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Single-Crystalline (100) Ge Stripes with High Mobilities Formed on Insulating Substrates by Rapid-Melting-Growth with Artificial Single-Crystal Si Seeds

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1. Introduction

High carrier mobility in the single-crystalline Ge is very attractive for thin-film transistors (TFTs) with ultra-high speed operation. Recently, we developed the rapid-melting-growth of amorphous Ge (a-Ge) on quartz substrates by employing the polycrystalline Si (poly-Si) islands as growth seeds [1, 2]. This realized giant single crystal Ge stripes (400 μm length) on quartz substrates. However, crystal orientations of the Ge stripes were distributed into (100), (110), and (111) directions reflecting the poly-Si seeds. Such random distributions of the crystal-orientations should be controlled to achieve high-speed Ge-channel TFT arrays with controlled threshold voltage.

In the present study, the Ge-growth features of the Si-substrate-free rapid-melting process are clarified by investigating their distributed crystal orientation statistically. Based on this knowledge, rapid-melting-growth is combined with the Si (100) micro-seed technique, recently developed by our group [3]. This achieves (100) orientation-controlled Ge stripes on quartz substrates.

2. Experimental Procedures

Amorphous Si (a-Si) (100 nm thickness) films were deposited on quartz substrates by using a molecular beam epitaxy (MBE) system. After poly-crystallization by furnace annealing (650^{o}C, 15 h), they were patterned by wet etching to form island areas, which were used as the seed for lateral growth. Subsequently, a-Ge layers (100 nm thickness) were deposited using the MBE system, and they were patterned into narrow stripe lines (400 μm length, 3 μm width), as shown in Fig.1 (a). Then SiO_2 films (800 nm thickness) were deposited by RF magnetron sputtering. Finally, these samples were heat-treated by rapid thermal annealing (RTA) at 1000^{o}C (1 s) to induce the rapid-melting growth.

3. Results and Discussion

Typical EBSD images of Ge-on-insulator (GOI) stripes grown from poly-Si seeds are shown in Fig. 1(b). Two types of growth morphology were found. Namely, some Ge stripes keep a constant orientation of the (100) plane in the whole length of 400 μm (Fig. 1(b)), others gradually change their orientations from (111) to (101), and finally to the (100) plane (Fig. 1(c)).

The fractions of crystal orientations in poly-Si grains, Ge grown-layers near (~10 μm) the seeding edges, and Ge at the growth edge (~350 μm away from the seed) are shown in Figs. 2(a), 2(b), and 2(c), respectively. Dynamical-change in crystal orientations in each Ge stripe during lateral growth is also examined for many samples. They are summarized in Fig. 2(d) as a function of the distance from the Si-seed. In these figures, the crystal orientations within 15^{o} from the exact (100), (101), and (111) orientations are classified into (100), (101), and (111) groups.

These results show that the orientation distributions of Ge layers near the Si-seed (Fig. 2(a)) quite agree with those of poly-Si islands (Fig. 2(b)). This indicates that one of the crystal-grains in the poly-Si island incidentally acts as the seed to cause the rapid-melting growth of the Ge stripes. On the other hand, the orientation distributions of Ge at the growth edge (Fig. 2(c)) show that as many as 70% of Ge layers are oriented to the (100) plane and the rest to the (101) plane. Results shown in Fig. 2(d) clearly indicate that the randomly distributed crystal-orientations in the initial stage gradually converge to the (100) plane through (101) plane. Since the interfacial free energy is the lowest between (100) Ge and SiO_2 layers, the (100) plane is considered to become dominant at the final stage in growth to minimize the interfacial energy [4].

The fact that all Ge initiated with the (100) plane continuously grows with keeping its orientation is particularly worth noting. This triggers the idea of advanced rapid-melting growth method combined with the (100) Si micro-seed technique. Very recently, we have developed the interfacial-oxide modulated aluminum-induced crystallization (AIC) method, which achieved the formation of (100) Si crystal-grains on quartz substrates [3]. Such (100) Si crystal-grains are the candidate to be used as artificial single-crystal seed for the rapid-melting Ge growth. The EBSD image of the Ge stripe grown with the (100) Si seed is displayed in Fig. 3(a), which exhibits the (100)-oriented single crystal Ge growth in the whole region. This results demonstrate that the epitaxial growth of a-Ge is initiated from the (100) Si micro-seed and propagates for 400 μm with keeping its orientation. TEM observation reveals no-defects in the lateral growth regions (Fig. 3(b)). The electrical characteristics of Ge stripes are also evaluated as a function of distance from Si seed by measuring the temperature dependence of the electrical conductivity (Fig. 3(c)). This demonstrated the high hole mobility over 1000 cm^2/Vs in whole growth regions.

4. Conclusions

Crystal orientations of Ge stripes obtained by the Si-substrate-free rapid-melting-growth method, where poly-Si islands are used as growth seeds, have been examined comprehensively. Statistical studies have clarified that the Ge growth starting with (100) orientation is the key point to achieve the orientation-controlled Ge lateral-growth on insulating substrates. This has triggered the development of the advanced rapid-melting growth method combining with the Si (100) micro-seed technique. As a result, single-crystal (100) Ge giant-stripes with 400 μm length have been achieved on insulating substrates, which demonstrate high hole mobility exceeding 1000 cm^2/Vs. This orientation-controlled rapid-melting growth method opens up the possibility of high performance TFTs with high mobility Ge channel and controlled threshold voltage.

References

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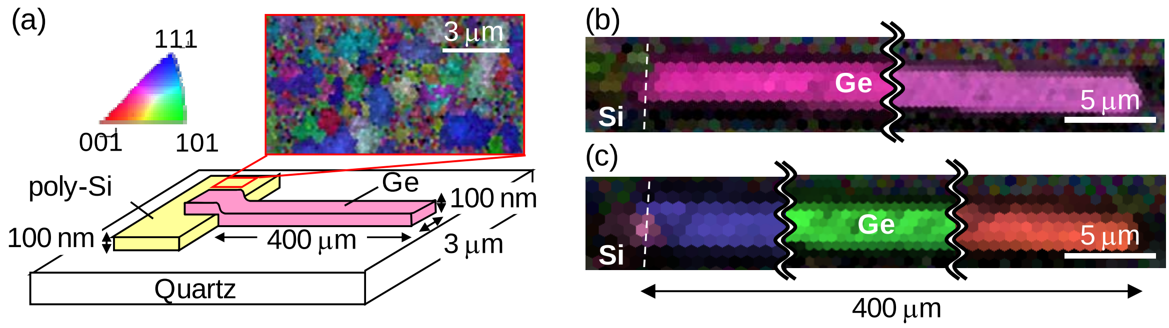

Fig.1 Schematic structure of the sample with poly-Si seeds (a), and typical EBSD images of melt-grown GOI with a constant orientation (b) and changing orientations (c). An EBSD image of poly-Si seed is also shown in the insert of (a).

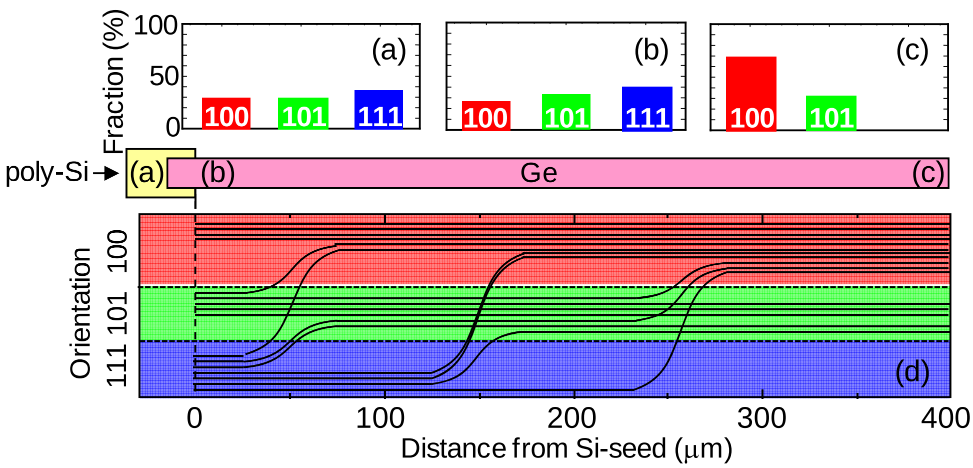

Fig.2 The orientation distributions in the poly-Si seed (a), GOI near the seed (b), and GOI at the growth edge (c). Change in orientations of GOI samples as a function of distance from Si-seeds (d).

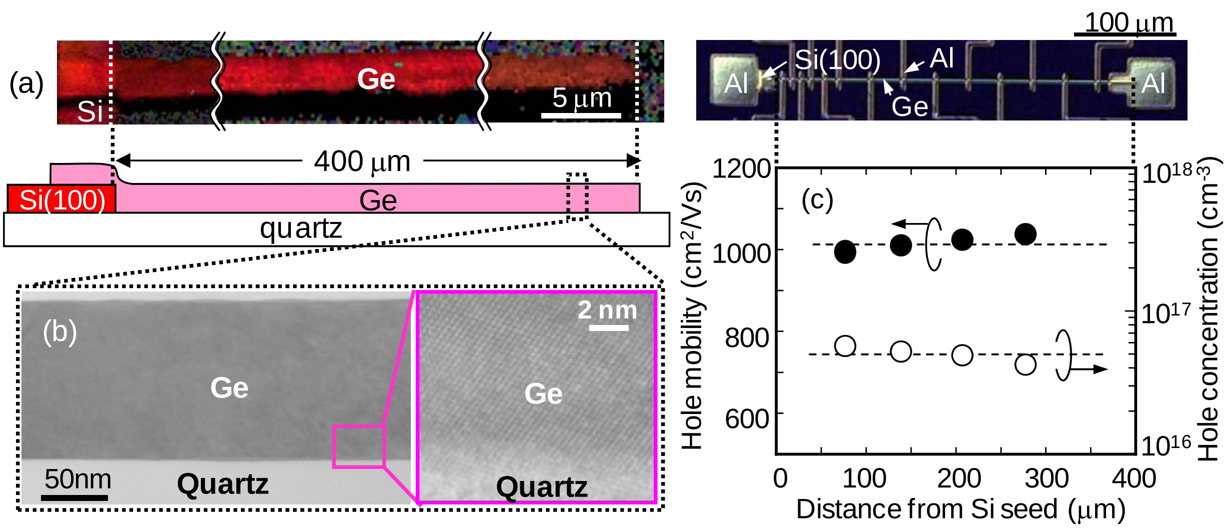

Fig.3 EBSD image (a), cross-sectional TEM images (b), and the growth length dependent electrical properties (c) for the GOI sample grown with the artificial-Si(100) seed.