Spin-dependent electron transport in NiFe/GaAs Schottky barrier structures

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Photoexcitation at the Schottky barrier formed between 5 nm thick $Ni_{80}Fe_{20}$ films and both n^+- and p^--type GaAs(100) substrates with doping density in the range $10^{23} \leqslant n(p) \leqslant 10^{25}$ m^{-3} was investigated using circularly polarized laser light. A helicity-dependent photocurrent dependent upon the magnetization configuration of the film and the Schottky barrier height was detected. The results provide evidence of spin-dependent electron transport through the NiFe/GaAs interface and show that the Schottky barrier height controls the spin-dependent current passing from the semiconductor to the ferromagnet.
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I. INTRODUCTION

Spin-dependent tunneling through metal/oxide/semiconductor (MOS) junctions has recently attracted great interest for potential applications in magnetoelectronic devices and memory elements.[1] Since Prinz *et al.* reported a spin-dependent tunneling current through a Co/Al_2O_3/GaAs thin film tunnel junction,[2] a great many studies of spin-dependent tunneling through MOS junctions have been reported.[3] Such systems can be used for spin-polarized scanning tunneling microscopy (SP-STM).[4,5] However, due to the presence of the oxide layer, the mechanism of the spin-dependent tunneling through the MOS junction is complicated. For the direct ferromagnet (FM)/semiconductor (SC) interface, a Schottky barrier arises which also gives rise to tunneling under appropriate bias conditions. Recent studies show that a spin-dependent current is transmitted by the Schottky barrier in FM/SC direct interfaces based on NiFe/GaAs.[6]

In this article, in order to clarify the dependence of the spin-polarized transport on the Schottky barrier height and the roles of photoexcitation in the SC and the FM, we produced samples of 5 nm $Ni_{80}Fe_{20}$/GaAs(100) in ultrahigh vacuum (UHV) with different levels of doping of the GaAs. For the GaAs substrates, three doping densities were used: $n^+ = 10^{23}$, 10^{24}, and $p^- = 10^{25}$ m^{-3}. Conventional $I-V$ measurements were carried out with and without photon excitation. A circularly polarized laser was used to excite electrons with a spin polarization perpendicular to the film plane for both perpendicular and in-plane magnetized states.

II. EXPERIMENTAL PROCEDURE

This study was carried out using a conventional photon excitation setup with front illumination at room temperature (see Fig. 1).[6] He–Ne laser ($\lambda = 632.8$ nm) light perpendicular to the sample surface was used and the bias dependence of the current through the NiFe/GaAs interface ($-2.5 < V < 1.5$ V) was measured both with and without optical excitation. In the absence of laser illumination, this dependence is the same as that of a conventional $I-V$ measurement. The polarization of the beam was then modulated using a photoelastic modulator (PEM) with 100% circular polarization at 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 in the remanent state (I^0)and under the application of a magnetic field ($H = 1.8$ T) sufficient to saturate the magnetization along the plane normal (I^n). In the case of I^0, the photon helicity is perpendicular to the magnetization of the FM, while the helicity is parallel or antiparallel to the magnetization with I^n. I^0 and I^n are a measure of the difference in photocurrent for right and left circular polarization for the in-plane and perpendicular magnetization configurations, respectively.

We produced a sample of 3 nm Au/5 nm NiFe/GaAs(100) ($n^+ = 10^{23}$, 10^{24}, and $p^- = 10^{25}$ m^{-3}) using

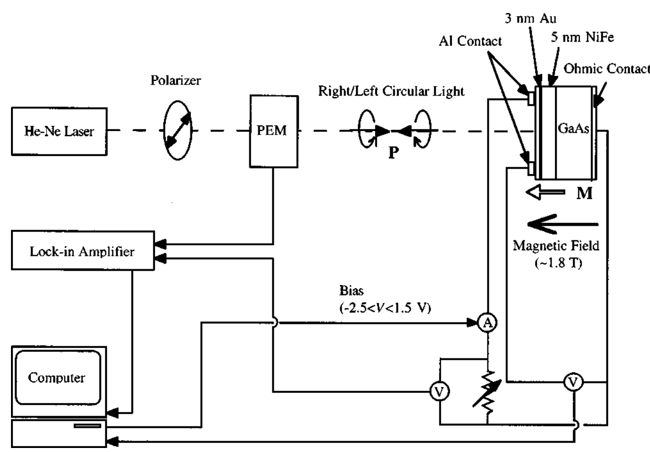

FIG. 1. Schematic configuration of the photon excitation experiment. The laser is polarized in the 45° direction. Right/left circular light is produced using a PEM. The bias dependent photocurrent is determined by $I-V$ measurement methods combined with a lock-in technique. A schematic view of the $Ni_{80}Fe_{20}$/GaAs hybrid structure is also shown in this diagram. Two Al contacts on the surface (0.5 mm×0.5 mm×550 nm) and an ohmic contact on the bottom are used for the measurement. The value of the variable resistance for the measurement was chosen to be approximately the same as that of the resistance between the $Ni_{80}Fe_{20}$ and the GaAs substrate ($n^+ = 10^{23}$, 10^{24}, and $p^- = 10^{25}$ m^{-3} doped), typically 60, 200, and 15 Ω, respectively. The magnetization **M** in the FM and the photon helicity **P** are also shown with the field applied normal to the sample.

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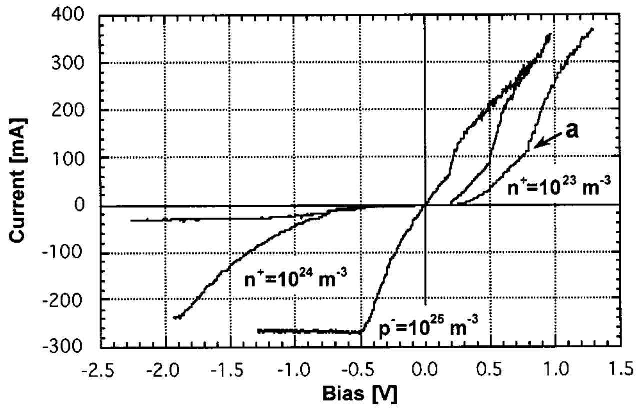

FIG. 2. Bias dependence of the current through the $Ni_{80}Fe_{20}$/GaAs interface obtained without photon excitation ($I-V$ curve).

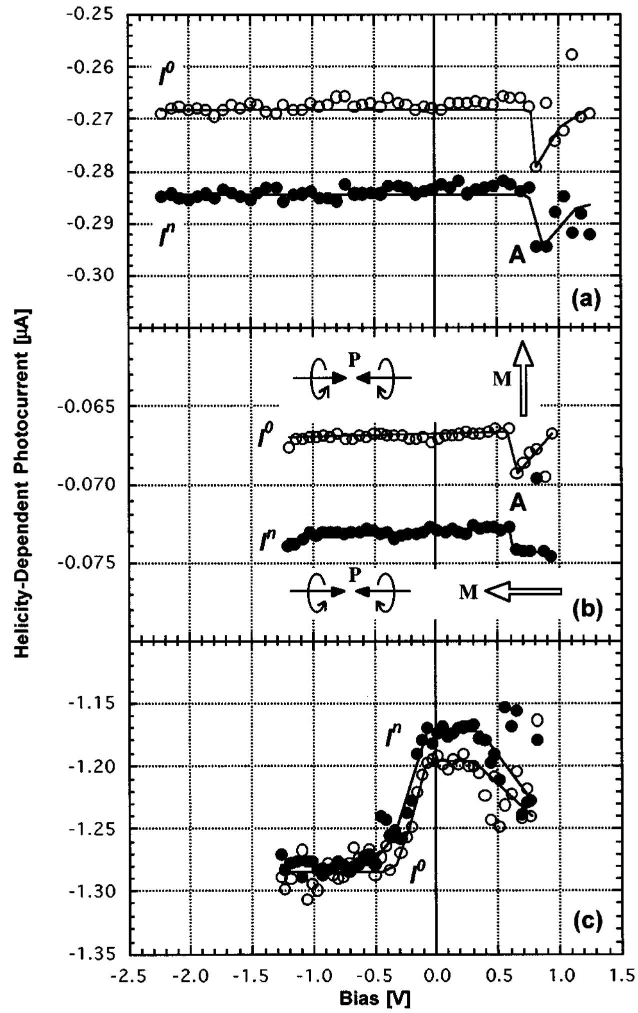

FIG. 3. Bias dependence of the helicity-dependent photocurrent without (solid line with open circles, I^0) and with the applied magnetic field (solid line with closed circles, I^n) in the case of $n^+=10^{23}$, 10^{24}, and $p^-=10^{25}$ m^{-3} doped substrates. Magnetization **M** in the FM and photon helicity **P** are also shown without and with the field application.

molecular-beam epitaxy (MBE) techniques in UHV.[6] The ohmic contacts on the bottom of the *n*- and *p*-type substrates were prepared by evaporating 100 nm thick GeAuNi and AuBe, respectively, and then annealing at 770 K for 2 min. The GaAs substrates were cleaned for 2 min using an oxygen plasma and then loaded into the UHV chamber. The NiFe films were epitaxially grown at a rate of approximately 1 monolayer/min by *e*-beam evaporation. The substrate temperature was held at 300 K and the pressure was around 7×10^{-10} mbar during the growth. The deposition rate was monitored by a quartz microbalance which was calibrated using reflection high-energy electron diffraction (RHEED) oscillations of Fe on a Ag(100) single crystal. After the growth, the NiFe films were covered by a Au capping layer. Two Al electrical contacts (550 nm thick) were evaporated on the Au layer. A computer controlled bias voltage was applied between one Al contact and the bottom ohmic contact and the current through the other Al contact and the substrate was measured using a lock-in technique. As the polarized laser beam enters from the Au capping layer side, these structures provide a way of avoiding laser absorption at the bottom surface of the SC, as occurs under back illumination.[7]

III. RESULTS AND DISCUSSION

Figure 2 shows the $I-V$ curves of the $Ni_{80}Fe_{20}$ samples without photon excitation measured by the usual four-terminal method. It should be noted that every $I-V$ curve possesses a small feature (a) around the Schottky barrier height as observed previously.[6] The ideality factor[7] was calculated to be 6.69, 5.37, and 4.04 for $n^+=10^{23}$, 10^{24}, and $p^-=10^{25}$ m^{-3}, respectively. These values are comparable with those of the previously reported permalloy samples.[6]

The helicity-dependent photocurrent is shown in Fig. 3 with (I^n) and without (I^0) perpendicular saturation. In the case of $n^+=10^{23}$ m^{-3} [see Fig. 3(a)], for instance, it should be noted that the helicity-dependent photocurrent values for I^n and I^0 are observed to satisfy $I^n<I^0$ as previously reported.[6] This provides clear evidence that the spin-dependent transport from the SC to the FM occurs under the application of a perpendicular magnetic field. The bias dependence of the helicity-dependent photocurrent difference $\Delta I(=I^n-I^0)$ of $\sim$0.015 μA is almost constant in the bias range of $V<0.7$ V. In Fig. 3(a), peak A appears at $V=0.83$ V for I^0 and shifts to $V=0.85$ V for I^n. The shift of peak A between I^n and I^0 is 0.02 V, which is almost the same value as the width of the maximum peak of the total spin polarization of permalloy.[8] Since electrons are excited in the permalloy layer by both the bias and the photon energy and then propagate over the barrier,[7] peak A is likely to be related to the spin-dependent transport from the FM to the SC. The Schottky barrier height ϕ_b has been reported to be 0.66–0.70 eV for Ni and Fe,[6] which is approximately the same as the bias voltage for peak A.

With $n^+=10^{24}$ m^{-3}, a similar tendency can be seen in Fig. 3(b), although peak A for I^n is much broader than that of I^0. In reverse bias, a constant difference between I^0 and I^n is again observed. The magnitude of the difference is $\sim$0.06 μA. In the case of $p^-=10^{25}$ m^{-3}, on the other hand, both the position of the helicity-dependent photocurrent features and the sense of the peak A is opposite compared with the samples discussed above, suggesting that these features are related to the height of the Schottky barrier at the interface.

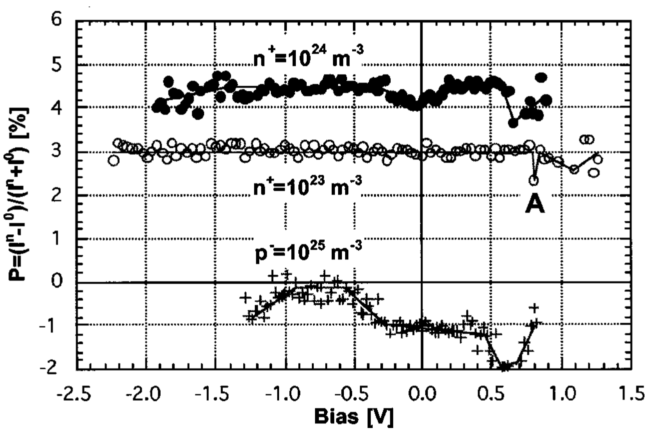

FIG. 4. Bias dependence of the ''polarization'' $P=(I^n-I^0)/(I^n+I^0)$ with $n^+=10^{23}$, 10^{24}, and $p^-=10^{25}$ m^{-3} doped substrates.

Both I^0 and I^n are again constant in reverse bias but of almost the same magnitude, which means that there is no significant spin-dependent current through the interface.

Figure 4 shows a measure of the polarization of the spin-dependent current through the NiFe/GaAs interface $P=(I^n-I^0)/(I^n+I^0)$. With $n^+=10^{23}$ m^{-3}, for example, almost constant polarization ($P\sim 3\%$) can be seen at the bias range of $-2.2<V<0.7$ V, which is likely to be related to the spin-dependent photocurrent from the SC to the FM. For $n^+=10^{24}$ m^{-3}, the corresponding value is $P\sim 4.5\%$, while for $p^-=10^{25}$ m^{-3}, $P\sim 0$. We conclude from the above results that the magnitude of the spin-dependent current in reverse bias scales with the Schottky barrier height as is expected for spin-dependent tunneling across the barrier. This polarization is much larger than the estimated value (0.2%) caused by magnetocircular dichroism (MCD)[6] and the MCD effects can be excluded. Small features A at the Schottky barrier heights ϕ_b are again seen in this figure, although the features are small. The position of these features are almost the same as those of peak A in Fig. 3, which is likely to be evidence that the spin-dependent current from the FM to the SC is enhanced at $V\sim\phi_b$. In the sample with $n^+=10^{23}$ m^{-3}, peak A at $V\sim 0.8$ V corresponds to peak A in Fig. 3(a). At peak A, $\Delta I/I^0$ is estimated to be 5%, which is much larger than what was observed previously (1%).[6] This suggests that the spin-dependent photocurrent from the SC to the FM is suppressed by the electron transport from the FM to the SC due to the reduction of ϕ_b under the application of forward bias $V\sim\phi_b$.

IV. CONCLUSIONS

We have observed a clear difference in the helicity-dependent photocurrent through the NiFe/GaAs interface according to the orientation of the sample magnetization at room temperature. An almost constant difference between the helicity-dependent photocurrent for perpendicular and parallel configurations is observed below the Schottky barrier height for $n^+=10^{23}$ and 10^{24} m^{-3}, which corresponds to a measure of the spin-dependent photocurrent passing from the SC to the FM. At an applied bias voltage approximately equal to the Schottky barrier height, a minor change in the bias dependence of the helicity-dependent photocurrent was observed, suggesting that the existence of electron transport from the FM to the SC.

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