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Laterally Graded SiGe-on-Insulator with Universal Si Profile by Cooling-Rate-Controlled Rapid-Melting-Growth

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1. Introduction

Integration of new functional devices on Si-LSI is essential to break through the scaling limit of Si-CMOS performance. The laterally graded SiGe-on-insulator (SGOI) structure is a big candidate for this purpose, because it provides epitaxial template with laterally graded lattice constants. This enables 2-dimensional integration of optical and spintronic materials, such as GaAs, GaInAsP, Fe_3Si, and CoS_2 with various lattice constants.

Recently, we developed SiGe-mixing-triggered rapid-melting growth, which achieved defect-free single-crystal GOI stripes (~400 μm) [1]. By applying this method to the crystallization of a-SiGe, we observed Si segregation phenomena during the melt-back process [2]. To achieve laterally graded SiGe epitaxial template, Si segregation features should be clarified and controlled.

The present study investigates Si segregation kinetics during rapid-melting growth of a-SiGe. Universal SiGe lateral-profiles are obtained by optimizing cooling-rate, which enables graded SGOI with controlled Si profiles.

2. Experiments

Si(100) substrates covered with Si_3N_4 films (100 nm thick) were employed. The Si_3N_4 films were locally removed to form seeding areas. Subsequently, a-$Si_{0.15}Ge_{0.85}$ layers (100 nm thick) were deposited by molecular beam technique and patterned into narrow stripes (width: 3 μm) with a wide range of stripe length (L: 10-500 μm). The sample structure is illustrated in Fig. 1(a). Then, SiO_2 capping layers were deposited. Finally, the samples were heat-treated (1200°C, 1 s) by RTA to induce melting growth from seeding areas. The cooling rate after RTA was selected from a wide range of 10-19°C/s.

3. Results and Discussions

Crystal orientation of the grown SGOI was evaluated by electron backscattering diffraction (EBSD). The result indicates (100)-oriented single crystal in the whole region, as shown in Fig. 1(b). Moreover, transmission electron microscopy (TEM) observations revealed no defects in the grown layers, as shown in Fig. 1(c).

Si concentration profiles in SGOI (L: 10-500 μm) evaluated by μ-Raman spectroscopy (spot size: ~1 μmϕ) are shown in Fig. 2, where cooling rate after RTA was fixed to 17°C/s. For all samples, Si concentrations at the seeding edges are ~45% and decrease with increasing growth distance (x), reaching ~0% around stripe edges. However, the detailed features are different depending on L. Namely, for L=10-200 μm, Si concentrations decrease monotonically. This results in the Si profiles consisting of single falling curves. On the other hand, for L=300-500 μm, the Si profiles consist of double falling curves.

To analyze Si segregation kinetics for L=10-200 μm, Si profiles are plotted as a function of the distance normalized by the stripe length (x/L) in Fig. 3(a). All profiles can be fitted with an identical curve, which was calculated based on the segregation theory. Here, we assume that the length of melting SiGe regions is so short that segregated Ge atoms distribute uniformly in melting regions due to sufficient Ge diffusion. The segregation coefficients obtained by fitting are indicated by closed circles in Fig. 3(b), which agree well with those evaluated from the SiGe phase diagram shown by the broken line.

Si profiles for L=300-500 μm are re-plotted in Fig. 4(a). As described above, the Si profiles can be divided into two falling curves. The observation of the first-falling curves suggests that the length of melting SiGe regions is too long to realize uniform Ge distribution in the melting region as far as the growth fronts exist in the first-falling regions. On the other hand, Ge distributions become uniform, when the length of the melting SiGe become short, namely growth fronts approach the stripe edges. This results in the appearance of the second-falling curves. Interestingly, the length of the second-falling regions (ΔL) decreases with increasing L, as shown in Fig. 4(a). From these results, it is speculated that growth rates increase with increasing L.

To examine this speculation, ΔL is summarized as a function of L in Fig. 4(b). In the figure, the results for various cooling rate (13-19°C/s) are plotted. It is found that ΔL decreases with increasing cooling rate. Since the growth rate increases with increasing cooling rate in melting growth, this clearly indicates that ΔL decreases with increasing growth rate. This supports our speculation that growth rates near stripe edges, i.e., in the second-falling regions, are higher for longer L. From these results, it is expected that ΔL approaches L by further decreasing cooling rate. In other word, the deviation of the Si profiles from the theoretical curve is expected to disappear by further decreasing the cooling rate.

To examine this, cooling rate was decreased to 10°C/s. Si profiles of samples (L=10-500 μm) are shown in Fig. 5. It is found that all profiles consist of single-falling curves. To analyze the kinetics, the profiles are plotted as a function of x/L in Fig. 6. Interestingly, this shows that all profiles can be fitted with an identical theoretical curve. This shows that laterally graded SGOI with a universal Si profile has been realized for a very wide range of L (10-500 μm). Consequently, the lateral gradient of lattice constants can be preciously controlled by tuning L.

4. Summary

Si segregation kinetics in the rapid-melting growth of a-SiGe are significantly affected by the cooling rate. By controlling the cooling rate, laterally graded SGOI with a universal profile has been realized. This is a powerful technique to achieve epitaxial template with laterally variable lattice constants for 2-dimensional integration of multi-functional devices on Si-LSI.

References

1. M. Miyao et al., Appl. Phys. Express **2**, 045503 (2009).
2. T. Tanaka et al., Appl. Phys. Express **3**, 031301 (2010).

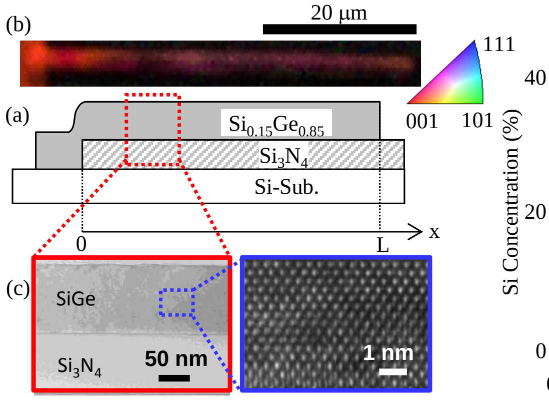

Fig. 1 (a) Cross-sectional structure of sample, (b) TEM and (c) EBSD images of SGOI (L = 50 μm).

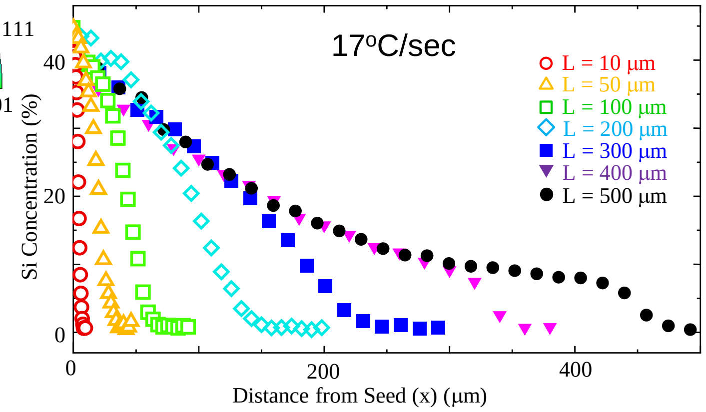

Fig. 2 Si concentration profiles in SGOI for L=10-500 μm (cooling rate: 17°C/s).

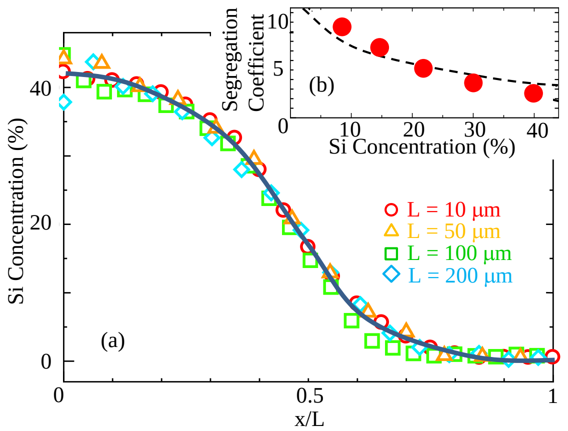

Fig. 3 (a) Si profiles for L=10-200 μm as a function of x/L and (b) Si-concentration-dependent segregation coefficient. The closed circles and broken line in (b) show the coefficient obtained from fitting and SiGe phase diagram, respectively.

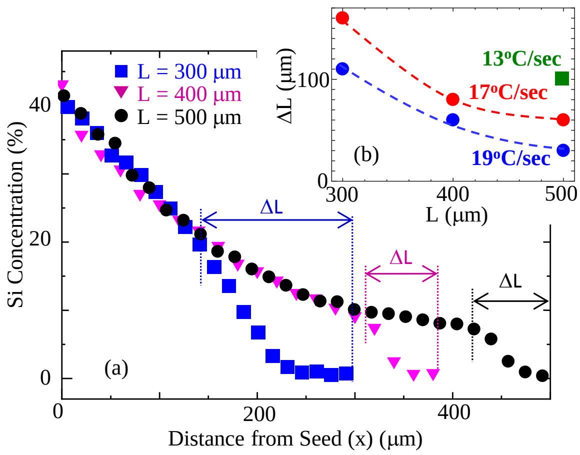

Fig. 4 (a) Si concentration profiles for L=300-500 μm (cooling rate: 17°C/s) and (b) ΔL as a function of L (cooling rate: 13-19°C/s).

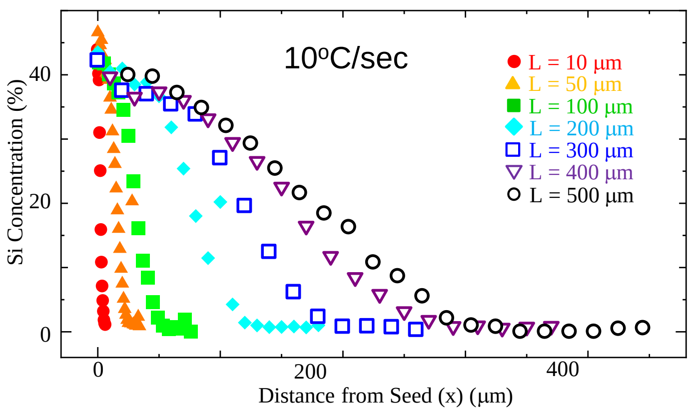

Fig. 5 Si concentration profiles in SGOI for L=10-500 μm (cooling rate: 10°C/s).

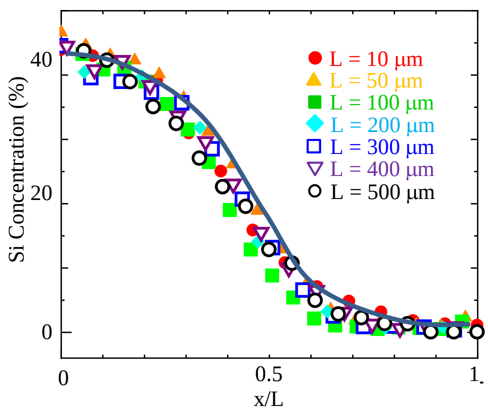

Fig. 6 Si concentration profiles for L=10-500 μm as a function of x/L (cooling rate: 10 °C/s).