Spin caloritronics in magnetic/non-magnetic nanostructures and graphene field effect devices

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Chapter 1

Introduction

1.1 Spintronics: charge and spin transport

The electron is a perhaps one of the most fascinating quantum objects that occupies a special position in solid state physics. It is not only a particle with a charge but it also behaves as a tiny magnet. These distinct properties allow the electron to interact with different externally applied forces, forming the basis for electromagnetism and (thermo) electricity. The wide range of applications that we use on a daily basis such as accurate temperature measurements using thermocouples, long distance radio wave transmissions, information processing and the like would not have been possible without the ability to controllably manipulate the interaction of the electrons with these different applied fields.

In modern nanoelectronics, one of the biggest challenges is reducing the large production of unwanted heat (Joule heating) associated with the flow of electrons. When not effectively channeled away in a controlled manner, it can deter the performance of an electronic device. In this regard, using the intrinsic angular momentum (spin) of the electron for data storage and information processing applications has the potential for low power electronics. This quantum mechanical property of the electron, which manifests itself either as *spin up* or *spin down*, provides the possibility of binary operations for integrated memory applications.

The use of the electron spin for device applications is studied in the field of spin based electronics or in short spintronics. In the development and understanding of spintronic phenomena, Mott's theory of two-spin channel model [1] and its experimental validation in transition metal alloys [2] laid the foundation for the discovery of the giant magnetoresistance (GMR) effect in artificial thin-film multilayers [3, 4]. In 1988, A. Fert and P. Grünberg independently showed that the in-plane resistance of Fe/Cr multilayers changes by several tens of percent when the magnetization directions are aligned or antialigned to each other. The immediate application of the GMR effect in the read-heads of hard disk drives enhanced the storage density of today's computers. Other variations of the GMR effect, such as the giant tunnel magnetoresistance (TMR) effect observed in magnetic tunnel junctions (MTJs) with textured MgO tunnbel barrier [5–7] are used in recent hard disk drives. Nonvolatile magnetic random access memories utilizing the spin-transfer torque effect in MTJs is currently being developed by leading companies, including Toshiba and Samsung, for future lower-power and large-density memory devices.

All spintronic devices so far used in the hard disk drive read heads are based on the flow of spin-polarized charge currents, that is, imbalance in the density of spin up and spin down electrons accompanying the flow of charge current. It is desirable to develop spintronic devices that utilize the flow of spin angular momentum (spin current) without the presence of a charge current. Current spintronic research directions are therefore geared towards finding such spin current sources, for example, electrical spin-injection in the nonlocal geometry [8, 9], spin pumping from a microwave driven ferromagnet [10–13] , thermally driven spin current sources [14–16] and spin-orbit coupling induced Hall effects [17–20].

1.2 Spin caloritronics: spin and heat transport

The connection between electrical and thermal transport is studied in thermoelectricity. The Seebeck effect, that describes the conversion of heat into charge current, and the Peltier effect, that relates the reversible conversion of charge current into heat current, are two of the most common thermoelectric effects that have found applications in temperature sensing, thermoelectric conversion and solid state refrigeration technologies. In a ferromagnetic material (F), the thermoelectric coefficients that quantify the two process, known as the Seebeck S and Peltier Π coefficients, are spin-dependent. It is therefore expected that the amount of energy carried by spin up electrons can be different from that of spin down electrons that, when exploited at a device level, can potentially provide additional functionalities to present and future spintronic devices.

Spin caloritronics is a new field that essentially combines the best of thermoelectricity and spintronics where the coupled transport of charge, spin and heat is studied. The concept of spin caloritronics dates back to the 1987 seminal work by Johnson & Silsbee [21] who proposed that the flow of charge in a magnetic material is also accompanied by the flow of spin and heat currents. In the late 1990s and beginning of 2000s thermoelectric effects in magnetic multilayers were investigated as complementary tools for understanding of the giant magnetoresistance effect. Notable works in this regard are the work by Shi *et al.* [22], Gravier *et al.* [23–25] and Fukushima *et al.* [26]. It was however the discovery of the spin Seebeck effect by Uchida *et al.* [27] in 2008 that gave the field the impetus for becoming an active area of research.

In the past 10 years, the study of the spin-dependent counterparts of the Seebeck and Peltier effects have been an active field of research. The spin (dependent) Seebeck effect has been reported for metallic spin valves [15, 28, 29], magnetic tunnel junctions [16, 30, 31] and insulating magnetic systems [32]. The spin (dependent) Peltier effect has been observed both for all metallic spin valves [29] as well as thes magnetic-insulator yttrium iron garnet [33]. The possibility of manipulating the flow of heat in metallic spin valves was also shown [34]. Spin-related thermoelectric effects are therefore expected to play a vital role in the development of nanoscale and localized thermopower generation and refrigeration application. However, their efficiency is limited compared to already existing technologies and finding good thermoelectric and spintronic materials that efficiently exploit the full potential of the electronic spin are highly required.

1.3 Motivation and outline

The main objective of this thesis is to explore and understand various spin related thermoelectric effects in ferromagnetic-normal metal (F/N) nanostructures that are either purely of electronic in nature or somehow mediated by collective excitations induced by thermal currents. Thermoelectric phenomena in a truly two-dimensional system, known as graphene, are also studied. The remaining part of the thesis is organized as follows

- ***Chapter 2*** presents a general introduction to the field of thermoelectricity, spintronics and spin caloritornics. Starting from the discussion of basic electrical and heat conduction, concepts in thermoelectricity are first introduced. Then spin transport in lateral and local pillar spin valve nanostructures is presented based on the classical two channel model for spin transport. Various spin caloritronic phenomena that arise from spin or heat accumulation at an F/N interface are discussed. Finally we discuss both electrical and thermal properties of graphene.

- ***Chapter 3*** presents thermally driven spin injection in Co and NiFe based nanopillar spin valve devices. Here, a nanopillar subjected to a temperature gradient provides an alternative means to create non-equilibrium spin accumulation in a nonmagnetic metal. The spin-dependent Seebeck coefficient, that governs the efficiency of this process, is accurately determined for two of the most commonly used ferromagnetic metals, permalloy and Co.

- ***Chapter 4*** focuses on the first experimental observation of a magnetic heat valve both at room and low temperatures. Here, it was possible to control heat flow in a nanopillar spin valve by changing its magnetic configuration from parallel to antiparallel configurations. Furthermore, we extend our current understanding of spin caloritronic phenomena, that is based on the two-spin channel model for spin up and spin up electrons, to include differences in the effective temperatures of spins as well as comment on its implication on the results presented in Chapter 3.

- ***Chapter 5*** describes the experimental validation of the Thomson-Onsager reciprocity relations (T-ORR) for spin caloritronics. Symmetry-relations that are known to hold for the charge Seebeck and Peltier effects are tested for the spin dependent counterparts. We further identify the linear thermal response regime in which the T-ORR is valid. In the non-linear regime, for large thermal/electrical biases, a deviation in the current-voltage relationships is observed whose origin can be understood using a three dimensional spin caloritronic model that includes higher order thermal/electrical effects.

- ***Chapter 6*** is devoted to the investigation of the interaction of pure spin current, in a metal, with the local magnetic moments, in a ferrimagnet insulator [yttrium iron garnet (YIG)]. Although the exchange of electrons across the metal/YIG interface is not allowed, spin exchange, due to the spin-mixing conductance $G_{\uparrow\downarrow}$ of the interface, is allowed. Using nonlocal spin valve devices fabricated on YIG, we investigate how spin transport is affected by the magnetization of the YIG. By comparing these results with similar measurements on the non-magnetic SiO_2 substrate, for which the parameters governing spin transport are well known, we quantify the spin-mixing conductance of the Al/YIG interface. A generic non-collinear spin transport model was also developed to understand spin injection processes and also extract $G_{\uparrow\downarrow}$ of the Al/YIG interface.

- ***Chapter 7*** focuses on the experimental investigation of the Seebeck and Peltier effects in graphene field effect transistors. Graphene's unique electronic band structure presents the possibility of tunning the Seebeck and Peltier coefficient from large negative values (in the electron regime) to large positive values (in the hole regime) opening up possibilities for graphene-based tunable thermoelectric conversion or refrigeration applications. Finally, by comparing separate measurements of S and Π we validate the Thomson-Onsager reciprocity relation in graphene.

The ***Appendix*** gives details regarding the nanofabrication and measurement techniques used in this thesis.

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