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Spin-Dependent Electron Transport through the Ferromagnet/Semiconductor Interface Induced by Photon Excitation

A. Hirohata, Y.B. Xu, C.M. Guertler, and J.A.C. Bland
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, England

***Abstract*—Circularly polarized light was used to excite electrons with a spin polarization perpendicular to the film plane in 3 nm Au/5 nm Co/GaAs (110) structures. At perpendicular saturation, the bias dependence of the photocurrent was observed to change in the range around 0.7 eV, corresponding to the Schottky barrier height. The photocurrent is observed to change significantly as a function of the magnetization direction with respect to the photon helicity, indicating spin-dependent transport between the semiconductor and the ferromagnetic layer at room temperature.**

***Index Terms*—Photon excitation, polarized laser, ferromagnet/semiconductor interface, Schottky barrier.**

I. INTRODUCTION

The combination of ferromagnetic (FM) and semiconductor (SC) materials [1] in magnetoelectronic FM/SC hybrid structures has recently become a key topic in device physics [2]. Since the observation of a spin-dependent tunneling current in Co/Al_2O_3/GaAs thin film tunnel junctions by Prins *etal.* [3], a great many studies of spin-dependent tunneling through metal/oxide insulator/semiconductor (MOS) junctions have been reported [4]. Some recent experiments suggest [5] that such systems may provide possibilities for spin polarized scanning tunneling microscopy (SP-STM) [6]. However, due to the presence of the oxide layer, the mechanism of the spin-dependent tunneling through the MOS junction is extremely complicated.

For the direct FM/SC interface, on the other hand, a Schottky barrier arises which also gives rise to tunneling under appropriate bias conditions. We have reported preliminary observations of spin polarized electron transport through the NiFe/GaAs interface [7].

In this paper, in order to confirm the Schottky barrier height dependence of possible spin polarized transport effects using Co as the FM layer, we fabricated a 5 nm thick Co film directly onto GaAs (110) substrates in an ultrahigh vacuum (UHV) chamber. *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 Co/GaAs interface at room temperature.

II. EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic set up for the photon excitation experiment. He-Ne laser (λ=632.8 nm, 50 mW) light perpendicular to the sample surface was modulated in intensity using a chopper operated at a frequency of 120 Hz. The bias dependence of the current through the Co/GaAs interface (-2.2<V<1.8 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 photo-elastic modulator (PEM) with 100 % circular polarization at a frequency of 50 kHz. For the polarized illumination mode, the bias dependence of the photon excited current through the interface was measured both in the remanent state and with a magnetic field (H=1.8 T) using a permanent magnet sufficient to saturate the magnetisation parallel to the plane normal, achieving an anti-parallel configuration between photon helicity and a field. Without an applied field, the magnetization lies in the film plane and the light helicity is perpendicular to the magnetization. The synchronous signal observed at 50 kHz is referred to as the helicity dependent photocurrent.

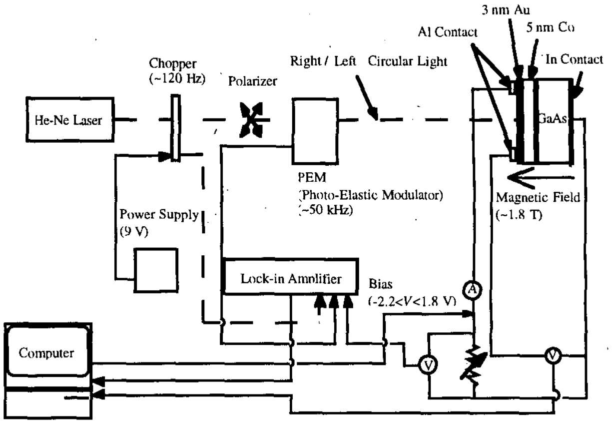

Fig. 1. Schematic configuration of the photon excitation experiment. The laser is chopped and polarized in the 45° direction. Right/left circular light is produced using a PEM. The bias dependent photocurrent is determined using a lock-in detection technique. A schematic view of the Co/GaAs hybrid structure sample is also shown in this diagram. Two Al contacts on the surface (0.5 mm × 0.5 mm × 400 nm) and an In 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 Co layer and the GaAs substrate, typically 65 Ω.

We produced ultrathin film samples of the structure 3 nm Au/5 nm Co/GaAs ((110), n^+=10^{24} m^{-3}) using molecular beam epitaxy (MBE) techniques in ultrahigh vacuum (UHV). The Co film was prepared in the same way as that of permalloy [7]. After the growth, the Co layer was covered by a Au capping layer. Two Al electrical contacts (400 nm thick) were evaporated on the Au layer and one In ohmic contact was attached to the bottom of the substrate (see Fig. 1). 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.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the *I-V* curves of the Co samples obtained without photon excitation measured by the usual four-terminal method. Intensity modulation using the chopper operated at a frequency of 120 Hz is used also to generate a reference signal for the lock-in amplifier. A jump (J) seen at the bias of -1.3 V is likely to be related to the current breakdown of the semiconductor device [8].

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A. Hirohata, 44-1223-337006, fax 44-1223-337333, ah242@cam.ac.uk, http://homer.phy.cam.ac.uk/TFM_Home.html; J.A.C. Bland, 44-1223-337436, fax 44-1223-350266, jacb1@phy.cam.ac.uk.

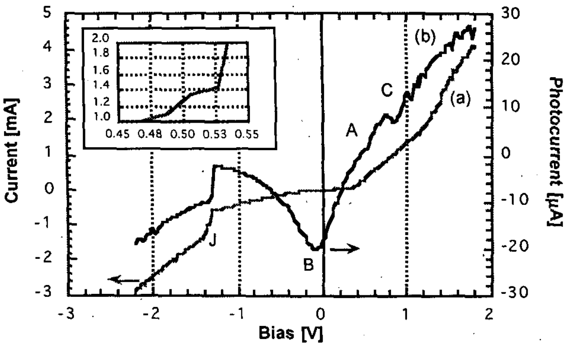

Fig. 2. Bias dependence of photocurrent through the Co/GaAs interface (a) without photons (I-V curve) and (b) with photons (bias dependence of photocurrent). Feature A is magnified in the inset.

Figure 2(b), on the other hand, indicates representative I-V curves of the specimen with unpolarized photon excitation corresponding to the bias dependence of the photocurrent. The same set-up as that of the I-V measurement was used but with laser illumination. Intensity modulation of the laser beam was used in order to separate the photocurrent contribution to the total current. Part of the I-V curves are shifted to negative current values as expected [9]. In this figure, three features (A, B and C) are seen: one small feature (A), another large feature (B) and the other feature (C) at a bias of 0.5, -0.1 and 0.8 V, respectively. The Schottky barrier height ϕ_b has been reported to be 0.42-0.66 eV for Co [10], which is almost the same as the bias voltage for feature A. Since electrons are excited in the Co layer by the light and propagate over the barrier, feature A is likely to be related to transport across the FM/SC interface. The large feature B, corresponding to a current as large as 20 μA observed around zero bias, is unusual and does not occur in Si based Schottky diode structures for example [9]. These two features are similar to those observed with the NiFe/GaAs interface [7]. The other feature C at V=0.8 V, however, is a unique feature for the Co/GaAs system, of which the origin is not clear at present.

Under the application of circularly polarized light in zero magnetic field, feature B disappeared from the helicity dependent photocurrent as observed in permalloy samples [7], while features A and C are still seen as shown in Fig. 3(a). The photocurrent for polarized light in zero field is almost the same as the I-V curve of Fig. 2(a). Close to feature A, the helicity dependent photocurrent results for the anti-parallel configuration I^a and without field I^0, respectively are observed to satisfy $I^a<I^0$(see the inset of Fig. 3(a)). The shift of feature A between I^a and I^0 is 0.03 V, which is almost the same value (<0.1 eV at the surface) as the energy gap between the Fermi energy and the maximum peak in the density of the minority spin states with Co [11]. This suggests that the feature shift of the helicity-dependent current is related to the band structure of Co.

Figure 3(b) shows the bias dependence of the helicity dependent photocurrent difference $\Delta I=I^a-I^0$. This graph shows that the difference ΔI is almost constant in the bias range of $-1.5<V<0$ V, which is likely to be due to magneto-optical dichroism. Since the helicity dependent photocurrent signal becomes noisy at larger absolute bias values as shown in Fig. 3(a), ΔI in this region has a larger variation than that around zero bias.

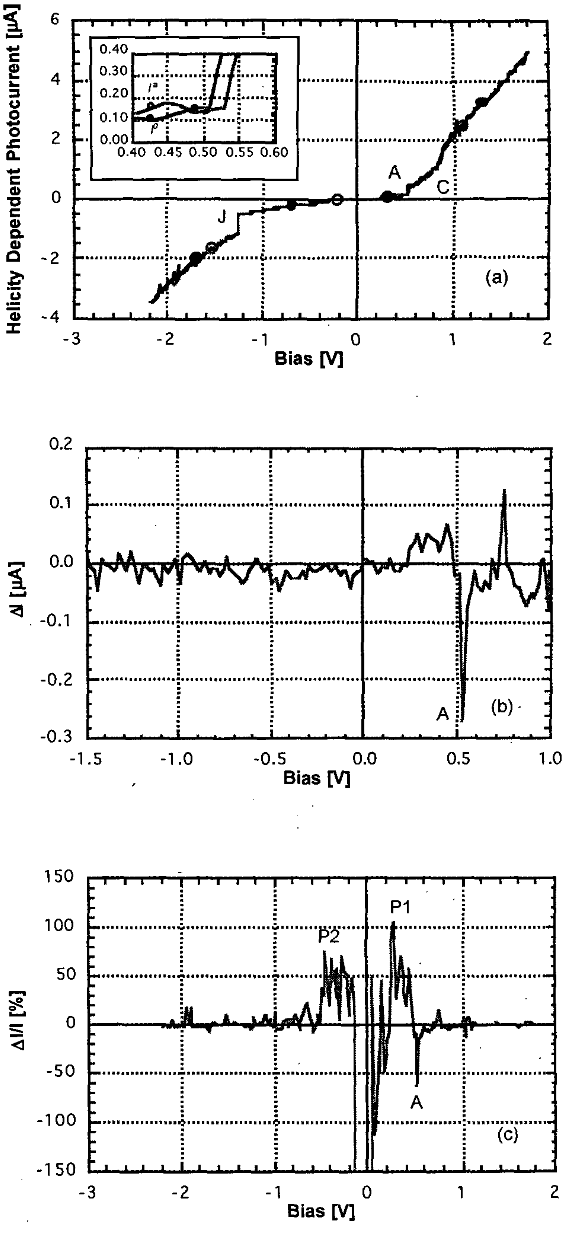

Fig. 3. (a) Bias dependence of the helicity dependent photocurrent without (open circles, I^0) and with the applied magnetic field (closed ones, I^a). Feature A is magnified in an inset of (a). (b) Bias dependence of helicity dependent photocurrent difference $\Delta I=I^a-I^0$. Typical error bar at several points are also shown in this figure. (c) Bias dependence of magnetization dependent signal $\Delta I/I^0=(I^a-I^0)/I^0$. $\Delta I/I$ is diverged around V=0 V because I^0~0 μA. A negative feature A at V~0.5 V is due to the shift of feature A.

The average bias dependence of the normalized difference $\Delta I/I=(I^a-I^0)/I^0$ in the helicity-dependent signal between that obtained with a magnetic field applied along the film normal (I^a) and without an applied field (I^0) is shown in Fig. 3(b). This figure clearly shows that almost no difference between the measurements for the two configurations (a and 0) is observed in the bias range $V<-1$ and $1<V$, as is consistent with magneto-

optical dichroism only, which has been reported to be ~0.15 % [4]. The helicity-dependent difference signal is observed to change significantly around ±0.3 eV, which is a different feature from that observed with the Co/Al_2O_3/GaAs system [4]. In the latter structure, $\Delta I/I$ diverges gradually and does not show any features around ±0.3 eV. A negative dip (feature A) is seen at V~0.5 V. With Co, the density of states at the Fermi energy exhibits a broad maximum within ±0.5 eV from the Fermi energy [11]. This shape is different from that in the case of permalloy [7], for which the density of states is at its maximum at the Fermi surface and sharply decreases away from the Fermi level [12], suggesting the bias dependence of photocurrent should create a sharp feature. Since these significant changes in ΔI ($\Delta I/I \geq 50$ %) with Co occur around V~0.5 V, these features are likely to be related to the Schottky barrier of Co [10].

At forward bias, the electrons flow from the SC to the FM and this current creates a positive net current. Since the bias dependence of the helicity-dependent photocurrent difference shows a negative feature as shown in Fig. 3(a), the electrons in the FM are likely to be excited by the photons and flow into the SC, which therefore suppresses the positive current. At the anti-parallel configuration, especially, this suppression effect is observed to be larger than that without an applied field, which suggests that the significant feature observed in Fig. 3(c) is due to spin-dependent transport from the FM to the SC.

IV. CONCLUSION

We have observed the I-V characteristics of a Co/GaAs hybrid structure both with and without photon excitation and found characteristics similar to those of NiFe/GaAs. A significant change ($\Delta I/I \geq 50$ %) occurs in the bias dependence of the helicity-dependent photocurrent $\Delta I/I$ in the bias range around 0.5 eV, corresponding to the Schottky barrier height. This suggests that the spin-dependent current from the FM is enhanced when the magnetization in the FM is aligned along the plane normal by an external field. Although the change in ΔI is small, these preliminary results provide evidence for room temperature spin-dependent electron transport across the FM/SC interface which is both significant and detectable.

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