PERSPECTIVE

National Science Open
4: 20250009, 2025
https://doi.org/10.1360/nso/20250009

Materials Science

Special Topic: Thermoelectric Materials and Devices

Thermoelectric cooling goes cooler

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Received 2 March 2025; Revised 10 March 2025; Accepted 21 March 2025; Published online 24 March 2025

Thermoelectric cooling (TEC) is a solid-state technology that utilizes electricity to pump heat from one side of a material or device to the other. It leverages the dual role of charge carriers, which transport charge and heat, enabling heat redistribution under external electric and/or magnetic fields. This technology offers advantages including miniaturization, solid-state operation, vibration-free performance, and long-term reliability, making it particularly beneficial in applications where conventional compressor-based cooling is less suitable. Currently, TEC has been mainly employed in near-room-temperature scenarios, including but not limited to refrigerators, precise temperature control in optical modules, and polymerase chain reaction detectors. In recent years, there has been a growing demand for solid-state cooling technologies capable of operating at lower temperatures. For instance, cooling infrared detectors to temperatures below 150 K is crucial to minimize noise and improve sensitivity [1]. This brings new challenges for TEC to achieve enhanced cooling capabilities—operating at lower temperature ranges while delivering superior performance.

The currently commonly used TEC technology mainly relies on the Peltier effect, a phenomenon discovered by French physicist Jean Charles Athanase Peltier in 1834. In the Peltier effect, the direction of the electric current corresponds either parallel or antiparallel to the thermal gradient (Figure 1a), depending on the type of charge carriers. Typically, a TEC module consists of alternating N-type and P-type thermoelectric materials arranged in a Π-shape series configuration (Figure 1b). When electric power is applied, electrons in the N-type leg and holes in the P-type leg move directionally, generating a cooling effect on one side and a heating effect on another. Materials that have been commonly employed for Peltier cooling include Bi-Sb, Bi_2Te_3, and $Mg_3Bi_{2-x}Sb_x$ [2]. Due to the limitations on the z value and the reduction in T, the thermoelectric (TE) figure of merit (zT) of these materials generally decreases with decreasing temperature. However, it is noteworthy that Bi-Sb exhibits an optimal operating temperature range below room temperature, with its zT peaking between 120–200 K, reaching approximately 0.6 [2,3]. By further introducing a magnetic field to enhance the Seebeck coefficient while reducing electronic thermal conductivity, the zT value of Bi-Sb alloys at low temperatures can be further improved. A maximum zT value exceeding 1.5 in the temperature range of

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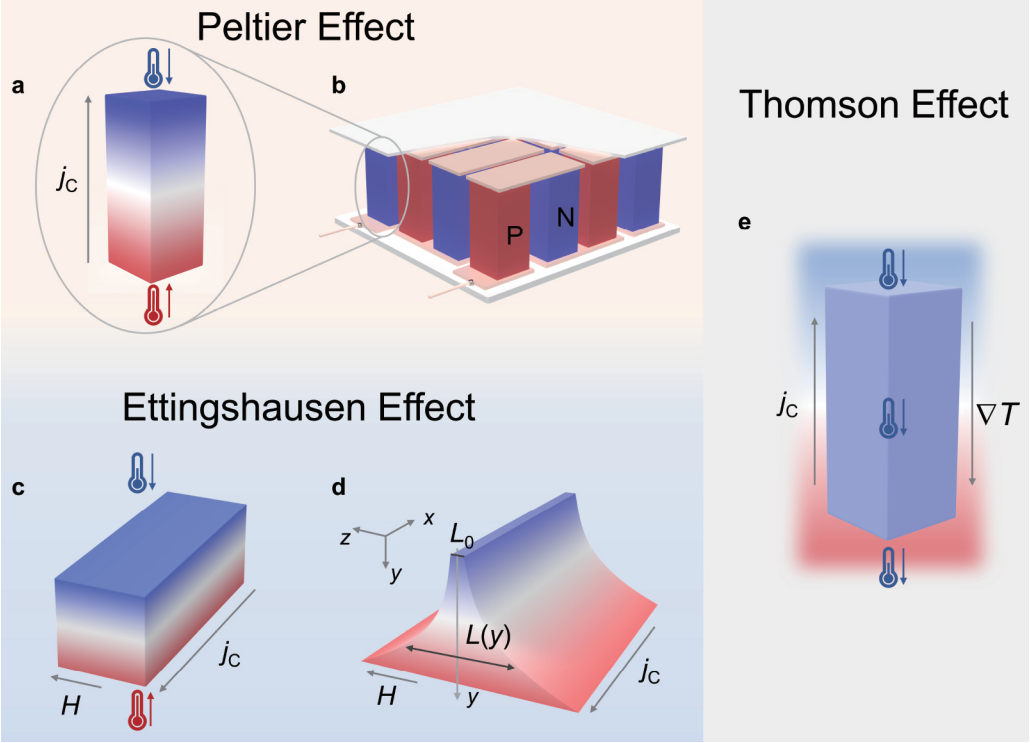

Figure 1 (a) Schematic of the direction of current and thermal gradient in the Peltier effect, where j_c represents the applied current density. The red and blue areas indicate temperature increase and decrease (N-type material), respectively. (b) A typical longitudinal TE device. The white rectangles at the top and bottom represent ceramic plates, while the red and blue rectangles represent P-type and N-type TE legs, connected in a Π-shape. (c) Schematic of the Ettingshausen effect, where H represents the applied magnetic field. The resulting thermal gradient is oriented perpendicular to both the applied magnetic field and the applied current directions. (d) Diagram of an infinite-stage Nernst-Ettingshausen device. (e) Schematic of the Thomson effect, where ∇T represents applied thermal gradient. For N-type materials, under the influence of the illustrated current and thermal gradient, the whole material exhibits heat absorption.

120–225 K was achieved in the single-crystal $Bi_{88}Sb_{12}$ by modulating the magnetic field within 1 T [3], a magnetic field that can be realized using advanced permanent magnets. The dispersive-band-contributed high carrier mobility underlies the pronounced magneto-enhanced TE effect in Bi-Sb alloys, which has also been proven to be effective in topological semimetals with linear band dispersion. For instance, the peak zT value increases from 0.2 at zero magnetic field to 1.2 under a magnetic field of 7 T for Dirac semimetal Cd_3As_2 [4]. Therefore, exploiting the magneto-enhanced Peltier effect in emerging materials with high carrier mobility is a potential route for TEC to go cooler.

Applying a longitudinal electric field and an orthogonal magnetic field to a solid material could modulate the carrier transport in the longitudinal direction and generate a transverse heat gradient via the Ettingshausen effect (Figure 1c). This heat gradient arises from the generation and recombination of electron-hole pairs. Materials with nearly equally high mobility and substantial concentrations of both electrons and holes could achieve a pronounced Ettingshausen effect. This is why semimetals with sharp linear band dispersion and comparable electron and hole concentrations, typically bismuth, exhibit a pronounced Ettingshausen effect at low temperatures (typically below 200 K [5]) as the carrier mobility increases (usually exceeding 10^4 cm^2 V^{-1} s^{-1}). Due to the orthogonal relationship between the electric current and the thermal gradient, the coupling between thermal transport and electrical transport can be naturally mitigated, thereby overcoming the constraints on the z value and offering unique advantages. Moreover, this orthogonality makes the scale

parameters in the thermal current expression no longer negligible, allowing a method of obtaining an infinite-staged cascade using a single piece of the material. By considering the heat flow ratio across each infinitesimal element Δy, an exponential relationship for the shape design can be derived (Figure 1d), in which the width along the z-axis can be expressed as

$$L(y) = L_0 \exp\left(\frac{(1+z_{NE}T)^{1/2}+1}{T\left[(1+z_{NE}T)^{1/2}-1\right]} y \frac{dT}{dy} \right), \quad (1)$$

where y is the distance from the cold end along the y-axis, L_0 is the width of the cold end in the z-direction, T is the temperature, and $z_{NE}T$ is the Nernst-Ettingshausen figure of merit. Such a single-arm device is referred to as an infinite-stage Nernst-Ettingshausen cooler [6]. Experimentally, under a magnetic field of 11 T and an electric current of 60 A, the bismuth infinite-stage Nernst-Ettingshausen cooler achieved a maximum temperature difference of 101 K, with the hot side at 302 K [5]. Theoretically, if keeping the ratio $L(y)_{max}/L_0$ of 100 and $z_{NE}T$ of 0.75, the cold side can be cooled to 60 K with a hot side temperature of 290 K [6], which meets the refrigeration demands of many applications. Consequently, looking for new materials with ultrahigh carrier mobility (typically exceeding 10^4 cm^2 V^{-1} s^{-1}), comparable electron and hole concentrations, and low thermal conductivity, typically in the category of semimetals, is crucial for the developing high-performance Nernst-Ettingshausen cooler.

However, achieving a pronounced Ettingshausen effect often necessitates high magnetic fields, which can be challenging to generate without low-temperature superconducting magnets. An alternative strategy involves employing ferromagnetic or antiferromagnetic materials, which can exhibit a significant anomalous Ettingshausen effect even under low or zero magnetic fields. This effect has been investigated in conventional ferromagnetic and antiferromagnetic systems. Recently, it has been discovered that the entanglement of bands in magnetic topological materials could generate a substantial Berry curvature in momentum space. Due to the breaking of time-reversal symmetry, the nonzero Berry curvature integral near the Fermi level contributes substantially to the intrinsic term, which enhances the anomalous Nernst effect—the reversible effect of the anomalous Ettingshausen effect. Typically, in the topological Heusler magnet Co_2MnGa, an order-of-magnitude increase in the anomalous Nernst thermopower was achieved compared to conventional magnets [7]. The further fabrication of the Nernst-Ettingshausen device using Co_2MnGa, as well as the construction of the device performance measurement system, demonstrates a paradigm for promoting topological magnets for transverse TE conversion [8].

Despite the anomalous Nernst-Ettingshausen effect being realized at zero or low magnetic field, the anomalous Nernst thermopower remains relatively small compared to the ordinary Nernst thermopower observed in typical non-magnetic semimetals. To further improve the anomalous Nernst-Ettingshausen effect of currently discovered topological magnets, the band structure tuning to enhance the intrinsic Berry curvature, together with the utilization of the extrinsic contributions from magnon drag, skew scattering, and side jump mechanisms, provide promising ways. Moreover, hybrid device designs that employ anomalous Nernst/Ettingshausen effect materials serving simultaneously as both TE materials and magnetic field sources in combination with either ordinary Nernst/Ettingshausen effect materials or off-diagonal TE effect materials are expected to further improve transverse TE performance and provide an alternative pathway toward practical applications [9].

Besides the Peltier and Ettingshausen effects, the Thomson effect (Figure 1e), conventionally considered negligible in conventional TE materials, was recently found to be effective in enhancing TEC at lower temperatures. As demonstrated in $YbInCu_4$, a temperature span exceeding 5 K was achieved at $T = 38$ K, near the electronic phase transition point, where the hybridization between itinerant and localized 4f electrons results in the reconstruction of the bands [10]. With continued advancements in understanding novel band structures and electronic phase transitions in solid materials, the development of new Peltier-Thomson coolers is anticipated.

In short, the interplay among the charge, spin, and heat degrees of freedom in solid materials enables versatile ways for deriving electrons to pump heat. This provides new opportunities for TEC to go cooler—operating at lower temperatures as well as delivering better performance.

Funding

This work was supported by the National Key Research and Development Program of China (2024YFA1409200), the National Natural Science Foundation of China (52471239), and the Fundamental Research Funds for the Central Universities (226-2024-00075).

Conflict of interest

The authors declare no conflict of interest.

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