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High uniaxial magnetic anisotropy of the $Fe_{1-x}Si_x$ films synthesized by MBE

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ABSTRACT

The structure and the magnetic anisotropy of the films obtained by simultaneous deposition of iron and silicon on n-Si(111) 7×7 at 130 °C are investigated. It is found the uniaxial magnetic anisotropy field for the $Fe_{1-x}Si_x$ films with x=0.25 (Fe_3Si stoichiometric ratio) deposited on Si(111) 7×7 depends on both the surface miscut angle and the oblique sputtering direction and changes from 0.82 Oe up to 117.26 Oe.

1. Introduction

Thin magnetic films (TMF) are widely used in various fields of science and technology [1]. Based on TMF many microelectronic and microwave devices are developed. Fe-Si films attract the great interest of researchers and device engineering community due to their unique physical properties, one of the examples is Schottky barrier in the interface between n-Si and Fe_3Si [2]. As well as electron spin polarization degree of Fe_3Si silicide is expected to be up to 80–100% [3]. Therefore, it can be used to create both magnetic sensors and spintronics devices. Depending on the type of the application, it may require the materials with high, medium or low magnetic anisotropy. Thus, for producing the weak magnetic field sensors materials with uniaxial anisotropy are used [4].

2. Experimental

The experiment was carried out with ultrahigh vacuum molecular-beam epitaxy "Angara" set-up [5] equipped with a system of reflection high-energy electron diffraction (RHEED). The base pressure in the growth chamber was 6.5×10^{-8} Pa. The n-Si(111) substrates with 0.1°, 1.0° and 4.0° surface miscut were used. The substrates were prepared by the special chemical treatment in air and a thermal flashing at 900 °C in vacuum [6].

The $Fe_{1-x}Si_x$ films were prepared by molecular-beam epitaxy (MBE) technique with simultaneous deposition of Si and Fe on heated at 130 °C Si(111) 7×7 substrate, with x=0.25, to achive Fe_3Si stochiometric ratio. The deposition rates were Fe – 1.24 nm/min, Si – 0.88 nm/min. The component materials were evaporated from Knudsen effusion cells. The films thickness estimated by laser ellipsometry technique was about 60 nm. The films were deposited at the oblique incidence angle, so-called the oblique sputtering. The angle between the Fe flow direction and the normal to the substrate surface was 14°.

The structure formation was monitored by reflection high energy electron diffraction *in situ*.

The magnetic properties of the films were investigated with the ferromagnetic resonance (FMR) scanning spectrometer at 3.329 GHz pump frequency and external magnetic field up to 500 Oe [7]. The angular dependence of the resonance field $H_R(\varphi)$ were measured in the film plane (2° per step). To determine the main magnetic parameters (the effective saturation magnetization M_{eff}, and the magnetic anisotropy fields) of the investigated samples from the angular dependence of FMR field the phenomenological model of an epitaxial thin magnetic film on a (111) vicinal surface [8] was used. The calculation of the magnetic characteristics was carried out by fitting the experimental and theoretical angular dependence of FMR field.

Two types of $Fe_{1-x}Si_x$ films were produced, which differed in the Fe flow direction, parallel (type I) and perpendicular (type II) to $[110]_{Si}$ substrate one.

3. Results and discussions

Fig. 1. shows experimental RHEED patterns for the Fe-Si films deposited on Si(111) 7×7 substrates with the different surface miscut (Fig. 1a–c). The theoretically calculated pattern for Fe_3Si crystal structure is depicted in Fig. 1d [9].

The same reflections geometry can be easily seen on the RHEED

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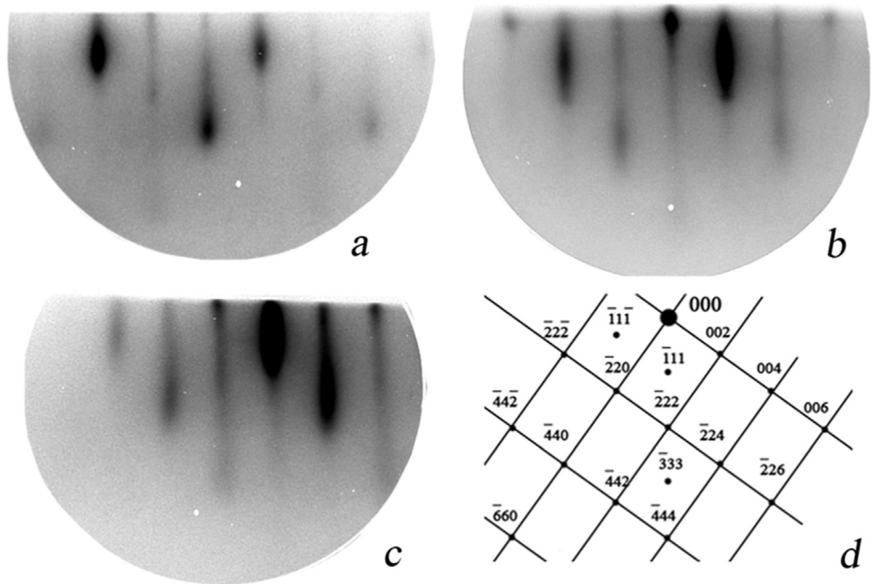

Fig. 1. The RHEED patterns for $Fe_{1-x}Si_x$/Si(111) 7×7 structure with different Si(111) surface miscut: a – 4°; b – 1°; c – 0.1°; and d – the theoretical RHEED pattern for Fe_3Si silicide [8].

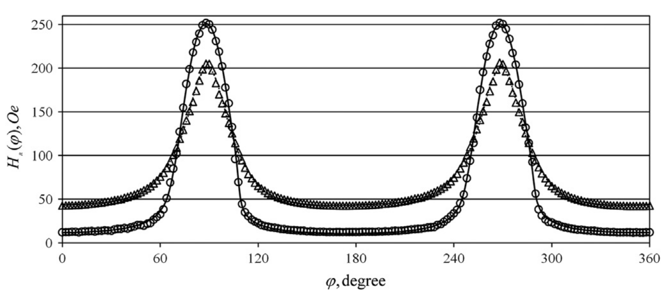

Fig. 2. The angular dependences of the FMR field for $Fe_{1-x}Si_x$/Si(111)7×7, with x=0.25. When the Fe flow was perpendicular to $[110]_{Si}$: circles – experimental, solid line – theoretical calculated; when Fe flow was parallel to $[110]_{Si}$: triangles – experimental, dot line – theoretically calculated.

patterns for all samples. There are reflections in the form of points that elongate in the vertical direction. It indicates the formation of single-crystalline epitaxial islands on the surface, while the elongation degree for the different miscut angles may indicate the size of the islands. The lower the miscut the greater the island width is. From the comparison of the experimental and theoretical diffraction patterns it can be concluded that formation Fe_3Si silicide has taken place.

Fig. 2. demonstrates the ferromagnetic resonance investigation results for the $Fe_{1-x}Si_x$ films deposited on the Si substrates with 4° miscut, when iron flow was perpendicular and parallel to $[110]_{Si}$ direction.

The experimental and theoretically calculated angular dependences of the ferromagnetic resonance field, shown in Fig. 2, are in good correspondence. Thus, in our experiment the magnetic anisotropy fields were estimated from these theoretical curves. For the film deposited with the Fe flow parallel to $[110]_{Si}$ uniaxial magnetic anisotropy H_a is 75.45 Oe, however when Fe flow was perpendicular $[110]_{Si}$ uniaxial magnetic anisotropy is about 117.26 Oe. It shows that the magnetic anisotropy depends on the oblique sputtering.

The same composition $Fe_{1-x}Si_x$ films were also prepared on the Si substrates with 1° and 0.1° Si(111) plane miscut (the FMR curves are not presented). The uniaxial magnetic anisotropy fields were estimated. For the $Fe_{1-x}Si_x$ film deposited on Si(111) substrate with 1° miscut and with the Fe flow parallel to $[110]_{Si}$ the H_a is 1.19 Oe, but in the case when Fe flow was perpendicular to $[110]_{Si}$ the uniaxial anisotropy field is H_a=8.13 Oe. These results confirm that the oblique sputtering affects the magnetic anisotropy. It can be also seen that the uniaxial magnetic anisotropy field of the films deposited on the substrate with 4° miscut is much bigger than for the 1° miscut ones. It shows that the Si(111) plane miscut affects the magnetic anisotropy too. The FMR investigation of the $Fe_{1-x}Si_x$ film deposited on Si(111) with 0.1° miscut confirms this observation. The film was deposited with the Fe flow parallel to $[110]_{Si}$ direction. The FMR investigation shows that the H_a for this film decreases and equals 0.82 Oe.

4. Conclusions

The Fe_3Si epitaxial magnetic films were obtained by iron and silicon co-deposition on the Si(111) 7×7 heated to 130 °C. The dependences of the uniaxial magnetic anisotropy field H_a on both the Si substrate miscut and the oblique sputtering were found. The epitaxial $Fe_{0.75}Si_{0.25}$ (Fe_3Si stochiometric ratio) film on Si(111), which exhibits H_a=117.26 Oe at pump frequency 3.329 GHz, was obtained by deposition Fe and Si on the 4° miscut Si(111) substrate with the Fe flow perpendicular to $[110]_{Si}$ direction. These films have perspectives for uses in the microelectronics and the microwave devices. For example, the most widely used for microwave devices $Ni_{80}Fe_{20}$/poly-Al_2O_3 have H_a≈5 Oe at pump frequency 2.3 GHz [4].

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Appendix A. Supplementary material

Supplementary data associated with this paper can be found in the online version at doi:10.1016/j.jmmm.2016.12.051.

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