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Highly efficient spin filtering of ballistic electrons

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Spin dependent electron transport in hybrid Au/Co/Cu/NiFe/*n*-GaAs spin valve Schottky barrier structures was investigated using photoexcitation at various wavelengths. For excitation with the photon energy well above the Schottky barrier height we found a ~2400% increase in helicity dependent photocurrent on switching the spin valve from parallel to antiparallel alignment. Our observations provide clear evidence for highly efficient spin filtering of spin polarized ballistic electrons.

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The newly emerging field of spintronics, based on the exploitation of the spin of the electron rather than its charge, has recently attracted considerable attention.[1,2] Proposed room-temperature spintronic devices, such as the spin transistor[3] or the spin light-emitting diode,[4] offer the possibility of adding a new dimension to existing electronic devices, significantly improving the device performance in terms of speed, size, and power consumption. A prerequisite for their realization is, however, achieving efficient spin dependent electron transport between semiconductors (SC) and ferromagnetic (FM) materials based on a clear understanding of the underlying physical processes. This includes both spin injection from a FM into a SC and spin detection of electrons passing from a SC into a FM. Spin injection in FM/SC (Refs. 5 and 6) and FM/tunnel barrier/SC structures[7] has been demonstrated by several groups for metallic FM but to date efficiencies are small at room temperature. So far it remains an open question what factors limit these efficiencies and whether the spin dependent transport process is purely an interface effect.

Our group has recently demonstrated room temperature electron-spin detection in single FM layer/SC structures using photoexcitation techniques.[8,9] The photoexcited electrons passing from the SC into the FM layer have different transmission probabilities at the SC/FM interface depending on their spin orientation with respect to the layer magnetization. This is termed spin filtering and gives rise to a modulation of the photocurrent when the polarization state of the illumination light is changed from right to left circularly polarized. Studies of FM/GaAs structures with different FM thicknesses suggested that the electron-spin filtering process is not a pure interface effect since an increase in spin polarization with increasing FM layer thickness was observed.[9] However, in these experiments the observed photocurrent modulation with applied field is still relatively small [~1% (Ref. 9)]. One very promising way of achieving a large current modulation is the spin valve transistor,[10,11] where unpolarized electrons propagate from a Si emitter to a Si collector over a metallic spin valve multilayer. This suggests that new spin filtering effects might be expected in a hybrid spin valve/SC structure where polarized electrons enter the spin valve from the SC. We therefore chose to investigate spin dependent transport in spin valves grown on GaAs, where spin accumulation can be achieved by optical pumping.[12] The use of a spin valve on top of the GaAs enables us (i) to search for different spin filtering mechanisms and (ii) to study the ballistic electron transport processes in the FM metal in more detail. In such a structure the two FM layers can be switched independently, enabling us to distinguish between the spin filtering processes taking place at the SC/FM interface and those within the spin valve. A further advantage is that, in contrast to the case of a single FM layer/SC structure, the spin valve structure allows for a separation of the photocurrent components passing into the SC and into the FM metal multilayer. We are therefore able to quantify the observed spin filtering effect.

All measurements discussed in this study were carried out at room temperature on a polycrystalline Au(2nm)/Co(2nm)/Cu(5nm)/$Ni_{80}Fe_{20}$(3nm)/*n*-GaAs(100) hybrid spin valve structure with an ohmic NiGeAu bottom contact. For the growth of the bottom contact at the back of the GaAs substrate (Si doped, $n=10^{24}$ m^{-3}) and the cleaning of the substrate surface, the procedure followed in previous studies[8] was used. The growth of the metal layers was done by *e*-beam evaporation under ultrahigh vacuum conditions with a growth rate of approximately 0.2 nm/min monitored by a quartz crystal precalibrated by atomic force microscopy. During the growth the pressure was maintained at 6×10^{-10} mbar and the substrate was held at room temperature. Subsequently two 400 nm thick electrical Al contacts were evaporated on the Au capping layer by thermal evaporation. Conventional three contact *I*-*V* measurements[8] were carried out in order to characterize the Schottky behavior of the sample. The barrier height was found to be 0.26 eV.

The magnetic sample properties were investigated with magneto-optical Kerr effect (MOKE) magnetometry, revealing a growth induced in-plane uniaxial anisotropy. The hysteresis loop along the easy axis exhibited a double switching behavior typical for a spin valve. The NiFe layer was found to switch first at about 5 Oe as the magnetic field H was swept from saturation, followed by the Co layer at about 14 Oe, resulting in a field range of about 9 Oe where the layers are aligned antiparallel. All optical measurements were carried out at zero applied bias using an in-plane setup as follows: the magnetic field was applied parallel to the sample plane along the easy axis; electrons were photoexcited in the GaAs by laser illumination incident at an angle $\theta = 45°$ from the sample surface normal. In this case the photon helicity has an in-plane component and therefore electrons with an in-plane spin-polarization component (parallel to the FM

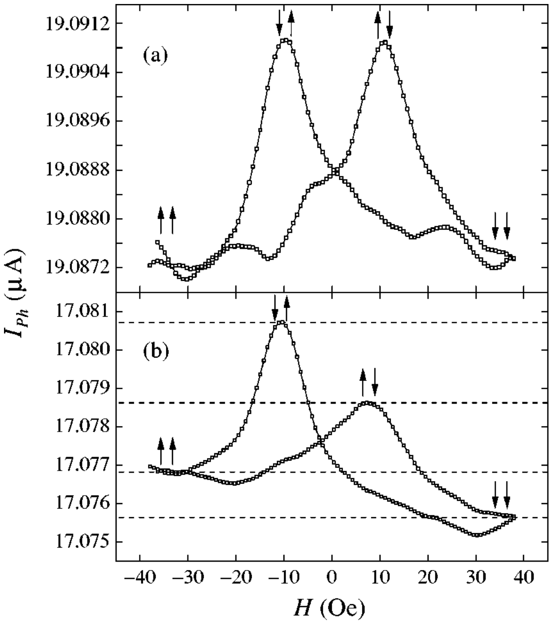

FIG. 1. Photocurrent vs applied magnetic field with $\lambda = 632.8$ nm for (a) illumination with linearly polarized light and (b) illumination with circularly polarized light. The solid line is a guide to the eye. The dashed lines and the arrows denote the parallel and antiparallel states of the spin valve.

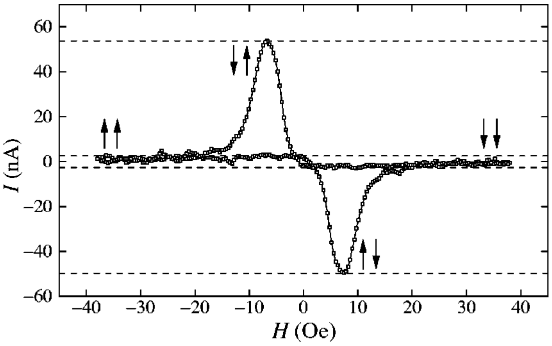

FIG. 2. Helicity dependent photocurrent vs applied magnetic field with $\lambda = 632.8$ nm. The solid line is a guide to the eye. The dashed lines and the arrows denote the parallel and antiparallel states of the spin valve.

layer magnetization) are excited in the SC. The majority of the measurements discussed here was carried out using a He-Ne laser with a wavelength λ of 632.8 nm (corresponding photon energy $h\nu = 1.96$ eV), but laser diodes with a λ of 670 nm (1.85 eV) and 785 nm (1.58 eV) were also used. The light intensities of the three lasers were of similar magnitude allowing for direct comparison of the measurements.

For illumination with linearly polarized light ($\lambda = 632.8$ nm) [Fig. 1(a)] we observed symmetric photocurrent peaks for the two antiparallel states of the spin valve. These peaks arise due to unpolarized photoexcited electrons passing from the SC into the spin valve and are a consequence of the conventional giant magnetoresistance (GMR) effect only: unpolarized electrons entering the spin valve are scattered according to the relative alignment of the two FM layers. Similar results have been reported by Rippard and Buhrman,[13] who used a nonmagnetic scanning tunneling microscopy tip to inject unpolarized electrons into a Co/Cu/Co trilayer structure. The finding of peaks instead of dips shows that the net measured photocurrent at zero bias flows into the bulk of the GaAs. In contrast to the case of a single FM layer on GaAs,[8,9] the use of a spin valve now enables us to separate the contribution of the photocurrent passing from the SC into the spin valve from the net measured photocurrent, allowing for a detailed study of the different transport processes involved in our experiment. The total photocurrent generated in the spin valve/SC structure I_{total}, which is the sum of the current component flowing away from the interface into the bulk of the SC (I_{SC}) and the current component flowing into the spin valve (I_{SV}) [Fig. 3 (top)],[14] is given by $I_{\text{total}} = I_{SV} + I_{SC} = 2\Delta I_{Ph}/\gamma + I_{Ph}(\uparrow\uparrow)$. Here $I_{Ph} = I_{SC} - I_{SV}$ is the net measured photocurrent, $\Delta I_{Ph} = I_{Ph}(\downarrow\uparrow) - I_{Ph}(\uparrow\uparrow)$ is the height of the photocurrent peaks [Fig. 1(a)] and γ is the GMR ratio. Therefore the fraction I_{SV}/I_{total} of the total photocurrent that passes across the SC/FM interface is

$$\alpha = \left(2 + \gamma \frac{I_{Ph}(\uparrow\uparrow)}{\Delta I_{Ph}} \right)^{-1}. \tag{1}$$

Assuming $\gamma = 0.7\%$ obtained in current in plane (CIP) MR measurements[15] as a lower limit we find that $\alpha = 2.6\%$.[16]

For illumination with circularly polarized light [Fig. 1(b)] using a λ/4 plate we found a significant asymmetry induced in the photocurrent peaks for the two antiparallel spin valve states. Switching the circular light polarization from left to right reverses the observed asymmetry, showing that the spin filtering process in the spin valve structure is dependent on the initial polarization of the photoexcited electrons. In a very simple qualitative model, the existence of an asymmetry might be expected to originate from a simple combination of spin filtering at the SC/FM interface (as observed in single FM layer/SC structures[8,9]) and conventional GMR [Fig. 1(a)]. In this case the photocurrent from the SC into the spin valve would depend on the relative alignment of the photoexcited electron spin with the magnetization of the first FM layer (NiFe). As a consequence, for a given circular light polarization, the ↑↑,↓↑ configurations would no longer be equivalent to the ↓↓,↑↓ configurations, respectively, resulting in an asymmetry of the GMR peaks as observed [Fig. 1(b)]. However, while the dc measurements give the qualitative dependence of the polarized photocurrent on magnetic field, they cannot be used for a quantitative description, due to the insufficiently precise alignment of the λ/4 plate and drift effects at saturation. Moreover we shall now show that a quantitative analysis based on ac measurements rules out the validity of this simple model.

In order to circumvent these problems we used a photoelastic modulator to switch between left and right circular polarization of the light and a lock-in amplifier to detect the signal. Figure 2 shows the measured helicity dependent photocurrent $I = p(i^{+} - i^{-})$ dependence on applied magnetic field at zero bias for $\lambda = 632.8$ nm. Here p is a phase factor ($p = 1$ in our measurements) and i^{+} and i^{-} are the net photocurrents for illumination with right and left circularly polarized light, respectively. We observed a relatively small change in I between the two parallel configurations of the spin valve but found a much larger change between the two antiparallel states (Fig. 2): $I(\uparrow\downarrow)$-$I(\downarrow\uparrow)$ is about 25 times larger than $I(\uparrow\uparrow) - I(\downarrow\downarrow)$. The height of the peaks for the two antiparallel states in Fig. 2 corresponds to the asymmetry of the photocurrent peaks [Fig. 1(b)] for illumination with right and left circularly polarized light, respectively. The observation of a $\sim 2400\%$ increase in helicity dependent photocurrent on switching the spin valve from parallel to antiparallel alignment clearly rules out a simple superposition of spin filtering at the SC/FM interface and conventional GMR in the spin valve. In this case changing the alignment of the second magnetic layer (Co) would only weakly modulate the photocurrent (due to GMR), resulting in a relative change of helicity dependent photocurrent between the parallel and antiparallel spin valve configuration of 8% (Ref. 17 and 18) at most. The strong dependence of the helicity dependent photocurrent on the alignment of the Co layer shows that the spin dependent transport process is not purely an interface effect and that spin filtering within the metal structure plays an important role.

As pointed out above, the possibility of separating the photocurrent across the spin valve from the net measured signal allows us to quantify the observed spin filtering effect. We are therefore able to give a lower limit for the spin polarization of the photocurrent passing the spin valve $P(\sigma)$ defined as

$$P(\sigma)=\frac{I_{SV}^{+}(\sigma)-I_{SV}^{-}(\sigma)}{I_{SV}^{+}(\sigma)+I_{SV}^{-}(\sigma)}, \qquad (2)$$

where I_{SV}^{+} and I_{SV}^{-} are the components of the photocurrent propagating across the SC/FM interface into the spin valve for the case of right and left circularly polarized light illumination, respectively. Here $\sigma=\uparrow\uparrow,\downarrow\downarrow,\uparrow\downarrow,\downarrow\uparrow$ denotes the possible states of the spin valve. Now $I_{SV}^{+}+I_{SV}^{-}=2\alpha I_{\text{total}}$ for the two parallel spin valve configurations and $I_{SV}^{+}+I_{SV}^{-}=2\alpha I_{\text{total}}-\Delta I_{Ph}^{+}-\Delta I_{Ph}^{-}$ for the two antiparallel spin valve configurations, with ΔI_{Ph}^{+} and ΔI_{Ph}^{-} being the photocurrent peak heights for illumination with right and left circularly polarized light, respectively. Taking into account that $I_{SV}^{+}-I_{SV}^{-}=i^{+}-i^{-}$ (Fig. 2), since I_{SC} is unaffected by the alignment of the magnetic layers with respect to the spin direction of the excited electrons, we estimate $P(\sigma)\approx+(-)5.9\%$ for the two antiparallel configurations of the spin valve which is more than 28 times larger than the value for the two parallel states $P(\sigma)\approx+(-)0.2\%$. We note that in the case of a simple superposition of spin filtering at the SC/FM interface and conventional GMR in the spin valve, P would *only* be dependent on the alignment of the first magnetic layer (NiFe) with respect to the photon helicity irrespective of the configuration of the spin valve. The strong dependence of P on the relative alignment of the two FM layers suggests that ballistic electrons propagating through the potential energy "landscape" of the spin valve are involved in the spin filtering process. Furthermore the spin polarization of 5.9% observed in the antiparallel state shows that this transport mechanism is highly spin dependent, since for illumination with He-Ne laser light the spin polarization of the electrons photoexcited in the GaAs is $\lesssim$ 10%.[12] Therefore, these electrons must be spin filtered in the spin valve structure with a high degree of efficiency.

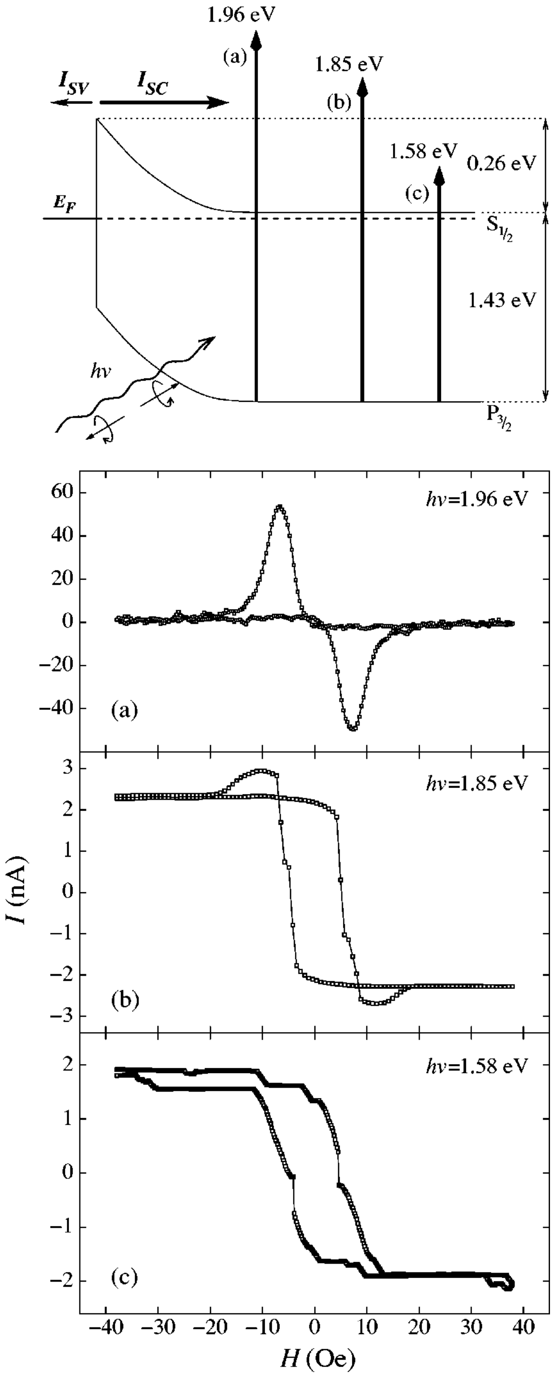

FIG. 3. Schematic of electron photoexcitation in the GaAs close to the Schottky barrier for three different photon energies (top). Here $S_{1/2}$ and $P_{3/2}$ denote the conduction and light/heavy hole valence bands, respectively. Helicity dependent photocurrent vs applied magnetic field for photon energies of (a) 1.96 eV, (b) 1.85 eV, and (c) 1.58 eV.

Our picture of ballistic electron spin filtering is further supported by the photon energy dependence of the helicity dependent photocurrent. Figure 3 shows the variation of I with the applied magnetic field for three different photon energies of (a) 1.96 eV, (b) 1.85 eV, and (c) 1.58 eV. In the first two cases the energy of the photoexcited electrons lies above the Schottky barrier height whereas in the latter case it lies below, as depicted in Fig. 3 (top).[19] As can be seen the relative height of the helicity dependent photocurrent peaks at antiparallel alignment decreases with decreasing photon energy [Figs. 3(a) and 3(b)] although the spin polarization of the electrons excited in the GaAs is increased to about 20%.[12] For $h\nu = 1.58$ eV [Fig. 3(c)] the peaks disappear, suggesting that either very few electrons travel across the SC/FM interface or that at this energy the electron transport process is only weakly sensitive to the relative alignment of the initial spin polarization in the GaAs and the magnetization of the Co layer. We conclude that, in contrast to single FM layer/SC structures where electron tunneling is found to be the dominant spin dependent transport mechanism,[20] ballistic electron spin filtering is responsible for the observed effects in spin valve/SC structures. In this case spin polarized electrons are excited in the GaAs, enter the spin valve above the Schottky barrier and ballistically propagate through the metal layers. Some of these electrons are reflected at the FM/nonmagnetic metal interfaces in the spin valve, due to band structure mismatches and the requirement of transverse momentum conservation. The reflection and transmission probabilities depend on the details of the Fermi surfaces in the different materials and consequently are spin dependent.[21] The strong variation of the helicity dependent photocurrent with photon energy is therefore likely to be related to the energy dependence of the electronic band-structure in the different metal layers. Hot electron spin transport in single FM films has been studied for example by Weber *et al.* in transmission[22] and reflection,[23] using various injection energies ($\geqslant 5$ eV). In the latter case, energy dependent changes of the electron spin transport properties were observed and shown to be in good agreement with the details of the band structure. A comparison with our results is, however, difficult, due to substantial differences in the electron injection mechanism, the investigated metal structure, the relative alignment of electron spin and FM layer magnetization and the energy range probed. In order to gain a more profound understanding of the spin filtering effect observed in our experiment, a realistic computational model including actual band-structure parameters is necessary.

In conclusion we have investigated spin dependent electron transport in hybrid spin valve/GaAs structures. A $\sim$2400% increase in helicity dependent photocurrent was observed on switching the spin valve from parallel to antiparallel alignment. This finding clearly rules out a simple superposition of spin filtering at the SC/FM interface and conventional GMR and demonstrates that the observed spin filtering process is not a pure interface effect. Furthermore the spin valve/SC structure enables us to separate the photocurrent across the SC/FM interface from the net measured signal therefore allowing the observed spin filtering effect to be quantified. An increase in spin polarization P by a factor of more than 28 was found when the FM layers were switched from parallel to antiparallel alignment. P was found to be 5.9% for the antiparallel spin valve states for $h\nu = 1.96$ eV. This shows that high energy electrons are spin filtered with a high degree of efficiency, taking into account the spin polarization of the electrons excited in the GaAs ($\lesssim 10\%$). The strong dependence of the helicity dependent photocurrent on photon energy suggests that electrons passing over the Schottky barrier are involved in this filtering process. Our combined data provides clear evidence that spin polarized ballistic electrons are strongly spin filtered in the spin valve structure.

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[16] The electron transport in our measurement geometry is likely to be a combination of CIP and current perpendicular to the plane (CPP) components; the CPP contribution is suppressed due to the relatively large aluminium contact diameter ($\sim$0.5 mm), so that the CIP contribution dominates the measurement. Since γ is larger for the case of CPP transport, we give γ_{CIP} as a lower limit.

[17] Note that we give the value for CPP GMR here as an upper limit.

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