# Theory of the spin Peltier effect

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In the field of electronics, the thermoelectric effects which are the mutual conversions of electric and heat currents have been studied in terms of the energy conservation. Generation of an electromotive force from a temperature gradient applied in a metal or a semiconductor is called the Seebeck effect. Conversely, creation of a temperature difference from an electromotive force is called the Peltier effect. Since the thermoelectric conversion enables us to use a waste heat, it has been studied extensively from the viewpoint of the suppression of the energy consumption.

The spin current, flow of the spin angular momentum of electrons, has attracted attention in the field of spintronics aiming at using and controlling both of the spin and charge degrees of freedom. In particular, the pure spin current without the electric current is expected to enable communication with reduced energy consumption since it is free from the Joule heat.

Recently, the establishment of interconversion between the spin and heat currents has been discussed in the field of spintronics. When a temperature difference is applied to a magnetic material, the spin current is generated. This phenomenon is called the spin Seebeck effect [1]. The inverse phenomenon in which a temperature difference occurs when the spin current is injected into a magnetic material is called the spin Peltier effect [2, 3]. Clarification of the interconversion between the spin and heat currents may lead to a new energy-saving device. The microscopic theory of the spin Seebeck effect has been built. In the case of the spin Peltier effect, however, no microscopic theory has ever been proposed.

In our paper, a microscopic theory of the spin Peltier effect has been constructed. We assume the bilayer system composed of a paramagnetic metal (PM) and a ferromagnetic insulator (FI), coupled magnetically at the interface (Fig.1).

First, we show the mechanism of the heat current generation from the spin current in our system. When the electric current is applied to PM, the spin current is generated by the spin-orbit interaction in PM, which is called the spin Hall effect. The spin current makes a reservoir of the spin-polarized conduction electrons at the interface. This is called the spin accumulation. The spin current is injected into FI by the spin accumulation through the magnetic coupling at the interface. In FI, the spin current is carried by the magnons which is the low energy magnetic excitation in FI. Since the magnons carry both of the spin and the energy, the heat current is also created. This is our scenario for describing the mechanism of the spin Peltier effect.

Next, we describe the spin and heat transports at the PM/FI interface using the non-equilibrium Green's function method. We define the spin and heat currents as the time derivatives of the spin of the conduction electrons in PM and the Hamiltonian in FI, respectively. Performing the perturbative calculation of the magnetic coupling at the interface, we obtain the expression of the spin current represented by the product of the spectral functions of the spin fluctuations in PM and FI, and the difference of the non-equilibrium distribution functions between PM and FI. We also derive the expression of the heat current represented by the product of the spin current and the energy passing through the PM/FI interface.

Using the obtained formulas, we give a description of the spin Seebeck and spin Peltier effects. Substituting the difference of distribution functions generated by the temperature difference between PM and FI as well as by the spin accumulation into the spin and heat currents, we obtain the formulas of the spin Seebeck and spin Peltier effects, respectively. Comparing these formulas, we confirmed that the spin Seebeck and spin Peltier effects are summarized using the Onsager's reciprocal relation.

Further, we estimate the temperature change due to the spin Peltier effect. At the interface, magnons are excited and accumulated by the spin Peltier effect. The energy change at the interface is generated by the accumulation of magnons. Then, the temperature change is obtained from the energy change. Our estimation is consistent with the experimental result [3].

In conclusion, a microscopic theory of the spin Peltier effect in a bilayer system composed of PM and FI was formulated using the non-equilibrium Green’s function method. We derived the spin and heat currents driven by temperature gradient as well as by spin accumulation at the interface in terms of the spectral and distribution functions of the spin fluctuations in PM and FI. These currents have been summarized using Onsager’s reciprocal relation. In addition, we estimated temperature change at the interface due to the spin Peltier effect. Our theory will provide a microscopic understanding of the interconversion between spin and heat currents at the PM/FI interface.

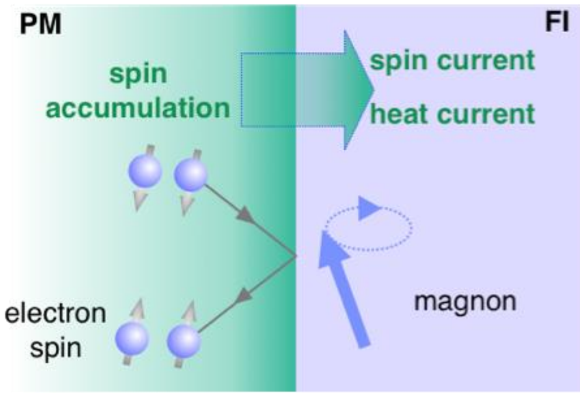


Fig.1 Schematic view of the spin Peltier effect. We consider spin and heat transports in a bilayer structure consisting of a paramagnetic metal (PM) and a ferromagnetic insulator (FI), where the electron spins in PI are coupled with the localized moments in FI via the magnetic interaction. The spin accumulation at the interface is found to be a driving force of spin and heat current.

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