2-9-2009

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Publication Information

Wang, Xianjie; Sui, Yu; Tang, Jinke; Li, Yao; Zhang, Xingquan; Wang, Cong; Liu, Zhiguo; and Su, Wenhui (2009). "Amplification of magnetoresistance and Hall effect of Fe 3 O 4 – SiO 2 – Si structure." *JOURNAL OF APPLIED PHYSICS* .105, 07B101-1-07B101-3.

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AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **105**, 07B101 (2009); doi: 10.1063/1.3065987
View online: http://dx.doi.org/10.1063/1.3065987
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/105/7?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **105**, 07B101 (2009)

Amplification of magnetoresistance and Hall effect of $Fe_3O_4-SiO_2-Si$ structure

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(Presented 13 November 2008; received 10 September 2008; accepted 1 November 2008; published online 9 February 2009)

In this paper, we report the magnetoresistance and the Hall effect in the $Fe_3O_4-SiO_2-Si$ structure. Single phase magnetite films were deposited on *n*-type silicon substrates using laser molecular beam epitaxy. When the temperature is increased beyond 230 K, the resistance drops rapidly because the conduction path starts to switch from the Fe_3O_4 film to the inversion layer underneath the native SiO_2 via thermally assisted tunneling. A large negative magnetoresistance is observed at about 230 K, and this maximum shifts to higher temperature with increasing film thickness. Hall effect data of the structure show that the carriers are holes above the channel switching temperature. Our results confirm that the large magnetoresistance at ~230 K originates from the amplification of the magnetoresistance of the magnetite in the $Fe_3O_4-SiO_2-Si$ structure. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3065987]

I. INTRODUCTION

Half-metallic oxide Fe_3O_4 films have long been investigated due to its speculated high spin polarization and high Curie temperature of 840 K, which is desirable for spin electronic device applications.[1] One of the main device concepts involving Fe_3O_4 is the magnetic tunnel junction (MTJ). Magnetic read heads based on MTJs have been on the market for several years. However, the MTJ uses transition-metal electrodes that have typical spin polarization of 40%. If 100% spin polarization of the tunneling electrons can be realized as expected, MTJs that show higher magnetoresistance (MR) and thus higher signal will find application in magnetic random access memory and magnetic read heads. However, Fe_3O_4 based MTJs have so far shown small tunneling MR.[2–5]

Recently, we observed the amplification of MR of magnetite in an $Fe_3O_4-SiO_2-Si$ structure with current-controlled channel switching of electron transport between the Fe_3O_4 film and the inversion layer underneath the SiO_2 via thermally assisted tunneling.[6] Similar conductance channel switching has been observed in other $M-SiO_2-Si$ structures (M=metals), and attributed to the formation of an inversion layer at the $Si-SiO_2$ interface.[7–12] The inversion layer is the basis for metal-oxide-semiconductor field-effect transistor (MOSFET), which provides a low resistive path for carrier transport along the surface of the Si substrate.[13] The amplification of MR in this $Fe_3O_4-SiO_2-Si$ MOSFET structure may have useful applications. Clearer experimental evidence and understanding of the mechanism of the amplification of the MR are, however, still lacking.

In this paper, we report the MR and the Hall effect in the $Fe_3O_4-SiO_2-Si$ structure. A large negative MR is observed at about 230 K. Hall effect data of the structure confirm that the carriers are holes above the channel switching temperature, and suggest the large MR originates from the amplification of the MR of the magnetite in the $Fe_3O_4-SiO_2-Si$ structure.

II. EXPERIMENT

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 $\alpha-Fe_2O_3$ powders. The films were prepared in a vacuum of 10^{-7} Torr at substrate temperature of 350 °C.[14] 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 nm/s and the film thickness is 35 nm. After deposition, the film and substrate were annealed for 30 min under the same condition. The resistivity and Hall effect were measured using a physical properties measurement system from Quantum Design.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of zero-field resistance of the $Fe_3O_4-SiO_2-Si$ structure measured in the plane of the Fe_3O_4 film. Below 200 K, the resistance in-

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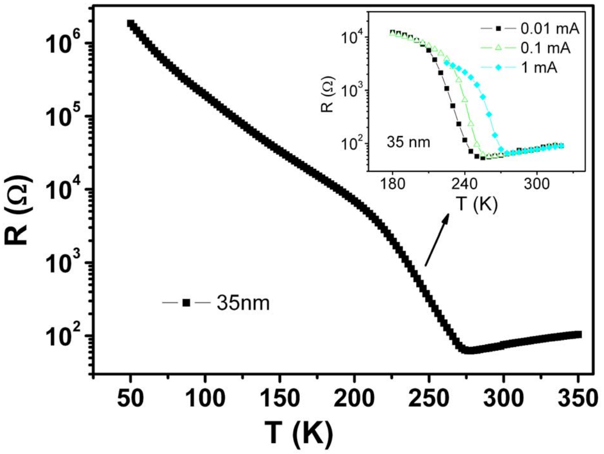

FIG. 1. (Color online) Temperature dependence of the zero field resistance of the $Fe_3O_4-SiO_2-Si$ structure. Inset shows the temperature dependence of resistance at different measuring currents.

creases with decreasing temperature, which shows a typical behavior of thin Fe_3O_4 film. However, the resistance drops sharply at about 230 K and becomes metallic at higher temperatures. Similar temperature dependence of resistance have been observed in an Fe_3C-SiO_2-Si structure and explained in terms of the current channel switching between the upper Fe_3C film and the inversion layer due to the thermally assisted tunneling by Tang *et al.*[7] In $Fe_3O_4-SiO_2-Si$, the carriers are electrons in the Fe_3O_4 film and should be holes in the inversion layer on *n*-type Si substrate, thus the Hall effect is an effective tool and used to confirm the conducting channel switching effect. Figure 2 shows the Hall voltage for the $Fe_3O_4-SiO_2-Si$ structure at 350 K. It is well known that the carries of pure Fe_3O_4 film are electrons with extraordinary Hall[15] and the Curie temperature of Fe_3O_4 film is about 840 K. Thus, the extraordinary Hall effect for pure Fe_3O_4 film is expected at 350 K. However, the measured result of Hall data is an ordinary Hall effect and the carriers are holes at 350 K. These data demonstrate the channel switching from the Fe_3O_4 film to the inversion layer in the $Fe_3O_4-SiO_2-Si$ structure as the temperature increases, which is consistent with the channel switching observed in the$M-SiO_2-Si$ structure.[7–12]

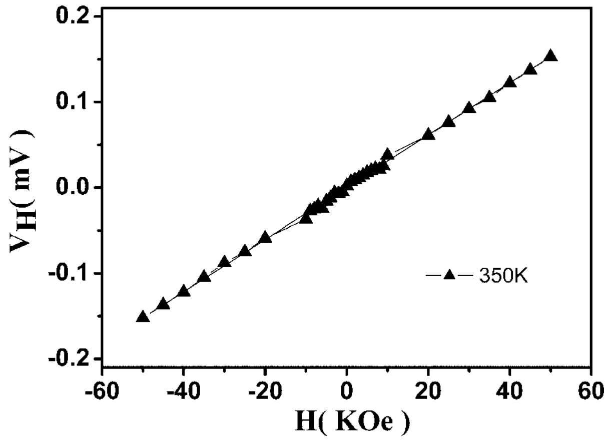

FIG. 2. Hall data of the Fe_3O_4(35 nm)$-SiO_2-Si$ structure at 350 K.

The channel switching in the $Fe_3O_4-SiO_2-Si$ structure exhibits bias voltage dependence that can be explained on the basis of a MOSFET. Here the ferromagnetic Fe_3O_4 film is the gate.[6] The carrier transport of the $Fe_3O_4-SiO_2-Si$ structure is strongly influenced by the voltage on the Fe_3O_4 film. The inset in Fig. 1 shows the temperature dependence of the resistance at different measuring currents. Clearly the switching temperature increases with increasing measuring currents. This current-dependence switching temperature is due to the following. Higher current results in higher voltage on the Fe_3O_4 film, which can attract electrons from the *n*-type Si substrate and reduce the hole conductance in the inversion layer. As a result, the carriers emitted cross the SiO_2 layer by thermal excitation will accumulate at the interface region of SiO_2/Si. This charge accumulation can raises the effective barrier height and prevent the transfer of the carriers from the film to the inversion layer. Therefore, the current in the inversion layer reverts to the film at higher voltage and the current switching temperature is increased. This current-dependent switching temperature, combined with the Hall data, suggests that the inversion layer plays an important role in the transport in the $Fe_3O_4-SiO_2-Si$ structure.

A large low field negative MR was found in $Fe_3O_4-SiO_2-Si$ at the channel switching temperature, as shown in Fig. 3, where the resistance was measured in the plane of the Fe_3O_4 film. The MR is defined as $MR=[R_{(H)}-R_{(0)}]/R_{(0)}$, where $R_{(0)}$ and $R_{(H)}$ are the measured resistance of the sample in zero field and external field H, respectively. The magnetic field was applied perpendicular to both the film and the current. At low temperature, the current only flows in the Fe_3O_4 film and a small negative MR is observed. The MR value is much lower than the reported data on pressed Fe_3O_4 powders and polycrystalline films (the maximum MR of Fe_3O_4 powders is about 22.8% at 280 K and 14 T) but it is similar to the data of typical of thin Fe_3O_4 films.[14,16] Near the switching temperature of 230 K, the $Fe_3O_4-SiO_2-Si$ structure shows a greatly magnified low field negative MR, as shown in Fig. 3(a). When a magnetic field is applied, the measured resistance of the film drops, which leads to a reduced voltage on the film and opens up the inversion layer, and a much enhanced low-field negative MR of −1.91% at 0.05 T is observed. 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.[6] As discussed above, when a magnetic field is applied to the film, the resistance of the Fe_3O_4 film is reduced, which means the voltage on the 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.

Figure 3(b) shows the temperature dependence of MR data of $Fe_3O_4-SiO_2-Si$ with different Fe_3O_4 film thicknesses measured at 0.05 T. The maximum MR value shifts to higher temperature with increasing film thickness. This is consistent with the change in the channel switching temperature of the $Fe_3O_4-SiO_2-Si$ structure for the 75 and 35 nm thick Fe_3O_4 films, 280 and 230 K, respectively.[6] The amplification effect is the strongest near the switching tempera-

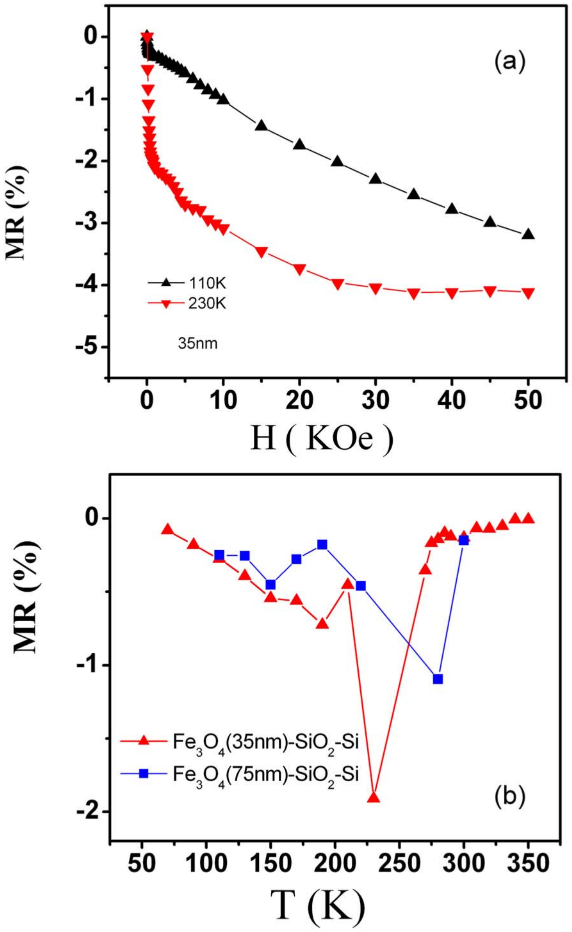

FIG. 3. (Color online) (a) MR vs *H* curves at 110 and 230 K for the $Fe_3O_4-SiO_2-Si$ structure. The thickness of Fe_3O_4 is 35 nm. (b) Temperature dependence of the MR of the $Fe_3O_4-SiO_2-Si$ structure with Fe_3O_4 film thickness of 35 and 75 nm at 0.05 T.

ture. At lower temperatures, the current runs mainly in the film, while it runs mainly in the inversion layer above the switching temperature. Therefore the amplification of the MR of the film is not as obvious. The value of the MR enhancement seems to increase with decreasing Fe_3O_4 film thickness, which suggests that reducing the film thickness may enhance the amplification effect. Thinner films have higher resistance, so the carriers are emitted into the Si inversion layer at lower temperature, which corresponds to a lower channel switching temperature.

IV. CONCLUSIONS

In summary, we observed the current channel switching and greatly amplified low-field negative MR of Fe_3O_4 film in a $Fe_3O_4-SiO_2-Si$ structure at the same temperature. Hall data imply that the inversion layer play an important role in the charge transport of the $Fe_3O_4-SiO_2-Si$ structure. The much enhanced low field negative MR achieved in the $Fe_3O_4-SiO_2-Si$ structure with ultrathin Fe_3O_4 film may have useful application in spintronic devices.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 10804024 and 50672019), the Natural Scientific Research Innovation Foundation in Harbin Institute of Technology (Grant No. HIT.NSRIF.2008.03), the Program for New Century Excellent Talents in University (Grant No. NCET-06-335), NSF, and UW SER/MGF.

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