

Printed Conductors and Resistive Elements in Photopolymer Systems: Percolation, Contact Resistance, Drift and Reliability

Juan Segurola

3Dresyns by Resyner Technologies S.L.

© 2026 Juan Segurola. All Rights Reserved.

Correspondence: info@3Dresyns.com · www.3Dresyns.com

ER-261 · Engineering Review · Version 0.2 · 22 September 2026

Abstract

Printed conductive photopolymers are not qualified by a single resistance value. Their electrical state emerges from filler dispersion, percolation, cure and shrinkage, conductor geometry, surface condition and electrode interfaces, and it can drift under strain, temperature, humidity and repeated current or mechanical cycling. This review defines a qualification framework for conductive tracks and resistive elements produced in photopolymer systems. It separates bulk or volume conduction from contact resistance and geometry, treats percolation as a processing-dependent transition rather than a transferable filler threshold, and distinguishes intended piezoresistive response from uncontrolled drift. A non-compensatory matrix is proposed linking printability, dimensional state, electrical uniformity, interface stability, environmental conditioning and cyclic reliability. The central conclusion is that an electrically functional photopolymer element is a coupled material-process-interface device whose qualified resistance must remain inside a declared operating envelope after relevant conditioning, not merely at time zero.

Keywords: vat photopolymerization; conductive composites; carbon nanotubes; percolation; contact resistance; resistivity; drift; reliability; printed electronics

1. Significance and scope

Vat-photopolymerized conductors and resistive elements can integrate sensing, heating, current routing, electromagnetic functions and embedded electronics directly into three-dimensional structures. The same additives that create conductivity can also increase viscosity, absorb or scatter curing light, reduce penetration depth and alter conversion. Electrical performance therefore cannot be separated from printability and cured geometry. This review owns the qualification of printed conductive paths and resistive elements after fabrication. It does not define a universal conductive formulation, semiconductor device physics or electrochemical electrode qualification. Demonstrations of conductive photocurable composites show the coupled effects of dispersion, optical shielding and electrical network formation in specific systems [1-3,6].

1.1 Ownership boundary

ER-261 owns device-level qualification of printed conductive paths and resistive elements across percolation, actual geometry, contact resistance, drift and cyclic reliability. ER-157 retains the broader qualification of electrically and thermally functional nano/micron materials, including conductivity, percolation, interfaces and anisotropy; ER-16 retains conductive-composite formulation and anisotropy; WP-27 retains the wider conductive/electronics resin application space. ER-036 retains rheology, recoating and dispersion control of highly filled suspensions; ER-084 retains photocuring-pathway mechanisms; ER-207 retains dispersion-state metrology; ER-231 retains print-process capability and ER-240 retains reliability architecture at the broader manufacturing level. ER-262 separately owns capacitive sensing and dielectric-state calibration, while ER-264 and later electrochemical reviews own electrolyte-facing electrodes. The boundary matters because a low two-terminal resistance can be dominated by contact quality, while a stable bulk conductivity can still produce an unstable device if the interface or geometry changes.

2. Percolation is a state, not a recipe

Conductive fillers create a connected network only after concentration, aspect ratio, dispersion and matrix-filler interactions jointly reach a suitable state. In photocurable systems the same dispersion process also changes rheology and optical attenuation. Published vat-photopolymer studies show that electrical and rheological percolation need not occur at the same filler fraction, and that improved nanotube dispersion can shift the electrical threshold. Consequently, a filler percentage cannot be transferred as a universal design rule. Qualification should map conductivity together with viscosity, working-curve behaviour, conversion and dimensional fidelity for the actual resin and dispersion route. Carbon-nanotube photopolymer studies directly show that dispersion quality can alter conductivity and that electrical and rheological percolation need not coincide [1,3].

3. Bulk resistance, geometry and anisotropy

The resistance of a printed path combines material resistivity with length and effective cross-sectional area. Layer stair-stepping, edge overcure, voids, sedimentation, recoating gradients and build orientation can make that area different from the nominal CAD geometry. Conductive networks may also become anisotropic if fillers align during mixing, recoating, shear or shrinkage. Therefore both resistance and measured dimensions should be reported, and volume resistivity or conductivity should be calculated only when geometry is known with adequate uncertainty. A geometry change that compensates a conductivity loss is not proof of material stability. Printed conductive nanocomposites also show geometry- and process-dependent electrical behaviour rather than a single transferable bulk number [1,2,4].

4. Contact resistance and electrode interfaces

Two-terminal measurements include specimen resistance, lead resistance and both electrical contacts. The contact contribution can change with clamping force, electrode area, surface contamination, local heating, oxidation and deformation. Four-terminal or Kelvin methods are preferable when bulk resistance is the claimed measurand. When the final device depends on a bonded, printed, plated or mechanically clamped electrode, that interface becomes part of the qualification object and must be cycled with the conductor. Contact design, preparation method, pressure and measurement current should be reported because they can dominate low-resistance specimens. Piezoresistive composite studies reinforce the need to separate material response from the complete contacted-device measurement [5,6].

5. Drift mechanisms

Resistance can drift without visible damage. Polymer physical ageing, residual cure, moisture uptake, thermal expansion, matrix relaxation and filler rearrangement can change tunnelling distances between conductive particles. Mechanical strain can reversibly change contact density, creating useful piezoresistive behaviour, but irreversible network rearrangement produces baseline drift and hysteresis. Current loading can add Joule heating and accelerate local changes. A reliability plan should therefore distinguish reversible sensitivity, zero-offset drift, hysteresis, irreversible resistance change and catastrophic open-circuit failure. Repeated electromechanical cycling can preserve useful response while still requiring explicit baseline-drift and hysteresis control [5,6].

6. Environmental and cyclic conditioning

Conditioning should reproduce the stresses relevant to the intended function: temperature range, humidity, immersion if applicable, flexure or compression, vibration, electrical duty cycle and storage time. Measurements should be taken before, during when feasible, and after conditioning so transient coefficients are not confused with permanent damage. For strain-sensitive conductors, the mechanical strain field must be defined because identical global displacement can produce different local strains in different geometries. Reliability is demonstrated by bounded evolution across the declared cycle count, not by survival of an unspecified bench test. The published cyclic demonstrations are device- and condition-specific and therefore support a conditioning architecture, not a universal cycle-life claim [5,6].

7. Non-compensatory qualification matrix

A conductive element should not pass because excellent initial conductivity offsets failure in dimensional or cyclic stability.

Gate	Required evidence	Failure meaning
G1 Print/process	Stable dispersion, printable viscosity and cure window	Electrical state not reproducibly manufacturable
G2 Geometry	Measured path length/cross-section and orientation	Resistance cannot be separated from dimensional error
G3 Bulk electrical	Defined method, preferably four-terminal where applicable	Conductive network not established or not uniform
G4 Contacts	Interface method and contact contribution bounded	Device result dominated by uncontrolled interface
G5 Environment	Temperature/humidity or service conditioning	Operating envelope not established
G6 Cycling/drift	Baseline, hysteresis and irreversible change through cycles	Reliability claim unsupported

8. Minimum reporting set

Report formulation identity at the controlled level, filler type and lot, dispersion route, mixing energy or defined process, storage time before printing, viscosity condition, optical/cure characterization, printer and wavelength, layer thickness, build orientation, post-cure, specimen geometry, electrode material and attachment, two- or four-terminal method, test current or voltage, temperature, humidity, number of specimens, mapping locations, conditioning history, cycle count and acceptance limits. For resistive sensors, report gauge factor or sensitivity together with hysteresis, baseline drift, recovery and repeatability. For heaters, report resistance-temperature behaviour and duty cycle rather than room-temperature resistance alone.

9. Process windows and change control

The useful formulation window can lie between electrical percolation and the point where viscosity or optical shielding makes printing unreliable. A change in nanofiller lot, dispersion protocol, sonication, matrix chemistry, photoinitiator, pigment, exposure, post-cure or electrode interface can move that window. Requalification should therefore be triggered by changes that can alter network topology, conversion, geometry or contacts. Equivalence may be demonstrated by a bounded comparison, but nominally identical filler loading is not sufficient evidence of equivalence.

10. Knowledge boundary and limitations

Published studies demonstrate that conductive photopolymer composites can be printed with useful conductivity and can support sensing structures, but the reported conductivity ranges and thresholds are formulation- and process-specific. This review does not establish a universal percolation exponent, maximum current density, service temperature, cycle life or acceptable resistance drift. Those limits must be derived from the actual device claim, geometry, measurement uncertainty and risk of failure. The cited literature spans different matrices, fillers, dispersion routes, geometries and test methods [1-6], so numerical thresholds remain source-specific.

11. Conclusions

Printed conductive photopolymers should be qualified as devices, not as isolated conductivity values. Percolation, printable rheology, optical cure, geometry, contact resistance and environmental history are coupled variables. Robust qualification requires a measurement architecture that separates bulk and contact contributions, records actual geometry, quantifies drift and hysteresis, and demonstrates bounded resistance after representative conditioning. Initial low resistance is necessary for many applications, but it is not a substitute for reproducibility or reliability.

References

1. Dahyun Daniel Lim, Jaemin Lee, Jinwoo Park, Wonjoon Choi. High-resolution and electrically conductive three-dimensional printing of carbon nanotube-based polymer composites enabled by solution intercalation. *Carbon*. 2022;194:1-9. <https://doi.org/10.1016/j.carbon.2022.03.042>
2. Francesco Iervolino, Alessio Bonessa, Giuseppe Foti, Marinella Levi, Raffaella Suriano. Additive Manufacturing of Electrically Conductive Nanocomposites Filled with Carbon Nanotubes. *Advanced Engineering Materials*. 2022;24:2200947. <https://doi.org/10.1002/adem.202200947>
3. Veronika Sevriugina, David Pavlinak, Frantisek Ondreas, Ondrej Jasek, Martina Staffova, Petr Lepcio. Matching Low Viscosity with Enhanced Conductivity in Vat Photopolymerization 3D Printing: Disparity in the Electric and Rheological Percolation Thresholds of Carbon-Based Nanofillers Is Controlled by the Matrix Type and Filler Dispersion. *ACS Omega*. 2023;8(48):45566-45577. <https://doi.org/10.1021/acsomega.3c05683>
4. Yuanyuan Zhang, Houmin Li, Xin Yang, Tao Zhang, Kaiqiang Zhu, Wei Si, Zhen Liu, Huaping Sun. Additive manufacturing of carbon nanotube-photopolymer composite radar absorbing materials. *Polymer Composites*. 2018;39(S2):E671-E676. <https://doi.org/10.1002/pc.24117>
5. Jiwan Kang, Mingyu Kang, Soonjae Pyo, Keun Park. Photopolymerization additive manufacturing of highly stretchable CNT nanocomposites for 3D-architected sensor applications. *Composite Structures*. 2025;372:119614. <https://doi.org/10.1016/j.compstruct.2025.119614>

6. Cristian Mendes-Felipe, Luis Rubio-Peña, Pedro Costa, Viktor Petrenko, Leide Passos Cavalcanti, Mohamed Zbiri, Maksym Golub, Jörg Pieper, Marco Sangermano, Senentxu Lanceros-Mendez. Photocurable Carbonaceous Composites with Tunable Piezoresistive Response. Advanced Composites and Hybrid Materials. 2026;9:251.
<https://doi.org/10.1007/s42114-026-01770-2>

Copyright

© 2026 Juan Segurola. All Rights Reserved.