Observation of Spin Injection at a Ferromagnet-Semiconductor Interface

P. R. Hammar, B. R. Bennett, M. J. Yang, and Mark Johnson
Naval Research Laboratory, Washington, D.C. 20375
(Received 18 February 1999)

Spin injection at a ferromagnet-semiconductor interface is observed by projecting the spin-polarized current in the ferromagnet onto the spin-split density of states of a high mobility two-dimensional electron gas (2DEG). For a given polarization of carriers in the 2DEG, reversing the magnetization orientation of the ferromagnet modulates the interface resistance. Equivalently, reversing the polarization of the 2DEG carriers by reversing the bias polarity gives the same resistance modulation. Interface resistance changes of order 1% at room temperature indicate interfacial current polarizations of order 20%.

PACS numbers: 75.25.+z, 73.40.Qv, 73.50.–h, 73.61.–r

The injection and detection of spin-polarized carriers at a ferromagnet-semiconductor interface is recognized as an important problem in condensed matter physics [1], with one focus of interest centered on the creation of a spin-injected high electron mobility transistor (HEMT) [2]. Spin injection across a ferromagnet-nonmagnetic metal interface [3] provided a cornerstone for the field of spin-dependent transport in metals [1], and spin injection at a ferromagnet-superconductor interface has recently been demonstrated [4]. Despite considerable effort, however, the goal of generalizing spin injection to a ferromagnet-semiconductor system has remained elusive.

Spin-dependent transport in a two-dimensional electron gas (2DEG) is uniquely interesting because a spin-orbit effect causes a spin splitting of the density of states. The Fermi wave vector $k_F = \sqrt{2\pi n_s}$ of the 2DEG carriers is of order 10^6 cm^{-1} for typical carrier densities of order $n_s \sim 10^{12}$ cm^{-2}, and the Fermi velocity $v_F \sim 10^7$ cm/s is weakly relativistic. An electric field $\mathbf{E} = E_z\hat{z}$ perpendicular to the plane of the 2DEG transforms, in the frame of the carriers, as an effective magnetic field H^* with components in the x-y plane. This magnetic field can interact with the spin magnetic moment of the carriers, μ_B, and split the conduction band into spin subbands separated by an effective Zeeman energy $\Delta_{\mathrm{SO}} \propto \mu_B H^*$. When the source of E_z is a gradient of the confining potential, the appropriate spin-orbit Hamiltonian is [5]

$$\mathcal{H}_{\mathrm{SO}} = \alpha(\vec{\sigma} \times \vec{k}) \cdot \hat{z}\,, \tag{1}$$

where σ are the Pauli matrices, and α describes the strength of the spin-orbit coupling. Values of $\Delta_{\mathrm{SO}} \approx 2\alpha k = 2$ to 5 meV have been measured by analyzing the beat pattern of Shubnikov–De Haas oscillations [6,7]. A variable field E_z can be applied using a gate voltage [2], and the corresponding changes in the value of α were experimentally measured in an $In_xGa_{1-x}As/InAl_{1-y}As$ HEMT [6].

Recently, the excitation of spin-polarized carriers into the conduction band of GaAs, and their subsequent detection, was demonstrated by a synchronous optical pump-probe technique. Pulses of circularly polarized light were used to generate a population of spin-polarized carriers, and polarization analysis of reflected probe pulses gave a measurement of the carrier spin lifetime [8]. Spin diffusion lengths of order several μm were also measured, and it was shown that an electric field could push the spin-polarized carriers over distances of order 100 μm, larger than typical source-drain separations. Similar photo excitation experiments used a polarization analysis of photoluminescence in a GaInAs quantum well to measure spin diffusion in a GaAs overlayer [9].

While these experiments address aspects of spin-dependent transport in semiconductor systems, the missing ingredient is the use of a ferromagnetic film to inject and/or detect spin-polarized carriers. In this Letter, we describe a direct observation of the injection and detection of a spin-polarized current from a ferromagnetic film into a 2DEG. A recent theory [10] predicted that spin-polarized current flow across a ferromagnet-2DEG interface could be detected by an appropriate measurement of the interface resistance R_i of a simple diode structure [Figs. 1(a) and 1(b)]. In the formalism of spin-dependent transport, a unique conductance is defined for each spin subband of the ferromagnet (F) and semiconducting 2DEG (S). For example, carriers moving in a quasi-one-dimensional semiconductor channel have sufficiently low density that the conductance $g_{S,i}$, with $i = \uparrow$ or $\downarrow$, is proportional to the carrier density $n_{S,i}$ [10], and the spin-orbit effect of Eq. (1) causes the densities to differ, $n_{S,\uparrow} \neq n_{S,\downarrow}$. Carriers with momentum $+k_x$ have spin polarization along $-\hat{y}$ [Fig. 1(c), diagram (i)], and carriers moving with opposite momentum, $-k_x$, have spin polarization along $+\hat{y}$ [Fig. 1(c), diagram (ii)]. For InAs heterostructures, the net spin polarization $P = (g_{S,\uparrow} - g_{S,\downarrow})/(1/2)(g_{S,\uparrow} + g_{S,\downarrow})$ is about $P = 10\%$ [7].

The conductance of each spin subband of a transition metal ferromagnet is proportional to the density of states near the Fermi level, E_F. For a single domain ferromagnetic film with magnetization along $+\hat{y}$, the simple band model of Fig. 1(c), diagram (iii), shows that the

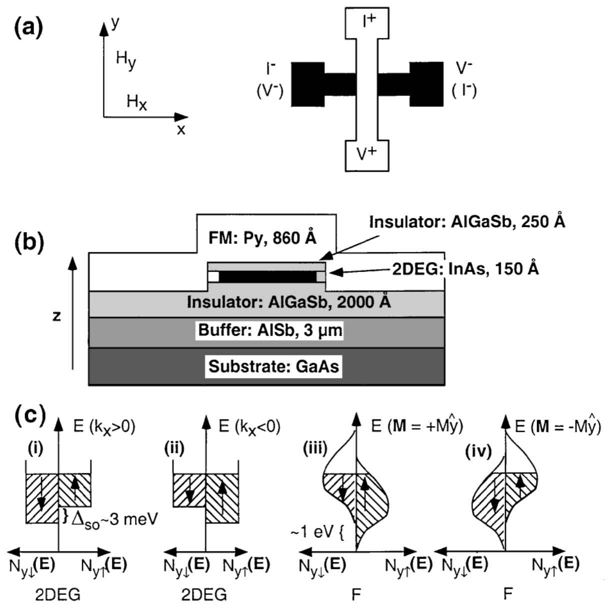

FIG. 1. (a) Top view of the measurement geometry. Current direction in the 2DEG is reversed by swapping V^- and I^-. (b) Cross section of the 2DEG heterostructure. (c) Schematic of the density of states of the 2DEG for different current directions, and of the ferromagnet for different magnetization orientations [10]. Diagrams are not drawn to scale. $N_{y,i}(E)$ denotes the density of states with carrier spin $i = \uparrow, \downarrow$ measured along the y axis.

conductance of spin-down carriers is greater than that of spin-up carriers, $g_{F,\downarrow} \propto N_{F,\downarrow}(E_F) > g_{F,\uparrow} \propto N_{F,\uparrow}(E_F)$. When the magnetization orientation is reversed, the conductance of spin-up carriers is larger than that of spin-down, $g_{F,\uparrow} > g_{F,\downarrow}$ [Fig. 1(c), diagram (iv)]. For Permalloy ($Ni_{0.8}Fe_{0.2}$, Py), the difference of subband conductance is given by the net polarization $\eta = (g_{F,\uparrow} - g_{F,\downarrow})/(1/2)(g_{F,\uparrow} + g_{F,\downarrow})$ with values of about $\eta = 40\%$ [11].

Spin subband conductances are orthogonal and intermix only by spin flip scattering. Assuming negligible interfacial spin flip scattering, the interfacial conductance $1/R_i$ of our structures is large when spin-up conductances on both sides of the interface are large [Fig. 1(c), diagrams (ii) and (iv)] or when both spin-down conductances are large [diagrams (i) and (iii)]. The interface conductance is otherwise small [diagrams (i) and (iv), and diagrams (ii) and (iii)]. The difference of resistance depends on details of the structure but is proportional to a product of the polarizations [10]:

$$\frac{\Delta R_i}{\overline{R}_i} \approx \frac{2(g_{S,\uparrow} - g_{S,\downarrow})}{(g_{S,\uparrow} + g_{S,\downarrow})} \frac{(g_{F,\uparrow} - g_{F,\downarrow})}{(g_{F,\uparrow} + g_{F,\downarrow})} = \frac{\eta P}{2}. \quad (2)$$

Experimentally, the difference ΔR_i can be measured by fixing a direction of bias current and changing the magnetization $\vec{M}$ of F from $+\hat{y}$ to $-\hat{y}$, or by fixing the magnetization orientation and reversing the direction of bias current between $+\hat{x}$ and $-\hat{x}$. By contrast, when the magnetization orientation is orthogonal to the spin quantization axis in the 2DEG ($\vec{M}$ parallel to the direction $\hat{x}$ of current in S), the spin subband conductances are intermixed and one therefore expects $\Delta R_i = 0$ for fixed bias current and changes of magnetization orientation from $+\hat{x}$ to $-\hat{x}$. The prediction of Eq. (2), and the qualitative manifestations of the interfacial effect, are valid for any kind of interfacial transport. A quantitative interpretation varies for two- and one-dimensional transport in the 2DEG and depends on mechanisms of interfacial transport and definitions of the conductances $g_{S,i}$ and $g_{F,i}$.

The cross-sectional view of Fig. 1(b) depicts our high mobility heterostructure grown by molecular beam epitaxy [12]. The 2DEG is confined to a 15 nm thick layer of InAs doped by an As soak, which is covered by a 25 nm barrier of $Al_{0.6}Ga_{0.4}Sb$ and capped with a 3 nm thick layer of InAs for passivation. The carrier density, mobility, and sheet resistance at 296 K (77 K) were determined from a Hall measurement to be 1.47×10^{12} cm^{-2} (9.0×10^{11} cm^{-2}), 23 500 cm^2 V^{-1} s^{-1} (63 500 cm^2 V^{-1} s^{-1}), and 181 $\Omega/\square$ (109 $\Omega/\square$), respectively. Mesa isolation of the 2DEG channel was achieved by optical lithography and an Ar ion mill, with a typical mesa height of 76 nm. A selective wet etch was then used to dissolve the InAs cap, and to remove a small amount of InAs from the edge of the mesa in order to avoid accidental electrical contact. By maintaining the integrity of the barrier in the vicinity of interfacial contact, spin splitting of the 2DEG is preserved and the transport model described schematically by Fig. 1(c) is valid.

The ferromagnetic layer was e-beam deposited from a single source of $Ni_{0.8}Fe_{0.2}$ in a pressure of 10^{-6} Torr, and the top wire was patterned by optical lithography and lift-off. The thickness of the metal layer was about 86 nm, slightly larger than the mesa height in order to ensure electrical connectivity. Results from eight devices were comparable, and the data presented here are from a single, representative sample. The area of the interface was 56 μm^2. A control sample was made using nonmagnetic Au as the F layer, having interfacial area 64 μm^2. For this sample, the Au was thermally deposited from a Au source with purity of 5-9's, and the film thickness was 80 nm. A thin layer of nonmagnetic Ti, about 10 nm thick, was used to promote adhesion of the Au to the semiconductor surface.

In a standard four-probe configuration for measuring interface resistance [Fig. 1(a)], the voltage drop across the metal/2DEG interface was measured for an imposed bias current, with positive current flowing from F to the 2DEG. The interface resistance was first measured using a linear fit to current-voltage (I-V) traces over a voltage range of order 0.1 V centered at $V = 0$. For the Py (Au) sample, R_i was 20 Ω (120 Ω) at 295 K, increasing to 110 Ω (290 Ω) at 75 K. The relatively low values of R_i suggest that the AlGaSb barrier is a high transmission tunnel barrier or that tunneling is not the dominant transport mechanism. The magnetization orientation of F was controlled by using a two axis Helmholtz coil to apply an external magnetic field $\vec{H}$ in the plane of the 2DEG, along $\pm\hat{y}$ or $\pm\hat{x}$. The sample was cooled in an Oxford He flow cryostat with optical access.

Differences of the interface resistance ΔR_i arising from spin-dependent transport were measured by manipulating the magnetization orientation and, separately, the polarity of bias current. The I-V characteristic showed small deviations from Ohmic behavior for R_i in the experimental range 50 μA $\leq I \leq$ 1 mA, but values of $\Delta R_i/\overline{R}_i$ were independent of bias in this range [13]. The interface resistance, measured at a fixed bias current of $+1.0$ mA for four temperatures, is plotted as a function of externally applied magnetic field H_y in Fig. 2(a). The observed relative change $\Delta R_i/\overline{R}_i = 0.91\%$ is independent of temperature. The coercivity of the F film was measured *in situ* by Kerr photometry [14] at $T = 291$ K, focusing a HeNe laser probe beam on a portion of the film remote from the interface. The Kerr rotation of the reflected beam is proportional to the voltage output of the sensing photodiode and is shown in Fig. 2(b). Whereas the coercivity H_c of an unpatterned Py film deposited on quartz is about 4 Oe, the coercivity of our microfabricated Py film, deposited on $Al_{0.6}Ga_{0.4}Sb$, is seen to be about 35 Oe. The interface resistance plotted in Fig. 2(a) changes abruptly at the same field. The observation of hysteresis in the field dependent interface resistance measurement, with a coercive field value that matches the measured H_c of the Py, confirms that the change ΔR_i is associated with the magnetization orientation $+M\hat{y}$ or $-M\hat{y}$, and is not associated with any other effect of the magnetic field.

As explained above, when the magnetization direction is orthogonal to the spin quantization axis in the 2DEG, the spin subband conductances are intermixed and R_i is independent of the magnetization direction. Thus, for fixed bias current and changes of magnetization orientation from $+\hat{x}$ to $-\hat{x}$, the interface resistance should be constant, $\Delta R_i = 0$. This is confirmed with the data of Fig. 2(c), taken for field sweeps along $\pm\hat{x}$ at $T = 75$ K. An upper bound for the magnitude of any hysteretic feature is 0.1%, at least 9 times smaller than the 0.9% resistance change of Fig. 2(a). More generally, as a function of magnetization orientation in the x-y plane, ΔR_i should have a $\cos(\theta)$ symmetry ($\theta = 0$ corresponds to $+\hat{y}$). This was verified by taking data in angular steps of ten degrees.

Theory also predicts that an equivalent change of interface resistance will result when the magnetization orientation is fixed along $\hat{y}$ and the direction of bias current is reversed, so that the momentum of the sampled carriers in the 2DEG changes from $+k_x$ to $-k_x$. This effect has been called "spin dependent rectification" [10]. The data of Fig. 2(d) result from field sweeps along $\pm\hat{y}$ at $T = 75$ K for current polarities corresponding to $+k_x$ and $-k_x$ achieved by switching the I^- and V^- leads [refer to Fig. 1(a); configuration denoted (V^-) and (I^-)]. The hysteresis loop $R_i(H_y)$ is the same for both data sets, with the sole exception that the symmetry is reversed. Equivalently stated, for a given magnetization orientation of F ($H_y < 60$ Oe or $H_y > 60$ Oe), the interface resistance differs for the two current directions, $\pm k_x$, and the difference $\Delta R_i/\overline{R}_i$ has the same magnitude as observed in Fig. 2(a).

As a final test of our results, measurements were made on a sample with a nonmagnetic metal (Au) film in place of the ferromagnetic one. The dependence of interface resistance with magnetic field, $R_i(H_y)$, is shown in Fig. 3. The value of R_i remains constant for field sweeps of a range comparable with the data of Fig. 2. The null result, $\Delta R_i = 0$, of this control experiment gives further validation of the data and verification of our interpretation.

All plausible sources of a spurious effect can be ruled out. The anisotropic magnetoresistance (AMR) of the ferromagnetic film was measured *in situ*. As magnetic field is rotated by angle θ in the sample plane, the symmetry of the measured AMR is $\cos(2\theta)$ but the symmetry of ΔR_i is $\cos(\theta)$. Futhermore, the magnitude of the AMR of the entire length of the ferromagnetic wire was less than half the magnitude of ΔR_i, implying any AMR contribution to the interface resistance is negligibly small. Fringe fields originating at the edges of the ferromagnetic film, which are known to cause a Hall effect on the carriers in the 2DEG [15], represent another plausible mechanism. These fringe fields arise from magnetic "poles" at edges of F parallel with the $\hat{y}$ axis when the magnetization is along $\pm\hat{x}$, and

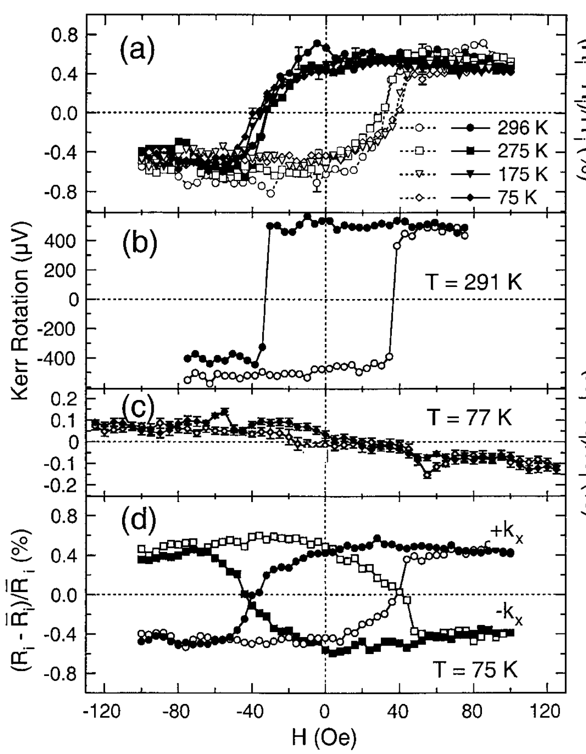

FIG. 2. Response to magnetic field. Open symbols are for increasing field and closed symbols for decreasing field. (a) R_i versus field applied along $\pm\hat{y}$, normalized to $\overline{R}_i$, for four temperatures. (b) Kerr rotation measured *in situ* on a ferromagnetic film, field applied along $\pm\hat{y}$. (c) $\Delta R_i/\overline{R}_i$ versus field applied along $\pm\hat{x}$, showing a null result. Note the change of scale. Average of 20 sweeps. (d) $\Delta R_i/\overline{R}_i$, for current in the $+\hat{x}$ and $-\hat{x}$ directions, with field applied along $\pm\hat{y}$.

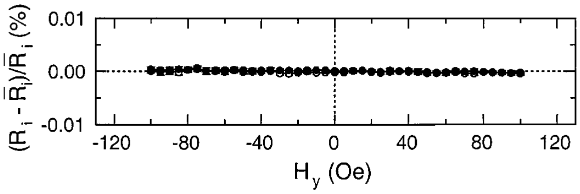

FIG. 3. $\Delta R_i / \overline{R}_i$ versus H_y for a nonmagnetic metal device. A null result is observed, $\Delta R_i = 0$.

from poles at edges parallel with the $\hat{x}$ axis when the magnetization is along $\pm\hat{y}$. As seen in Fig. 1(a), when $\vec{M}$ is along $\pm\hat{y}$, the poles are far from the interface and the fringe fields near the interface are negligibly small. When $\vec{M}$ is along $\pm\hat{x}$, the poles are close to the interface and could create substantial fringe fields. The data of Fig. 2(c) show small features near the coercive field ($H_c \approx 60$ Oe for $\vec{M}$ along $\hat{x}$). The features may represent spin injection effects generated when the magnetization reorientation involves partial alignment along $\pm\hat{y}$. In any event, we can clearly give an upper bound of 0.05% to fringe field effects in our geometry.

The data are in complete qualitative agreement with the predictions of the theory of Ref. [10], and a limited quantitative analysis can also be made. An order of magnitude estimate of $\Delta R_i / \overline{R}_i$ can be made using Eq. (2) and polarization values determined by alternative techniques. The polarization of carrier in Py films is $\eta = 0.4$ in tunneling experiments [11], and that of 2DEG carriers in InAs is $P = 0.1$ in Shubnikov–De Haas measurements [7]. The observed value of $\Delta R_i / \overline{R}_i = 0.009$ (0.9%) is in reasonable agreement with the estimate $\Delta R_i / \overline{R}_i \approx \eta P/2 \approx 0.02$.

In summary, we have observed spin injection at a ferromagnetic-2DEG interface by projecting the spin-polarized current of the ferromagnet on the spin-split density of states of the 2DEG. For a given polarization of the 2DEG carrier spins, determined by the polarity of the bias current, reversing the magnetization orientation along the appropriate axis modulates the interface resistance. Alternatively, reversing the direction of bias current for a fixed magnetization orientation gives an equivalent interface resistance modulation. While the magnitude of the observed interface resistance change is relatively small, the results confirm the presence of interfacial currents with spin polarization of order 20% and realization of a spin-injected HEMT is plausible. Theory predicts that the polarization of carriers in an appropriate 2DEG will be enhanced by spin injection [10], and the source-drain modulation of an optimized spin-injected HEMT can be expected to be of order 1%–10%.

This work was supported by the Office of Naval Research and the Advanced Research Project Agency. P. R. H. acknowledges financial support from the National Research Council. M. J. gratefully acknowledges the partial support of ONR Grant No. N000-1499-AF0002.

[1] G. Prinz, Phys. Today **48**, No. 4, 58 (1995).
[2] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[3] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).
[4] V. A. Vas'ko, V. A. Larkin, P. A. Kraus, K. R. Nikolaev, D. E. Grupp, C. A. Nordman, and A. M. Goldman, Phys. Rev. Lett. **78**, 1134 (1997).
[5] Y. A. Bychkov and E. I. Rashba, Sov. Phys. JETP Lett. **39**, 78 (1984).
[6] J. Nitta, T. Akazaki, and H. Takayanagi, Phys. Rev. Lett. **78**, 1335 (1997).
[7] J. Lou, H. Munekata, F. F. Yang, and P. J. Stiles, Phys. Rev. B **38**, 10 142 (1988); **41**, 7685 (1990).
[8] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998); Nature (London) **397**, 139 (1999).
[9] D. Hägele, M. Oestreich, W. Rühle, N. Nestle, and K. Eberl, Appl. Phys. Lett. **73**, 1580 (1998).
[10] M. Johnson, Phys. Rev. B **58**, 9635 (1998).
[11] R. Meservey and P. M. Tedrow, Phys. Rev. B **7**, 318 (1973); R. Meservey, D. Paraskevopoulos, and P. M. Tedrow, Phys. Rev. Lett. **37**, 858 (1976).
[12] B. R. Bennett, M. J. Yang, B. V. Shanabrook, J. B. Boos, and D. Park, Appl. Phys. Lett. **72**, 1193 (1998).
[13] In a relaxation time approximation, the shift of the Fermi disk under a 1 mA bias is of the order of 20 mV, much less than the Fermi energy $E_F \approx 300$ mV and within a linear response regime. At bias of a few mA, the interface I-V characteristic departs from linearity and $\Delta R_i \rightarrow 0$. See J. B. Boos *et al.*, IEEE Trans. Electron Devices **45**, 1869 (1998).
[14] M. Ramesh, R. W. Crowell, and S. Dey, Rev. Sci. Instrum. **64**, 1931 (1993).
[15] M. Johnson, B. Bennett, M.-J. Yang, M. M. Miller, and B. V. Shanabrook, Appl. Phys. Lett. **71**, 974 (1997).