



Screen printing as a scalable manufacturing approach for thermoelectric devices

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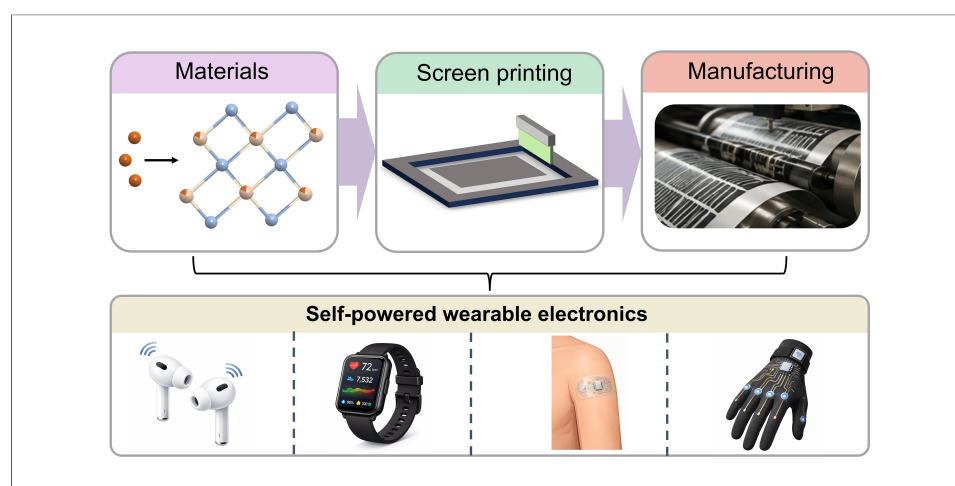
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Abstract

Thermoelectric technology is widely regarded as a promising solution for next-generation energy harvesting and thermal management. To date, extensive efforts have been devoted to enhancing the intrinsic performance of thermoelectric materials, as well as to optimizing device structures and configurations. However, comparatively less attention has been paid to translating these high-performance materials into scalable industrial applications. This paper highlights screen printing as a critical bridge between laboratory-scale research and industrial manufacturing of thermoelectric devices (TEDs), particularly for wearable electronics. We provide a unique and comprehensive overview of the versatility of screen printing across a broad range of thermoelectric materials and device architectures. Furthermore, a systematic fabrication framework is proposed and discussed, offering practical guidelines for constructing TEDs with diverse structural designs via screen printing. This approach enables application-oriented device engineering and facilitates the realization of targeted performance outcomes in real-world scenarios.



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INTRODUCTION

Thermoelectric technology enables the direct interconversion between heat and electricity via the Seebeck, Peltier, and Thomson effects, offering a solid-state solution for waste heat recovery, localized power generation, and thermal management^[1,2]. A typical thermoelectric device (TED) comprises n-type and p-type thermoelectric legs that are electrically connected in series and thermally coupled in parallel^[1-3]. Although the output performance of a TED can be partially optimized through geometric design of the thermoelectric legs, its ultimate conversion efficiency (η) is fundamentally constrained by the intrinsic properties of the thermoelectric materials^[4]. The performance of thermoelectric materials is commonly evaluated by the dimensionless figure of merit, ZT , defined as $ZT = S^2\sigma T/\kappa$, where S denotes the Seebeck coefficient, σ the electrical conductivity, κ the thermal conductivity, and T the absolute temperature^[4,5]. Due to the strong temperature dependence of charge carrier and phonon transport, different thermoelectric materials exhibit peak ZT values within distinct temperature ranges^[5]. Accordingly, thermoelectric materials are generally classified into room-temperature, mid-temperature, and high-temperature systems^[6]. For example, Bi_2Te_3 -based alloys dominate near-room-temperature applications (≈ 300 -500 K), GeTe- and SnSe-based materials perform effectively in the mid-temperature regime (≈ 400 -700 K), whereas oxide- and perovskite-based materials are more suitable for high-temperature operation (> 800 K)^[6-8].

Over the past decade, substantial advances in band engineering, defect modulation, and nanostructuring have driven remarkable enhancements in thermoelectric performance. Peak ZT values exceeding 1.9 have been achieved in state-of-the-art Bi-Sb-Te alloys near room temperature, while record average ZT values approaching 3 have been reported in single-crystalline SnSe within the mid-temperature regime^[9,10]. Despite these impressive laboratory-scale accomplishments, the large-scale industrial deployment of thermoelectric technologies remains limited^[11,12]. A critical bottleneck lies not solely in intrinsic material performance, but rather in the high cost, processing complexity, and limited scalability associated with conventional device fabrication strategies^[12,13]. Most advances in thermoelectric research continue to emphasize material-centric optimization, concentrating on crystal structure engineering, electronic band modulation, and phonon transport suppression to maximize ZT ^[5,14]. Laboratory-scale demonstrations are typically conducted on small-area specimens or proof-of-concept devices, where considerations such as fabrication scalability, manufacturing yield, and system-level integration remain secondary^[15,16]. In contrast, successful industrial deployment requires manufacturable device architectures, compatibility with large-area processing, high process reliability, and cost-effective production strategies^[11,16]. This fundamental misalignment between laboratory research priorities and industrial manufacturing requirements has significantly impeded the effective translation of high-performance thermoelectric materials into practical technologies, as schematically illustrated in Figure 1^[12,13,17-19].

Screen printing represents a compelling yet underexplored strategy to bridge this translational gap^[3,16]. As a mature, cost-effective, and scalable manufacturing technology, screen printing has been extensively adopted across industries, including batteries, photovoltaics, printed electronics, and sensors^[16]. Notably, it offers several intrinsic advantages that align closely with the requirements of TED fabrication^[20]. Screen printing accommodates a wide thickness range, from micrometer-scale films to millimeter-scale thick layers, supports powders with diverse compositions, morphologies, and particle sizes, and enables seamless scaling from laboratory prototyping to industrial production^[20-23]. Collectively, these attributes position screen printing not simply as an alternative processing route, but as a strategic manufacturing platform that effectively bridges fundamental material innovation with device-level implementation^[24].

Recent reviews on flexible, printed, and wearable thermoelectrics have provided comprehensive summaries of material systems, device performance, printing methods, and application prospects. In contrast, this paper does not aim to provide another progress-oriented review. Instead, it reframes screen printing as a

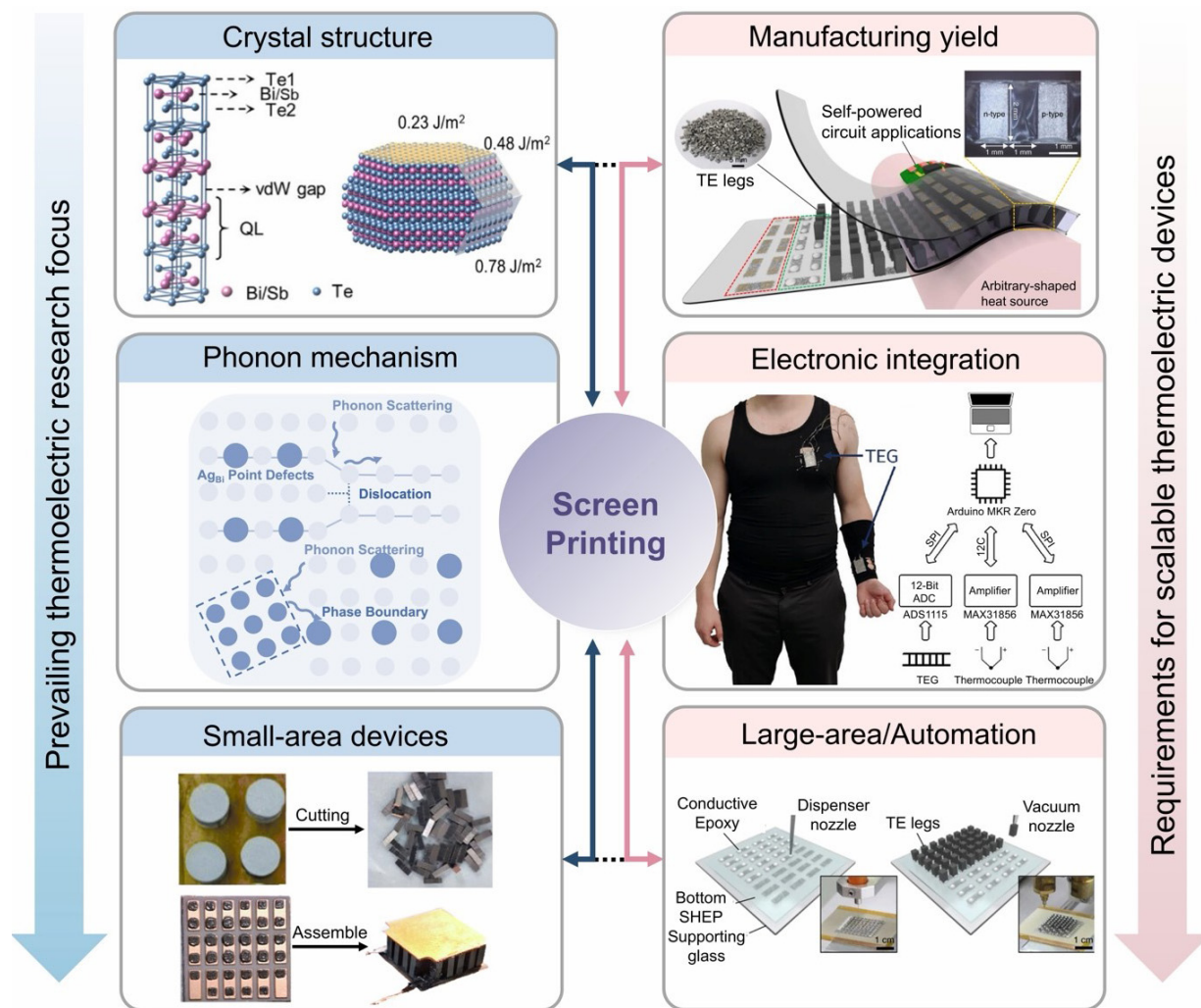


Figure 1. Schematic illustration of the fundamental mismatch between laboratory research priorities and industrial manufacturing requirements, motivating screen printing as a scalable interface for thermoelectric device (TED) fabrication. Inset images include: Bi₂Te₃-based crystal structure; Reproduced with permission^[17]. Copyright 2026, Wiley. Phonon transport mechanism; Reproduced with permission^[18]. Copyright 2023, Elsevier. Small-area proof-of-concept devices; Reproduced with permission^[19]. Copyright 2025, Royal Society of Chemistry. Manufacturing yield; Large area/automated production; Reproduced under a Creative Commons Attribution 4.0 International License^[20]. Copyright 2020, Springer Nature. Electronic system integration; Reproduced with permission^[21]. Copyright 2024, Wiley. QL: Quintuple layer; TE: thermoelectric; TEG: thermoelectric generator; SHEP: soft heat transfer and electrical interconnection platform.

manufacturing interface that connects laboratory-scale thermoelectric materials to industrially relevant device fabrication. Specifically, we focus on three interrelated aspects that have received less systematic attention: a material-agnostic processing window for diverse thermoelectric inks, a geometry-enabled design space spanning film-based and bulk-like architectures, and an application-driven decision-making framework for selecting device structures according to practical constraints. This paper highlights how screen printing can move thermoelectric research from material-centric optimization toward manufacturing-informed device design. In this work, we propose screen printing as an effective manufacturing interface that bridges laboratory-scale thermoelectric research with industrial device requirements. We first discuss thermoelectric material systems, encompassing both inorganic and organic materials, that are compatible with screen-printing processes, together with key considerations in ink formulation and processing. We then examine screen-printing-enabled device architectures and the associated structural design flexibility they offer. Finally, we introduce a decision-making framework that links target applications with appropriate

printing strategies, device configurations, and anticipated system-level performance outcomes. By shifting the emphasis from material performance alone to manufacturable design pathways, this work seeks to provide practical guidance for accelerating the industrial translation and large-scale deployment of thermoelectric technologies.

MATERIAL-AGNOSTIC PROCESSING WINDOW FOR SCREEN-PRINTED THERMOELECTRIC

Screen printing is a mature and widely adopted manufacturing technology across multiple industries, capable of processing both inorganic and organic materials on diverse substrates through precise control of key processing parameters^[25–28]. In the field of thermoelectrics, it similarly establishes a material-agnostic processing window, within which materials of varied compositions, morphologies, and physical properties can be formulated into printable thermoelectric inks, as schematically illustrated in Figure 2^[20,29–34]. Besides, a summary of state-of-the-art screen-printed thermoelectric materials is shown in Table 1, indicating the broad compatibility of the screen-printing technique in thermoelectric materials. Printable thermoelectric inks can be systematically engineered by tailoring mesh counts, squeegee shapes, angle of printing, ink rheology, particle size distribution, and interfacial chemistry, thereby enabling the fabrication of both thin-film configurations and thick, bulk-like thermoelectric architectures^[20,21,35,36]. Notably, this versatility arises not from material-specific optimization, but from the intrinsic process adaptability of screen printing itself^[29–31]. Such characteristics align closely with the fundamental requirements of industrial deployment (including process reliability, scalability, and cost-effectiveness), thereby positioning screen printing as a strategic manufacturing interface that bridges laboratory-scale thermoelectric material innovation with industrially relevant device fabrication.

Fundamental processing parameters of screen printing

The key processing parameters in screen printing include mesh count, squeegee pressure, and squeegee angle, which strongly influence the properties of the printed films, including thickness, uniformity, and pattern fidelity^[60–62]. The selection of these parameters is primarily guided by the characteristics of the ink, the type of substrate, and the required level of pattern detail^[61,63].

Ink properties play a central role in determining suitable printing conditions. High-viscosity inks, such as plastisol, typically require lower mesh counts (110–156), moderate squeegee pressures (20–25 N), and relatively low angles (around 45°) to ensure adequate ink transfer and coverage^[60–62]. In contrast, low-viscosity inks, such as water-based formulations, benefit from higher mesh counts (≥ 230), higher squeegee pressures (25–35 N), and steeper angles (around 75°) to control ink flow and prevent excessive penetration into the substrate^[62,64,65]. Metallic inks, which contain larger particles, generally require even lower mesh counts (38–86), along with reduced pressure (15–20 N) and lower angles to accommodate particle size and maintain print quality^[62,64,65].

In addition to ink properties, substrate characteristics are a critical factor in parameter selection. Screen-printing substrates can be broadly categorized into textiles, smooth surfaces, and rough surfaces^[62,65]. Textiles, such as fabrics, typically require lower mesh counts (110–156) to compensate for ink absorption and surface porosity. In contrast, smooth substrates, including paper and plastics, allow for higher mesh counts (230–305), enabling finer feature definition and improved pattern resolution^[62].

Beyond conventional printing quality, these parameters are particularly critical for thermoelectric inks because they directly influence electrical percolation, porosity evolution, and interparticle transport pathways. Thermoelectric inks typically require relatively high particle loading (commonly > 60–80 wt.% for inorganic systems) to establish continuous conductive networks and preserve thermoelectric transport, whereas excessive binder content, although beneficial for printability and adhesion, may introduce insulating

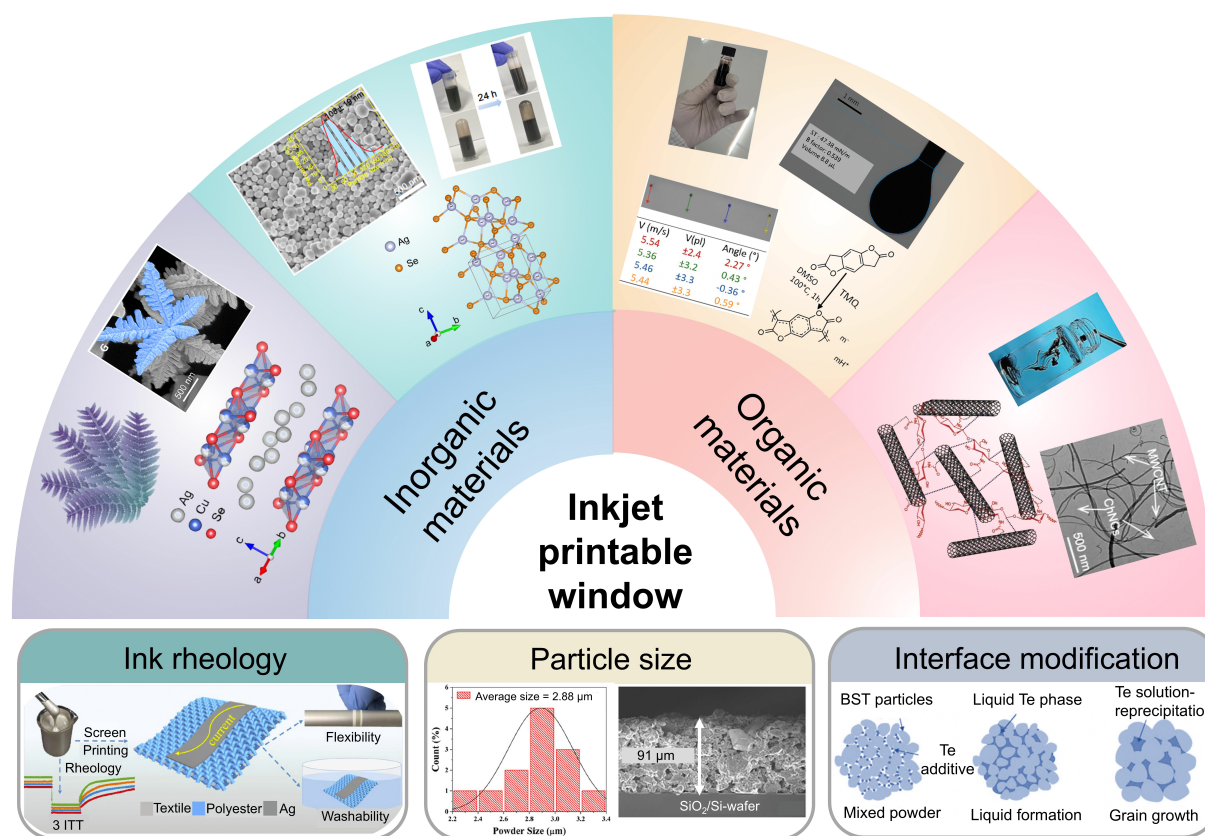


Figure 2. Material-agnostic processing window for screen-printed thermoelectrics. Schematic illustration showing how ink rheology, particle characteristics, and interfacial modification collectively define a microstructure-preserving printability window, enabling diverse inorganic and organic thermoelectric materials to be translated into screen-printed films. Inset images of inorganic materials: Left; Reproduced with permission^[20]. Copyright 2025, Wiley. Right; Reproduced under a Creative Commons Attribution 4.0 International License^[29]. Copyright 2024, Springer Nature. Inset images of organic materials: Left; Reproduced with permission^[30]. Copyright 2024, Wiley. Right; Reproduced under a Creative Commons Attribution 4.0 International License^[31]. Copyright 2022, Wiley. Ink rheology; Reproduced with permission^[32]. Copyright 2021, Elsevier. Particle size; Reproduced with permission^[33]. Copyright 2024, Springer Nature. Interface modification; Reproduced with permission^[34]. Copyright 2019, Wiley.

interfaces that reduce σ . Accordingly, most reported systems maintain the combined binder and solvent content below ~ 20 wt.%^[36,47,48,54,66]. Similarly, commonly reported viscosity windows for thermoelectric inks range from 1000 to 5000 mPa·s, balancing mesh transfer and pattern fidelity with particle dispersion, densification, and microstructure evolution during post-treatment^[66]. Insufficient densification can lead to high porosity and poor electrical contact between thermoelectric particles, ultimately increasing internal resistance and degrading device-level performance. Additionally, solvent selection and drying conditions play an important role in determining film formation and thermoelectric performance. Solvents with different volatilities and boiling points can significantly influence evaporation kinetics during drying, thereby affecting particle redistribution, film uniformity, and microstructure evolution^[31,64]. Uncontrolled solvent evaporation may induce thickness non-uniformity and coffee-ring effects, leading to spatial variations in σ and S across the printed film^[64]. Therefore, appropriate solvent selection and drying control are essential for achieving homogeneous thermoelectric films with reproducible transport properties and device performance. Therefore, thermoelectric-specific screen-printing windows must balance printability with electrical continuity, microstructure preservation, and interfacial transport.

Inorganic thermoelectric within the screen-printing processing window

Inorganic thermoelectric materials generally exhibit superior thermoelectric performance; however, their development has traditionally proceeded along two largely independent fabrication routes. Bulk

Table 1. Summary of state-of-the-art screen-printed thermoelectric materials

Materials	Ink system	Substrate	Thickness (μm)	Post-treatment temperature ($^{\circ}\text{C}$)	$S^2\sigma$ ($\mu\text{W cm}^{-1} \text{K}^{-2}$)	κ ($\text{W m}^{-1} \text{K}^{-1}$)	ZT	Ref.
p-type: $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ n-type: $\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	Ethyl cellulose/Butyl carbitol acetate	Al_2O_3	650	500	p-type: 25.6 n-type: 25.9	p-type: 0.87 n-type: 0.88	p-type: 0.88 n-type: 0.57	[37]
$\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	Nitrocellulose/BCA	Ceramic	600	500	17.2	0.65	0.88	[38]
PbTe-SrTe	Disperbyk-110/ α -terpineol	Alumina	100	700	13.8	0.82	1	[39]
p-type: $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ n-type: $\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	Polypropylene glycol diglycidyl ether epoxy resin/methylhexahydrophthalic anhydride	Polyimide	-	300	p-type: 3.21 n-type: 1.24	-	-	[40]
Bi_2Te_3	Ethyl cellulose/terpineol	Polyimide	-	350	3.63	0.586	0.2	[41]
p-type: Sb_2Te_3 n-type: $\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	Polypropylene glycol diglycidyl ether/epoxy resin	Polyimide	75	300	p-type: 1.5 n-type: 0.6	-	-	[42]
$\text{Bi}_{0.4}\text{Sb}_{1.6}\text{Te}_3$	Disperbyk-110/ α -terpineol	Polyimide	27	450	30	0.9	1	[34]
Bi_2Te_3	Ethyl cellulose/diethylene glycol butyl ether acetate/dibutyl phthalate	Polyimide	166	400	4.65	-	-	[43]
p-type: $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ n-type: $\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	PVP/N-methyl-2-pyrrolidone	Glass	25	70	p-type: 16 n-type: 10.5	p-type: 0.62 n-type: 0.47	p-type: 1.45 n-type: 0.75	[44]
$\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$	Epoxy resin/methylhexahydrophthalic anhydride/2-ethyl-4-methylimidazole	Polyimide	45	300	15.1	-	-	[45]
$\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$	Epoxy resin/methylhexahydrophthalic anhydride/2-ethyl-4-methylimidazole	Polyimide	139	300	24.7	0.78	0.91	[46]
$\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$	Ethyl cellulose/ α -terpineol	Polyimide	3	450	7.45	0.78	0.5	[47]
Sb_2Te_3	Ethylenediamine	Si/ SiO_2	91	180	-	-	1.04	[33]
$\text{Bi}_{0.4}\text{Sb}_{1.6}\text{Te}_3$	Disperbyk-110/ α -terpineol	Polyimide	-	250	35	0.77	1.3	[48]
Ag_2Se	Ethanol	Nylon	5.4	200	18.82	0.696	0.8	[49]
Ag-Se-based	Methyl cellulose/thermoplastic resin	Glass	25	300	5.4	0.28	0.6	[50]
Ag_2Se	Polystyrene-toluene	Glass	25	200	17	0.5	1.03	[51]
Ag_2Se	N-methyl-2-pyrrolidone	Polyimide	13	200	13	0.45	0.92	[52]
Ag_2Se	Methyl cellulose/water	Nylon	30	180	30.02	-	-	[53]
Ag_2Se	Methyl cellulose/water	Nylon	-	290	16.41	-	-	[35]
Ag_2Se	α -terpineol	Nylon	-	200	15.5	0.57	0.8	[36]

Ag ₂ Se/carbon	PVP/ethylene glycol	Polyimide	-	450	16.17	-	-	[25]
Ag ₂ Se/carbon	PVP/ethylene glycol	Polyimide	10	450	17.61	0.66	0.81	[23]
p-type: Cu ₂ Se n-type: Ag ₂ Se	-	Polyimide	p-type: 20.6 n-type: 9.38	150	p-type: 0.42 n-type: 4.68	p-type: 0.283 n-type: 0.3	p-type: 0.07 n-type: 0.51	[54]
Cu ₂ Se	Methyl cellulose/water	Nylon	7.11	290	1.22	-	-	[55]
CuAgSe	MC/water	Glass fiber fabric	20	350	18	0.95	0.48	[20]
Cu _{0.6} Ni _{0.4}	Ethyl cellulose/glycerol/EG	Si	5	500	28.64	-	-	[56]
p-type: SnSe n-type: Sn _{0.98} Bi _{0.02} Se _{0.97} Te _{0.03}	CAP/diacetone alcohol	PET	72	400	-	-	-	[57]
Graphene	Ethyl cellulose/terpineol	Polyimide	2.5	350	-	-	-	[58]
ChNCs/MWCNT	Water	Paper	8	-	0.0045	-	-	[31]
PANI/Graphite	Cellulose acetate/diacetone alcohol	polyester	2.5	-	-	-	-	[59]
PBFDO	-	Kapton	1.7	120	0.07	2.2	-	[30]

The table is sorted by the materials type from inorganic to organic materials. $S^2\sigma$: Power factor; κ : thermal conductivity; ZT: figure-of-merit; BCA: butyl carbitol acetate; PVP: the polyvinylpyrrolidone; CAP: cellulose acetate propionate; PANI: polyaniline; ChNC: chitin nanocrystal; MWCNT: multiwall carbon nanotube; PBFDO: n-type poly(benzodifurandione).

thermoelectric materials are typically produced via powder-based approaches, including solvothermal synthesis^[18,20,67], melt processing^[8,9], and ball milling^[68,69]. In contrast, thermoelectric thin films are commonly fabricated using vacuum-based techniques, such as magnetron sputtering^[70,71], co-evaporation^[72], and other physical vapor deposition (PVD) methods^[73,74]. This inherent separation between bulk and thin-film processing pathways not only limits process compatibility but also complicates device integration, thereby posing substantial challenges for scalable and cost-effective manufacturing.

Screen printing provides a distinct advantage by integrating these traditionally separated material forms within a unified, powder-based processing framework^[20,29-34,75]. Powders synthesized via conventional bulk-material routes can be directly utilized as printable feedstocks, enabling the fabrication of both bulk-like thick films and thin-film thermoelectric components through careful control of particle morphology and size distribution^[34,66]. Importantly, this strategy preserves the microstructural features responsible for high thermoelectric performance, while simultaneously introducing enhanced design flexibility at the device level^[41,47]. For instance, CuAgSe powders with dendritic, topology-driven micro-nano architectures synthesized through solution-based methods inherently generate hierarchical structures and complex grain boundary networks during post-printing densification, resulting in suppressed lattice thermal conductivity (κ_l)^[20]. These microstructural characteristics can be effectively retained and incorporated into TED architectures via screen printing^[20]. Similarly, solution-synthesized n-type Bi₂Te₃ nanorods and nanoplates, as well as p-type Bi_{0.4}Sb_{1.6}Te₃ nanoparticles prepared by ball milling, have been successfully processed into high-performance thermoelectric films using screen-printing techniques^[3,30]. Collectively, these examples demonstrate that the compatibility of screen printing with diverse inorganic thermoelectric powders is not

material-dependent but fundamentally enabled by the adaptability of the printing process itself. However, most inorganic thermoelectric films require post-printing annealing or sintering at relatively high temperatures, commonly ranging from 200 to 500 °C, as summarized in Table 1. Consequently, substrate selection for inorganic screen-printed thermoelectric is often limited to thermally stable materials such as polyimide, ceramics, Al₂O₃, glass, and SiO₂. Although screen printing provides a material-agnostic processing pathway, this high-temperature requirement restricts compatibility with low-cost polymer substrates and roll-to-roll manufacturing processes, thereby limiting scalability and increasing manufacturing complexity. Addressing the trade-off between high-temperature densification and substrate compatibility therefore remains a critical challenge for translating laboratory-scale inorganic thermoelectric materials into industrial manufacturing.

By bridging bulk-derived powders with film-based device architectures within a unified manufacturing framework, screen printing significantly reduces fabrication complexity, development cycles, and associated production costs. These advantages align closely with industrial demands, reinforcing the role of screen printing as an effective manufacturing interface for inorganic thermoelectric systems. Nevertheless, the continued reliance on particle-based inks and high-temperature densification processes constrains precise microstructural control and may limit large-scale manufacturing efficiency. This highlights the necessity for advanced strategies that can preserve bulk-level carrier transport properties while enabling scalable fabrication of screen-printed thermoelectric films.

Organic thermoelectric enabled by low-temperature screen printing

Compared with inorganic thermoelectric materials, organic thermoelectrics offer intrinsic advantages in cost-effectiveness, mechanical flexibility, and biocompatibility^[76–79]. Owing to their polymeric nature, organic thermoelectric materials are inherently well suited to screen-printing processes, allowing precise tuning of ink rheology, low-temperature film formation, and the fabrication of mechanically compliant thick-film architectures^[59,80]. In contrast, inorganic thermoelectric inks typically consist of particulate suspensions that may suffer from dispersion instability and generally require high-temperature sintering, thereby restricting substrate selection and complicating device integration^[41,49,81].

The low-temperature processing characteristics of organic thermoelectrics substantially broaden the accessible manufacturing window for screen-printed TEDs. For example, n-type poly(benzodifurandione) (PBFDO) can be fabricated into uniform thermoelectric films via screen printing, followed by mild thermal annealing at approximately 100–120 °C^[30]. The resulting films and devices demonstrate excellent environmental stability across a wide temperature range (−8 °C to 200 °C) and under high-humidity conditions (up to 90% relative humidity), underscoring the structural robustness and practical viability of screen-printed organic thermoelectric architectures^[30].

Beyond purely organic systems, the low thermal budget associated with screen printing further enables the integration of organic thermoelectric materials with bio-derived and flexible components, giving rise to hybrid thermoelectric systems that are inaccessible through conventional high-temperature processing routes. Such hybridization facilitates direct printing onto a wide range of flexible substrates (including polymer films, textiles, and paper), thereby enabling conformal contact with human skin and highlighting strong potential for wearable thermoelectric applications^[27,31,76]. For example, hybrid thermoelectric films composed of multiwall carbon nanotubes (MWCNTs) and chitin nanocrystals (ChNCs) have been successfully fabricated on cellulose paper substrates via screen printing^[31]. As naturally derived nanomaterials extracted from shrimp and crab shells, ChNCs impart intrinsic biocompatibility to the printed devices while preserving functional thermoelectric performance^[31]. Collectively, these examples demonstrate that the compatibility of screen printing with organic and hybrid thermoelectric materials is not incidental, but

fundamentally enabled by its low-temperature, rheology-governed processing characteristics.

By extending the screen-printing processing window beyond rigid inorganic systems to encompass flexible, biocompatible, and hybrid materials, screen printing establishes a versatile manufacturing interface for emerging thermoelectric applications, particularly in wearable and human-centric energy harvesting. Future progress will require concurrent enhancement of σ and thermal stability while preserving low-temperature processability, thereby enabling the development of integrated hybrid organic-inorganic printing platforms for scalable TED fabrication.

Processing parameters defining material compatibility and printability

The material compatibility of screen printing across diverse thermoelectric systems can be rationalized within a unified processing window defined by three interrelated parameters: ink rheology, particle attributes, and interfacial chemistry^[20,29,32,34]. Rather than being material-specific, printability arises from the dynamic balance among viscous, capillary, and interfacial forces that govern ink transfer, mesh filling, and pattern fidelity during the printing process^[82]. This balance can be quantitatively described using dimensionless relationships that couple surface tension (γ), viscosity (η), and printing speed (U). In particular, the capillary number (Ca) provides a generalized framework for predicting printable regimes across different material systems, thereby establishing a process-based criterion for screen-printing compatibility^[82]. Here,

$$Ca = \frac{\eta U}{\gamma}$$

Particle size and morphology play a dual role within this processing framework. They influence not only the ability of the ink to infiltrate the screen mesh and form continuous, thickness-controlled films, but also the microstructural evolution during post-printing densification, which ultimately governs thermoelectric transport properties^[47,83]. Carefully engineered particle size distributions facilitate uniform film formation while preserving critical microstructural features, such as grain boundaries and hierarchical architectures, that contribute to reduced κ_i and optimized carrier transport^[20]. For example, Sb_2Te_3 inks formulated with smaller particle sizes yield films with superior thickness uniformity and enhanced thermoelectric performance compared with those derived from coarser powders, underscoring the importance of particle-size-controlled film formation^[33].

Interfacial modification further broadens the printable processing window by mitigating the intrinsic porosity and weak interparticle contacts commonly observed in screen-printed films^[34,41]. The incorporation of organic binders and conductive polymers can enhance film continuity and reduce porosity; for example, introducing acid-doped polyaniline (PANI) into Cu_2Se inks significantly decreases film porosity while simultaneously improving the power factor ($S^2\sigma$)^[83]. In parallel, inorganic nanosolders and secondary phases can facilitate densification and strengthen interfacial coupling without compromising electronic transport^[34,47]. For instance, the addition of Te into Bi-Sb-Te systems suppresses defect formation and promotes sintering, enabling screen-printed films to achieve thermoelectric performance comparable to, or even surpassing, that of conventionally processed bulk counterparts^[34,47,48]. Importantly, these strategies extend beyond simple improvements in film integrity; they enable the retention or even enhancement of thermoelectric performance through deliberate tuning of carrier filtering effects, contact resistance, and phonon scattering mechanisms.

These considerations underscore a critical distinction for thermoelectric systems: printability alone is insufficient. A truly material-agnostic processing window must not only enable pattern formation, but also preserve the microstructural features that govern thermoelectric transport. However, the establishment of

quantitative printability metrics that explicitly correlate rheological parameters with transport performance remains an open challenge for predictive thermoelectric manufacturing. Defining microstructure-preserving printability would provide a rigorous and predictive framework for translating diverse thermoelectric materials into screen-printed architectures, thereby laying the foundation for the device-level design strategies discussed in the following section.

ARCHITECTURE DESIGN OF DEVICES ENABLED BY SCREEN PRINTING

Beyond material compatibility, the defining advantage of screen printing lies in its concurrent control over film thickness and lateral resolution, which together establish a continuous geometric design space for TEDs^[20,21]. Rather than constituting two discrete categories, film-based and bulk-like architectures can be regarded as limiting cases within this continuum, spanning from planar thin-film geometries with high pattern fidelity to vertically stacked, thick architectures with substantial cross-plane dimensions. In film-based configurations, thermoelectric elements are laterally defined through mesh-controlled patterning and rheology-governed ink flow, enabling large-area coverage, operation under small temperature differences (ΔT s), and seamless integration with flexible substrates^[35,54]. By contrast, bulk-like architectures are realized through layer-by-layer deposition of thick thermoelectric units, facilitating three-dimensional (3D) stacking, increased leg thickness, and improved tolerance to large thermal gradients^[21,84]. This geometry-enabled design flexibility positions screen printing as a versatile platform for tailoring TED architectures to application-specific requirements, as illustrated in Figure 3^[20,21,31,37,66,85]. Table 2 summarizes the most recent screen-printed TEDs.

Film-based architectures

Film-based TEDs represent the planar limit of the screen-printing design space and are typically fabricated on flexible substrates to enable conformal integration with curved or soft surfaces. Their lateral geometry facilitates large-area coverage and efficient operation under small ΔT s, making them particularly well-suited for body-heat harvesting and distributed thermal sensing applications. For example, wearable CuAgSe-based arrays printed on textile substrates demonstrate the feasibility of screen-printed thermoelectrics for body-heat harvesting, highlighting the compatibility of planar architectures with flexible and fabric-based platforms (nanofiber membranes, PI, and glass fiber fabrics), as shown in Figure 3A^[20]. Beyond energy harvesting, the high pattern fidelity enabled by mesh-controlled printing allows thermoelectric elements to be integrated into circuit-like layouts. Pattern-defined thermoelectric tracks fabricated from printable composite inks composed of ChNCs and MWCNTs illustrate how thermoelectric functionality can be embedded within electronic architectures, thereby enabling multifunctional energy-harvesting and sensing platforms, as shown in Figure 3B^[31]. At higher pattern resolutions, micro-thermoelectric generators with radially defined p-n geometries ($\text{Sb}_2\text{Te}_3/\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$), shown in Figure 3C, further demonstrate the capability of screen printing to produce compact, device-level architectures while retaining the advantages of planar heat spreading^[85].

Collectively, these examples reveal a resolution-dependent functional regime: low-resolution, large-area patterns tailored for wearable and distributed applications; intermediate-resolution layouts enabling circuit-level integration; and high-resolution micro-architectures designed for compact energy harvesting. This pattern-enabled design flexibility represents a defining feature of screen-printed film-based thermoelectrics, offering a direct pathway to match device geometry with application-specific thermal conditions. Nevertheless, scaling planar architectures toward higher power densities (ω) while preserving mechanical compliance remains a central challenge for wearable and distributed thermoelectric systems.

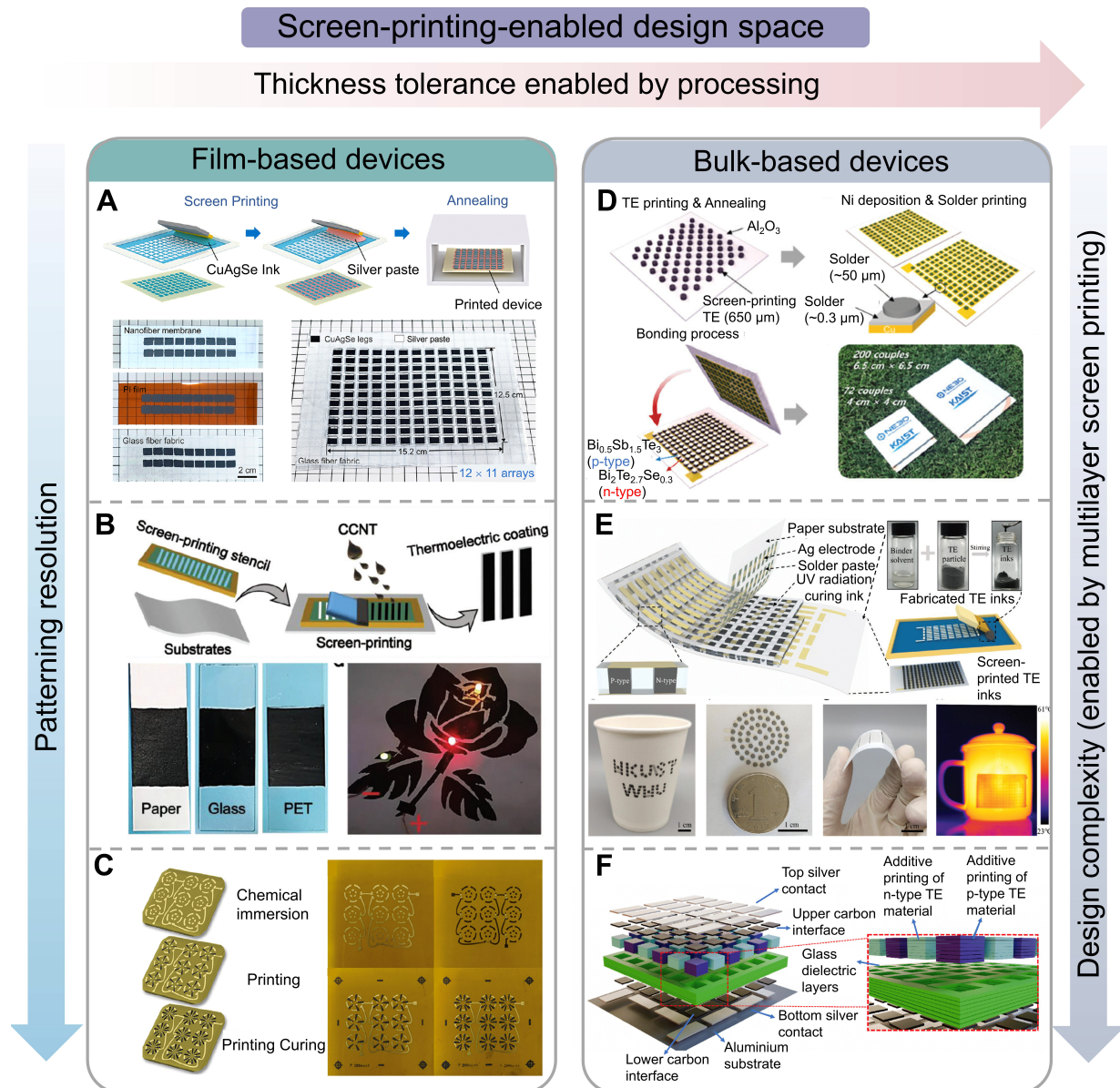


Figure 3. Screen-printing-enabled geometric design space for TEDs. Film-based architectures: (A) Wearable CuAgSe thermoelectric arrays fabricated on flexible substrates for body-heat harvesting. Reproduced with permission^[20]. Copyright 2025, Wiley; (B) Pattern-defined thermoelectric tracks demonstrating circuit-level integration on diverse substrates. Reproduced under a Creative Commons Attribution 4.0 International License^[31]. Copyright 2022, Wiley; (C) High-resolution micro-thermoelectric generators featuring radially defined p-n geometries. Reproduced with permission^[85]. Copyright 2019, Elsevier; Bulk-based architectures: (D) Vertically integrated p-n arrays on ceramic substrates enabled by layer-by-layer printing and hybrid microfabrication. Reproduced with permission^[37]. Copyright 2017, Royal Society of Chemistry; (E) Semi-flexible multilayer TEDs fabricated on paper-based substrates. Reproduced with permission^[66]. Copyright 2023, Wiley; (F) Stacked thermoelectric modules incorporating interfacial layers for contact-resistance reduction. Reproduced under a Creative Commons Attribution 3.0 International License^[21]. Copyright 2025, Royal Society of Chemistry. CCNT: Chitin nanocrystals/multiwalled carbon nanotube; PET: polyethylene terephthalate; TE: thermoelectric; UV: ultraviolet.

Bulk-based architectures

Bulk-like TEDs represent the thickness-dominated limit of the screen-printing design space, where cross-plane heat transport and multilayer stacking enable higher ω and operation under larger ΔT s. In this regime, device performance is determined not only by intrinsic material properties but also by structural parameters such as the number of printed layers, leg thickness, and interfacial engineering. As illustrated in Figure 3D, thermoelectric legs fabricated via screen printing can be integrated with sputtered electrodes and

Table 2. Summary of screen-printed TEDs

Architecture	$\Delta T_{\max}$ (K)	Pairs	P (mW)	ω (mW cm ⁻²)	Ref.
Bulk-based	28	200	310	7.34	[37]
Bulk-based	25.6	72	-	6.32	[38]
Bulk-based	40	80	0.94	-	[66]
Bulk-based	50	24	-	0.04787	[86]
Bulk-based	10	60	-	0.069	[84]
Bulk-based	60	42	-	0.234	[54]
Bulk-based	43	50	1.22	0.067	[21]
Film-based	61.2	21	0.00011	0.00269	[30]
Film-based	29.5	800	-	0.015	[47]
Film-based	28.3	5	0.000923	0.606	[47]
Film-based	9.5	4	0.00000671	0.00472	[55]
Film-based	68	-	-	0.51	[44]
Film-based	10	-	0.24	0.000024	[87]
Film-based	48.3	5	0.00631	-	[40]
Film-based	80	4	0.054	18.8	[34]
Film-based	48	50	0.114	0.514	[85]
Film-based	105	1	0.0271	3.265	[43]
Film-based	30	4	0.0032	2.2	[49]
Film-based	110	13	-	0.321	[50]
Film-based	75	2	0.00019	-	[51]
Film-based	188.4	30	1.26	-	[42]
Film-based	80.7	21	0.37	-	[52]
Film-based	20	5	-	0.69	[53]
Film-based	100	8	-	0.00238	[83]
Film-based	97.5	6	0.84	27	[48]
Film-based	14.1	4	-	0.351	[35]
Film-based	35.4	4	-	2.91	[25]
Film-based	34.1	6	-	1.62	[36]
Film-based	140	4	0.000583	-	[56]
Film-based	137	8	0.000008	-	[88]
Film-based	120	8	0.000007	-	[57]
Film-based	31.4	4	0.0055	2.29	[23]
Film-based	7	132	0.002	-	[20]

The table is sorted based on the architecture type of TED. TED: Thermoelectric device; $\Delta T_{\max}$: maximum temperature difference; P : output power; ω : output power density.

conventional bonding processes on ceramic substrates, demonstrating compatibility with established microfabrication workflows and enabling densely packed p-n arrays for compact power-generation modules^[37]. Beyond rigid platforms, vertically integrated multilayer architectures can also be realized on flexible or paper-based substrates, producing semi-flexible devices that retain the advantages of thickness-controlled thermoelectric legs. Figure 3E shows flexible TEDs comprising thermoelectric arrays (p-type Bi_{0.5}Sb_{1.5}Te₃ and n-type Bi₂Te_{2.7}Se_{0.3}) fabricated by screen printing on printed copy paper substrates^[66]. Such architectures underscore the capability of screen printing to translate bulk-like device concepts into

mechanically compliant formats. Importantly, multilayer designs also offer an effective strategy to mitigate one of the principal limitations of printed thermoelectrics (namely, high contact resistance) by incorporating engineered interfacial layers and conductive interconnects. For example, the introduction of carbon-based interlayers reduces contact resistance and enables milliwatt-level power output from stacked screen-printed devices, as shown in Figure 3F^[21].

These examples delineate a thickness-dependent functional regime in which increasing the number of printed layers and leg thickness enhances cross-plane thermal gradients and ω , while interfacial engineering critically determines electrical continuity and overall device efficiency. Together with the planar architectures discussed above, bulk-like configurations complete the continuous geometric design space enabled by screen printing, offering a scalable pathway from flexible, low-temperature-gradient systems to compact, high-output thermoelectric modules. Despite these advances, contact resistance remains a central challenge, underscoring the urgent need to develop low-resistance, thermally stable interlayers to realize high-efficiency multilayer thermoelectric modules.

DECISION-MAKING FRAMEWORK FOR APPLICATION-DRIVEN DESIGN

Thermoelectric applications can be broadly categorized into three representative regimes according to their dominant operational constraints: wearable and low-grade heat harvesting, Internet of Things (IoT) and self-powered nodes, and industrial heat-flux recovery. Rather than prescribing fixed device architectures, a decision-making framework can be constructed by systematically mapping these application-specific constraints onto the geometric design space enabled by screen printing, as illustrated in Figure 4.

For wearable and low-grade heat-harvesting applications, the primary constraints include small ΔT s, large-area coverage, and mechanical compliance^[31,36,44,89]. These requirements favor planar, film-based architectures fabricated on flexible substrates, where lateral patterning enables distributed thermoelectric arrays with precisely controlled pattern fidelity^[20,29,48]. For example, because wearable thermoelectric systems typically operate under low ΔT s (< 10 – 20 °C), maximizing thermal contact area is more beneficial than increasing device thickness. Therefore, planar architectures are generally preferred. A representative example is a 12×11 array of CuAgSe thermoelectric legs printed on nanofiber membrane, PI film, and glass fiber fabric substrates, which provides a large contact surface and generates a stable output voltage of approximately 50 mV from body heat^[20]. Such geometries maximize surface conformability and user comfort while ensuring stable operation under low ΔT conditions, making them particularly well suited for body-heat harvesting and conformal energy-harvesting platforms^[30,50].

In contrast, IoT and self-powered node applications require higher ω within confined device footprints, typically operating under moderate thermal gradients^[38,40]. In this regime, thickness-controlled and vertically stacked architectures become advantageous, as increased leg thickness and multilayer integration enhance cross-plane heat transport and overall power output^[66,90]. A representative example is a screen-printed vertical TED comprising Ag electrodes and 160 thermoelectric legs deposited on a paper substrate, which achieves an output power of 940.8 μ W under a ΔT of 40 °C^[66]. However, this configuration introduces additional constraints, particularly increased interfacial resistance and manufacturability challenges associated with multilayer stacking. The central design challenge, therefore, lies in achieving an optimal balance among ω , electrical continuity, and scalable fabrication^[21].

For industrial heat-flux harvesting applications, system-level considerations become predominant, including manufacturing yield, cost-effectiveness, and modular integration^[11,21]. For example, an additive screen-printing strategy incorporating glass dielectric layers enabled multiple printing cycles of thermoelectric legs while maintaining structural integrity and electrical connectivity, achieving an output power of 1.22 mW

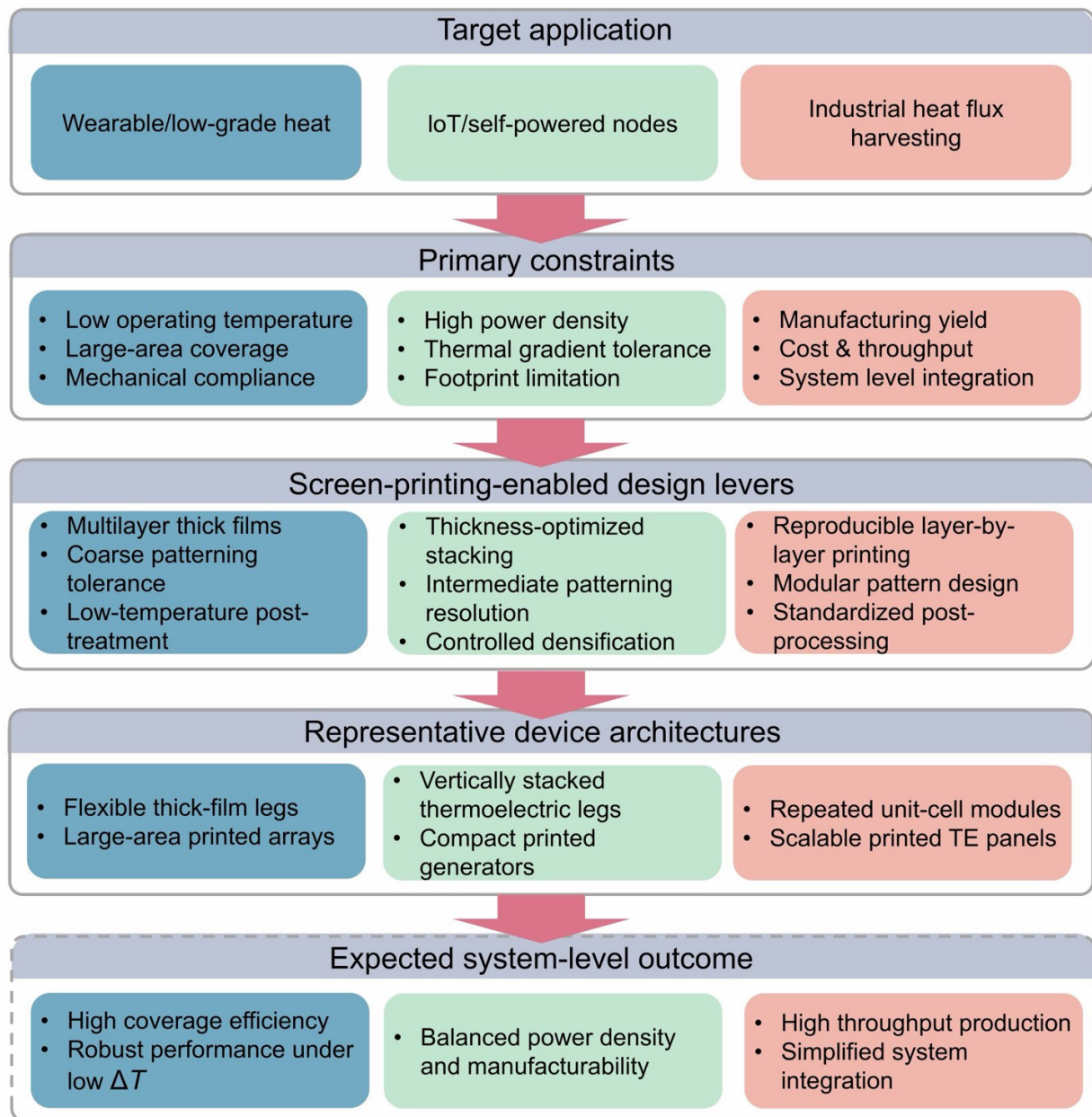


Figure 4. Decision-making framework for application-driven TED design. Schematic illustration of a constraint-driven design flow that maps key application requirements (temperature gradient, device footprint, mechanical flexibility, and target power density) onto the geometric design space enabled by screen printing (lateral resolution and thickness). This mapping facilitates the rational selection of film-based or bulk-like architectures, together with appropriate processing strategies and interfacial engineering approaches. IoT: ΔT : temperature difference; TED: thermoelectric device.

under a ΔT of 43 °C^[21]. This example demonstrates how process repeatability and modular fabrication can be leveraged to overcome conventional thickness limitations and facilitate scalable thermoelectric manufacturing^[21]. Accordingly, the emphasis shifts from optimizing individual device performance to ensuring architectural repeatability, production reliability, and seamless integration into larger thermal management and energy-conversion systems.

Collectively, these regimes demonstrate how application-specific constraints can be systematically mapped onto thickness and resolution parameters within the screen-printing design space. This constraint-driven geometric selection establishes a practical design workflow that links application requirements to

architectural configuration, thereby elevating screen printing from a fabrication technique to a predictive manufacturing interface for thermoelectric technologies. Future efforts should extend this framework toward device-system co-design, enabling quantitative performance prediction under realistic thermal boundary conditions and operational environments.

CONCLUSION AND OUTLOOK

The misalignment between laboratory-scale thermoelectric research and industrial manufacturing requirements has remained a fundamental barrier to the large-scale deployment of thermoelectric technologies. In this work, we identify screen printing as a manufacturing interface capable of bridging this gap by offering both a material-agnostic processing window and a geometry-enabled design space for TEDs. By unifying material compatibility, architectural configurability, and application-driven constraints within a single framework, we establish a decision-making strategy that elevates screen printing from a conventional fabrication technique to a predictive and scalable platform for TED development.

Despite this progress, several critical challenges must be addressed to realize manufacturing-informed thermoelectric design. First, the absence of standardized printability metrics limits the transferability of processing conditions across different material systems, underscoring the need for quantitative printability maps that correlate rheology, particle attributes, and film-formation behavior. Second, the performance of screen-printed thermoelectrics is governed by complex processing-microstructure-transport coupling that remains insufficiently understood; establishing a predictive theoretical framework for this interdependence is therefore essential to ensure reproducibility and scalable optimization. Third, multilayer architectures introduce additional interfacial resistance that constrains overall device efficiency, highlighting the necessity for systematic interlayer engineering and the development of scaling laws governing electrical and thermal contacts. Finally, long-term reliability under cyclic thermal and mechanical loading remains largely unexplored and will be crucial for the practical deployment of ink-processed thermoelectric systems.

Looking forward, the advancement of screen-printed thermoelectrics will require coordinated progress in several key areas:

(1) Establishing quantitative printability metrics. The development of standardized printability metrics that link ink rheology, particle characteristics, and printing conditions with film quality and thermoelectric performance will be essential for improving reproducibility and accelerating process optimization.

(2) Building process-structure-transport coupling theories. Future research should establish rigorous frameworks that correlate processing parameters with microstructure evolution and thermoelectric transport properties. Such understanding will facilitate predictive design rather than empirical optimization of screen-printed thermoelectric materials.

(3) Developing interface-engineered device architectures. Advanced multilayer architectures require effective strategies to reduce contact resistance and improve interfacial transport. Interface engineering will therefore play a critical role in enabling high-performance and scalable TEDs.

(4) Enhancing long-term reliability and manufacturability. Reliability-oriented device design, including stability under thermal cycling, mechanical deformation, and long-term operation, will be crucial for translating laboratory-scale demonstrations into practical technologies.

(5) Enabling manufacturing-informed thermoelectric design. Beyond incremental improvements in materials and device configurations, the emergence of manufacturing-informed thermoelectric design has

the potential to fundamentally reshape how thermoelectric technologies are conceived, engineered, and deployed. By integrating quantitative printability metrics, process-structure-transport coupling, and geometry-driven architectural strategies, screen printing facilitates a shift from material-centric optimization toward system-aware, multi-scale design. This paradigm creates new opportunities for digital manufacturing, high-throughput device prototyping, and data-driven optimization of thermoelectric modules tailored to specific thermal boundary conditions and operational environments.

In the long term, the convergence of scalable printing, predictive modelling, and modular device integration may enable thermoelectric technologies to transition from laboratory demonstrations to deployable energy-harvesting and thermal-management systems. In this context, screen printing should be regarded not merely as a fabrication technique, but as a potential platform for manufacturing-enabled thermoelectric innovation.

DECLARATIONS

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Authors' contributions

Supervised the whole project: Chen, Z. G.; Shi, X. L.

Prepared the first draft: Chen, W.

Provided the constructive suggestion on the manuscript: Li, M.

Reviewed and edited the manuscript: Chen, W.; Chen, Z. G.; Shi, X. L.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (Version 5.5, Release Date: 2026-04-23) was used for language editing, the icons of manufacturing, smartwatch, earphone, skin patches, and smart gloves in the Graphical Abstract were generated specifically for this work using the OpenAI ChatGPT (Version 5.5, Release Date: 2026-04-23) image-generation tool. The tools did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Chen, Z. G. is the Guest Editor of the Special Topic “*Stretchable Thermoelectric: Strategies, Performances, and Applications*” and an Editorial Board Member in *Soft Science*. He had no involvement in the review or editorial process of this manuscript, including, but not limited to, reviewer selection, evaluation, or the final decision, while the other authors have declared no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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