# Spin-valve effects in a semiconductor field-effect transistor: A spintronic device

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We present a spintronic semiconductor field-effect transistor. The injector and collector contacts of this device were made from magnetic permalloy thin films with different coercive fields so that they could be magnetized either parallel or antiparallel to each other in different applied magnetic fields. The conducting medium was a two-dimensional electron gas (2DEG) formed in an AlSb/InAs quantum well. Data from this device suggest that its resistance is controlled by two different types of spin-valve effect: the first occurring at the ferromagnet-2DEG interfaces; and the second occurring in direct propagation between contacts. [S0163-1829(99)04335-0]

The idea of electronic devices that exploit both the charge and spin of an electron for their operation has given rise to the new field of ‘‘spintronics,’’ literally spin electronics.[1,2] The two-component nature of spintronic devices is expected to allow a simple implementation of quantum computing algorithms as well as producing spin transistors and spin-based memory devices.[1,2] However, this new field has yet to have any real impact on the semiconductor microelectronics industry since no implementation of a spintronic device has appeared in the form of a semiconductor field-effect transistor (FET).

Spin-polarized electron transport from magnetic to nonmagnetic metals has been the subject of intense investigation since the early 70s when Tedrow and Meservey[3] demonstrated the injection of a spin-polarized current from ferromagnetic nickel to superconducting aluminum. This paper was subsequently extended to include spin-dependent transport between other materials. The investigation of ferromagnetic-ferromagnetic/paramagnetic materials[4,5] resulted in the important discovery of the giant magnetoresistance effect.[6,7] Work on ferromagnetic-semiconductor systems has so far been more limited. Alvarado and Renaud[8] have demonstrated spin-polarized tunneling from a ferromagnet into a semiconductor by analyzing luminescence induced by a tunneling current between a nickel tip and a GaAs surface in a scanning tunneling microscope (STM). Similar experiments were conducted by Sueoka *et al.*[9] and Prins *et al.*[10]

In this paper, we present results from a spintronic semiconductor FET based on the *theoretical* ideas of Datta and Das.[11] In their proposed FET, resistance modulation is achieved through the spin-valve effect[12] by varying the degree of spin precession that occurs in a two-dimensional electron gas (2DEG) between identical ferromagnetic contacts. In our device, resistance modulation is also achieved through the spin-valve effect but by having ferromagnetic contacts with different coercivities and varying an applied magnetic field. We show that the low-field magnetoresistance of the device results from two types of spin-valve effect: a ferromagnet-semiconductor contact resistance; and a direct effect between the magnetic contacts.

The device consisted of a 2DEG formed in a 15 nm-wide InAs well between two AlSb barriers. The top barrier was 15-nm thick and had a 5-nm GaSb cap layer to prevent oxidation of AlSb. Two parallel ferromagnetic permalloy ($Ni_{80}Fe_{20}$) contacts [see inset of Fig. 1(a)], one 5 $\mu$m wide (contact *A*) and the other 1 $\mu$m wide (contact *B*), were patterned using electron beam lithography. They were placed 1 $\mu$m apart and stretched across a 25 $\mu$m-wide Hall bar produced by optical lithography. The different aspect ratios of these contacts ensured that they had different coercivities with an easy axis of magnetization along their long axes.[13] This allowed them to be magnetized either parallel or antiparallel to each other in different ranges of external magnetic field. To ensure good ohmic behavior between the contacts *A* and *B* and the 2DEG, the top GaSb and AlSb layers were etched away selectively in the area of the contacts using Microposit MF319 developer.[14] Any oxide on the InAs surface, which could act as spin scatterer, due to the paramagnetic nature of oxygen, was removed by dipping the sample in $(NH_4)_2S$. This is known to passivate the InAs surface with

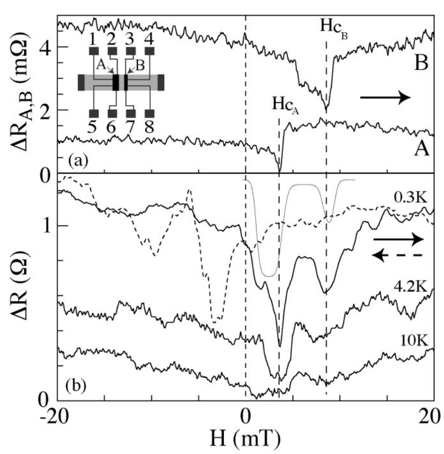


FIG. 1. (a) Change in resistance of contacts *A* and *B* with external magnetic field *H*, averaged over 4 up sweeps. $H_{C_A}$ and $H_{C_B}$ coercive fields of *A* and *B*. Inset: schematic of device: black pads — magnetic contacts *A,B;* dark gray — NiCr/Au ohmic contacts; light gray-Hall bar mesa. (b) Change in device resistance at 0.3 K averaged over 9 sweeps (up—solid, down—dashed lines) and 4.2 and 10 K averaged over 2 up sweeps. Gray line: schematic showing the expected sum of the two spin-valve effects. The arrows indicate the direction of the field sweep. All traces are offset for clarity.

 

sulfur and decelerate the oxidation process.[15] Moreover, it has been shown to improve the tunneling properties in STM studies of InAs.[16] It is also expected to remove any Sb residue which is known to be present after etching AlSb with the MF319 developer.[14] Within 5 min of passivation, a film of 50 nm of permalloy was evaporated followed by 20 nm of Au in order to protect the permalloy from oxidation. A network of extended NiCr/Au contacts [shown as 1-8 in Fig. 1(a), inset], patterned by optical lithography, was used to connect contacts *A* and *B* with external circuitry. A layer of polyamide insulated this network from the device surface. Nonmagnetic NiCr/Au ohmic contacts used for four-terminal device characterization were patterned at each end of the Hall bar. For basic nonmagnetic characterization an identical Hall bar without magnetic contacts was prepared on the same wafer.

A reduction in mobility of the device 2DEG from $\mu=4.9$ to 0.09 $m^2\,s^{-1}\,V^{-1}$ (at 0.3 K) was observed after removal of the AlSb barrier in the regions of contacts *A* and *B* and subsequent dipping of the device in $(NH_4)_2S$. A reduction in mobility (from 3.6 to 0.5 $m^2\,s^{-1}\,V^{-1}$ at 0.3 K) was observed in a reference sample, having no magnetic contacts, after removal of the AlSb barrier above the InAs well over the whole surface of the Hall bar. We believe that the reduction in mobility in the device is partly due to lateral etching of the AlSb barrier layer located between the magnetic contacts after dipping in $(NH_4)_2S$. It is known that $(NH_4)_2S$ attacks GaSb and AlSb chemically.[17] It is also possible that inhomogeneous band bending at the sulfur-passivated surface produces greater charge scattering than an oxide surface.

The spin transport properties of the 2DEG are important to the operation of the device. There are two parts to this: a 2DEG in an InAs quantum well is diamagnetic;[18,19] and has strong spin precession.[20,21] This spin precession results from the Rashba[20] term in the spin-orbit interaction. In transport, the combination of multiple elastic scattering from nonmagnetic impurities and spin-precession results in a randomization of spin orientation and can give rise to weak antilocalization.[21] This effect was observed in our characterization Hall bar (at the center of a weak localization peak) enabling us to estimate the spin dephasing length $l_{sd}$ and the related zero-field spin-splitting energy $\Delta E$ of the device 2DEG. These measurements were made in a magnetic field applied perpendicular to the 2DEG.

By fitting the weak antilocalization peak as described in Ref. 21 we estimated the spin dephasing time $\tau_s$ to be 9 ps. For the calculations we used an electron density $n=6\times10^{15}\ m^{-2}$, calculated from the Shubnikov-de-Haas oscillations, a mobility of $\mu=4.9\ m^2\,s^{-1}\,V^{-1}$ and the effective mass for InAs $m^*=0.04m_o$ ($m_o$=electron rest mass).[22] $l_{sd}$, was calculated from the expression, $l_{sd}=(l v_F \tau_s)^{1/2}$, where $l$ is the elastic mean-free path and $v_F$ is the Fermi velocity in our system, and found to be $l_{sd}=1.8$ $\mu$m. $\Delta E$ at zero magnetic field was calculated using an expression for $(\tau_s)^{-1}$ given in Ref. 21, $(\tau_s)^{-1}=(\langle\Delta E^2\rangle\tau_e)/4\hbar^2$, where $\langle\Delta E^2\rangle$ is the Fermi-surface average of $\Delta E^2$, and $\tau_e$ is the relaxation time for elastic scattering and was found to be $\langle\Delta E^2\rangle=0.16\ (\mathrm{meV})^2$. From the expressions for $\tau_s$ and $l_{sd}$ we can see that $l_{sd}=2\hbar v_F/\sqrt{\langle\Delta E^2\rangle}$ implying that $l_{sd}$ is independent of the mobility. Our device should therefore be expected to have a similar $l_{sd}$ to the characterization Hall bar since they have similar carrier concentrations and zero-field spin splitting.

Weak antilocalization was not observed after sulfur passivation since a reduction in mobility causes a reduction in the inelastic scattering length $l_\varphi$ and can therefore break the condition for observation of weak antilocalization ($l_\varphi$ comparable or larger than $l_{sd}$). For our characterization Hall bar we estimated $l_\varphi=1$ $\mu$m by fitting the weak localization part of the magnetoresistance.[23] From the ratio of the mobilities with and without sulfur passivation we estimate $l_\varphi\sim0.1$ $\mu\mathrm{m}\ll l_{sd}$ after sulfur passivation.[24]

In order to determine the magnetic properties of the contacts *A* and *B* we performed four-terminal magnetoresistance measurements at 0.3 K using a constant ac current of 100 $\mu$A. For contact *A* the current was applied between positions 2 and 6 [see inset in Fig. 1(a)] and the voltage drop between contacts 1 and 5 was recorded by lock-in amplification techniques. Similarly for contact *B* the current was applied between positions 3 and 7 and the voltage drop was recorded between positions 4 and 8 of the contact. These measurements are shown in Fig. 1(a) with the magnetic field being applied along the long axis of the contacts *A* and *B*. The sharp minimum in each curve corresponds to the switching of the magnetization of the contact and therefore occurs at its coercive field.[13] For contact *A* we measured a coercive field $Hc_A=3.5$ mT and for contact *B*, $Hc_B=8.5$ mT.

In order to observe the spintronic properties of the device, magnetoresistance measurements were carried out in magnetic fields applied parallel to the plane of the 2DEG and along the easy axis of the contacts *A* and *B* at temperatures ranging from 0.3 to 10 K. A constant ac current of 1 $\mu$A was applied between positions 1 and 4 [see inset in Fig. 1(a)] of the magnetic contacts and the voltage drop between positions 5 and 8 was recorded. Figure 1(b) shows these measurements, plotted as the change in the magnetoresistance $\Delta R$

$$\Delta R=R(H)-R(H=0), \tag{1}$$

from its zero-field value $R(H=0)=588\Omega$. $H$ is the applied magnetic field. At 0.3 K Fig. 1(b) shows both an up sweep (solid line) and a down sweep (dashed line). The principal features in these sweeps are a peak in magnetoresistance between the two coercive fields $H_{C_A}$ and $H_{C_B}$ and a dip on either side of this peak. The dip on the low-field side is deeper than the one on the high-field side. This structure is repeated symmetrically on opposite sides of zero field for the up and down sweeps.

By comparing four-terminal resistance measurements made between the contacts *A* and *B* with those made between the nonmagnetic contacts the interface conductance, *G*, was found to be 10 mS. Furthermore, the spin conductance of the 2DEG $g_s$ defined as the conductance of a length of the bulk material equal to $l_{sd}$,[25] was found to be 2 mS. Therefore, since *G* and $g_s$ are comparable we expect a contribution from both the interface and the 2DEG in the device magnetoresistance. The magnetoresistance ($\Delta R$) of our device will therefore have the following contributions:

$$\Delta R=\Delta R_A+\Delta R_B+\Delta Rc_A+\Delta Rc_B+\Delta R_s \tag{2}$$

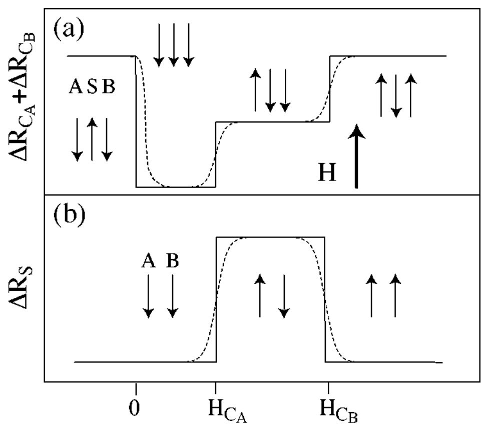


FIG. 2. (a) Schematic of the interface spin-valve effect: $\Delta Rc_A + \Delta Rc_B$. Arrows indicate magnetization direction in *A* and *B* and 2DEG S. *H* is the external field which is being swept up from negative value. (b) Schematic of direct spin-valve effect: $\Delta R_s$. Dashed lines in (a), (b) indicate averaging over the local switching of different magnetic domains in *A* and *B*.

where $\Delta R_A$ and $\Delta R_B$ are the magnetoresistance changes of contacts *A* and *B*, respectively, $\Delta Rc_A$ and $\Delta Rc_B$ are those of the interface between the 2DEG and contacts *A* and *B*, respectively, and $\Delta R_s$ is the resistance change due to electrons propagating from one ferromagnetic contact to the other without spin scattering.

As can be seen by comparing Figs. 1(a) and 1(b) the contributions $\Delta R_A$ and $\Delta R_B$ ($\simeq 2$ m$\Omega$) are 500 times smaller than the magnetoresistance changes in $\Delta R$ ($\simeq 1\ \Omega$). The results in Fig. 1(b) cannot therefore be attributed to changes in the magnetoresistances of the contacts themselves. The part of the interface resistance $\Delta Rc_A + \Delta Rc_B$, which results from the spin-valve effect,[12] and therefore has a dependence on applied field, will have the schematic form shown in Fig. 2(a). Its shape derives from both the spin properties of the 2DEG and the difference in coercive fields of the contacts *A* and *B*. It is a maximum when the magnetizations of contacts *A* and *B* are parallel to each other and antiparallel to the spin orientation of the 2DEG. It has a minimum value when the magnetizations in *A* and *B* are both parallel to the spin orientation in the 2DEG and an intermediate value when the contact magnetizations are antiparallel. The part of the resistance contribution from direct propagation between contacts *A* and *B*, $\Delta R_s$, which results from the spin-valve effect[12] will have the form shown schematically in Fig. 2(b). This resistance is a minimum when both ferromagnetic contacts are magnetized parallel to each other and maximum between the two coercive fields where the magnetization of the two contacts is antiparallel to each other. The broken lines in Fig. 2 represent a more realistic picture of the magnetoresistance changes resulting from the two spin-valve effects. They represent an average over the local switching of different magnetic domains in the ferromagnetic contacts. A schematic representation of the sum of the two spin-valve contributions to $\Delta R$ is shown as a gray line in Fig. 1(b), taking the coercive fields from the contact magnetoresistances in Fig. 1(a). This line has the same shape as the experiment and appears in the correct place for both up and down field sweeps. The depth and width of the high-field magnetoresistance dip depend upon the extent to which the shape of the up peak in Fig. 2(b) exactly compensates the dip down between the coercive fields in Fig. 2(a). If these are identical there will be no high-field dip.

The small amplitude of the device resistance modulation $\Delta R/R(H=0) \approx 0.2\%$ shown in Fig. 1(b) is consistent with the above picture. Electrons contributing to the direct spin-valve effect shown in Fig. 2(b) have to take fairly direct paths between contacts *A* and *B*. Those which take paths involving multiple scattering pick up random angles of spin orientation and therefore on average will cancel with each other and not contribute to the effect. The temperature dependence of the magnetoresistance is also consistent with our picture. The peak between the two coercive fields decreases in amplitude with increasing temperature and almost disappears at 10 K [see Fig. 1(b)]. At this temperature $k_BT$ ($=0.8$ meV) is greater than the zero-field spin splitting and therefore thermal activation has sufficient energy to destroy both spin-valve effects shown in Fig. 2(b).

Alternative mechanisms that could produce the magnetoresistance oscillations observed would have to be capable of: producing the symmetry we see in up and down field sweeps [solid and dashed lines in Fig. 1(b)]; producing features of an appropriate shape that align with the contact coercive fields; and persist up to temperatures of 10 K in a 2DEG with a zero field resistance of 588 $\Omega$ and an inelastic scattering length one tenth the length of the device. Such fluctuations are unknown in the literature. Universal conductance fluctuations (UCF's) could occur in a device of such low resistance. However, their period in magnetic field ($H_{C_B} - H_{C_A} = 5$ mT) is consistent with a phase coherent area of $\sim 1$ ($\mu$m)$^2$, which is two orders of magnitude larger than that estimated from the inelastic scattering length of the device ($l_\varphi \sim 0.1\ \mu$m). In addition UCF's are not seen in magnetic fields applied parallel to a 2DEG.[26,27] Also, since the field was applied along the easy axis of the contacts A and B there should be no stray fields with a significant component perpendicular to the 2DEG. The most likely origin of the small amplitude random modulations appearing in the data and the differences in shape between up and down magnetic field sweeps is the complex pattern of domain formation in the contacts *A* and *B* and their pattern of switching as a function of external field.

In conclusion, we have provided evidence that we observed experimentally two kinds of spin-valve effect in a spintronic FET. The first effect results from the ferromagnet-2DEG interface resistance and the second effect results from spins propagating from one ferromagnetic contact to the other. The combination of these effects produces a resistance maximum between the coercive fields of the two contacts and dips in resistance on either side. Both effects are suppressed with increasing temperature as the thermal smearing becomes comparable to the zero-field spin splitting.

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[1] The term ‘‘spintronics’’ was apparently coined by Lucent Technologies as ‘‘electronic devices in which the direction an electron spin is pointing is just as important as its charge.’’ http://public1.lucent.com/press/ 0798/980731.bla.html
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