Double-injector source of spin polarized current with controllable polarization

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We present low-temperature measurements of Co/Al spin valves with a double-injector source of spin polarized current. Using an in-plane magnetic field, the injector electrodes were magnetized in opposite directions. The spin polarization of the injected current was controlled by changing the ratio of currents through the two electrodes and was continuously varied from zero up to the maximum spin polarization of Co. This result was verified by measuring the spin valve signal, using the detector electrode magnetized to align with one of the injectors. This source can be used for spintronic applications as well as in research on hybrid ferromagnet/superconductor structures. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2220547]

Spintronic devices using electron spin for device function have been the focus of solid state research for the past two decades due to their application in data storage and manipulation. Their potential advantages over conventional semiconductor devices are their smaller size and higher operating frequencies (see Ref. 1 for a review on spintronics). Highlights of recent progress in this area include the discovery of giant magnetoresistance (GMR),[2] the tunneling magnetoresistance,[3] and the demonstration of an all-metal spin valve at room temperature.[4] An essential element of a spintronic device is a source of spin polarized current. Most spintronic devices are based on the spin valve effect: a dependence of the resistance of the device on the mutual orientation of the magnetization in two ferromagnetic electrodes. For example, in magnetic sensors such as a GMR read head, the state of a magnetic data bit is obtained by aligning the magnetization in one of the read-head electrodes with that of the data bit. However, in order to build an active device, such as a spin transistor, one needs to be able to rotate the magnetization by electrical means. Several ideas have been proposed: reversing the magnetization of a thin film by injecting the spin polarized current,[5] moving domain walls,[6] and applying an electric field.[7] However, the first two mechanisms require high current densities of the order of 10^8 A/cm^2. The third mechanism is due to the orbital mechanism of spin coupling to the applied electric field and requires strong electric fields and long interaction times. Due to these problems, a spin transistor has not been built to date. While the mainstream of spintronics research is dedicated to finding an effective method to rotate the *direction* of the spin polarization of the current, little attention has been paid to the possibility of changing the *absolute* value of the spin polarization.

In this letter we demonstrate a simple spin polarized source in which the polarization can be changed continuously from zero up to the maximum possible value for a given ferromagnetic electrode. The source consists of two ferromagnetic injectors placed within spin diffusion length and magnetized in opposite directions. By changing the ratio of currents going through each injector, the total polarization is varied. The result was verified by using a third electrode as a detector, whose magnetization was aligned with one of the injectors.

The samples were fabricated using multiple e-beam lithography and standard processing. The geometry of the structures is shown in Fig. 1. First, 30 nm thick Co ferromagnetic injector electrodes F_1 and F_2 and a detector electrode D were fabricated on a Si substrate covered by its native oxide. Second, 40 nm thick Al wire was deposited on top of the ferromagnets. Both Co and Al were evaporated in a vacuum of the order of 10^{-6} mbar at the rate of about 0.5 nm/s. In order to obtain a clean interface between Co and Al, the samples were etched in an Ar^+ plasma before evaporation of the second layer. The length of each ferromagnetic electrode was 14 μm and the widths were 230, 330, and 160 nm for D, F_1, and F_2, respectively. Then the samples were bonded with Au wires to the chip carrier, oriented so that the longer dimension of the F electrodes was parallel to the direction of the magnetic field inside a cryostat. The measurements were carried out in a ^{4}He cryostat at the base temperature of 4.2 K in magnetic fields up to 400 mT. The voltage at the detector electrode was measured using a lock-in amplifier working at a frequency of 17.7 Hz. Currents I_1 and I_2 through F_1 and F_2 were set by the output

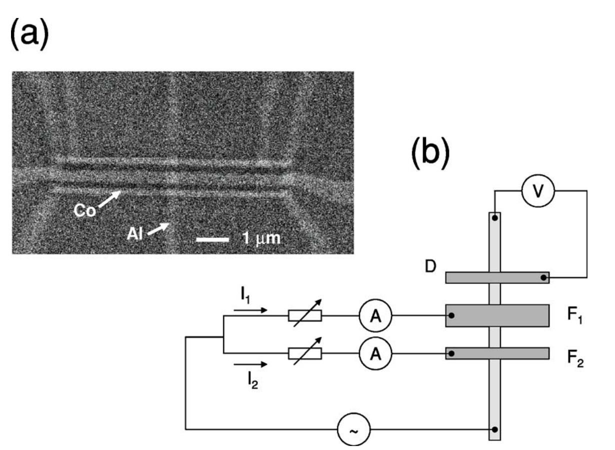

FIG. 1. (Color online) (a) SEM micrograph of one of the measured samples. (b) A schematic diagram of the experiment. Voltage on detector electrode D is measured by the lock-in amplifier. F_1 and F_2 are injectors connected to the oscillator output. Magnetic field is parallel to the long dimension of the ferromagnetic electrodes.

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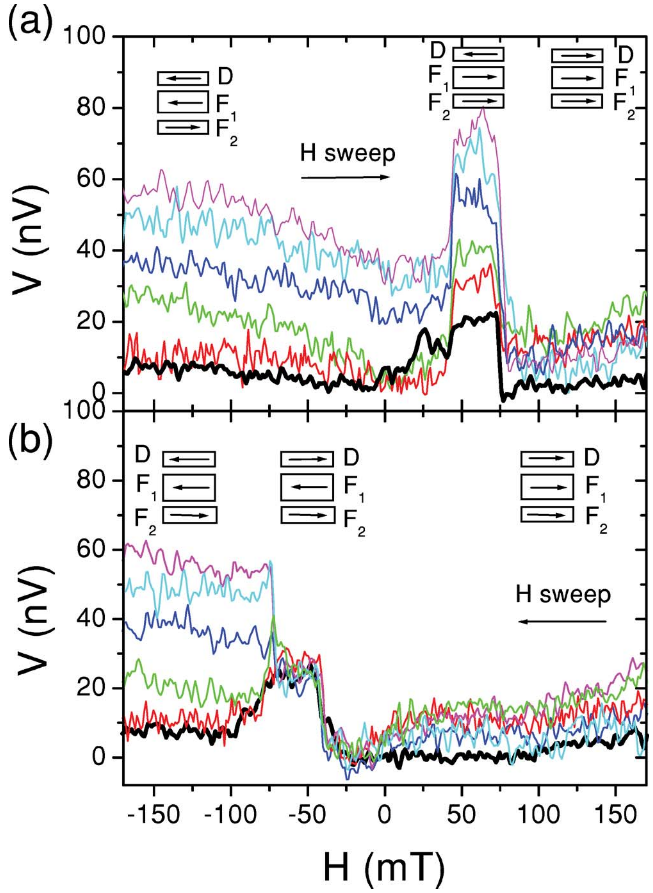

FIG. 2. (Color online) Spin valve signal at $T=4.2$ K as a function of applied magnetic field for different values of I_2. $I_1=5$ μA=const, $I_2=0$ (black), $I_2=2$ μA (red), $I_2=5$ μA (green), $I_2=7$ μA (blue), $I_2=10$ μA (cyan), and $I_2=12$ μA (magenta). Magnetic field is swept (a) from left to right and (b) from right to left. Sketches show the relative orientations of magnetization in the three ferromagnetic electrodes at various values of magnetic field.

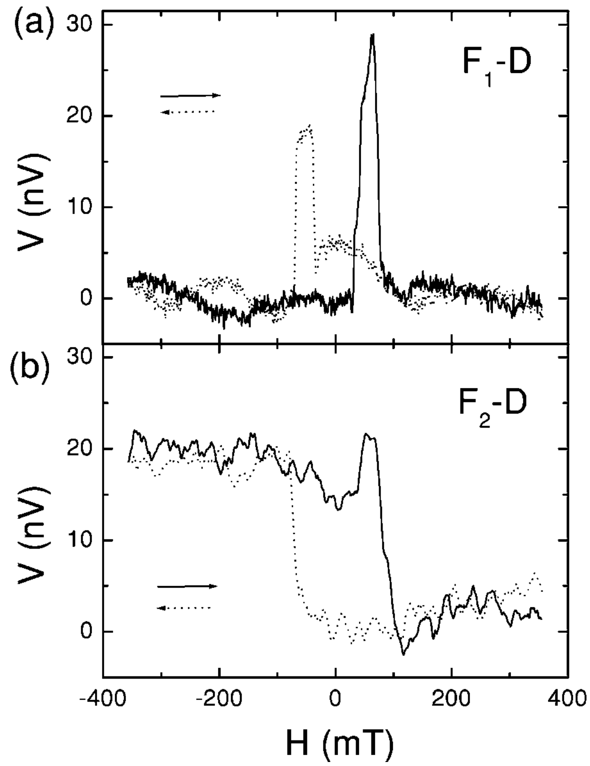

FIG. 3. Spin valve signal at $T=4.2$ K as a function of applied magnetic field. The solid and dotted curves correspond to opposite directions of the field sweep. (a) Voltage on D electrode due to current $I_1=5$ μA. (b) Voltage on D electrode due to current $I_2=5$ μA.

of a lock-in amplifier oscillator and the values of variable resistors in each injector line. Both the oscillator and the lock-in input were connected to the sample through decoupling transformers.

Figure 2 shows the spin valve signal on D at the base temperature $T=4.2$ K as a function of magnetic field at constant value of I_1 and different values of I_2. The value of I_2 was varied by changing the variable resistor in F_2 line [see Fig. 1(b)], while I_1 was kept constant by adjusting the oscillator output. Sketches show the direction of the magnetization in the ferromagnetic electrodes at various applied magnetic fields. Switching fields for the reversal of the magnetization in D was 75 mT, in F_1 it was 40 mT, and in F_2 it was above 400 mT so that the magnetization of F_2 remained constant during the whole experiment. The magnetization state of each electrode at a given point during a magnetic field sweep was determined by measuring the spin valve signal on pairs of electrodes F_1-D and F_2-D (see Fig. 3). For the F_1-D pair (top panel in Fig. 3), one can see transitions from the parallel configuration to the antiparallel one upon switching the magnetization of F_1 at $H=40$ mT first, because it has a lower coercive force due to its wider dimension perpendicular to the field. This corresponds to the maximum in the spin valve voltage. At $H=75$ mT the magnetization of D is reversed, so that the two are in the parallel state again and the spin valve voltage drops back to zero. Changing the magnetic field sense, the process is repeated in the opposite direction. For the F_2-D pair (bottom panel in Fig. 3), only switching of D at $H=\pm 75$ mT takes place within the range of fields used. The system changes from the antiparallel state on the left in Fig. 3 to the parallel one on the right.

Knowing the mutual orientation of the magnetization in the three ferromagnetic electrodes, it is easy to understand the results presented in Fig. 2. Starting from the left in the top panel of Fig. 2, we have magnetizations in D and F_1 which are parallel, while those of D and F_2 are antiparallel. Therefore, the spin valve signal at this point is due to I_2 only. Correspondingly, we see an increase of the measured voltage from zero, proportional to I_2. A small spin valve signal due to I_1 in this area can be attributed to a possible misalignment of the direction of the applied magnetic field and the easy axis of the ferromagnetic electrodes, which is unimportant here. At $H=40$ mT the magnetization of F_1 flips over, so that both injectors are in the antiparallel state with the detector and the spin signal due to I_1 is added. Finally, D flips over at $H=75$ mT so that all three electrodes have parallel magnetization and the spin valve voltage drops to zero (again ignoring contributions due to the misalignment). Reversing the magnetic field sense, we start at the all-parallel configuration at the right in the bottom panel of Fig. 2. At $H=-40$ mT we observe a magnetization flip in F_1 accompanied by a voltage jump due to I_1, but since D and F_2 are in the parallel state, there is no dependence on I_2 in this area and it appears again only when D is switched at $H=-75$ mT.

The switch of D at $H=-75$ mT, shown in the bottom panel of Fig. 2, is a crucial point to determine the total spin polarization of our double-injector source. Note that the two injectors are magnetized in opposite directions. One can say that the total spin polarization of the current is zero when there is no change in the voltage on D upon switching its magnetization. This happens when $I_2 \approx 6\ \mu$A.

The spin valve voltage measured in this experiment is due to the spin accumulation arising at F/N interfaces, when a spin polarized current in F is converted into a spinless one in N. The nonequilibrium build up of spins at the interface leads to the difference in chemical potentials of spin-up and spin-down electrons decaying over the spin relaxation length (λ_N for N and λ_F for F) from the interface. This spin accumulation is measured by the electrode D. The potential difference between D and N is a function of the mutual orientation of magnetizations in the injector and detector electrodes and can be calculated using a simple spin accumulation model.[8–10] In particular, in the limit of transparent interfaces between F and N, the voltage V due to the spin valve effect can be presented as follows:[11]

$$V = 4p_F^2 R_N \frac{x^2}{(1+2x)^2 - 1} e^{-L/\lambda_N} I, \tag{1}$$

where L is the distance between F electrodes, p_F is the spin polarization in F, $x = R_F/R_N$ is a resistance mismatch factor, $R_F = \rho_F \lambda_F / A_F$, $R_N = \rho_N L / A_N$, ρ_F and ρ_N are resistivities of F and N, respectively, and A_F and A_N are cross sections of F and N wires, respectively. We assume that $L < \lambda_N$ and $p_F^2 \ll 1$. For F_1 and F_2 we have $L_2 = 2L_1$ and $A_{F1} = 2A_{F2}$ (see Fig. 1), hence the factor x remains the same. Thus, at the compensation point we get $(L_2 - L_1)/\lambda_N = \ln(R_{N2} I_2 / R_{N1} I_1)$, which gives $\lambda_N = 0.6\ \mu$m, in reasonable agreement with values reported earlier.[12,13] Substituting values of $\lambda_F = 60$ nm,[14] $\lambda_N = 0.6\ \mu$m, $p_F = 0.11$,[12] $\rho_F \approx 10\ \mu\Omega$ cm, $\rho_N \approx 1\ \mu\Omega$ cm, $A_N = 160 \times 40$ nm^2,[2] $A_F = 330 \times 30$ nm^2,[2] $L = 0.5\ \mu$m, and $I_1 = 5\ \mu$A for F_1 into (1), we get $V = 10.5$ nV in reasonable agreement with our experiment.

In conclusion, we have demonstrated a simple source of spin polarized current, with variable absolute value of polarization, by using two ferromagnetic injectors placed within spin diffusion length of normal metal and magnetized in opposite directions. By changing the ratio of currents I_1 and I_2, we have been varying the net polarization of current from zero up to the maximum value for Co. The source can be used in spintronic applications as well as in research in hybrid F/N and F/S structures, where transport properties are functions of the spin polarization of the current.

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