Effects of Pattern Dimensions on Stabilization of Crystal Orientation for (111) Ge-on-Insulator in Rapid Melting Growth

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Effects of Pattern Dimensions on Stabilization of Crystal Orientation for (111) Ge-on-Insulator in Rapid Melting Growth

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Abstract: (111)-oriented Ge-on-insulator (GOI) is the key material structure for next generation multifunctional large scale integrated circuits. The (111) GOI structure can be implemented for high-speed transistor channels, as well as templates for the integration of optoelectronic and spintronic materials on the Si platform. The rapid melting growth technique is an effective way to obtain high-quality GOI structures on Si substrates. However, in formation of GOI strips (width: ~3 µm, thickness: 100 nm) from Si(111) seed, rotation of crystal orientation occurs along <112> growth direction. In this study, we investigate the effects of GOI pattern-dimensions on orientation stability and demonstrate the suppression of crystal rotation by narrowing the strip width. This enables the formation of (111) GOI strips with any growth direction.

Keywords: Germanium-on-insulator, Rapid-melting growth, Orientation-stabilized growth

1. Introduction

For further improvement of performance of large-scale integrated circuits (LSIs), intensive investigation is being performed to develop high mobility functional materials to replace Si.[1-6] The recent development of high quality and stable passivation layers on Ge has opened up the possibility to implement its high electron and hole mobility for the next generation LSIs.[7-9] Research has also been focused on the development of Ge-on-insulator structures, which is essential for the fabrication of high speed transistors.[2-4] For this purpose, control of the crystal orientation is necessary, since the maximum electron and hole mobility are orientation dependent. The (111) oriented Ge is needed for high-speed n-channel transistors, because the inversion layer mobility of electrons in Ge metal-oxide-semiconductor structures shows the maximum value on the (111) plane.[4] The (111) Ge is also necessary in multifunctional device integration, since it can be used as epitaxial templates for spintronic materials such as Fe_3Si.[10]

To develop the much needed GOI on the ubiquitous Si platform, the rapid melting growth (RMG) process has been developed, which enables lateral growth of microstructured GOI from Si substrates over insulating films.[11-23] We have made significant improvement in this technique and demonstrated the fabrication of chip length (~1 cm) single crystalline GOI strips (width: ~3 µm, thickness: 100 nm),[20] the formation of mesh structures,[18, 19] hybrid integration of (100), (110), and (111) GOI on a single chip,[21] and the fabrication of narrow-spacing strip arrays.[23] In the course of these experiments, we encountered the difficulty in orientation-control of (111) GOI. Here, rotation of the crystal orientation occurred for strips grown along <112> and nearby directions, whereas stable (111) oriented growth was achieved in <011> direction.[17,19] Such rotational growth was attributed to the weak bonding force between lattice planes along <112> which results in lattice plane slipping at the growth front.[17]

This difficulty in growth of (111) GOI strips along any direction severely limits the freedom of device design. In the present study, we investigate the growth characteristics of (111) GOI in order to develop a process for the stable growth along any direction. A strong influence of the strip dimensions (i.e. width and thickness) on the orientation stability is observed. It is clarified that orientation stability of (111) GOI along any direction is increased by narrowing of the strip width.

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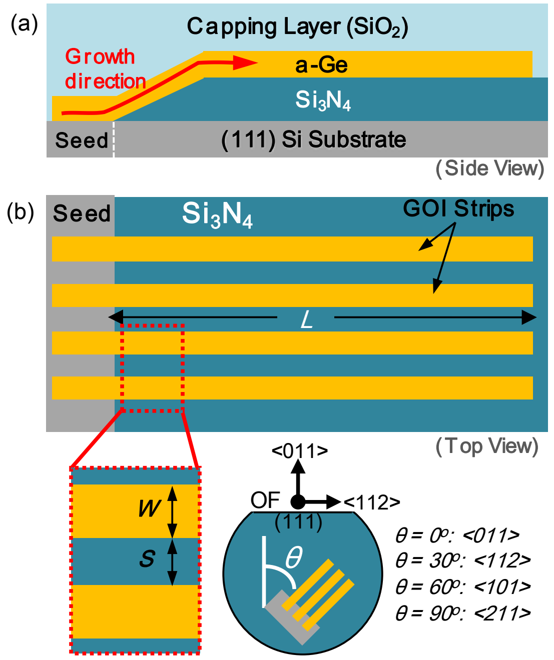

Fig. 1 Schematic cross-sectional (a) and plane views of sample (b). Explanation of growth directions is shown in (b).

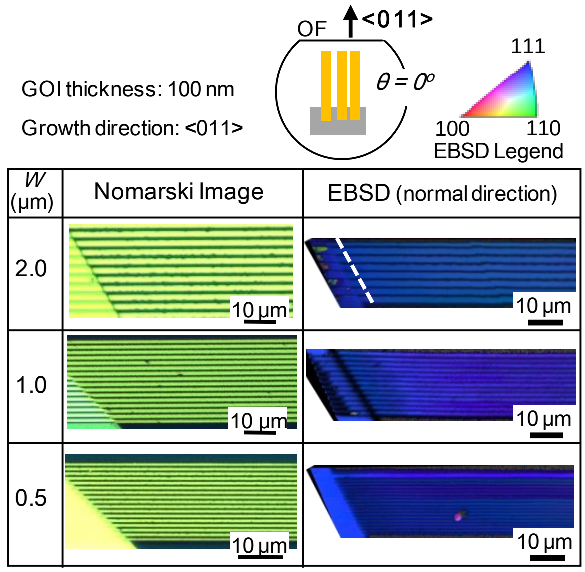

Fig. 2 Nomarski optical micrographs and EBSD images of 100-nm-thick GOI strips grown along <011>.

2. Experimental Procedure

The sample structure used for the rapid melting growth of the (111) GOI is shown in **Fig. 1(a)**. Seed windows were opened through the Si_3N_4 layer on Si(111) substrates by lithography and dry etching. The samples were cleaned using the RCA process to remove organic and metallic contamination. The a-Ge layers were deposited on these substrates at room temperature using a Knudsen-cell in a molecular beam epitaxy system under ultra high vacuum ($5x10^{-10}$ Torr). In-situ thermal cleaning at 550ºC was performed prior to the deposition. Patterning of the Ge layers into strip structures (width *W*: 0.5 – 2 μm, length *L*: 250 μm length, spacing *S*: 0.5 μm) was performed by electron beam lithography and reactive ion etching using CF_4. The schematic structure of the patterns is shown in **Fig. 1(b)**. In the schematic, θ is the angle between <011> of the Si substrate and the strip growth direction. Strips were fabricated with θ = 0º, 30º, 60º, and 90º corresponding to <011>, <112>, <101>, and <211> direction of the substrate, respectively. The a-Ge strips were capped with SiO_2 layers (thickness: ~800 nm). The melting growth was performed by rapid thermal annealing (RTA) at 1000ºC (1 sec).

3. Results and Discussion

3.1 Thick (~100 nm) (111) GOI Growth

Growth features were characterized by Nomarski optical microscopy and electron backscattering diffraction (EBSD). The results of the <011>-directed samples (*W*: 0.5-2.0 μm) are shown in **Fig. 2**. For all samples, completely (111)-oriented growth is achieved in the entire growth regions. This agrees with our previous work.[17] **Figure 3** shows the EBSD images obtained in the normal direction and growth direction of strips grown along <112> direction. As expected from our previous result,[17] gradual crystal misorientation along the strip length is observed in the normal-direction EBSD images for the wide strips (2.0 and 1.0 μm). Namely, the growth is initiated from the seed in the (111) orientation. However, the crystal orientation deviated from (111) after several micron growth. Examination of the EBSD images taken along different axis reveals that growth progresses with a rotation of the lattice planes along the <011> axis. The crystal rotation for growth along <112> was explained previously on the basis of the weak binding force between lattice planes at the growth front.[17] No such

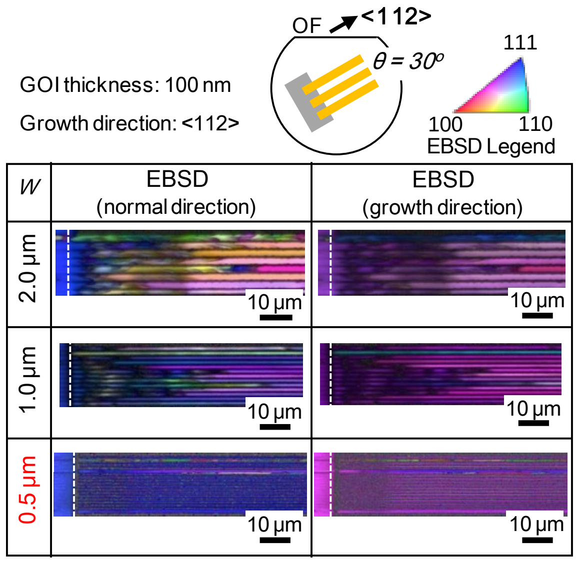

Fig. 3 EBSD images along normal and growth directions of 100-nm-thick GOI strips grown along <112>.

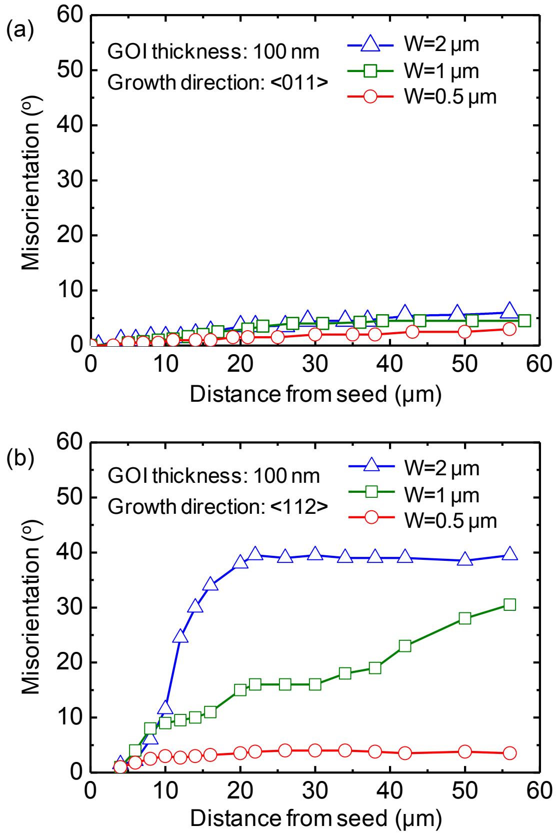

Fig. 4 Crystal misorientation profile for strips along <011> (a) and <112> directions with various strip widths (b).

rotation occur in <011> directed growth as shown in **Fig. 2**, because of the stronger bonding of the lattice planes in this direction. Interestingly, the degree of misorientation appears to decrease with decreasing strip width and seems to be completely suppressed.

To investigate the growth features quantitatively, the misorientation angle of strips grown along <011> and <112> were evaluated for different strip widths as a function of the distance from the seed edge. The results are summarized in **Figs. 4(a)** and **4(b)**, respectively. For growth along <011>, the misorientation angle is almost zero and does not increase for all strip width, as shown in **Fig. 4(a)**, which indicates completely orientation-controlled formation of (111) GOI along <011>. On the other hand, for growth along <112>, rotational growth occurs for wide strips, as shown in **Fig. 4(b)**. Namely, in the 2 μm-wide strip, the rotation rapidly increases and reaches ~40° at about 20 μm from the seed. In the 1.0 μm-wide strip, the onset of rotation appears to be slightly gentle, and the maximum misorientation of about 30° occurs at a distance of over 50 μm from the seed. This indicates an improvement of orientation stability over the 2 μm-wide strips. Moreover, the complete suppression of rotation is clear in the 0.5 μm-wide strips, where the misorientation is negligible and shows no increase at all. This trend of stabilization of growth orientation with decreasing strip width is very clear. These results demonstrate a successful method for the fabrication of (111) GOI with any growth direction. Although the physical mechanism of this stabilization is not clear, it is assumed that strain developed in Ge during solidification can affect such phenomena in the crystal growth.

3.2 Thin (~50 nm) (111) GOI Growth

For application to fully depleted transistors, the RMG process must be capable of producing very thin (~50 nm) GOI strips. To investigate the effects of Ge layer thinning on growth characteristics, ~50 nm thick GOI strip growth was performed from Si(111) seed. Similar to the previous experiments, 0.5, 1.0 and 2.0 μm wide strips were fabricated under the same processing conditions. The results of the <011> and <112> directed growth is given in **Fig. 5**. Surprisingly, the thinning of the Ge layer resulted in the appearance of misorientation even for the <011> direction. Crystal orientation measurement shows that the growth does

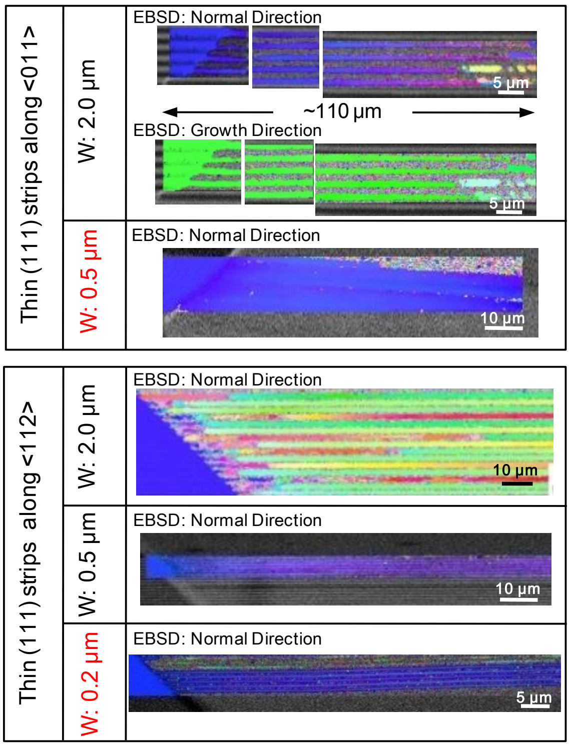

Fig. 5 EBSD images of 50-nm-thick (111) GOI strips.

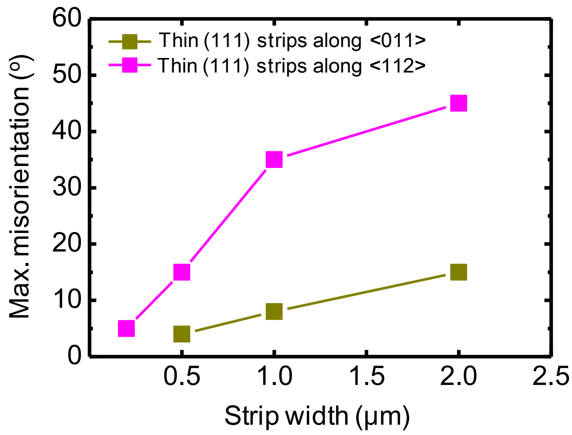

Fig. 6 Maximum crystal misorientation as a function of strip width for 50 nm thickness (111) GOI grown along <011> and <112>.

initiate from the seed and the orientation deviates gradually along with growth length. The EBSD images taken along the normal and growth direction of the strips indicated the misorientation results from rotation of crystal orientation along the <011> axis. This means the rotation process is similar to that seen in the 100-nm-thick (111) GOI strips (*W*: 1 – 2 μm) along <112>. Also similar to the thick (111) GOI, the stabilization of growth orientation appears to improve with decreasing strip width. Significant difference in the misorientation behavior is seen between strips along the <011> and <112> direction, where <011> directed growth appears more stable compared to <112> growth. The maximum values of misorientation observed at a growth distance of 50 μm are summarized in **Fig. 6**. In 2 μm-wide strips, the maximum misorientation from the seed orientation is about 45° in <112>-direction strips, while it is only about 15° in <011>-direction strips. Narrowing the strips resulted in reduction of misorientation for both directions. At the strips width of 0.5 μm, misorientation in the <011>-direction strips was almost completely suppressed. However, in the <112>-direction strips, a misorientation of about 15° is still observed.

The above trend indicates that further narrowing of the strip width can suppress the rotation in <112> direction strips completely. For this purpose, we fabricated thin GOI strips down to 0.2 μm width. Interestingly, as shown in **Fig. 5**, we see a complete suppression of rotation in these strips.

3.3 Guideline for (111) GOI Fabrication

The growth features obtained for stripes aligned to <011> and <112> directions are summarized as a function of strip width and Ge thickness in **Figs. 7(a)** and **7(b)**, respectively. For growth along <011>, (111)-oriented GOI (100 nm thickness) is obtained for all strip width. However, crystal rotation is observed for thin GOI (50 nm thickness) with wide strips (1-2 μm). Such orientation rotation phenomena are effectively suppressed by narrowing the strips (≤0.5 μm). On the other hand, for growth along <112>, crystal rotation occurs even for thick (100 nm) GOI with strips width of 1-2 μm. The rotation is suppressed for narrow stripes (≤0.5 μm). For thin (50 nm) GOI, orientation control is achieved only for strip width below 0.2 μm. It is noted that much more narrowing is necessary to realize complete orientation control along <112>, compared with <011>. This is attributed to the weak bonding of lattice planes of (112) growth fronts. Based on these findings of the effects of strip dimensions on orientation stability of GOI grown from Si(111) seed, a guideline for the fabrication of orientation-controlled (111) GOI structures has been quantitatively obtained.

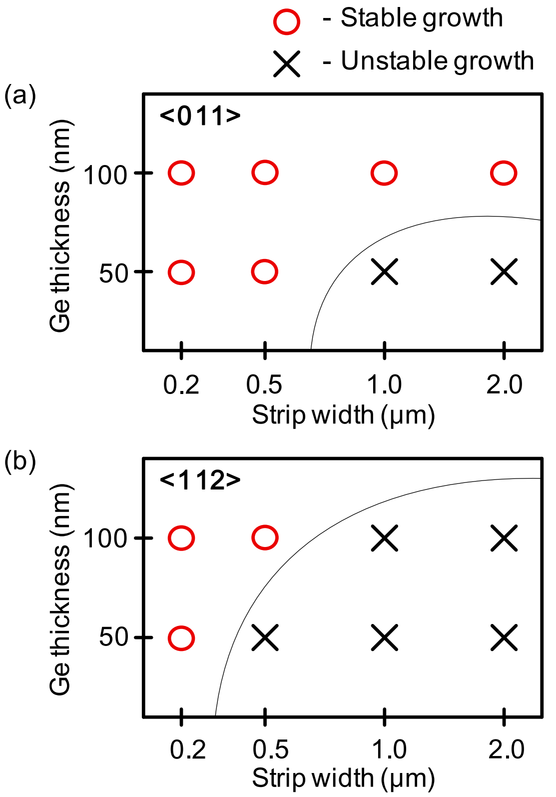

Fig. 7 Summary of (111) GOI growth stability dependence on Ge thickness and strip width for stripes aligned to <011> (a) and <112> (b).

4. Conclusions

The effect of stripe dimensions on the rapid-melting growth characteristics of GOI from Si(111) seed has been investigated. Crystal orientation becomes unstable by thickness reduction of the Ge layer. In addition, growth along <112> direction is more unstable compared to <011>-direction growth. Such instability of crystal orientation is completely suppressed by strip narrowing, where much more narrowing is necessary for <112> compared to <011>. Based on these results, a guideline for growth of orientation-controlled (111) GOI structures have been clarified. This technique facilitates next-generation LSIs, where multi-functional devices are integrated on the Si platform.

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