

Breaking the transport trade-off in Bi_2Te_3 films via interface reconstruction and magnetic coupling

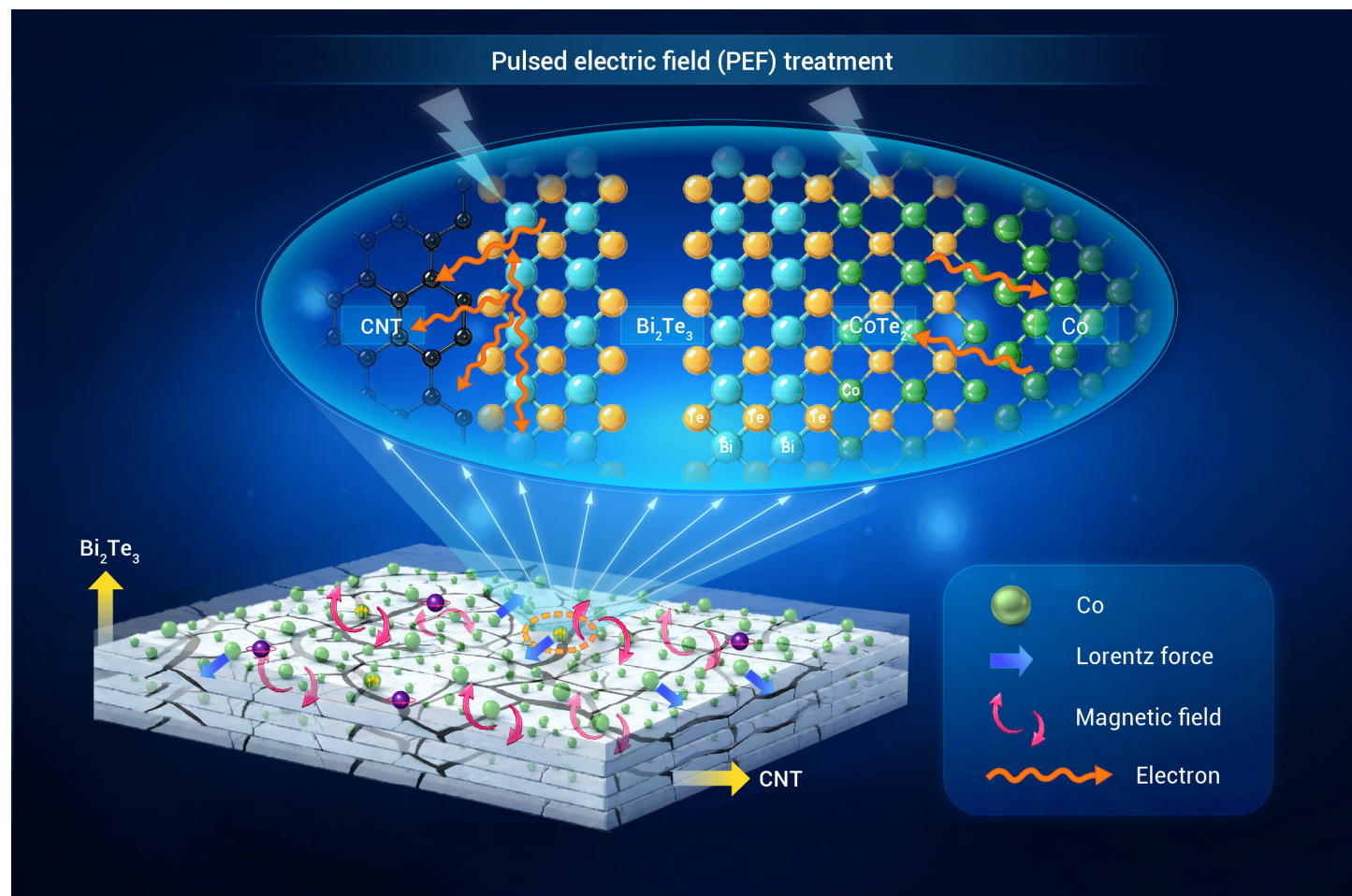
Mingdi Lan,^{1,4} Lifeng Jiang,^{2,4} Ming Liu,^{1,*} Muchun Guo,³ Pengyuan Zhang,¹ Dongbo Wang,¹ Yuke Zhu,¹ Huijun Kang,^{2,*} and Jiehe Sui^{1,*}

*Correspondence: mingliu@hit.edu.cn (M.L.); kanghuijun@dlut.edu.cn (H.K.); suijiehe@hit.edu.cn (J.S.)

Received: June 15, 2026; Accepted: August 20, 2026; Published Online: August 20, 2026; <https://doi.org/10.59717/j.tip.2026.100014>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Bi_2Te_3 films are promising for compact thermoelectric generators and light detectors.
- PEF treatment crystallizes key interfaces and reduces carrier scattering.
- Magnetic Co nanoparticles tune carrier transport through magnetoelectric interaction.
- The optimized film improves thermoelectric output and ultraviolet photodetection.

Breaking the transport trade-off in Bi_2Te_3 films via interface reconstruction and magnetic coupling

Mingdi Lan,^{1,4} Lifeng Jiang,^{2,4} Ming Liu,^{1,*} Muchun Guo,³ Pengyuan Zhang,¹ Dongbo Wang,¹ Yuke Zhu,¹ Huijun Kang,^{2,*} and Jiehe Sui^{1,*}

¹Key Laboratory of Precision Hot Forming change to National Key Laboratory of Precision Hot Forming, Harbin Institute of Technology, Harbin 150001, China

²Key Laboratory of Solidification Control and Digital Preparation Technology, School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China

³School of Materials Science and Engineering, Xihua University, Chengdu 610039, China

⁴These authors contributed equally

*Correspondence: mingliu@hit.edu.cn (M.L.); kanghuijun@dlut.edu.cn (H.K.); suijiehe@hit.edu.cn (J.S.)

Received: June 15, 2026; Accepted: August 20, 2026; Published Online: August 20, 2026; <https://doi.org/10.59717/j.tip.2026.100014>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

Citation: Lan M., Jiang L., Liu M., et al. (2026). Breaking the transport trade-off in Bi_2Te_3 films via interface reconstruction and magnetic coupling. *The Innovation Physics* 1:100014.

Bi_2Te_3 films play a pivotal role in semiconductor applications, particularly for thermoelectric and photo-thermoelectric energy conversion. Doping is the primary method to regulate their functional properties, yet parameter trade-offs cap the achievable power factor and detectivity. Here, we introduce a synergistic strategy combining pulsed electric field (PEF) treatment with magnetic nanoparticle incorporation to achieve the decoupling of electrical transport parameters. PEF treatment facilitates the crystallization of the carbon nanotube (CNT)/ Bi_2Te_3 interface and the formation of a coherent Co/CoTe₂/ Bi_2Te_3 interface, which increases carrier transport pathways while reducing carrier scattering, significantly enhancing carrier mobility. Magnetic Co nanoparticle incorporation induces magnetoelectric interaction, boosting the density-of-states effective mass, while both Co nanoparticles induce carrier injection, increasing the carrier concentration. Consequently, a synergistic enhancement of carrier mobility, density-of-states effective mass, and carrier concentration is realized in Bi_2Te_3 film. Furthermore, we fabricated single-leg thermoelectric and optoelectronic devices that achieve high output power density of 10.26 W m^{-2} at a temperature difference of 39 K and excellent detectivity of 5.95×10^9 Jones at 365 nm light illumination, respectively. This work highlights the significant role of interface modulation and magnetoelectric interaction in regulating electrical transport properties.

INTRODUCTION

Since the discovery of Bi_2Te_3 as a functional semiconductor in the early 1950s, it has shown great promise in the fields of thermoelectrics, photo-thermoelectrics, and spintronics due to its unique chemical bonding mechanism and electronic band structure.^{1,2} Nowadays emerging industries such as 5G communications, wearable electronics, and the Internet of Things call for miniaturized devices based on high-performance Bi_2Te_3 films.³ Doping has been widely employed to tailor the performance of Bi_2Te_3 films, and dopant-induced electronic property tuning plays a critical role in enhancing thermoelectric and photo-thermoelectric performance.⁴⁻⁶ The key quantities of electrical transport properties are the power factor (PF , $PF \propto m^* \mu n^{-1/3}$) for thermoelectric performance, and the detectivity (D^* , $D^* \propto m^* \mu^{1/2} n^{-1/6}$) for photo-thermoelectric performance. They are closely related to the density-of-states effective mass m^* , carrier mobility μ , and carrier concentration n .^{7,8} Therefore, it is only through the synergistic regulation of μ , m^* and n that PF and D^* can be enhanced. However, an enhanced m^* induced by dopants often results in reduced μ .⁹ Doping that optimizes n tends to reduce μ .¹⁰ Thus, optimizing thermoelectric and photo-thermoelectric performance remains a significant challenge.

To address the limitation of dopant-induced electronic property modulation, additional degrees of freedom have been introduced to enhance μ and overall performance. For instance, texture modification by the synthesis of single crystals and increasing the grain size in anisotropic Bi_2Te_3 is an important approach to enhance μ .¹¹⁻¹⁴ However, the relatively long preparation process and the limited mechanical robustness of single crystals still pose challenges for their practical implementation.^{2,15} The complexity of the process for increasing grain size also hinders its scale-up application.¹⁶ Moreover, texture modification has no effect on the electronic band structure or constituents, and thus does not affect m^* and n .¹⁷ Another method to enhance μ is the embedding of high-mobility carbon nanotubes (CNT) as

additional carrier transport channels in Bi_2Te_3 , as proposed by Jin et al.¹⁸ Nevertheless, CNT incorporating does not alter the electronic band structure, and thus the m^* remains unchanged.^{3,18} Meanwhile, an amorphous layer forms at the CNT/ Bi_2Te_3 interface, restricting a substantial improvement in μ .¹⁹ In this regard, eliminating the amorphous layer to enhance mobility while introducing other additives that increase the m^* and regulates n are the best choices for further performance improvement of Bi_2Te_3 films.

In bulk thermoelectrics, the electrical transport properties can be effectively decoupled by magnetic nanoparticles incorporation.^{20,21} Embedding $\text{BaFe}_{12}\text{O}_{19}$ nanoparticles into $\text{Ba}_{0.3}\text{In}_{0.3}\text{Co}_4\text{Sb}_{12}$ matrix induces the trapping of electrons below the Curie temperature (T_C) and the release of the trapped electrons above T_C via a magnetic transition of $\text{BaFe}_{12}\text{O}_{19}$ from ferromagnetism to paramagnetism, simultaneously enhancing n and Seebeck coefficient despite their conventional trade-off.²² Co magnetic nanoparticles in $\text{Ba}_{0.3}\text{In}_{0.3}\text{Co}_4\text{Sb}_{12}$ give rise to electron multiple scattering, increasing scattering parameters and Seebeck coefficient. Moreover, the introduction of CrSb magnetic particles into bulk Bi_2Te_3 induces a drag effect that increases the m^* and thermoelectric performance.²³ Inspired by magnetoelectric interaction in bulk thermoelectrics, introducing suitable magnetic nanoparticles into Bi_2Te_3 films may offer more advanced routes for tailoring electrical transport properties. This could expand the tuning space and thus create new opportunities for enhancing PF and D^* .

In this work, a synergistic optimization of the electrical transport properties in CNT embedded Bi_2Te_3 films has been realized by modulating interfaces and introducing magnetoelectric interaction. The crystallized CNT/ Bi_2Te_3 interface and the coherent Co/CoTe₂/ Bi_2Te_3 interface are formed by a pulsed electric field (PEF) treatment. This optimizes carrier transport pathways while suppressing interfacial scattering, significantly enhancing μ . The incorporation of magnetic Co nanoparticles gives rise to magnetoelectric interaction and carrier injection, contributing to an increased m^* and n . Moreover, the in-situ formed CoTe₂ also induces carrier injection to increase n . As a result, we have achieved synergistic enhancement of μ , n , and m^* through PEF treatment and magnetic nanoparticle incorporation. A high PF of $51.68 \mu\text{W}\cdot\text{cm}^{-1}\cdot\text{K}^{-2}$ at room temperature is obtained in the PEF-Co/CNT/ Bi_2Te_3 film (Figure 1A).^{12,24-40} The single-leg thermoelectric and optoelectronic devices achieve a high output power density of 10.26 W m^{-2} at a temperature difference of 39 K (Figure 1B)⁴¹⁻⁵⁰ and an excellent D^* of 5.95×10^9 Jones under 365 nm light illumination (Figure 1C, calculated by Formula 1), respectively.⁵¹⁻⁵⁴ This work demonstrates that the synergistic combination of interface modulation and magnetoelectric interaction effectively decouple electrical transport parameters, enabling high-performance Bi_2Te_3 films for thermoelectric power generation and photo-thermoelectric detection.

MATERIALS AND METHODS

Choice of the SiO_2 substrate

First, SiO_2 is an electrically insulating material. The insulating substrate helps prevent the applied PEF from being shunted through the substrate, ensuring that the electric-field effect is effectively introduced into the CNT/Co/ Bi_2Te_3 film. Second, SiO_2 is an amorphous substrate, the growth orientation of Bi_2Te_3 film on the SiO_2 is less affected by substrate-induced effects. Based on these considerations, SiO_2 was selected because it provides good electrical insulation during PEF treatment and minimizes the influence of the substrate on the growth orientation of the Bi_2Te_3 film.

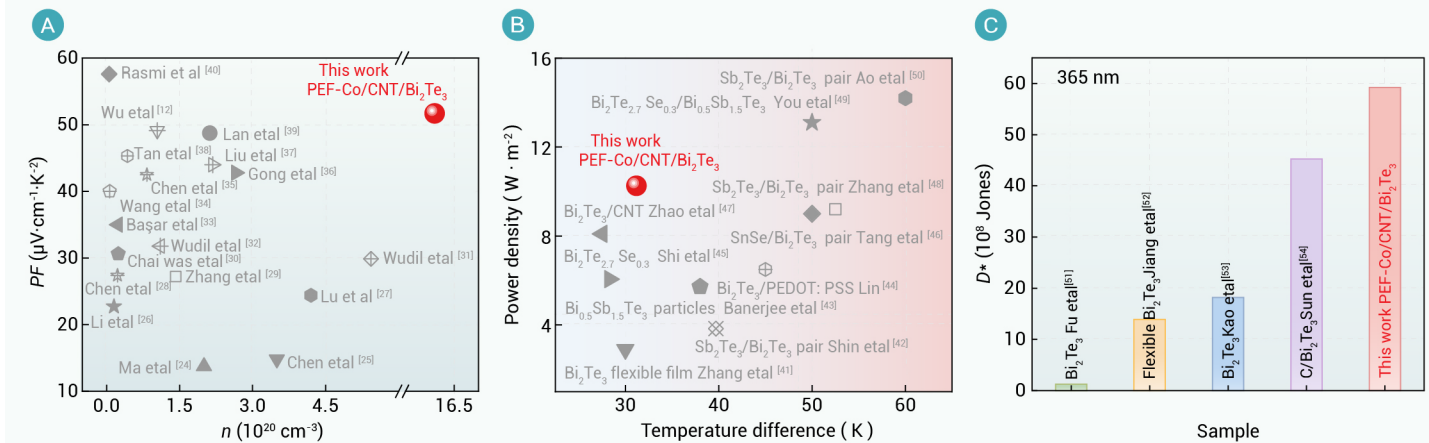


Figure 1. Superior thermoelectric and photodetection performance of the PEF-Co/CNT/Bi₂Te₃ film (A) Comparison of room-temperature power factor as a function of carrier concentration for the PEF-Co/CNT/Bi₂Te₃ film and previously reported Bi₂Te₃-based materials. (B) Comparison of output power density versus temperature difference for the PEF-Co/CNT/Bi₂Te₃ film device and previously reported Bi₂Te₃-based film generators. (C) Comparison of detectivity under 365 nm light illumination for the PEF-Co/CNT/Bi₂Te₃ film device and previously reported Bi₂Te₃-based photodetectors from the ultraviolet to far-infrared regions.

CNT substrate by spin coater

CNT solution with mass concentration of 0.02% is spin coated on the SiO₂ substrate with six successive layers by spin coater. The spin coating speed is 10000 rpm. The spin coating acceleration 2000 rpm. Each spin coating time is 90 s. After spin-coating CNT, the Bi₂Te₃ film is deposited on the substrate. The surface morphologies of the Bi₂Te₃ film and the CNT/Bi₂Te₃ film, as shown in Figure S1. The Bi₂Te₃ film and the CNT/Bi₂Te₃ film show uniform and compact morphology. Although some local surface fluctuations are observed in the CNT/Bi₂Te₃ film, the overall film surface remains compact and continuous. Therefore, the optimized CNT spin-coating process does not significantly deteriorate the smoothness or continuity of the subsequently deposited Bi₂Te₃ film.

Magnetron sputtering for Co and Bi₂Te₃ composite films

The multilayer Co/Bi₂Te₃ structure was adopted to preserve the Co nanoparticles and their magnetic performance. First, compared with co-sputtering, layer deposition can control the distribution of Co in the Bi₂Te₃ and prevent Co from completely reacting with Te to form Co-Te bonds. In previous study, co-sputtering of Co and Bi₂Te₃ was found to be easy to generate CoTe₂ due to the difference in electronegativity of Co and Te, which weakens the magnetic from metallic Co. The layer deposition of Bi₂Te₃ and Co enables Co to be embedded as discontinuous nanoparticles within the Bi₂Te₃ film. Therefore, this structure can retain magnetic moments and generate local magnetic fields, which contribute to carrier regulation and magnetoelectric interaction. Second, we previously prepared Co/Bi₂Te₃ films with three different number of layers, including 5 layers, 9 layers and 17 layers. Among them, the film with layers of 9 exhibited the best thermoelectric performance (Figure S2). Therefore, the layer of 9 was selected in the subsequent work. Finally, because Co is susceptible to oxidation when exposed to air, Bi₂Te₃ was deposited as the top layer to isolate the Co nanoparticles from direct surface exposure, thereby to preserve the magnetic performance (Bi₂Te₃ of 5 layers, Co of 4 layers).

During the magnetron sputtering process for fabricating the composite films, the base pressure is 3.0×10^{-3} Pa, the working pressure is 0.8 Pa. The Ar flow rate is 80 SCCM. The substrate temperature is 220°C. Bi₂Te₃ films are deposited by medium frequency magnetron sputtering with sputtering power of 240 W. Each Bi₂Te₃ layer is sputtered for 180 s, with five layers. Co is deposited by direct current magnetron sputtering with sputtering power of 280 W. Each Co layer is sputtered for 5 s, with four layers.

PEF treatment

Co/CNT/Bi₂Te₃ films are post-treated using PEF, as shown in Figure S3. The pulse current is 0.3 A. The pulse period is 0.1 s. The treatment time is 600 s.

TE devices and photodetector device

The size of PEF-Co/CNT/Bi₂Te₃ films is 10 mm×10 mm. The electrode in the TE device is Ag. In photodetector device, the interdigital electrodes are made of Pt. Because the work function of Pt is relatively large, it is easier to achieve self-driven operation of photodetector device. TE devices and photodetector device are all fabricated using individual n-type PEF-Co/CNT/Bi₂Te₃ films.

Interface calculation

The electronic band structures of Bi₂Te₃ and its composite structures were calculated based on density functional theory (DFT) using the Vienna Ab-initio Simulation Package (VASP). For specific details, please refer to the Supporting Information. Specific model construction parameters for simulating the internal magnetic field strength of Co/Bi₂Te₃ by COMSOL Multiphysics. The simulation was carried out using the Magnetic Fields, No Currents module. The model consisted of Co nanoparticles with a diameter of 20 nm embedded in a Bi₂Te₃ matrix represented by a cube with an edge length of 100 nm. The Co was assigned a recoil magnetic permeability of 1.05 and a remanent magnetic flux density of 0.145 T. The Bi₂Te₃ matrix was approximated as a non-magnetic material with a relative magnetic permeability of 1. Magnetic insulation with $n \cdot B = 0$ was applied as the boundary condition.

Structural and performance measurement

CNT network structure was analyzed using an Atomic Force Microscope (AFM, Nanosurf, Flex-Axiom, Switzerland). The surface and cross-sectional morphologies were analyzed by Scanning Electron Microscopy (SEM, FLASH, Apreo 2, Thermo Fisher, USA). Interface of composite film is determined by Transmission Electron Microscopy (TEM, Spectra Ultra S, Thermo Fisher, USA). The magnetic field and magnetic domain around Coare determined by Lorentz TEM (Talos f200x, Thermo Fisher, USA). CoTe₂ content were analyzed by Raman spectrometry (RM2000, Renishaw, UK; $\lambda = 532$ nm). Work function of the thin film was analyzed using Ultraviolet Photo-electron Spectroscopy (UPS, Thermo Scientific, Nexsa, USA). Magnetic hysteresis loop was analyzed using Vibrating Sample Magnetometer (VSM, LakeShore, 7404, USA).

Resistivity, Seebeck coefficient, and power factor were measured using the Seebeck Coefficient/Electric Resistance Measurement System (ZEM-3; Advance-Riko, Japan). Carrier concentration and mobility were measured by the Hall Effect Measurement System (MMR-K7250- 5RLP, USA). The open-circuit voltage and power density of the film was measured by a digital source meter (Keithley, 2450, USA), as shown in Figure S4. The heat transfer process is obtained through an infrared thermal imager (FOTRIC 3610, China). The film I_{on} and I_{off} are tested by using the photocurrent testing system (Keithley, 2400, USA), as shown in Figure S5. Under the test system

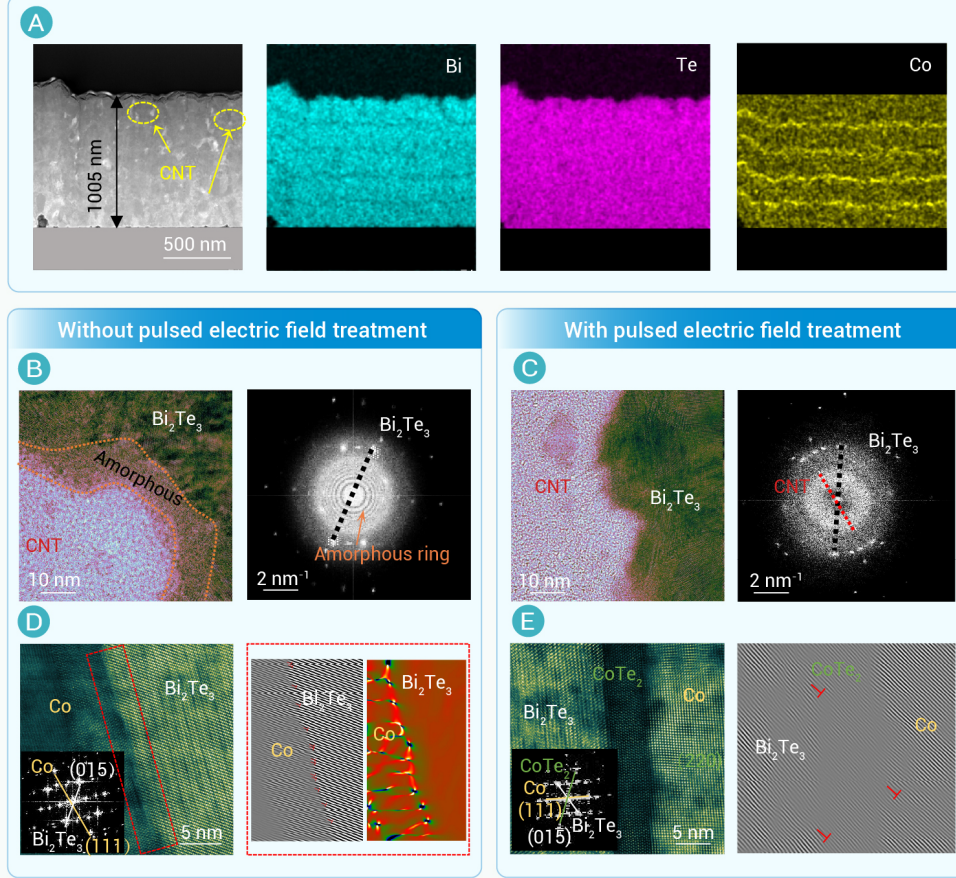


Figure 2. Microstructural characterization and interfacial features of the PEF-Co/CNT/Bi₂Te₃ film (A) Cross-section TEM image and corresponding elemental mappings of the Co/CNT/Bi₂Te₃ film. (B) The interface of CNT and Bi₂Te₃ of the Co/CNT/Bi₂Te₃ film. (C) The interface of Co and Bi₂Te₃ of the Co/CNT/Bi₂Te₃ film. (D) The interface of CNT and Bi₂Te₃ of the PEF-Co/CNT/Bi₂Te₃ film. (E) The interface of Co and Bi₂Te₃ of the PEF-Co/CNT/Bi₂Te₃ film.

Bi₂Te₃. In Bi₂Te₃ films, constructing multilayer structures can synergistically regulate the thermoelectric transport behavior, and thereby Co is incorporated as nanoscale layers into Bi₂Te₃ films in this work.^{56,57} Firstly, CNT solution was spin-coated onto a SiO₂ substrate to form a CNT film, and the individual CNTs have an average diameter of ~1.78 nm and form a network structure, as displayed in Figure S6. Secondly, nine alternating layers of Co and Bi₂Te₃ were deposited onto a CNT substrate by magnetron sputtering to form the Co/CNT/Bi₂Te₃ films with a thickness of approximately 1005 nm (Figure S7). To examine the form of Co, the I-V curve and surface morphologies were characterized. The non-Ohmic I-V behavior indicates that Co does not form a continuous metallic conduction path, otherwise, a nearly linear Ohmic response would be expected (Figure S8), and transmission electron microscopy (TEM) and atomic force microscopy (AFM) images further confirm that Co exists as nanoparticles (Figure

composed of 0.365–14 μm, (λ) light source meter (0.01 W/cm²) and photocurrent testing system (Keithley, 2400, USA), the time dependence and R of the film photodetector are tested.

Formula

$$D^* = \sqrt{(A \cdot \Delta f) / NEP} \quad (1)$$

Where A is effective area of the detector, m²; Δf is representing the frequency range that the detector can respond to, Hz; $NEP = I_n / R$, NEP is minimum optical power, W·Hz⁻¹, I_n is noise current after turning off the light source, A; R is responsivity, A·W⁻¹.

$$B(r) = \frac{\mu}{4\pi} \cdot \frac{2MsV}{r^3} \quad (2)$$

Where μ is relative permeability, 4×10⁻⁷ H·m⁻¹; M_s is saturation magnetization intensity, 1.44×10⁶ A·m⁻¹; V is volume of Co, 4.19×10⁻²⁴ m³.

$$P_{\text{density}} = P_{\text{out}} / A \quad (3)$$

Where P_{out} is output power, W; P_{density} is output power density, W·m⁻²; A is the effective device area, m².

$$EQE = R \cdot 1240 \cdot 100\% / \lambda \quad (4)$$

Where λ is response band, nm.

RESULTS AND DISCUSSION

Modified microstructures by pulsed electric field treatment

Among various ferromagnetic candidates, Co nanoparticles were selected in this study because the strong magnetic properties and easily formed as nanoscale magnetic domains. Magnetic Co nanoparticles have been proven to optimize the thermoelectric property in CoSb₃-based and Mg₃(Sb,Bi)₂-based thermoelectric materials.^{22,55} Thus, we added Co nanoparticles to introduce magnetism as an initial property optimization step in CNT embedded

S9).

Figure 2A shows the TEM image and corresponding elemental mappings of Co/CNT/Bi₂Te₃ film. The CNTs are uniformly distributed in the thin film (Figure 2A1). Cross-sectional mappings reveal that Bi and Te exhibit a homogeneous distribution throughout the Co/CNT/Bi₂Te₃ film, while Co exhibits pronounced enrichment layers (Figures 2A2-4). The Co content is determined to be approximately 1.73%. To further uncover the interfacial relationship of Bi₂Te₃ with Co and CNT, aberration-corrected scanning transmission electron microscopy (STEM) was utilized. As shown in Figure 2B1, a significant amorphous layer is observed at the CNT/Bi₂Te₃ interface. The fast Fourier transform (FFT) image shows both the Bi₂Te₃ diffraction spots and a pronounced diffuse amorphous halo (Figure 2B2), indicating the presence of the interfacial amorphous layer. As illustrated in Figure 2C1, the STEM image reveals a sharp and well-bonded interface between the Co layer and the Bi₂Te₃ matrix. The FFT pattern exhibits two distinct sets of diffraction spots (inset of Figure 2C1), originating from the Co and Bi₂Te₃ phases, confirming their different crystal orientations across the interface. Notably, the interface exhibits numerous misfit dislocations (Figure 2C2). These dislocations act to accommodate the lattice mismatch between the two phases. This structural feature is the hallmark of a semi-coherent interface, i.e., the Co/Bi₂Te₃ interface is semi-coherent. The presence of the amorphous layer and the semi-coherent interface at the boundary introduces strong scattering sources for charge carriers, which impedes carrier transport and limits a substantial increase in μ (see a schematic diagram in Figure S10).

During the fabrication of films like Zr, Co, ZnO, and Sb₂Te₃, introducing an electric field can facilitate atomic migration, modify the atomic growth orientation, and affect domain wall motion.⁵⁸⁻⁶¹ Similarly, the electrostatic force induced by PEF treatment was found to drive atomic migration at grain boundaries and promote the transformation of high-angle grain boundaries into low-angle grain boundaries in previous study on pure Bi₂Te₃ films.⁶² To modulate CNT/Bi₂Te₃ and Co/Bi₂Te₃ interfaces, we applied pulsed electric field (PEF) treatment to the as-prepared samples. After PEF treatment, the amorphous layer disappears (Figure 2D1), accompanied by the absence of the amorphous halo in the FFT image (Figure 2D2), indicating that the PEF

treatment induces crystallization of the CNT and Bi_2Te_3 interface. This enhances carrier transport pathways. Meanwhile, a CoTe_2 nanolayer forms between Co and Bi_2Te_3 , as shown in Figure 2E1. The Raman spectrum of the sample before PEF treatment exhibits only one peak associated with Co. In contrast, after PEF treatment, two distinct peaks appear, which are characteristics of Co and CoTe_2 , further confirming the existence of CoTe_2 (Figure S11).⁶³ The negligible misfit dislocations at both the Co/ CoTe_2 and $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interfaces indicates a well-defined coherent relationship between them (Figure 2E2). The PEF-induced crystallization of the CNT/ Bi_2Te_3 interface and the formation of the coherent Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interface will enhance carrier transport. Notably, during PEF treatment of the Co/CNT/ Bi_2Te_3 films, the surface temperature initially rises and then gradually stabilizes (Figure S12). The small surface-temperature increase of 3.2 K indicates that the formation of CoTe_2 is not caused by the thermally driven interfacial reaction. This is because the electric-field force provided by PEF treatment promotes atomic migration. The applied electric field exerts electrostatic force on interfacial atoms during PEF treatment. Because Co and Bi_2Te_3 have different work functions and electronic structures, charge redistribution occurs at the Co/ Bi_2Te_3 interface, leading to a localized electric-field effect near the heterointerface.⁶⁴ Therefore, the formation of CoTe_2 is attributed to an electric-field interfacial reaction induced by PEF treatment, rather than to thermally driven reaction.

Electrical transport behavior

Figure 3A shows the room-temperature carrier concentration n and mobility μ of CNT/ Bi_2Te_3 , Co/CNT/ Bi_2Te_3 and PEF-Co/CNT/ Bi_2Te_3 films. The n increases with Co addition, while PEF treatment does not change it. To probe the mechanism of the variation of n , the UPS spectrums were employed. The

work functions (φ_m) of Co (5.0 eV) and CoTe_2 (4.7 eV) are lower than that of Bi_2Te_3 (5.3 eV), indicating Ohmic contact for Co/ Bi_2Te_3 and Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interfaces (Figure 3B). Driven by the chemical potential difference, electrons will move directionally from Co and CoTe_2 to Bi_2Te_3 until a new equilibrium is established near the interface, namely carrier injection.⁶⁵ And CoTe_2 is formed in situ as atomic-level interfacial layer between Co and Bi_2Te_3 after PEF treatment. Although the CoTe_2 has a lower work function than Bi_2Te_3 , it does not introduce a large amount of additional carrier source. Therefore, the n is significantly enhanced after Co addition by carrier injection. As shown in Figure 3A, both PEF treatment and Co incorporation enhance the carrier mobility μ . The μ enhancement may be attributed to the one-dimensional tubular structure provide high-mobility transport pathways along the tube direction.⁶⁶⁻⁶⁷ However, the amorphous CNT/ Bi_2Te_3 interfacial in the untreated film hinders carrier transfer between CNTs and Bi_2Te_3 . Therefore, the μ enhancement by PEF treatment is attributed to the elimination of the amorphous layer and the formation of a coherent interface, together with the low interfacial resistance of the Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ heterointerface.

The charge-density difference is used to evaluate the interfacial charge redistribution and electronic coupling at the Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interface. The charge accumulation at the interface indicates electron transfer and orbital interaction between the interfacial components in the calculation (Figure 3C). The continuous charge redistribution across the Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interface suggests a more continuous carrier transport pathway across the heterointerface. In addition, compared with the semi-coherent interface of highly localized charge redistribution, a smoother interfacial charge distribution means a reduced interfacial transport barrier. Therefore, carriers pass through the Co/ $\text{CoTe}_2/\text{Bi}_2\text{Te}_3$ interface with less interfacial scattering. This contributes to an increased μ . The μ improvement by Co originates from the

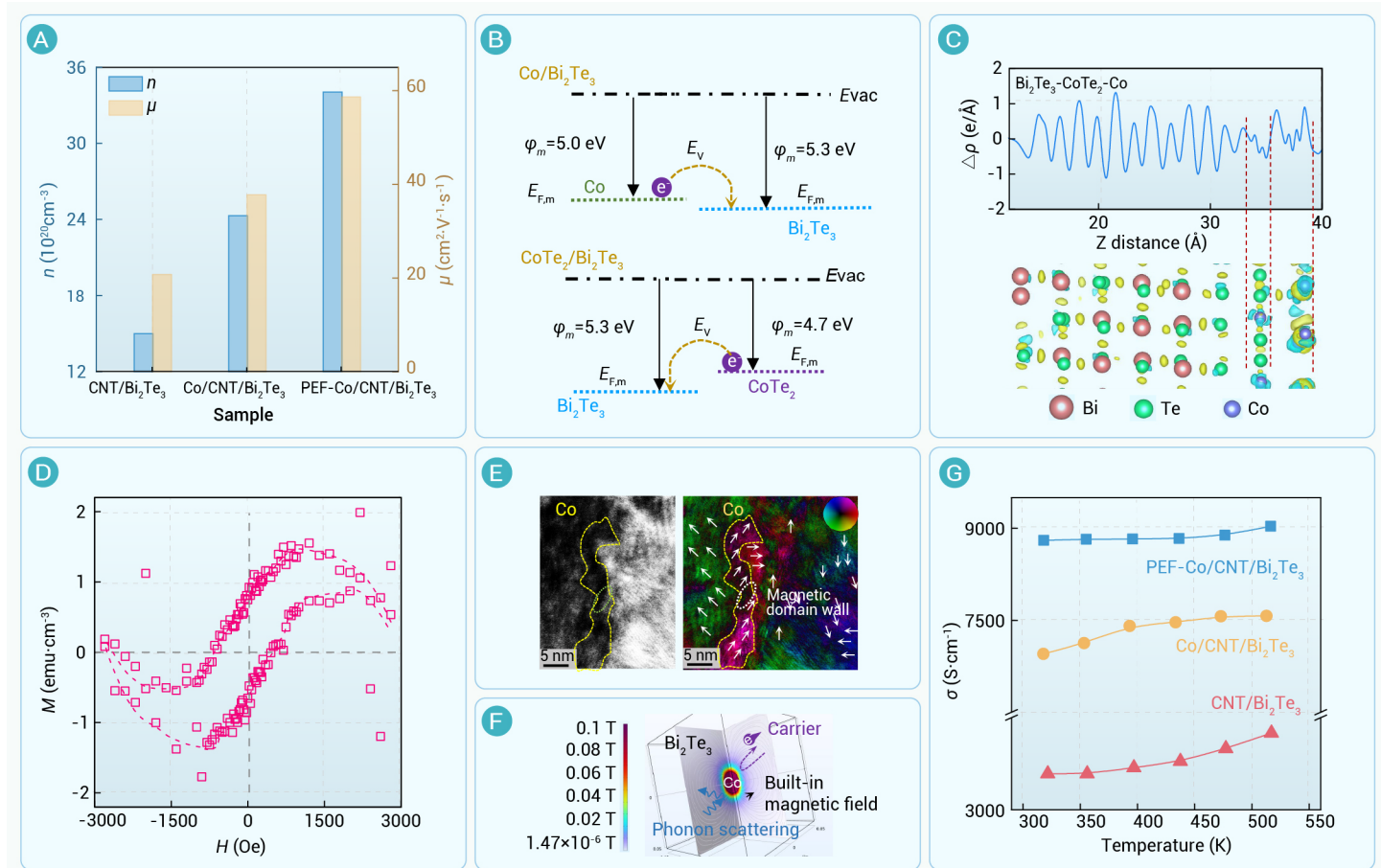


Figure 3. Carrier transport and built-in magnetic field mechanism in the PEF-Co/CNT/ Bi_2Te_3 film (A) Room-temperature carrier concentration and mobility of CNT/ Bi_2Te_3 , Co/CNT/ Bi_2Te_3 , and PEF-Co/CNT/ Bi_2Te_3 films. (B) Schematic diagram of carrier transport at the ohmic contact interface. (C) Charge density difference ($\Delta\rho$) at the Bi_2Te_3 - CoTe_2 -Co and Bi_2Te_3 -Co junctions, where Z is the position of the atom. (D) Magnetic hysteresis loops of the PEF-Co/CNT/ Bi_2Te_3 film. (E) Lorentz TEM (LTEM) image, which shows magnetic domain direction. (F) Built-in magnetic field of Co nanoparticles by COMSOL simulation. (G) Temperature-dependent electrical conductivity of CNT/ Bi_2Te_3 , Co/CNT/ Bi_2Te_3 , and PEF-Co/CNT/ Bi_2Te_3 films.

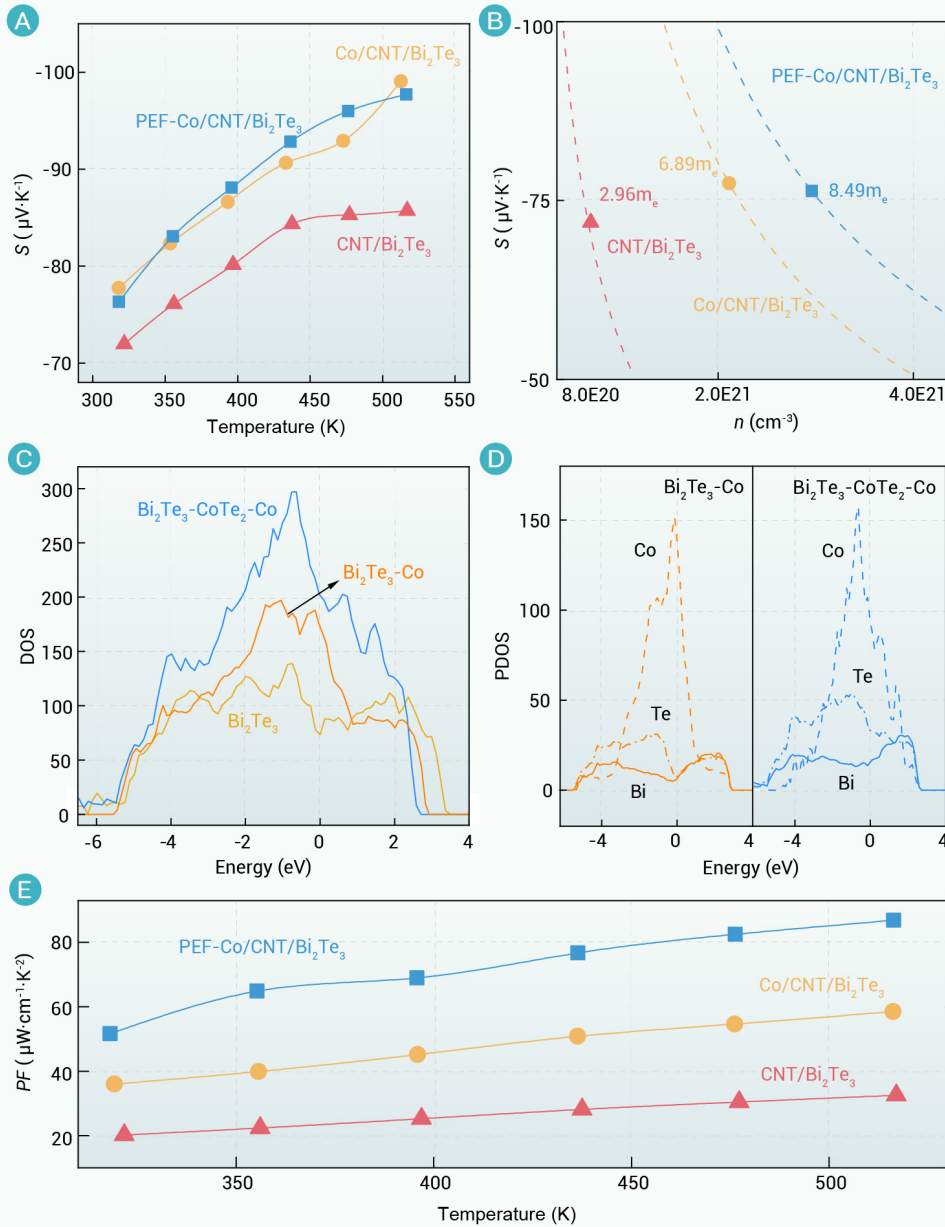


Figure 4. Enhanced thermoelectric transport through carrier and electronic structure regulation (A) Temperature-dependent Seebeck coefficient of CNT/Bi₂Te₃, Co/CNT/Bi₂Te₃, and PEF-Co/CNT/Bi₂Te₃ films. (B) Carrier-concentration-dependent Seebeck coefficient. (C) Total DOS of Bi₂Te₃, Bi₂Te₃-Co, and Bi₂Te₃-CoTe₂-Co. (D) PDOS of Bi₂Te₃-Co and Bi₂Te₃-CoTe₂-Co. (E) Temperature-dependent power factor of CNT/Bi₂Te₃, Co/CNT/Bi₂Te₃, and PEF-Co/CNT/Bi₂Te₃ films.

CNT/Bi₂Te₃, Co/CNT/Bi₂Te₃, and PEF-Co/CNT/Bi₂Te₃ films. Owing to the inverse relationship between n and S , S should gradually decrease with Co incorporation and PEF treatment. However, the opposite trend is observed. Besides its dependence on n , S also depends on the density-of-states effective mass m^* . As shown in Figure 4B, m^* is significantly enhanced from $2.96 m_e$ for CNT/Bi₂Te₃ to $6.89 m_e$ for Co/CNT/Bi₂Te₃, and then to $8.49 m_e$ for PEF-Co/CNT/Bi₂Te₃, which compensates for the conventional n - S trade-off and leads to an improved S . In addition to the increased density-of-states effective mass, interfacial energy filtering may also contribute to the enhanced S . Nevertheless, the dominant contribution to the improved S is attributed to the increased m^* , as supported by the carrier concentration and the DOS/PDOS calculations. However, the m^* is different from the transport effective mass that directly governs carrier mobility. Although a larger transport effective mass usually reduces mobility when the relaxation time is unchanged, PEF treatment increases the carrier relaxation time through crystallizing the CNT/Bi₂Te₃ interface and Co/CNT/Bi₂Te₃ coherent interface, and enables simultaneous enhancement of μ and m^* . This successfully decouples electrical transport parameters. To investigate the effect of Co and CoTe₂ on the electronic density-of-states DOS in Bi₂Te₃, we conducted the DOS calculations for Bi₂Te₃, Co-

Bi₂Te₃, Co-CoTe₂-Bi₂Te₃, and the results are shown in Figures 4C-D. As can be seen, Co and CoTe₂ incorporation markedly boost the DOS. The increased DOS facilitates the enhancement of m^* . The partial DOS (PDOS) results show that the DOS enhancement in Co-Bi₂Te₃ mainly originates from Co, whereas in Co-CoTe₂-Bi₂Te₃ it comes from both Co and Te. Because of the enhancement of n , μ , and m^* after Co incorporation and PEF treatment, the power factor PF is gradually increased (Figure 4E). The ultrahigh PF of 51.68 $\mu\text{W}\cdot\text{cm}^{-1}\cdot\text{K}^{-2}$ at room temperature is achieved in the PEF-Co/CNT/Bi₂Te₃ film.

introduced ferromagnetism. The magnetic properties of the PEF-Co/CNT/Bi₂Te₃ film were characterized by vibrating sample magnetometer (VSM) (Figure 3D). The film exhibits remanence and high coercivity, indicating the presence of magnetizable Co.⁶⁸ The increased coercivity reflects the stabilization of magnetic domains around Co nanoparticles. Lorentz TEM (LTEM) reveals magnetic vortex structures surrounding the Co nanoparticles (Figure 3E). The formation of the CoTe₂ phase and its coherent interface with Bi₂Te₃ enhances the pinning of magnetic domain walls, which suppresses domain expansion and contributes to the increased coercivity. Based on the magnetic dipole model, the calculated magnetic field intensity is approximately 15 mT (Formula 2). COMSOL simulations further confirm a field intensity range of 10-50 mT of Co nanoparticles (Figure 3F). Owing to the strong spin-orbit coupling of the Bi₂Te₃ film, this stable built-in magnetic field can suppress multiple carrier scattering and modulate carrier transport pathways, thereby increasing the carrier relaxation time and contributing to the enhanced μ .⁶⁹⁻⁷¹ Benefiting from the enhanced n and μ , the electrical conductivity σ is significantly increased after Co incorporation and PEF treatment (Figure 3G). Room-temperature σ is boosted from 3586.9 S cm^{-1} for CNT/Bi₂Te₃ to 6951.3 S cm^{-1} for Co/CNT/Bi₂Te₃, and then to 8804.6 S cm^{-1} for PEF-Co/CNT/Bi₂Te₃.

Figure 4A displays the temperature-dependent Seebeck coefficient S of

Bi₂Te₃, Co-CoTe₂-Bi₂Te₃, and the results are shown in Figures 4C-D. As can be seen, Co and CoTe₂ incorporation markedly boost the DOS. The increased DOS facilitates the enhancement of m^* . The partial DOS (PDOS) results show that the DOS enhancement in Co-Bi₂Te₃ mainly originates from Co, whereas in Co-CoTe₂-Bi₂Te₃ it comes from both Co and Te. Because of the enhancement of n , μ , and m^* after Co incorporation and PEF treatment, the power factor PF is gradually increased (Figure 4E). The ultrahigh PF of 51.68 $\mu\text{W}\cdot\text{cm}^{-1}\cdot\text{K}^{-2}$ at room temperature is achieved in the PEF-Co/CNT/Bi₂Te₃ film.

Thermoelectric and photo-thermoelectric devices

Based on the optimized PEF-Co/CNT/Bi₂Te₃ films, we fabricated single-leg thermoelectric and photo-thermoelectric devices. The output voltage and output power of the thermoelectric device were measured as functions of the temperature difference (Figure 5A). The output voltage of the thermoelectric device increases with hot-end temperature, attributed to the enhanced Seebeck coefficient under a larger temperature difference. Meanwhile, the output current also increases with the temperature difference, indicating that a larger thermal driving force enhances carrier transport and increases the device's electrical conductivity. The maximum output power reaches 0.11 μW at a temperature difference of 39 K. The power density of the film is calculated by Formula 3, thermoelectric devices achieve a high output power

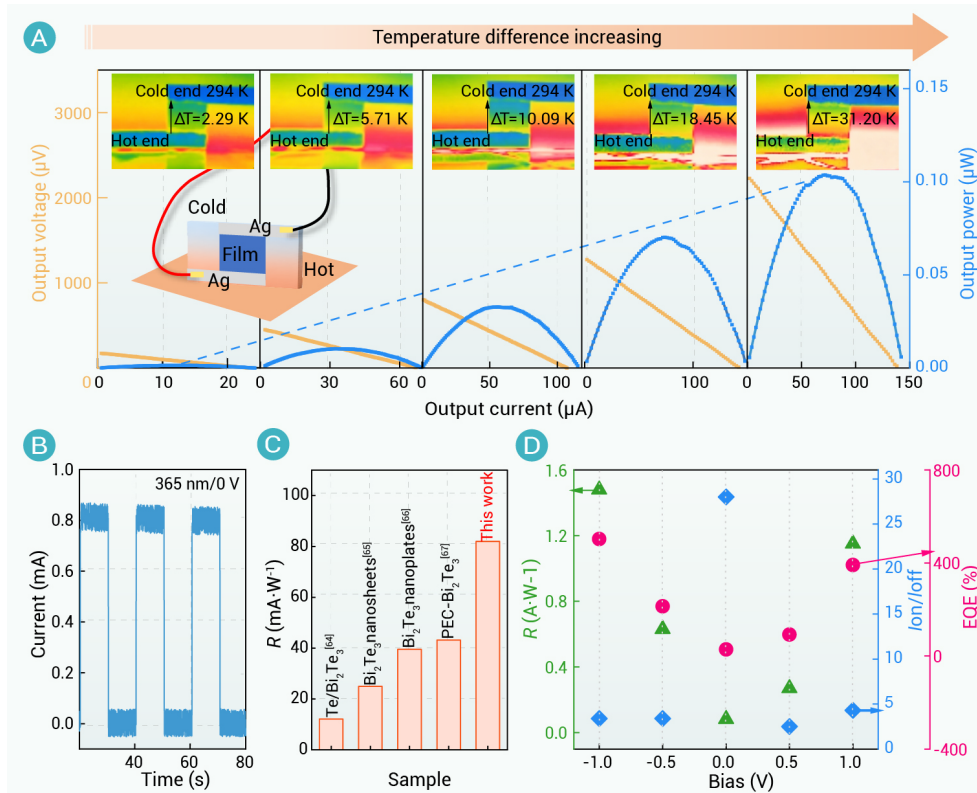


Figure 5. thermoelectric energy conversion and photodetection performance of the PEF-Co/CNT/Bi₂Te₃ device (A) Variation of output power with hot end temperature of PEF-Co/CNT/Bi₂Te₃ thermoelectric device. (B) Photocurrent-time curve of PEF-Co/CNT/Bi₂Te₃ photodetector. (C) Comparison of the responsivity for the PEF-Co/CNT/Bi₂Te₃ photodetector and previously reported Bi₂Te₃-based photodetector. (D) The responsivity, on/off ratio, and external quantum efficiency under various bias voltages of PEF-Co/CNT/Bi₂Te₃ photodetector.

μ improve the collection efficiency of photogenerated carriers. Finally, the optimized composite interfaces reduce interfacial scattering, thereby improving the R and D^* . Overall, the PEF-Co/CNT/Bi₂Te₃ film device enables both low-temperature thermoelectric power generation and high-sensitivity ultraviolet light photodetection.

CONCLUSION

In summary, we demonstrate a synergistic strategy combining PEF treatment with magnetic nanoparticle incorporation to concurrently enhance carrier concentration, mobility, and density-of-states effective mass in CNT embedded Bi₂Te₃ films. The PEF treatment crystallizes the CNT/Bi₂Te₃ interface and forms

a coherent Co/CoTe₂/Bi₂Te₃ interface, which increases carrier transport pathways and reduces carrier scattering, thereby boosting carrier mobility. The enhanced density-of-states effective mass arises from magnetoelectric interaction induced by magnetic Co nanoparticles, whereas the increased carrier concentration results from carrier injection by both the Co nanoparticles and the in-situ formed CoTe₂ phase. Consequently, the optimized film achieves a power factor of 51.68 μW cm⁻¹ K⁻² at room temperature. The fabricated single-leg devices realize a thermoelectric power density of 10.26 W m⁻² at ΔT = 39 K and a photo-thermoelectric detectivity of 5.95 × 10⁹ Jones under 365 nm illumination, ranking among the best values for Bi₂Te₃-based films. This work highlights the important role of interface modulation and magnetoelectric interaction in decoupling electrical transport parameters to enhance the thermoelectric and photo-thermoelectric performance.

REFERENCES

- Wong W., Elsa G., Mustafa M., et al. (2025) Bismuth telluride-based thermoelectric generators: advances in synthesis, performance enhancement, and device applications. *J. Power Sources* **653**:237722. DOI:10.1016/j.jpowsour.2025.237722.
- Li Z., Deng T., Qiu P., et al. (2025). Plasticity of Bi₂Te₃-family thermoelectric crystals. *Nat. Commun.* **16**:5190. DOI:10.1038/s41467-025-60465-2
- Tang X., Li Z., Liu W., et al. (2022). A comprehensive review on Bi₂Te₃-based thin films: Thermoelectrics and beyond. *InfoMat* **4**:e12209. DOI:10.1002/inf2.12209
- Zheng Z.H., Shi X.L., Ao D.W., et al. (2023). Harvesting waste heat with flexible Bi₂Te₃ thermoelectric thin film. *Nat. Sustain.* **6**:180–191. DOI:10.1038/s41893-022-01003-6
- Chen Y.X., Zhang J.-Z., Nisar M., et al. (2023). Realizing high thermoelectric performance in n-type Bi₂Te₃-based thin films via post-selenization diffusion. *J. Materials* **9**:1068–1076. DOI:10.1016/j.jmat.2023.01.003
- Das S., Supriya S., Alagarasan D., et al. (2024). Investigating the temperature-dependent Raman spectroscopy of Se/Bi₂Te₃ thin films and its enhanced photoresponse for optoelectronic applications. *J. Appl. Phys.* **136**:065302. DOI:10.1063/5.0216795
- Zhu J., Zhang X., Guo M., et al. (2021). Restructured single parabolic band model for quick analysis in thermoelectricity. *npj Comput. Mater.* **7**:116. DOI:10.1038/s41524-021-00587-5
- Tang L., Fu J., Chen Y., et al. (2024). An in-situ online method for extracting Seebeck coefficient of thermopile infrared sensors across a wide temperature range (300–600 K). *Measurement* **226**:114101. DOI:10.1016/j.measurement.2023.114101
- Wei P.C., Li Z., Chen X., et al. (2019). Enhancing thermoelectric performance by Fermi level tuning and thermal conductivity reduction in weakly degenerate p-type GeTe by Bi doping. *Sci. Rep.* **9**:10227. DOI:10.1038/s41598-019-45071-9
- Cha J., Zhou C., Cho S.-P., et al. (2019). Ultrahigh power factor and electron mobility

density of 10.26 W m⁻² at ΔT = 39 K.

Figures 5B & S13–S14 show the photocurrent-time curve of the PEF-Co/CNT/Bi₂Te₃ photodetector under ultraviolet, visible, and infrared illumination at 0 V bias, respectively. Upon ultraviolet illumination (365 nm), the photocurrent (the difference between the total photocurrent and the dark current) rapidly rises to ~0.85 mA and quickly returns to the dark current after the light is turned off. The photocurrent remains stable over multiple on/off cycles without degradation, demonstrating that the PEF-Co/CNT/Bi₂Te₃ photodetector enables stable and repeatable rapid photodetection. In contrast, although Bi₂Te₃ is a narrow-bandgap semiconductor and responds to an infrared illumination range, the PEF-Co/CNT/Bi₂Te₃ photodetector shows relatively weak photoresponse and higher dark current under visible (Figure S13) and infrared illumination (Figure S14). This indicates that the device is more suitable for ultraviolet light detection than for visible and infrared light detection. The stronger response under 365 nm illumination is mainly attributed to the higher photon energy of ultraviolet light, which enables more efficient carrier excitation and stronger local photothermal conversion, thereby generating a larger light-induced temperature gradient and a stronger photo-thermoelectric response. In addition, the introduction of Co, CoTe₂, and heterointerfaces create impurity-related energy levels, providing extra carrier excitation pathways and contributing to the broadband photoresponse.

As can be seen from Figure 5C, the responsivity (R) of our PEF-Co/CNT/Bi₂Te₃ device at 0 V exceeds that of previously reported single-leg Bi₂Te₃-based devices, showing strong potential for high-sensitivity ultraviolet light detection.^{72–75} Figure 5D presents the R , on/off ratio (I_{on}/I_{off}), and EQE, (Formula 4) under various bias voltages. Ultrahigh R is observed under negative bias, suggesting that a reverse electric field enhances the separation and collection of photogenerated carriers, thereby improving the photoelectric conversion efficiency. The device maintains a high I_{on}/I_{off} ratio under both negative and positive biases, and EQE follows a bias-dependent trend similar to that of R . These results confirm that the applied electric field treatment effectively increases the collection efficiency of photogenerated carriers, allowing more incident photons to contribute to the photocurrent. The enhanced ultraviolet photoresponse is related to the optimized electrical transport properties of the PEF-Co/CNT/Bi₂Te₃ film. First, the increased S and m^* are beneficial for generating a stronger photo-thermoelectric voltage under the light-induced temperature gradient. In addition, the enhanced σ and

- in n-type $\text{Bi}_2\text{Te}_{3-x}\text{Cu}$ stabilized under excess Te condition. *ACS Appl. Mater. Interfaces* **11**:30999–31008. DOI:10.1021/acsami.9b10394
11. Zhang H., Momand J., Levinsky J., et al. (2022). Nanostructure and thermal power of highly-textured and single-crystal-like Bi_2Te_3 thin films. *Nano Res.* **15**:2382–2390. DOI:10.1007/s12274-021-3743-y
 12. Wu Z., Mu E., Che Z., et al. (2020). Nanoporous (001)-oriented Bi_2Te_3 nanoplate film for improved thermoelectric performance. *J. Alloys Compd.* **828**:154239. DOI:10.1016/j.jallcom.2020.154239
 13. Kianwimol S., Sakdanuphab R., Chanlek N., et al. (2020). Effect of annealing temperature on thermoelectric properties of bismuth telluride thick film deposited by DC magnetron sputtering. *Surf. Coat. Technol.* **393**:125808. DOI:10.1016/j.surfcoat.2020.125808
 14. He Z., Chen Y.X., Zheng Z., et al. (2020). Enhancement of thermoelectric performance of n-type Bi_2Te_3 based thin films via in situ annealing during magnetron sputtering. *Ceram. Int.* **46**:13365–13371. DOI:10.1016/j.ceramint.2020.02.117
 15. Chen M., Mao Z., Ji Y. et al., (2024). Bi_2Te_3 -based flexible thermoelectrics. *Mater. Today Phys.* **49**:101972. DOI:10.1016/j.mtphys.2024.101972.
 16. Huang H., Cui H., Lu X., et al. (2009). Influence of annealing on thermoelectric properties of bismuth telluride films grown via radio frequency magnetron sputtering. *Thin Solid Films* **517**:3731–3734. DOI:10.1016/j.tsf.2009.01.015
 17. Poudel B., Hao Q., Ma Y., et al. (2008). High-thermoelectric performance of nanostructured bismuth antimony telluride bulk alloys. *Science* **320**:634–638. DOI:10.1126/science.1156446
 18. Jin Q., Jiang S., Zhao Y., et al. (2019). Flexible layer-structured Bi_2Te_3 thermoelectric on a carbon nanotube scaffold. *Nat. Mater.* **18**:62–68. DOI:10.1038/s41563-018-0217-z
 19. Nunna R., Qiu P., Yin M., et al. (2017). Ultrahigh thermoelectric performance in Cu_2Se -based hybrid materials with highly dispersed molecular CNTs. *Energy Environ. Sci.* **10**:1928–1935. DOI:10.1039/c7ee01737e
 20. Zhao W., Liu Z., Sun Z., et al. (2017). Superparamagnetic enhancement of thermoelectric performance. *Nature* **549**:247–251. DOI:10.1038/nature23667
 21. Liu S., Chen M., Fu C., et al. (2023). The interplay of magnetism and thermoelectricity: A review. *Adv. Phys. Res.* e202300015. DOI:10.1002/aprx.202300015.
 22. Zhao W., Liu Z., Wei P., et al. (2017). Magnetoelectric interaction and transport behaviors in magnetic nanocomposite thermoelectric materials. *Nat. Commun.* **8**:15070. DOI:10.1038/ncomms15070
 23. Fortulan R., Li S., Reece M.J., et al. (2024). Enhanced thermoelectric performance of p-type BiSbTe through incorporation of magnetic CrSb . *Appl. Phys. Lett.* **125**:203903. DOI:10.1063/5.0235499
 24. Ma F., Liu X., Liu M., et al. (2025). Trace doping leads to texture engineering and boosts thermoelectric performance of $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ -based flexible thin films. *Chem. Eng. J.* **522**:167341. DOI:10.1016/j.cej.2025.167341.
 25. Chen N., Yang D., Zhang Z.L., et al. (2025). Simultaneous enhancement of thermoelectric performance and mechanical flexibility in S-doped Bi_2Te_3 thin films. *Appl. Surf. Sci.* **713**:164306. DOI:10.1016/j.apsusc.2025.164306
 26. Li H., Ke S., Yu X., et al. (2025). Ultrasonically induced liquid-phase exfoliation boosts excellent performance of $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3/\text{PVDF}$ thermoelectric films. *J. Mater. Chem. A* **13**:7149. DOI:10.1039/d4ta08211g.
 27. Lu F., Liu S., Dai M., et al. (2025). Spin-coating co-reduction method to prepare Bi_2Te_3 films and its tunable thermoelectric properties. *J. Alloys Compd.* **1018**:179183. DOI:10.1016/j.jallcom.2025.179183
 28. Chen Y., Nie X., Sun C., et al. (2022). Realizing high-performance BiSbTe magnetic flexible films via acceleration movement and hopping migration of carriers. *Adv. Funct. Mater.* **32**:2111373. DOI:10.1002/adfm.202111373
 29. Zhang C., Chen Z., Bai H., et al. (2023). Manipulating the interfacial band bending for enhancing the thermoelectric properties of $1\text{T}'\text{-MoTe}_2/\text{Bi}_2\text{Te}_3$ superlattice films. *Small* **19**:2300745. DOI:10.1002/sml.202300745
 30. Chaiwas S., Kasayapanand N., Vora-ud A., et al. (2024). Enhanced thermoelectric power factor of magnetron Co-sputtered Pd-added Bi_2Te_3 thin films. *Vacuum* **230**:113696. DOI:10.1016/j.vacuum.2024.113696
 31. Wudil Y.S., Gondal M.A., Rao S.G., et al. (2020). Improved thermoelectric performance of ternary $\text{Cu}/\text{Ni}/\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$ nanocomposite prepared by pulsed laser deposition. *Mater. Chem. Phys.* **253**:123321. DOI:10.1016/j.matchemphys.2020.123321.
 32. Wudil Y.S., Gondal M.A., Rao S.G., et al. (2020). Substrate temperature-dependent thermoelectric figure of merit of nanocrystalline Bi_2Te_3 and $\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$ prepared using pulsed laser deposition supported by DFT study. *Ceram. Int.* **46**:24162–24171. DOI:10.1016/j.ceramint.2020.06.196.
 33. Boz R.B., Sevik C. and Turan S. (2025). The effect of spark plasma sintering parameters on the microstructure and thermoelectric properties of p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ alloys. *J. Solid State Chem.* **348**:125395. DOI:10.1016/j.jssc.2025.125395.
 34. Wang Y.L., Chen T.H., Giri K., et al. (2022). Periodic DLC interlayer-functionalized Bi-Sb-Te-based nanostructures: a novel concept for building heterogenized superarchitectures with enhanced thermoelectric performance. *ACS Appl. Mater. Interfaces* **14**:9307–9317. DOI:10.1021/acsami.1c23206
 35. Chen Y.F., Wei F., Wang H., et al. (2021). Structural control for high performance $\text{Bi}_2\text{Te}_{3-x}\text{Se}_x$ thermoelectric thin films. *Acta Phys. Sin.* **70**:207303. DOI:10.7498/aps.70.20211090
 36. Gong T., Ma C., Li L., et al. (2025). High-performance planar thin-film thermoelectric cooler based on sputtered nanocrystalline $\text{Bi}_2\text{Te}_3/\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ thin films for on-chip cooling. *ACS Appl. Mater. Interfaces* **17**:17008–17017. DOI:10.1021/acsami.4c19653.
 37. Liu S., Li G., Lan M., et al. (2021). Thermoelectric performance enhancement of film by pulse electric field and multi-nanocomposite strategy. *Small* **17**:e2100554. DOI:10.1002/sml.202100554
 38. Tan M., Shi X., Liu W., et al. (2021). Synergistic texturing and Bi/Sb-Te antisite doping secure high thermoelectric performance in $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ -based thin films. *Adv. Energy Mater.* **11**:2102578. DOI:10.1002/aenm.202102578.
 39. Lan M., Tan Y., Liu S., et al. (2025). Atomic migration and grain size are regulated by pulse period to maintain carrier concentration and increase mobility of Bi_2Te_3 films. *J. Electron. Mater.* **54**:10593–10602. DOI:10.1007/s11664-025-12195-w
 40. Rasmi T., Chandra Bose R.S., Varun T.S., et al. (2025). Enhanced thermoelectric performance of n-type Bi_2Te_3 thin films via thermal evaporation and optimized post-annealing. *J. Alloys Compd.* **1036**:181378. DOI:10.1016/j.jallcom.2025.181378
 41. Zhang L., Wang H., Zhang B., et al. (2025). Enhanced thermoelectric performance of screen-printed Bi_2Te_3 flexible films and generators through controlled thermal processing. *ACS Appl. Energy Mater.* **8**:14813–14821. DOI:10.1021/acsaem.5c02536
 42. Shin K.J. and Oh T.S. (2015). Micro-power generation characteristics of thermoelectric thin film devices processed by electrodeposition and flip-chip bonding. *J. Electron. Mater.* **44**:2026–2033. DOI:10.1007/s11664-015-3647-2
 43. Banerjee P., Huang J., Ambade R.B., et al. (2021). Effect of particle-size distribution and pressure-induced densification on the microstructure and properties of printable thermoelectric composites and high energy density flexible devices. *Nano Energy* **89**:106482. DOI:10.1016/j.nanoen.2021.106482
 44. Lin S., Zhang L., Zeng W., et al. (2022). Flexible thermoelectric generator with high Seebeck coefficients made from polymer composites and heat-sink fabrics. *Commun. Mater.* **3**:44. DOI:10.1038/s43246-022-00263-1
 45. Shi J., Wu X., Geng X., et al. (2023). Anisotropy engineering in solution-derived nanostructured Bi_2Te_3 thin films for high-performance flexible thermoelectric devices. *Chem. Eng. J.* **458**:141450. DOI:10.1016/j.cej.2023.141450
 46. Tang Z., Sun X., Yu F., et al. (2025). High-quality SnSe thin films for self-powered devices and multilevel information encryption. *ACS Appl. Mater. Interfaces* **17**:2648–2655. DOI:10.1021/acsami.4c18795
 47. Zhao K., Liu C., Shao T., et al. (2023). Enhanced thermoelectric performance of Bi_2Te_3 by carbon nanotubes and silicate aerogel co-doping toward ocean energy harvesting. *Mater. Today Sustain.* **23**:100476. DOI:10.1016/j.mtsust.2023.100476
 48. Zhang W., Yang J. and Xu D. (2016). A high power density micro-thermoelectric generator fabricated by an integrated bottom-up approach. *J. Microelectromech. Syst.* **25**:744–749. DOI:10.1109/JMEMS.2016.2565504. DOI:10.1109/JMEMS.2016.2565504
 49. You H., Li Z., Shao Y., et al. (2022). Flexible Bi_2Te_3 -based thermoelectric generator with an ultra-high power density. *Appl. Therm. Eng.* **202**:117818. DOI:10.1016/j.applthermaleng.2021.117818
 50. Ao D., Liu W., Zheng Z., et al. (2022). Assembly-free fabrication of high-performance flexible inorganic thin-film thermoelectric device prepared by a thermal diffusion. *Adv. Energy Mater.* **12**:2202731. DOI:10.1002/aenm.202202731
 51. Fu Z., Liu X., Wang F., et al. (2024). High-performance Vis-NIR photodetectors based on two-dimensional Bi_2Te_3 thin film and applications. *Photonics* **11**:1052. DOI:10.3390/photonics11111052
 52. Jiang J., Fan X., Yu H., et al. (2025). Flexible broadband photothermoelectric detector for self-powered gas monitoring. *Adv. Opt. Mater.* **13**:2502244. DOI:10.1002/adom.202502244
 53. Kao Q., Xiao Y., Jia Y., et al. (2024). Infrared photoelectric detection of polycrystalline Bi_2Te_3 thin films prepared by pulsed laser deposition. *J. Vac. Sci. Technol. A* **42**:023421. DOI:10.1116/6.0003343
 54. Jiang J., Lian Y., An B., et al. (2024). Flexible Bi_2Te_3 photothermoelectric thin film detector with broadband response at room temperature. *Proc. SPIE* **13496**:3048088. DOI:10.1117/12.3048088
 55. Bano S., Khan A.U., Aftab M., et al. (2024). $\text{Mg}_2(\text{Sb,Bi})_2$ -based materials and devices rivaling bismuth telluride: A review. *Mater. Futures* **3**:042601. DOI:10.1016/j.device.2024.100408
 56. Venkatasubramanian R., Siivola E., Colpitts T., et al. (2001). Thin-film thermoelectric devices with high room-temperature figures of merit. *Nature* **413**:597–602. DOI:10.1038/35098012
 57. Choi H., Jeong K., Chae J., et al. (2018). Enhancement in thermoelectric properties of Te-embedded Bi_2Te_3 by preferential phonon scattering in heterostructure interface. *Nano Energy* **47**:374–384. DOI:10.1016/j.nanoen.2018.03.009
 58. Islam Z., Wang B. and Haque A. (2018). Current density effects on the microstructure of zirconium thin films. *Scr. Mater.* **144**:18–21. DOI:10.1016/j.scriptamat.2017.09.032
 59. Lamirand A.D., Adam J.-P., Ravelosona D., et al. (2019). In situ monitoring of electric field effect on domain wall motion in Co ultrathin films in direct contact with an electrolyte. *Appl. Phys. Lett.* **115**:032402. DOI:10.1063/1.5109024
 60. Lu W., Dong Y., Li C., et al. (2014). Preparation of ZnO films with variable electric field-assisted atomic layer deposition technique. *Appl. Surf. Sci.* **303**:111–117. DOI:10.1016/j.apsusc.2014.02.097
 61. Tan M., Hao L., Li H., et al. (2020). Approaching high-performance of ordered structure Sb_2Te_3 film via unique angular intraplanar grain boundaries. *Sci. Rep.*

- 10:5978. DOI:10.1038/s41598-020-63062-z
62. Lan M., Sun S., Liu S., et al. (2024). Thermoelectric properties of Bi_2Te_3 films with low-angle grain boundaries formed through high pulse current density. *Chem. Eng. J.* **484**:149519. DOI:10.1016/j.cej.2024.149519
 63. Choe D.-H., West D. and Zhang S. (2017). Built-in potential and band alignment of matter. *npj Comput. Mater.* **3**:29. DOI:10.1038/s41524-017-0032-0
 64. Arellano-Tánori O., Chávez-Mendiola E., Gámez-Corrales R., et al. (2019). Obtaining nano structures of cobalt telluride by a simplified ion exchange reaction at aqueous solution. *Chalcogenide Lett.* **16**:57-61. WOS:000458201100002.
 65. Zhao Y., Nie X., Sun C., et al. (2021). Excellent thermoelectric performance from in situ reaction between Co nanoparticles and BiSbTe flexible films. *ACS Appl. Mater. Interfaces* **13**:58746–58753. DOI:10.1021/acsami.1c19143
 66. Javey A., Guo J., Wang Q., et al. (2003). Ballistic carbon nanotube field-effect transistors. *Nature* **424**:654–657. DOI:10.1038/nature01797
 67. Dürkop T., Getty S.A., Cobas E., et al. (2004). Extraordinary mobility in semiconducting carbon nanotubes. *Nano Lett.* **4**:35–39. DOI:10.1021/nl034841q
 68. Judy V., Diaz Pardo R., Torres W., et al. (2018). Pinning of domain walls in thin ferromagnetic films. *Phys. Rev. B* **98**:054406. DOI:10.1103/PhysRevB.98.054406
 69. He H.T., Wang G., Zhang T., et al. (2011). Impurity effect on weak anti-localization in the topological insulator Bi_2Te_3 . *Phys. Rev. Lett.* **106**:166805. DOI:10.1103/PhysRevLett.106.166805
 70. Lu H., Shi J. and Shen S. (2011). Competition between weak localization and antilocalization in topological surface states. *Phys. Rev. Lett.* **107**:076801. DOI:10.1103/PhysRevLett.107.076801
 71. Siegfried P., Bhandari H., Qi J., et al. (2023). CoTe_2 : A quantum critical Dirac metal with strong spin fluctuations. *Phys. Rev. Mater.* **7**:104201. DOI:10.1103/PhysRevMaterials.7.104201
 72. Yang S., Jiao S., Nie Y., et al. (2024). Boosting photoresponse and stability of a self-powered photoelectrochemical-type Bi_2Te_3 imaging photodetector by a novel quasi-solid-state gel electrolyte. *J. Alloys Compd.* **982**:173718. DOI:10.1016/j.jallcom.2024.173718
 73. Zhang Y., You Q., Huang W., et al. (2020). Few-layer hexagonal bismuth telluride (Bi_2Te_3) nanoplates with high-performance UV-Vis photodetection. *Nanoscale Adv.* **2**:1333–1339. DOI:10.1039/d0na00006j
 74. Zhao C., Wang D., He W., et al. (2024). Self-powered broadband RGB imaging

photodetector based on air-stabilized Bi_2Te_3 nanosheets. *Mater. Today Nano* **25**:100455. DOI:10.1016/j.mtnano.2023.100455

75. Zhao C., Wang D., Cao J., et al. (2024). Highly efficient 1D p-Te/2D n- Bi_2Te_3 heterojunction self-driven broadband photodetector. *Nano Res.* **17**:1864–1874. DOI:10.1007/s12274-023-5905-6

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 52502233, 524B2021, and U23A20556), and the China Postdoctoral Science Foundation (2026T191109 and 2025M774303), the National Key Research and Development Program of China (2023YFB3809400), and Heilongjiang Graduate Excellence Funding Program (LJYXLZR2025-002). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

M.Lan, M.Liu, and J.S. provided the main idea of this article. M.G. carried out the theoretical calculations. L.J., H.K., and P.Z. conducted aberration-corrected STEM experiments. M.Lan, D.W., and Y.Z. performed the experiments and measurements. The manuscript was drafted by M.Lan and M.Liu, and revised by J.S. All authors discussed the results and commented on the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.tip.2026.100014>.