Spin-Dependent Transmission of Electrons through the Ferromagnetic Metal Base of a Hot-Electron Transistorlike System

A. Filipe,[1,2] H.-J. Drouhin,[1] G. Lampel,[1] Y. Lassailly,[1] J. Nagle,[2] J. Peretti,[1] V. I. Safarov,[1] and A. Schuhl[2]
[1]*Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, 91128 Palaiseau Cedex, France*
[2]*Laboratoire Central de Rechercches Thomson-CSF, Domaine de Corbeville, 91404, Orsay, France*
(Received 12 May 1997)

A quasimonoenergetic spin-polarized electron beam, emitted in vacuum from a GaAs photocathode, is injected into a thin ferromagnetic metal layer deposited on an n-doped GaAs substrate. The current transmitted through this Schottky barrier is measured. The striking feature of this hot-electron transistorlike system is a current gain spin dependency as high as 20%. The measured variations of the current gain and its spin dependency with the injection energy are well explained by a very simple analytical model describing the transport of hot electrons in metallic thin films. [S0031-9007(98)05318-6]

PACS numbers: 73.30.+y, 73.50.Bk, 75.30.–m

Electron transport at the Fermi level in ferromagnetic metals has been largely investigated since the discovery of giant magnetoresistance [1]. At energies well above the vacuum level, spin selective electron transmission through a magnetized layer, the so-called spin filter effect, has been demonstrated using electron spectroscopy techniques and spin polarimetry [2]. Experiments reported at intermediate energies (a few eV above the Fermi energy E_F) are very scarce: among them, the overlayer photoemission technique on cesiated magnetic surface [3], hot-electron transport in a metal-base spin-valve transistor [4], and transmission of spin-polarized electrons through free-standing ultrathin magnetic structures [5]. We present here a new experiment where the magnetic metallic layer is grown on a GaAs substrate and acts as a spin filter on polarized electrons injected from vacuum and detected as a transmitted current in the semiconductor. All these configurations may be analyzed as a hot-electron transistor with a spin-dependent transport in the magnetic base. The current gain (or transmission coefficient) may be defined as $\alpha = I_c/I_e, I_e(I_c)$ being the injected (collected) current. In experiments using spin-polarized injected electrons, a transmission asymmetry A is obtained by reversing the saturation magnetization from $+M$ to $-M : A = [\alpha(+M) - \alpha(-M)]/[\alpha(+M) + \alpha(-M)]$. The peculiarity of our experiment is to measure α and A in a carefully engineered base-collector contact while the spin polarization P_e and the energy E (referred to as E_F) of the incident electrons are well-defined, and E may be varied over a wide range.

The sample preparation and characterization are described in detail elsewhere [6]; here we only recall the main features. A 1-μm-thick n-doped (10^{16} cm^{-3}) GaAs layer is grown on an n^+-doped (001) GaAs substrate, and subsequently oxidized *ex situ* during 5 min in a commercial ultraviolet/ozone system, leading to a 2-nm-thick oxide layer. Then, a 3.5-nm-thick Fe layer is grown on the oxide surface at a substrate temperature of 50 °C. It is covered with 5 nm of Pd in order to prevent Fe from oxidation during the transportation from the growth chamber to the experiment chamber. The oxide layer was shown to avoid the interdiffusion between Fe and GaAs. We have measured the magnetic moment indeed expected for a 3.5-nm-thick Fe layer. Magnetization is in plane, and an almost square hysteresis loop is measured with a remanence of 90% and a coercive field of about 20 Oe. Microscopy measurements show that the Fe layer is polycrystalline and continuous, with a mean roughness of about 1 nm. Then the sample is introduced into the experiment chamber, where a base pressure in the 10^{-11} Torr range is obtained after bakeout at 200 °C during 24 h.

The experimental setup, schematized in Fig. 1, mainly consists of the spin-polarized electron source, the electron optics, and the sample set between *in situ* magnetic coils used to magnetize the Fe layer. The electron source is a

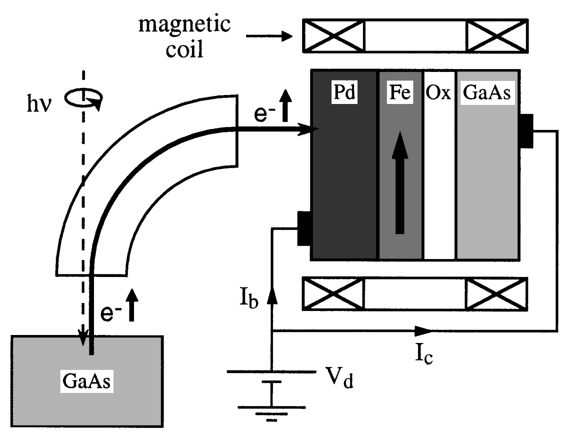

FIG. 1. Schematic view of the experimental setup. The boldface arrow indicates the electron spin-polarization vector. The excitation circularly polarized light of energy $h\nu$, the base current I_b, and the collector current I_c are figured. The Schottky diode reference potential V_d is applied on both sides of the sample.

negative electron affinity GaAs photocathode [7]. Under circularly polarized near-bandgap illumination (energy $h\nu = 1.6$ eV), it yields a longitudinal electron-spin polarization at emission $P_e \approx 25\%$. In the electrostatic electron optics, a 90° deflection of the electrons converts the longitudinal spin polarization into a transverse spin polarization parallel to the magnetization. The electron current I_e of a few 100 nA is incident from the vacuum onto the sample with a 200 meV energy distribution FWHM [7]. The injected current I_b is measured at the metallic base and the transmitted current I_c at the collector. No bias potential is applied to the base/collector contact in order to minimize shot noise. The injection energy E is varied by changing the sample potential V_d, while keeping constant the source and optics potentials. The lowest possible value of E is the Pd work function which was measured to be 4.8 eV from the onset of I_b.

We checked that the sample is well described by a perfect Schottky diode in parallel with a capacitor and a leakage resistor, and a serial resistor corresponding to the resistance between the metallic base front contact and the injection area. The contribution of the GaAs oxide layer is neglected due to its low thickness. The nonzero value of the base resistance slightly polarizes the Schottky diode. Therefore, even if there is no transmission (the actual current gain $\alpha = 0$), we may detect a current in the semiconductor (the measured current gain $\alpha^* \neq 0$). A careful study of the sample electrical characteristics allowed us to deduce the values of the equivalent circuit components and to determine α from α^* [6]. The asymmetry measurement is also affected by the parasitic current gain, and the actual asymmetry A is related to the measured asymmetry A^* by $A\alpha = A^*\alpha^*$. Using a conventional I-V technique, we also deduced from this study the value of the GaAs barrier height $\Phi_b = 0.78$ eV [6].

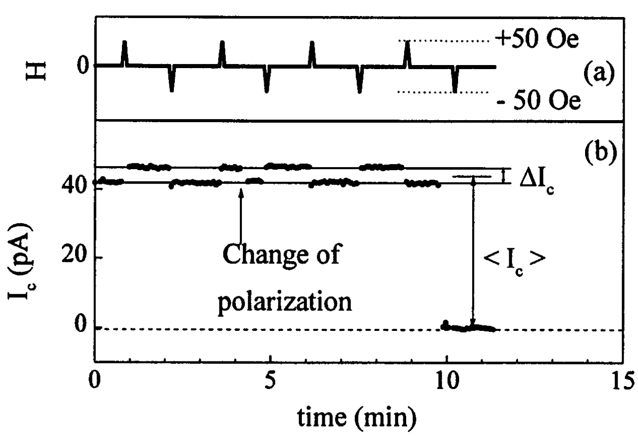

FIG. 2. Time recording of I_c for $I_e = 200$ nA, $P_e = 25\%$, and $E = 5.2$ eV. The magnetization is periodically flipped by alternate magnetic field pulses ($H = \pm 50$ Oe). At $t = 4$ min, the incident electron polarization is reversed. At $t = 10$ min, the electron source is switched off.

Figure 2(b) shows the time recording of I_c under the periodic reversal of Fe magnetization, for $P_e = 25\%$ and $E = 5.2$ eV. Fe magnetization is flipped periodically by sending alternate current pulses into the magnetic coils producing magnetic field pulses of ± 50 Oe [Fig. 2(a)]. This results in a square modulation of I_c of amplitude ΔI_c, and we find $A^* = \Delta I_c / 2\langle I_c \rangle = 5\%$, where $\langle I_c \rangle$ is the mean transmitted current. This means that for a 100% spin-polarized beam, we would measure a current-gain spin dependency of 20%. When reversing the electron polarization [as indicated by the arrow in Fig. 2(b)], we observe a reversal of ΔI_c. So the asymmetry is directly linked to the relative orientation of the incident spin polarization and Fe magnetization. This is the fingerprint of electron spin-dependent transport in Fe. Moreover, the sample magnetization being initially saturated by a magnetic field pulse of -50 Oe, we define $I_c(H)$ as the collector current in zero external magnetic field after a magnetic field pulse H. The variation of $I_c(H)$ as a function of H (Fig. 3) reproduces very well the hysteresis loop measured prior to the introduction into the experiment chamber [6].

In Figs. 4(a) and 4(b) are plotted the variations versus E of $\alpha(E)$ (measured with an unpolarized electron beam) and $S(E) = A(E)/P_e$ (measured at remanent magnetization). The quantity $S(E)$, which is the asymmetry for a 100% incident spin polarization, defines the spin filter efficiency, analogous to the Sherman function in spin polarimetry [8]. We observe that $\alpha(E)$ increases with E, whereas $S(E)$ decreases. To interpret these variations, we develop a model in which we consider independently the processes of transmission through each layer (neglecting multiple backscattering). We denote as $I_i^{\uparrow}$ and $I_i^{\downarrow}$ the currents of electrons at the entrance of the ith layer with spin, respectively, up and down. The transmission through the ith layer is described by a 2×2 matrix,

$$\begin{bmatrix} I_{i+1}^{\uparrow} \\ I_{i+1}^{\downarrow} \end{bmatrix} = \tilde{\alpha}_i \begin{bmatrix} I_i^{\uparrow} \\ I_i^{\downarrow} \end{bmatrix}. \quad (1)$$

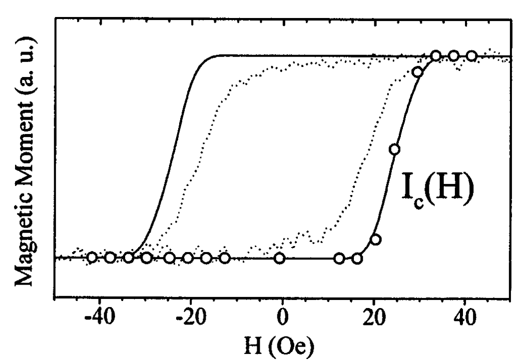

FIG. 3. Variations of $I_c(H)$ (in arbitrary units) versus the magnetic field pulse amplitude H for $E = 5.2$ eV. The circles are the experimental points. The full line is the extrapolated hysteresis loop. The dotted line is the measured hysteresis loop prior to the introduction into the experiment chamber.

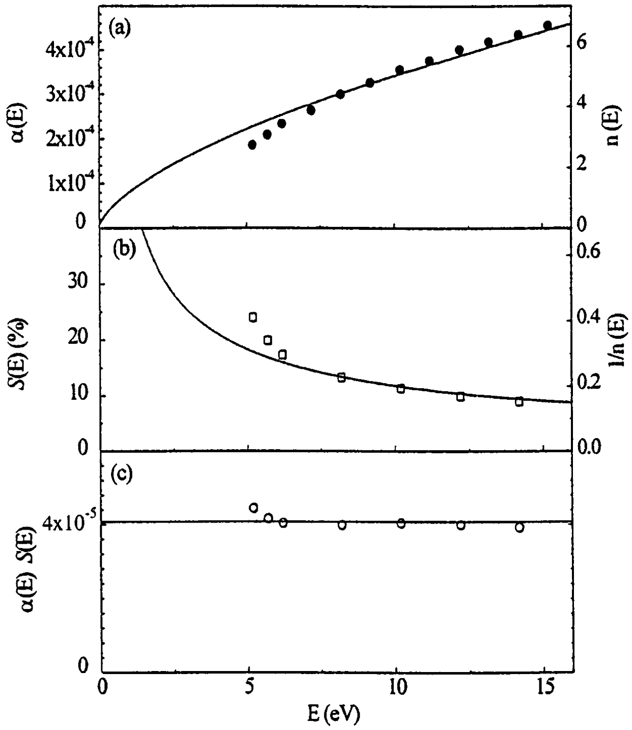

FIG. 4. Variations with E of (a) $\alpha(E)$, (b) $S(E)$, and (c) $\alpha(E)S(E)$. The symbols are the experimental points. The full lines in (a) and (b) (right-hand scale) represent, respectively, the variations of $n(E)$ and $1/n(E)$ according to Eq. (8).

The current-gain matrix $\tilde{\alpha}$ of the whole structure is simply $\tilde{\alpha} = \Pi \tilde{\alpha}_i$. Introducing the mean current $I_i = (I_i^{\uparrow} + I_i^{\downarrow})/2$, the spin polarization $P_i = (I_i^{\uparrow} - I_i^{\downarrow})/(I_i^{\uparrow} + I_i^{\downarrow})$, and the transformation matrix $\tilde{T} = \tilde{T}^{-1} = (1/\sqrt{2})\left[\begin{smallmatrix} 1 & 1 \\ 1 & -1 \end{smallmatrix}\right]$, we define the transformed current-gain matrix $\overline{\alpha} = \tilde{T}\tilde{\alpha}\tilde{T}$ and obtain

$$I_c \begin{bmatrix} 1 \\ P_c \end{bmatrix} = \overline{\alpha} I_e \begin{bmatrix} 1 \\ P_e \end{bmatrix}. \quad (2)$$

The injection into the metallic layer is described by the matrix $\tilde{\alpha}_e$, as a generalization of the emission efficiency in a transistor. This injection from vacuum into the nonmagnetic metal (Pd) should conserve the spin, so $\tilde{\alpha}_e = \alpha_e I_2$, where I_2 is the 2×2 identity matrix. In the explored energy range (from 5 to 15 eV), we measured that I_b was almost constant and equal to I_e. Therefore we take $\alpha_e \approx 1$, as expected theoretically [9].

In the metallic layer, the injected electrons suffer inelastic scattering and excite secondary electrons from the Fermi sea. As the overall electron mean-free path is short in the considered energy range when compared to the metallic layer thickness and decreases with increasing energy, this process is very efficient and leads, whatever the injection energy, to the formation of an electron distribution with a mean energy much smaller than Φ_b. For the same reasons, almost all the electrons which are transmitted above the barrier to form the collector current have an energy very close to Φ_b, and only their number depends on E. We assume that this low energy electron distribution is completely formed in Pd close to the surface, and that the subsequent transmission to the collector is ballistic at energy Φ_b. We define in Pd at energy Φ_b two quantities: $n(E)$ the number of electrons per incident electron and α_{Pd} the ballistic transmission coefficient. The mean transmitted current is therefore $\alpha_{\text{Pd}} n(E) I_e$. Since the $n(E) - 1$ secondary electrons are unpolarized, the spin polarization at the Pd/Fe interface is diluted by these unpolarized electrons, and is equal to $P_e/n(E)$ (neglecting spin-flip scattering). Therefore, the transformed transmission matrix in Pd is given by

$$\overline{\alpha}_{\text{Pd}} = \alpha_{\text{Pd}} n(E) \begin{pmatrix} 1 & 0 \\ 0 & 1/n(E) \end{pmatrix}. \quad (3)$$

In the Fe layer, we only consider ballistic transport at energy Φ_b and neglect spin-flip scattering. So the off-diagonal terms in $\tilde{\alpha}_{\text{Fe}}$ are zero. We introduce α_{Fe}^{+} and α_{Fe}^{-}, the transmission coefficients associated with spin-up and spin-down electrons. The difference between α_{Fe}^{+} and α_{Fe}^{-} leads to the spin filter effect. So

$$\tilde{\alpha}_{\text{Fe}} = \begin{pmatrix} \alpha_{\text{Fe}}^{+} & 0 \\ 0 & \alpha_{\text{Fe}}^{-} \end{pmatrix}, \qquad \text{and} \qquad \overline{\alpha}_{\text{Fe}} = \langle \alpha_{\text{Fe}} \rangle \begin{pmatrix} 1 & s \\ s & 1 \end{pmatrix}, \quad (4)$$

where $\langle \alpha_{\text{Fe}} \rangle = (\alpha_{\text{Fe}}^{+} + \alpha_{\text{Fe}}^{-})/2$ and $s = (\alpha_{\text{Fe}}^{+} - \alpha_{\text{Fe}}^{-})/(\alpha_{\text{Fe}}^{+} + \alpha_{\text{Fe}}^{-})$ are, respectively, the mean transmission coefficient and spin filter efficiency in the Fe layer at energy Φ_b.

The matrix $\tilde{\alpha}_c$ describes the transmission from the Fe layer through the thin oxide layer into the collector just above the barrier Φ_b, and the transport in GaAs. Since those mechanisms should not depend on the spin, we use a scalar (and constant) transmission α_c.

Within this multiple-steps transport mechanism, we obtain from Eqs. (3) and (4)

$$\overline{\alpha} = \alpha(E) \begin{pmatrix} 1 & s/n(E) \\ s & 1/n(E) \end{pmatrix}, \quad (5)$$

where the mean current gain is

$$\alpha(E) = \alpha_c \langle \alpha_{\text{Fe}} \rangle \alpha_{\text{Pd}} n(E). \quad (6)$$

Then, $S(E)$ is given by

$$S(E) = s/n(E). \quad (7)$$

As compared to the spin filter efficiency s in the Fe layer alone at energy Φ_b, $S(E)$ is reduced by the factor $n(E)$ which describes the dilution of the primary polarization by excitation of secondary electrons in the Pd overlayer. The simple multiple-step model is strongly supported by the fact that the product $\alpha(E)S(E) = \alpha_c \langle \alpha_{\text{Fe}} \rangle \alpha_{\text{Pd}} s$ remains constant, as shown in Fig. 4(c).

To go a little further, we need an analytical form for $n(E)$. Assuming a constant density of states in Pd, an incident electron colliding with an electron of the Fermi sea produces one inelastic electron at a mean energy $E/3$ and one secondary electron at a mean energy $E/3$. The remaining energy $E/3$ is given to a hole in the Fermi sea. Iterating this process to k collisions leads to $n(E) = 2^k$ electrons with a mean energy $E/3^k$. Therefore, the average number of collisions suffered by the electrons to reach the energy Φ_b is $k = \ln(E/\Phi_b)/\ln(3)$, giving

$$n(E) \approx (E/\Phi_b)^{0.63}. \tag{8}$$

The variations of $n(E)$ and $1/n(E)$ are plotted in Figs. 4(a) and 4(b) in the same frame as $\alpha(E)$ and $S(E)$ to show the consistency of this simple model with the experimental results. The discrepancy between experiment and calculation at low injection energy is due to the fact that our transport model is valid for at least a few collisions, i.e., for $E/3 \gg \Phi_b$. One gets $\alpha_c\langle\alpha_{\mathrm{Fe}}\rangle\alpha_{\mathrm{Pd}} = (6.8 \pm 0.1) \times 10^{-5}$ and $s = 0.6 \pm 0.1$ which corresponds to a very large asymmetry of the spin transport in the Fe layer.

In the Fe layer, the ballistic transport at energy Φ_b can be described by an exponential decay, with inelastic mean-free paths λ_+ and λ_- for majority and minority spins. The transmission through the Fe layer of thickness d_{Fe} is $\alpha_{\mathrm{Fe}}^{\pm} = \exp(-d_{\mathrm{Fe}}/\lambda_{\pm})$. Let us define $1/\lambda_{\pm} = 1/\lambda \mp 1/\delta$ [5], then $s = \tanh(d_{\mathrm{Fe}}/\delta)$ and $\langle\alpha_{\mathrm{Fe}}\rangle = \exp(-d_{\mathrm{Fe}}/\lambda)\cosh(d_{\mathrm{Fe}}/\delta)$. The length δ which characterizes the mean-free path spin dependency is equal to 5 nm. The asymmetry is large because λ is of the order of d_{Fe}, so that the spin filtering effect is fully effective during the crossing of the Fe layer. On the other hand, the transmission through the Fe layer is quite low because $d_{\mathrm{Fe}}/\lambda \gg 1$. This transmission can be estimated by using the value of $(\lambda_+ - \lambda_-)/(\lambda_+ + \lambda_-) = \lambda/\delta \approx 0.28$ from Ref. [10]. It leads to $\langle\alpha_{\mathrm{Fe}}\rangle = 8 \times 10^{-2}$. A value of $\alpha_c\alpha_{\mathrm{Pd}}$ of a few 10^{-3} was measured for injection energies of about 1 eV on a 5-nm-thick Pd layer on Si [11]. It is consistent with our estimation of $\alpha_c\langle\alpha_{\mathrm{Fe}}\rangle\alpha_{\mathrm{Pd}}$.

From the point of view of spin detection, the figure of merit [8] is $F = \alpha(E)S^2(E) = \alpha_c\langle\alpha_{\mathrm{Fe}}\rangle\alpha_{\mathrm{Pd}}s^2/n(E)$. This expression shows that the large figure of merit of the bare Fe layer at energy Φ_b, $\langle\alpha_{\mathrm{Fe}}\rangle s^2 \approx 3 \times 10^{-2}$, is strongly counterbalanced by the transmission through surrounding layers and the polarization dilution due to secondary electrons. By using thinner layers and lower injection energies (which may be achieved by cesium activation of the front surface), one could expect to design a very efficient spin detector.

To conclude, we have demonstrated a spin filter effect in the collection of electrons by a ferromagnetic metal/semiconductor diode. We have identified the main transport mechanisms which result in a spin filter efficiency S up to about 25% for the whole structure. Our model allows us to deduce a spin filtering efficiency of 0.6 in the Fe layer at an energy of the order of 1 eV above the Fermi level unprobed by other techniques. This experiment is a significant step in an emerging field associating magnetic properties of metals with transport properties of semiconductors.

The authors thank A. J. van der Sluijs for very fruitful discussions. This work was supported in part by the commission of the European Community through the "SPIDER" ESPRIT project.

[1] E. Vélu, C. Dupas, D. Renard, J.-P. Renard, and J. Seiden, Phys. Rev. B **37**, 668 (1988).

[2] D. P. Pappas, K.-P. Kämper, B. P. Miller, H. Hopster, D. E. Fowler, C. R. Brundle, A. C. Luntz, and Z.-X. Shen, Phys. Rev. Lett. **66**, 504 (1991).

[3] J. C. Gröbli, D. Guarisco, S. Frank, and F. Meier, Phys. Rev. B **51**, 2945 (1995).

[4] D. J. Monsma, J. C. Lodder, Th. J. A. Popma, and B. Dieny, Phys. Rev. Lett. **74**, 5260 (1995).

[5] H.-J. Drouhin, A. J. van der Sluijs, Y. Lassailly, and G. Lampel, J. Appl. Phys. **79**, 4734 (1996).

[6] A. Filipe, H.-J. Drouhin, G. Lampel, Y. Lassailly, J. Peretti, V. I. Safarov, and A. Schuhl, in *Proceedings of the MRS Spring Meeting, San Francisco, CA, 1997,* edited by J. Tobin, MRS Symposia Proceedings No. 475 (Materials Research Society, Pittsburgh, 1997), p. 75.

[7] H.-J. Drouhin, C. Hermann, and G. Lampel, Phys. Rev. B **31**, 3859 (1985); **31**, 3872 (1985) .

[8] J. Kessler, *Polarized Electrons* (Springer-Verlag, Berlin, 1985), 2nd ed.

[9] A. J. Dekker, in *Secondary Electron Emission,* edited by F. Seitz and D. Turnbull, Solid State Physics Vol. 6 (Academic Press, New York, 1958).

[10] H. C. Siegmann, J. Electron Spectrosc. Relat. Phenom. **68**, 505 (1994).

[11] R. Ludeke and A. Bauer, Phys. Rev. Lett. **71**, 1760 (1993).