-functionalisation of CNTs, PEG-coating of silver nanoparticles) shifts the effective χ toward the hydrophilic or hydrophobic end of the host envelope and is one of the principal formulation handles for stabilising conductive-component-loaded photopolymer formulations beyond the rheological-additive strategy of §3.11. The cured-network compatibility evolves during cure and post-cure as the network topology stiffens: a system that is compatible in the liquid state can transition into a phase-separated state during cure if the χ value crosses the critical threshold for the increasing-crosslink-density cured network, producing the

post-cure microstructural heterogeneity that is sometimes observed in conductive-composite literature without polymer-physics interpretation. Time-dependent realised electrical behaviour and the manufacturing-aware characterisation problem. The polymer-physics framework developed above interprets the cured-part properties at a single time point, typically the as-released state from the manufacturer post-cure protocol. The realised electrical performance of an electrically functional VPP photopolymer part is not a single time-point quantity; it evolves through a sequence of states that the manufacturing-and-service workflow induces. Recognising and characterising this time trajectory is one of the meaningful contributions that the SDCF framework brings to the field beyond single-time-point performance reporting. Six characteristic stages of the time-dependent realised electrical behaviour can be identified across the route taxonomy. Stage 1 — As-printed state, immediately after the layer-by-layer cure cycle. The cured part is at partial conversion (typically 60-85% for acrylate and methacrylate matrices [1,5,26]) with residual reactive species at the surface (oxygen-inhibited skin) and within the bulk. The conductive component has assumed an orientation distribution set by the cure-time flow field (§3.4), with the percolation network in an initial configuration that the post-cure protocol will modify. Realised electrical performance in the as-printed state is typically below the engineering target. Stage 2 — Post-cure stabilised state. Following the manufacturer-recommended post-cure thermal-and-UV protocol (typically 30-120 minutes at controlled temperature and irradiance, optionally followed by 30-minute annealing at 80-140 °C [PR17]), the cure conversion approaches its asymptotic value (>95% for most engineering formulations), residual reactive species are consumed, and the conductive-network configuration stabilises. For silver-based routes, partial sintering at filler-particle interfaces produces an order-of-magnitude conductivity increase relative to Stage 1 [15,PR17]. For PEDOT:PSS routes, the conducting-polymer phase locks into its final spatial distribution. This is the state typically reported in manufacturer datasheets and in single-time-point academic studies. Stage 3 — Environmental equilibration state. The cured part reaches equilibrium with its service environment over hours-to-days following release. Humidity absorption follows Fickian diffusion (§3.9 polymer-physics paragraph) and shifts the realised electrical performance: PEDOT:PSS routes exhibit conductivity increases of 1-2 orders of magnitude at high RH equilibrium [12,17,28,38]; ESD-focused routes exhibit surface-resistivity shifts within the Regime A envelope; ceramic-loaded dielectric composites exhibit minor permittivity drift through interfacial polarisation effects. The Stage 3 state is the operationally relevant state for service performance but is rarely the state characterised in published studies. Stage 4 — Service-condition cyclic state. Under operational cycling — temperature cycling, humidity cycling, mechanical load cycling, electrical-bias cycling — the realised performance follows hysteresis loops that depend on the cycling history. PEDOT:PSS humidity

hysteresis loops typically open at amplitudes of 0.5-1 order of magnitude in conductivity over a 30-90% RH cycle [12,38]. Silver-based routes under DC bias accumulate electromigration damage that translates into progressive conductivity loss over months-to-years [11,19,29]. The Stage 4 state is the integration of the cycling history and is intrinsically history-dependent. Stage 5 — Long-term ageing state. Over service lifetimes of months to years, the cured network undergoes slow ageing: oxidative chain scission at exposed surfaces, polymer-relaxation-driven dimensional drift, gradual filler-matrix interface degradation, and (for silver routes) progressive sulfur-tarnishing and surface-oxide growth (§3.8). The Stage 5 state quantifies the long-term performance envelope and is essential for

engineering specifications targeting multi-year service. The published literature on the Stage 5 envelope is sparse for all conductive-VPP routes, and accelerated-ageing protocols specific to electrically functional photopolymers are not standardised. Stage 6 — End-of-life state. The cured part transitions out of engineering-acceptable performance through a route-specific dominant mechanism: electromigration-induced short for silver,

humidity-induced conductivity collapse for PEDOT:PSS without recovery, percolation-network fracture for filler-based composites under sustained mechanical fatigue, or dielectric-loss accumulation for ceramic-loaded composites at high field. The end-of-life criterion is

application-dependent rather than material-intrinsic. The conventional manufacturer-datasheet reporting and the conventional single-time-point academic study capture only Stage 2. The cross-stage evolution of the realised performance — and the corresponding manufacturing-aware characterisation that includes Stage 3 environmental equilibration, Stage 4 cycling response and Stage 5 ageing under representative service conditions — remains the systematic gap between published conductive-VPP performance and engineering-deployed conductive-VPP performance. Closing this gap is identified as a community-level priority in §13.11.

Table F. Trade-offs and unavoidable compromises in the conductive-VPP design space.

Property improved	Property compromised	Underlying mechanism	Representative route
Higher conductivity (filler-based)	Optical attenuation (cure-depth budget)	Higher filler loading → more wavelength absorption/scattering	Routes 3, 4, 6
Higher conductivity (filler-based)	Rheological printability	Higher filler loading → higher viscosity, non-Newtonian	Routes 3, 4, 6, 7
Higher conductivity (PEDOT:PSS)	Mechanical envelope retention	Hydrophilic-host backbone with lower modulus/Tg	Route 5 + Bio variants of Routes 2-4
Higher conductivity (silver microparticle)	Cure layer thickness	Optical opacity → 10-20 μm layers vs 50-200 μm	Route 6b microparticle
Higher mechanical performance	Compatibility with PEDOT:PSS	Hydrophobic high-performance hosts incompatible with aqueous conducting-polymer phase	Route 5
Higher aspect ratio (nanowires)	Coiling-prone handling	Entropic relaxation toward coiled state, low-viscosity matrices accelerate coiling	Route 6a AgNW
Higher cure speed	Network shrinkage stress	Faster crosslinking → less relaxation time → higher residual stress	All filler routes
Higher relative permittivity ϵ_r	Loss tangent $\tan \delta$	Higher ceramic loading → higher	Route 7

		interfacial polarisation losses	
Stable temperature-independent ϵ_r	Maximum achievable ϵ_r	TiO ₂ (non-ferroelectric) lower ϵ_r than BaTiO ₃ ; BaTiO ₃ Curie-point drift	Route 7
Long-term humidity stability	Conducting-polymer compatibility	Hydrophobic-host stability vs PEDOT:PSS phase separation	Route 5
Higher percolation network density	Network fragility under cure shrinkage	Brittle filler-rich networks fracture under matrix contraction	Routes 6 microparticle, 7 ceramic
More mature product-specific biological evidence Evidence is grade-, specimen-, workflow-, endpoint- and contact-specific; no formulation-level certification is implied	Mechanical/HDT envelope	Bio-compatible backbones typically softer and lower HDT than aromatic structural hosts	Bio variants of all routes
Higher print resolution	Throughput	Thinner layers → longer print time at fixed print height	Routes 6b, 7 ceramic-loaded

The trade-offs are not formulation defects but structural design tensions of the SDCF, operating within and across routes and constraining the simultaneous optimisation of multiple performance axes.

The framework developed in this review consolidates a set of trade-offs that are not formulation defects but rather structural design tensions of the SDCF. The trade-offs operate within and across routes and constrain the simultaneous optimisation of multiple performance axes. The table consolidates the most consequential design-axis tensions encountered across the seven electrical-function routes and the orthogonal dielectric route.

Property improved Property compromised Underlying mechanism Representative route

Higher conductivity Optical attenuation Higher filler loading → more Routes 3, 4, 6 (filler-based) (cure-depth budget) wavelength absorption/scattering

Higher conductivity Rheological printability Higher filler loading → higher Routes 3, 4, 6, 7 (filler-based) viscosity, non-Newtonian

Higher conductivity Mechanical envelope Hydrophilic-host backbone Route 5 + Bio variants of (PEDOT:PSS) retention with lower modulus/Tg Routes 2-4

Higher conductivity (silver Cure layer thickness Optical opacity → 10-20 μm Route 6b microparticle microparticle) layers vs 50-200 μm

Higher mechanical Compatibility with PEDOT:PSS Hydrophobic Route 5 performance high-performance hosts incompatible with aqueous conducting-polymer phase

Higher aspect ratio Coiling-prone handling Entropic relaxation toward Route 6a AgNW (nanowires) coiled state, low-viscosity matrices accelerate coiling

Higher cure speed Network shrinkage stress Faster crosslinking → less All filler routes relaxation time → higher residual stress

Higher relative permittivity ϵ_r Loss tangent $\tan \delta$ Higher ceramic loading → Route 7 higher interfacial polarisation losses

Stable Maximum achievable ϵ_r TiO₂ (non-ferroelectric) lower Route 7 temperature-independent ϵ_r ϵ_r than BaTiO₃; BaTiO₃ Curie-point drift

Long-term humidity stability Conducting-polymer Hydrophobic-host stability vs Route 5 compatibility
PEDOT:PSS phase separation

Higher percolation network Network fragility under cure Brittle filler-rich networks Routes 6
microparticle, 7 density shrinkage fracture under matrix ceramic contraction

More mature product-specific biological evidence | Evidence is grade-, specimen-, workflow-,
endpoint- and contact-specific; no formulation-level certification is implied

Higher print resolution Throughput Thinner layers → longer print Routes 6b, 7 ceramic-loaded time
at fixed print height

The trade-offs in Table F are not formulation failures; they are structural consequences of the
underlying chemistry-process-property couplings. The engineering response is not to eliminate the

The purpose of the comparison is to identify an application-specific operating point and the evidence
still required. Route selection cannot establish biological suitability. Product-specific electrical,
mechanical, ageing, processing and biological evaluation remains necessary before any deployment
claim.

3.10 Failure modes and mitigation

Failure mode Underlying cause Affected workflows Mitigation

Sub-percolation conductivity Filler loading below threshold Routes 3, 4 after extended Verify
dispersion per TDS or aggregation reducing storage or under inadequate protocol; consider intrinsic
effective dispersion below the re-dispersion (Route 2) or silver (Route 6) printable threshold for
applications where dispersion variability is intolerable

Geometry-dependent Filler orientation modulated Filler-based routes (3, 4, 6, 7), Specify print
orientation in performance scatter by build direction and part particularly Route 4 at high
engineering specification; geometry aspect ratio calibrate per orientation

Layer-to-layer conduction Inter-layer cure boundary Routes 3, 4 with poor Optimise layer thickness
and discontinuity produces a resistive interface inter-layer cure overlap inter-layer exposure
overlap; exceeding the within-layer verify Z-direction conductivity percolation-network separately
from in-plane resistance

Humidity-driven PEDOT:PSS Doping-state equilibration Route 5 in uncontrolled Specify post-cure
protocol drift with ambient water storage and storage atmosphere; characterise at fixed humidity
history

Silver oxidative drift Surface oxidation under Route 6 in unmanaged Specify service-environment
humid and high-temperature environments limits; consider encapsulation conditions or coating for
outdoor use

Silver electromigration DC-bias-driven dendrite Route 6 under DC bias in Pulse-bias operation where
growth under humidity humid environments applicable; spatial separation of adjacent silver
conductors; conformal coating

Silver sulfur tarnishing H₂S exposure producing Route 6 in Atmosphere control or sealed non-
conductive silver sulfide industrial-atmosphere enclosures; periodic layer environments conductivity
verification

Ferroelectric Curie-point drift BaTiO₃ tetragonal-to-cubic Route 7 in applications Select transition
near 120 °C crossing the Curie temperature-independent temperature filler (TiO₂) or
Curie-point-shifted variant; characterise ϵ_r across the service temperature range

ESD-band drift Surface contamination, Route 1 in service Periodic surface resistivity humidity adsorption or environments outside verification; cleanroom or chemical exposure altering specification controlled-atmosphere the static-dissipative loading handling for critical state applications

Cure-depth limitation in Conductive filler or ceramic High-loading routes (3, 4, 6, Reduce filler loading; increase filler-loaded prints absorbs/scatters curing 7) on platforms with limited exposure time; verify cure wavelength, producing irradiance budget depth on specific printer-resin under-cure beneath surface combination layer

Surface-roughness-driven Cured-part surface roughness All routes when used for Specify surface finish; contact-resistance variability producing variable electrical printed-electronics interfaces consider post-print polishing contact area or conductive coating for critical contact interfaces

Viscosity drift during storage Sedimentation, agglomeration Filler-based routes (3, 4, 6, 7) Verify shelf-life conditions per or partial pre-polymerisation and high-loading TDS; re-disperse per protocol during shelf-life of the conducting-polymer routes (5) prior to printing; characterise uncured formulation post-storage rheology if storage exceeds nominal shelf-life

Oxygen inhibition at the cured Atmospheric oxygen All routes; particularly Post-cure under inert surface scavenging radicals at the relevant for thin-feature parts atmosphere or with controlled cured-part surface during VPP and for routes where surface UV-flood-cure protocol; cure, producing a partially conductivity is the characterise surface vs bulk cured surface layer with engineering target [26] resistivity separately for elevated surface resistivity critical applications

Failure mode Underlying cause Affected workflows Mitigation

Post-cure shrinkage cracking Differential shrinkage High-loading routes (3, 4, 6, Optimise post-cure thermal between conductive 7) under aggressive post-cure ramp; characterise post-cure filler/ceramic and thermal cycles microstructure; select lower photopolymer matrix during thermal-expansion-mismatch post-cure thermal cycle, filler-matrix combinations producing microcracks that where possible disrupt the percolation network

Conductivity loss after solvent Removal of soluble Routes 5 (water-soluble CDP Specify wash solvent washing conducting-polymer phase or variants), Routes with compatibility per route; stabiliser by post-print solvent stabiliser-dependent characterise post-wash cleaning dispersion electrical performance; use non-aqueous cleaning for water-soluble conducting-polymer routes where critical

Metallic-nanowire self-coiling Tendency of high-aspect-ratio Route 6 silver-nanowire Maintain matrix viscosity in metallic nanowires to coil morphology the upper VPP envelope during synthesis, storage and (1,500–4,000 mPa·s) or dispersion, reducing effective introduce a yield-stress aspect ratio and percolation contribution to immobilise the efficiency; low matrix wires below a critical shear; viscosity accelerates the dispersion at lowest shear coiling relaxation rather than intensity that achieves suppressing it [PR17] uncoiling without breakage; specify dispersion protocol in engineering specification

Printability ceiling at high Viscosity rise above standard Route 6 silver-microparticle Heated-vat printing at 30–60 microparticle loading VPP envelope (>5,000 mPa·s) and silver-microflake °C above ambient; thin-layer at the high volumetric loading morphologies printing (10–20 µm); (tens of wt%) required for reactive-diluent formulation; silver microparticle and nanowire morphology microflake routes to reach substitution where compatible Regime C

PEDOT:PSS dispersion Cluster formation in Route 5 PEDOT:PSS systems Controlled-temperature flocculation PEDOT:PSS dispersions during storage; gentle re-dispersion storage or under elevated before printing; use within temperature/shear, producing documented shelf-life; verify sea-island cluster structures dispersion state prior to print rather than percolation [PR17] network

Hydrophobic-host phase Phase separation between Route 5 PEDOT:PSS in Restrict host chemistry to separation aqueous PEDOT:PSS non-hydrophilic photopolymer water-soluble or strongly dispersion and hydrophobic hosts hydrophilic resins, oligomers host monomer/oligomer, and monomers (PEG-acrylate, destroying hydroxyethyl-acrylate or conducting-polymer equivalent); verify continuity before cure compatibility per host [38,48–49]

Table 3. Common failure modes of electrically functional photopolymer additive manufacturing

Application-specific implementation examples are described in the body text; no separate application table is presented in this version.

systems, their underlying causes, the workflows in which they most commonly appear, and the engineering mitigations available. None of the failure modes is intrinsic to the chemistry — each is the realised consequence of formulation, cure conditions, geometry or service environment falling outside the validated operating window.

3.11 Manufacturing and process scalability constraints

Engineering-grade deployment of electrically functional VPP photopolymers depends on a set of manufacturing constraints that the peer-reviewed academic literature documents less systematically than the chemistry and physics constraints of §3.1–§3.10. This subsection consolidates the principal manufacturing constraints from publicly available industrial instructions-for-use documentation [PR17,PR1,PR2,PR4,PR5,PR6,PR8] cross-referenced with the recent peer-reviewed literature on VPP process science [1,5–6,14,26,33–34,44].

Filler-density mismatch and sedimentation kinetics. The principal manufacturing constraint for metallic-filler routes is the density mismatch between the conductive filler and the photopolymer matrix. Metallic silver fillers (density approximately 10.5 g/cm³) sit approximately one order of

magnitude above typical photopolymer matrix densities (0.95–1.05 g/cm³) [PR17,15]. The mismatch drives gravitational sedimentation in the uncured vat with timescales of minutes to hours under static conditions, depending on filler particle size and matrix viscosity. Carbon-based fillers (CNT, GNP) sit closer to the matrix density but agglomerate through electrostatic and van-der-Waals interactions that produce effective sedimentation behaviour at sufficient cluster size [7,33]. Ceramic fillers (BaTiO₃, TiO₂) at engineering-grade loading (50–70 wt%) face severe sedimentation that

constrains practical vat-residence time. Stabilisation through dispersant addition (e.g.

anti-sedimentation auxiliaries [PR17]) extends the practical vat-residence time but does not eliminate the underlying density-mismatch physics. Storage shelf-life and temperature sensitivity. Conductive photopolymer formulations exhibit limited shelf-life relative to non-filler-loaded photopolymers. Documented manufacturer specifications indicate shelf-life of approximately 6 months at controlled ambient temperature (<25 °C) for filler-based and conducting-polymer products [PR1,PR4,PR17], with refrigerated storage (approximately 4 °C) extending this window. The principal failure mode at elevated storage temperature (>40–50 °C) for

metallic-nanomaterial-loaded products is premature gelation during shipping or storage [PR17], a manufacturing failure that occurs before the user begins printing and that is decoupled from the user's process. Quality-control implications are substantial: cold-chain logistics,

temperature-monitored shipping, and date-code tracking are required for products at the upper end of the conductivity envelope. Dispersion equipment and shear sensitivity. Achieving the percolation-active state of the conductive component in the cured part requires the conductive component to be fully wetted, deagglomerated, stabilised and homogenised in the uncured formulation [PR17]. The dispersion-equipment landscape includes overhead rotary mixers (effective with controlled shear and small Conn blades for batches up to several litres), vortex mixers (suitable for small test-tube batches and low-viscosity systems), high-speed dispersers and homogenisers (effective but

constrained by foam generation, local heating and premature polymerisation at excessive speed), and ultrasonic baths or probe sonicators (effective for nano-submicron dispersion but requiring temperature control to prevent premature polymerisation). Magnetic stirrers are typically insufficient for high-loading or high-viscosity systems. The principal shear-sensitivity constraint for nanowire and microfibre conductive routes is mechanical breakage at excessive shear: the goal is full wetting and deagglomeration at the lowest shear intensity that delivers the dispersion state, with simultaneous foam control and temperature control [PR17]. High-aspect-ratio metallic nanowires (silver nanowires being the principal documented example) present an additional coiling sensitivity: as-supplied nanowire dispersions exhibit a tendency toward self-coiling that reduces the effective aspect ratio and consequently the percolation-network efficiency of the cured composite [PR17,57]. The dispersion goal is to uncoil the nanowires without breaking them — a narrow process

window that distinguishes the silver-nanowire route from the silver-microparticle and silver-microflake routes in terms of dispersion-equipment requirements. High-loading viscosity and heated-printer requirements. Silver-microparticle and silver-microflake routes face a viscosity-driven manufacturing constraint distinct from the dispersion-handling constraints of the nanowire route. The high volumetric filler loading required for these morphologies to reach the high-conductivity printed-conductor regime regime (typically tens of wt%) increases the viscosity of the uncured formulation above the standard

MSLA/DLP/LCD operating window of approximately 2,000–5,000 mPa·s [5–6]. Two

formulation-and-platform pathways address the constraint. The first is temperature-controlled heated-vat printers operating typically at 30–60 °C above ambient: the viscosity of typical acrylate and methacrylate photopolymer matrices decreases by approximately one order of magnitude across this temperature range, bringing high-loading silver-microparticle formulations within the printable envelope. The second is formulation adjustment through reactive diluents, low-viscosity host monomers or co-solvent strategies,

accepting the corresponding adjustment in cured-part mechanical envelope. The combined optical-opacity constraint of high-loading silver microparticle systems further requires print-resolution operation at thin layer thicknesses of approximately 10–20 µm rather than the 50–200 µm typical for non-loaded photopolymer prints (§3.11 wavelength-attenuation paragraph).

The viscosity-and-opacity coupling explains the practical preference for nanowire morphologies in applications where standard ambient-temperature MSLA/DLP/LCD platforms are the target deployment environment, and the practical preference for microparticle/microflake morphologies in industrial workflows where heated-vat hardware and thin-layer throughput are tolerated. PEDOT:PSS suspension-stability constraints. The PEDOT:PSS conducting-polymer route faces a different manufacturing-handling profile from the metallic-filler routes. The aqueous PEDOT:PSS dispersion is prone to flocculation during storage and during incorporation into host photopolymer matrices, with cluster formation accelerating under elevated temperature or shear and producing the "sea-island" cluster structures referenced in §3.11 troubleshooting practice [PR17,42]. Re-dispersion through gentle agitation is partially effective on early-stage flocculation but cannot restore the as-supplied colloidal state on advanced flocculation. The aqueous nature of the conductive phase also constrains the host-photopolymer compatibility envelope: only water-soluble and strongly hydrophilic resins, oligomers and monomers preserve a stable single-phase mixture with the PEDOT:PSS dispersion. Hydrophobic photopolymer hosts produce phase separation that destroys the percolation network before cure can lock the conductive phase in place. The compatibility constraint is reflected in the published PEDOT:PSS-photopolymer literature in the predominance of PEG-acrylate, hydroxyethyl-acrylate and similar hydrophilic-host chemistries [38,48–49]. Manufacturing implications include

shorter shelf-life relative to non-aqueous photopolymers, controlled-temperature storage to slow flocculation, and limited compatibility of PEDOT:PSS-loaded

formulations with the non-aqueous cleaning-fluid chemistry deployed across the rest of the conductive portfolio (§3.11 cleaning-solvent paragraph). Vat volume, recoating dynamics and surface plasticisation. During VPP printing, the cured part remains in contact with the uncured resin during the inter-layer dwell time. Extended contact between the cured part and the conductive-component-loaded uncured resin produces a surface plasticisation effect that affects dimensional stability and the through-thickness electrical homogeneity of the cured part [1,6,26]. The mitigation is minimisation of the vat volume during printing — the volume of uncured resin in contact with the cured part should be the smallest compatible with the build, with automatic resin feeders or equivalent volume-control systems replenishing the vat as the print progresses [PR17]. The constraint is more acute for conductive systems than for non-conductive photopolymers because the surface-plasticisation effect propagates directly into the realised electrical performance. Wavelength attenuation and cure-depth budget. Conductive fillers, conducting polymers and ceramic fillers attenuate the curing wavelength through absorption and scattering [4-5,18,28,49]. The cure-depth budget per layer is correspondingly reduced relative to the non-loaded photopolymer baseline, and the relationship between cure dose and cure depth is non-linear. The practical implications are higher exposure energy per layer, thinner layer thickness, and platform-specific re-calibration on initial use of a new conductive product. Calibration files (e.g. test prints designed for cure-depth characterisation) should be re-printed when changing between conductive products or between platforms [PR17]. Cleaning solvent compatibility. Post-print cleaning is the final manufacturing step before the conductive part enters service. Solvent selection is a system-dependent decision: aliphatic alcohols (isopropanol IPA) are effective at removing uncured resin from the cured part surface but can produce mechanical embrittlement and reduce flexural strength through extraction of un-crosslinked oligomers [PR17]. Non-IPA cleaning fluids (water-based or low-aggressivity solvents [PR9]) preserve mechanical performance better but may be incompatible with certain conducting-polymer routes (Route 5 PEDOT:PSS systems with water-soluble matrix components) where aqueous cleaning would dissolve the conductive function. The conductivity-loss-after-washing failure mode (Table 3 §3.10) is the direct consequence of solvent-route mismatch.

Metrology heterogeneity. Two-probe contact-resistance multimeter measurements are widely used in routine quality control but typically underestimate the conductivity of high-conductivity printed parts due to contact resistance at the probe-part interface [PR17,15]. Four-probe Kelvin-method instruments separate the contact-resistance contribution from the bulk-conductivity contribution and are the engineering reference for low-resistance characterisation of printed conductive parts.

Cross-study conductivity comparison in the peer-reviewed literature is therefore complicated by metrology heterogeneity: a 4-probe value cannot be directly compared to a 2-probe value on nominally identical material, and a "single value" report in a publication is meaningful only when accompanied by the measurement method, the contact protocol and the geometry (§13.1). Annealing as a manufacturing post-process step. Thermal annealing of cured conductive parts at approximately 80–140 °C for approximately 30 minutes is documented to improve electrical contact within the percolation network [PR17,15]. The mechanism is matrix relaxation that brings adjacent filler particles into closer contact and, for metallic systems, partial sintering at the filler-particle interfaces. The annealing temperature and time depend on the matrix glass-transition temperature, the filler chemistry and the desired final conductivity. Annealing is documented as a manufacturer-recommended post-process step in industrial workflows for high-end conductive performance, but is rarely included in academic single-process-step characterisation studies — a methodological gap that contributes to the scatter in the published conductivity envelope per chemistry route. Manufacturing implications for engineering specification. The manufacturing constraints summarised in this subsection imply that engineering specifications for parts using electrically functional VPP photopolymers should include, at minimum: the validated platform and process parameters; the storage condition history of the uncured resin; the dispersion protocol used to

prepare the resin for printing; the print orientation relative to the conductive-direction-of-interest; the cleaning solvent and protocol; the post-cure thermal cycle and atmosphere; and the conductivity measurement protocol (probe configuration, contact protocol, geometry). The current convention in many manufacturer datasheets and a subset of the peer-reviewed literature to report a single conductivity value detached from this specification context propagates the resin-only mismatch identified in §1.4 and is the central manufacturing-science contribution of this review (§13.1). Manufacturing alternatives beyond direct VPP. Several of the manufacturing constraints developed above — high-loading viscosity ceiling for the silver microparticle route, hydrophilic-host mechanical penalty for the PEDOT:PSS route, optical-rheological coupling that constrains the maximum filler loading at acceptable VPP printability — set a system-level ceiling on what direct VPP printing can deliver in a single cured part. The conductive-AM literature documents four manufacturing alternatives that relax these constraints by decoupling the conductive function from the structural function or by relaxing the photopolymer-specific viscosity-and-optical envelopes. Indirect AM via 3D-printed molds with conductive slurry casting. A VPP-printed sacrificial or reusable mold is filled with a metal-particle-loaded slurry whose viscosity, optical attenuation and density mismatch are unconstrained by VPP printability. The green part is subsequently debound and sintered to deliver a metallic part with conductivity approaching bulk-metal values. The route bypasses the VPP-specific limitations on filler loading at the cost of requiring a separate debinding-and-sintering thermal post-process, and is widely deployed in metal injection moulding (MIM) and ceramic injection moulding (CIM) workflows adapted to AM-produced molds. The advantage relative to direct conductive VPP is that the metal does not need to be melted — densification proceeds through solid-state sintering at temperatures typically below the bulk melting point — which expands the accessible metal palette beyond the metals compatible with high-temperature laser melting. The sacrificial-template literature for tissue engineering [55] and the engineered-vasculature literature [56] document the broader manufacturing-architecture space of which the conductive-slurry indirect route is one specialisation; recent peer-reviewed work has used PEGDA-based DLP-printed molds with subsequent functional-ink infusion for ready-to-use microfluidic systems [57], demonstrating the cross-fertilisation between the sacrificial-template route and the conductive-AM route.

Lithography-based metal manufacturing (LMM) with high-loading conductive feedstocks. LMM is a VPP-adjacent technology in which the printed feedstock is a highly loaded paste-like photopolymer-metal-particle composite, typically at metal loadings of 50–60 vol%, that is photocured layer-by-layer and subsequently debound and sintered to deliver dense metal parts [PR1,PR2]. The high-loading paste feedstock is impractical in standard MSLA/DLP/LCD platforms because of the viscosity envelope and recoating constraints discussed in §3.5, but LMM hardware is engineered specifically for this rheological regime through controlled recoating, heated processing

and feedstock-specific build dynamics. The advantage is that LMM enables a direct AM route to high-loading conductive geometries at resolutions intermediate between MSLA/DLP/LCD and metal binder jetting, without the mold-and-cast step of the indirect route. Inkjet photopolymer deposition and its complementary limitation. At the opposite end of the viscosity envelope, inkjet AM uses single-droplet ejection through fine nozzles and is constrained to feedstock viscosities typically below 50 mPa·s at the operating temperature [PR2]. The viscosity constraint imposes the opposite manufacturing limit to LMM: inkjet feedstocks cannot accommodate the high volumetric loadings of conductive fillers that MSLA/DLP/LCD platforms tolerate (let alone the higher loadings achievable in LMM), because high-loading inkjet feedstocks produce nozzle clogging, droplet-formation instability and inconsistent deposition. Inkjet conductive AM is therefore practical for low-to-moderate-loading conductive composites at sub-50-mPa·s viscosity, with the corresponding ceiling on achievable conductivity per cured layer. The inkjet-LMM-VPP triad defines a viscosity-and-loading landscape in which different conductive-AM applications find their optimal platform. Conductive surface coatings

on cured photopolymer substrates. A fourth manufacturing alternative decouples the structural function (delivered by a standard VPP photopolymer with full hydrophobic mechanical envelope) from the conductive function (delivered by a post-print surface coating of a conductive paint). Water-based conductive paints based on nano-graphene dispersions or PEDOT:PSS dispersions are applied to the cured photopolymer surface and deliver localised conductive function without requiring the bulk photopolymer to be conductive [PR8,PR15]. The 3D-PAINT GrapeK2 Bio nano-graphene-based water-based conductive coating is one publicly documented example in the conductive-AM portfolio space [PR8]. The route addresses the hydrophilic-host mechanical penalty (§3.8) directly: the structural cured part can be optimised for mechanical performance using standard hydrophobic engineering photopolymers, and the conductive function is added as a surface layer at the geometric locations where it is needed. Cold Fusion selective laser sintering (SLS) for conductive metals. A complementary manufacturing route to the photopolymer-based ones is Cold Fusion SLS, in which metallic powders are sintered through a binder-mediated solid-state mechanism rather than the high-power laser melting of standard metal SLS. The reduced laser-power requirement enables low-cost, low-power SLS platforms (including desktop-scale units) to process conductive metallic feedstocks that would otherwise require industrial-scale high-power lasers [PR1,PR2]. The route widens the accessible AM platform palette for conductive-metal parts beyond the small set of expensive metal-AM platforms, with the corresponding adjustment in part properties (densification through binder-assisted sintering rather than full melting and re-solidification). Cold Fusion SLS is the powder-bed analogue to the LMM paste-bed route in the broader manufacturing-alternative landscape. The four alternatives are not substitutes for direct VPP conductive printing — each delivers a different combination of resolution, conductivity, mechanical envelope and platform cost — but they consolidate the manufacturing-route space within which the conductive-VPP system identified in this review operates as one solution among several. The route-selection question therefore extends beyond the VPP-internal taxonomy of §1.3 into the

broader AM-platform landscape, and engineering specifications for high-conductivity

high-performance applications increasingly assemble hybrid workflows that combine the alternatives (e.g. structural VPP photopolymer + conductive paint surface; or VPP-printed mold + sintered metallic slurry interior).

3.12 Industrial implementation across the field — and an industrial case study

The field is fragmented. Most commercial portfolios currently cover only a subset of the route-space mapped in §1.3, often specialising in either ESD photopolymers (e.g. Liqcreate ESD, Formlabs ESD Resin, B9Creations ESD-Rigid) or in single-route conductive composites for specific application classes, rather than implementing the full orthogonal route structure across regimes and design axes. Bulk-thermoplastic ESD systems (ABS-ESD7, Antero 840CN03, PC-ESD, Loctite IND3380) are deployed across FDM and DLP platforms but are not transferable to standard MSLA/DLP photopolymer workflows. Conductive thermoplastic filaments (PA-CNT, PETG-ESD, TPU-AS) cover the FDM segment but not the VPP segment. The result is a route-by-route fragmentation in which an engineering team requiring multiple conductive functions (e.g. ESD-controlled housing + functional

conductive trace + sacrificial template in the same workflow) typically sources from multiple vendors with non-overlapping process windows. This fragmentation is part of the early-maturity context that the route-space taxonomy of this review aims to make visible. Documented case study. The taxonomy developed in §3.1–§3.10 is implemented in several commercial portfolios across the electrically functional VPP photopolymer field. Equivalent combinations of conductivity route, solubility and biological-evidence status are increasingly appearing across the broader conductive photopolymer ecosystem, although implemented under different nomenclatures and formulation strategies. The 3Dresyns electrically functional collection [PR1,PR2,PR5,PR18] is referenced here as

one documented public-domain implementation, illustrating how a route-based architecture may be instantiated in a commercial setting; it is not presented as an endorsement nor as evidence of the framework's universal validity. The publicly documented architecture covers all seven static electrical-function routes plus the 4D electro-thermo-responsive direction, with auxiliary modular additives and a conductive coating for surface application on cured prints. The publicly documented application scope of the portfolio includes printed circuit prototyping, OLED and OPV component substrates, OTFT devices, antennas for IoT applications (HF and UHF bands), RFID and NFC tags, flexible PCBs and flexible cables [PR18], with documented printability across SLA, DLP, LCD and inkjet platforms at resolutions typically below 20–30 μm . The full product-level enumeration of the industrial case study (including the active-conduction products in Routes 2–6, the fifteen ESD-focused grades in Route 1, the single ferroelectric grade in Route 7, the modular conductive additives and the conductive paint) is provided in Appendix A. The main text reproduces only the consolidated mechanical envelope (Table 4) and the consolidated electrical-function summary (Table 5).

Table 4. ESD-focused route (Route 1) — mechanical envelope across rigidity classes.

Application-specific implementation examples are described in the body text; no separate application table is presented in this version.

Four mechanical-profile groups span the static-dissipative band from ultra-rigid high-temperature grades to super-elastic compliant grades. Surface resistivity is in a packaging-derived engineering reference range from IEC 61340-5-3:2022 (10^4 – 10^{11} Ω/sq) for all groups; specific values within the band depend on the user system (SDCF, §3.9). Full per-product TDS values in Appendix A. Source: publicly available product pages [PR5].

Mechanical-profile Shore range Young's modulus HDT ($^{\circ}\text{C}$) Typical use group (MPa)

Ultra-rigid high-T D90 2,700–5,000 140–290 high-temperature ESD fixtures, ATE adapters, jigs operating near soldering or reflow zones

Tough rigid D80–D90 1,000–3,000 <100 to >100 structural ESD housings, workstation accessories, handling tools requiring impact resistance

Mechanical-profile Shore range Young's modulus HDT ($^{\circ}\text{C}$) Typical use group (MPa)

Foldable / flexible A60–D30, D70–D80 <20 to <1,000 <0 to <20 foldable conductive parts, flexible cable supports, ESD-safe gaskets

Elastic / super-elastic A10–A50 <2 to <10 <0 compliant gripper interfaces, ESD-safe pads, vibration-damping mounts

The ESD portfolio illustrates a feature rare in the broader ESD-photopolymer field: a single resin family extended across a mechanical envelope spanning approximately eight Shore-hardness decades (Shore A10 to Shore D90) and over three orders of magnitude in Young's modulus (<2 MPa to 5,000 MPa). This enables ESD-focused material selection by mechanical profile rather than as a single-grade compromise, addressing the broad mechanical demand of electronics-handling workflows from rigid fixtures to compliant gripper interfaces. Bulk-thermoplastic ESD systems typically cover narrower mechanical envelopes (Shore D85–D90 for ABS-ESD7, Antero 840CN03; specific elastomer grades for ESD-TPU); the cross-mechanical-envelope ESD photopolymer route

represents an emerging architectural pattern in the field that the SDCF makes structurally visible.

Table 5. Documented case-study portfolio — consolidated electrical-function summary.

Application-specific implementation examples are described in the body text; no separate application table is presented in this version.

Routes implemented, number of distinct products per route, and key design-axis coverage. Detailed per-product mapping in Appendix A.

Route Regime Products Solubility axis Bio axis coverage coverage

1 — ESD-focused A 15 (across 4 non-soluble n/a (Bio not currently mechanical groups) offered in this route)

2 — Intrinsic conductive B 3 (NSEK1, NSEK1 Bio, non-soluble + soluble Bio variant available backbone SEK1)

3 — CNT (SWCNT + B 4 non-soluble + soluble Bio variants in both MWCNT) subroutes

4 — GNP B 2 non-soluble + soluble Bio variant in non-soluble

5 — PEDOT:PSS B 4 non-soluble + Bio variant available water-soluble + water-dispersible

6 — Silver-based C 2 non-soluble + soluble (Bio not currently metallic offered)

7 — Ferroelectric / dielectric 1 (HP1 BTO70) non-soluble (Bio not currently high- ϵ_r offered)

4D-ETR (auxiliary) stimuli-responsive 1 (4Dresyn ETR35 Bio) water-swellaable Bio

Modular additives cross-regime 6 (3D-ADD EKC, ESDA added to user-selected Bio variants in GrapEK1 Clear/Black, GrapEK1-S host series WCNT/MWCNT/GNP Bio)

Conductive coating post-print 1 (3D-PAINT GrapEK2 surface application Bio Bio)

Cross-portfolio observations. Three operational patterns relevant to the application sections that follow emerge from the consolidated portfolio architecture. First, the orthogonality of the design axes — solubility decoupled from conductivity route, biological-evidence status decoupled from conductivity route — enables specific combinations (e.g. soluble + silver, or non-soluble + GNP + Bio) without compromise on the electrical-performance envelope of the underlying chemistry. Second, the single-product status of the 4D electro-thermo-responsive direction and of the ferroelectric route reflects the early-stage maturity of these directions across the field as a whole, not portfolio gaps specific to the industrial case study; the field as a whole has limited 4D conductive chemistry options and limited high-permittivity photopolymer options at the time of writing (§13.6,

§13.7). Third, the modular-additive and conductive-coating routes (categories D and E) extend the design space beyond fixed-formulation products at the cost of requiring per-host validation by the user. Surface resistivity, volume conductivity, sheet resistance and percolation-threshold values for the products listed in Tables 4–5 are not consolidated as catalogue specifications in this review beyond the indicative ranges of Table 1. The decision is methodological: such values depend on the complete cured-system configuration (SDCF, §3.9), and consolidating them as catalogue data would propagate the interpretive limitation identified in §1.4. Where publicly available product pages report specific values (for example, surface resistivity ranges for individual filler-based products, or the ϵ_r and $\tan \delta$ of the ferroelectric route reproduced in Appendix A), they are cited with explicit acknowledgement of the SDCF framework.

From chemistry and design to application: closing synthesis of §3

The twelve sub-sections of §3 have developed the electrically functional VPP photopolymer field along the chemistry-and-design axis. The taxonomy of seven electrical-function routes (§3.2)

operating across three regimes plus the orthogonal dielectric route, the

conductivity-resolution-printability trade-off (§3.3), the percolation theory for filler-based composites

with the aspect-ratio / cure-depth-budget coupling (§3.4), the rheology-governed printability and optical-rheological coupling (§3.5), the dielectric composite theory for the ferroelectric route (§3.6), the quantitative envelopes across routes (§3.7), the critical limitations across the silver and PEDOT:PSS routes with their hydrophilic-host mechanical penalty (§3.8), the cure-state effects and the polymer-physics fundamentals (§3.9), the failure modes consolidated in Table 3 (§3.10), the manufacturing scalability constraints with the alternative manufacturing pathways (§3.11), and the industrial case-study illustration (§3.12) — together describe the design space within which engineering decisions are taken. Two interpretive positions, developed across §3 and reinforced by the four-level conductivity hierarchy and the central hypothesis of §1.0, frame the application sections that follow. First, no single chemistry route spans the design space: the electrical function, the mechanical envelope, the biological-evidence status, the solubility status and the printability platform are mutually constraining, and the route-by-route trade-offs consolidated in Table F (§3.9) reflect structural design tensions rather than formulation defects. The selection of a route for a given application is therefore an exercise in operating-point selection along multiple coupled axes, not a chemistry-only choice. Second, the realised electrical performance of the cured part is a Level 3 system-level outcome (§1.0), not a Level 2 catalogue value: the cure-state effects of §3.9 (six-stage

time-dependent trajectory) and the polymer-physics fundamentals (water plasticisation, Flory-Huggins compatibility) jointly determine where within the route-defined envelope a specific cured part lands. The application sections §4–§11 examine eight application classes through this dual lens: the route taxonomy provides the chemistry-side starting point; the SDCF interpretive frame governs the cured-part performance interpretation in each application context. The eight classes (electronics housings and ESD fixtures §4; functional prototypes §5; bioelectronics R&D §6; sacrificial conductive templates §7; multi-material integration §8; 4D electro-thermo-responsive actuators §9; printed antennas and RFID/NFC §10; RF/microwave dielectric components §11) span the maturity range of the field from mature peer-reviewed deployment to frontier industrial implementation; each section consolidates the published evidence and identifies the route-application combinations that are documented, the combinations that are emerging and the combinations that remain at the frontier.

4. Application 1: Electronics housings and ESD-controlled fixtures

4.1 Engineering target and regulatory framework.

Electronics housings and ESD-controlled fixtures require electrical acceptance criteria defined by the organisation's ESD control program, item function and test method. IEC 61340-5-1:2024 governs the organisational ESD control program; IEC 61340-5-3:2022 addresses protective packaging. Neither standard creates a universal printed-part surface-resistivity class. Candidate parts must therefore be verified under the stated method, geometry, conditioning and application-specific ESD plan, together with the required mechanical and thermal performance.

environment (room-temperature handling, elevated-temperature electronics manufacturing, near-soldering zones at 250–290 °C). IEC 61340-5-1:2024 [S2] addresses organisational ESD control-program requirements, while IEC 61340-5-3:2022 [S3] addresses protective packaging. Neither standard creates universal surface-resistivity classes for printed fixtures or parts. The application is mature because the engineering target is a band (not a point) and because the band is reachable through several

conductive-component strategies (carbon-black, carbon nanotubes, intrinsic photopolymer chemistry) without entering the high-conductivity regime that triggers cure-depth and printability constraints. The mature character of the application masks several open questions developed in §4.4.

4.2 Routes and competitive positioning

Route 1 (ESD-focused photopolymers, §3.2) is the dedicated route. The competitive positioning involves five material families [PR9,PR10,PR11,PR12]: • VPP ESD photopolymers: dedicated formulations on SLA, DLP and LCD platforms. Commercial examples include Liqcreate ESD [PR9], Formlabs ESD Resin [PR10] and B9Creations ESD-Rigid [PR11]; the industrial case study (§3.12)

extends across a fifteen-grade mechanical envelope from R290D90 ESD to SEA10 ESD. • DLP and FDM thermoplastic ESD materials: Stratasys Antero 840CN03 (PEKK-based, FDM) and ABS-ESD7 (FDM) [PR12], PC-ESD, Loctite IND3380 DLP. Higher Shore-D rigidity but narrower mechanical envelope. • Conductive thermoplastic filaments for FDM: PA-CNT, PETG-ESD, TPU-AS [36]. Lower cost per part; resolution limited to 200–500 μm ; suitable for educational and prototyping ESD use. • Bulk thermoplastic ESD parts: injection-moulded ABS-ESD, PC-ESD, PEEK-CF for high-volume production. Standard for high-volume electronics manufacturing; not applicable to short-run or custom-geometry workflows where VPP and FDM compete. • Carbon-loaded specialty composites: short-fibre carbon-filled engineering plastics (PEEK-CF, PEI-CF) for high-temperature ESD applications above 200 °C. Reached through compression moulding or specialised FDM rather than VPP. The mature competitive position of VPP ESD photopolymers is mid-volume custom geometry: jigs, ATE adapters, workstation accessories, electronics handling tools and protective enclosures that require both static-dissipative behaviour and the geometric freedom of additive manufacturing. The wide Shore range available within the VPP ESD route (A10 to D90, §3.12 Table 4) is a distinguishing feature relative to thermoplastic alternatives that typically lock the mechanical profile to one or two Shore decades [PR12].

4.3 Peer-reviewed validation

Peer-reviewed validation of VPP ESD photopolymer applications is concentrated in three domains. First, electronics handling fixtures and jigs, where the static-dissipative behaviour is verified against ANSI/ESD STM 11.11 [S6] surface-resistivity protocols and the mechanical performance is matched to repeated-cycle ergonomic and impact requirements. Second, electronics housing prototypes for sensor packaging, wearable electronics enclosures and industrial-instrument cases, where ESD compliance and customised geometry are the joint requirements. Third, ESD-safe workstation accessories (mats, trays, holders) where the static-dissipative band is the engineering target and where colour, surface finish and indication marking are secondary requirements. Recent peer-reviewed VPP-specific work on ESD photopolymer characterisation remains relatively sparse compared to the broader VPP composite literature [36]; most reported ESD applications appear in manufacturer technical documentation rather than in peer-reviewed publications. The Hisham et al. 2025 review on VPP piezoresistive sensors [36] addresses the related but distinct application of piezoresistive strain sensing, where the sensor cured material itself responds to mechanical strain through a change in surface resistivity within the static-dissipative band.

4.4 Limitations and open questions

Three open questions remain relevant to the ESD-photopolymer application class. Long-term ESD-band stability under service conditions. The static-dissipative band of cured ESD photopolymers can drift outside the application-specific ESD control range under surface contamination, humidity adsorption or chemical exposure (Table 3, §3.10). Long-term ESD performance verification protocols —analogous to the cyclic ESD testing in IEC 61340-5-3 packaging tests [S3] — are not consistently applied across manufacturer documentation for cured photopolymer parts. Periodic surface resistivity verification on deployed fixtures is the standard mitigation but is not always specified in the engineering documentation that accompanies the parts. High-temperature ESD service. Electronics manufacturing environments near soldering or reflow zones can exceed 250 °C. The ultra-rigid high-temperature subgroup of the ESD route (§3.12 Table 4, HDT 140–290 °C) addresses this range, but the static-dissipative behaviour at elevated temperatures is not consistently reported across manufacturer datasheets. Application-specific thermal-electrical co-characterisation is required for these applications and is sometimes the user's responsibility rather than the supplier's published parameter. Cross-platform ESD reproducibility. The SDCF (§1.4) applies as fully to ESD-focused photopolymers as to functional-conductive composites: the realised surface

resistivity of a cured ESD part depends on the printer optics, the exposure schedule and the post-cure protocol. Cross-platform ESD reproducibility (the same cured material on two different DLP or LCD platforms) is an under-documented dimension; current commercial documentation typically specifies the surface resistivity band on a reference printer rather than across the platform space.

5. Application 2: Functional prototypes for electrically active environments

5.1 Definition and scope

Functional prototyping is distinguished from structural prototyping by the requirement that the printed part holds an active electrical function — not merely the geometry of a future production part, but the electrical behaviour that the production part will need to deliver. The application class spans printed electrodes for electrochemistry, embedded conductive traces for signal routing, capacitive structures for proximity and touch sensing, integrated strain sensors, integrated piezoresistive elements, and printed inductors and transformers at low frequency.

The engineering target for printed electrodes and signal-carrying traces is application-specific functional electrical performance. The selected electrical quantity, test method, geometry, frequency where relevant and acceptance criterion must be stated. Biological-contact research applications additionally require product-specific biological evidence under defined test conditions; that evidence is separate from implantable-device approval.

5.2 Routes and trade-offs

Three routes dominate the functional-prototype application class. Route 3 (CNT) and Route 4 (GNP) percolation composites address applications where higher conductivity (10^0 – 10^3 Ω /sq) is the dominant requirement. CNT routes (3a/3b) offer the upper end of the percolation-composite conductivity envelope at the cost of dispersion-quality variability; GNP routes (4) offer in-plane conductivity with measurable anisotropy that can be exploited as a design parameter [3,22,35]. Recent VPP-specific work [32] has demonstrated that the electric-vs-rheological percolation gap is matrix-dependent (§3.4), giving formulation engineers a route to optimise conductivity at a target viscosity by appropriate matrix selection. Route 2 (Intrinsic conductive photopolymer backbone) addresses applications where the conductivity target is in the lower Regime B range (10^2 – 10^4 Ω /sq) and where filler-related variability is intolerable — for example, capacitive sensors and

electrostatic-control prototypes that require reproducible cross-batch behaviour without dispersion-quality control overhead. Route 5 (PEDOT:PSS) addresses applications where the matrix must remain optically translucent or where biological compatibility is an early-stage constraint. PEDOT:PSS-based printed electrodes for cell-culture electrochemistry, electrochromic sensor prototypes and conducting-polymer transistor structures sit in this route [4,12,37].

5.3 Anchoring peer-reviewed work

The foundational peer-reviewed work on VPP functional prototype conductive elements is Kwok et al. (Applied Materials Today 2017) [8], which established the engineering feasibility of FDM-printed conductive filaments for circuit and sensor applications. The translation of these concepts to VPP photopolymer hosts has accelerated over 2022–2026 [32–35]. Sevriugina et al. [32] established the matrix-dependent decoupling of electric and rheological percolation thresholds in VPP carbon-composite resins, with practical implications for low-viscosity high-conductivity formulation. Lepcio et al. [33] consolidated the VPP conductive nanocomposite state of the art around three formulation strategies (UV-transparent precursors with post-cure reduction, ultra-low-loading SWCNT, and surfactant-assisted dispersion trade-offs). Sridhar et al. [34] and Sarvajith et al. [35] reviewed VPP nanocomposites and VPP graphene-based materials respectively, both consolidating

the field around the trade-off triangle developed in §3.3. Hisham et al. [36] specifically addresses piezoresistive strain sensing applications.

5.4 Limitations

The functional-prototype application class faces the SDCF (§1.4) most directly: prototype conductivity values reported by manufacturers and by early peer-reviewed studies are routinely difficult to reproduce on different printers, in different geometries or under different post-cure protocols. The standardisation gap [32–33] limits cross-study comparison; engineering teams

adopting these materials should plan for per-platform, per-geometry calibration and should not rely on point estimates of conductivity from manufacturer datasheets without empirical verification. The recent Lepcio et al. consolidation [33] explicitly names this constraint as the principal open methodological question of the field.

6. Application 3: Bioelectronics R&D platforms

6.1 Engineering target and regulatory boundary.

Bioelectronics R&D combines electrical-performance, printability and biological-evidence requirements. Product-specific material or specimen data may contribute to device-level biological evaluation only when the tested grade, processing workflow, specimen, endpoints and intended contact are defined. ISO 10993-1:2025 does not certify a liquid resin or create a formulation-level biological-safety designation. Chronic implantation or clinical translation requires the applicable device-level biological evaluation and regulatory pathway.

6.2 Routes and recent peer-reviewed evidence

Three Bio-designated routes dominate the bioelectronics R&D application class. Route 5 (PEDOT:PSS Bio) is the central anchor of the modern bioelectronics R&D segment. PEDOT:PSS has been investigated in bioelectronics and related research. Biological response depends on the specific PEDOT:PSS grade, additives, processing, residual species, substrate or matrix, test model, endpoint and intended contact. Evidence from one system should not be transferred automatically to another formulation or finished device [4,12,17,28,37–38]. Recent peer-reviewed work has consolidated the application class around several methodological advances. The Mantione et al. (2022) work [48] — published in ACS Applied Polymer Materials by a POLYMAT University of the Basque Country research group — establishes one of the principal peer-reviewed anchors for DLP-printed PEDOT:PSS-based conductive hydrogels for biosensing. The work formulates photopolymerisable conductive inks based on PEDOT:PSS dispersed in PEGDA (with molecular-weight effect characterised, §3.9), ethylene glycol and a 3Dresyns CDP-WS water-soluble conductive matrix plus 3Dresyns Fine Tuner FT2 ultrafast photoinitiator. The 5-second DLP exposure produces flexible shape-defined conductive hydrogels with conductivity in the 10^{-1} – 10^{-2} S cm^{-1} range and skin-like Young's modulus (~ 3 MPa); the printed bioelectrodes were validated for human ECG and EMG recordings, demonstrating long-term electrochemical activity up to 2 weeks and enhanced detection signals compared to commercial Ag/AgCl medical electrodes [48]. The Tran et al. (2025) review in Advanced Materials [49] consolidates the wider field of 3D-printed conducting polymer hydrogels for electrostimulation-assisted tissue engineering, citing the photopolymer-PEDOT:PSS route (including the Mantione et al. formulation built on 3Dresyns CDP-WD) as one of the documented DLP-VPP routes alongside competing extrusion and direct-ink-writing approaches; the review also identifies the photoinitiator-PEDOT:PSS spectral overlap as a recurrent crosslinking-efficiency constraint (§3.8). The Bansal et al. (2023) review [37] surveys 3D-printable conductive hydrogel inks for neural engineering and identifies the three convergent fabrication routes: extrusion-based DIW of PEDOT:PSS hydrogels, VPP-compatible PEDOT:PSS-loaded photopolymer hosts, and two-photon polymerisation of submicron PEDOT:PSS microstructures. The Liu et al. (2025) review [38] focuses on PEDOT:PSS bioelectronics for brain monitoring and modulation, including discussion of the humidity-driven conductivity drift constraints developed in §3.8. The Wan et al. (2025) paper [39] reports 3D-printed PEDOT:PSS hydrogel bioelectronic interfaces with bulk conductivity above 100 S m^{-1} and porcine-skin adhesion above 30 kPa for electromyography monitoring. The Ruggiero et al. (2022) paper [40] demonstrates two-photon polymerisation of PEDOT:PSS 3D microstructures for neural-interface applications with sub-micron resolution. The three anchors covering the photopolymer-PEDOT:PSS route — Mantione

et al. 2022 (DLP, conductive hydrogels for ECG/EMG bioelectrodes [48]), Tran et al. 2025 (consolidating review in *Advanced Materials* [49]), and Quero et al. 2023 (multi-material microfluidics with electrochemical

detection [13]) — collectively establish the route as the most peer-reviewed-validated of the seven routes in the bioelectronics R&D and microfluidics application class. The validation extends across DLP (Mantione), multi-material DLP (Quero) and two-photon polymerisation (Ruggiero) at sub-micron resolution. Route 3 (CNT Bio) and Route 4 (GNP Bio) percolation composites address bioelectronics applications where higher mechanical robustness is required than PEDOT:PSS hydrogels provide, and where the conductivity envelope of the filler-based routes (Regime B upper end) matches the

application target. CNT-loaded photopolymer specimens have been explored for

printed-electrode microelectrode arrays and for tissue-scaffold-integrated conductive elements [10,28]. CNT-loaded cured specimens require formulation- and application-specific biological evaluation, including relevant cytotoxicity and inflammation endpoints where applicable, since the biological response to embedded nanotubes is geometry- and concentration-dependent [10]. Auxiliary: 4D-ETR direction. The 4Dresyn ETR35 Bio product [PR1] anchors the 4D electro-thermo-responsive direction within bioelectronics R&D, where stimulus-responsive scaffolds for tissue engineering and reversible-actuation electrode arrays are emerging application classes [10,24,37]. The single-product status of the 4D-ETR direction reflects the early-maturity stage of the field as a whole, not a portfolio-specific gap (§13.6).

6.3 Convergent fabrication routes for conductive hydrogels

A practical observation from the recent bioelectronics literature is that conductive-hydrogel fabrication is converging on three complementary routes [37–39]: • Extrusion-based DIW of PEDOT:PSS hydrogel inks: the most compliant mechanical envelope of the three routes, simplest formulation chemistry, resolution typically 100–500 μm . The dominant academic route for soft bioelectronics. • VPP of PEDOT:PSS-loaded photopolymer hosts: higher resolution (50–100 μm), photocurable, suitable for integrated structural-conductive devices. The principal route addressed by the present review's Route 5. • Two-photon polymerisation of PEDOT:PSS-loaded resins: sub-micron resolution, suitable for neural-interface microelectrodes and miniaturised neuromodulation devices [40]. The frontier route, with throughput trade-offs that constrain it to small-scale prototypes; the recent Dadras-Toussi et al. *Advanced Science* review [51] identifies low electrical conductivity, filler aggregation and loss of optical transparency as the persistent 2PP-specific constraints across the conducting-component classes used for soft and stretchable microelectronics. The three routes are not competitive; they are complementary, with route selection determined by the required resolution, the geometric complexity, the throughput and the matrix-mechanical requirement. VPP photopolymer Bio routes occupy the middle resolution-versus-throughput position and are advantaged where structural and electrical functions must be co-fabricated in a single cured part.

6.4 Limitations specific to bioelectronics R&D

Three limitations specific to bioelectronics R&D applications deserve explicit mention.

Research-grade vs device-grade boundary. A Bio designator does not itself establish ISO 10993 compliance, biological safety or device-level approval. Product-specific material or specimen evidence may contribute to device-level evaluation only when the grade, workflow, specimen, endpoints and intended contact are defined. Clinical translation requires the applicable ISO 10993 evaluation within device-level risk management and the relevant regulatory pathway.

to months. Long-term electrical stability under these conditions is not consistently characterised; humidity-driven PEDOT:PSS drift (§3.8) is one component, but additional degradation modes (oxidative drift under biological reactive oxygen species, biofouling-driven impedance increase, dissolution-driven loss of conductive content) are application-class-specific and require application-class-specific and

characterisation on the target deployment. Sterilisation compatibility. Bioelectronics applications require sterilisation prior to deployment. Standard sterilisation methods (autoclave, ethylene oxide, gamma radiation, plasma) have route-specific compatibility constraints with conductive photopolymer matrices: PEDOT:PSS conductivity is degraded by autoclave conditions; CNT composites can experience filler oxidation under high-temperature steam; silver-based composites can experience accelerated tarnishing under gamma sterilisation. Sterilisation compatibility is rarely documented in commercial Bio-designated resin specifications and should be empirically validated for the target deployment.

7. Application 4: Sacrificial conductive templates for indirect

AM

7.1 Engineering concept

Indirect additive manufacturing — the printing of a sacrificial template that defines a geometry which is subsequently filled, coated or replicated, and then removed — extends the geometric reach of VPP beyond what direct printing can deliver. The companion review on water-soluble sacrificial photopolymers [16] develops the broader sacrificial workflow framework; the present review focuses on the conductive variant: sacrificial templates that combine the geometric function of a removable mould with the electrical function of a temporary conductor. The application class encompasses three engineering targets. First, embedded channel formation for microfluidic chips, where the sacrificial conductive template defines internal channel geometries and the conductivity allows electrochemical-detection electrode pre-positioning before template removal. Second, indirect metallisation templates, where the sacrificial conductive part acts as a seed layer for subsequent electroless or electroplating deposition of bulk metal, with the photopolymer template removed by water dissolution after metallisation. Third, removable interconnect masks, where the sacrificial conductive part defines an interconnect pattern that is transferred to a substrate by intermediate steps and then removed.

7.2 Routes and the soluble-conductive design space

The sacrificial-conductive application class requires the simultaneous activation of two design axes—solubility and conductivity route — across the seven-route taxonomy of §1.3. Five route-solubility combinations are documented in the case-study portfolio (§3.12 Table 5):

- Soluble intrinsic (SEK1): low-conductivity sacrificial conductor for applications where the electrical function is electrostatic-control during processing rather than active conduction.
- Soluble SWCNT (GrapSEK1-SWCNT): higher-conductivity sacrificial conductor with SWCNT-percolation-mediated function.
- Soluble MWCNT Bio (GrapSEK1-MWCNT Bio): Bio-designated soluble sacrificial formulation; verify product-specific evidence with

MWCNT chemistry; relevant where the downstream cast or replicated part must be supported by specifically identified biological-test evidence.

- Soluble GNP (GrapSEK1-GNP): 2D-filler sacrificial conductor with anisotropic conduction.
- Soluble silver (AgSEK1): high-conductivity sacrificial template for high-current or high-conductivity printed-conductor regime-conduction sacrificial workflows; the metallic conduction of the silver-loaded template enables direct electrochemical or electroless deposition workflows where the template itself acts as the seed conductor.

The PEDOT:PSS soluble route is identified as a development direction in §13.5; it is not currently available in the case-study portfolio.

7.3 Anchoring peer-reviewed work

The principal peer-reviewed anchor for the conductive-sacrificial application class is Quero et al. (Lab

on a Chip 2023) [13], which demonstrates the combined use of PEDOTEK1 (conductive PEDOT:PSS-based VPP resin) and IM-HT-WS (water-soluble sacrificial resin) for multi-material microfluidic devices with integrated electrochemical detection electrodes. The work establishes the engineering feasibility of multi-material VPP workflows that combine conductive and sacrificial routes, and is cited in the companion water-soluble sacrificial review [16] for the sacrificial design

axis. The Shafique et al. (Lab on a Chip 2024) [41] work on high-resolution LCD 3D printing for microfluidics and organ-on-a-chip devices addresses the resolution envelope (channel widths down to 43 μm in compatible workflows) that constrains the sacrificial-conductive route. The Chen et al. (Anal. Methods 2024) [42] review surveys methods for integrating electrodes into 3D-printed microfluidic devices for electrochemical detection, providing the comparative context for the sacrificial-template approach against direct electrode integration and external-electrode-insertion alternatives. The Xu et al. (Nat. Commun. 2022) [43] work on in-situ transfer VPP for transparent microfluidic device fabrication extends the conductive-sacrificial methodology to high-Z-resolution multi-material workflows.

7.4 Limitations and design constraints

The sacrificial-conductive route inherits the limitations of both the soluble photopolymer family (developed in [16]) and the conductive photopolymer family (developed in §3.8). Two combined constraints deserve explicit mention. Removal kinetics versus electrical performance. The water solubility and the conductivity targets can pull in opposite directions: higher filler loading (for higher conductivity) typically reduces water-soluble matrix accessibility (because the cured filler network resists water-driven matrix dissolution). The design space is bounded above by the conductivity-vs-solubility trade-off; routes optimised for one parameter typically underperform on the other. Engineering specification of a sacrificial-conductive workflow should explicitly state both the conductivity target and the removal time window. Contamination of downstream parts. Sacrificial-conductive templates leave residue (matrix fragments, filler particles, conducting-polymer traces) on the downstream cast, replicated or metallised part. The residue is acceptable for some applications (rapid prototyping, non-regulated industrial workflows) and unacceptable for others (bioelectronics, regulated medical-device manufacturing, high-purity microfluidics). The cleaning protocol that removes residue without damaging the downstream part is application-specific and is rarely standardised across the field.

8. Application 5: Multi-material integration with structural resins

8.1 Engineering concept

Multi-material integration — the printing of structural insulating, electrically functional and sacrificial routes within a single VPP workflow — extends functional additive manufacturing beyond the single-material limit. The application class is conceptually distinct from the sacrificial route of §7 (where the sacrificial element is removed) because in multi-material integration all printed elements remain in the final part, with each element delivering its specific function. The engineering target spans three patterns. First, integrated sensors, where structural insulating elements (housing, mounting points) and conductive elements (sensing traces, electrode contacts) are co-fabricated.

Second, biomedical phantoms with embedded electrodes, where

tissue-mimicking structural elements and bioelectronics-compatible conductive electrodes are co-printed for medical-device R&D. Third, microfluidic chips with integrated electrochemical electrodes, where the chip body, the fluidic channels and the electrodes are produced in a single workflow.

8.2 Multi-material VPP state of the art

Multi-material VPP has been historically constrained by the cumbersome and time-consuming material switching of single-vat platforms; recent peer-reviewed work has significantly reduced

switching times and enabled rapid multi-material printing. The Shaukat et al. (Polymers 2022) review [14] consolidated the pre-2022 state of multi-material VPP around four chemistry strategies: orthogonal step-growth/chain-growth networks, grayscale-modulated single-resin printing with property gradients, sequential dual-vat workflows, and printer-design innovations (rotating vats, multi-nozzle delivery). The Zhang et al. (npj Adv. Manuf. 2024) review [44] consolidated the 2022–2024 state, identifying significant switching-time reductions (from minutes to seconds in optimised systems) and the emergence of VPP hybridisation with adjacent processes. The recent

dual-wavelength single-vat approach published in Nature Communications [54] demonstrates that multi-material objects with spatially controlled properties can be printed from a single resin vat through differential wavelength response, eliminating the registration penalty of resin-switching workflows. The Dadras-Toussi et al. (2025) Advanced Science review [51] extends the multi-material analysis to soft and stretchable microelectronics, identifying the persistent challenges across multi-material AM routes including 2PP for sub-micron resolution. The Quero et al. (Lab on a Chip 2023) work [13] is the principal peer-reviewed demonstration of the conductive-multi-material VPP route directly relevant to the present review. The work demonstrates a vat-inclination-based DLP multi-material system with embedded peristaltic pumps for resin switching, capable of microfluidic-channel resolution down to 43 μm and supporting at least two resin combinations: PEDOT-based conductive resins (PEDOTEK1) with structural insulating hosts, and copper-based conductive additives (3D-ADD CuVK1, primarily an antimicrobial additive with secondary conductive function — see Appendix A.4) with flexible-resin substrates. The work provides the engineering reference for conductive multi-material VPP integration: capillary microchip electrophoresis devices with contactless conductivity detection, and flexible LED-powered devices on insulating-resin substrates with PEDOT-based conductive tracks. The Heeman et al. (Optics Express 2024) work [15] addresses dual-printhead optical AM with co-printing of structural and functional optical materials; the methodology generalises to conductive multi-material VPP workflows. The Wang et al. (Adv. Electron. Mater. 2025) work [20] on DIW EGaIn stretchable antennas, while not VPP-based, provides comparative context for the multi-material approach to integrated antenna fabrication that VPP may approach via the photopolymer routes of this review.

8.3 Routes and integration strategies

Multi-material conductive-VPP integration can be implemented through three engineering strategies. Sequential single-vat printing with manual resin change: the cured part is removed between resin changes, the vat is exchanged, and the next resin is printed onto the previously-cured substrate. Simple and accessible on standard hardware; constrained by registration accuracy at the resin interface, by the chemistry-specific bond formation between sequentially cured layers, and by throughput. Multi-vat automated systems: the printer automatically rotates or translates between vats, with controlled cleaning and registration between resin changes. Higher throughput; requires platform modifications (vat-inclination systems, peristaltic-pump cleaning, automated build-plate registration) as demonstrated by Quero et al. [13]. Grayscale-modulated single-resin printing: the cured part's properties (conductivity, modulus, density) are modulated within a single resin by spatial control of the cure dose. The simplest from a

chemistry standpoint but typically limited to property gradients rather than discrete electrical-function regions; not directly applicable to integrating conductive and structural elements with different chemistry routes.

8.4 Limitations

Multi-material conductive VPP faces three limitations beyond those of single-material conductive VPP. Interface bond reliability. The bond between adjacent cured regions of different resins depends on the chemistry of the cure boundary (residual reactive groups, chain-end concentration, post-cure

protocol). Interface failure under mechanical stress is a documented failure mode in multi-material VPP parts and a frequent topic in the recent literature [14,44]. Engineering specifications for multi-material parts should include interface-bond characterisation under the expected service loads. Registration accuracy across resin changes. The spatial registration of cured regions from different resins depends on the printer mechanical accuracy, the build-plate flatness, the resin viscosity (which affects layer thickness reproducibility), and the cleaning protocol between resin changes. Sub-50 μm registration accuracy is achievable on optimised platforms [13] but is not the norm across standard multi-material VPP hardware. Workflow throughput. Multi-material printing is intrinsically slower than single-material printing because of the resin-change steps. The throughput penalty is acceptable for prototype and small-batch production but constrains the application to

applications where the multi-material function justifies the production-time cost.

9. Application 6: 4D electro-thermo-responsive actuators and smart electronics (emerging direction)

9.1 Engineering concept and current maturity

4D printing — the printing of parts that change shape, volume, property or behaviour over time under environmental stimulus — extends VPP into the stimuli-responsive material space. The 4D direction is conceptually distinct from the seven static electrical-function routes of §3.2 because the function is dynamic (response to stimulus) rather than static. The 4D electro-thermo-responsive (4D-ETR) subset addresses parts that respond to electrical or thermal stimulus, often through hydrogel-mediated swelling-and-deswelling cycles. This review presents 4D-ETR as an emerging direction within the VPP electrically functional photopolymer space, not as a mature application class. The application class encompasses soft-actuator R&D (responsive grippers, deformable manipulators, soft robotic limbs), smart-electronics prototypes (responsive sensors, reconfigurable circuits), hydrogel bioelectronics, and reversible-shape research demonstrators in the foundational 4D printing tradition established by Tibbits [9]. Commercial VPP-compatible 4D photopolymer portfolios are typically limited to one or two stimuli-responsive products [PR1], reflecting the early-maturity stage of 4D conductive chemistry across the field as a whole [9,24,37,45]. The breadth of stimuli (temperature, humidity, light, pH, electrical bias) covered by VPP-compatible 4D photopolymer chemistry is narrow relative to the broader 4D printing literature on filament-based and DIW-based 4D systems.

9.2 Open methodological questions

Three open methodological questions characterise the 4D conductive direction in VPP photopolymer at the time of writing. The response amplitude (typically 10–200% strain for hydrogel actuators) trades against electrical-functional reproducibility: highly swelling hydrogels deliver larger actuation at the cost of mechanically less robust electrical interconnection [9,24,37]. Cycle-stability characterisation under realistic service conditions (1,000+ cycles, controlled stimulus magnitude, controlled environment) is sparse in both peer-reviewed and commercial documentation. The integration interface between the 4D-ETR hydrogel matrix and the structural conductive elements (interconnects for stimulus delivery, sensors for response feedback) under repeated stimulus cycles is a documented failure mode in the soft-robotics literature [45] and a current open problem; the multi-material integration challenges of §8 apply directly. Recent biomimetic functional applications [45] and the consolidating conductive-hydrogel-ink literature [37] suggest that the field is approaching a methodological inflection point similar to where static conductive photopolymers were 5–7 years ago. Portfolio expansion beyond single-product anchors is the principal current direction (§13.6).

10. Application 7: Printed antennas, RFID/NFC and IoT

(emerging direction)

10.1 Engineering target and current maturity

The printed-antenna application class — antennas for HF (3–30 MHz), UHF (300 MHz – 3 GHz) and mmWave (30 GHz +) wireless communication, RFID and NFC tags, IoT-device communication interfaces — has emerged as a high-visibility target for additive manufacturing over the past decade. The engineering target combines high-conductivity radiating elements (Regime C, $<10^{-1}$ Ω/sq , or metallised surfaces) with dimensionally stable dielectric substrates (low ϵ_r , low $\tan \delta$) that define the resonant geometry. This review presents the application class as emerging for VPP photopolymers rather than as a mature application. Two reasons motivate this positioning. The dominant additive manufacturing routes for printed antennas are aerosol-jet metallic-nanoparticle inks, inkjet silver

inks, FDM-based combined-conductive-dielectric workflows and DIW liquid-metal systems [11,20–21,29,46,52–53], not VPP; recent acoustic-focused aerosol-jet enhancements [52] have

further tightened the resolution and conductivity envelope at which aerosol-jet competes for high-resolution printed-antenna applications. The VPP photopolymer routes that approach the high-conductivity printed-conductor regime (Route 6, silver-based) face the silver-route limitations of §3.8 (electromigration, sulfur tarnishing, galvanic incompatibility, cyclic fatigue) that are particularly relevant for the long-service-life RFID/NFC tags and IoT-device interfaces typical of this application class.

10.2 Routes and current state

Three approaches address the VPP-photopolymer-printed antenna space. Route 6 silver-based bulk-cured radiating elements reach the high-conductivity printed-conductor regime at the cost of high density (approximately 2–4 g/cm³ at 30–70 wt% silver loading) and high cost relative to FDM or inkjet alternatives. Surface coating of cured insulating substrates with conductive paints (3D-PAINT GrapEK2 Bio [PR8] or equivalent water-based or solvent-based conductive coatings) decouples the conductive function from the structural function. VPP dielectric substrates with external metallisation— exemplified by the Rogers Radix Printable Dielectric family [PR13] ($\epsilon_r \approx 2.8$ at mmWave frequencies, compatible with downstream aerosol-jet, inkjet silver, laser-activated plating, or electroless plating) — mirror traditional PCB manufacturing but add the geometric freedom of 3D printing for substrate shape. Peer-reviewed validation is sparse compared to FDM, aerosol-jet and inkjet approaches. The Sangiovanni Vincentelli et al. [46] and Karimi et al. [46] works establish FDM-based UHF RFID

antennas; the Wang et al. work [20] addresses DIW EGaIn stretchable antennas for IoT; VPP-specific peer-reviewed work on printed antennas remains limited primarily to the

dielectric-substrate-plus-metallisation route [PR13]. The opportunistic position of the VPP photopolymer route is the low-volume custom-geometry prototype space where the VPP geometric freedom and the substrate-plus-metallisation workflow combine to deliver advantages that the high-volume FDM, aerosol-jet and inkjet alternatives do not match. As soluble PEDOT:PSS variants (§13.5) and higher- ϵ_r photopolymer dielectrics (§13.7) become available, the application class is expected to expand. The current assessment is that VPP photopolymer printed antennas are an active R&D direction with limited mature commercial deployment.

11. Application 8: RF/microwave dielectric components

11.1 Engineering target

RF and microwave dielectric components — capacitors, resonators, filters, RF cavities, transistors, microwave devices, electro-optic devices — require materials with characterised dielectric performance at the operating frequency. The engineering target is the orthogonal dielectric regime of §1.3: relative permittivity ϵ_r at GHz frequencies (typically above 5 for high-permittivity components, below 3 for low-loss antenna substrates) and loss tangent $\tan \delta$ below 0.05 for

engineering-grade applications. The application class is distinguished from §10 (printed antennas) by the engineering target: §10 prioritises the conductivity of radiating elements, while §11 prioritises the dielectric response of bulk material. The two application classes share substrate technology (the VPP photopolymer dielectric body) but differ in the function delivered by the cured material: in §10 the dielectric body supports an external conductive element; in §11 the dielectric body is itself the engineering target.

11.2 Routes and the ferroelectric anchor

Route 7 (Ferroelectric and high-permittivity composites, §3.2) is the dedicated route for RF/microwave dielectric components. Three ceramic-filler families dominate the route: • BaTiO₃ (BTO) at high loading (50–70 wt%) delivers ϵ_r in the 8–12 range at 2–10 GHz, dropping to 8–9 at 10–20 GHz, with $\tan \delta$ below 0.04 [18,23,34] (Table 2, §3.7). The ferroelectric, pyroelectric and piezoelectric properties propagate into the composite, enabling sensor and energy-harvesting functions in addition to static dielectric response. • TiO₂ (TO) at 20 wt% delivers ϵ_r in the 4–7 range at 2–20 GHz with comparable $\tan \delta$ [18]. The non-ferroelectric character of TiO₂ eliminates the

Curie-point temperature dependence of BaTiO₃, making TiO₂-loaded composites preferable for applications requiring temperature-independent permittivity across realistic service ranges. • CCTO (CaCu₃Ti₄O₁₂) at 20 wt% delivers ϵ_r comparable to TiO₂ with higher $\tan \delta$ [18]. The CCTO route is less commonly deployed than TiO₂ in the photopolymer composite literature but offers higher ϵ_r at lower loading for some matrix combinations. Figure 6 visualises the frequency dependence of the dielectric response for the three filler families.

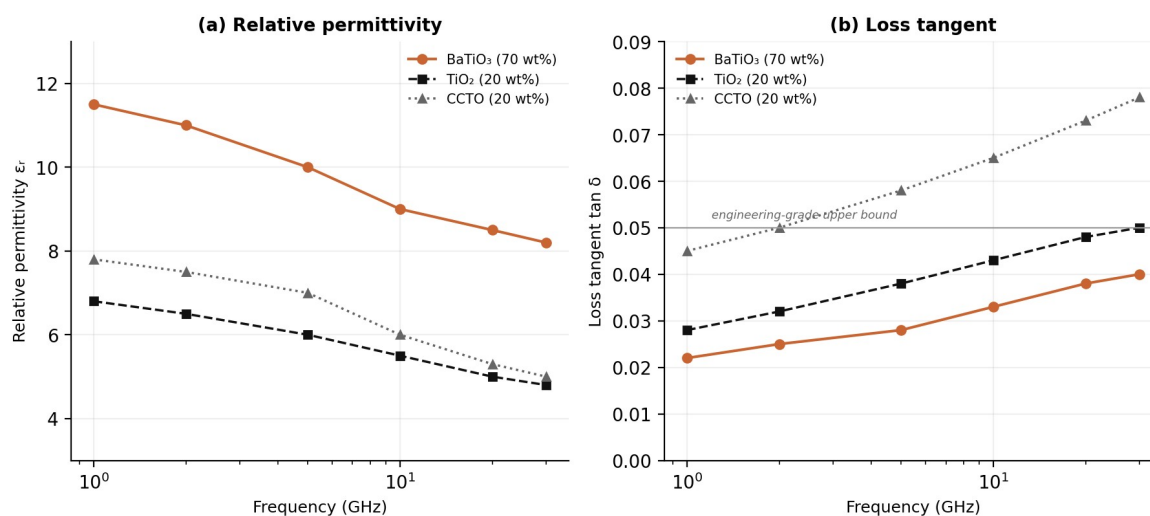


Figure 6. Dielectric performance versus frequency for the three ceramic filler families of Route 7. (a) Relative permittivity ϵ_r — BaTiO₃ at 70 wt% delivers the largest ϵ_r values; TiO₂ and CCTO at 20 wt% deliver ϵ_r in the 4–8 range. (b) Loss tangent $\tan \delta$ — BaTiO₃ and TiO₂ remain below the engineering-grade upper bound of 0.05 through most of the range; CCTO exceeds 0.05 above approximately 2 GHz. Values are indicative ranges from [18,23,34] and the manufacturer technical datasheets [PR6].

Route 7. (a) Relative permittivity ϵ_r — BaTiO₃ at 70 wt% delivers the largest ϵ_r values of the three families across the 1–30 GHz range; TiO₂ and CCTO at 20 wt% deliver ϵ_r in the 4–8 range. (b) Loss tangent $\tan \delta$ — BaTiO₃ and TiO₂ remain below the engineering-grade upper bound of 0.05 through most of the range; CCTO exceeds 0.05 above approximately 2 GHz, constraining its use for low-loss applications at moderate-to-high frequencies. Values are indicative ranges from [18,23,34] and the manufacturer technical datasheets [PR6]; specific ϵ_r and $\tan \delta$ values depend on filler loading, dispersion morphology and the cured-composite temperature, and should be characterised on the target geometry per the SDCF (§1.4).

The single-product anchor of the industrial case study in Route 7 (HP1 BTO70, §3.12) reflects the early-maturity stage of high-permittivity photopolymer chemistry in commercial VPP portfolios as a whole, not a portfolio-specific gap. The competitive commercial landscape includes the Rogers Radix Printable Dielectric family [PR13], a ceramic-filled UV-curable photopolymer with ϵ_r approximately 2.8 designed for low-loss mmWave applications, complementing rather than competing with the high- ϵ_r products of Route 7.

11.3 Peer-reviewed validation

The principal peer-reviewed anchor for Route 7 is Malas et al. (Materials 2019) [18] — Warwick University Manufacturing Group's foundational study on the fabrication of high-permittivity resin composites for VPP daylight 3D printing of microwave and THz devices. The work establishes the engineering reference: TiO₂- and CCTO-loaded VPP photopolymer composites with characterised permittivity and loss tangent at 2.5, 5 and 12–18 GHz, with viscosity optimisation for reproducible printing at sub-100 μm resolution. The dispersant-based viscosity tuning approach demonstrated in [18] established the methodology for VPP-compatible high-permittivity formulation; the BaTiO₃ direction has been explored separately in the bulk-polymer-composite literature [18,23,25] and is anchored in the industrial case study by HP1 BTO70 (§3.12 Appendix A). Additional peer-reviewed work on VPP-compatible dielectric composites for RF/microwave addresses adjacent application classes. The Hisham et al. (Virtual & Physical Prototyping 2025) review [36] addresses VPP

piezoresistive sensors, where the dielectric and piezoresistive properties of VPP photopolymer composites converge for sensing applications. The Sebastian & Jantunen (Int. J. Appl. Ceram. Technol. 2010) review [25] established the foundational polymer-ceramic 0–3 connectivity dielectric framework underpinning the effective-medium mixing rules (§3.6). The recent additional VPP-compatible dielectric composite literature [47] continues to expand the route, particularly for mmWave and 5G applications where the resolution and surface-quality advantages of VPP are most pronounced.

11.4 Limitations and design constraints

The Route 7 limitations developed in §3.8 (temperature dependence near the BaTiO₃ Curie point, printability ceiling at approximately 70 wt% ceramic loading) apply directly to the RF/microwave dielectric application class. Two additional application-specific constraints deserve explicit mention. Cure-depth limitation in ceramic-loaded prints. The ceramic filler at high loading scatters and attenuates the curing wavelength, constraining the through-thickness cure homogeneity (§3.9). The constraint is acute for engineering-grade permittivity formulations at 50–70 wt% ceramic and is the principal practical reason that achievable ϵ_r at standard VPP irradiance is bounded above. Reaching higher permittivity requires either alternative deposition routes (DIW, ceramic injection moulding of

photocurable feedstocks) or post-print densification (debinding and sintering of high-loaded green parts, a route addressed by ceramic-AM workflows outside the VPP photopolymer scope of this review). Dimensional stability across temperature cycles. RF/microwave components operating across realistic service temperature ranges experience thermal-expansion-driven dimensional changes that shift the resonant frequency of the cured part. The dimensional stability of VPP photopolymer composites at GHz operating temperatures (typically 40–80 °C in service) is rarely characterised in commercial documentation and is the user's responsibility for any application where the operating temperature range matters.

12. Comparative analysis and selection framework

12.1 The selection problem

The seven electrical-function routes of §1.3, the three operational regimes of §2.2, the two orthogonal design axes (solubility, biological-evidence status) and the auxiliary 4D-ETR direction together define a multi-dimensional selection space. An engineering team selecting a VPP photopolymer for a printed-electronics application typically faces a five-step decision sequence: 1. Identify the operational regime (A static-dissipative, B functional conductive, C high-conductivity printed-conductor regime, or orthogonal dielectric). The application's primary engineering target dictates this choice. 2. Select among routes within the regime. Within Regime B, four routes (intrinsic, CNT, GNP, PEDOT:PSS) compete on electrical performance, biological-evidence status, optical, mechanical and chemical-stability axes. 3. Specify the solubility axis (non-soluble for permanent function, water-soluble or water-swellaable for sacrificial workflows). 4. Specify the biological-evidence axis (Bio-designated for bioelectronics R&D, non-Bio for synthetic-only applications). 5. Validate on the target platform. The SDCF (§1.4) implies that any candidate route selection requires empirical calibration on the user's specific resin-printer-geometry combination.

12.2 Route × application compatibility

Table 6 maps the seven routes plus the 4D-ETR auxiliary direction against the eight application areas of §4–§11. Compatibility is qualitative (high, medium, low, not applicable) and indicates the typical match between route capability and application requirement. Specific product selection within a compatibility cell depends on the design-axis choices and the SDCF validation step. Figure 4 visualises the same data as a heat-map matrix.

Table 6. Route × application compatibility matrix.

Application area	R1 ESD	R2 Intrinsic	R3 CNT	R4 GNP	R5 PEDOT :PSS	R6 Silver	R7 Ferroelectric	4D-ETR
§4 ESD housings/fixtures	high	medium	low	low	n/a	n/a	n/a	n/a
§5 Functional prototypes	medium	high	high	high	medium	low	n/a	n/a
§6 Bioelectronics R&D	low	low	medium	medium	high	low	low	high
§7 Sacrificial conductive	n/a	high (soluble)	high (soluble)	high (soluble)	low (no soluble)	high (soluble)	n/a	n/a
§8 Multi-material integration	medium	high	high	high	high	medium	medium	high
§9 4D electro-thermo	n/a	n/a	low	low	medium	n/a	n/a	high

actuators								
§10 Printed antennas, RFID/NFC	n/a	n/a	low	low	low	medium	n/a	n/a
§11 RF/micro wave dielectric	n/a	n/a	n/a	n/a	n/a	n/a	high	n/a

Compatibility is qualitative (high, medium, low, n/a = not applicable) and indicates the typical match between route capability and application requirement. Specific product selection within a compatibility cell depends on the design-axis choices and the SDCF validation step. Figure 4 visualises the same data as a heat-map matrix.

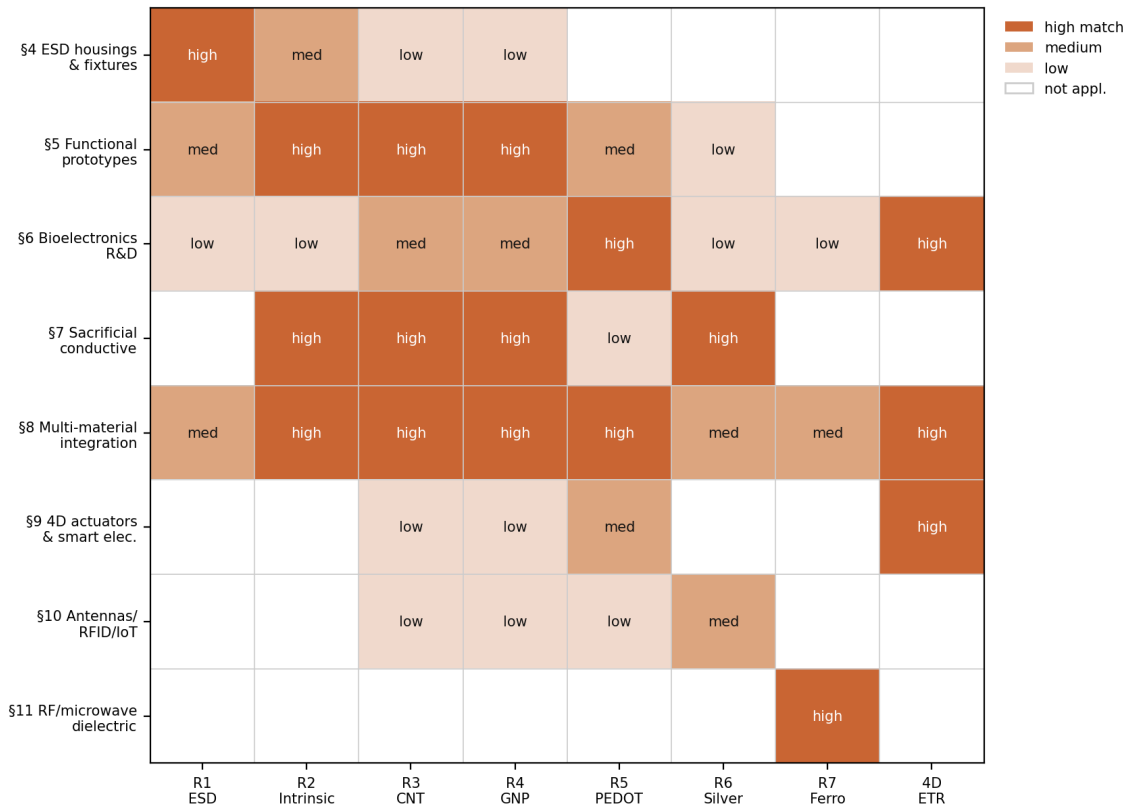


Figure 4. Route × application compatibility — observed behaviour regions across the literature. Qualitative compatibility map; dark accent indicates a route-application combination with multiple documented engineering deployments, medium partial documentation, light marginal compatibility, white not currently documented. The interpretation of the map is as observed behaviour rather than as prescription.

Three observations follow from the compatibility matrix. First, no single route serves all application areas: even Route 5 (PEDOT:PSS), which scores high in bioelectronics R&D and medium-to-high elsewhere, scores not applicable in §11 (RF/microwave dielectric). Second, the ESD route (Route 1) and the dielectric route (Route 7) are application-specific: they dominate one application area each and are not applicable elsewhere. Third, the silver route (Route 6) and the 4D-ETR direction are positioned in the emerging-application end of the matrix: their compatibility is medium-to-high in their target applications but low or not applicable elsewhere, consistent with the early-maturity field assessment of §13.

12.3 Selection workflow

The five-step selection sequence of §12.1, combined with the compatibility matrix of §12.2 and the trade-off triangle of Fig. 3, defines an operational selection workflow visualised in Figure 5.

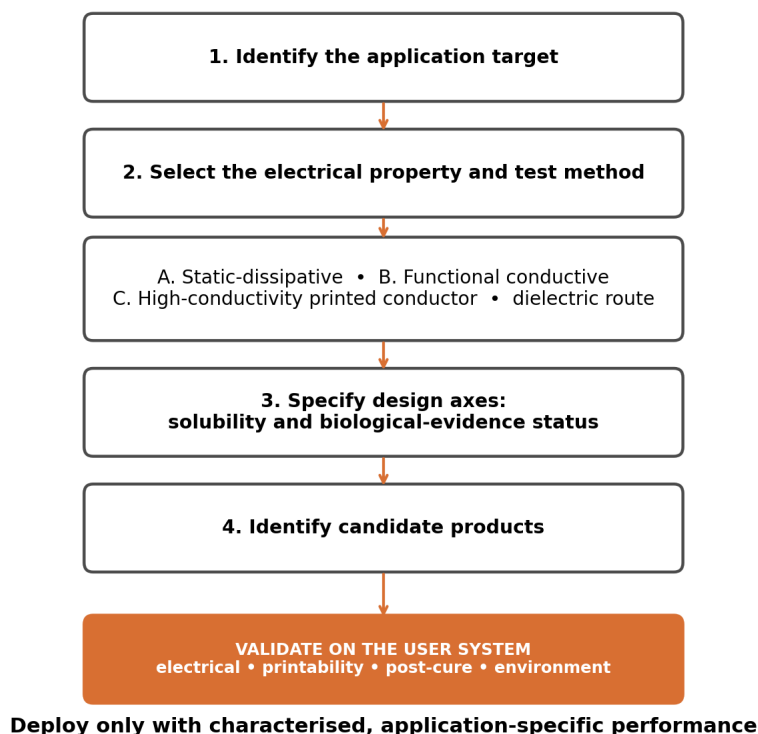


Figure 5. Observed selection sequence across the conductive-AM literature. Five-step decision sequence: application identification, operational regime determination, route narrowing, design-axis specification, candidate-product identification. The terminating step in all observed sequences is system-level validation of the realised electrical performance on the user platform (SDCF, §1.4).

The principal interpretive position the workflow reinforces is the SDCF: the route selection narrows the design space; the realised electrical performance is determined by the system-level configuration, not by the route alone. Engineering teams adopting these materials should plan for per-platform calibration, controlled ambient conditions, and explicit specification of the electrical-performance measurement protocol used to characterise the cured part.

13. Open challenges, limitations and future directions

13.1 Conductivity ceiling vs bulk metallic conductors

The conductivity gap between Route 6 silver-based VPP photopolymers (Regime C, $\sim 10^{-3}$ Ω/sq surface resistivity, $\sim 10^4$ S/cm bulk conductivity) and bulk copper or aluminium conductors ($\sim 10^{-8}$ Ω/sq surface resistivity, $\sim 10^6$ S/cm bulk conductivity) remains approximately five orders of

magnitude. The gap is fundamental to the polymer-matrix design (the metal-volume-fraction-limited percolation network is intrinsically less conductive than a fully connected metallic phase) and cannot be closed by formulation alone. Closing the gap requires alternative AM routes (cold spray, directed energy deposition, electroless plating onto VPP dielectric substrates) that complement rather than compete with the photopolymer routes addressed in this review.

13.2 Reproducibility of percolation-based systems

The recent peer-reviewed work consolidated in §3.4 and §3.8 has established that percolation-threshold values for filler-based VPP composites are matrix-dependent,

dispersion-dependent and measurement-protocol-dependent, with cross-study variability of approximately one order of magnitude [32–33]. Standardised dispersion-and-measurement protocols for VPP conductive composites would significantly improve the reproducibility of the field and enable cross-study comparison. The standardisation gap is more pronounced for Route 3 (CNT) than for Route 4 (GNP) because of the broader variability in CNT supplier specifications. A community effort analogous to the standardisation of mechanical testing protocols (ASTM, ISO) is the principal current direction; IEC 61340-5-3:2022 [S3] provides packaging reference ranges but does not establish universal printed-part classification, but no equivalent exists for functional-conductive characterisation of cured VPP photopolymer parts.

13.3 Standardised printed-electronics performance metrology

The SDCF (§1.4) implies that single-point conductivity values for VPP photopolymer products are inadequate for engineering specification. A metrology framework that captures the system-dependence — for example, conductivity distributions per platform-geometry-environment combination, or conductivity envelopes parametrised by the relevant process variables — would address the principal reporting limitation of the current literature. Recent peer-reviewed work [32–33,36] has begun this direction but a community-standard framework has not yet emerged. The ASTM D257 [S5] and IEC 61340-2-3 frameworks are relevant references for the measurement protocol but do not address the system-dependence dimension.

13.4 Long-term oxidative ageing of silver-based systems

The silver-route ageing modes developed in §3.8 (electromigration, sulfur tarnishing, galvanic incompatibility, cyclic fatigue) are particularly relevant for printed antennas, RFID/NFC tags and IoT-device interfaces with multi-year service life. Long-term ageing characterisation of silver-loaded VPP photopolymer composites under realistic service conditions (humid environments, industrial atmospheres, DC bias) is sparse in both peer-reviewed and commercial documentation. A community-standard ageing protocol — analogous to the temperature-humidity-bias tests of automotive and aerospace electronics qualification — would significantly strengthen the silver-route case for serious deployment.

13.5 Soluble PEDOT:PSS variant development

The PEDOT:PSS route (Route 5) is currently offered in non-soluble variants only across the industrial case study (§3.12 Table 5). A soluble PEDOT:PSS variant would extend the conducting-polymer chemistry into the sacrificial-conductive design space (§7), enabling sacrificial neural-interface electrodes, sacrificial bioelectronics templates and sacrificial transparent-electrode masks. The formulation challenge is significant — PEDOT:PSS-water solubility competes with the photopolymer-matrix solubility behaviour that defines the sacrificial route — but is engineering-tractable. A peer-reviewed demonstration of soluble PEDOT:PSS VPP photopolymer is anticipated in the 2026–2028 window based on the trajectory of the recent literature [37–39].

13.6 4D conductive portfolio expansion beyond single-product anchors

The 4D-ETR direction currently anchors on a single product across the industrial case study and on a small number of products across the broader field [9,24,37]. Portfolio expansion to multiple stimuli (temperature, humidity, light, pH, magnetic field, electrical bias), multiple matrix mechanics (hydrogel, elastomer, rigid stimuli-responsive) and multiple electrical-function combinations

(conductive 4D, dielectric 4D, transducer 4D) is the principal current direction. The biomimetic functional applications direction emerging in the recent literature [45] suggests that the field is at a methodological inflection point similar to where static conductive photopolymers were 5–7 years ago.

13.7 Higher- ϵ_r photopolymer dielectric development

The printability ceiling at approximately 70 wt% ceramic loading (§3.6, §3.8) sets a hard upper bound on the achievable ϵ_r of VPP photopolymer dielectrics at standard hardware irradiance. Reaching the ϵ_r values of bulk ceramic dielectrics (50–10,000 depending on material) requires either alternative deposition routes (DIW with high-load ceramic slurries, ceramic injection moulding into VPP-printed sacrificial moulds) or post-print densification (debinding and sintering of high-loaded green parts). Direct VPP photopolymer dielectrics with ϵ_r above 20 at GHz frequencies are an open research direction; the temperature-independent permittivity routes (TiO₂, CCTO) are particularly relevant for service applications where the BaTiO₃ Curie-point dependence is intolerable.

13.8 Bioprinting integration at full VPP resolution

The convergence of conductive photopolymer chemistry and bioprinting workflows is an active research direction with significant engineering payoff. Full-VPP-resolution conductive bioelectronics— printed-cell-embedded conductive scaffolds, conductive organoids-on-chip platforms, conductive bioelectronics implant prototypes — would extend the addressable application space of Route 5 PEDOT:PSS Bio and Route 4 GNP Bio significantly. The principal current constraints are the cytotoxicity of the conductive component under VPP cure conditions (which can produce reactive species in the cell-containing photopolymer matrix), the dispersion of the conductive filler at loadings compatible with the relevant cell-containing workflow, and the post-cure protocol that completes cure without damaging encapsulated cells. The recent Bansal et al. [37] review identifies this direction as a principal target of the conductive-hydrogel-ink field.

13.9 Sustainability of metallic-particle systems

The silver-route environmental impact (silver mining, energy-intensive nanoparticle synthesis, end-of-life recycling) is a growing concern as the deployment of silver-loaded VPP photopolymers extends beyond research prototypes into industrial applications. Silver recovery from cured parts at end-of-life is technically feasible but operationally challenging; the field-level sustainability profile of the silver route is comparable to the broader printed-electronics silver-ink segment and shares the recycling-infrastructure constraints of that segment [19,29]. Alternative metallic-particle systems (copper, where oxidation is more aggressive; aluminium, where the percolation behaviour is less mature) and alternative high-conductivity printed-conductor regime routes (printed-then-electroless-plated dielectric substrates) are open research directions with sustainability implications.

13.10 Limitations of the proposed framework

This review proposes a route taxonomy, a regime structure, the SDCF and an industrial case-study portfolio. Five specific limitations of the proposed framework deserve explicit acknowledgement. Single-author industrial-academic origin and structural bias risk. The author is the founder and Scientific Director of the manufacturer of the industrial case study (§3.12 and Appendix A). The route taxonomy and the regime structure proposed in this review align closely with the architecture of the case-study portfolio. The alignment is not coincidental: the author's industrial experience over three decades has informed the taxonomy proposal, and the case-study portfolio has been designed under that taxonomy. The structural bias risk is that the taxonomy may appear inevitable when it is, in fact, one possible organisation of the field among several reasonable alternatives. A community-based or multi-author consolidation of the field structure would be a valuable complement to the present single-author proposal. The field-fragmentation paragraph in §3.12 partially mitigates this concern by acknowledging that most commercial portfolios cover only subsets of the route-space, but the structural alignment between the proposed framework and the case-study portfolio remains a documented constraint on the framework's neutrality. Reporting

convention: quantitative envelopes from literature, not from industrial case-study portfolio. Tables 1 and 2 (§3.7) consolidate quantitative ranges from the peer-reviewed and adjacent polymer-composite literature, not from the case-study portfolio. Specific TDS values from the case-study portfolio are reproduced only for parameters where the case-study portfolio publishes them directly (Appendix A, e.g. HDT and Shore values for ESD photopolymers, ϵ_r and $\tan \delta$ for HP1 BTO70). This convention is methodologically deliberate (SDCF, §1.4) but limits the

cross-comparability of the case-study portfolio to the published TDS attributes. Cross-portfolio quantitative benchmarking against competitor products (Liqcreate ESD, Formlabs ESD, Rogers Radix, etc.) would require systematic measurement under controlled conditions and is not provided in this review. Reliance on formulation logic rather than direct characterisation for some claims. Several claims about route behaviour — particularly the cure-state effects of §3.9 — derive from formulation logic and adjacent polymer-composite literature rather than from direct VPP-specific characterisation. The Sevriugina et al. [32] work has begun the direct characterisation of VPP-specific percolation behaviour, but the cure-state effects on filler orientation, post-cure conductivity drift kinetics and storage-history-driven dispersion drift remain inferred rather than systematically measured for the seven routes. Direct experimental benchmarking would strengthen the framework. Metrology gap. No standardised printed-electronics resistivity protocol for VPP photopolymer parts exists at the time of writing. The IEC 61340-5-3:2022 standard [S3] addresses static-dissipative packaging materials but not functional-conductive characterisation of cured 3D parts. The ASTM D257 [S5] DC resistance/conductance protocol is applicable but does not address the system-dependence dimension that the SDCF emphasises. Until a community-standard framework emerges, cross-study comparison of reported conductivity values remains limited by methodological heterogeneity. Literature skew toward proof-of-concept studies. The peer-reviewed literature on VPP electrically functional photopolymers is heavily weighted toward proof-of-concept demonstrations rather than systematic engineering characterisation across the route space. Application-specific deep characterisation (e.g. silver-route ageing under industrial-atmosphere conditions, PEDOT:PSS-Bio cytotoxicity across full ISO 10993 cascade, ESD-band stability under sustained service) is less abundant. The framework consolidation of this review is therefore necessarily incomplete: it organises the available literature without filling the systematic-characterisation gaps that the field itself has not yet closed.

13.11 A consolidated critical assessment of the field

The route taxonomy, the regime structure and the SDCF developed in this review consolidate the documented field but do not resolve the cross-cutting limitations that constrain industrial-grade deployment of electrically functional VPP photopolymers. Beyond the route-specific limitations of §3.8 and the framework-specific limitations of §13.10, seven field-level limitations operate across the route space and deserve explicit synthesis. Reproducibility deficit across nominally equivalent systems. Reported percolation thresholds, surface resistivities, volume conductivities and dielectric loss tangents for nominally equivalent filler-matrix systems vary by factors of 2-10 across published studies, even when the nominal filler chemistry and loading are identical (§3.8 percolation paragraph). The principal contributor is the heterogeneity in dispersion protocols, in nominal-versus-effective filler loading, in measurement geometry and in post-cure protocol. The field lacks a standardised dispersion-and-measurement protocol that would enable direct cross-study comparison, and consequently published values cannot be transferred from one resin-printer combination to another without empirical re-calibration. The reproducibility deficit is structural rather than methodological at the individual-study level; it reflects the SDCF (§1.4) operating across uncontrolled-variable axes. Storage stability documentation gap. Manufacturer-published shelf-life of 6 months at controlled ambient temperature (§3.11) is rarely matched by peer-reviewed long-duration storage-stability studies for VPP conductive formulations. The published evidence base on whether reported conductivity values represent the as-printed-from-fresh state, the typical end-of-shelf-life state or some intermediate state is sparse. The systematic comparison would require multi-month storage-and-test protocols that the academic publication cycle does not naturally support, and the manufacturer-side QC data are typically proprietary. The field's

understanding of storage-stability behaviour is therefore based on individual-product case studies rather than on cross-route consolidated evidence. Humidity sensitivity beyond PEDOT:PSS. The PEDOT:PSS humidity-drift literature [12,17,28,38] is well-developed and is now treated as a

route-defining limitation in §3.8. The analogous humidity sensitivity of ESD-focused photopolymers, of carbon-filled composites and of ceramic-loaded dielectric composites is less systematically documented, despite the published evidence that humidity-driven changes in surface resistivity, percolation-network conductance and dielectric loss tangent operate on all four routes at non-negligible amplitude. The cross-route humidity-response characterisation across the 0-95% RH operational envelope is one of the most accessible systematic studies that the field could undertake and is currently absent from the published consolidation. Scale-up between laboratory demonstration and industrial deployment. The peer-reviewed conductive-VPP literature concentrates on laboratory-scale demonstrations: prints of $<100\text{ cm}^3$ part volume, single-print proof-of-concept, validation on a single platform, characterisation at a single time point post-cure. The industrial-scale dimensions of the manufacturing problem — vat stability over multi-hour print runs, reproducibility across consecutive prints from the same vat, performance variability across the shelf-life of the uncured resin, batch-to-batch variability in the manufactured formulation, qualification under industrial QA/QC protocols — are largely absent from the academic literature and are documented only fragmentarily in manufacturer technical documentation. The gap between "this system works in the laboratory" and "this system is manufacturable at engineering scale" is one of the most consequential evidence gaps in the field. Cure-window instability and oxygen-inhibition variability. The cure window of conductive-loaded photopolymer formulations (the dose envelope in which

through-thickness cure is achievable without over-cure-induced shrinkage cracking or under-cure-induced surface tackiness) is documented to be narrower than for the corresponding unloaded photopolymers, due to the wavelength-attenuation effect of the conductive component (§3.4, §3.11). The narrowing varies with filler chemistry, loading and dispersion state — the same nominal formulation can exhibit different cure-window widths between batches or after storage drift. Oxygen-inhibition behaviour at the cured-part surface (Table 3 §3.10) is similarly variable across formulations and atmospheric

conditions, and the surface-vs-bulk conductivity distinction it produces is rarely characterised systematically in academic studies. These two cure-process variability sources jointly contribute to the realised-vs-nominal performance gap that the SDCF formalises. Overclaimed conductivity contextualisation. A subset of the peer-reviewed literature presents results that nominally claim "conductive electronics" applications when the achieved conductivity sits firmly within the static-dissipative regime (Regime A, §1.3) rather than within the functional-conductive regime (Regime B). The conflation of regimes obscures the actual performance envelope of the demonstrated systems and complicates the interpretation of the field by readers seeking to map the route space to applications. The consistent regime-application mapping proposed in §12 and the conductivity-regime table (Table 1 §3.7) are intended to constrain this conflation and to make the regime claim explicit per demonstration. Single-time-point characterisation gap and the

manufacturing-aware alternative. A complementary cross-route gap follows from the time-dependent realised behaviour developed in §3.9 (Stages 1-6 trajectory). Both the manufacturer-datasheet convention and the academic single-time-point study capture only Stage 2 (post-cure stabilised state) of the trajectory. The Stage 3 environmental-equilibration response, the Stage 4 cycling hysteresis and the Stage 5 long-term ageing envelope — which together determine the engineering-deployed performance over the service life — are reported fragmentarily for some routes (PEDOT:PSS humidity drift is well-documented; silver electromigration is documented in adjacent printed-electronics literature) and almost absent for others (ESD-focused routes, ceramic dielectric composites, 4D electro-thermo-responsive systems). A manufacturing-aware characterisation protocol that systematically reports the Stage 2 → Stage 3 → Stage 4 trajectory over representative service conditions would substantially close the gap between published values and engineering-deployed values. The protocol does not require new measurement technology — surface-resistivity meters, four-probe Kelvin instruments, impedance analysers and humidity

chambers are widely available — but rather a community convention to report

environmental-equilibration response and cycling hysteresis alongside the as-released Stage 2 number. The cross-stage characterisation is the routine engineering practice for adjacent printed-electronics materials (sintered silver inks, conducting hydrogels, conductive thermoplastics) and its absence in the conductive-VPP literature is a methodological gap rather than a measurement-capability constraint. These seven field-level limitations are not a critique of any specific publication or manufacturer; they consolidate cross-route patterns that constrain the consolidation of electrically functional VPP photopolymers as a mature engineering discipline. Taken together, they describe what can reasonably be called a reproducibility-and-transferability deficit in

conductive VPP photopolymer reporting: a published conductivity value from one

resin-printer-protocol combination is rarely transferable to another combination without empirical re-calibration, and the present reporting convention does not flag this limitation to the reader. The deficit is structural rather than methodological: it reflects the gap between resin-only reporting and the SDCF system-level interpretation that the present review argues is the necessary interpretive frame for the field. Closing each of the seven gaps requires community-level standardisation efforts

(the dispersion-and-measurement protocol of the reproducibility gap; the multi-month

storage-stability studies of the storage gap; the cross-route humidity characterisation of the humidity gap; the laboratory-to-industry-scale transfer of the scale-up gap; the

cure-window-variability characterisation of the cure-window gap; the regime-application consistency of the overclaim gap; and the manufacturing-aware characterisation convention of the single-time-point gap) that no single research group or single industrial actor can deliver alone. A minimum near-term convention that the field could adopt without standardisation infrastructure is to report electrical performance values with explicit specification of (i) the cured-system configuration (platform, layer thickness, post-cure protocol), (ii) the measurement-state context (level in the

four-level hierarchy of §1.0, ambient conditions, time after release), and (iii) the

conductivity-trajectory profile rather than a single end-point value. The framework proposed in this review is intended as one input to that community effort, not as a replacement for it.

14. Conclusions

This review has proposed a structural map of the electrically functional VPP photopolymer field as it has consolidated over the 2015–2026 period. Three principal contributions are identified. A seven-route taxonomy operating across three regimes. The seven electrical-function routes (intrinsic conductive photopolymer backbone; ESD-focused; 1D filler CNT; 2D filler GNP; PEDOT:PSS conducting polymer; silver-based metallic; ferroelectric high-permittivity) operating across three operational regimes (static-dissipative, functional conductive, high-conductivity printed-conductor regime) plus the orthogonal dielectric regime structure the design space of the field. Two orthogonal design axes (solubility, biocompatibility) cross each route. The taxonomy is intended as a structural map of the field rather than a portfolio-driven enumeration, although the alignment between the taxonomy and the case-study portfolio is documented and acknowledged as a structural bias risk (§13.10). The System-Dependent Conductivity Framework (SDCF). The realised electrical performance of a cured VPP photopolymer part is a system-level outcome of seven process-chain stages (Fig. 1), not an intrinsic resin property. The SDCF reframes the persistent reporting convention in the field —single-point conductivity values per product — as an under-addressed interpretive limitation. Engineering specifications based on SDCF principles require per-platform calibration, explicit specification of the cure conditions and the post-cure protocol, and characterisation of the conductivity distribution rather than the conductivity point estimate. Eight application areas with consolidated peer-reviewed and industrial documentation. Electronics housings and ESD-controlled fixtures (§4), functional prototypes for electrically active environments (§5), bioelectronics R&D platforms (§6), sacrificial conductive templates for indirect AM (§7), multi-material integration with structural resins (§8), 4D electro-thermo-responsive actuators (§9), printed

antennas and RFID/NFC for IoT (§10), and RF/microwave dielectric components (§11). The application sections consolidate the peer-reviewed evidence from the 2014–2026 window with emphasis on 2022–2026 recent work,

and identify the mature, emerging and frontier subsegments within each area. The review identifies nine open challenges (§13.1–§13.9) that define the agenda for the coming decade: closing the conductivity ceiling gap relative to bulk metallic conductors, standardising percolation and resistivity metrology, characterising long-term oxidative ageing of silver-based systems, developing soluble PEDOT:PSS variants, expanding 4D conductive portfolios beyond single-product anchors, developing higher- ϵ_r photopolymer dielectrics, integrating conductive photopolymers with bioprinting at full VPP resolution, and addressing the sustainability of metallic-particle systems. The brutally honest limitations section (§13.10) acknowledges the single-author industrial-academic origin of the review, the structural alignment between the proposed framework and the case-study portfolio, the reliance on formulation logic for some claims, the metrology gap, and the literature skew toward proof-of-concept studies. The consolidated critical assessment (§13.11) identifies seven cross-route field-level gaps — reproducibility deficit (2–10× variability across nominally equivalent systems), storage stability documentation gap, humidity sensitivity beyond PEDOT:PSS, scale-up between laboratory demonstration and industrial deployment, cure-window instability, overclaimed conductivity contextualisation, and the single-time-point characterisation gap that motivates a manufacturing-aware characterisation convention — and frames their closure as a community-level standardisation effort. The principal interpretive position of the review can be restated in closing: the conductivity of a VPP photopolymer printed part is a system-level outcome, not an intrinsic resin property; the route taxonomy proposed here narrows the design space but does not eliminate the need for empirical calibration on the user's specific system. The field is mature in electronics housings and ESD-controlled fixtures, in printed electrodes for bioelectronics R&D and in sacrificial PEDOT:PSS templates for multi-material microfluidics; it is emerging in 4D actuators, in printed antennas and in RF/microwave dielectric components; it is at the frontier in soluble PEDOT:PSS, in higher- ϵ_r photopolymer dielectrics and in bioprinting-integrated conductive workflows. The next decade of the field will be defined by the closure of the metrology gap, by the consolidation of multi-material

integration workflows, by the cross-route adoption of manufacturing-aware characterisation conventions, and by the expansion of the 4D and dielectric routes beyond single-product anchors.

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customers and academic partners worldwide whose collaboration has provided the application context that this review consolidates.

Disclosure

The author is the founder and Scientific Director of 3Dresyns by Resyner Technologies S.L., the manufacturer of the electrically functional photopolymer resin collection referenced as the

documented representative case study in §3.12 and Appendix A of this review. The review is written from a single-author industrial-academic position; the consequences for interpretive scope are made explicit in §13.10 (Limitations), where the structural alignment between the proposed framework and the case-study portfolio is acknowledged as a documented constraint on the framework's neutrality. Peer-reviewed publications cited have been selected for their direct relevance to electrically functional VPP photopolymer additive manufacturing; the selection includes three independent peer-reviewed studies that characterise or use 3Dresyns products in published research — Quero et al. Lab on a Chip 2023 [13] (multi-material microfluidics with PEDOTEK1 and 3D-ADD CuVK1), Mantione et al. ACS Applied Polymer Materials 2022 [48] (DLP-printed PEDOT:PSS conductive hydrogels using 3Dresyns CDP-WS and Fine Tuner FT2), and Tran et al. Advanced Materials 2025 [49] (consolidating review citing 3Dresyns CDP-WD as a documented DLP-conductive resin route). The companion peer-reviewed paper Segurola 2026 [16] on water-soluble sacrificial resins is also relevant to §7. Where publicly available manufacturer technical datasheets are cited for specific TDS values (HDT, Shore hardness, modulus, surface resistivity, ϵ_r , $\tan \delta$), the values are cited with explicit acknowledgement of the System-Dependent Conductivity Framework stated in §1.4 and §3.9. Manufacturer documentation references carry the prefix [PR] in the reference list to enable readers to distinguish them from peer-reviewed sources. The review does not constitute a product endorsement or a substitute for direct engineering validation on the user's specific platform, geometry and service environment.

Appendix A — Industrial case-study portfolio: representative architecture

This appendix summarises the route-by-route architecture of the industrial case study referenced in §3.12. The exhaustive product-level enumeration (15 ESD grades with full per-product TDS values, 6 modular additives, 1 ferroelectric grade, 1 conductive coating) is provided as Supplementary Information accessible through the manufacturer technical documentation at www.3Dresyns.com and is not reproduced here at the catalogue level.

A.1 Route architecture summary

Route Solubility coverage Bio coverage Representative architecture

1 — ESD-focused non-soluble (Bio not currently offered) mechanical envelope from ultra-rigid high-T (Shore D90, HDT to 290 °C) to super-elastic compliant (Shore A10, modulus <2 MPa); see §A.2 for mechanical-family summary

2 — Intrinsic conductive non-soluble + soluble Bio variant available core matrix family NSEK1 backbone (non-soluble), NSEK1 Bio (Bio-designated; verify product-specific evidence), SEK1 (sacrificial soluble)

3 — CNT (SWCNT + MWCNT) non-soluble + soluble Bio variants in both subroutes GrapNSEK1-SWCNT/MWCNT Bio + sacrificial variants; published TDS for GrapSEK1-MWCNT Bio: sheet resistance <0.004–4 kΩ/sq (250 µm films) [PR4]

4 — GNP non-soluble + soluble Bio variant in non-soluble GrapNSEK1-GNP Bio + sacrificial variant; published TDS GrapNSEK1 Bio base: sheet resistance ≥150 kΩ/sq [PR1]

5 — PEDOT:PSS non-soluble + soluble + Bio variant available two subroutes: (a) dispersible ready-to-print PEDOTEK1 / PEDOTEK1 Bio [used in 17]; (b) user-formulated CDP-WS / CDP-WD matrix components combined with user-selected PEDOT:PSS dispersion and host monomer [used in 54, 55] — see §A.3

6 — Silver-based metallic non-soluble + soluble (Bio not currently offered) AgNSEK1 (non-soluble) + AgSEK1 (sacrificial)

7 — Ferroelectric / high- ϵ_r non-soluble (Bio not currently offered) HP1 BTO70: BaTiO₃ 70 wt%, ϵ_r 8–9 at 10–20 GHz, $\tan \delta < 0.04$ [PR6]

4D-ETR (auxiliary) water-swallowable Bio 4Dresyn ETR35 Bio: electro-thermo-responsive hydrogel, shared with bio-scaffold collection

The SDCF (§1.4) applies to all routes: realised electrical performance depends on the full cured-system configuration and should be empirically validated on the user's platform.

A.2 ESD route — mechanical envelope reference

The ESD route covers the static-dissipative regime across four mechanical-profile groups summarised in Table 4 of §3.12 (Ultra-rigid high-T, Tough rigid, Foldable/flexible,

Elastic/super-elastic), spanning Shore A10 to Shore D90 with Young's modulus from < 2 MPa to 5,000 MPa and HDT from < 0 °C to 290 °C. The exhaustive per-product enumeration with HDT, Shore hardness, flexural strength, elongation, Young's modulus and tensile strength values for the fifteen ESD grades is available at the manufacturer technical datasheet pages [PR5] and is not reproduced in this review. Manufacturer documentation positions the products for static-dissipative use; any packaging-derived reference range from IEC 61340-5-3:2022 requires user-system verification under the stated test method and ESD control plan; specific values within the band are SDCF-dependent and should be validated per user system (§1.4 Table A1).

A.3 PEDOT:PSS route — subroute architecture

The PEDOTEK1 versus CDP-WS / CDP-WD subroute distinction merits brief explanation since both serve the bioelectronics R&D community at different points on the

customisation-versus-ready-to-use trade-off. PEDOTEK1 and PEDOTEK1 Bio are ready-to-print formulated conductive resins designed for direct VPP processing without additional component preparation by the user; published in Quero et al. Lab on a Chip 2023 [13] for multi-material microfluidics. CDP-WS (water-soluble) and CDP-WD (water-dispersible) are matrix components designed to be combined by the user with a selected PEDOT:PSS dispersion, a chosen photoinitiator (e.g. Fine Tuner FT2 [PR16]) and a host monomer (typically PEGDA of selected molecular weight, see §3.9), enabling formulation-level control of swelling ratio, mechanical compliance and printability resolution; published in Mantione et al. ACS Applied Polymer Materials 2022 [48] (DLP conductive hydrogels for ECG/EMG bioelectrodes) and cited in Tran et al. Advanced Materials 2025 [49] review.

A.4 Modular additives, adjacent copper additives, conductive coating

Six modular conductive additives (3D-ADD EKC silver nanowire, ESDA Clear / Black antistatic, GrapEK1-SWCNT/MWCNT/GNP Bio carbon-based) extend the conductive design space beyond fixed formulation by enabling user-controlled addition to a chosen host resin; per-product validation of the host-additive combination on the user's specific platform is required. A distinct family of three copper-based additives (3D-ADD CuVK1, CuVK2, CuVK2C [PR14]) is also available; these are designed primarily as antimicrobial additives leveraging the intrinsic antimicrobial activity of metallic copper rather than as electrical conductors. The conductive component does propagate into the cured matrix and can deliver functional-conductive behaviour at sufficient loading, as documented in the multi-material microfluidic application of Quero et al. [13] where CuVK1 was used with PEDOTEK1. The conductive-route classification of the CuVK family is therefore secondary to the

antimicrobial primary classification. A complementary conductive paint (3D-PAINT GrapEK2 Bio [PR8]) operates outside the bulk-photopolymer scope of the main review but is included as a documented complement to the bulk-cured routes for applications where surface conductivity rather than bulk conductivity is the engineering target.

Reference-control note. ISO 10993-1:2025 [S1] supplies the device-level biological-evaluation and risk-management context, while Regulation (EU) 2017/745 [S4] supplies the EU medical-device regulatory context. Manufacturer entries [PR3] and [PR7] identify the two PEDOT:PSS product-documentation routes; [PR15] identifies the water-soluble sacrificial-resin route. These manufacturer sources document product positioning and instructions only; they do not independently establish electrical, biological, clinical or regulatory performance of a finished part or device.

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