Current-controlled channel switching and magnetoresistance in an Fe 3 C island film supported on a Si substrate

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Current-controlled channel switching and magnetoresistance in an Fe$_3$C island film supported on a Si substrate

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A film of magnetic Fe$_3$C islands separated by nanochannels of graphite was prepared with pulsed laser deposition on a Si substrate with a native SiO$_2$ surface. When the temperature is increased above 250 K the resistance suddenly drops because electron conduction switches from the film to the Si inversion layer underneath. The film shows a negative magnetoresistance. The inversion layer exhibits a large positive magnetoresistance. The transition to the low resistance channel can be reversed by applying a large measuring current, making possible current-controlled switching between two types of electron magnetotransport at room temperature. © 2002 American Institute of Physics. DOI: 10.1063/1.1447880

Spin-dependent transport of electrons in magnetic multilayered and nanostructured films is at the focus of the exiting field of spin electronics, or spintronics. The spin degree of freedom provides an added dimension to semiconductor-based electronic transport and is leading to substantial improvements in information technology [1]. The utilization of the giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) effects in magnetic sensors and magnetic random access memory (MRAM) is a remarkable example of the fast development in this area. Recently, it was demonstrated that the magnetization of a thin film element can be switched by applying a spin-polarized current [2], which exerts a torque on the magnetic moments. Current-controlled switching eliminates the need for the application of a magnetic field and has the potential to achieve higher density MRAMs [3]. We report the current-controlled switching between two channels of electron transport. One channel is a thin film of Fe$_3$C islands and the other one is the inversion layer in the Si substrate underneath (the highly conducting region next to the native SiO$_2$ layer). Because these two components exhibit drastically different magnetic field-dependent transport characteristics, this system might be useful for spintronics applications such as multistate memories and quantum computing.

Samples were prepared with pulsed laser deposition using an Fe$_3$O$_4$/C target with a KrF excimer laser. The substrate, a Si wafer with a 1.5 nm thick native SiO$_2$ layer on the surface, was kept at room temperature. Figure 1 shows a transmission electron microscopy (TEM) image of the film. It consists of flat islands with an average diameter of 50 nm and a thickness of 25 nm. They are separated from each other by a few nanometers of graphite. The high resolution image (inset in Fig. 1) shows that the graphite layer has its c-axis perpendicular to the interface between two neighboring islands. Most of the islands are single crystals. X-ray diffraction indicates the presence of Fe$_3$C and graphite, but because of peak overlap, the existence of metallic Fe in the sample cannot be ruled out.

X-ray photoelectron spectroscopy was performed to determine the composition of the islands. Figure 2 shows the Fe$2p$ region of the sample and a polycrystalline iron film (used as reference) that was slightly oxidized on its surface. The narrow peak at the low-energy onset of the reference spectrum is indicative of metallic iron. The Fe peak of the thin-film sample is shifted by 0.2 eV to higher binding en-
nergy as compared to the reference sample; a clear indication of Fe$_3$C.  

Figure 3(a) shows the electric resistance of the sample, measured in the plane of the film. The measurements were made with a four-point method using silver paste. Below ~250 K the resistance remains roughly constant. The slight decrease with increasing temperature is typical for thin films with nanoscale dimensions where localization effects play a role. The resistance drops sharply at about 250 K and decreases by more than an order of magnitude as the temperature is increased to room temperature.

The temperature dependence of the resistance can be explained by a conducting channel switching between the Fe$_3$C film and the inversion layer at the SiO$_2$–Si interface underneath. At room temperature, the native Si oxide layer is transparent to electrons. The electrons in the Fe$_3$C films can be emitted into the Si inversion layer by thermal excitation. Since the inversion layer has a lower resistivity, most of the current is carried by the electrons in the inversion layer. When the temperature is lowered, the thermal excitation and thus the number of electrons emitted to the Si inversion layer decreases exponentially. The current flow is restricted to the film, which has a higher resistance. A similar temperature dependence has also been observed in ultrathin Cu and Co films deposited on Si substrates with a native SiO$_2$ layer. For thicker metallic films, the conductance of the films becomes higher than that of the Si inversion layer. The electrons travel in the metallic films even at room temperature, and the channel switching does not occur.

Interestingly, the temperature range over which the channel switching takes place depends on the applied current. In Fig. 3(a), inset, the measuring current is increased from 10 $\mu$A to 1000 $\mu$A, and the midpoint of switching (defined as the middle point between the high resistance and low resistance values) increases from 270 to 300 K. Another way to look at the same phenomenon is the $I–V$ characteristics measured at a fixed temperature. In the high-resistance state below the switching, $I–V$ curve is linear. Above switching [e.g., at a temperature of 300 K in Fig. 3(b)] it is clearly nonlinear. At low currents, the sample exhibits low resistance, and at high currents it switches to the high resistance state. The curve becomes linear at very high currents, with a slope close to the one measured at 200 K, i.e., below the switching temperature.

The current-dependent switching temperature implies that the barrier preventing the transfer of electrons from the film to the inversion layer depends on the current. It is likely that charge accumulation at the interface region between the film, SiO$_2$, and the inversion layer increases with the current, which raises the effective barrier height and prevents the further flow of the electrons across the boundary between the film and the inversion layer. The electrons traveling in the inversion layer at 300 K thus revert to the film at high current values. Experiments on a nearly identical film of smaller
thickness (and consequently higher resistance) show that the
reversal of the electrons to the film occurs at a smaller cur-
rent than in the thicker film, supporting the view of charge
accumulation. Such a current-controlled switching of con-
ducting channels has not been observed before. This phe-
nomenon provides a unique, novel way to control by an ap-
plied current the switching between two channels of
electronic transport in a thin-film system in a temperature
range useful for technical applications.

Drastically different magnetotransport properties were
found at temperatures above and below the switching tem-
perature. Figure 4 shows the MR in both $H_\parallel$ and $H_\perp$ at
120 K, i.e., at a temperature where the current flows pre-
dominantly in the Fe$_3$C/graphite island film. In low fields
the sign of the MR is opposite for the two orientations, positive
for $H_\parallel$ and negative for $H_\perp$. The high-field negative MR is
likely attributed to several mechanisms including localiza-
tion$^6$ and spin-dependent scattering by the Fe$_3$C
islands.$^{12}$ It may also be intrinsic to the graphite, as certain
graphite carbons exhibit negative magnetoresistance.$^{11}$ The
details will be discussed in a forthcoming article.

While the nature of the magnetotransport of this com-
plex Fe$_3$C/graphite island film is in itself interesting, one
result is quite clear: Its response to an applied magnetic field
is very different from the one of the Si inversion layer. For
example, in the $H_\parallel$ configuration, it is possible to change the
sign of the MR, from negative for conduction in the film to
positive for conduction in the inversion layer. The principle
of a current-controlled switching of spin-dependent transport
may offer independent control of states by current and field
and should be of interest to a variety of spintronics applica-
tions such as multistate storage/sensing and quantum com-
puting. While the observed MR effect for conduction in the
island film is small, it might be possible to achieve higher
values by controlling the microstructure of the Fe$_3$C/graphite
film, e.g., by reducing the island size or by artificial pattern-
ning. We also hope that our results will lead to effort in search
of greater MR signals in other GMR multilayered films de-
posited on an appropriately modified SiO$_2$/Si substrate that
has similar channel switching characteristics.

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FIG. 4. (a) Magnetoresistance (MR) of the sample as a function of magnetic
field $H$ at $T$= 350 K (high-conductance state). (B) MR at 120 K (low-
conductance state).

current is applied parallel to the field. The MR is positive for
both field directions, with the MR for $H_\perp$ greater than that
for $H_\parallel$. At $H$= 90 kOe, the MR reaches values of about 45%
and 17% for $H_\parallel$ and $H_\perp$, respectively. The large positive MR
is due to the high mobility electrons in the Si inversion layer$^9,10$ and
originates from the Lorentz force acting on the
electrons. Figure 4(b) shows the MR in both $H_\parallel$ and $H_\perp$ at
120 K, i.e., at a temperature where the current flows pre-
dominantly in the Fe$_3$C/graphite island film. In low fields
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