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Characterization of Subgrain Boundaries in Laterally Seeded Epitaxial SOI Films Recrystallized by an Electron Beam

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Comprehensive and systematic studies on the characterization of subgrain boundaries in SOI films recrystallized by an obliquely scanned pseudo-line electron beam are presented. It was found that the directions of subboundaries were governed by the crystal orientation of the substrate at a scanning velocity of 10cm/s, while that their directions were perpendicular to the pseudo-line beam at velocities below 1cm/s. Simple models assuming the formation of {111} facets at the solidification front was set up to explain these results.

1. Introduction

Recently, considerable efforts have been made to form silicon-on-insulator(SOI) structures using melting and recrystallization methods with such energy sources as laser[1], electron beam(e-beam)[2], carbon heater[3], and so on. However, subgrain boundaries(subboundaries) are consistently observed in SOI films recrystallized by these methods, which causes degradation of device properties. So, a large amount of work has been devoted to reduction of the subboundaries, but discussions on their detailed behaviors are very few as well as perfect suppression of the subboundaries has not been realized. Then, we study comprehensively and systematically the material properties of laterally seeded epitaxial SOI films recrystallized by a pseudo-line e-beam, in which a spot e-beam is scanned along a line faster than the thermal response time of the substrate so that a linear heating effect can be expected during movement of the beam along one direction. In this study, SOI samples with seed stripes are used and the pseudo-line beam is always scanned parallel to the seed stripes. Whereas, the seed direction to the crystal orientation of the substrate and an oblique angle between the scanning direction and the normal direction of the line beam are changed, in order to investigate the behavior of the subboundary.

In this paper, we characterize the properties of subboundaries and discuss the origin of these phenomena.

2. Experimental Procedure

In the sample preparation, 1μm-thick SiO_2 films were first deposited on Si(001) wafers using plasma-enhanced chemical vapor deposition(P-CVD) and were then etched in patterns of 50μm-wide oxide stripes and 5μm-wide seed stripes of bare Si. The stripes were aligned to <100>, <130>, or <110> axes of the substrate. After patterning, poly-Si films 0.6μm-thick were deposited by a vacuum evaporation method and finally capped by 0.5μm-thick P-CVD oxide films.

The schematic diagram of the electron beam annealing system used in this experiment is shown in Fig.1. An obliquely scanned pseudo-line electron beam was synthesized by scanning a spot beam with 400kHz sinusoidal signals which were applied to the X and Y electrostatic deflection plates. The acceleration voltage and the diameter of the spot beam were 10kV and 240μm, respectively. The pseudo-line beam was then scanned electromagnetically as a whole with velocities from 1mm/s to 10cm/s. The length of the pseudo-line beam was 450μm and the oblique angle θ was from 0° to 60° by changing the ratio of the X and Y amplitudes. In the recrystallization experiment, the samples were placed on a carbon holder kept at 500°C and the beam was scanned along the seed stripes on the

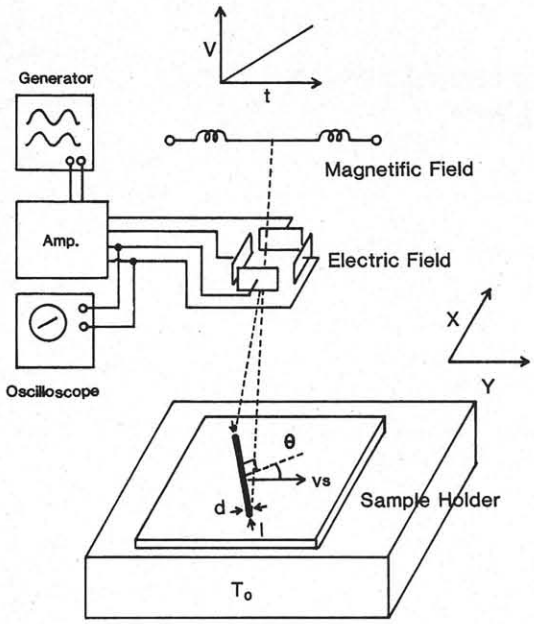

Fig.1 Schematic diagram of an electron beam annealing system.

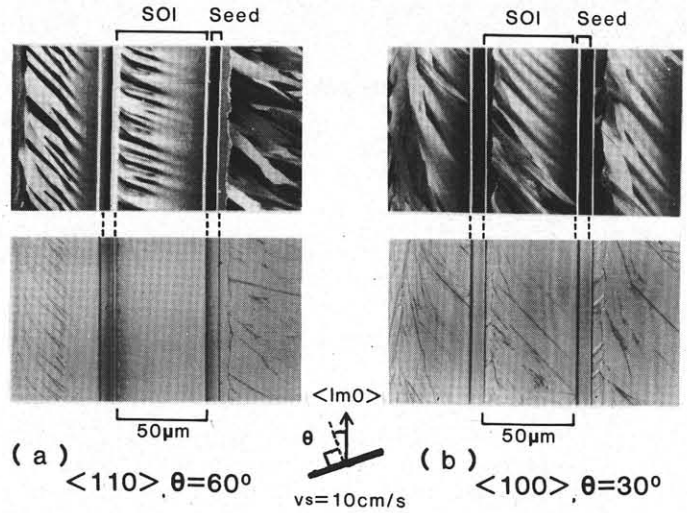

Fig.2 Electron channeling contrast micrographs of the recrystallized samples before Wright etching-(top) and Nomarski optical micrographs of the same area after etching(bottom). The samples were recrystallized at 10cm/s (a) along the <110> axis with the oblique angle of 60° and (b) along the <100> axis with 30°.

sample.

After recrystallization, the cap oxide was etched and the samples were dipped in Wright etchant to make the subboundaries in the Si films clear. The surface morphology of the samples was observed with Nomarski optical microscope and SEM.

3. Experimental Results

Figure 2 shows comparison of the electron channeling contrast micrographs(top) with the Nomarski optical micrographs taken after Wright etching(bottom) in the same areas. We can see from this figure that the subboundaries delineated by Wright etching match well with the channeling contrast image which reflects the difference of the crystal orientations. However, as shown in the center stripes in the figures, the contrast image also appears in the areas where no subboundaries were observed by optical microscopy. Since the channeling contrast is formed by fluctuation of the crystal orientations, these results suggest that even in the so-called subboundary-free area there exist a kind of subboundaries which are difficult to be delineated by Wright etchant.

Next, we consider the direction of subboundary and investigate the subboundary angle θ_b between a typical direction of the subboundary and the direction of the seed stripe. The relation between the oblique angle θ and the subboundary angle θ_b for the samples with <110> seed stripes is shown in Fig.3, in which each data point represents an average angle of 5 to 10 subboundaries in an SOI stripe and the solid line of $\theta_b = \theta$ corresponds to a situation that the subboundaries are generated perpendicular to the pseudo-line beam. Open and closed circles in the figure show the results for the hardly etched and easily etched subboundaries at a scanning velocity of 10cm/s, respectively. In case of 1cm/s, only open triangles are plotted, since it was difficult to distinguish easily etched subboundaries from hardly etched ones. As can be seen from the figure, the subboundary angle θ_b is proportional to the oblique angle θ at a scanning velocity of 1cm/s, which means that the subboundaries are perpendicular to the pseudo-line beam. On the other hand, the θ_b values at 10cm/s are concentrated around particular angles, independent of θ. The angles are about 45° for the easily etched subboundaries and about 80° for the hardly etched ones.

In order to understand the above phenomena further, similar experiments at a scanning velocity of 10cm/s were done using other samples with seed stripes parallel to <130> or <100> axes of the substrate. The results are summarized for easily etched subboundaries in Fig.4 which schematically shows the experimental outline for the scanning direction of [110], [130] and [010] axes,

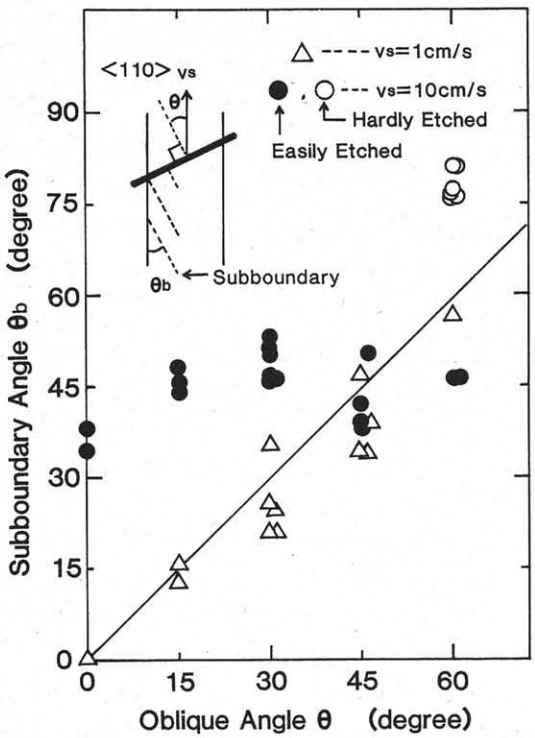

Fig.3) Relations between the oblique angle θ and the subboundary angle θ_b for the scanning velocities of 1cm/s(Δ) and 10cm/s(●○).

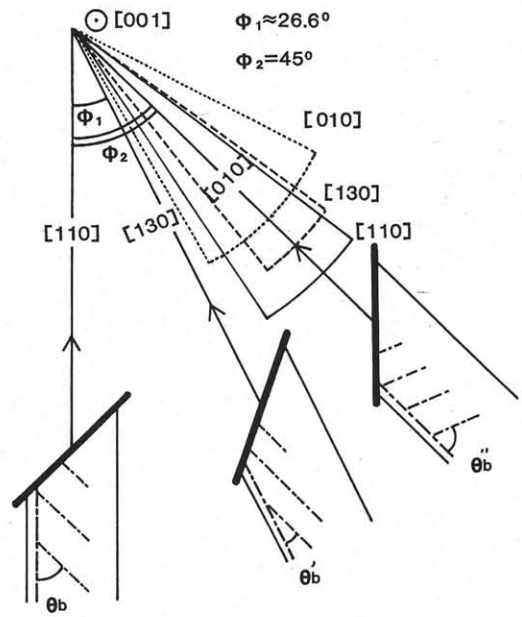

Fig.4 The schematic diagrams of experimental outline. The fun shape regions shown by the solid, dashed and dotted lines represent the extent of subboundaries for the seed directions of [110], [130] and [010]axes, respectively.

and the direction of subboundaries in recrystallized SOI films on the (001) substrate. In this figure, experimental results on the subboundary directions are also shown from a view point of crystallography as follows: the solid, dashed and dotted-line fun shape regions correspond to the extent of subboundary direction for the seed directions of [110], [130] and [010], respectively, in which the regions for [010] axis are reduced to the equivalent direction using four-fold symmetry of Si crystal. We can see from this figure that the easily etched subboundaries are mainly aligned to the <100> axis. It is interesting to note that at a scanning velocity of 10cm/s the directions of subboundaries are not determined by the oblique angle, but they are determined by the crystallographic orientation of the substrate. Also, the hardly etched subboundaries were found to be aligned around the <110> direction.

4. Discussion

It is well known that {111} facets are formed at the S-L interface and subboundaries are generated at the trailing corners of folded {111} facets[3]. Then, based on these informations, we discuss a few models in Fig.5 to explain the direction of easily etched subboundaries in our experiments. For simplicity, we assume that a line beam with infinite length is scanned along a [110] direction of a (001) substrate with an oblique angle θ and that step-like {111} facet planes are regularly formed in the region where the substrate temperature is in between T_m and $T_m-\Delta T_m$ as shown in Fig.5(a). When the pseudo-line beam is scanned by Δy, the {111} facet follows it as shown in Fig.5(a) using a broken line.

In the model(a), generation time of a nucleus on a flat plane is assumed to be much longer than the spreading time in which lateral growth originating from the nucleus is completed on that plane forming a new atomic layer. Thus, the growth rates $v_{//}$ along the [110] axis and $v_{\perp}$ along the [$\bar{1}$10] axis are proportional to the respective lengths of the facet planes[4] and subboundaries are so generated that the subboundary angle θ_b is equal to θ. This means that the subboundaries are generated perpendicular to the pseudo-line.

In the model(b), the generation time of nuclei is assumed to be much shorter than the spreading time. According to this model, $v_{//}$ is equal to $v_{\perp}$ and the direction of subboundaries is parallel to the [010] direction for any angle of

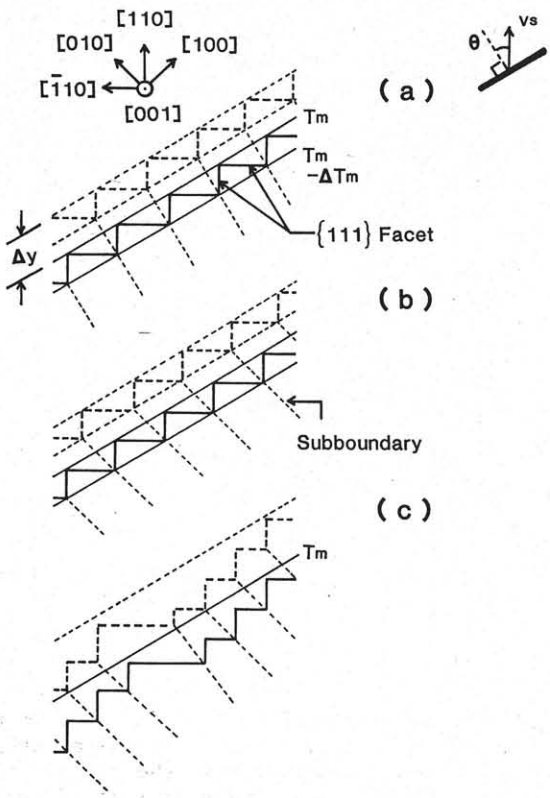

Fig.5 Schematic drawings of the {111} facet at the S-L interface and the directions of subboundaries. (a) Slow nucleation case (b) fast nucleation case and (c) saw tooth shape of the facet.

θ. However, we have no direct evidence that the nucleation rate is enhanced at faster scanning velocities as formation of microtwins in solid-phase epitaxy of amorphous Si[5].

An alternate approach to explain the direction of subboundaries is shown in model(c) which is the same as the model(a) except the equal length of each plate. Thus, the relation that $v_{//}=v_{\perp}$ holds and the subboundaries are aligned to the [010] direction. This saw tooth facet composed of {111} planes with equal length is considered to be energetically stabler than general {111} facets with asymmetric shapes at least under the dynamic condition, since it is often observed in the unseeded growth in ZMR. However, in this model, the facet front composed of the regular steps is always 45° off from the scanning direction of the beam and this angle generally does not coincide with the oblique angle θ. So, in order to explain this discrepancy, it is necessary to introduce irregular steps as schematically shown in Fig.10 (c). There is no direct experimental evidence to support this model. However, we speculate that at fast scanning velocities as 10cm/s, control of the S-L interface by the pseudo-line beam becomes weaker and the dynamically stable saw tooth facets are locally generated as well as irregular steps connecting them.

In conclusion, the models (a) and (c) seem to be appropriate to explain the directions of easily etched subboundaries in the slow and fast scanning cases, respectively.

5. Conclusion

We characterized the properties of subboundaries in SOI films recrystallized by an obliquely scanned pseudo-line electron beam. It was found in the samples with 50μm-wide SOI and 5μm-wide seed Si stripes that at a scanning velocity of 10cm/s, subboundaries generated in the SOI stripes were roughly aligned to the <100> or <110> directions of the substrate, while that at velocities lower than 1cm/s they were aligned normal to the pseudo-line beam. In order to understand these phenomena, simple models based on stability of the {111} facet at the S-L interface and controllability of the temperature profiles in the substrate by the pseudo-line beam were set up. We can expect from these and other results that the subboundary-free region will be expanded by the pseudo-line electron beam recrystallization in which the S-L interface is exactly matched to the <110> direction of the substrate and the thermal fluctuation during growth is so reduced that no facet corners are generated at the S-L interface. We will further discuss the above possibility.

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