Perpendicular Hot Electron Spin-Valve Effect in a New Magnetic Field Sensor: The Spin-Valve Transistor

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A new magnetic field sensor is presented, based on perpendicular hot electron transport in a giant magnetoresistance $(Co/Cu)_4$ multilayer, which serves as a base region of an n-silicon metal-base transistor structure. A 215% change in collector current is found in 500 Oe (77 K), with typical characteristics of the spin-valve effect. The in-plane magnetoresistance was only 3%. The transistor structure allows the investigation of energy resolved perpendicular transport properties, and in particular spin-dependent scattering of hot electrons in transition-metal as well as rare-earth-based multilayers.

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The discovery of giant magnetoresistance in magnetic multilayers [1] (also called the spin-valve effect [2]) has led to a large number of studies on giant magnetoresistance systems. Usually, the resistance of the multilayer is measured with the current in plane (CIP). This is the easiest experimental approach of electrical transport in magnetic multilayers. Devices exhibiting CIP giant magnetoresistance are under development as magnetic field sensors, for instance, in read-back magnetic heads used in magnetic recording technology. However, from a fundamental point of view, the CIP configuration suffers from several drawbacks; the CIP magnetoresistance (MR) is diminished by shunting and channeling [2,3]. In particular, uncoupled multilayers or sandwiches with thick spacer layers suffer from this problem, whereas the saturation field in such systems is usually small. Moreover, diffusive surface scattering reduces the MR for sandwiches [2] and thin multilayers [4]. Finally, fundamental parameters of the effect, such as the relative contributions of interface and bulk spin-dependent scatterings, are difficult to obtain using the CIP geometry [5]. Measuring with the current perpendicular to the planes (CPP) solves most of these problems, mainly because the electrons cross all magnetic layers, but a practical difficulty is encountered; the perpendicular resistance of the ultrathin multilayers is too small to be measured by ordinary techniques. The first CPP-MR experiments were reported on Co/Ag multilayers [6], where the multilayer was sandwiched between superconducting Nb leads. In this way, CPP experiments could be performed, albeit only at liquid helium temperatures. The use of microfabrication techniques for CPP measurements from 4.2 to 300 K was first shown for Fe/Cr multilayers [7], where the multilayers were etched into micropillars to obtain a relatively large resistance (a few mΩ). Both types of measurements have confirmed the larger MR effect for the CPP configuration, but they suffered from the general complexity of realization and measurement techniques. Experiments using electrodeposited nanowires showed CPP-MR up to 15% at RT [8].

In this Letter, we present the design, prospects, and experimental results of a new magnetic field sensor and measurement tool based on perpendicular hot electron transport in a spin-valve multilayer: the spin-valve transistor. Here, a spin-valve multilayer serves as a base region of an n-silicon metal-base transistor structure. Metal-base transistors have been proposed for ultrahigh frequency operations [9] because of their negligible base transport time and low base resistance; however, low gain prospects have limited their advent. Its use for investigating transport properties has been shown for Au, Ag, Al, and Pd base films [10]. With the spin-valve transistor, we present the first evidence of a spin-valve effect for hot electrons $\approx$1 eV above E_F in (Co/Cu) multilayers. We find a very large change (215% at 77 K) in collector current under application of a magnetic field of 500 Oe, with typical giant magnetoresistance characteristics, such as saturation field and hysteresis. The hot nature of the electrons and the possibility to vary the electron energy accurately in a range of about 0.2–3 eV raises exciting possibilities for fundamental research of the spin-valve effect and may lead to unforeseen effects and new spin valves. In contrast to usual conduction electrons which are sensitive to the density of states (DOS) at the Fermi energy (E_F), the hot electrons are sensitive to DOS above E_F. Manipulation of electron energy may offer important insights into the relative importance of the band structure (DOS) and scattering potentials, which are understood to form the basis of the scattering asymmetry between majority and minority conduction electrons [11]. Spin polarization of hot electrons in magnetic films is known for energies larger than about 5 eV relative to the Fermi level [12]. The electron energy range of the spin-valve transistor is particularly attractive, because the asymmetry in DOS of spin-split $3d$ bands is most pronounced for energies up to 2 eV above the Fermi level in Co and Fe [13].

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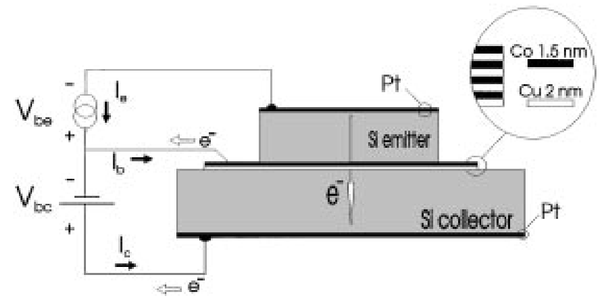

FIG. 1. Schematic cross section of the spin-valve transistor. A (Cu 2 nm/Co 1.5 nm)$_4$ multilayer base is rf sputtered onto the Si(100) collector substrate. The emitter has been direct-bonded to the base multilayer. Bias in the common base configuration and electron transport are shown for clarity. The base area is 2.7×2.7 mm^2; the emitter area is 1.6×1.6 mm^2.

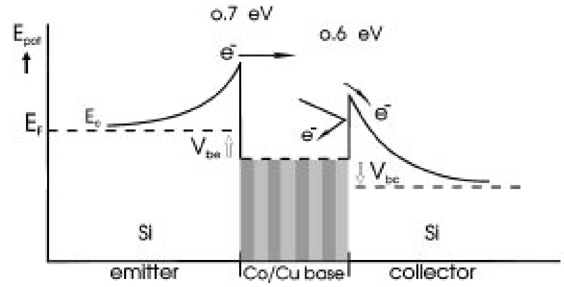

FIG. 2. Schematic energy band diagram of the spin-valve transistor under forward bias. The emitter Schottky barrier is slightly larger than the collector Schottky barrier, reducing quantum mechanical reflections. The collected electron current is exponentially dependent on the (inverse of the) MFP of the injected electrons in the Co/Cu multilayer base.

For the preparation of the transistor, we applied direct bonding, both to obtain device quality semiconductor material for the emitter and to allow room temperature processing. In direct bonding two flat, optically smooth, and clean materials can form a permanent electrical and mechanical connection by means of spontaneous adhesion. This technique is new for the fabrication of metal base transistors and is described in more detail in [14]. A cross section of the spin-valve transistor is shown schematically in Fig. 1. The starting material for both emitter and collector is a 380 μm, 5–10 Ω cm, nSi(100) wafer. After backside n^{++} implantation, the wafer is dry oxidized to anneal the implant and to form a protective SiO_2 layer. After depositing a Pt Ohmic contact onto the backside, the wafer is sawn into 10×10 mm collectors and 1.6×1.6 mm emitters. A collector is subsequently dipped in HNO_3, 2% HF (removal of native oxide on silicon fragments), 5% tetramethyl ammoniumhydroxide at 90 °C (removal of silicon fragments, 8 min), and buffered HF (removal of thermal oxide). Following each step, the collector is rinsed in demineralized water. After this procedure the base multilayer, (Cu 2 nm/Co 1.5 nm)$_4$, is rf sputtered through a laser-cut metal shadow mask onto the collector substrate, defining square base regions slightly larger than the emitter surface. Directly after cleaning the emitter in a similar manner, its hydrophobic surface is contacted to the multilayer surface, forming a bond through spontaneous adhesion. The bonding strength for Si-Co, as determined by spring force measurements, is 5–10 kg/cm^2.

The energy band diagram of the bonded Co/Cu spin-valve transistor is shown in Fig. 2. The collector (emitter) barrier height is about 0.7 eV (0.6 eV). The emitter and collector Schottky barrier are in forward and reverse bias, respectively, as illustrated by the common base configuration in Fig. 1. The emitter bias accelerates the electrons over the emitter barrier, after which they constitute the hot, "ballistic" electrons in the base. The probability of passing the collector barrier is limited by collisions in the base, which affect their energy and trajectory, by optical phonon scattering in the semiconductors and by quantum mechanical reflections at the base-collector interface. For a metal-base transistor with a single metal-base film, this can be expressed by the common base current transfer ratio or current gain $\alpha_0 = (J_c - J_{\text{leak}})/J_e = \alpha_e \alpha_c \alpha_{\text{qm}} e^{-W/\lambda}$ [9], in which α_e, α_c, and α_{qm} represent emitter efficiency, collector efficiency, and quantum mechanical transmission, respectively. W is the base width and λ is the hot electron mean free path (MFP) in the base. The factor $e^{-W/\lambda}$ represents the probability of transmission of the hot electrons through the base. J_c is the total collector current, J_{leak} is the collector leakage current, determined by the reverse-biased collector Schottky barrier, and J_e is the injected emitter current. The factors α_c and α_e depend, among others, on the type and quality of the semiconductors. In the spin-valve transistor under consideration, the thicknesses of the individual layers (Co or Cu) are much smaller than the spin-flip diffusion length (a few nm as compared to several tens of nm). Neglecting, therefore, spin-flip scattering, we may consider the spin ↑ and spin ↓ electrons to carry the current in parallel (two current model). Furthermore, it has been shown [15] that in this limit no spin relaxation occurs in the CPP-MR and that consequently the perpendicular transport properties can be very simply described by considering a network of serial resistances for each channel of electrons corresponding to the resistance of the successive layers and interfaces. Following this idea, as a first approach, the collector current of the Co/Cu spin-valve transistor can be expressed as

$$\begin{aligned} J_c &= J_{c+} + J_{c-} \\ &= J_e \alpha_e \alpha_c \alpha_{\text{qm}} \Big[\prod_i P_{i+} + \prod_i P_{i-} \Big] + J_{\text{leak}} , \quad (1) \end{aligned}$$

where $\prod_i P_{i+(-)}$ denotes the product of transmission probabilities of spin up $(+)$ and down $(-)$ electrons through each layer and interface. In first approximation we take α_e, α_c, and α_{qm} similar for the two species of electrons since these quantities reflect the properties of the semiconductors and Schottky barriers. At saturation, all Co layers have their magnetization parallel. The sum of the transmission probability factors for the two spin channels can then be written as

$$\left[\prod_i P_{i+} + \prod_i P_{i-}\right]_{\mathrm{P}} = e^{-W_{\mathrm{Cu}}/\lambda_{\mathrm{Cu}}}\left(e^{-W_{\mathrm{Co}}/\lambda_{\mathrm{Co}\uparrow}} e^{-W_{F/N}/\lambda_{F/N\uparrow}} + e^{-W_{\mathrm{Co}}/\lambda_{\mathrm{Co}\downarrow}} e^{-W_{F/N}/\lambda_{F/N\downarrow}}\right). \tag{2}$$

At the coercive field, this quantity becomes

$$\left[\prod_i P_{i+} + \prod_i P_{i-}\right]_{\mathrm{AP}} = e^{-W_{\mathrm{Cu}}/\lambda_{\mathrm{Cu}}}\left(2e^{-W_{\mathrm{Co}}/2\lambda_{\mathrm{Co}\uparrow}} e^{-W_{\mathrm{Co}}/2\lambda_{\mathrm{Co}\downarrow}} e^{-W_{F/N}/2\lambda_{F/N\uparrow}} e^{-W_{F/N}/2\lambda_{F/N\downarrow}}\right), \tag{3}$$

where W_{Co} expresses the sum of all Co layer widths (total Co thickness), W_{Cu} the total Cu thickness, $\lambda_{\mathrm{Co}\uparrow(\downarrow)}$ the majority (minority) MFP's in the Co layers, λ_{Cu} the MFP in the Cu layer, and $\exp(-W_{FN}/\lambda_{FN\uparrow(\downarrow)})$, a spin-dependent factor which takes into account the spin-dependent scattering at the interfaces. The values of the collector current in the parallel (P) and antiparallel (AP) magnetic configurations are then obtained by inserting expressions (2) and (3) into (1). The first part of the right-hand side of Eq. (1) will be denoted by J_{MC}, the magnetocurrent.

The buildup of the spin-valve transistor has some major implications for its transport properties; the electrons flow perpendicularly through the base multilayer, and the energy of the electrons in the multilayer can be varied by altering the Schottky barrier heights, providing electron energy spectroscopy. Furthermore, in contrast to the usual CPP-GMR in which the CPP resistance varies linearly with the MFP's, the collector current in the spin-valve transistor is exponentially dependent on the (inverse of the) MFP's in the separate layers and interfaces, allowing a strong amplification of the perpendicular spin-valve effect at the output, which is a high impedance magnetocurrent. Measurements can be done at cryogenic and room temperature. Many spin valves of 0 to ≈100 nm thickness can be implemented, where the upper limit is set by the ratio $J_{\mathrm{MC}}/J_{\mathrm{leak}}$. Since the scattering processes appear as products in the transfer equation, the spin-dependent scattering centers can be located accurately and, in contrast to common CPP-MR, the relative change in magnetocurrent MC (%) is not decreased by *spin-independent* scattering processes such as in the Cu layers or in the semiconductors (factors α). As a consequence of the direct MFP dependence of the transmission across the base, the spin-valve transistor allows quantification of spin-dependent electron MFP's $\lambda_{\downarrow(\uparrow)}$ of the individual layers and interfaces. This can be done by calculating $\lambda_{\downarrow(\uparrow)}$ and $\alpha_e\alpha_c\alpha_{\mathrm{qm}}$ from Eqs. (1)–(3) for different base layer thicknesses. The relation between the change in magnetocurrent and the mean free path ratio $\lambda_\uparrow/\lambda_\downarrow$, expected from the transport equations (1)–(3) is illustrated in Fig. 3. Here, the relative change in magnetocurrent $\mathrm{MC} = (J_{\mathrm{P}} - J_{\mathrm{AP}})/J_{\mathrm{AP}}$ is

$$\mathrm{MC} - \cosh\left[\frac{W}{2\lambda_\downarrow}\left(\frac{\lambda_\downarrow}{\lambda_\uparrow} - 1\right)\right] - 1 \tag{4}$$

and

$$\text{CPP-MR} = \frac{\lambda_\downarrow}{4\lambda_\uparrow} + \frac{\lambda_\uparrow}{4\lambda_\downarrow} - 0.5, \tag{5}$$

where CPP-MR is $(R_{\mathrm{AP}} - R_{\mathrm{P}})/R_{\mathrm{P}}$ [16]. Figure 3 shows that the structure may both amplify or attenuate the intrinsic perpendicular hot-electron MR effect, depending strongly on W/λ of the used multilayer. This is due to the varying influence of λ on the transmission. The ratio $J_{\mathrm{leak}}/J_{\mathrm{MC}}$ and, for applications, the desired output level of the spin-valve transistor, set an upper limit to $W/\lambda_\downarrow$.

The barrier heights of collector and emitter, as determined at room temperature by the "current-voltage" method are ≈0.7 and ≈0.6 eV, respectively. Because of the low barrier height and large area of the collector, the leakage current is quite large ($I_{\mathrm{leak}} \approx 30\ \mu$A) and exceeds the magnetocurrent for an injection current of 100 mA. Therefore, magnetocurrent measurements have been performed at 77 K, reducing the leakage current to acceptable values. Magnetocurrent measurements have been performed with the common base setup of Fig. 1, with $I_e = 100$ mA and $V_{bc} = 0$ V. The collector current versus the (in-plane) applied magnetic field is plotted in Fig. 4. A large current change with field is observed, with typical GMR characteristics of a second peak Co/Cu multilayer, such as saturation field and hysteresis (e.g., [17]). The corresponding CIP-MR value of the implemented multilayer was only 3% in 10 kOe (77 K). The large values of MC (%) and J_e/J_c indicate a short $\lambda_{\downarrow(\uparrow)}$ [of the order of 0.5(1) nm]; however, precise determination of the interface and bulk mean free paths will require further measurements.

In conclusion, we have shown the possibilities of the spin-valve transistor concept as a powerful scientific tool

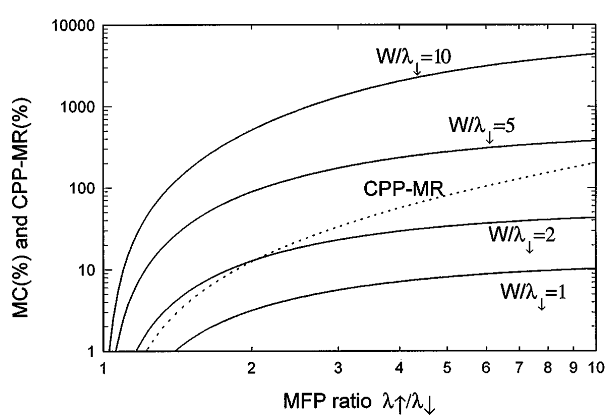

FIG. 3. Transmission characteristics of the spin-dependent transport. The relative change in magnetocurrent MC (%) and the relative change in perpendicular hot-electron spin valve effect in the base CPP-MR (%) are plotted versus the MFP ratio $\lambda_\uparrow/\lambda_\downarrow$.

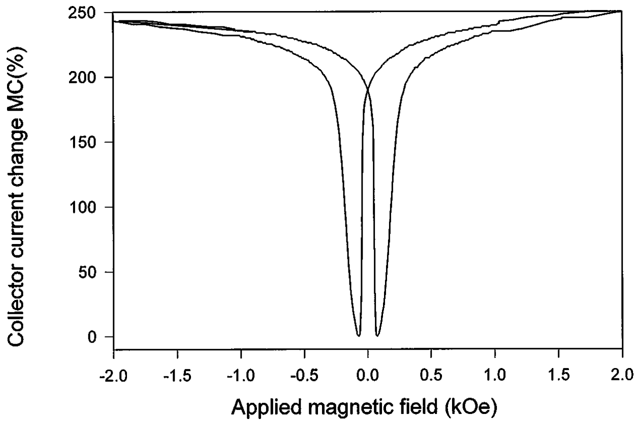

FIG. 4. The magnetocurrent of the (Cu 2 nm/Co 1.5 nm)$_4$ spin-valve transistor at 77 K. The value at coercive field is 0.1 μA, at $\pm$10 kOe, 0.5 μA, resulting in more than 390% magnetocurrent change.

for investigating spin-dependent scattering properties in an important uncovered electron energy range. An initial model of the spin-valve transistor has been proposed, which allows one to quantify the spin-dependent mean free paths in the base layers, provided experimental data with different base layer thicknesses are available. The measurements have been performed at 77 K to reduce a parasitic leakage current. Room temperature measurements may be performed by using higher barriers or smaller area geometries. The Schottky barriers of the spin-valve transistor may alternatively be replaced by (ferromagnetic) tunneling barriers. We hope that this study will stimulate further experimental and theoretical investigations of hot-electron transport properties in magnetic multilayers.

[1] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).
[2] B. Dieny, J. Magn. Magn. Mater. **136**, 335 (1994).
[3] A. Fert, T. Valet, and J. Barnas, J. Appl. Phys. **75**, 6693 (1994); S. Zhang and P. M. Levy, Phys. Rev. B **47**, 6776 (1993).
[4] H. A. M. van den Berg and G. Rupp, IEEE Trans. Magn. **30**, 809 (1994).
[5] S. F. Lee, W. P. Pratt, Jr., R. Loloee, P. A. Schroeder, and J. Bass, Phys. Rev. B **46**, 548 (1992).
[6] W. P. Pratt, Jr., S. F. Lee, J. M. Slaughter, R. Loloee, P. A. Schroeder, and J. Bass, Phys. Rev. Lett. **66**, 3060 (1991).
[7] M. A. M. Gijs, S. K. J. Lenczowski, and J. B. Giesbers, Phys. Rev. Lett. **70**, 3343 (1993).
[8] A. Fert *et al.*, Appl. Phys. Lett. **65**, 2484 (1994); A. Blondel *et al.*, Appl. Phys. Lett. **65**, 3019 (1994).
[9] S. M. Sze, *Physics of Semiconductor Devices* (Wiley-Interscience, New York, 1969), Chap. 11.
[10] C. R. Crowell and S. M. Sze, Phys. Rev. Lett. **15**, 659 (1965); S. M. Sze, C. R. Crowell, G. P. Carey, and E. E. LaBate, J. Appl. Phys. **37**, 2690 (1966).
[11] P. M. Levy, J. Magn. Magn. Mater. **140–144**, 485 (1995).
[12] *Polarized Electrons in Surface Physics*, Advanced Series in Surface Science Vol. 1, edited by R. Feder (World Scientific, Singapore, 1985); R. J. Celotta, J. Unguris, and D. T. Pierce, J. Appl. Phys. **75**, 6452 (1994).
[13] V. L. Moruzzi, J. F. Janak, and A. R. Williams, *Calculated Electronic Properties of Metals* (Pergamon, New York, 1978).
[14] D. J. Monsma, J. Holleman, H. van Kranenburg, P. de Haan, and J. C. Lodder (to be published).
[15] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).
[16] In this example, for simplicity, the interfacial and bulk scattering has been averaged in Eqs. (4) and (5), and spin-independent scattering has been neglected in (5). In the picture of the resistance network for CPP-MR, configuration R_P is proportional to $1/\lambda_\uparrow + 1/\lambda_\uparrow$ in parallel with $1/\lambda_\downarrow + 1/\lambda_\downarrow$ leading to $R_P \propto 2/(\lambda_\uparrow + \lambda_\downarrow)$, while R_{AP} is proportional to $1/\lambda_\uparrow + 1/\lambda_\downarrow$ in parallel with $1/\lambda_\downarrow + 1/\lambda_\uparrow$ so that $R_{AP} \propto (\lambda_\uparrow + \lambda_\downarrow)/(2\lambda_\uparrow\lambda_\downarrow)$.
[17] D. H. Mosca, F. Petroff, A. Fert, P. A. Schroeder, W. P. Pratt, Jr., and R. Loloee, J. Magn. Magn. Mater. **94**, L1 (1991).