Optical studies of spin injection and detection at ferromagnet / semiconductor interfaces

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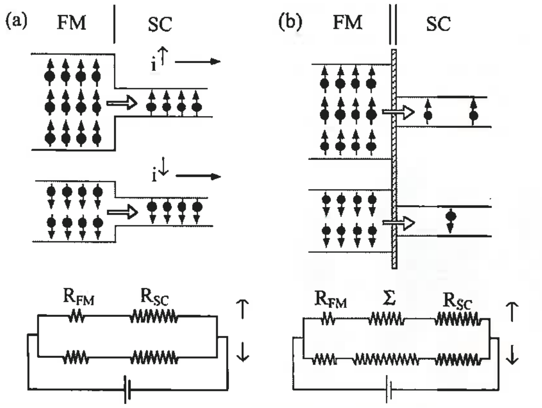
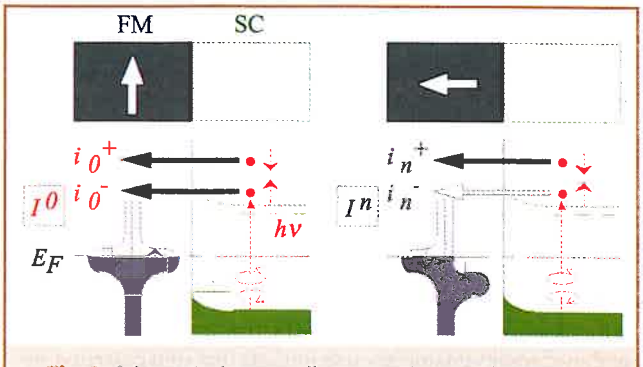
Recently, the newly emerging field of spintronics has attracted considerable attention. Significant advances in device performance, in terms of speed, size scaling and power requirements could be achieved by creating spin electronic devices based on the manipulation of spin polarized electrons [1]. Proposed spin analogues to conventional electronic devices have stimulated great interest, *e.g.* the spin polarized field effect transistor (spin FET) [2,3] and the spin polarized light-emitting diode (spin LED) [4,5]. In order to realize such spin electronic devices, spin dependent electron transport needs to be better understood. It is very important to note that efficient spin dependent transport depends on achieving *both* efficient spin injection from a ferromagnet (FM) into a semiconductor (SC) [4-8], *and* efficient spin detection of electrons passing from the SC into the FM. Efficient spin injection has been reported by Fiederling *et al.* [4] and Ohno *et al.* [5] using a magnetic SC but only at low temperature in all SC device structures. Recently, spin injection from a FM metal into a SC has been achieved at room temperature with an efficiency of 2 % [6] and 30 % [7] in Schottky barrier structures, and at 80 K with an efficiency of 9 % in FM/AlO_x barrier/SC structures [8], respectively. The question remains as to whether room temperature efficient operation is possible and also whether strong spin trans-



▲ **Fig. 1:** Schematic of spin dependent electron transport at (a) a FM/SC interface and (b) a FM/tunnel barrier/SC interface. A resistor model is also shown for both cases, where R_{FM}, R_{SC} and Σ denote the resistance in the FM and the SC and the tunnel barrier contact resistance, respectively.



▲ **Fig. 2:** Schematic diagrams illustrating the spin filtering mechanism for electron transport at the FM/Schottky barrier/SC interface. Averaged density of states of FM is shown for the case of I^0 for simplicity.

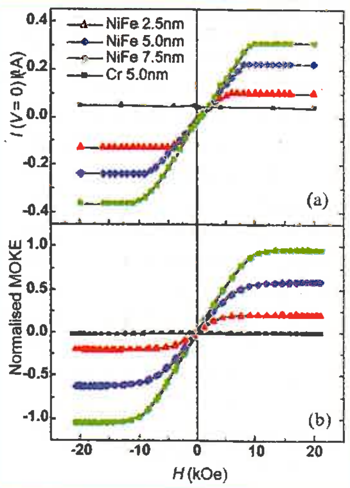
mission can be achieved between FM metals and SC. Theoretically, it has been suggested that there may be fundamental obstacles to achieving efficient spin transmission across FM metal/SC interfaces via a diffusive electron transport process [9] due to the conductivity mismatch between the FM metal and the SC. In this case the electron transport properties are dominated by the large resistance of the SC, diluting any spin dependent effects at the interface (Fig. 1a). It is expected, however, that spin dependent electron transport can be achieved via electron tunneling at FM/SC interfaces [10]. If the tunneling process is spin dependent and the tunnel barrier contact resistance is larger than the resistance of the SC, spin injection and detection efficiencies of up to 100% can be expected (Fig. 1b). So far very few studies have been conducted on spin detection and further clarification of the mechanisms involved is highly desirable.

We investigated spin filtering across FM/SC Schottky interfaces as a function of FM material, FM layer thickness and applied magnetic field using photoexcitation techniques [11,12]. Polarized photoexcitation in FM/SC structures was employed to create a population of spin polarized electrons in the SC substrate (GaAs). The spin dependent electron transport across the FM/SC interface at room temperature was detected as an electrical response, the strength of which varies according to the configuration of the photon helicity with respect to the FM layer magnetization (inset of Fig. 4). We achieved a change in helicity dependent photocurrent when the magnetization was realigned from perpendicular to parallel to the photon helicity, which is attributed to spin filtering at the FM/SC interface due to the spin split density of states (DOS) in the FM. These spin transport effects increase with increasing FM layer thickness and applied magnetic field. Applying dc measurement techniques, we were furthermore able to quantify the spin polarization of the electrons filtered at the FM/SC interface. Based on our results we discuss a simple model for the spin transport mechanism across the Schottky barrier.

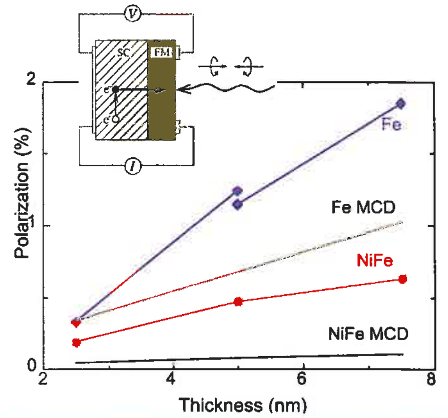
We used ultrahigh vacuum (UHV) deposition techniques to fabricate 2.5, 5.0 and 7.5 nm thick polycrystalline $Ni_{80}Fe_{20}$ and Fe layers directly onto GaAs substrates (Si doped, $n=10^{23}$ m^{-3} and 10^{24} m^{-3} for the NiFe and Fe samples, respectively), capped with 3 nm thick Au layers. An antiferromagnetic Cr sample (5.0 nm, $n=10^{23}$ m^{-3}) was also prepared as a reference. A bias voltage was applied between one Au electrical contact on the surface of the sample and an ohmic contact attached to the back of the substrate. The current flowing through these two pads was measured (both with and without photoexcitation), while the voltage across the sample was also measured using a separate top contact as shown in the inset of Fig. 4 [11]. A circularly polarized laser beam (with photon energy $h\nu = 1.96$ eV) was used together with an external magnetic field to investigate the spin dependence of the photoexcited electron current at room temperature. The polarization of the beam was modulated from right to left circular using a photo-elastic modulator with 100 % circular polarization at a frequency of 50 kHz.

As discussed above, the process (tunneling, thermionic emission etc.) by which electrons are transported from the SC into the FM is a key issue for the realization of spin detection. Photoexcitation measurements we recently carried out on band gap engineered FM/AlGaAs tunnel barrier/SC structures [13] clearly showed that significant spin filtering can only be expected for tunneling electrons, in good agreement with the theoretical predictions [9,10]. Our discussion of the spin dependent transmission process will therefore focus just on the tunneling of electrons through the Schottky barrier followed by ballistic transport in the FM.

The helicity dependent photocurrent I was measured by modulating the photon helicity from right (σ^+) to left (σ^-). The two helicity values correspond to opposite spin angular momentum values of the incident photons and the helicity gives rise to opposite spin polarizations of electrons photoexcited in the GaAs [14]. The magnetization (M) in the FM is aligned perpendicular or in plane (H=0) using an external field. For $\sigma // M$ (or anti-parallel), the electrons in the FM and the SC share the same spin quantization axis, while for $\sigma \perp M$, on the other hand, the two possible spin states created by the circularly polarized light are equivalent when projected along the magnetization direction in the FM (Fig. 2). Consequently, in the remanent state ($\sigma \perp M$), since M is orthogonal to the photoexcited spin polarization, both up and down spin polarized electrons in the SC can flow into the FM, opposing the electron current from the FM. At perpendicular saturation ($\sigma // M$), on the other hand, the up spin electron current from the SC is filtered due to the spin split DOS in the FM. This means that a greater net negative current now flows with $\sigma // M$ than that for $\sigma \perp M$, since the current from the metal to the SC is largely independent of the magnetization configuration. Spin filtering is therefore turned on or off by controlling the relative axes of σ and M, and is detected as the helicity dependent photocurrent I. With $\sigma \perp M$, there is no spin filtering, while spin filtering is turned on by rotating to $\sigma // M$. The helicity dependent photocurrents I^0 and I^n correspond to the magnetization configurations $\sigma \perp M$ (Fig. 2, left) and $\sigma // M$ (Fig. 2, right), respectively. I^0 and I^n are



◀ **Fig. 3:** Applied magnetic field dependence of (a) I and (b) MOKE signal for NiFe/GaAs (t=2.5, 5.0 and 7.5 nm) and Cr (5.0 nm)/GaAs samples.



▲ **Fig. 4:** Thickness dependence of spin polarization across the FM/GaAs interface for the case of both NiFe and Fe as the FM. The magnitude of the calculated MCD effects is also shown as positive values. In the inset a schematic of the experimental set up is shown.

proportional to the difference between the current components for right and left circularly polarized light for each magnetization configuration: $I^0 \propto i_0^+ - i_0^-$ and $I^n \propto i_n^+ - i_n^-$. As shown in Fig. 2, $i_0^+ = i_0^-$ is expected for the case of the remanent state, while $i_n^+ \neq i_n^-$ is expected for the case of perpendicular saturation. Due to our experimental geometry, where the light enters the SC through the FM layer, we can expect a contribution from magnetic circular dichroism (MCD, i. e. the different absorption of right and left circularly polarized light in a magnetic material) to I.

The magnetic field dependence of the helicity dependent photocurrent at zero applied bias for the three permalloy samples is shown together with the corresponding polar magneto-optical Kerr effect (MOKE) measurements in Fig. 3 (a) and (b), respectively. The MOKE signal is proportional to the magnetic moment of the FM film and therefore provides a qualitative measure of the FM magnetization. As can be seen in Fig. 3, the field dependence of the helicity dependent photocurrent matches that of the MOKE signals, showing the magnetic nature of the effect. Similar results were obtained for the Fe samples. We can therefore conclude from this observation that there are no significant background effects due to Zeeman splitting in the GaAs. Although the Cr sample shows a small offset, the signal does not possess any field-dependence (due to a possible SC-related background), confirming that the Zeeman splitting effect is negligible in our measurement.

In order to study the spin filtering effect quantitatively, we performed dc photoexcitation measurements. Circularly polarized light was generated using a $\lambda/4$ plate, and the dc helicity dependent photocurrent was observed for both right (I^+) and left circular (I^-) configurations. The spin polarization of the spin filtering effect was estimated as $P = (I^+ - I^-)/(I^+ + I^-)$. Figure 4 shows the thickness dependence of both the estimated spin polarization and the magnitude of the MCD effect for both NiFe and Fe samples. The spin polarization increases with the FM layer thickness t and is larger than the calculated MCD effect as shown in Fig. 4. A similar thickness dependence of the spin polarization has been reported by van't Erve *et al.* [15], suggesting that spin filtering occurs in the ballistic regime. It should be noted that the signs of spin polarization for spin filtering are the same for both NiFe and Fe but that the sign of MCD is expected to be opposite for NiFe and Fe.

In conclusion spin polarized electron transport across FM/SC hybrid structures has been investigated for different FM materials (NiFe and Fe), FM layer thicknesses and applied magnetic fields. At room temperature, we observed a clear difference in the helicity dependent photocurrent through the FM/GaAs interface according to the orientation of the sample magnetization with respect to the helicity. This difference in photocurrent corresponds to a measure of the spin polarized photocurrent passing from the SC into the FM. The crucial transport mechanism in this spin filtering process is the tunneling of photoexcited electrons through the Schottky barrier. Antiferromagnetic Cr/GaAs shows no spin dependence as expected and provides an important test of the validity of our experiments. The spin polarization increases with the FM layer thickness, which provides further support of the view that spin filtering is associated with ballistic transport in the metal. Our combined results unambiguously indicate that spin polarized electrons are transmitted from the SC to the FM with high efficiency.

Acknowledgments

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