Thermo-Spintronics: A New Direction for Spins

“Observation of the Spin Seebeck Effect,”

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Recommended with a Commentary by **Roland Kawakami, University of California, Riverside**

One of the big challenges of nano-electronics is the problem of power. As the transistors are reduced in size and packed more densely, the power density increases and generates large amounts of heat that could destroy the circuit. In addition, everybody would like to have portable electronics that use less energy for less frequent battery charging. For low power electronics, spintronics might someday provide an attractive alternative. The spin Seebeck effect, observed for the first time in this paper, may provide an important building block.

One aspect of spintronics that relates to power is the use of spin currents as opposed the charge currents used in conventional electronics.[1] One type of spin current is the “spin-polarized current” which is a charge current where the carriers have spin-polarization. This is what happens for electrical spin injection from a ferromagnetic electrode into a non-magnetic material. Because there is a charge current associated with the spin current, there will be ohmic power dissipation. The second type of spin current in the “pure spin current” in which there is a flow of spin but there is no charge current. For example, if electrons with spin-up move to the right and an equal number of electrons with spin-down move to the left, the net flow of charge is zero but there is a net flow of spin. Two examples of pure spin currents are electron spin diffusion and spin Hall effect. To illustrate the former, a popular type of measurement in spintronics that utilizes the pure spin current is the so-called “non-local” measurement (Figure 1). A charge current loop (red) injects spin-polarization from a ferromagnet into the non-magnet. Then, through electron spin diffusion there is a pure spin current that flows toward the right (green). But while pure spin currents have been achieved, there usually must be a charge current somewhere else in the device.

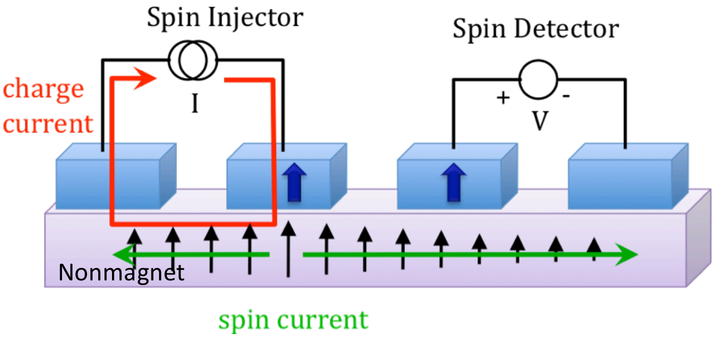

Figure 1: Non-local measurement

A major challenge is to generate pure spin currents without a charge current elsewhere in the device.

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[1] Another important aspect of spintronics related to power is the ability for ferromagnets to store information without power. This is the principle behind magnetic recording and magnetic RAM. This is well known and therefore not discussed here.

This is the major achievement of the current work. The authors observe the "spin Seebeck effect" in which a pure spin current is generated inside a ferromagnet by applying a temperature gradient. Furthermore, this spin current can be extended into a non-magnetic material just by attaching it to the surface of the ferromagnet, thus operating as a "spin battery" which generates spin-dependent chemical potential in a non-magnetic material. I note that optical pumping methods can also achieve these goals in semiconductors, but probably cannot be applied to metals.

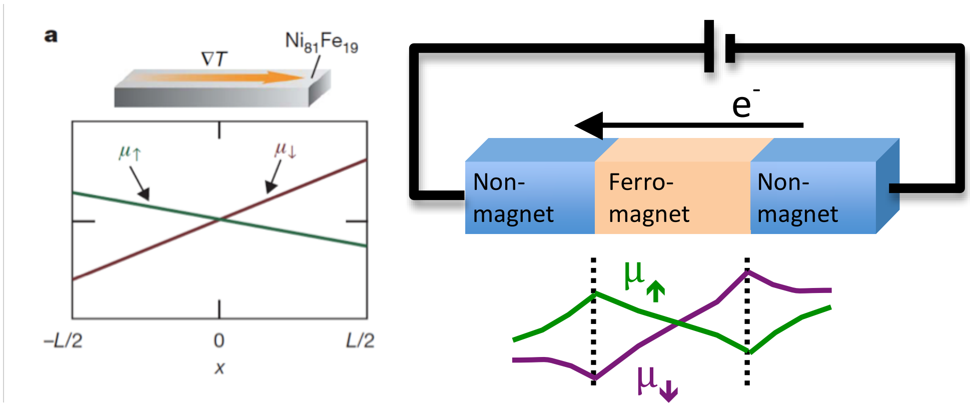

Figure 2: (left) Spin Seebeck effect: spin accumulation generated by temperature gradient, (right) Electrical spin injection geometry: spin accumulation generated by electric current

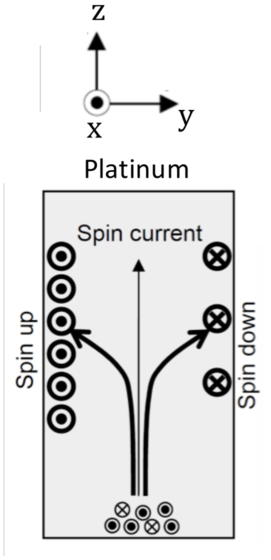

Figure 3: Inverse spin Hall Effect

The spin Seebeck effect and its measurement

For a material in a temperature gradient, carriers diffuse from the hot to cold regions and reach a steady state when the charges accumulate and produce a counter-balancing electric field. This is the Seebeck effect. In a ferromagnet, because the conductivity depends on spin, the diffusion current generated by the temperature gradient should also be spin-polarized. In steady state, the spin current should generate spin accumulation (i.e. spin-dependent chemical potentials) in the ferromagnet that varies with position as shown in the left panel of Figure 2. This is the spin Seebeck effect. Another way to think about it is to consider it as the thermoelectric analog of electrical spin injection, where the temperature gradient takes the place of the charge current (Figure 2, right). The geometry is the familiar spin injection geometry, but instead of considering the spin accumulation in the nonmagnetic regions, we should focus on the spin accumulation in the ferromagnet. Here, the spin accumulation is similar to the spin Seebeck effect, but with the notable difference that the spin accumulation in the spin Seebeck effect spans distances (6 millimeters in this experiment) much longer than the spin diffusion length.

The big challenge in measuring the spin Seebeck effect is to avoid spurious signals that could be originating from other sources. This is accomplished by using the inverse spin Hall effect (ISHE) in a

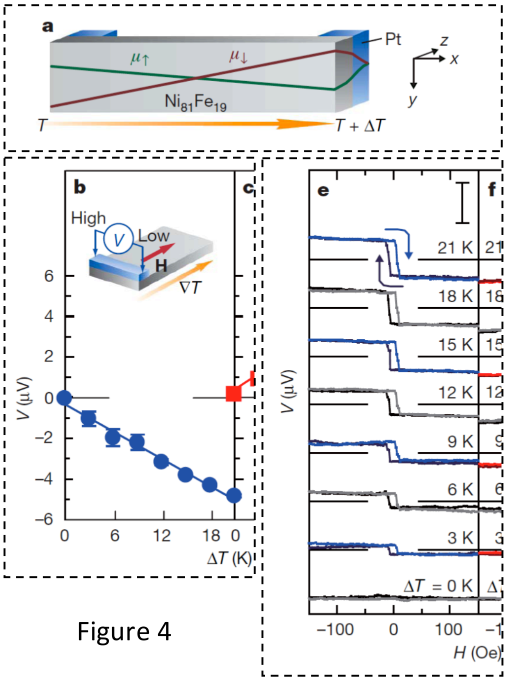

Figure 4

platinum (Pt) electrode to detect the spin current. Briefly, in the ISHE (Figure 3), a spin current flows along the z-axis. Spin-orbit coupling causes the spin-up (+x) to veer to the left and spin-down (-x) to veer to the right (assuming positive g-factor), and the spin-imbalance generates a transverse voltage which is the ISHE signal.

In this study, a thermal gradient is applied along the long axis of a permalloy ($Ni_{0.81}Fe_{0.19}$) wire to generate spin accumulation that varies with position. A Pt mesa fabricated on top of the permalloy wire is used to detect this spin accumulation via the inverse SHE. In Figure 4a, the magnetic field and spin are oriented along the x-axis, the spin current flows from the permalloy into the Pt (z-direction), and the ISHE voltage is measured along the transverse direction (y-axis). Figure 4b and 4e (Figure 3 of paper) shows the main data of the paper. The Pt detector is at the cold side of the permalloy and the magnetic field dependence of the inverse SHE voltage maps out the hysteresis loops of the permalloy wire. In addition, this inverse SHE signal increases linearly with the temperature difference across the permalloy. These are the expected characteristics for the spin Seebeck effect. Beyond this initial measurement, the authors perform many systematic checks to ensure that this signal comes from the spin Seebeck effect as opposed to spurious signals.

Concluding remarks

This work demonstrates the importance of thermoelectric effects for spintronics. Another recent paper also utilizes thermoelectric measurements to address a long-standing issue, namely the intrinsic or extrinsic origin of the anomalous Hall effect.[2] These advances are creating a new research area: “thermo-spintronics.”

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[2] Y. Pu, D. Chiba, F. Matsukura, H. Ohno, J. Shi, “Mott Relation for Anomalous Hall and Nernst Effects in $Ga_{1-x}Mn_xAs$ Ferromagnetic Semiconductors,” Phys. Rev. Lett. 101, 117208 (2008).