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Room-temperature spin polarization of epitaxial Fe_3Si films with *D*0_3-ordered structures estimated by tunneling magnetoresistance measurements

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1. Introduction

Semiconductor spintronic devices are expected to be able to reduce electric power consumption in existing semiconductor devices[1]. As a ferromagnetic material which has compatibility with semiconductor devices, we have focused on *D*0_3-type Fe_3Si with a high Curie temperature[2], because its lattice constant is close to that of Si, Ge, and GaAs. To date, we have already realized epitaxial growth of highly *D*0_3-ordered Fe_3Si films on Si(111)[3] and Ge(111)[4] by molecular beam epitaxy (MBE). Using high-quality Fe_3Si/n^+-Si or Fe_3Si/n^+-Ge Schottky-tunnel-barrier contacts, we recently observed spin accumulation signals created electrically in Si[5] or Ge[6], respectively. However, the detection of the spin accumulation signals has been limited at low temperature. As a result, we could not understand the spin-related function for *D*0_3-Fe_3Si at room temperature.

Up to now, the spin polarization (*P*) of ~0.45 for a *D*0_3-type Fe_3Si film was estimated by means of the point contact Andreev reflection (PCAR) method at 4.2 K[7]. Unfortunately, this method can not be used at room temperature. Although tunnel magnetoresistance (TMR) effect was explored at room temperature using a magnetic tunnel junction (MTJ) with Fe_3Si electrodes[8], the *P* value of Fe_3Si could not be estimated. To apply this material to real spin devices which can operate at room temperature, the room-temperature *P* is essential information.

In this study, in order to examine room-temperature *P* for *D*0_3-type Fe_3Si, we investigate room-temperature TMR effect of the MTJs consisting of epitaxial Fe_3Si films with *D*0_3-ordered structures and conventional CoFe alloys on Si.

2. Samples and Measurements

Using our low-temperature MBE technique[3,4], we formed high-quality Fe_3Si films on non-doped Si(111) substrates (ρ ~ 5000 Ωcm) at a growth temperature of 130^{o}C. The thickness of the Fe_3Si layer was about 25 nm. Next we deposited Al layers (2 nm) on the Fe_3Si layer in the same chamber and Al-O_x layers (~3 nm) were formed by ex-situ air oxidation. After we returned the sample to the chamber, CoFe top layers (10 nm) were formed on top of it. As described above, we formed CoFe/Al-O_x/Fe_3Si structures. Representative reflection high-energy electron diffraction (RHEED) patterns during the fabrication of the CoFe/Al-O_x/Fe_3Si structure are shown in Fig. 1. The RHEED image for the Fe_3Si layer [Fig. 1(a)] clearly exihibits the symmetrical streak due to the good two-dimensional epitaxial growth. Figure 1(b) shows the RHEED pattern of the surface after Al deposition. Although the streak was observed, the pattern was slightly changed. After the oxidation of the Al layer, we can see halo-like dark pattern, indicating that the formed Al-O_x layer is amorphous [Fig. 1(c)]. After the deposition of CoFe layer [Fig. 1(d)], we can see ring-like pattern which indicates the formation of poly-crystalline CoFe.

Field dependence of the magnetization (*M*-*H* curve) for the fabricated multilayer structure was measured by means of vibrating sample magnetometer (VSM) at room temperature. Conventional processes with electron-beam lithography, Ar^+ ion milling, and reactive ion etching were used to fabricate MTJs for measurements of TMR effect. The junction size of MTJs was ~50 μm^2. TMR measurements were performed by a d.c. two-probe method. TMR ratio is defined as $(R_{ap} - R_p)/R_p$, where R_p and R_{ap} are the tunnel resistance when the magnetizations of the two electrodes are aligned in parallel and antiparallel, respectively.

3. Results and Discussion

Figure 2(a) shows a cross-sectional transmission electron microscopy (TEM) image of the CoFe/Al-O_x/Fe_3Si structure. The Al-O_x tunnel barrier is very smooth [Fig. 2(b)], indicating the successful fabrication of MTJs. From the observation of nanobeam electron diffraction patterns of the Fe_3Si layer, we confirm the presence of *D*0_3-ordered structure [Fig. 2(c); see solid circles].

Figure 3(a) shows the *M*-*H* curve of the fabricated CoFe/Al-O_x/Fe_3Si layer at room temperature. The shape of the *M*-*H* curve has a step, implying the differences in coercivity between Fe_3Si and CoFe layers. Figure 3(b) shows the current-voltage characteristic of an MTJ measured at room temperature without external magnetic field. A non-linear characteristic is clearly observed, indicating that tunnel conduction through the Al-O_x layer is realized. Accordingly, this CoFe/Al-O_x/Fe_3Si structure is suitable for TMR measurements.

Using such MTJs, we measured the TMR effect at room temperature. As shown in Fig. 4, we clearly observed a magnetoresistance (MR) curve under a bias current of 0.5 μA. The maximum TMR ratio of ~20.5 % was obtained. We observed similar MR curves with the TMR ratio of ~20 % in many MTJs fabricated by the same processes. Thus, the TMR ratio value of ~20 % is reliable. By using Julliere's formula[9], we can estimate the room temperature *P* value for the Fe_3Si film at ~ 0.19 when we assume that the *P* value for the CoFe is 0.5[10]. Recently, we also estimated room-temperature *P* value for an Fe_3Si film by means of the nonlocal voltage measurements in Fe_3Si/Cu lateral spin valve devices[11]. The P value obtained from this method was close to ~0.19[11]. Therefore, the room-temperature P for our MBE grown Fe_3Si is nearly 0.2, and this value is quite reliable.

4. Summary

We have obtained a clear TMR at room temperature in MTJs consisting of a $D0_3$-ordered Fe_3Si film as a ferromagnetic electrode. As a result, we were able to estimate the value of the room temperature spin polarization (P) of ~0.19, which is reliable. Further evaluation of spin-related functions of Fe_3Si is required to apply Fe_3Si to spin devices operating at room temperature.

Acknowledgements

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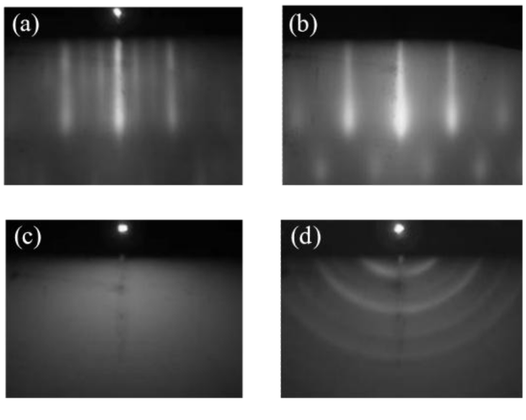

Fig. 1. RHEED patterns for (a) Fe_3Si layer, (b) Al layer, (c) Al-O_x layer, and (d) CoFe layer.

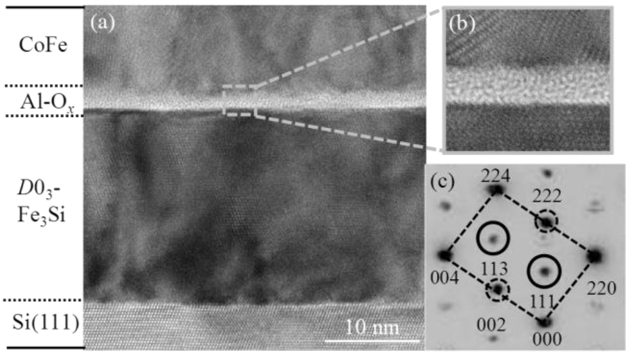

Fig. 2. (a) Cross-sectional TEM image of the CoFe/Al-O_x/Fe_3Si structure. (b) Magnification of the Al-O_x tunnel barrier. (c) Nanobeam electron diffraction pattern of the epitaxial Fe_3Si layer. The axis of the incident electrons is parallel to the [$1\bar{1}0$] direction.

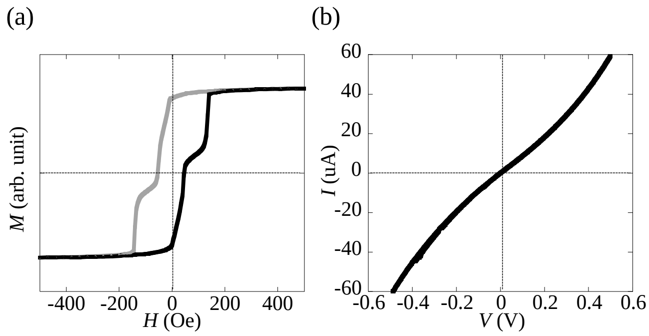

Fig. 3. (a) The M-H curve of the fabricated CoFe/Al-O_x/Fe_3Si structure. (b) The I-V characteristic of an MTJ measured at room temperature.

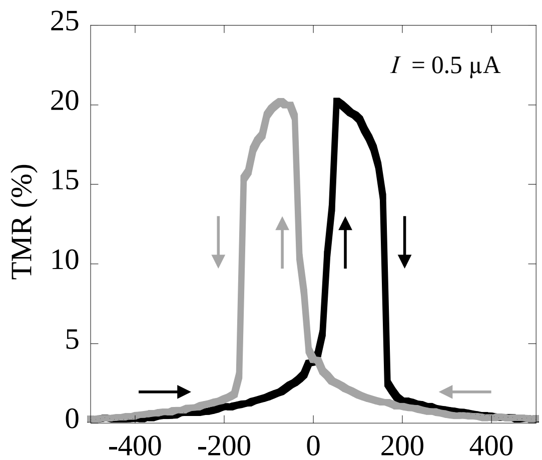

Fig. 4. Room-temperature magnetoresistance curve of a CoFe/Al-O_x/Fe_3Si structure.