Amplification of magnetoresistance of magnetite in an Fe$_3$O$_4$ – SiO$_2$ – Si structure

Xianjie Wang  
*Harbin Institute of Technology, People's Republic of China*

Yu Sui  
*Harbin Institute of Technology, People's Republic of China; International Center for Materials Physics, People's Republic of China*

Jinke Tang  
*University of Wyoming, jting2@uwyo.edu*

Cong Wang  
*Harbin Institute of Technology, People's Republic of China*

Xingquan Zhang  
*Harbin Institute of Technology, People's Republic of China*

*See next page for additional authors*

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**Publication Information**

Wang, Xianjie; Sui, Yu; Tang, Jinke; Wang, Cong; Zhang, Xingquan; Lu, Zhe; Liu, Zhiguo; Su, Wenhui; Wei, Xiankui; and Yu, Richeng (2008). “Amplification of magnetoresistance of magnetite in an Fe$_3$O$_4$ – SiO$_2$ – Si structure.” *APPLIED PHYSICS LETTERS* 92, 0121122-1-0121122-3.

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Amplification of magnetoresistance of magnetite in an Fe$_3$O$_4$ – SiO$_2$ – Si structure

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Citation: Applied Physics Letters 92, 012122 (2008); doi: 10.1063/1.2823609
View online: http://dx.doi.org/10.1063/1.2823609
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/92/1?ver=pdfcov
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Amplification of magnetoresistance of magnetite in an Fe$_3$O$_4$–SiO$_2$–Si structure

Xianjie Wang
Center for Condensed Matter Science and Technology (CCMST), Department of Physics, Harbin Institute of Technology, Harbin 150001, People’s Republic of China

Yu Su$^{a)}$
Center for Condensed Matter Science and Technology (CCMST), Department of Physics, Harbin Institute of Technology, Harbin 150001, People’s Republic of China and International Center for Materials Physics, Academia Sinica, Shenyang 110015, People’s Republic of China

Jinke Tang
Department of Physics & Astronomy, University of Wyoming, Laramie, Wyoming 82071, USA

Cong Wang, Xingquan Zhang, Zhe Lu, Zhiguo Liu, and Wenhui Su
Center for Condensed Matter Science and Technology (CCMST), Department of Physics, Harbin Institute of Technology, Harbin 150001, People’s Republic of China

Xiankui Wei and Richeng Yu
Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100080, People’s Republic of China

Received 1 September 2007; accepted 20 November 2007; published online 11 January 2008

Film of Fe$_3$O$_4$ 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$_3$O$_4$ film to the inversion layer underneath the SiO$_2$ via thermally assisted tunneling. A greatly magnified low field negative magnetoresistance of Fe$_3$O$_4$ 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. The inversion layer shows interesting metal-insulator transition and MR effects. Recently, Tang et al. reported the anomalous MR effect and the current-controlled channel switching of electron transport between Fe$_3$C film and inversion layer in an Fe$_3$C–SiO$_2$–Si structure. They also suggested that the materials having high MR signal and poor conductivity could be used in place of the upper layer of Fe$_3$C 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.

In this letter, we investigate the magnetotransport properties of Fe$_3$O$_4$–SiO$_2$–Si structure. This system shows a current channel switching between the Fe$_3$O$_4$ 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$_3$O$_4$, an effect similar to the amplification in MOSFET.

The Fe$_3$O$_4$ 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$_2$O$_3$ that was prepared by pressing α-Fe$_2$O$_3$ 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. The pulsed excimer laser uses KrF (λ = 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 Kα 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$_3$O$_4$ film. Only the reflections from the (311) family of Fe$_3$O$_4$ are observed, indicating that a single-phase Fe$_3$O$_4$ 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$_3$O$_4$–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$_3$O$_4$ film. The change of the measured resistance at Verwey 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...
 INTERFACE has a low resistivity. At high temperature, the electrons emitted cross the SiO2 layer by thermal excitation, due to lack of holes, accumulate at the interface region of SiO2/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. 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–SiO2–Si film with bias voltage due to the reduction of hole conduction in the inversion layer.

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 Fe3O4 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 $MR=\frac{|R(H)-R(0)|}{R(0)}$. At low temperature, current flows in the Fe3O4 film, negative MR is observed although it is much lower than the reported data on pressed Fe3O4 powders and polycrystalline films. The temperature dependence of MR at 5 T exhibits a peak near the Verwey transition temperature.

Interestingly, our Fe3O4 film on Si substrate with native SiO2 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 Fe3O4 film and the other is from the inversion layer. When a magnetic field is applied to the film, the resistance of Fe3O4 film is reduced, which means that the voltage of Fe3O4 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 Fe3O4 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. 4.
The conductor of the inversion layer increases with increasing field due to the decrease in the resistance of Fe$_3$O$_4$. However, 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$_3$O$_4$–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.

In summary, we have observed a greatly amplified low-field negative MR in a Fe$_3$O$_4$–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$_3$O$_4$ 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$_3$O$_4$–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.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 10304004 and 50672019) and Sharp Laboratories of America.