Room-temperature spin polarization of epitaxial Fe$_3$Si films with D0$_3$-ordered structures estimated by tunneling magnetoresistance measurements

Yuichi Fujita, Shinya Yamada, Soichiro Oki, Yuya Maeda, Masanobu Miyao, and Kohei Hamaya

Department of Electronics, Kyushu University, 744 Motooka, Fukuoka 819-0395, Japan
Phone: +81-92-802-3738 E-mail: y_fujita@nano.ed.kyushu-u.ac.jp

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 D0$_3$-type Fe$_3$Si 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 D0$_3$-ordered Fe$_3$Si films on Si[111][3] and Ge[111][4] by molecular beam epitaxy (MBE). Using high-quality Fe$_3$Si/n'-'Si or Fe$_3$Si/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 D0$_3$-Fe$_3$Si at room temperature.

Up to now, the spin polarization (P) of about 0.45 for a D0$_3$-type Fe$_3$Si film was estimated by means of the point contact Andreev reflection (PCAR) method at 4.2 K[7]. Unfortunately, this method cannot be used at room temperature. Although tunnel magnetoresistance (TMR) effect was explored at room temperature using a magnetic tunnel junction (MTJ) with Fe$_3$Si electrodes[8], the P value of Fe$_3$Si 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 D0$_3$-type Fe$_3$Si, we investigate room-temperature TMR effect of the MTJs consisting of epitaxial Fe$_3$Si films with D0$_3$-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$_3$Si films on non-doped Si(111) substrates ($\rho \sim 5000 \Omega cm$) at a growth temperature of 130°C. The thickness of the Fe$_3$Si layer was about 25 nm. Next we deposited Al layers (2 nm) on the Fe$_3$Si layer in the same chamber and Al-0$_x$ 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-0$_x$/Fe$_3$Si structures. Representative reflection high-energy electron diffraction (RHEED) patterns during the fabrication of the CoFe/Al-0$_x$/Fe$_3$Si structure are shown in Fig. 1. The RHEED image for the Fe$_3$Si layer [Fig. 1(a)] clearly exhibits 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-0$_x$ 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 $\mu$m$^2$. TMR measurements were performed by a d.c. two-probe method. TMR ratio is defined as ($R_{up} - R_{down}$)/$R_{up}$, where $R_{up}$ and $R_{down}$ 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-0$_x$/Fe$_3$Si structure. The Al-0$_x$ 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$_3$Si layer, we confirm the presence of D0$_3$-ordered structure [Fig. 2(c); see solid circles].

Figure 3(a) shows the M-H curve of the fabricated CoFe/Al-0$_x$/Fe$_3$Si layer at room temperature. The shape of the M-H curve has a step, implying the differences in coercivity between Fe$_3$Si 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-0$_x$ layer is realized. Accordingly, this CoFe/Al-0$_x$/Fe$_3$Si 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 $\mu$A. 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 Juliere's formula[9], we can estimate the room temperature P value for the Fe$_3$Si 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$_3$Si film by means of the nonlocal voltage measurements in Fe$_3$Si/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$_3$Si 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 $DO_3$-ordered Fe$_3$Si 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$_3$Si is required to apply Fe$_3$Si to spin devices operating at room temperature.

Acknowledgements
This work was partly supported by CREST-JST, STARC, and NEDO.

References

Fig. 1. RHEED patterns for (a) Fe$_3$Si layer, (b) Al layer, (c) Al-O, layer, and (d) CoFe layer.

Fig. 2. (a) Cross-sectional TEM image of the CoFe/Al-O$_3$/Fe$_3$Si structure. (b) Magnification of the Al-O$_3$ tunnel barrier. (c) Nanobeam electron diffraction pattern of the epitaxial Fe$_3$Si layer. The axis of the incident electrons is parallel to the [110] direction.

Fig. 3. (a) The $M$-$H$ curve of the fabricated CoFe/Al-O$_3$/Fe$_3$Si structure. (b) The $I$-$V$ characteristic of an MTJ measured at room temperature.

Fig. 4. Room-temperature magnetoresistance curve of a CoFe/Al-O$_3$/Fe$_3$Si structure.