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Amplification of magnetoresistance of magnetite in an Fe_3O_4–SiO_2–Si structure

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Film of Fe_3O_4 was prepared with laser molecular beam epitaxy deposition on a Si substrate with a native SiO_2 layer. When the temperature is increased above 250 K, the resistance drops rapidly because the conduction path starts to switch from the Fe_3O_4 film to the inversion layer underneath the SiO_2 via thermally assisted tunneling. A greatly magnified low field negative magnetoresistance of Fe_3O_4 is observed at 280 K. The effect is similar to a metal-oxide-semiconductor field-effect transistor. The magnetoresistance becomes positive with further increase in the magnetic field due to the Lorentz force and other effects on the carriers in the inversion layer. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2823609]

It is well known that an inversion layer forms at the interface of SiO_2/Si in a metal-oxide-semiconductor structure. The inversion layer is the basis of metal-oxide-semiconductor field-effect transistor (MOSFET), which can provide a low resistive path for carrier transport along the surface of the Si substrate.[1–3] The inversion layer shows interesting metal-insulator transition and MR effects.[3–5] Recently, Tang *et al.* reported the anomalous MR effect and the current-controlled channel switching of electron transport between Fe_3C film and inversion layer in an Fe_3C–SiO_2–Si structure.[6] They also suggested that the materials having high MR signal and poor conductivity could be used in place of the upper layer of Fe_3C to enhance the MR effect, which might be useful for spintronics applications. Similar results have been observed in the thin films of Co, Cu, NiMnSb, and FeSi deposited on Si substrate with native SiO_2 layer.[7–10]

In this letter, we investigate the magnetotransport properties of Fe_3O_4–SiO_2–Si structure. This system shows a current channel switching between the Fe_3O_4 film and inversion layer at 250 K. A large low-field MR is observed at 280 K, which originates from the amplification of the negative MR of Fe_3O_4, an effect similar to the amplification in MOSFET.

The Fe_3O_4 thin films were grown by laser molecular beam epitaxy on *n*-type Si (100) substrates that have a 1.5 nm thick native SiO_2 layer on the surface. The target was α-Fe_2O_3 that was prepared by pressing α-Fe_2O_3 powders into a pellet and sintered at 1000 °C for 4 h. The films were prepared in vacuum of 10^{-7} Torr at a substrate temperature of 350 °C.[11] The pulsed excimer laser uses KrF ($\lambda=248$ nm) and produces a laser beam with an intensity of 1–2 J/cm^2 and a repetition rate of 3 Hz. The deposition rate is about 1∼2 nm/s and the film thickness is 70 nm. After the deposition, the film and substrate were annealed for 30 min under the same condition.

X-ray diffraction (XRD) data were collected using the Bede D1 XRD spectrometer with Ni-filtered Cu $K\alpha$ radiation. High-resolution transmission electron microscopy experiments were carried out on a Tecnai F20 electron microscope with a field-emission gun operated at an acceleration voltage of 200 kV. The resistivity measurement by standard dc four-probe method was carried out using a physical properties measurement system from Quantum Design.

Figure 1 shows the XRD pattern of Fe_3O_4 film. Only the reflections from the (311) family of Fe_3O_4 are observed, indicating that a single-phase Fe_3O_4 film is formed. The inset of Fig. 1 shows the high-resolution transmission electron microscopy (HRTEM) images of the sample. The HRTEM micrographs give a clear view of the Fe_3O_4–SiO_2–Si structure.

Figure 2 shows the temperature dependence of zero-field resistance and the inset shows a schematic view of electrical contact configuration for the transport measurement. Below 250 K, the resistance increases with decreasing temperature, which shows a typical behavior of thin Fe_3O_4 film.[12] The change of the measured resistance at Verway transition is not as sharp as those observed in relatively thick epitaxial films; however, our data is similar to the relatively thin films. It is known that strain and size effects might be responsible for

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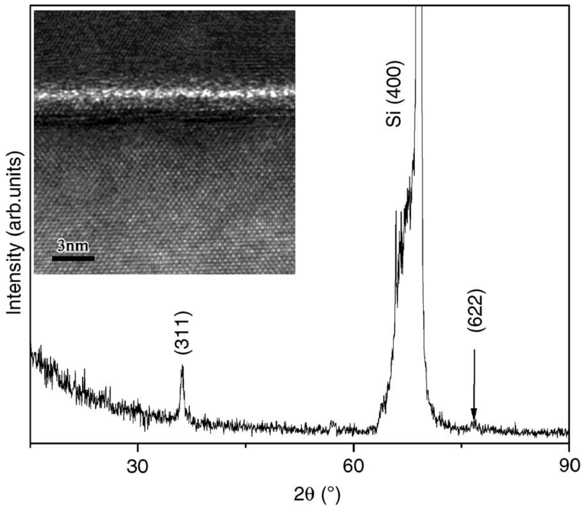


FIG. 1. The room temperature XRD pattern of Fe_3O_4 film grown on Si (100), the inset shows the high-resolution transmission electron microscopy images.

this behavior.[11,12] Furthermore, the temperature dependence of the MR (at 5 T) does show an anomaly near the Verwey transition [see Fig. 4(a)]. When the temperature is above 250 K, the resistance decreases sharply. Similar temperature dependence of resistance had been observed in an Fe_3C-SiO_2-Si structure and explained by the conducting channel switching effect between the upper Fe_3C film and the inversion layer.[6] The phenomenon observed in the Fe_3O_4 film on Si substrate is attributed to the same conducting channel switching effect. The inversion layer at the SiO_2/Si interface has a low resistivity. At high temperature, the electrons in the Fe_3O_4 film can be emitted into the inversion layer by thermal excitation. So most of the carriers travel in the inversion layer, and the measured resistance is low. The amount of electrons emitted into the inversion layer decreases exponentially with decreasing temperature. Below 220–230 K, the electrons are restricted to the Fe_3O_4 film. Thus, high resistance of the thin Fe_3O_4 film is observed.

Figure 3(a) shows the current-voltage (*I-V*) curve measured at 300 K. It is clear that the current increases nonlinearly with increasing voltage. The structure of the $Fe_3O_4-SiO_2-Si$ film is similar to the MOSFET. Here, the ferromagnetic Fe_3O_4 film is the gate, thus the voltage on the

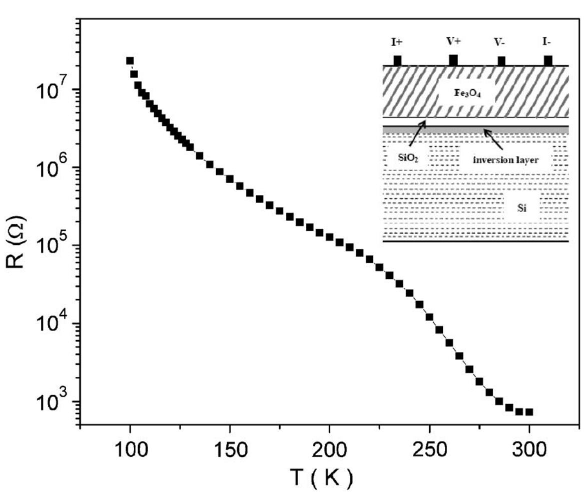


FIG. 2. Temperature dependence of the zero field resistance. The inset shows a schematic view of the electrical contact configuration.

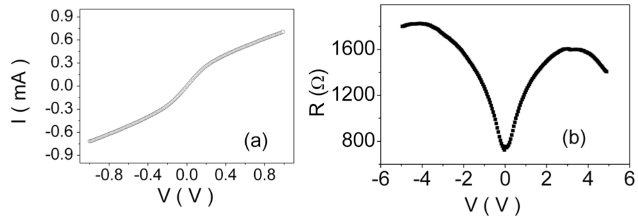
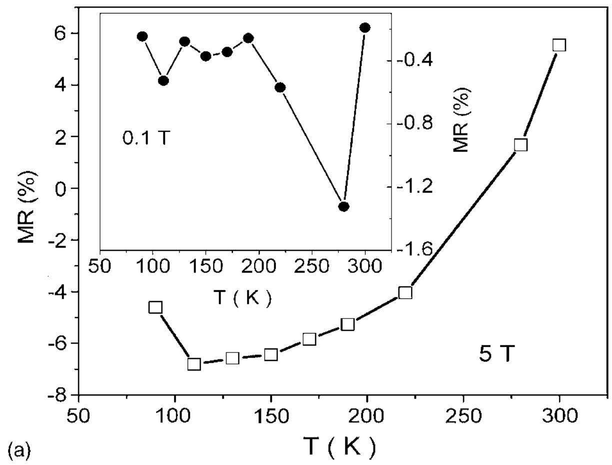


FIG. 3. (Color online) The *I-V* curve at 300 K. (b) The *R-V* curve at 300 K.

Fe_3O_4 film will strongly influence the total current. At low voltage, most of the current is carried by the holes in the inversion layer and the current increases linearly with voltage. However, the voltage of Fe_3O_4 film increases with increasing applied voltage. Higher voltage attracts electrons in the *n*-type Si substrate and closes the inversion layer conduction channel. Effectively, the electrons emitted cross the SiO_2 layer by thermal excitation will, due to lack of holes, accumulate at the interface region of SiO_2/Si. The charge accumulation can prevent the transfer of electrons from the film to the inversion layer. As a result, the current in the inversion layer reverts to the film at higher voltage.[6] The charge accumulation is a consequence of the decrease or disappearance of the hole-channel in inversion layer due to high gate voltage. These data are consistent with the result that conducting channel switching effect is suppressed in the $Co-SiO_2-Si$ film with bias voltage due to the reduction of hole conduction in the inversion layer.[8] Another way to look at this is the resistance-voltage (*R-V*) characteristics measured at high voltage. Figure 3(b) gives the *R-V* curve up to 5 V at 300 K. Obviously, the resistance increases rapidly with applied voltage and nearly saturates at 2.5 V. High applied voltage results in the conduction channel switching and the resistance changes from that of the inversion layer to that of the Fe_3O_4 film.

Magnetoresistance (MR) of the film at different temperatures was shown in Fig. 4. The magnetic field was applied perpendicular to the film and the current. The MR is defined as $MR=[R_{(H)}-R_{(0)}]/R_{(0)}$. At low temperature, current flows in the Fe_3O_4 film, negative MR is observed although it is much lower than the reported data on pressed Fe_3O_4 powders and polycrystalline films.[11,13,14] The temperature dependence of MR at 5 T exhibits a peak near the Verwey transition temperature.

Interestingly, our Fe_3O_4 film on Si substrate with native SiO_2 layer shows a greatly enhanced low-field negative MR near the switching temperature of 280 K, as shown in Figure 4. A positive MR is observed in higher fields. To gain understanding of the observed phenomenon, it helps to realize that the total contribution to the measured resistance is divided into two parts with parallel connection near the switching temperature: one is from the Fe_3O_4 film and the other is from the inversion layer. When a magnetic field is applied to the film, the resistance of Fe_3O_4 film is reduced, which means that the voltage of Fe_3O_4 film (gate voltage) decreases. The conductance of the holes in the inversion layer increases accordingly. Thus, the measured resistance is greatly reduced, and a much enlarged low-field negative MR of −1.35% at 0.1 T is observed. This MR, although small in its value, is significantly magnified over the value expected for the Fe_3O_4 film at 280 K (see Fig. 4). The applied voltage for the MR measurement is 0.15 V. The resistance decreases sharply with decreasing voltage at low voltages, as shown in Fig.



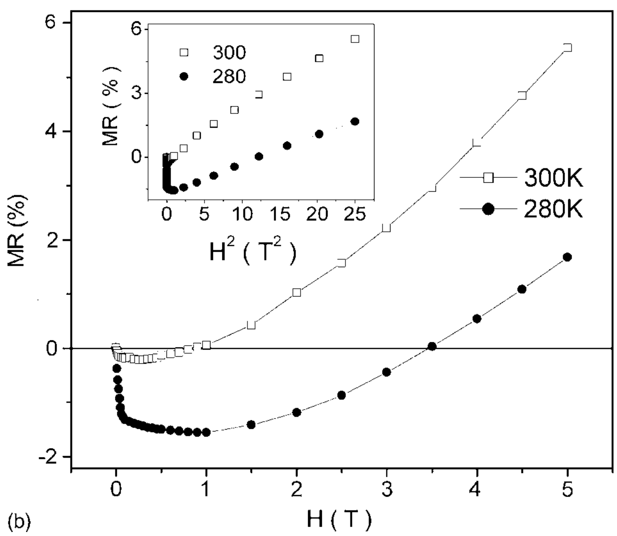


FIG. 4. The temperature dependence of MR at 5 T, the inset shows the MR at 0.1 T. (b) MR vs H curves at 280 and 300 K, the inset shows the MR vs H^2 curves at 280 and 300 K.

3(b), which strongly supports the above view. In other words, the enhanced low-field negative MR is the amplification of the negative MR of the Fe_3O_4 film in this $Fe_3O_4-SiO_2-Si$ structure, similar to the amplification effect of a MOSFET, where the ferromagnetic Fe_3O_4 film is the gate. The conductance of the inversion layer increases with increasing field due to the decrease in the resistance of Fe_3O_4. However, the Lorentz force and other effects on the holes in the inversion layer, which results in positive MR, begins playing an important role in higher fields. The measured MR is a combination of negative MR in low fields and positive MR in high fields. The negative MR saturates at $H=0.1$ T and maintains roughly unchanged between $0.1\ T < H < 1$ T. It increases with further increase of the field, and a positive MR of 1.68% is observed at 5 T. The resistance is very small at 300 K, suggesting that the current in the inversion layer is increased with the increased thermally assisted tunneling into the inversion layer at higher temperature. Although the influence of the MR of the Fe_3O_4 film on the gate voltage still exists, most of the current flows in the inversion layer and the current in the Fe_3O_4 film is much smaller, which means a smaller voltage. Therefore a small low-field negative and large high-field positive MR are observed at 300 K. It is found that the positive MR in high fields follows a field dependence of $MR \sim H^2$, as shown in the inset of Fig. 4(b), which suggests that the positive MR is due to the Lorentz force and other effects on the high-mobility holes in the inversion layer.[15,16]

In summary, we have observed a greatly amplified low-field negative MR in a $Fe_3O_4-SiO_2-Si$ structure at 280 K. The inversion layer plays an important role in the conductance and magnetotransport near room temperature and at higher temperatures. Reminiscent of a MOSFET, the negative MR of Fe_3O_4 reduces the gate voltage and causes an increase of current in the inversion layer. Thus, the measured resistance is much reduced and a greatly amplified low-field negative MR is achieved at 280 K. Meanwhile, the Lorentz force and other effects on the holes in the inversion layer results in a positive MR in high fields. The amplification of magnetoresistance in this $Fe_3O_4-SiO_2-Si$ MOSFET structure is different from the spin-transistors currently pursued in many laboratories but reveals another route to achieve integration of spins and electronics and may have useful applications.

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