

Giant magneto-resistance in p–n junction composed of β -FeSi₂–Si

Koji Yamada, Hirohisa Ogawa, Zentarou Honda, Kiyoshi Miyake*

Department Materials Sciences, Saitama University, Saitama 338-8570, Japan

Received 6 September 2005; received in revised form 30 December 2005; accepted 18 January 2006

Available online 17 April 2006

Abstract

Fe–Si alloy system was investigated on the magneto-resistance (MR) effects in a temperature range between 77K–RT and in high fields up to 30 T. The samples were prepared by sputtering Fe(200 nm) on *n*-Si(1 0 0) surface and variously annealed up to β -FeSi₂ are obtained. The MR effects were found small less than several %, negative at RT and positive at $T = 77$ K for Fe-rich samples. For a sample at the stoichiometric β -Fe–Si₂ on *n*-Si as a p–n junction, we found a positive MR as large as 30% at RT in $B = 30$ T. The physical mechanism of the large MR is tentatively given by the carrier freeze-out effect in between the p–n.

Keywords: β -FeSi₂; p–n junction; Large magneto-resistance; Magneto-transistor; High fields

1. Introduction

Nowadays, Silicon is widely used for electronic devices because of the stable covalent bonding and the high purity substrate is obtainable. Further, the large amount of Si exists in earth and shows no pollution. However, Si exhibits some demerit of low mobility of 1350 cm²/Vs, which are not available for the high speed optical and communication devices. For these purposes, GaAs is widely used because of the high mobility as 8500 cm²/Vs instead of Si. However, as it is well known that GaAs shows extremely strong poison. In these 10 years, we are eager to search some semiconductors with high mobility and without pollution. In this study, we first report magneto-resistance (MR) in the p–n junction composed of β -FeSi₂ on Si(1 0 0) substrate, in which the material are completely safe for the environments. Here, the MR effects are of great interest for new electronic devices or as physics. We investigated on the MR effects for variously prepared samples of β -FeSi₂ alloy system obtained by sputtering Fe on Si(1 0 0) surface. The samples were annealed at different conditions of annealing durations and at various temperatures, to obtain different sample of x ($0 < x < 1$) in Fe _{x} Si_{1– x} including the stoichiometric β -FeSi₂ on *n*-Si(1 0 0) substrate. Fur-

ther, the MR phenomena were investigated in a high magnetic field range up to 30 T at room temperature (RT) or $T = 77$ K by using pulsed magnetic fields with long pulsed half-widths of about 20 ms. For this purpose, we constructed a pulsed high magnetic field generator using a condenser bank of 17 mF and thyristers for an available current switch of 60 kA maximum. The prepared samples were examined by X-ray diffraction (XRD) and scanning electron microscope (SEM) and were assigned the property of the substrate and transport properties.

2. Experiments

2.1. Sample preparations

The samples were fabricated on a Si(1 0 0) substrate by a radio frequency (RF) sputtering device as shown in Fig. 1. The RF sputtering system was composed of Fe target of 6 mm ϕ and 150 mm length with a purity of 5N(99.999%) set at the center of RF coil of 50 mm ϕ . After evacuating the sputtering system in the background vacuum level of 10^{-4} Pa. Ar gas was introduced in the chamber up to 8 Pa. The incident power to the RF coil was 200 W at 13.56 MHz and the reflected power was minimized to 5 W by using an impedance matching box. Further, the Fe target was biased at a negative voltage of 1.2 kV of d.c. to the ground, locating 50 mm apart from the Si substrate. The neutral Fe molecular beam was obtained with these conditions in the

* Corresponding author at: Graduate School, Saitama University, Saitama 338-8570, Japan. Tel.: +81 48 858 3526; fax: +81 48 858 6465.

E-mail address: Yamasan@fms.saitama-u.ac.jp (K. Miyake).

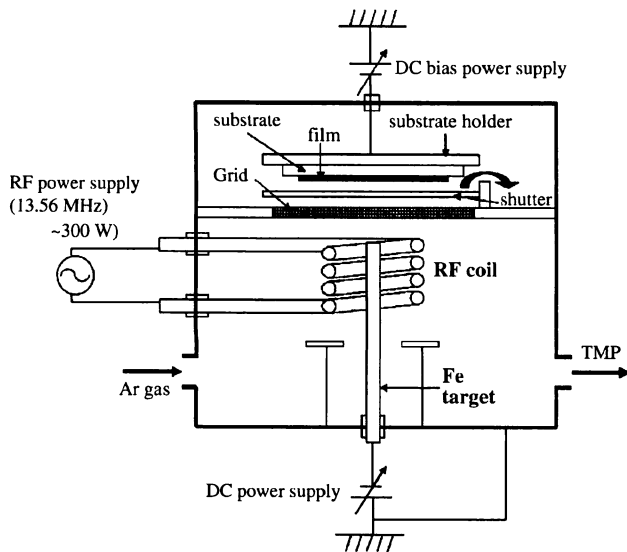


Fig. 1. RF deposition system.

plasma. The sputtering was performed for 30 min up to 200 nm deposition at a substrate temperature of about 100 °C and with the zero substrate bias against the ground [1,2]. The samples were variously annealed in a temperature range of 400–900 °C for a duration range 1–2 h.

Fig. 2 (a) shows the XRD spectra observed for samples with different annealing temperatures at 600, 800 and 900 °C for 1 h. As seen in this figure, a sample annealed at 900 °C, shows several large peaks of β -FeSi₂. On the contrary, the sample annealed at 600 °C shows peaks of almost metal Fe. In between the two annealing temperatures, we obtain several peaks for Fe and the multiplex of Fe_x-Si_{1-x} crystals. The XRD spectra for a sample annealed at 850 °C, 2 h show limited crystal peaks of β -FeSi₂ as shown in Fig. 2(b).

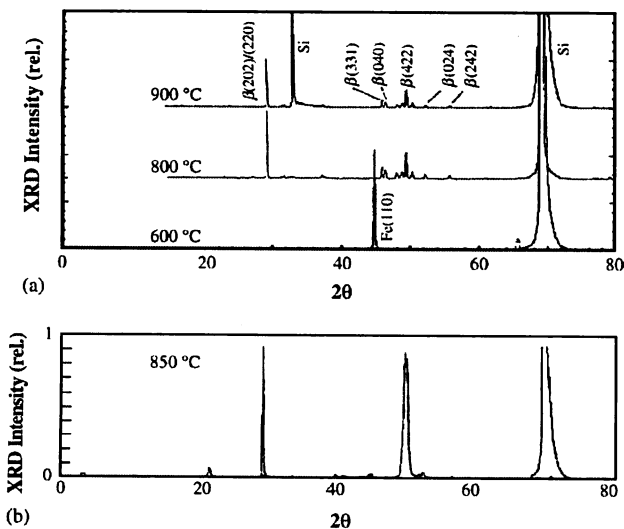


Fig. 2. XRD spectra obtained for differently annealed samples at (a) $T = 600$, 800 and 900 °C, 1 h, respectively and (b) that at $T = 850$ °C, 2 h.

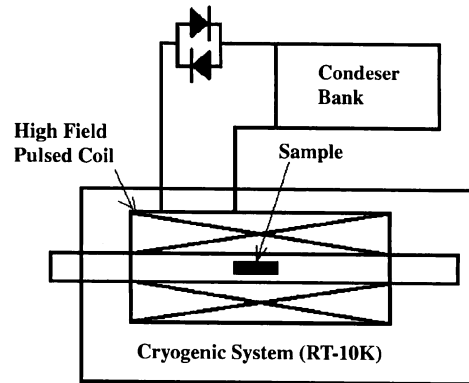


Fig. 3. Schematic picture of pulsed high field generator coupled with cryogenic system.

2.2. Pulsed high magnetic field generator

Pulsed magnetic fields were generated by a laminated solenoid coil with Liq. N₂ immersion, and the coil currents were generated by discharging a condenser bank of 17 mF, 2.5 kV (40 kJ). The coil current on/off were performed by a large thyristers array available up to 60 kA. The magnetic coils of 10 mH typ. with 10 mm Φ Bohr were made of conventional soft copper wire of 1.5–2.0 mm Φ covered by a 3 mm thick lamination of Kevlar thread (Toray co.) to prevent swelling of the coil by Lorentz force. Fig. 3 shows the schematic picture of the experimental set-up of the pulsed high field generator with the cryogenic freezer. The half-width of the generated pulsed field was about 20 ms. The increasing rate and the half-width of the applied magnetic fields were able to change by choosing the coils with different copper wire diameters and with winding turns.

2.3. MR observations

The MR effects were observed for samples with a constant current supplier composed of a battery of $V_B = 9$ V with a series resistor of 20 k Ω in cases of the sample resistances less than 1 k Ω . The sample current, in this case, was about 0.5 mA by which the temperature of the sample was almost preserved constant. The MR effects were calculated by subtracting the two sample drop voltages supplied by $V_B = 9$ V and $V_B = 0$ to eliminate the induced noise caused by pulsed high fields. The temporal responses of the signals were recorded by an Analogue to digital converter (ADC) of 16 bits with the sampling rate of 8 μ s, and were recorded up to 120 ms (15 kwords).

3. Experimental results

We performed observations of MR effects for variously annealed samples as shown in Fig. 4 in the ambient temperatures of 77 K and room temperature (RT), respectively in pulsed fields up to 30 T. For samples with an annealing temperature of 400 °C, the MR effects expressed by resistance ratio of $(R(B) - R(0))/R(0)$ were negative at room temperature (RT), positive at $T = 77$ K, respectively with small MR effects less than several % even in $B = 30$ T. On the other hands, MR effects for a sample with an annealing temperature of 800 °C (1 h), were positive at RT and negative at $T = 77$ K, respectively. Further, these were found pronounced as large as 30% in 30 T for a sample with the annealing at 850 °C, 2 h. The resistivity of the properly annealed samples increased with ambient

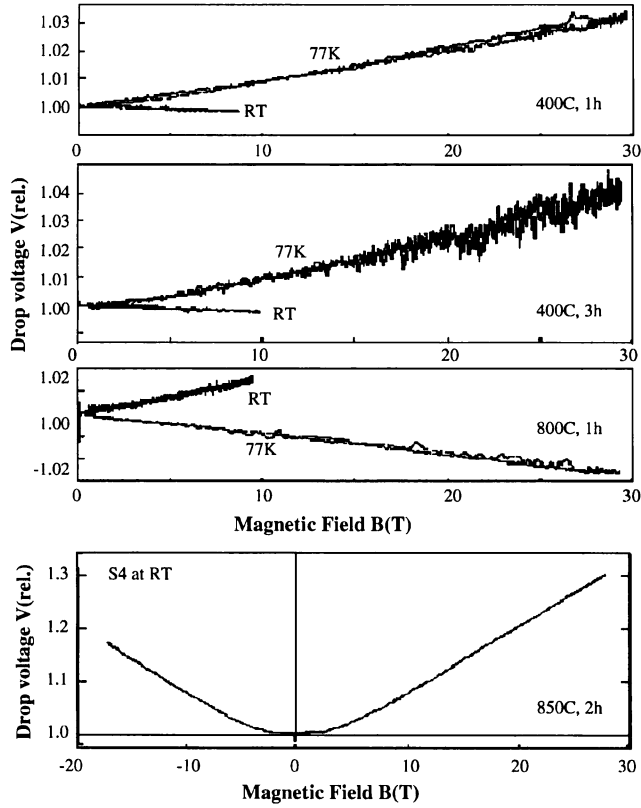


Fig. 4. MR effects for differently annealed samples, plotted by the sample drop voltages as a function of magnetic fields.

temperature decrease as 800Ω at RT and $180 \text{ k}\Omega$ at $T = 77 \text{ K}$, respectively. Further, we performed the observation of V - I characteristics of the sample with the large MR during the magnetic fields sweep up to 15 T at RT as shown in Fig. 5. Note here that the V - I traces were repeatedly drawn at $f = 800 \text{ Hz}$ ($-5 < V < 5 \text{ V}$), where the magnetic field change (ΔB) was about 0.25 T for ($B_{\text{max}} = 15 \text{ T}$) during the sample voltage sweep between 0 and 5 V within Δt ($= 1/800/4$). As pointed out by an arrow in Fig. 5, MR effects were observed only in the positive currents range, whereas no MR was observed in the reversed voltage range. Here, it must be noted here about the contacts to the sample. We obtain the same V - I characteristics with the reversed contact to the sample, which ensured the ohmic nature of the two probes by using Ag past.

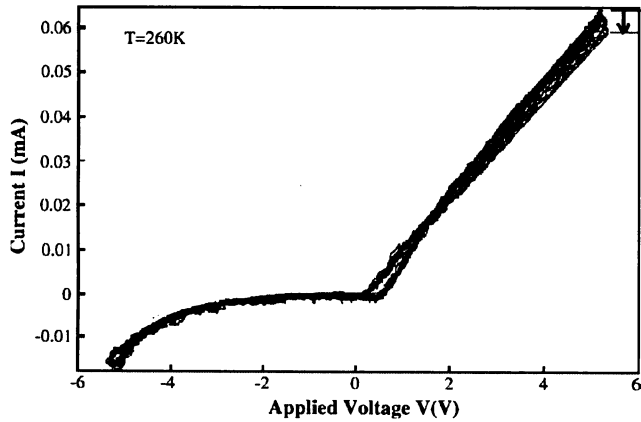


Fig. 5. V - I characteristics of the sample with the largest MR with the annealing condition of 850°C , 2 h .

4. Discussions

The discussions must be on (1) the characterizations of samples and on (2) the physical mechanism of MR for samples annealed at higher temperatures than 800°C . It is apparent that the XRD spectra for a sample annealed at above 800°C did not show metal Fe any more. The important nature of the sample must be the crystal structures of $\beta\text{-FeSi}_2$ and the inter layer with Si(1 0 0) surface. The XRD spectra around at $2\theta = 50$ – 60° showed several candidates for crystal formations of $\beta\text{-FeSi}_2$. Therefore, the annealed samples must be uniform along the plain direction. However, the crystalline structure along the thickness direction was not investigated in this experiment. Especially, the amounts of excess Fe or Si in the $\beta\text{-FeSi}_2$ as a function of the distance from the interface must be known because the transport properties of a semiconductor junction depend on the impurities deviated from the stoichiometry. Here, in discussions, because of our technological or scientific interests, we examine on the MR effects in the samples with large MR effects.

In general, the resistivity changes of a semiconductor with any shapes are caused by the several parameters variations such as the carrier density, the carrier mobility or the material shape in externally applied fields. For a conventional semiconductor with low mobility as $50 \text{ cm}^2/\text{Vs}$ or less, the resistance change of 10% at RT cannot be given rise by the other parameters than the

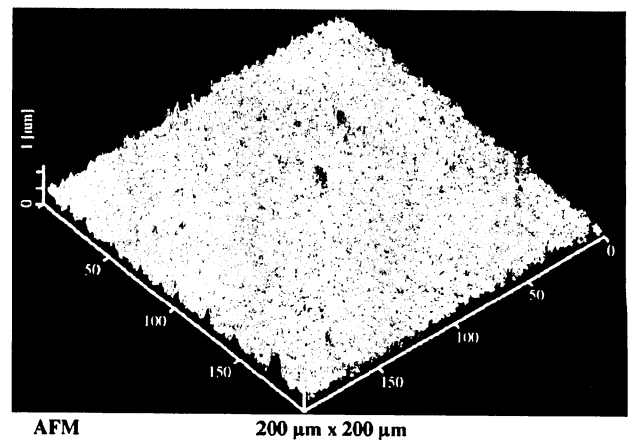


Fig. 6. SEM and AFM pictures of a sample with 850°C , 2 h .

carrier density in magnetic field application. Therefore, the plausible physical mechanism for the observed positive MR at RT, might be caused by the carrier density decrease with increasing magnetic fields. For this occurrence, the acceptor, as the majority carrier, activation energy might shift deeper with increasing applied magnetic fields, so-called freeze-out effect by Yafet [3]. In this paper, we tentatively adopt the physical model of freeze-out mechanism. Adopted by this model, the conductivity (σ) is controlled in a magnetic field (B) by the carrier density as

$$\sigma(B) = \frac{q^2 \tau}{m^*} n_0 \exp(-E_A(B)/k_B T) \quad (1)$$

Here, q stands for the charge of the carrier, τ , the mean free time, m^* , the effective mass, n_0 , the dopant density, $E_A(B)$, the activation energy of the impurity state, k_B the Boltzmann constant and T , the ambient temperature, respectively. The activation energy $E_A(B)$ becomes depending on applied fields for $\hbar q B / m^* > 2R_y$ (R_y : Rydberg energy of the ground state of the localized carrier in the impurity state) and it increase with increasing fields. This criterion is equivalent to $B[T] > 2 \times 10^5 (m^*/m_0 \epsilon)^2$ for a semiconductor with the dielectric constant of ϵ . Using the parameter set for p-type carrier of $m^*/m = 0.5-1.0$, $\epsilon = 32-62$, we obtain a magnetic field range between 13 T ($m^*/m_0 = 0.5$, $\epsilon = 62$) and 195 T ($m^*/m_0 = 0.5$, $\epsilon = 62$), respectively. Now, it is most plausible to consider the segregation of the excess Fe atoms in FeSi_2 or in n-Si because of the sample preparation process. The activation energy of this kind could change more sensitively in the applied magnetic field than that with single Fe atom in FeSi_2 and/or Si, due to the magnetization might be enhanced in the segregated Fe atoms.

Adopting this model, the onset value might be smaller than 13 T as observed in this study. Finally, the nature of the interlayer between the $\beta\text{-FeSi}_2$ and n-Si must be discussed. As shown in Fig. 6, the surface pictures by SEM and TEM show uniformly distributed $\beta\text{-FeSi}_2$ crystal over the surface. The current must flows through the crystals of $\beta\text{-FeSi}_2$ into Si. However, no information included in the SEM and TEM pictures about the interlayer between the two crystals. It is natural to suppose the graded Fe atom immigrations to n-Si from $\beta\text{-FeSi}_2$ layer. Further, Fe atom defects in $\beta\text{-FeSi}_2$ layer must be inserted along the interface.

For the future study, the origin of MR and the nature of the interface must be investigated.

5. Conclusions

In this paper, the large positive MR effects of 30% at RT were found in high fields up to 30 T for samples prepared by Fe deposition on Si(1 0 0) surface and annealed at about 850 °C for 2 h. The physical model of Freeze-out effects is tentatively adopted for explanations. However, the exact crystal structures for Fe deposition on Si(1 0 0) substrate must be investigated as a future study. The method presented here, might be hopeful for a new type magneto-transistor.

References

- [1] K. Miyake, K. Ohashi, Mater. Chem. Phys. 54 (1998) 321.
- [2] K. Miyake, et al., IEEE Trans. 98EX144 (1998) 550.
- [3] Yafet, et al., J. Phys. Chem. Solids 1 (1956) 137.