High-performance flexible thermoelectrics via nanobinder-assisted screen printing

Journal:	*Materials Lab*
Manuscript ID	MATLAB-2024-0020.R1
Manuscript Type:	Highlight
Date Submitted by the Author:	17-Jan-2025
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Keywords:	Flexible thermoelectrics, Bi2Te3, Nanobinder-assisted fabrication, Screen printing, Wearable electronics
Speciality:	Thermoelectrics

High-performance flexible thermoelectrics via nanobinder-assisted screen printing

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Abstract

Flexible thermoelectric devices (F-TEDs) have garnered significant attention for their potential applications in wearable electronics, by leveraging the human-environment temperature gradient for power generation and utilizing tiny electrical signal for cooling. Traditional thermoelectric film fabrication processes are hindered by limited scalability and insufficient mechanical stability, primarily due to energy-intensive and complex procedures. In this highlight, we review an innovative nanobinder-assisted screen printing method developed by Chen *et al.*, which integrates solvothermal synthesis and scalable fabrication to produce high-performance flexible thermoelectric films. This strategy employs Te nanorods as "nanobinders" to enhance flexibility and mechanical durability of Bi_2Te_3 nanoplates. The films produced exhibit an impressive figure of merit (*ZT*) of about 1.3 at 303 K and retain excellent mechanical stability through 1,000 bending cycles. Moreover, the assembled F-TEDs demonstrate 1.2 mW cm^{-2} power density with a cooling temperature variation of 11.7 K, underscoring their applicability in advanced wearable power systems and integrated circuit cooling. This scalable, cost-effective approach establishes a robust platform for flexible thermoelectrics and presents a pathway for exploring new material combinations.

Keywords

Flexible thermoelectrics, Bi_2Te_3, Nanobinder-assisted fabrication, Screen printing, Wearable electronics

Main text

As wearable electronic devices become increasingly ubiquitous, the demand for reliable and sustainable charging and cooling solutions continues to grow rapidly.[1] F-TEDs, or flexible thermoelectric devices, are gaining attention due to their potential to harness the temperature gradient between the external environment and human body for electricity generation or to enable cooling through targeted electrical power input.[2-4] This underscores the need for thermoelectric materials that combine high performance, flexibility, and stability under ambient conditions.[5]

Inorganic materials, particularly bismuth telluride (Bi_2Te_3), are renowned for their exceptional thermoelectric properties at room temperature, establishing them as prime candidates for F-TEDs.[6] Despite a remarkable dimensionless figure of merit (*ZT*) of 1.2 achieved through (00*l*)-oriented Bi_2Te_3 films, the fabrication processes remain energy-intensive and complex, limiting their scalability. While screen printing provides a cost-effective and scalable approach, challenges persist in improving the densification and flexibility of films.[7] Furthermore, optimizing Bi_2Te_3's thermoelectric performance necessitates precise powder design—balancing particle size for (00*l*) orientation with initial thermoelectric efficiency. However, larger particle sizes introduce risks of cracking, compromising flexibility and stability.[8] Thus, addressing these barriers is critical for advancing high-performance, Bi_2Te_3-based flexible films, given their immense application potential.

A recent study by Chen *et al*., published in *Science*, introduced an a pioneering and economical strategy that leverages solvothermal synthesis, together with screen printing to fabricate flexible thermoelectric films based on inorganic materials.[9] The films, composed of highly oriented Bi_2Te_3 nanoplates and reinforced with Te nanorods that act as "nanobinders", demonstrate superior thermoelectric performance, exceptional flexibility, cost-effectiveness, and scalability.

To fabricate flexible thermoelectric films, Chen *et al*. synthesized high-performance Ag-doped Bi_2Te_3 nanoplates via solvothermal synthesis and mixed them with Te nanorods to create ink suitable for screen printing, as schematically shown in **Figure 1a**. The Bi_2Te_3 nanoplates provide high (00*l*) orientation and superior thermoelectric performance, while the Te nanorods serve as "nanobinders", enhancing film density and flexibility. In particular, the introduction of Te plays crucial roles in decoupling the electrical and thermal transports for further optimizing the thermoelectric performance of Bi_2Te_3 (**Figure 1b**). Firstly, the incorporation of Te nanorods establishes energy-filtering barriers that increase the Seebeck coefficient (S) while retaining very high levels of electrical conductivity (σ), leading to an impressive power factor ($PF = S^2\sigma$) of 18.5 μW cm^{-1} K^{-2}. Secondly, Te addition in Bi_2Te_3 introduces lattice defects that strengthen phonon scattering greatly, thereby causing a reduction in lattice thermal conductivity (κ_l) to about 0.19 W m^{-1} K^{-1}. This modification results in a *ZT* of approximately 1.3 at 303 K, establishing the material as a leading candidate in the field of flexible thermoelectrics. Furthermore, mechanical tests show that the films exhibit only a 2% performance loss after enduring 1,000 bending cycles, highlighting their exceptional flexibility and durability.

More importantly, Chen *et al*. designed the high-performance p-type and n-type flexible thermoelectric films obtained in the previous step into F-TED, as depicted schematically in **Figure 1c**. Under a temperature gradient of 20 K, the output power density of the assembled F-TED reaches as high as 1.2 mW cm^{-2}, with the corresponding normalized power density exceeding 3 μW cm^{-2} K^{-2}, significantly outperforming other printing-based inorganic thermoelectric devices. On the other hand, the F-TED demonstrates a cooling temperature difference of 11.7 K when the input current is 84 mA, demonstrating its promising application potential for cooling advanced integrated circuit (IC) devices.

In conclusion, the nanobinder-assisted screen printing method offers significant advantages in terms of thermoelectric performance, flexibility, scalability, and cost- and time-efficiency, thereby making it a compelling approach for wearable power generation and cooling applications. The resulting films, composed of highly oriented Bi_2Te_3 nanoplates reinforced with Te nanorods functioning as "nanobinders", exhibit superior thermoelectric performance and exceptional mechanical flexibility. These attributes not only highlight their potential as a promising "hexagonal warrior" (**Figure 1d**) in the field of flexible thermoelectrics but also demonstrate its potential for large-scale production of flexible thermoelectric materials, including other inorganic film systems. Developing suitable nanobinders for other high-performance thermoelectric systems, such as SnSe-based materials,[10] could further pave the way for achieving even higher thermoelectric performance in the future.

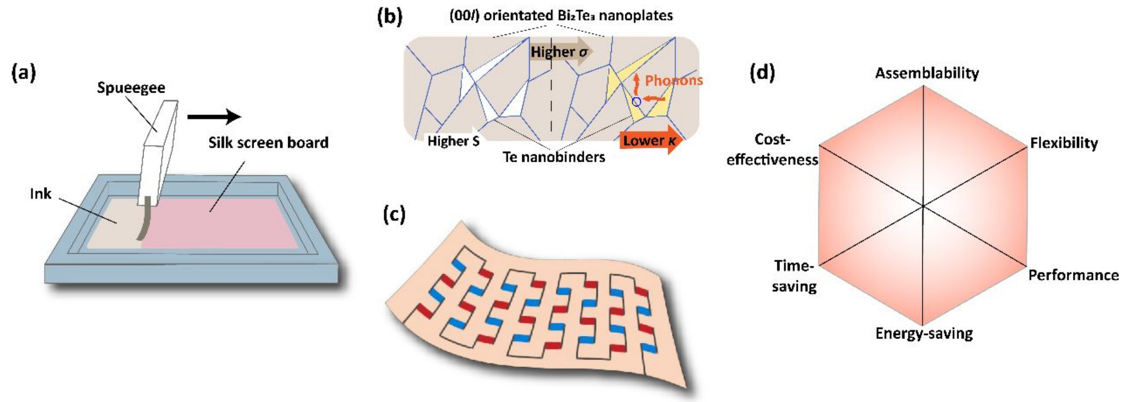

Figure 1. (**a**) Schematic diagram illustrating the screen-printing process. (**b**) Structural illustration of screen-printed Bi_2Te_3 thin films, highlighting their (00*l*)-oriented alignment and morphology (**c**) Structure of screen-printed flexible thermoelectric device. (**d**) Conceptual schematic depicting the constructed flexible thermoelectrics as analogous to a "hexagonal warrior".

Acknowledgments

This work was supported by the National Science Fund for Distinguished Young Scholars (51925101) and Tencent Xplorer Prize, the National Natural Science Foundation of China (52450001 and 22409014), the Natural Science Foundation of Shandong Province, China (No. ZR2022ME030), the China National Postdoctoral Program for Innovative Talents (BX20230456), and China Postdoctoral Science Foundation (2024M754057). This study was also supported by the funding for faculty visiting and research program of Shandong province-affiliated universities.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

This highlight was drafted by Dr. Chengchao Hu and revised by Dr. Bingchao Qin and Prof. Li-Dong Zhao. All authors have approved the final version of the manuscript.

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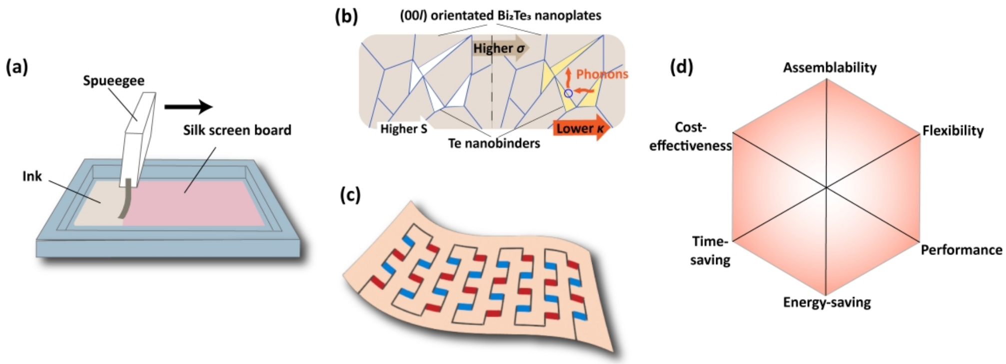

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