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Investigation of the Hall and Nernst-Ettingshausen Effects in Diluted Magnetic Semiconductors

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Abstract

This review explores the Hall and Nernst-Ettingshausen effects in various magnetic systems, including diluted magnetic semiconductors (DMS), topological insulators, superconductors, and novel composite materials. In DMS, the interplay of ferromagnetism and magnetic impurities introduces unique transport behaviors, particularly influencing the anomalous Hall effect (AHE) and thermomagnetic phenomena. We also examine the Nernst-Ettingshausen effect (NE) in topological insulators and superconductors, revealing the influence of band topology and vortex-like excitations. Special attention is given to the thermoelectric properties of graphene and its potential for tuning electronic transport via gate voltage. Furthermore, we delve into recent advancements in cryogenic applications utilizing NE-based coolers and the emerging field of composite spin-Seebeck effects, demonstrating their promise for efficient thermoelectric power generation. This comprehensive review synthesizes experimental and theoretical developments, emphasizing the significance of these effects in advancing future electronic and energy conversion technologies.

Keywords: Diluted magnetic semiconductors (DMS), graphene nanoribbons, Hall effect, Nernst-Ettingshausen effect, spin-Seebeck effect, thermomagnetic effects, topological insulators

INTRODUCTION

The discovery and investigation of the Hall and Nernst-Ettingshausen effects have significantly contributed to our understanding of the electronic and thermoelectric transport phenomena in magnetic materials. These effects, observed across a wide range of materials, from diluted magnetic semiconductors to superconductors and topological insulators, provide key insights into charge-carrier dynamics, scattering processes, and magnetic interactions. The study of these phenomena is particularly relevant for developing new technologies in spintronics, thermoelectric cooling, and energy conversion.

In diluted magnetic semiconductors, the anomalous Hall effect (AHE) is a crucial tool for probing the magnetic properties near the Curie point, particularly in systems with ferromagnetism induced by magnetic impurities. However, the nonlinear behavior of the Hall effect (HE) in such systems, which is influenced by internal magnetic fields, complicates the interpretation of transport phenomena. In contrast, thermomagnetic effects, such as the Nernst-Ettingshausen effect (NE), offer complementary insights by examining the response of charge carriers under a temperature gradient, rather than an applied electric field.

Topological insulators, particularly topological crystalline insulators (TCIs), constitute another fascinating area of research. The interplay between the surface states and bulk properties in these materials, especially near band-ordering transitions,

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underscores the importance of temperature and chemical composition in tuning the thermoelectric properties. Superconductors exhibit intriguing thermomagnetic effects, where vortex excitations and particle-hole asymmetry contribute to a large NE effect, particularly in materials such as cuprates.

Advancements in cryogenic applications, particularly Nernst-Ettingshausen coolers, highlight the potential of thermomagnetic materials for next-generation cooling technologies. Similarly, the development of composite materials, such as MnBi-Bi systems, shows promise for enhanced thermoelectric power generation driven by the spin Seebeck effect and magnetic field-induced anisotropy.

This review aims to provide a comprehensive overview of these effects, focusing on both fundamental scientific principles and emerging applications in electronic devices and energy-conversion technologies. The magnetic field dependence of the Hall and Nernst-Ettingshausen effects in diluted magnetic semiconductors (DMS), such as (In,Fe)Sb, (Ga,Fe)Sb, and (Ga,Mn)Sb, was studied. The samples were prepared via pulsed laser deposition on semi-insulating GaAs substrates. Experimental data revealed the presence of both anomalous Hall and Nernst-Ettingshausen effects in structures containing manganese. This study demonstrated that the distinct nature of ferromagnetism leads to the observed differences in the magnetic field dependences of these effects in Mn- and Fe-based systems.

Spintronics represents a promising field for future electronics development, particularly through the utilization of DMS with Curie temperatures near room temperature, enabling the spin degree of freedom in electronic devices. Analyzing the magnetic field dependence of the Anomalous Hall Effect (AHE) is a key method for investigating the magnetic properties of DMS near the Curie point. However, the intrinsic ferromagnetism in these structures cannot be fully described by the nonlinear magnetic field dependence of the Hall Effect (HE). Specifically, internal magnetic fields created by agglomerates of magnetic impurities can distort the linear behavior of the HE. Thermoelectric and thermomagnetic phenomena provide complementary methods for understanding the scattering processes and improving the accuracy of magnetic transport parameters.

The Nernst-Ettingshausen Effect (NE) occurs when a structure is exposed to both an external magnetic field and a temperature gradient, leading to a transverse potential difference. Although the NE and Hall effects are related, the NE is driven by a temperature gradient rather than an applied electric field. A unique feature of the NE effect is that charge carriers with opposite signs move in the same direction, making it challenging to determine whether electrons or holes are primarily responsible for the conduction. However, the NE effect can provide valuable information regarding dominant scattering centers [1–4].

Thermomagnetic Effects on Superconductors

To preserve the gauge invariance in a magnetic field, the magnetic term must be incorporated into the current heat operator when calculating the NE effect. In superconductors, calculations have shown that the Particle-Hole Asymmetry (PHA) remains unchanged by variations in the modulus of the order parameter. The thermomagnetic effects in the fluctuation region were minimal and proportional to the square of the PHA. The large NE effect observed in cuprates is attributed to vortex-like excitations outside the scope of Gaussian fluctuation theory.

Transverse NE Effect in $Pb_{1-x}Sn_xSe$ Alloys

Both experimental and theoretical investigations have explored the transverse NE effect and electron mobility in $Pb_{1-x}Sn_xSe$ alloys as a function of the temperature and chemical composition near the vanishing energy gap (Eg). Recent findings suggest that the energy gap can be tuned to pass through a zero value, contrary to previous assumptions that the NE effect changes its sign when the gap vanishes. Our study demonstrated the maximum bulk NE effect near the vanishing Eg. Furthermore, we explored the contribution of different scattering modes to the transport phenomena in $Pb_{1-x}Sn_xSe$ alloys and introduced damping to mitigate the singular behavior of some transport integrals near the zero-energy gap.

Topological Insulators and Nernst-Ettingshausen Effect

Topological crystalline insulators (TCIs) exhibit intriguing properties including metallic surface states protected by crystalline symmetries. Pb1−xSnxSe alloys are known to undergo a transition between trivial and nontrivial band ordering as the temperature decreases. This transition was confirmed by angle-resolved photoemission spectroscopy, and our work highlights the importance of temperature in achieving the right band ordering for specific chemical compositions (x). The interplay between surface and bulk properties of TCIs, along with their application in thermoelectric devices, offers exciting avenues for further research [5–8].

Nernst-Ettingshausen Effect on Tellurium

We report the first experimental observation of the NE effect in tellurium at low temperatures. Measurements of resistivity and Hall, Seebeck, and NE coefficients in tellurium samples provided insights into the scattering exponent (r), which reflects the energy dependence of the relaxation time (τ). The anisotropy of the scattering factor, r, attributed to dislocations, was confirmed through electron irradiation experiments.

Cryogenic Applications of Nernst-Ettingshausen Coolers

Thermomagnetic (TM) cryocoolers, which are based on the NE effect, are gaining attention as a competitive green technology for next-generation cooling applications. These coolers offer significant advantages, including localized cooling, high reliability, and reduced environmental impacts. Although traditional TE coolers are limited in their ability to achieve large temperature differentials, TM coolers can achieve higher performance at cryogenic temperatures. Recent advancements in material research and device geometry optimization, such as the use of BiSb alloys and infinite-stage cascading, have further enhanced the efficiency of NE cryocoolers. However, challenges remain, including optimizing the material properties and reducing the size and cost of devices through the use of strong rare-earth magnets.

Graphene and Thermoelectric Effects

The thermoelectric power of graphene nanoribbons was studied, focusing on the Nernst and Seebeck effects. The Nernst and Seebeck coefficients were obtained by combining the tight-binding Hamiltonian with the non-equilibrium Green function. The Seebeck coefficient is an odd function independent of the magnetic field, whereas the Nernst coefficient is an even function of the Fermi energy owing to electron-hole symmetry. These coefficients show peaks when the Fermi energy crosses the Landau levels, which are largely unaffected by the chirality and width of the nanoribbon under a strong magnetic field. For the Nernst effect, the height of the nth peak is [ln2/∣n∣][ln 2/|n|][ln2/∣n∣], whereas for the Seebeck effect, it is ln2/nln 2/nln2/n. Specifically, the zeroth peak of the Nernst effect had an abnormal height of 2ln22 ln 22ln2, and the Seebeck effect vanished at this point. Without a magnetic field, only the Seebeck effect, which is heavily influenced by nanoribbon chirality, remains, with different chiral ribbons showing peak differences that fade as the magnetic field strengthens. The Seebeck coefficient near the Dirac point of insulating armchair ribbons can be significantly large. Experimental advances allow control of graphene's charge carriers via gate voltage, tuning the Fermi level to be electron-like or hole-like relative to the Dirac points, and enhancing the study of the thermoelectric properties of graphene.

Thermoelectric power (TEP), including the Seebeck and Nernst effects, is essential for understanding electronic transport and offers insights beyond conductance probing. Recent experimental breakthroughs have allowed simultaneous measurement of the conductance of graphene and TEP. It was observed that holes and electrons contributed oppositely to the Seebeck effect. The Seebeck coefficient diverges near the Dirac point, whereas the Nernst signal intensifies. Oscillations in TEP, influenced by Fermi energy, appear at low temperatures, with the oscillation magnitude suppressed as the temperature increases [9, 10].

Magneto-Ambipolar Transport in Kagome Superconductors

Recent studies on the Seebeck and Nernst effects in the Kagome superconductor CsV3Sb5, complemented by magnetoresistance and Hall measurements, revealed a significant magneto-Seebeck signal when the Charge Density Wave (CDW) order fell below TCDW=94KT_{CDW} = 94 KTCDW = 94 K. The Nernst signal peaks at approximately 35 K, which is the point at which the Hall coefficient switches signs, a signature of the ambipolar transport of compensated bands. A sublinear Nernst signal and notable anomalous Nernst effect (ANE) were observed within the CDW phase, suggesting that small pockets with multiband profiles dominate the transport properties. The relationship between CDW, superconductivity, and topological band structure, especially in superconducting Kagome families such as AV3Sb5 (where A = K, Rb, Cs), demonstrates the importance of non-trivial band topology in quantum materials. The giant anomalous Hall effect (AHE) observed in the CDW phase is particularly intriguing, especially given the lack of local moments or long-range magnetic order, and points to the importance of Fermi surface topology reconstruction [11, 12].

Composite Spin-Seebeck Effect

The spin Seebeck effect (SSE) and Nernst effect are typically geometrically identical but can be combined in ferromagnet/non-magnetic (FM/NM) composites. An example of this is MnBi needles formed inside a Bi matrix via synthesis with in-field annealing, where the SSE combines with the Nernst effect in Bi to enhance thermopower. Magnons from the FM transfer the angular momentum to the electrons in the NM, leading to the inverse spin Hall effect. For energy-conversion applications, SSE composites present advantages over traditional heterostructures by allowing bulk materials to actively generate electrical power. For instance, MnBi precipitates can exhibit properties that allow for efficient thermoelectric conversion in SSE composites.

The magnetic properties of MnBi and the ease of creating composites with Bi suggest that MnBi is a strong candidate for SSE-enhanced Nernst effects. Research on MnBi-Bi composites has shown that annealing in a magnetic field result in MnBi needles with high aspect ratios, leading to anisotropic magnetic behavior. Measurements of the anisotropic resistivity and Seebeck and Nernst effects show that compositions containing MnBi exhibit a notable SSE-assisted boost to the Nernst coefficient, particularly for samples with lower MnBi concentrations. The combination of microstructural control and thermoelectric measurements offers new insights into the potential of SSE composites for enhancing thermoelectric power generation [13, 14].

CONCLUSION

In summary, the Hall and Nernst-Ettingshausen effects offer profound insights into the electronic and thermoelectric properties of a diverse range of materials, including diluted magnetic semiconductors, topological insulators, superconductors, and novel composite systems. Our review highlights the complex interplay between the magnetic properties, charge carrier dynamics, and thermoelectric phenomena across these materials.

In diluted magnetic semiconductors, the anomalous Hall effect (AHE) and Nernst-Ettingshausen effect (NE) reveal valuable information about ferromagnetism and magnetic interactions, while also showing the challenges posed by internal magnetic fields and impurity agglomerates. The study of topological insulators and superconductors further underscores the significance of temperature and band structure in influencing transport behaviors, with vortex-like excitations and particle-hole asymmetry playing key roles in their thermomagnetic responses.

Advancements in cryogenic cooling technologies, driven by Nernst-Ettingshausen coolers, demonstrate the potential of thermomagnetic effects for efficient and environmentally friendly cooling solutions. Additionally, the exploration of composite materials, particularly those combining the spin Seebeck effect with the Nernst effect, points to exciting prospects for enhanced thermoelectric power generation and improved energy-conversion efficiency.

Overall, this review underscores the critical role of these effects in advancing our understanding of electronic and thermoelectric phenomena and their application in emerging technologies. Future research should continue to explore these effects in novel materials and devices, aiming to harness their full potential for innovative technological advancements.

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