# Thermoelectric effects in magnetic nanostructures

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# Summary

The transport of negatively charged electrons in solid-state nanostructures (often called devices) is an essential mechanism for the functioning of modern computers and for a whole range of other electrical equipment. Whenever a voltage is applied between two spatially separated points on a metallic conductor, the freely available electrons start to diffuse from the negatively biased side towards the positive side, which leads to a flow of charge (an electrical current). Due to the high number of free electrons that are available for conduction in metallic systems, such a cloud of electrons moves at an extremely slow pace, typically a fraction of a millimeter per second for everyday currents. Nevertheless, the average velocity of a single electron is large, in the order of a fraction of the speed of light ($c = 300.000.000$ m/s). This contrast is caused by the many collisions between electrons which makes the system diffusive and behave like a gas, an electron gas. If instead of a voltage a temperature difference is applied between the two sides, the electron gas contributes to the transport of energy (heat) through the conductor. Hot electrons can transfer their energy to neighboring (colder) electrons during collisions and thereby create a flow of heat through the material, without electrons being physically moved from one side to the other. Since both charge transport and heat transport are a property of the electron gas it is not surprising that there exists an interaction between them. This interaction is called thermoelectricity and describes the generation of a voltage due to a temperature gradient (Seebeck effect) and the inverse effect, heating or cooling by charge currents (Peltier effect).

Additionally to charge and energy, electrons possess a third property: the electron spin or simply spin. This quantum mechanical spin describes the angular momentum that is associated with the electron. Since the electron has both a charge and spin it behaves as a small magnet with an intrinsic magnetic moment. The transport of electrons implies thus automatically a flow of magnetic moments, i.e.

a spin current. If the directions of the magnetic moments are completely randomized, then the charge current is not accompanied by a net flow of spin. However, in magnetic materials the majority of the electron spins point in the same direction and together they form the magnetization of the material. Hence, a charge flow in a magnetic material effectively transports magnetism. Whenever this current enters an adjacent non-magnetic metal, it injects this magnetic moment into the metal. This mechanism is called spin injection and makes the non-magnetic metal slightly magnetic. These injected spins can only survive over very short distances (in the order of hundreds of nanometers), whereafter a relaxation mechanism destroys this non-equilibrium situation. The relation between charge and spin transport has led to the research field of spin-based electrons (abbreviated: spintronics). By using the electron spin instead of its charge for processing and storage of information, novel and innovative functionality becomes possible for future spintronic devices.

This thesis describes the fundamental interactions between the three types of transport (charge, heat, spin) in magnetic nanostructures consisting of metallic elements. The work described here is part of a wider research direction, called spin-caloritronics, that studies the coupling between heat and spin transport in many different materials ranging from metals to ferromagnetic insulators. The spin-caloritronic experiments discussed in this thesis are based on the spin-dependency of regular thermoelectric effects, such as the Seebeck and Peltier effect. In spintronic devices, the transport of charge is generally described by two transport channels. A majority spin channel (usually named spin-up) for the electron spins that are pointing in the direction of the magnetization and a minority channel (usually named spin-down) for electron spins pointing anti-parallel to the magnetization. Spins pointing in a direction non-collinear with the magnetization do not survive for long in a magnetic material and can therefore be neglected. Generally, in ferromagnetic metals the majority channel has a larger conductivity since this channel contains more electrons than the minority channel. We have experimentally demonstrated that a similar approach is valid for the thermoelectric effects. One can assign different Seebeck and Peltier coefficients to the majority and minority electrons in a magnetic metal and hence, produce spin-thermoelectric effects without charge currents being involved. Whenever a temperature gradient is applied to a ferromagnet, due to the difference in Seebeck coefficients for spin-up and spin-down electrons, a spin current is generated in the ferromagnet. Such a spin current is special in the sense that it is a pure spin current, without an associated charge current. This spin current can for example be used as a thermally driven spin source for future spintronic devices. Inversely, we have shown that a spin current which is injected into a ferromagnet leads to the generation of a heat current, driven by the spin-dependent Peltier effect. This principle offers new functionality in the form of magnetically programmable heating and cooling using spin currents. Both these effects could add new (thermoelectric) functionality to spintronic devices.

Besides spin-dependent thermoelectric effects, regular thermoelectric effects are an interesting subject to study at the nanoscale. At shorter length scales, macroscopic (classical) models that are used to describe the physics at larger scales often break down at the nanoscale due to quantum-mechanical effects. Therefore, we experimentally investigated the regular Seebeck and Peltier effect in magnetic and nonmagnetic nanostructures and compared them to numerical simulations. It turns out that even though the device dimensions are approaching the mean free path length of the electrons, the system is still perfectly described by the classical equations for charge and heat transport. Moreover, we have found that thermoelectric effects are responsible for the spin-independent voltages that are often present in measurements of magnetic nanostructures, for example in nonlocal spin valves. The numerical simulations that are performed are 3D finite-element calculations using a diffusive transport model based on Ohm's and Fourier's law which is, for the spin-dependent thermoelectric effects, extended to a two (spin) channel model.

Thusfar, the discussed effects are stationary, i.e. they do not vary in time. However, magnetization reversal or the precessional motion of the magnetization are dynamical effects. The stable precession of the magnetization of a ferromagnet is called ferromagnetic resonance and adds a whole range of other effects to the field of spintronics. For example, the transfer of angular momentum from an adjacent metal into a ferromagnet leads to a torque on the magnetization and can ultimately, induce ferromagnetic resonance. On the other hand, a precessional magnetization motion pumps spins into an adjacent nonmagnetic metal as if it is a spin battery. In this thesis, the experimental work has focused on the coupling of magnetization dynamics with heat, being another branch of spin-caloritronics. We have studied the generation of heat during ferromagnetic resonance due to the damping and measured the temperature increase thermoelectrically. This novel technique provides an alternative method to characterize ferromagnetic resonance in a material and is applicable to conductive and non-conductive media.

The potential advantages of spin-caloritronic effects with respect to regular thermoelectricity can be found in the easy manipulation of magnetic textures at the nanoscale. This enables very localized and programmable control of heat flow which might prove useful for thermopower energy harvesting or refrigeration. However, the previously discussed effects are still weak and far from direct applications. Nonetheless, a combination of new developments in this field and by exploring novel materials it could one day lead to the implementation of spin-caloritronics in our everyday electronic devices.