Electrical Detection of Spin Transport in Lateral Ferromagnet-Semiconductor Devices

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

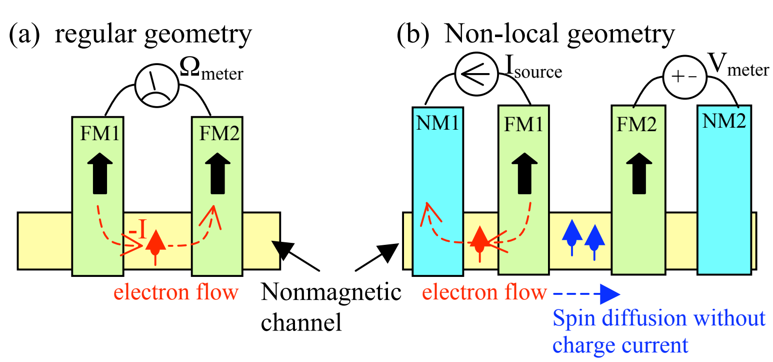
This is a very nice paper. To put this work in proper context, it is reasonable to say that it has been a challenge to convincingly demonstrate all-electrical spin injection and spin detection in a lateral semiconductor device. These efforts go back to 1990 with the proposal of Datta and Das for a spin field effect transistor (spin-FET) [1]. Some of the basic elements of this device are to use a ferromagnetic source to inject spin-polarized carriers into a semiconductor channel and a ferromagnetic drain to detect spin-polarized carriers. There are other aspects of this device, but it has taken 17 years to establish these first two aspects of device operation. One reason there is some much interest in developing the semiconductor spin devices (in light of very successful metal spin devices) is the fact of very long spin coherence times [2] and tunability of electronic and magnetic properties [3].

Electrical spin injection from a ferromagnetic electrode was established in 1999 through spin-LED experiments, which enabled systematic investigations needed to eliminate possible artifacts [4,5]. One innovation in those experiments was that they utilized magnetic semiconductors for efficient spin injection. At the time, many efforts utilized ferromagnetic metals, but they were largely unsuccessful. This turned out not to be pure coincidence; it was shown theoretically rather soon after the experimental results that spin injection from a metallic ferromagnet into a semiconductor is intrinsically limited due to a now famous conductivity mismatch problem [6]. Once the problem was identified, a theoretical solution to this problem was proposed: by introducing tunnel barriers in between the ferromagnet and the semiconductor, most of the voltage drop now falls in the neighborhood on the spin-dependent ferromagnetic interface and the spin-injection can be strong [7,8]. Work progressed on spin injection using tailored Schottky barriers or MgO layers to enhance the spin injection efficiency considerably. [9,10]

Electrical spin detection by ferromagnetic electrodes has not been as successful. Reports of semiconductor devices with all-electrical spin injection and detection have been controversial. Two key aspects of the Lou *et. al.* paper are (1) the non-local spin measurement developed originally by Mark Johnson [11] and (2) the Hanle effect. The latter is the clearest indication of spin-polarized transport. Both of these have been observed several years ago in the metallic lateral spin valves,[12] but until now nobody had achieved both of these in semiconductor systems.

Non-local spin measurement:

The figure to the right shows two typical geometries for electrical injection and detection of spin. In the "regular" geometry (which is what is used in the original spin-FET), spins are injected from FM1, and the spin-



polarized electron current flows to FM2 where they are detected. The signature of spin-polarized transport is a difference in resistance for the cases where the FM magnetizations are parallel or antiparallel (spin valve effect). Because these two magnetization alignments can be achieved by ramping an external magnetic field, the magnetoresistance measurement is the indicator of spin-polarized transport. While this is a very good measurement, the controversy comes about because there are other possible sources of magnetoresistance unrelated to spin-polarized transport such as anisotropic magnetoresistance of the FM electrodes and effects of magnetic fringe field on the electron motion. This is not to say that the two-terminal results are wrong, but just that further work should done.

The non-local geometry addresses many possible artifacts. In this geometry, spin polarized electrons are injected from FM1 and directs the carriers *away from FM2*. In this manner there is no electron drift toward FM2 and no electrical current toward FM2. However, there is electron diffusion, and in particular there is spin-diffusion. Electrons diffusing to the right are spin-polarized and the electrons diffusion to the left are unpolarized so that the net effect is for spin-polarization to diffuse to the right (without any net charge diffusion). The beauty of this geometry, for example, is that effects of orbital motion all cancel out because there is no net charge current between FM1 and FM2. Spins are detected by measuring the voltage between FM2 and NM2 (a nonmagnetic electrode in ohmic contact with the semiconductor). A voltage develops because the spin polarization under FM2 generates a spin-dependent chemical potential to shift the quasi Fermi level of FM2 up or down depending on the relative alignment of the magnetization and the spin in the semiconductor. Ramping an in-plane magnetic field results in parallel and antiparallel alignments due to the different magnetization switching fields of FM1 and FM2. This results in the hysteretic curves of Figure 1b of this paper.

Hanle effect

The clearest demonstration that this signal is generated by spin-polarization is the Hanle effect, which was observed in metals but not yet in semiconductors. The idea is to apply a large out-of-plane magnetic field to induce a precession of the spin-polarization in the semiconductor. If the spins precess 180 degrees by the time they reach FM2, the voltage signal will be reversed. Because the precession frequency increases with applied field, the voltage signal should oscillate with out-of-plane B field, which is precisely what is observed in Figure 1c. The reason this is a clear indication is that other magnetic properties such as the magnetizations of the ferromagnets and their fringe fields do not oscillate with B field, so the oscillatory phenomena is uniquely attributed to the electron spin precession. Figure 2 provides quantitative analysis, which uses known values for g-factor and independently measured values for diffusion constant, and a quantitative agreement is observed.

One last interesting question to ask is: What is special about their device which makes it work? My best guess is the tailored Schottky barrier. While the GaAs layer is n-doped in the 10^{16} cm^{-3} range (for long spin coherence times [2]), they linearly increase the doping to $5x10^{18}$ cm^{-3} in the last several nm before the Fe layer to narrow the Schottky barrier. This method was first used by Berry Jonker's group and leads to enhanced spin injection [9].

Overall, this is an important step for semiconductor-based spintronics which will build on these results to develop multiterminal lateral spin devices with spin manipulation capabilities.

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