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Magnetic properties of epitaxial Fe_3Si/Ge(111) layers for group-IV semiconductor spintronic applications

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1. Introduction

Because of an intrinsic limit of the technologies for complementary metal-oxide-semiconductor (CMOS) transistors, spin-based electronic (spintronic) device applications have been examined intensively. To date, the experimental studies of novel techniques such as spin injection from ferromagnetic materials into nonmagnetic semiconductors have been demonstrated on the basis of III-V semiconductor technologies [1]. To combine the spintronics with Si-based semiconductor industry, it will become important to explore ferromagnetic materials which are compatible with group-IV-semiconductor device applications from now on [2]. Recently, we realized epitaxial growth of ferromagnetic DO_3-type Fe_3Si layers, which have a high Curie temperature of ~ 840 K, on Ge (111) substrates with atomically flat interfaces [3]. This implies that the function of spins can be integrated with future Si-LSIs. In order to achieve group-IV semiconductor spintronic devices with Si and Ge channels, we firstly need to examine magnetic properties of the epitaxial Fe_3Si layers.

Here, we report on an unexpected in-plane uniaxial magnetic anisotropy of the epitaxial Fe_3Si layers. After post-growth annealing, we observe an anomalous switching of the direction of the magnetic easy axis without forming secondary phases at the Fe_3Si/Ge interface.

2. Experiments and Samples

Fe_3Si epilayers were grown on n-type Ge (111) substrates by low-temperature molecular beam epitaxy (MBE) at 130^{o}C. The thickness of the epilayers was about 50 nm. After the growth, post-annealing was carried out at 300 and 400 ^{o}C for 30 - 120 min. Their crystal structures and qualities were characterized by x-ray diffraction (XRD), Rutherford backscattering spectroscopy (RBS), and transmission electron microscopy (TEM). A cross-sectional TEM micrograph of the as-grown Fe_3Si/Ge(111) epilayer is shown in Fig. 1(a). We can see an atomically flat interface. Such abrupt interfaces were kept even for the samples annealed at 400 ^{o}C for 120 min [4]. The Fe_3Si layers investigated here included an ordered DO_3-type structure shown in Fig. 1(b) and no precipitates before and after annealing [3,4]. Also, we have confirmed that all the samples annealed have no atomic diffusion of Fe, Si, and Ge atoms at the Fe_3Si/Ge interface [4]. Field dependence of the magnetization, *M-H* curves, were measured by means of vibrating sample magnetometer (VSM) at room temperature. External magnetic fields (*H*) were applied parallel to the film plane. To characterize magnetic anisotropy of the Fe_3Si epilayers, the samples were rotated in the film plane to change the angle α between magnetic field direction and [-211] crystallographic axis [see-Fig. 1(c)].

3. Results and Discussion

Figure 2 shows *M-H* curves of an as-grown Fe_3Si eplilayer for field directions of α= (a) 0^o, (b) 30^o, (c) 60^o, and (d) 90^o, where the y-axes show the magnetization (*M*) normalized by the saturation magnetization (M_s), i.e., M/M_s. The shape of the *M-H* curves depends strongly on the field direction, indicating the presence of the magnetic anisotropy in the film plane. A summary of M_r/M_s as a function of α (polar plot) is shown in Fig. 2(e), where M_r is remanent magnetization. Although the DO_3-type Fe_3Si (111) has a six-fold crystal symmetry in the film plane, we can identify an unexpected uniaxial magnetic anisotropy with an easy axis parallel along to the direction of $\alpha \sim 165^o$. The uniaxial anisotropy was also confirmed for other as-grown epilayers, though the direction of the easy axis is different each other. The random oriented uniaxial anisotropy can become one of the problems in the device fabrication. The origin of the in-plane uniaxial anisotropy is now under investigation.

We further examine the effect of post-growth annealing on the magnetic anisotropy for the Fe_3Si (111) epilayers. In Fig. 3(a) we summarize a polar plot of the Fe_3Si layers annealed at 400 ^{o}C for 30 min, where the sample used here is the same one as shown in Figs. 2(a)-(e). Interestingly, the direction of the magnetic easy axis is markedly switched to the direction of $\alpha \sim 100^o$ after the annealing. The same sample was further annealed at 400 ^{o}C for 90 min, i.e., the total annealing time of 120 min, and the angular-dependent *M-H* curves were also measured. As a consequence, we find almost no switching of the magnetic easy axis, so that the easy axis of the Fe_3Si epilayers annealed at 400 ^{o}C is almost stabilized by short-time annealing (~ 30 min). These tendencies were reproduced for other samples, although the direction of their easy axes was different from that of the present sample. Namely, the post-growth annealing can modify the in-plane magnetic anisotropy of as-grown Fe_3Si (111) layers. We can utilize this technique as a method for stabilizing their magnetic properties on group-IV-semiconductor devices.

In the inset of Fig. 3(b), we present the *M-H* curves of the Fe_3Si epilayer annealed at 400 ^{o}C for 30 min, where the closed and opened plots show the data for magnetic easy and hard axes, respectively. To compare the strength of magnetic anisotropies between as-grown and annealed samples, we plot the anisotropy field (H_K) vs annealing temperature in Fig. 3(b). A sudden enhancement in H_K is observed at the annealing temperature of 400 °C. In general, the electric and magnetic properties of bulk Fe_3Si are influenced by the ordering of its crystal structure [5]. If there are disordered crystal regions in the as-grown Fe_3Si epilayers, we can improve them by using the post-growth annealing. We speculate that this enhancement in H_K originates from the increase in the ordered DO_3 phases in the Fe_3Si layers. The detailed analyses of the correlation between the ordering of the crystal structure and magnetic anisotropies are further required.

4. Summary

We have studied the magnetic anisotropy of the epitaxial Fe_3Si epilayers grown on Ge(111) substrates. An unexpected uniaxial anisotropy is observed in the film plane. After a post-growth annealing, a magnetic easy axis of the uniaxial anisotropy is switched to a stable direction without forming secondary phases at the Fe_3Si/Ge interface. This technique can be utilized as a method for stabilizing magnetic properties of the Fe_3Si epilayers on group-IV-semiconductor devices.

Acknowledgements

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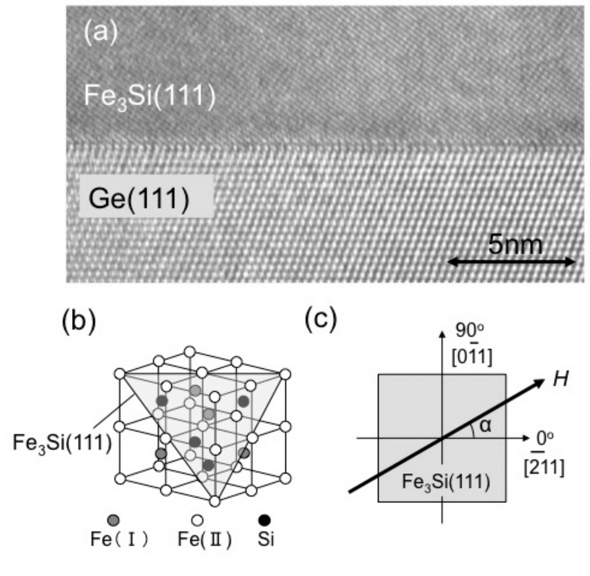

Fig. 1. (a) Cross-sectional TEM micrograph of an as-grown Fe_3Si/Ge(111). (b) Schematic diagram of the DO_3 unit cell of the Fe_3Si. (c) Definition of the direction of external magnetic fields (H) applied in the film plane.

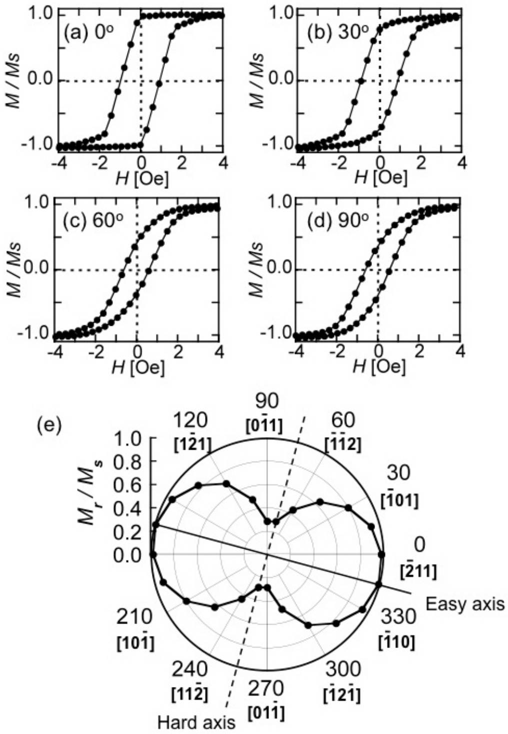

Fig. 2. Normalized magnetization curves of the as-grown Fe_3Si epilayer for field directions of α= (a) 0°, (b) 30°, (c) 60°, and (d) 90°. (e) The polar plot of normalized remanenct magnetization. The magnetic easy and hard axes are denoted as the solid and dashed lines, respectively.

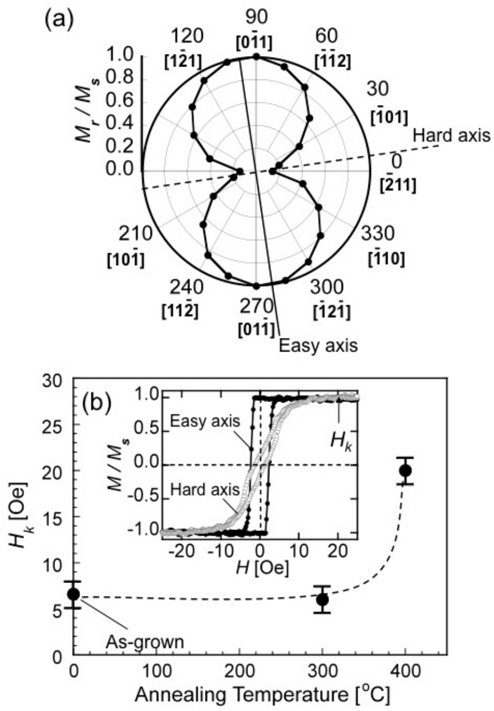

Fig. 3. (a) The polar plot of remanent magnetization normalized by saturation magnetization for the Fe_3Si layer annealed at 400°C for 30 min. (b) Anisotropy field as a function of annealing temperature (annealing time : 30 min). The inset shows normalized magnetization curves for the sample annealed at 400 °C for 30 min.