Orientation Stabilized Rapid Melting Growth of Thin (100) Ge-on-Insulator Structures and Their Implementation in Homoepitaxial Growth

Anisuzzaman, Mohammad
Department of Electrical and Electronic Engineering, Graduate School of Information Science and Engineering, Kyushu University : Graduate Student

Muta, Shunpei
Department of Electrical and Electronic Engineering, Graduate School of Information Science and Engineering, Kyushu University : Graduate Student

Hashim, Abdul, Manaf
Department of Electronics, Faculty of Information Science and Engineering, Kyushu University

Sadoh, Taizoh
Department of Electronics, Faculty of Information Science and Engineering, Kyushu University

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Orientation Stabilized Rapid Melting Growth of Thin (100) Ge-on-Insulator Structures and Their Implementation in Homoepitaxial Growth

Mohammad ANISUZZAMAN*, Shunpei MUTA*,
Abdul Manaf HASHIM** and Taizoh SADOH**

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Abstract: Integration of Ge on the Si platforms is essential for the development of next generation large-scale integrated circuits. The Ge-on-insulator (GOI) structure is suited for the realization of high-mobility transistors channels and as epitaxial templates for optoelectronic and spintronic materials. In this work, the fabrication of thin (~50 nm) (100) GOI by the rapid melting growth process has been investigated. Growth with unstable crystal orientation has been observed in wide (≥1 μm) GOI strips. However, orientation stabilized growth was achieved in narrow strips (~0.5 μm). Further stabilization of growth orientation was observed in mesh patterned growth with GOI width of 1 μm. Epitaxial growth of Ge was performed on the above structures and the formation of uniform epitaxial layer was demonstrated.

Keywords: Ge-on-insulator, Rapid-melting growth, Crystal-orientation control, Homoepitaxial template, Homoepitaxial growth

1. Introduction

Severe limitation is being imposed on the performance improvement of Si based microprocessors because of short channel effects. To continue the increase of processing power, it has become imperative to implement alternative materials with higher carrier mobility than Si.[1] Ge and III-V compound semiconductor materials are candidates for the replacement of Si. Ge is of particular importance because of its compatibility with the Si complementary metal-oxide-semiconductor (CMOS) processing techniques and also offer a balanced improvement of both electron and hole mobility over Si compared to III-V semiconductors.[2] The Ge-on-insulator (GOI) structure can significantly improve the performance of extremely scaled transistor by reducing the short channel effects.[3-5] GOI structures are also excellent buffer layer for the epitaxial growth of optoelectronic (*e.g.* GaAs) and spintronic (*e.g.* Fe_3Si) materials.[6,7]

In order to develop a Si platform compatible Ge CMOS process, we developed the lateral rapid melting growth (RMG) process to fabricate high quality single crystalline Ge-on-insulator (GOI) on Si substrates.[8-15] The general sample structure is illustrated in **Fig. 1(a)**. We have demonstrated the formation of GOI strips (~3 μm width) with length over 400 μm, where the crystal orientation follows that of the Si substrate. The state of the art of semiconductor processing requires the formation of fully depleted channels to prevent performance degradation by short channel effects. In order to fabricate fully depleted germanium-on-insulator (FD-GOI), the RMG process must be capable of producing very thin (<50 nm) GOI strips. In our recent work, we have demonstrated the fabrication of (100) oriented GOI strips with various thicknesses (20 – 100 nm).[16] It was shown that GOI strip thickness less than 50 nm tend to become unstable and random rotation of the crystal orientation along the growth direction is observed. However the work focused on wide strips. The growth characteristics of narrow strips and mesh patterns in thin GOI were not investigated. In this work, we demonstrate the stabilization of crystal orientation of thin GOI in the rapid melting growth process by strip width narrowing and also by forming mesh structures. We also demonstrate the feasibility of using the GOI structures as templates in the growth of uniform homo-epitaxial Ge layer.

2. Experimental Procedure

We used Si(100) substrates with an insulating top layer of 100 nm thick Si_3N_4. Seed windows were opened on to the insulator layer by lithography and dry etching. It was found that attempts to perform melt growth of

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* Department of Electrical and Electronic Engineering, Graduate Student
** Department of Electronics

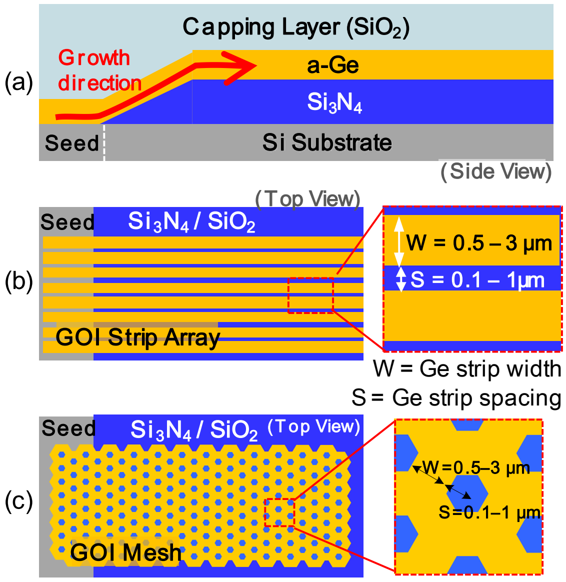

Fig. 1 Sample structure as prepared for growth (a), schematics of GOI strip array (b), and mesh (c).

GOI with thickness smaller than the insulator layer results in breaking at the seed edge. To prevent such breaking, the seed windows were made with a 30^{o} sloped edge that allowed growth continuation of the thin GOI over the seed edge. The samples were cleaned to remove metallic and organic contaminants and subsequently HF treated to leave a hydrogen passivated Si surface at the seed area. Amorphous Ge (thickness: 50 nm) was deposited at room temperatures in a molecular beam epitaxy (MBE) system at a base pressure of about 5×10^{-10} Torr. Prior to deposition, in-situ thermal cleaning was performed at a temperature of 550^{o}C for 20 min. Post-deposition thermal annealing was performed in the MBE chamber at 300^{o}C under the same vacuum condition.

Two types of GOI patterns were fabricated for investigation – (i) strip-arrays (width, W = 0.5 – 2.0 μm, spacing, S = 0.1 – 1.0 μm) as shown in **Fig. 1(b)**, and (ii) hexagonal mesh patterns (W = 0.5 – 3 μm, S = 0.2 – 1 μm) as shown in **Fig. 1(c)**. The patterns were created using electron beam lithography and transferred onto the GOI layer by dry etching. After patterning the a-Ge layer, a capping layer of SiO$_2$ (~800 nm) was deposited using magnetron sputtering to contain the Ge during the melting growth. The growth was performed by rapid thermal annealing (980^{o}C, 1 sec) in N$_2$ environment. The crystal orientation of the structures was evaluated by electron backscattering diffraction spectroscopy (EBSD).

Homoepitaxial growth of Ge films on the GOI strips and mesh structure was carried out in the MBE system. To remove contaminants, O$_2$ plasma ashing and HF treatment of the samples were performed followed by in-situ thermal cleaning prior to the epitaxy. The growth temperature was kept at 300^{o}C with a Ge deposition rate of 0.01 nm/sec. Scanning electron microscopy (SEM) and electron backscattering diffraction (EBSD) measurements were performed to investigate growth morphologies and crystal orientations of the epitaxial layers.

3. Results and Discussion

3.1 Characteristics of Thin (100) GOI Strips

In the efforts to fabricate thin (50 nm) GOI strip arrays, reliable growth was possible with a minimum strip spacing of 0.5 μm, whereas spacing smaller than 0.5 μm resulted in agglomeration of the strips due to weakening of the capping layer. The Nomarski micrograph of **Fig. 2(a)** shows a typical strip array with

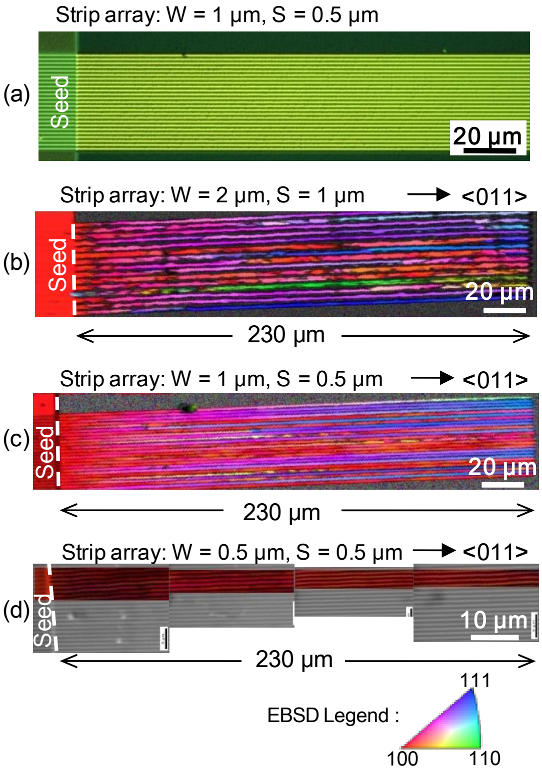

Fig. 2 Nomarski optical micrograph of a GOI strip array (a), z-plane EBSD images of 2 μm (b), 1 μm (c), and 0.5 μm (d) wide strip arrays after rapid melting growth.

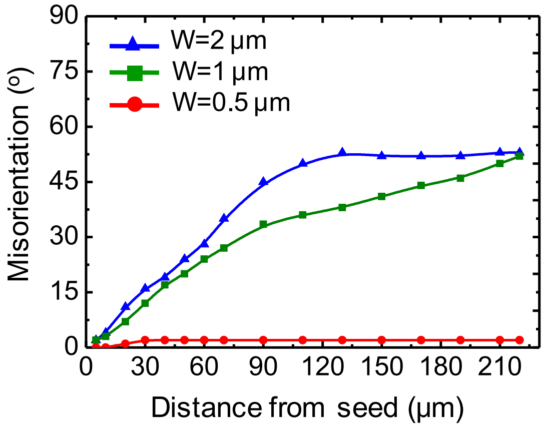

Fig. 3 Misorientation angle of GOI strips from (100) orientation as a function of distance from the seed edge for different strip widths.

W = 1um and S = 0.5 µm. **Fig. 2(a), (b), and (c)** show the EBSD measurement results obtained from strip arrays of W =2 µm (S = 1 µm), W = 1 µm (S = 0.5 µm), and W = 0.5 µm (S = 0.5 µm), respectively. It is evident from the color coded EBSD images that in the case of 2 and 1 µm wide strips crystal growth initiates from the Si seed in (100) orientation but goes through gradual rotation as the growth propagates along the strip lengths. The crystallographic misorientation from the seed orientation in the worst case scenario as a function of distance from the seed edge is plotted in **Fig. 3**. It is found that similar behaviors are obtained in 2 and 1 µm wide strips, where both cases result in a maximum misorientation of about 50°. However, the growth in the 0.5 µm wide strips seems to without any rotation at all and maintains the crystal orientation of the Si seed. The physical process for the appearance of rotational growth in thin GOI strips and it's suppression by narrowing is not well understood.

Homoepitaxial growth was performed on the strip array with the narrowest spacing (0.5 µm). The result is show in **Fig. 4(a)**, where we can see the growth morphology at growth thickness of 250 and 550 nm. At 250 nm epitaxy, the growth can be observed by the change in width of the strips, although the growth facets are not clearly visible. Some island formation was observed in the spaces among strips. We can see that the closing of the gaps is necessary for forming a uniform epitaxial layer. At 550 nm growth, the crystal facets are clearly visible. Also, island formations in the gaps appear to be overtaken by epitaxial growth. The EBSD measurement, shown in **Fig. 4(b)**, indicated (100) orientation all over the array. The expected growth features are schematically shown in **Fig. 4(c)**. However, even at 550 nm thickness, the still remaining gaps indicate that much thicker growth is needed to for a uniform epitaxial-layer. To achieve better uniformity of the epitaxial-layer at a reasonable thickness, we tried mesh structured growth. This is described in the next section.

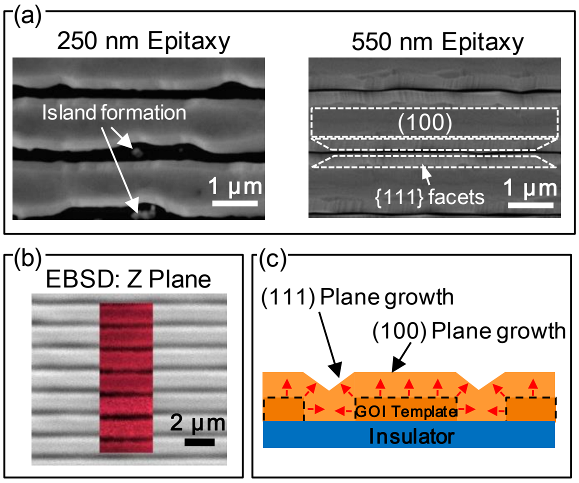

Fig. 4 SEM images of 1 µm side strips (S = 0.5 µm) after 250 and 550 nm homoepitaxial growth (a), schematic representation of the epitaxial growth process form template (b), and EBSD image of strips at 550 nm homo-epitaxial growth (c).

3.2 Characteristics of Thin (100) GOI Mesh

Recently, Yokoyama et al. reported self-organized formation of (100)-oriented GOI network template.$^{17)}$ In the results, rotation of crystal orientation was not observed even for thin Ge layer thickness (50 nm). This report triggers an idea that orientation stabilization of thin GOI also becomes possible by employing mesh-patterned Ge layers. The Nomarski micrograph and the EBSD images the minimum spacing mesh (W = 0.5 µm, S = 0.2 µm) and a wide spacing mesh structure (W = 1 µm, S = 1 µm) are shown in **Fig. 5(a) and (b)**, respectively. Whereas in the case of strip arrays the minimum spacing was limited to 0.5 µm, in the hexagonal mesh structures reliable growth was obtained with a minimum spacing of 0.2 µm and an arm width of 0.5 µm. The network structure with 0.5 µm arm width shows (100) orientation in the entire area. This result

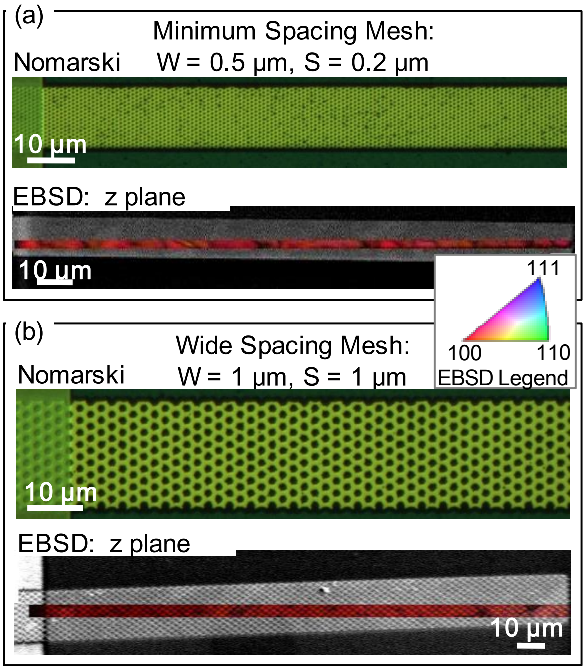

Fig. 5 Nomarski and EBSD images of the minimum spacing mesh (a) and a wide spacing mesh (b) after rapid melting growth.

agrees with those of the previous section. Moreover as expected, it is observed that the growth of 1 μm feature width mesh network is obtained without any significant rotation in orientation. This contradicts with the growth of 1 μm width strips, where significant misorientation (~50^{o}) was observed. It is assumed that the periodic merging of the growth front can work in favor of stabilizing the growth process by suppressing rotation.

Molecular beam homoepitaxy was performed on the mesh templates under similar conditions as in case of strip arrays. **Figure 6** shows the SEM images of the growth features on the minimum spacing mesh (W = 0.5 μm, S = 0.2 μm) and a wide spacing mesh (W = 0.5 μm, S = 0.5 μm) at growth thicknesses of 300, 550 and 800 nm. At 300 nm growth thickness the coverage of the spaces in the template appear more uniform in the minimum-spacing mesh than the wide-spacing one, although, the faceted growth is still not apparent. At 550 nm growth thickness, the minimum spacing mesh shows complete filling of the gaps and the faceted growth is clearly visible. Growth facets are visible in the wide spacing mesh also, however, the gaps still appear unfilled. At a further growth to 800 nm thickness the minimum spacing mesh appears significantly uniform and the growth facets almost disappear, giving a rather smooth (100) plane. EBSD measurements at this stage show (100) orientation and no polycrystalline grains could be detected. On the wide-spacing mesh, the template gaps are seen to have been filled. EBSD measurement showed a uniform (100) orientation. These results demonstrate the feasibility of using the thin (100) GOI mesh patterned templates to obtain uniform (100) oriented epitaxial Ge layer on insulator.

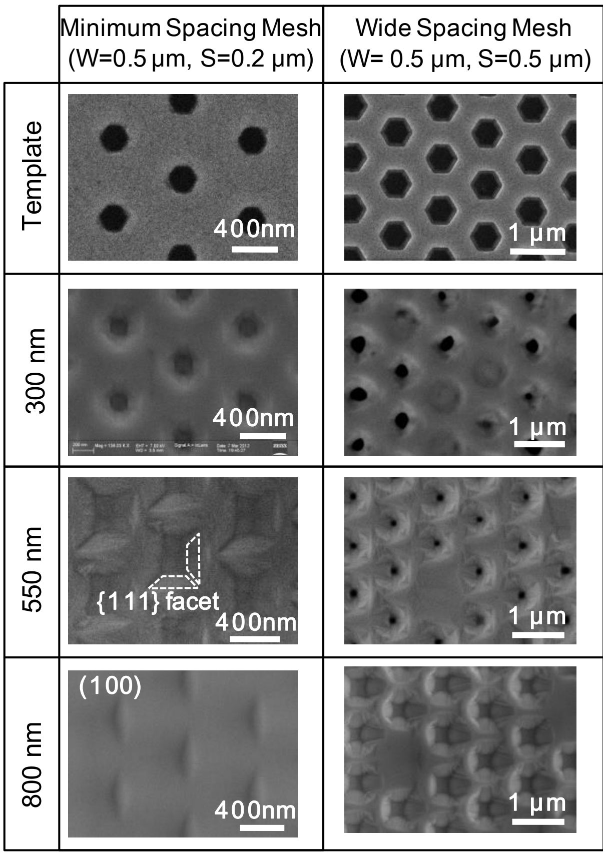

Fig. 6 SEM images showing the surface morphologies of hexagonal epitaxial templates and after homoepitaxial growth of 300, 550 and 800 nm thickness.

4. Conclusions

The rapid melting growth characteristics of thin (~50 nm) (100) GOI in strip array patterns were investigated with a view to suppress the rotational growth. It was found that narrowing the strip width down to 0.5 μm resulted in complete suppression of rotation during growth. As a result, rotation free growth of thin GOI becomes possible. Use of the minimum spacing strip arrays (S = 0.5 μm) as homoepitaxial templates was shown not satisfactory. Hexagonal mesh network of thin (100) GOI was fabricated in an effort to obtain a better epitaxial template. Interestingly, it was found that orientation stabilized growth of wide feature width (W = 1 μm) is possible in the mesh network. Homoepitaxial growth on the minimum spacing mesh (W = 0.5 μm, S = 0.2 μm) obtained a uniform (100) oriented epitaxial-layer with a relatively smooth surface. These results demonstrate the high potential of the rapid melting grown GOI structures in developing the next generation LSI.

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