Spin-dependent electron transport at the ferromagnet/semiconductor interface

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A search for spin-dependent electron transport at the ferromagnet/semiconductor interface has been made by measuring the bias dependence of a photon excited current through the interface. A circularly polarized laser beam was used to excite electrons with a spin polarization perpendicular to the film plane. In samples of the form 3 nm Au/5 nm $Ni_{80}Fe_{20}$/GaAs (110), a significant transport current was detected with a magnitude dependent on the relative orientation of the spin polarization and the magnetization vector. At perpendicular saturation, the bias dependence of the photocurrent is observed to change in the range 0.7–0.8 eV when the helicity is reversed. © *1999 American Institute of Physics.* [S0021-8979(99)26508-5]

I. INTRODUCTION

Following the proposal for a spin-dependent field effect transistor (spin FET) by Datta and Das,[1] a great number of studies[2–4] on device structures based on ferromagnet (FM)/semiconductor (SC) hybrid systems have been made. A spin FET offers the prospect of fast operation and miniaturization.[2] As the device operation would depend on the injection of a spin-dependent current into the SC, it is very important to clarify the FM/SC interface transport process.

The possibility of passing a spin-dependent current through thin film tunnel junctions of both Co/Al_2O_3/GaAs and Co/τ-MnAl/AlAs/GaAs has been discussed by Prins *et al.*[5] For the former structure, a spin-dependent tunneling current was reported. In the latter structure, however, only magneto-optical effects were seen. For the direct FM/SC interface, a Schottky barrier forms which gives rise to tunneling under appropriate bias conditions. However, it is not clear whether any spin dependent tunneling across the FM/SC interface occurs.

In this study, we fabricated 5 nm thick $Ni_{80}Fe_{20}$ layers directly onto GaAs(110) substrates in an ultrahigh vacuum (UHV) chamber. Current–voltage ($I-V$) measurements were performed both with and without photon excitation. A circularly polarized laser beam was used together with an external magnetic field to investigate the spin dependence of the photocurrent at the NiFe/GaAs interface.

II. EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic setup for the photon excitation experiment. He–Ne laser ($\lambda = 632.8\,\text{nm}$) light perpendicular to the sample surface was used and the bias dependence of the current through the FM/SC interface ($-1 < V < 1\text{V}$) 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 modulated using a photoelastic modulator (PEM) with 100% circular polarization. For both polarized and unpolarized illumination modes, the bias dependence of the photon excited current through the interface was measured both in the remanent state and under the application of a magnetic field ($H = \pm 7.5\,\text{kG}$) along the beam direction sufficient to saturate the magnetisation parallel to the plane normal.

We produced samples of 3 nm Au/5 nm NiFe/GaAs [(110), $n^+ = 10^{24}\,\text{m}^{-3}$] using molecular beam epitaxy (MBE) techniques in UHV. Two Al electrical contacts on the Au layer were attached by evaporation and one ohmic contact at the bottom of the substrate was prepared (see Fig. 2). The 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. In this structure, as the polarized laser beam enters from the Au capping layer side, the beam is attenuated due to the 8 nm thick metal overlayer.

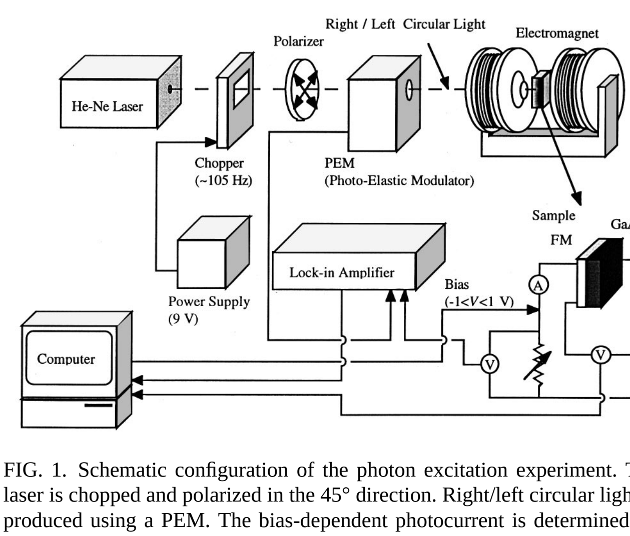

FIG. 1. Schematic configuration of the photon excitation experiment. The laser is chopped and polarized in the 45° direction. Right/left circular light is produced using a PEM. The bias-dependent photocurrent is determined by $I-V$ measurement methods combined with a lock-in technique. The value of the variable resistance for the measurement was chosen to be approximately the same as that of the resistance between the $Ni_{80}Fe_{20}$ layer and the GaAs substrate, typically 140 Ω.

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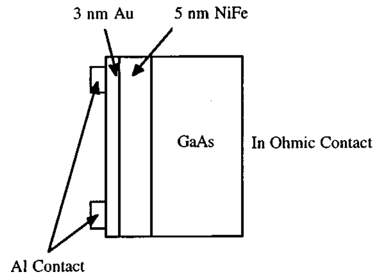

FIG. 2. Schematic view of the $Ni_{80}Fe_{20}$/GaAs hybrid structure sample. Two Al contacts on the surface and an In ohmic contact on the bottom are used for the measurement.

III. RESULTS AND DISCUSSIONS

Figure 3(a) shows a representative $I-V$ curve without photon excitation measured by the usual four-terminal method. The Schottky barrier defines the shape of the $I-V$ curve from which the Schottky characteristics were calculated. According to the thermionic-emission theory,[6] the current density at a certain temperature T is given by $J = A^{**}T^2 \exp[-q(\varphi_b - \Delta\varphi_{bi})/k_B T][\exp(qV/k_B T)-1]$, where A^{**}, q, φ_b, and $\Delta\varphi_{bi}$ stand for the Richardson constant modified to take into account the effective mass of electrons in the SC, the electron charge, the Schottky barrier height from the Fermi level, and the lowering of the barrier due to the image force.[7] Using an ideality factor n ($n=1$ with the ideal Schottky barrier diode), this equation can be modified to $J = J_0[\exp(qV/nk_BT)-1]$, where $J_0 = A^{**}T^2\exp[-q(\varphi_b - \Delta\varphi_{bi})/k_BT]$. The value of n for the sample was found to be 4.85. The Schottky barrier height has been reported to be 0.66–0.70 eV for both Ni/GaAs and Fe/GaAs.[8]

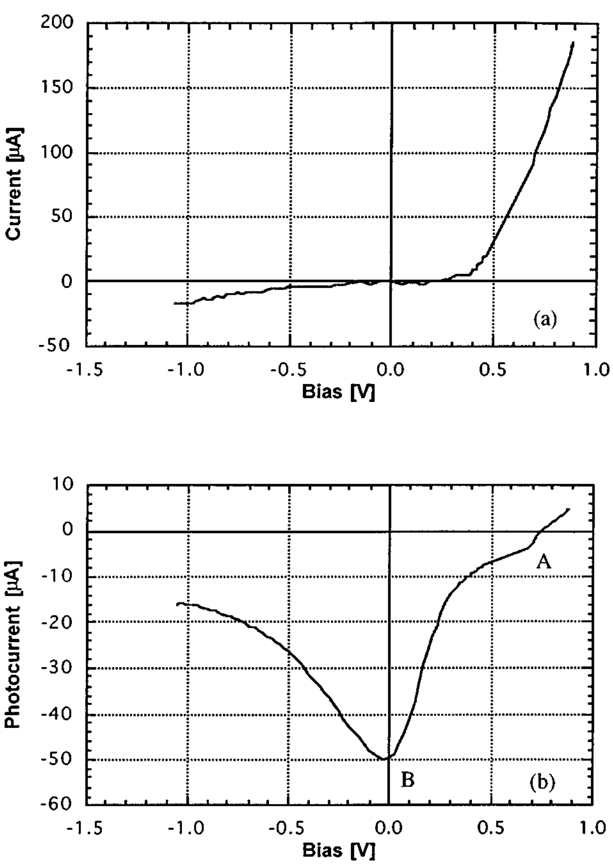

FIG. 3. Bias dependence of photocurrent through the $Ni_{80}Fe_{20}$/GaAs interface (a) without photons ($I-V$ curve) and (b) with photons (bias dependence of photocurrent).

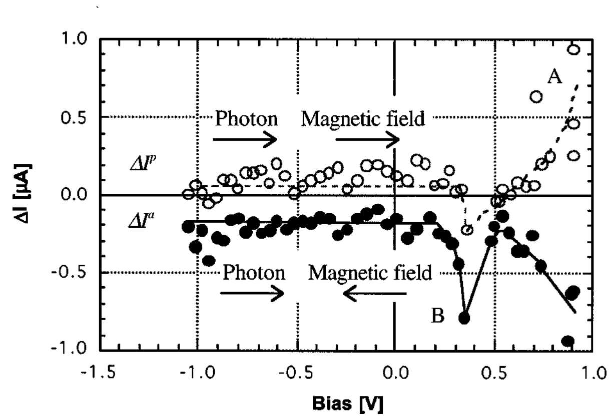

FIG. 4. Bias dependence of the photocurrent difference between with and without the application of a magnetic field with the $Ni_{80}Fe_{20}$/GaAs sample. Open (closed) circles stand for the spin parallel (antiparallel) to the circularly polarized laser illumination.

Figure 3(b), on the other hand, indicates a representative $I-V$ curve with unpolarized photon excitation corresponding to the bias dependence of the photocurrent. The same setup for the $I-V$ measurement was used but with laser illumination. Intensity modulation of the laser beam is used to separate the photocurrent contribution to the total current. A photon excited current as large as 50 μA was observed without the application of a bias between the surface and the substrate. Since permalloy has a large polarization difference at its Fermi level[9] and a small magneto-optical background, it is an appropriate choice for the spin-dependent transport experiment. In Fig. 3(b), the entire $I-V$ curve is shifted to negative current values as expected.[10] Two peaks (A and B) are seen: one small peak (A) can be seen at the bias $V = 0.8$ V, which is approximately the same as the Schottky barrier height. Considering that the electrons are excited by the bias and propagate over the barrier, the peak A is likely to be related to the transport through the FM/SC interface. The other large peak (B) observed is unusual and does not occur in Si-based Schottky diode structures for example.[10] The magnitude of this peak decays with the time period of the laser illumination, which suggests that the origin of the peak B is connected with the recombination of holes and electrons. Under the application of the circularly polarized laser beam in zero magnetic field, the position of the peak B shifts to $V = 0.36$ V. The photocurrent for polarized light in zero field is almost the same as that for the unpolarized beam as expected.

The bias dependence of the difference ΔI in the total current obtained with circularly polarized illumination between (a) that with a magnetic field applied along the film normal and (b) that without an applied field is shown in Fig. 4. Two sets of measurements are shown corresponding to the applied field parallel (p) and antiparallel (a) to the photon helicity. The constant difference between the measurements for the two configurations (a and p) $\Delta I^p - \Delta I^a = 0.3\,\mu$A

($\Delta I/I \sim 0.5\%$) observed at negative bias may be due to a helicity dependent variation in power due to magneto-optical effects. The magneto-optical dichroism is expected to be 0.2% (Ref. 11) which is comparable with ΔI at the negative bias range. The bias dependence of the photocurrent difference is observed to change significantly ($\Delta I/I \sim 1\%$) in the range 0.3–0.4 eV associated with a change in the position of the peak B. In this bias range, both the parallel and antiparallel configurations show a similar increase of ΔI, which means this peak is independent of the direction of the spin. However, a significant change in ΔI occurs in the range 0.7–0.8 eV, which is approximately the same as the Schottky barrier height and related to the peak A. When the direction of the magnetic field is along that of the photon helicity, the photon helicity and the spin are antiparallel and ΔI is negative. The bias and spin-configuration dependence of ΔI in the vicinity of the peak A is interpreted as evidence for spin dependent transport through the FM/SC interface. Low temperature measurements of ΔI should further clarify the origin of the photocurrent because at low temperature ΔI is expected to be larger than that at room temperature.

IV. CONCLUSIONS

We have observed a significant change ($\Delta I/I \sim 1\%$) in the bias dependence of the helicity dependent photocurrent ΔI in the bias range 0.7–0.8 eV in the $Ni_{80}Fe_{20}$/GaAs system, which shows a large photocurrent. This range corresponds to the Schottky barrier height and is dependent on the spin direction. Although the change in ΔI is small, these preliminary results provide evidence for a room temperature spin-dependent transport current across the FM/SC interface which is both significant and detectable.

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