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Effect of oblique-angle deposition on early stage of Fe–Si growth

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Abstract

We have investigated the initial stage of Fe growth on an Si substrate during reactive oblique-angle deposition (ROAD) at 470 °C by means of atomic force microscopy, reflection high-energy electron diffraction, and high-resolution Rutherford backscattering spectroscopy. During deposition along the normal direction, many Si atoms are displaced from their lattice positions because of reactions with the deposited Fe. However, for ROAD, the number of displaced Si atoms decreases significantly along with a selective growth of nanoislands with diameters of a few 10 nm. Evidently, the local nucleation processes required for iron silicide formation are modified by the geometrical deposition conditions.

Keywords: Iron silicide; Oblique-angle deposition; Rutherford backscattering spectroscopy; Ion channeling

1. Introduction

Oblique-angle deposition techniques have attracted the attention of many researchers since it enables the fabrication of unique nanostructures, such as zigzag [1] and helical [2] nanostructures. In addition to these complex morphologies, specific crystallographic phases can be selectively grown using oblique-angle deposition, as reported by Karabacak et al. [3]. They succeeded in selectively growing metastable β–W nanorods using an oblique-angle sputter deposition technique; peculiarities in the selectivity were attributed to the dependence of the surface mobility of the deposited W atoms on the crystallographic phase. This concept can be extended to the modification of the initial growth stage of a reactive system such as metal silicides since the local nucleation conditions strongly influence the phase of the resulting cluster of silicides [4,5].

Among the various silicides, we focus our attention on an Fe–Si system since iron silicides have diverse crystal structures and properties (semiconductor, metal, ferromagnetism, etc.) depending on their composition, such as FeSi, Fe_3Si, and $FeSi_2$. Further, they have been increasingly investigated as a strong candidate for device materials inducing smaller loads to the environment [6]. Although many attempts have been made to clarify the growth mechanism [7–10] or improve the film quality [11,12] of iron silicides, controlling the growth of iron silicides is insufficient for practical applications. As mentioned above, oblique-angle deposition seems to be useful for modifying the local nucleation conditions. However, reactive oblique-angle deposition (ROAD) has not been systematically studied. In this study, therefore, we attempt to modify the local nucleation conditions for the first time by using ROAD, where Fe was deposited on a hot Si substrate from an oblique direction.

2. Experiment

Samples were prepared in an ultrahigh vacuum (UHV) chamber connected to a 400-keV ion accelerator. After a surface-oxidized n-type Si(001) wafer with dimensions of $50 \times 7 \times 0.6$ mm^3 (resistivity $\rho \approx 5.0$ Ω cm) was loaded into the UHV chamber (base pressure of 7×10^{-10} Torr), it was cleaned by annealing at 1200 °C for 3 s to remove the oxide layer. Immediately after the cleaning procedure, Fe was evaporated on the Si(001) surface maintained at 470 °C by direct sublimation from an Fe wire (99.99% pure) at a deposition rate of 4–6 atoms/(nm^2 s). For ROAD, the deposition angle measured from the surface normal to the sample α was set as 85°. For normal deposition (ND), α was set as 0°. Iron was intermittently

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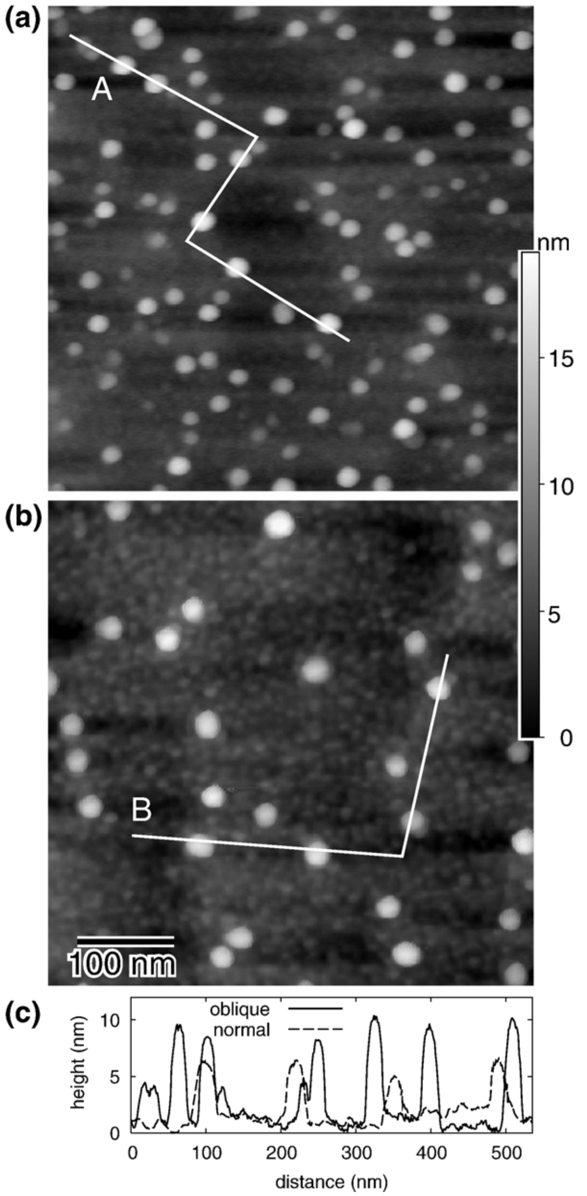

Fig. 1. AFM images of samples with (a) 85° oblique deposition and (b) 0° normal deposition after Fe deposition of 20 atoms/nm^2. Curves in (c) correspond with profiles along lines A and B.

deposited up to approximately 20 atoms/nm^2 (equivalent to 0.24 nm for bcc Fe) for both the ROAD and ND techniques. During the deposition process, the pressure was not greater than 1×10^{-8} Torr.

Between each deposition process, the samples were analyzed using high-resolution Rutherford backscattering spectroscopy (HRBS). The details of the HRBS system are described elsewhere [13]. Briefly, the HRBS measurements were performed using a beam of 400-keV He^+ ions collimated to 2×2 mm^2 and with a divergence angle of less than 2 mrad using a series of slit systems. The He^+ ions scattered at 50° were energy analyzed by a 90° sector magnetic spectrometer equipped with a one-dimensional position-sensitive detector. The energy resolution of the system was about 1.4 keV, including the energy spread of the incident beam. Channeling spectra along the <111> axis of the Si substrate were measured to derive the surface peak intensity (SPI), which is sensitive to the displacement of Si atoms from their original lattice position near the surface. The yields of ions scattered in bulk Si are strongly suppressed due to the channeling effect, and only the unshadowed Si scatters the incident ions. The atoms at the topmost surface and/or interface are never shadowed, and the ions scattered by these atoms appear as surface/interface peaks. In addition, atoms displaced from their lattice positions are unshadowed; therefore, they should act as the scattering centers. Therefore, the SPI value is a good index to represent the reactions between Fe and Si [14]. The HRBS random spectra were also measured to investigate a detailed distribution of the deposited Fe. During the sample preparation and measurements, sample surfaces were slightly oxidized owing to a small amount of residual oxygen. Contaminants other than oxygen did not influence the experimental results since their quantity was under the detection limit.

Ex situ atomic force microscopy (AFM) was conducted at the end of the experiments, and images were acquired from different sample locations.

3. Results and discussion

The AFM images for the ROAD and ND samples are shown in Fig. 1(a) and (b), respectively. The amount of Fe deposition was almost the same for both these samples (~20 atoms/nm^2). A number of clear spots corresponding to islands with diameters of a few 10 nm were observed in both the samples [see the profile in Fig. 1(c) acquired along the lines in Fig. 1(a) and (b)]. The results of the detailed analysis of the images acquired at different sample locations are summarized in Table 1. The average density and height of the islands for the ROAD sample are double those for the ND sample, while the diameter of the islands for the ROAD sample is slightly small. On the other hand, goose-bumps-like background structures found in the ND sample [see Fig. 1(b)] are never observed in the ROAD sample. Evidently, an enhancement in island formation and suppression in the formation of goose-bumps-like structures are characteristic to the ROAD sample.

Fig. 2 shows the typical RHEED patterns along the Si[100] azimuth for the samples deposited at $\alpha = 85°$ and 0°. The amount of Fe deposition was 5 atoms/nm^2 for both the samples. Although this value is smaller than that for a single monolayer, sharp patterns for clean Si surfaces disappear and get replaced by streaks and spots due to iron silicides. These spots occur due to 3D diffraction since their positions are independent of the angle of incidence of the electron beam. Although it is difficult to assign these spots to the index for any known Fe–Si phases,

Table 1
Detailed analysis of the AFM images in Fig. 1

		(a) ROAD	(b) ND
Islands	Number density (μm)	480 ± 150	230 ± 60
	Average height (nm)	6 ± 1	3 ± 1
	Average diameter (nm)	20 ± 5	25 ± 5
Background		Goose-bumps-like	