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SPIN INJECTION, SPIN TRANSPORT, AND ELECTRICAL DETECTION OF SPIN PRECESSION IN MESOSCOPIC SPIN VALVES.

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What happens to the spin of an electron if it goes from A to B in a metal or semiconductor? This is at the moment an outstanding question in the active field of spintronics. In semiconductors most efforts have focussed sofar on optical studies of spin injection, spin dynamics and spin detection. Recently, spin injection into semiconductors was studied in spin LEDs where a spin polarized current was injected electrically and the resulting circular polarization of the emitted light was used as a probe to measure the spin polarization of the injected electrons.

In metals the history of spin injection into non-magnetic metals dates back to the experiments of Johnson and Silsbee[1]. Their results were made possible by the use of a special high purity single crystal aluminium bar, which at low temperatures has a very low spin relaxation rate. We have studied spin transport in multiterminal mesoscopic spin-valve structures based on Cu and Al as the non-magnetic media, connected to ferromagnetic (Py, Ni and Co) electrodes, with transparent contacts[2]. The multi-terminal geometry has allowed us to exclude all spurious magnetoresistance effects and investigate the dependence of the spin signal on the spacing between injector and detector ferromagnetic electrodes. Thus we could obtain the spin flip lengths in Cu and Al, both at room temperature as well as 4.2 K. Also we learned from these experiments that spin polarization of the injected current is limited to only a few percent. The reason for this was identified as "conductance mismatch"[3]. This conductance mismatch has also prevented us from observing spin injection into a semiconducto[4].

Next we have studied a new design, based on injection and detection via tunnel junctions to improve the efficiency of spin injection and detection[5]. In the experiments (see fig 1) a current is sent from the left Co electrode through a tunnel junction and taken out at the left side of an Al strip. Therefore no (charge) current flows in the right side of the device. Nevertheless, if the spacing between the injector and detector ferromagnetic electrodes is shorter than the spin flip length, a spin accumulation signal can be detected between the detector ferromagnetic electrode and a contact on the right side of the Al strip

First we have done a systematic study of the dependence of the spin signal on the spacing of the injector and detector electrodes[5]. We obtain a bipolar signal, which changes sign when the relative magnetization of the ferromagnetic electrodes changes from parallel to antiparallel. This is a proof that the measured signal is due to spin accumulation only. From the decay of the spin signal as a function of separation we obtained the spin flip lengths in Al: approximately 350 nm at room temperature, and 700 nm at 4.2K. Futher analysis shows that the efficiency of spin injection and detection is now about 10%, which has resulted in an increase of the signal by about a factor of 100, compared to[2]. Next we have investigated the possibility to change the spin signal by inducing controlled spin precession by an magnetic field applied perpendicular to the substrate. Fig. 2 shows an example where we measure the signal as a function of an applied perpendicular magnetic field. In the parallel configuration the signal is positive in the absence of precession. A finite magnetic field makes the spins precess. At fields larger than about 100 mT the signal changes sign. When the electrodes are in the antiparallel configuration exactly the opposite happens. This can only mean that the average spin has precessed through about 180 degrees. Therefore the data of fig. 2 shows for the first time that the spin of the injected electrons can be made to rotate 180 degrees, in such a way that the spin valve signal can be made to change sign. Fig. 2 shows a detailed comparison with theory[5]. The parameters used for the theoretical fit in fig 2. are however very close to those determined independently from the spin signal dependence on the Co electrode spacing.

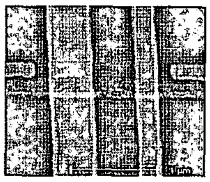

Fig. 1 Scanning electron microscope image of the mesoscopic spin valve structure. Two vertical Co strips make contact to the horizontal Al strip via tunnel barriers. (from ref.[5])

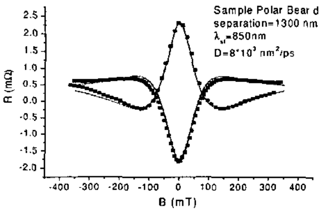

Fig. 2. Output signal measured between the right Co electrode and a contact to the right side of the Al strip. The data (squares) show controlled spin precession, and a comparison with theory (drawn lines) See text. (from ref.[5])

Finally, it is noted that because the spin flip length at room temperature is only reduced by a factor of about 2, the controlled precession can also be observed at room temperatur[6].

In summary, we have for the first time designed and fabricated devices in which only the spin degree of freedom (spin accumulation, spin currents, spin precession) determines the measured signal. This has allowed us to study the interplay between spin precession and spin-flip processes, and for the first time observe the controlled spin precession of injected electrons through 180 degrees or more in a purely electrical device. This type of device offers a unique way to study other transport phenomena associated with spin currents, such as an anomalous Hall effect caused by the skew scattering of spin polarized electrons by impurites and others.

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