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Test of ballistic spin-polarized electron transport across ferromagnet/semiconductor Schottky interfaces

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We previously reported highly efficient spin detection associated with spin filtering at single layer ferromagnet (FM)/GaAs interfaces (NiFe, Co, and Fe as the FM) using photoexcitation at room temperature, confirming that the Schottky barrier acts as a tunnel barrier. In order to consider explicitly possible background effects, e.g., magnetic circular dichroism, we therefore prepared antiferromagnetic (AF) Cr/GaAs structures as reference, using the same growth techniques as used for the FM structures. The Cr/GaAs samples showed very good Schottky characteristics and the difference in the helicity-dependent photocurrent was found to be negligible, indicating that no spin filtering occurs at the AF Cr/GaAs interfaces. These combined results conclusively show that high efficient spin detection can be achieved at room temperature. [DOI: 10.1063/1.1447198]

I. INTRODUCTION

Future spin electronic devices will require *both* spin injection from a ferromagnet (FM) to a semiconductor (SC) *and* spin detection from a SC to a FM.[1] Recently highly efficient spin injection has been achieved using dilute magnetic semiconductors (DMS)[2,3] in combination with long electron spin diffusion length.[4] Spin detection, on the other hand, has not stimulated great interest apart from a study using a metal point contact.[5]

Previously we reported highly efficient spin detection associated with spin filtering at single layer FM/SC interfaces (NiFe, Co, and Fe as the FM) using photoexcitation at room temperature, confirming that the Schottky barrier acts as a tunnel barrier.[6] We observed a current asymmetry of up to 20% in these structures corresponding to the normalized difference in helicity-dependent photocurrent obtained with magnetization perpendicular and parallel to the film plane. As a further test of the spin filtering mechanism, we subsequently investigated a spin valve structure, which provided evidence of ballistic spin-polarized electron transport effects.[7] However, in addition to intrinsic spin filtering effects, we also need to consider explicitly possible background effects, e.g., magnetic circular dichroism (MCD), the effect of a GaAs Zeeman splitting as well as the possibility of spin-dependent electron transport from the FM to the GaAs.

In this study, we therefore prepared antiferromagnetic (AF) Cr/GaAs structures as reference, using the same growth techniques as used for the FM structures. The Cr/GaAs samples showed very good Schottky characteristics and the difference in the helicity-dependent photocurrent was found to be negligible. We conclude that no spin filtering occurs at the Cr/GaAs interfaces. MCD effects can also be excluded since the spin filtering effects obtained with NiFe samples are seen to be much larger than those obtained with Fe and Co samples, whereas the MCD effects with Fe and Co are larger than those with NiFe. However a partial contribution of spin-dependent electron transport from the FM to the GaAs cannot be excluded for the FM/GaAs structures.

II. EXPERIMENTAL PROCEDURES

Molecular beam epitaxy (MBE) techniques were used to fabricate 5 nm thick metal layers (with $Ni_{80}Fe_{20}$, Co, and Fe as the FM, and AF Cr as reference) directly onto GaAs ($n=3.0\times10^{23}$ and 1.5×10^{24}) substrates, capped with 3 nm thick Au layers in an ultrahigh vacuum (UHV) chamber. The ohmic contacts on the back of the n-type substrates were prepared by evaporating 100 nm thick GeAuNi and then annealed at 770 K for 2 min. The GaAs substrates were cleaned for 2 min using an oxygen plasma together with chemical cleaning with acetone and isopropanol, and then loaded into the UHV chamber. The metal films were grown at a rate of ~1 monolayer (ML) per minute by electron-beam (e-beam) evaporation.[8] The substrate temperature was held at 300 K and the pressure was $\sim7\times10^{-10}$ mbar during the growth. The deposition rate was monitored by a quartz microbalance which was calibrated using both reflection high energy electron diffraction (RHEED) oscillations of Fe on a Ag (100) single crystal substrate and atomic force microscopy (AFM) observation. Two Al electrical contacts (0.5 mm×0.5 mm ×550 nm) were then evaporated onto the Au capping layer for $I-V$ measurements.

A bias voltage was applied between one Al contact on the surface of the sample and one ohmic contact attached to the back of the substrate. The current flowing through these two pads was measured (both with and without photoexcita-

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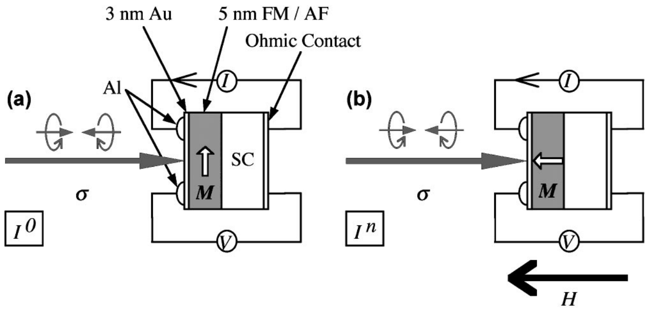

FIG. 1. Schematic configurations of the polar photoexcitation experiment. The laser ($h\nu = 1.96$ eV and 5 mW of power) is linearly polarized in the 45° direction with reference to the modulator axis pointing sample plane normal. Right/left circular light is produced using a PEM. The photocurrent is measured by $I-V$ measurement methods combined with a lock-in technique. The value of the variable resistance for the measurement is chosen to be approximately the same as that of the resistance between the metal and the GaAs substrate. The magnetization $\mathbf{M}$ in the FM and the photon helicity $\boldsymbol{\sigma}$ are shown with the field H applied normal to the sample. Two configurations, (a) without (I^0) and (b) with (I^n) a magnetic field, are employed as shown. The sheet resistance of the Au capping layer and the FM films is estimated to be 7×10^8 and $1-6 \times 10^9$ Ω, respectively, and therefore it is negligible.

tion), while the voltage across the sample was also measured using a separate top contact equivalent to a four-terminal geometry as shown in Fig. 1.[6] From the $I-V$ curves without photoexcitation, the Schottky characteristics were studied.

A circularly polarized laser beam was used together with an external magnetic field to investigate the spin dependence of the photoexcited electron current. All the measurements were carried out at room temperature in this study. The light was modulated from 100% right to 100% left circular polarization using a photoelastic modulator (PEM) with a frequency of 50 kHz. For the polarized illumination mode, the bias dependence of the ac helicity-dependent photocurrent I through the interface was probed both (i) in the remanent state (I^0) and (ii) under the application of a magnetic field ($H = 1.8$ T) sufficient to saturate the magnetization along the plane normal (I^n). With AF samples, since neighboring spins are aligned antiparallel each other, there is no spontaneous magnetization.[9] This means that AF Cr/GaAs should not show any difference in the helicity-dependent photocurrent between the two configurations.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the $I-V$ curve of a Cr sample without photoexcitation, which indicates that the sample is a very good Schottky diode (the Schottky barrier height ϕ_b is very small and the ideality factor n is estimated to be 1.53) with a small offset in reverse bias. Since all the samples, including NiFe/GaAs, Co/GaAs, Fe/GaAs, and Cr/GaAs, are prepared following the same procedures as mentioned above, this good Schottky characteristic from the Cr/GaAs suggests that the sample preparation procedures are relevant for epitaxial growth but may not be for good Schottky characteristics with some metals.

The helicity-dependent photocurrent is shown in Fig. 2(b) with (I^n) and without (I^0) perpendicular saturation. It should be noted that there is no difference between I^n and I^0 ($\Delta I = I^n - I^0$ is ~4 nA), suggesting that there is no spin-polarized electron current flow across the AF Cr/GaAs interface as expected. This is one of the crucial tests for the validity of the photoexcitation study.

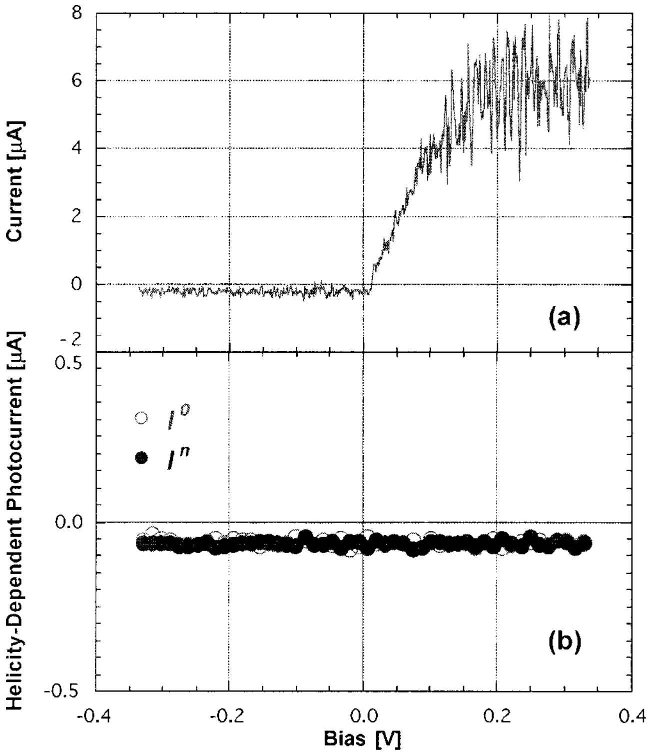

FIG. 2. (a) Bias dependence of current through the Cr/GaAs ($n = 10^{23}$ m^{-3}) interface obtained without photoexcitation. (b) Bias dependence of the helicity-dependent photocurrent without (open circles, I^0) and with the applied magnetic field (closed circles, I^n) with Cr/GaAs.

A small offset in I^0 is seen in Fig. 2, which is similar to that with the NiFe/GaAs samples (see Table I). NiFe, Co, and Fe samples possess the offset of approximately −260, −160, and −0.92 nA, respectively. Possible reasons for the offset are: (i) MCD effects, (ii) spin-dependent electron transport from the FM to the GaAs, (iii) a Zeeman splitting in the GaAs, (iv) properties of the metal/SC interface, and (v) the other experimental artifact (such as very small misalignment between the photon helicity quantum axis and the FM magnetization direction).

(i) MCD effects can be excluded because the NiFe/GaAs samples show much larger asymmetry $[A = (I^n - I^0)/(I^n - I^0) \sim 3\%]$ than that caused by MCD effects (~0.2%),[6] and also because the spin filtering effects obtained with NiFe samples are seen to be much larger than those obtained with Fe and Co samples, whereas the MCD effects with Fe and

TABLE I. Offset in I^0 and I^n for NiFe, Co, Fe and Cr deposited on GaAs substrates.

	NiFe ($n = 10^{23}$ m^{-3}) (nA)	Co ($n = 10^{24}$ m^{-3}) (nA)	Fe ($n = 10^{23}$ m^{-3}) (nA)	Cr ($n = 10^{23}$ m^{-3}) (nA)
I^0	~−270	~−160	~−0.92	~−60
I^n	~−285	~−200	~−4.3	~−64

Co are larger than those with NiFe. (ii) Spin transport from the FM to the SC might exist as the front illumination configuration (see Fig. 1) also excites spin-polarized electrons in the FM due to the spin–split density of states at the Fermi level. A partial contribution of spin-dependent electron transport from the FM to the GaAs cannot be excluded for the FM/GaAs structures. However, these two possibilities (i) and (ii) are not the main reason for the existence of the offset in I^0 since the Cr films show the offset. (iii) A Zeeman splitting in the GaAs needs to be taken into account at low temperature measurements,[2,3] while, at room temperature, that is reported to be negligible.[10] As $|I^0|$ seen with FM Fe/GaAs (~1 nA) is much smaller than that with FM NiFe/GaAs (~270 nA), (v) the other experimental artifact, such as very small misalignment between the photon helicity and the FM magnetization, should be in the order of a few nA, which is negligible. Since the magnitude of the offsets varies with metal overlayers on the GaAs substrates as listed in Table I, (iv) the properties of a metal/SC interface, such as band bending of the Schottky barrier, is likely to be the major reason for $|I^0| \neq 0$. The details of this effect require further investigation, however the offsets are intrinsic for the metal films, which means that the offsets are not due to experimental artifact.

These results clearly show that there is little difference between I^0 and I^n in AF Cr/GaAs, while significant difference ΔI is seen in FM samples, namely NiFe/GaAs and Co/GaAs as reported previously.[6] Therefore our previous work on FM/GaAs is solid, indicating that the Schottky barrier can be used as a tunnel barrier for spin-polarized electron transport across the FM/GaAs interfaces and highly efficient spin detection can be achieved dependent upon the spin–split density of states at the Fermi level in the FM at room temperature.

IV. CONCLUSION

We have fabricated AF Cr/GaAs samples using the same techniques as used for the FM/GaAs structures (NiFe, Co, and Fe as the FM). The Cr samples show very good Schottky characteristics and the difference in the helicity-dependent photocurrent is found to be negligible. This clearly indicates that no spin filtering occurs across the Cr/GaAs interfaces. Comparing these results with the previously reported highly efficient spin detection associated with spin filtering at FM/GaAs interfaces, we conclusively present that the Schottky barrier acts as a tunnel barrier and highly efficient spin detection can be achieved at room temperature.

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