

Piezoelectric Photopolymer Composites for Vat Photopolymerisation: Poling, Electromechanical Coupling and Device-Level Constraints

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ER-021 · Engineering Review · Version 1.2 · 2026

Statement of Significance

A printable dielectric composite does not become a piezoelectric device merely because it contains a piezoelectric ceramic. Particle loading, green-part quality, post-processing, electrical poling, electrode geometry, mechanical boundary conditions and measurement frequency all intervene between printable material and useful electromechanical response. This review separates three states - printable composite, polarised material and validated device - and defines the evidence required at each transition.

Keywords: piezoelectric composite; barium titanate; BaTiO₃; vat photopolymerisation; DLP; poling; d33; d31; electromechanical coupling; acoustic impedance; transducer; anisotropy

Abstract

VPP provides geometric freedom for piezoelectric ceramics and polymer-ceramic composites, but device performance cannot be inferred from filler identity or dielectric permittivity. Ceramic loading affects viscosity, scattering, cure depth and sintering; particle orientation and porosity affect anisotropy; poling determines domain alignment; and electrode, resonance and mechanical boundary conditions determine measured device response. Recent DLP studies of BaTiO₃ ceramics demonstrate the influence of particle grading, particle size and print/process parameters, while printed transducer studies show that near-pristine ceramic response requires careful manufacturing and device integration. This review develops a qualification framework centred on printable state, polarised state and device state. It separates d33/d31 from permittivity, coupling factor and acoustic response, and requires poling and measurement protocols to be reported explicitly. 3Dresyn HP1 BTO70 is included only as a commercial research implementation example and is not treated as pre-poled or as a finished piezoelectric device. [1–7]

1. Introduction

Piezoelectric additive manufacturing spans at least two material architectures. One route prints a highly filled ceramic green body followed by debinding and sintering; the final functional phase is predominantly ceramic. A second route retains piezoelectric particles inside a polymer network, producing a composite whose response depends on filler fraction, connectivity, orientation, polymer compliance and poling. In both cases, printability and piezoelectricity are separate qualification problems. [1–4]

The strongest failure in reporting occurs when a dielectric or ferroelectric label is used as a proxy for piezoelectric performance. BaTiO₃ is intrinsically ferroelectric, yet an unpoled random composite can show little useful macroscopic piezoelectric response. Likewise, a high relative permittivity can be relevant to field distribution without specifying d33, d31, coupling factor or device sensitivity. The correct evidence chain therefore moves from composition and geometry to poling, material coefficients and finally device behaviour.

2. Three material states

Domain	Measured output	Primary dependency	Claim boundary
Printable composite / slurry	Rheology, dispersion, cure depth, green geometry.	Particle fraction, size, optical scattering, matrix chemistry.	No macroscopic piezoelectric coefficient.
Processed ceramic/composite	Density, porosity, phase, dimensions, electrodes.	Debinding/sintering or cured network state.	No domain alignment unless poled.
Polarised material	d33/d31, dielectric and hysteresis response.	Poling field, temperature, time and electrode geometry.	No device performance without boundary conditions.
Integrated device	Sensitivity, resonance, bandwidth, output or actuation.	Geometry, electrodes, load, frequency, electronics.	Cannot be reduced to one bulk material coefficient.

Table 1. Engineering distinctions that must be preserved.

3. Printing and ceramic loading

High ceramic loading is attractive because it can raise functional phase content, but it increases viscosity and light scattering. DLP studies of BaTiO₃ show that particle size and grading alter slurry behaviour, green density and final ceramic properties. Cure calibration must therefore be repeated for each solids architecture. In sintered-ceramic routes, green-body defects become amplified by debinding shrinkage and densification; in polymer composites, incomplete cure and particle sedimentation can create z-dependent response. [1–4] Where zeta potential is used to characterise dispersion, the exact ISO 13099-1 method and conditions should be reported [8].

Variable	Manufacturing effect	Functional consequence	Minimum report
Particle size / grading	Changes packing, viscosity and scattering.	Affects density, porosity and field distribution.	Distribution and surface treatment where applicable.
Filler fraction	Changes rheology and active-phase connectivity.	Can raise response but reduce printability.	Mass/volume basis and density assumptions.
Layer/exposure	Controls green geometry and conversion.	Creates anisotropy or interlayer defects.	Layer thickness and exposure strategy.
Debinding/sintering	Removes binder and densifies ceramic.	Controls phase, grain size, porosity and shrinkage.	Thermal programme and atmosphere.
Electrodes	Define applied field and measured direction.	Affect effective poling and device response.	Material, area and placement.
Poling	Aligns ferroelectric domains.	Creates macroscopic piezoelectric response.	Field, temperature, time, medium and direction.

Table 2. Manufacturing variables that influence piezoelectric response.

4. Poling is a manufacturing step, not a footnote

Poling conditions strongly affect the measured coefficient and cannot be replaced by a generic voltage value. Electric field should be reported rather than voltage alone, and the specimen thickness, electrode geometry, temperature, poling medium and dwell should be stated. Excessive field can produce dielectric breakdown, while inadequate field leaves domains poorly aligned. For composites, local field concentration differs from the nominal macroscopic field because polymer and ceramic phases have different permittivity. The relevant VPP ceramic studies report process- and specimen-specific poling conditions rather than a transferable generic voltage [1–4].

5. d33, d31, permittivity and coupling answer different questions

d33 describes charge or strain along the poling direction under the corresponding mechanical/electric axis, whereas d31 couples orthogonal directions. Relative permittivity affects capacitance and field distribution. Electromechanical coupling factors describe conversion efficiency under resonant conditions and depend on geometry and mode. Reporting only one quantity can therefore obscure whether the intended application is sensing, actuation, energy harvesting or ultrasound. Because no single catch-all standard covers every coefficient and device configuration, the instrument, specimen geometry, orientation, frequency, electrodes and calculation must be reported directly [5–7].

6. Acoustic and transducer constraints

Ultrasound transducers add acoustic impedance, resonance frequency, bandwidth, matching layers and backing conditions to the material problem. Lu and co-workers demonstrated additive manufacturing and processing of miniaturised transducers using near-pristine piezoelectric ceramics, illustrating that the printed functional component must be integrated into an acoustic stack before device-level performance can be claimed. Porous piezoelectric structures can intentionally reduce effective acoustic impedance, but porosity also changes stiffness and dielectric response. [5,6]

Application	Material metrics	Device metrics	Critical boundary
Pressure sensor	d33/d31, dielectric loss, modulus.	Sensitivity, linearity, drift, hysteresis.	Bulk d33 alone does not predict packaged sensor output.
Energy harvester	d coefficient, permittivity, loss.	Power under defined load/frequency and circuit.	Open-circuit voltage alone is not harvested power.
Ultrasound transducer	Piezo coefficients, coupling, density.	Resonance, bandwidth, sensitivity, acoustic field.	Material coefficient does not establish imaging/therapy performance.
Actuator	d31/d33, modulus, dielectric strength.	Displacement/force versus field and cycles.	Single-cycle strain is not fatigue performance.

Table 3. Device-level validation by application.

7. Anisotropy and orientation

VPP introduces geometric and material anisotropy through layering, particle sedimentation, alignment and post-processing. Anisotropy may be beneficial when deliberately aligned with the desired electromechanical mode, but uncontrolled orientation complicates comparison. Piezoelectric coefficients should therefore be reported relative to print direction, poling direction and loading direction. Dielectrophoretic alignment provides adjacent additive-manufacturing evidence for deliberately oriented piezoelectric composites, but it is not direct VPP validation [7].

8. Stability and cycling

A functional device must retain polarisation and mechanical integrity. Depoling can occur with temperature, field reversal or time; polymer matrices can creep; interfaces can debond under cyclic stress. Device papers should include environmental conditioning and repeated cycling appropriate to the application rather than extrapolate lifetime from an initial d33 value.

Block	Minimum information	Why needed	Claim limit
Feedstock	Ceramic identity, size, loading, matrix.	Defines active phase and processability.	No response inferred from ceramic name.
VPP	Printer/wavelength, layer, exposure, orientation.	Defines green geometry and anisotropy.	No cross-printer transfer without calibration.
Post-process	Debind/sinter or polymer post-cure.	Defines final density/network.	Green-body values are not final material values.
Poling	Field, temperature, time, medium, direction, electrodes.	Defines domain alignment.	No piezo claim without documented poling where required.
Material test	d33/d31, permittivity/loss, frequency, orientation.	Separates functional coefficients.	One coefficient is not a complete device description.
Device test	Geometry, load, frequency, electronics and output.	Establishes application performance.	Supports only tested configuration.

Table 4. Minimum reporting set for VPP piezoelectric studies.

3Dresyns implementation examples

3Dresyn HP1 BTO70 provides a commercial example of a printable BaTiO₃-containing research material, but its manufacturer positioning must remain distinct from a poled-device claim [M1].

- 3Dresyn HP1 BTO70 is a manufacturer-described BaTiO₃-loaded, high-permittivity photopolymer for research and engineering workflows. The presence of BaTiO₃ and manufacturer-reported dielectric properties do not establish a macroscopic piezoelectric coefficient for the printed specimen [M1].
- Any piezoelectric claim for a printed specimen requires a documented poling state where applicable and direct measurement of the relevant coefficient or device output under defined geometry, orientation, electrodes, frequency and boundary conditions.
- Manufacturer-reported dielectric permittivity can support dielectric characterisation, but it must not be converted into an assumed d₃₃, d₃₁, coupling factor, ultrasound sensitivity or energy-harvesting output [M1].

The product is therefore an implementation starting point, not a finished piezoelectric device. Application-level performance remains dependent on printed geometry, processing, poling, electrodes and measurement conditions.

9. Conclusions

- Printable, polarised and device states are distinct qualification stages.
- BaTiO₃ identity or high permittivity does not by itself establish useful macroscopic piezoelectric response.
- Particle grading, loading and VPP optics determine whether a homogeneous green body or composite can be manufactured.
- Poling field, temperature, time, medium and direction must be reported explicitly.
- d₃₃, d₃₁, permittivity, coupling and device output are non-equivalent metrics.
- Anisotropy should be referenced to print, poling and measurement directions.
- Device claims require geometry-specific testing, cycling and environmental stability.

Limitations

This review does not pool piezoelectric coefficients because ceramic fraction, porosity, poling and test geometry differ across studies. Commercial product examples are not independently poled or characterised here.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns materials are identified only as implementation examples supported by controlled product documentation. They are not treated as independent peer-reviewed evidence and no proprietary formulation composition is disclosed.

Data availability

No new experimental dataset was generated for this review. Scientific statements are attributed to the cited literature and standards; commercial examples are separated from the independent evidence base.

Company information

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Manufacturer documentation

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