AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **91**, 8411 (2002); doi: 10.1063/1.1447880
View online: http://dx.doi.org/10.1063/1.1447880
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/91/10?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 10 15 MAY 2002

Current-controlled channel switching and magnetoresistance in an Fe_3C island film supported on a Si substrate

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A film of magnetic Fe_3C 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. [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_3C 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_3O_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_3C 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 Fe2*p* 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-

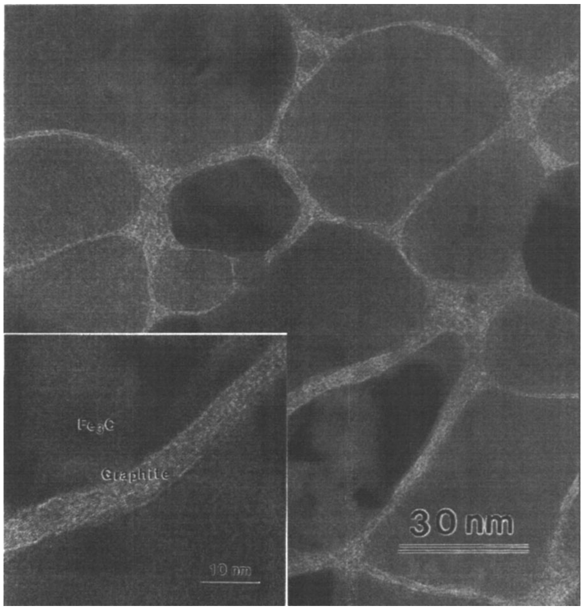

FIG. 1. TEM micrograph of a film consisting of non-overlapping Fe_3C islands on a SiO_2/Si wafer. Inset: View of the *c*-axis oriented graphite layer separating the Fe_3C islands.

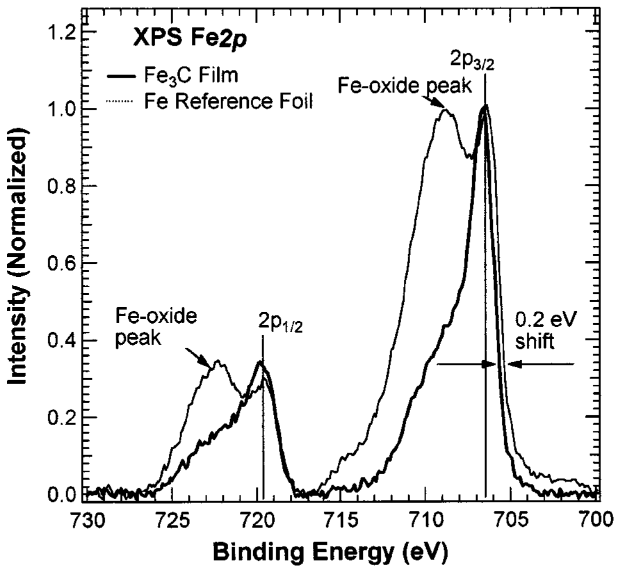

FIG. 2. X-ray photoelectron spectra of the Fe2p region of an Fe_3C island sample and a polycrystalline iron film (used as reference) after background subtraction.

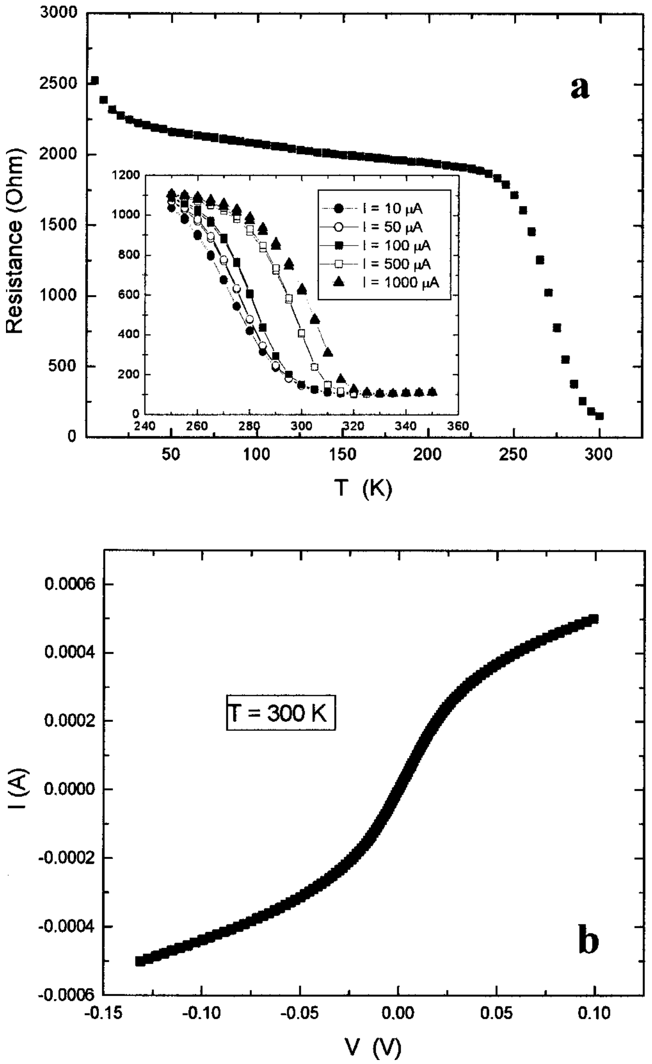

FIG. 3. (a) Resistance as a function of temperature T of a Fe_3C islands in graphite/SiO_2/Si sample. The measuring current I was 10 μA. The drastic decrease in resistivity above 250 K is attributed to a switching of conducting channels from the Fe_3C island film to the Si substrate. Inset: Conduction channel switching for different measuring currents. (b) $I-V$ curve of the sample measured at 300 K. The sample reverts to the high resistance state at higher currents.

ergy as compared to the reference sample; a clear indication of Fe_3C.[4]

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.[5–7] 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_3C film and the inversion layer at the SiO_2–Si interface underneath.[5,8] At room temperature, the native Si oxide layer is transparent to electrons. The electrons in the Fe_3C films can be emitted into the Si inversion layer by thermal excitation.[5] 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.[8] 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 μA to 1000 μA, 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

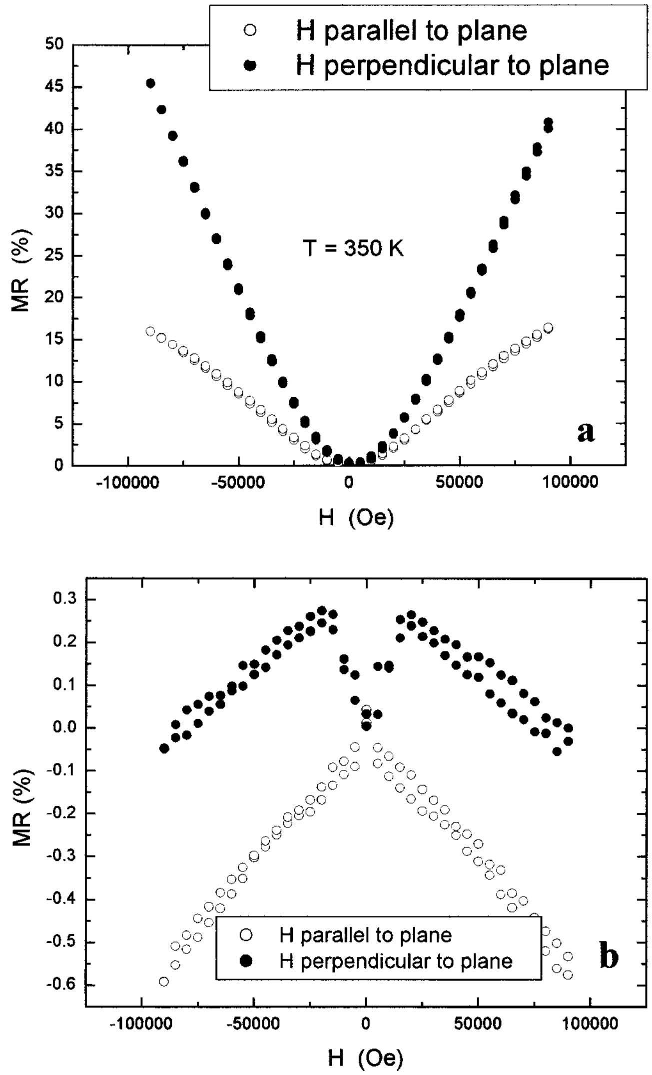

FIG. 4. (a) Magnetoresistance (MR) of the sample as a function of magnetic field H at $T = 350$ K (high-conductance state). (B) MR at 120 K (low-conductance state).

thickness (and consequently higher resistance) show that the reversal of the electrons to the film occurs at a smaller current than in the thicker film, supporting the view of charge accumulation. Such a current-controlled switching of conducting channels has not been observed before. This phenomenon provides a unique, novel way to control by an applied 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 temperature. Figure 4(a) shows the magnetoresistance (MR) of the sample as a function of magnetic field H at $T = 350$ K for two configurations; field perpendicular to the film plane ($H_\perp$) and field parallel to the film plane ($H_\parallel$). In $H_\parallel$, the 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 $H_\perp$ and $H_\parallel$, 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 $H_\perp$ and $H_\parallel$ at 120 K, i.e., at a temperature where the current flows predominantly in the Fe_3C/graphite island film. In low fields the sign of the MR is opposite for the two orientations, positive for $H_\perp$ and negative for $H_\parallel$. The high-field negative MR is likely attributed to several mechanisms including localization[6] and spin-dependent scattering by the Fe_3C 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 complex Fe_3C/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 applications such as multistate storage/sensing and quantum computing. 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_3C/graphite film, e.g., by reducing the island size or by artificial patterning. We also hope that our results will lead to effort in search of greater MR signals in other GMR multilayered films deposited on an appropriately modified SiO_2/Si substrate that has similar channel switching characteristics.

This work was partially supported by Sharp Laboratories of America, Louisiana Board of Regents Support Fund Grant No. LEQSF(2000-03)-RD-B-10, and the National Science Foundation (CHE-0109804).

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