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Anomalous conductivity and positive magnetoresistance in FeSi–SiO$_2$–Si structures in the vicinity of a resistive transition

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Electrical and magnetic transport properties of FeSi–SiO$_2$–Si junctions fabricated by depositing FeSi thin films on silicon substrates with the native oxide layer have been investigated. Near room temperature the carriers tunneled across the interface to the substrate with low resistance. With a decreasing temperature, the junction resistance increased more than three orders of magnitude near 270 K, which switched the current path to the film. The transition characteristics depend on the conductivity of the silicon substrate. A positive magnetoresistance that peaked near the transition temperature was observed. Similar behavior was seen for CoSi films while TiSi films did not show a transition in resistance. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2436634]

Carrier transport mechanisms in magnetic thin films and carrier tunneling across heterostructures have been of great interest for applications in giant magnetoresistance and spintronics. Magnetic properties of a variety of magnetic thin films deposited on silicon substrates have been reported.[1] Electrical properties of films deposited on silicon substrates covered with an ultrathin native oxide layer have been seen to behave differently than films on bare silicon or thermally oxidized silicon substrates. In the presence of interface states the Fermi level may be pinned at the Si–SiO$_2$ interface, leading to band bending and the formation of a depletion or an inversion layer.[2,3] This inversion layer, while creating a potential barrier for transport into the silicon substrate, could provide a low resistive path for carrier transport along the surface layer of the silicon substrate. For example, a transition in resistivity observed in thin films of Fe$_3$C, Co, Cu, and NiMnSb (Refs. 4–7) that were deposited on silicon substrates with the native oxide layer has been attributed to current switching between the film and an inversion layer.[7]

We have observed an anomalous metal-like to insulator-like transition in transition metal silicide films on silicon substrates. Enhancement in the positive magnetoresistance that coincides with the transition in resistance has also been observed. The presence of the ~2 nm thick native oxide layer is essential for the manifestation of this transition. This letter presents the electrical and magnetotransport properties of FeSi, CoSi, and TiSi films deposited by laser ablation on silicon substrates, and proposes a possibles mechanism for the observed transition.

Films were deposited on silicon substrates with native oxide layers by ablating a composite target of the desired material.[8,9] The substrates were heated to 400 °C in a vacuum of 10^{-6} Torr. The film thickness was in the range of 300–400 nm. The temperature dependent four-point-probe transport measurements of FeSi films deposited on *p*-doped silicon substrates with four different conductivities are shown in Fig. 1. Each data point is an average of ten measurements. The statistical errors in all the resistance measurements were within 1%–3%. Films on highly conducting substrates of resistivity less than 0.005 Ω cm (doping density of 1×10^{19} cm^{-3}) showed a metallic behavior down to a temperature of 20 K. Films on highly resistive substrates (>3000 Ω cm) showed an insulating behavior. However, for substrates of conductivity in the range of 1–10 Ω cm, films exhibited an anomalous transition in the resistance around 273 K. Above the transition temperature films showed a metallic conductivity that is similar to the bare silicon substrate. Metallic behavior of highly doped silicon down to about a temperature of 100 K is in agreement with previous reports.[10] Between the temperatures of 270 and 225 K, the resistance increased by about three orders of magnitude, followed by a slow increase in resistance down to a temperature of 20 K. The temperature dependence of film resistance after the transition is identical to that for a film deposited on an insulating substrate, such as quartz. This observation implies that the majority of the current transport above a temperature of 273 K takes place through the silicon substrate. At the transition point the current transport is switched to the film.

Two questions to be answered in this research are the following: does the current transport above the transition temperature takes place through an inversion layer at the silicon surface instead of through a bulk of the substrate? What is the mechanism that causes the interface resistance to increase rapidly around 273 K that switched the current transport to the film? A similar transition, but much smaller change in resistance, reported in Co, Cu, and Fe$_3$C films[4–7]

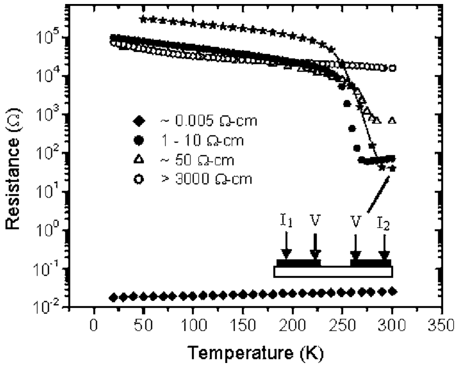

FIG. 1. Temperature dependence of the resistance of FeSi films deposited at 400 °C on *p*-type silicon substrate of resistivity, (a) 0.005 Ω cm, (b) 1–10 Ω cm, (c) 50 Ω cm, and (d) greater than 3000 Ω cm. *R* vs *T* for the discontinuous film shown in the inset is indicated by the arrow.

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on silicon substrates has been attributed to channel switching between the film and an inversion layer at the SiO_2/Si interface. An inversion layer would prevent carrier injection into the bulk of the silicon substrate, and thus, a continuous inversion layer between the current probes is required for transport through the substrate. However, as shown in Fig. 1, the conductivity measurements of a discontinuous FeSi film deposited on a p-doped silicon substrate with a resistivity of $1-10\ \Omega$ cm-cm also exhibited a similar transition, indicating that the carrier transport is taking place in the bulk of the substrate. Therefore, carriers are transported into the bulk across the depletion layer at the SiO_2/Si interface.

Carrier transport across the depletion layer can take place through several mechanisms. For transport via a Schottky emission process the current density is of the form $J \propto = T^2 \exp(+a\sqrt{V/T} - q\phi_B/kT)$, where V is the bias voltage and ϕ_B is the barrier height, while for transport via thermally excited carriers hopping between interface states and deep levels, the current density can be interpreted as $J = V \exp(\varepsilon/kT)$, where ε is the activation energy for hopping.[11] The IV characteristics of FeSi films have been observed to be linear above the transition temperature while it becomes non-linear below the transition temperature.[12] Therefore, the linear IV before the transition agrees with a trap-assisted hopping mechanism for carrier transport that is facilitated by Fe ions in the depletion layer.

The interaction of Fe films with Si substrates across a thin native SiO_2 layer has been well studied.[13] The high diffusivity of Fe in SiO_2 and Si has also been well documented.[14] The interstitial Fe forms a trap level in silicon at $E_v + 0.4$ eV.[15] A plausible explanation for the transport data is that, at high temperature, trap-assisted tunneling of the carriers across the depletion layer establishes a low resistant Ohmic contact between the film and the bulk of the substrate. With a decreasing temperature, the interaction between the carrier spin and the magnetic moment of the Fe atom causes localization of the carriers that leads to a high interface resistance. As a result, for a continuous film, the current path is switched to the film near the transition temperature. For a discontinuous film, localization effect in the depletion layer forces the carriers to follow a different transport mechanism, such as Schottky emission, that depends on the barrier potential. However, for substrates with high doping densities the width of the depletion layer, which is given by[11] $W = \sqrt{2\varepsilon/qN(V_{bi} - V - kT/q)}$, where ε is the permittivity of the semiconductor, q is the electron charge, N is the doping density, V_{bi} is the built-in potential, V is the bias voltage, and T is the temperature, becomes small. Therefore, without the assistance of hopping sites within the depletion layer, the carriers are able to tunnel through the barrier, and thus, form an Ohmic contact to the substrate at any temperature.

Results from similar experiments with CoSi and TiSi films on p-type silicon substrates are presented in Fig. 2. Comparison of these two materials is important since Co^{4+} has a magnetic moment of $2\mu B$ while Ti^{4+} is nonmagnetic. Only CoSi films showed a transition that is similar to FeSi where film resistance changed from about 20 Ω at 270 K to over $1 \times 10^4\ \Omega$ at 200 K. The transition was also absent in FeSi films deposited on silicon with a thick (~50 nm) thermally grown SiO_2. These experiments elucidate two important factors: (i) Carrier tunneling into the silicon substrate across the SiO_2 layer and transport through the substrate produce the metallic behavior at high temperature, (ii) the magnetic moment of the atoms diffused into the depletion layer may play an important role in enabling trap-assisted tunneling at high temperature followed by localization effects that manifest as the temperature is reduced, leading to a rapid increase in resistance.

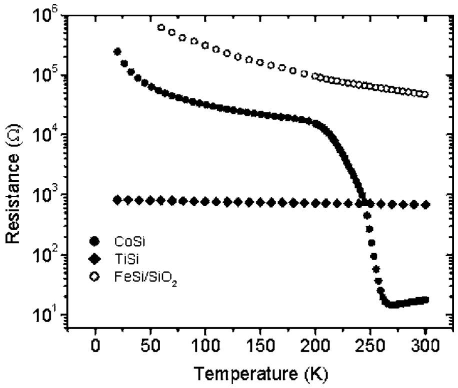

FIG. 2. Temperature dependence of the resistance for CoSi and TiSi films on p-type silicon substrates with native SiO_2 layers, and FeSi films on thermally grown thick SiO_2 layers. Substrate resistivity is $1-10\ \Omega$ cm.

Magnetotransport measurements of a FeSi film in a 7 T magnetic field are presented in Fig. 3. The film shows a positive magnetoresistance (MR) above the transition temperature. The increase in MR for a magnetic field applied parallel to the film is more pronounce than that for the perpendicular field. The peak value of positive MR coincided with the onset of the transition. When the magnetic field is applied parallel to both film and the direction of the current, the magnetic forces act mainly on the carriers that are tunneling across the interface, which are perpendicular to the field.

The field dependence of MR for a FeSi film before and after the transition temperature is shown in Fig. 4. The ratio of the in-field resistance and zero-field resistance R/R_0 showed a field dependence of the form $\rho/\rho_0 = \exp(B/B_0)^m$ with $m = 1.8$. This is very close to the quadratic field dependence ($m = 2$) developed by Shklovskii and Efros[15] for hopping magnetoresistance. Extended wave functions of the localized impurity states facilitate hopping conduction. The presence of a magnetic field shrinks the wave envelop in the direction perpendicular to the field direction. This leads to a reduction in the probability of hopping and thus an increase in the resistance. Our MR results agree well with this model,

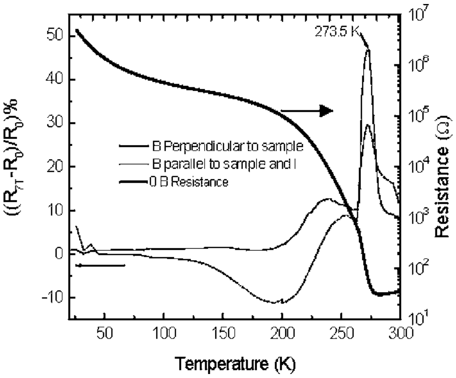

FIG. 3. Temperature dependence of zero-field resistance and magnetoresistance for a 7 T magnetic field applied parallel and perpendicular to the FeSi film.

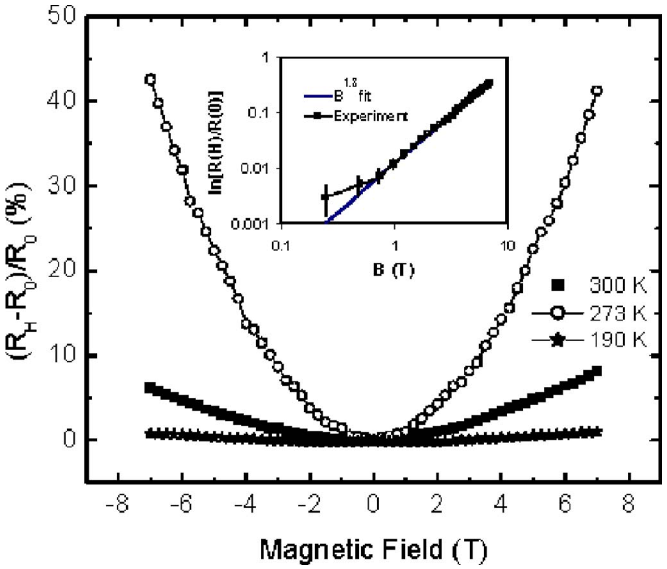

FIG. 4. Field dependence of magnetoresistance of a FeSi film before, at the onset, and after the transition. Field was applied parallel to the film. The inset shows $\ln(R/R_0)$ vs B on a log-log scale. The solid line corresponds to $\ln(R/R_0) \propto B^{1.8}$.

where the field applied parallel to the film has the highest influence on the hopping probability across the interface, leading to a maximum MR. Both electrical and magnetic transport results allude to different mechanisms of transport before and after the transition. The negative MR observed for perpendicular fields after the current was switched to the film has to be from contributions other than geometric effects.

In summary, we have shown that the current transports in FeSi and CoSi films that are deposited on low resistivity *p*-doped silicon substrates with native oxide layers take place through the silicon substrate at high temperature. This is enabled by the profuse diffusion of Fe and Co into the depletion layer that facilitated trap-assisted tunneling of carriers across the SiO_2/Si interface. With a decreasing temperature, the interaction of electrons with the magnetic moment of the transition metal ions caused the carriers to localize leading to a high interface resistance. Below this transition temperature the current transport switched to the film. Application of a magnetic field parallel to the film caused the wave functions of the tunneling electrons to shrink that reduce the hopping probability. This produced a positive magnetoresistance.

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