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Phosphorus Mediated Growth of Ge Layer on Si(001) Substrate

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1. Introduction

As a post-scaling material, Ge is expected to be used for high-speed field effect transistors, quantum-effect devices, and electronic optical devices. And the usage of a Ge layer on a Si substrate has advantages in terms of cost and integration with Si devices compared to the use of a Ge substrate. To form a flat Ge layer on Si substrate, a SiGe buffer layer method was reported that is used for relaxation of lattice mismatches between Si and Ge [1]. And surfactant mediated growth methods or low temperature growth methods were also reported that are used for suppression of Ge surface migration [2-4].

Recently, we have proposed a SiGe sputter epitaxy method for $Si_{1-x}Ge_x$ layer growth and we have obtained high crystalline layers [5]. Furthermore, we have reported on the method of formation of a flat Ge layer on a heavy boron- or phosphorous-doped Si(001) substrate with our proposed sputter epitaxy method [6, 7]. There have been few reports on P mediated Ge growth. In our previous work, we have found that the Ge layer flattening is caused on heavy P-doped Si with the lowest dopant concentration of $\sim 10^{18}$ cm^{-3} at the highest growth temperature of ~350 °C.

In this paper, to understand the flattening mechanisms, we have further investigated the P mediated effect on the Ge flattening during Ge growth on Si(001), and have compared the P mediated effect between the conventional gas-source molecular beam epitaxy (GS-MBE) method and our sputter epitaxy method.

2. Experimental

Both the GS-MBE and sputter epitaxy were carried out using separately prepared ultra-high vacuum chambers with a base pressure of $<1\times 10^{-9}$ Torr, and GeH_4 and a non-doped solid Ge target were used as a Ge source, respectively. Ge layers were grown on phosphorus doped Si(001) substrates at a growth temperature of 350 °C. Resistivities of Si substrates used in this work were 3.5 and 0.015 Ω cm.

The Ge deposition rate was 0.036 nm/s in the sputter case. 5, 10, 20, and 65 nm Ge layers were grown for flat Ge layer growth experiments. In the GS-MBE case, the GeH_4 flow rate was 1 sccm and the growth time was 3600 s, which leads to 60 to 70 nm Ge growth by reference to the report by Koide *et al.* [8].

3. Results and Discussion

In Fig. 1, we show that cross sectional SEM images of Ge on 3.5 Ω cm Si substrate formed by sputter epitaxy and GS-MBE. And Fig. 2 shows typical SEM images obtained from Ge surfaces on 3.5 and 0.015 Ω cm Si substrates formed by sputter epitaxy and GS-MBE. The deposition amounts of the Ge layers were almost the same between the sputter and GS-MBE methods as shown in Fig. 1.

With the GS-MBE method, island formation was observed from both the Ge layers on the 3.5 and 0.015 Ω cm Si substrates. However, the Ge island size is smaller and the Ge island surface coverage is larger with 0.015 Ω cm Si than with 3.5 Ω cm Si. On the other hand, no island formation was observed from the sputtered Ge layer on 0.015 Ω cm Si and the Ge layer surface was flat as shown in Fig. 1(d). It has been reported that inhibition of Ge surface migration causes suppression of the Ge islanding or the Stranski-Krastanov (SK) growth mode [4, 9]. Therefore, the difference in the surface morphology between the GS-MBE and sputter samples would result from a difference in the Ge migration length between the methods, which corresponds well to the case of the SiGe growth mode on Si(001) [10, 11], where a flat SiGe layer can be grown on Si(001) with less movable nonhydrogenated Si and Ge adsorbates by sputter epitaxy than hydrides by GS-MBE.

Fig. 3 shows Raman shift peak positions of Ge-Ge mode peaks that were measured for sputtered samples after Ge growths on 3.5 and 0.015 Ωcm Si substrates. The Ge-Ge mode Raman shift peak position of relaxed bulk Ge was 300.4 cm^{-1} [12]. Thus, the islanding Ge layer on 3.5 Ωcm Si with a thickness of approximately 10 nm was already fully relaxed. However, the Ge layer on a 0.015 Ωcm Si substrate had some strain.

Transmission electron microscopy (TEM) images show that the Ge layer on a 0.015 Ωcm Si substrate has mainly an array of pure edge dislocations in the Ge/Si interface and the Ge layer on a 3.5 Ωcm Si substrate has more complex dislocations in the Ge/Si interface as shown in Fig. 4. An in-plane TEM image of the interface of the Ge layer and the 0.015 Ωcm Si substrate is shown in Fig.4 (c). A pure edge dislocation network, where the line pitch was almost 10 nm, was observed. The pitch well corresponds to the P atom density in the heavy doped Si substrate. Therefore, the results have suggested that P atom works as an origin of pure edge dislocation generation. Thus, the Ge layer on 0.015 Ωcm Si were relaxed but not fully relaxed by P mediated dislocations at the Ge/Si interface and this partial relaxation is enough to cause a coherent growth mode for the Ge layer growth.

4. Conclusions

We have investigated the phosphorus mediated effects on Ge layers on Si(001) formed by our sputter epitaxy and GS-MBE methods. By comparison between the methods, it has been found that the Ge flat growth on Si(001) is caused only with a combination of our sputter epitaxy method and a heavy P-doped Si substrate. We also have investigated the mechanism of the flat Ge layer formation. Experimental results suggest that pure edge dislocations are generated by the influence of P atoms. The Ge layer is partially relaxed by the dislocations, which results in Ge flat growth. Thus a limited amount of P atoms change the Ge growth mode from the SK to layer-by-layer growth mode. The flat Ge layer formation on a heavily doped Si substrate by the sputter epitaxy method is suggestively caused by a combination of less movable Ge adsorbates than with GS-MBE and P atoms which generate pure edge dislocations.

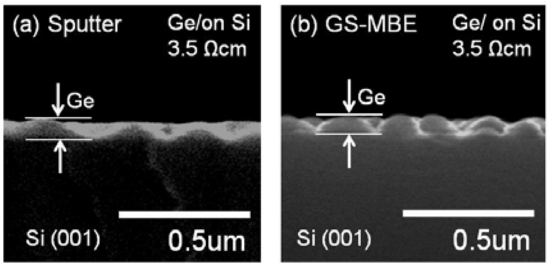

Fig. 1 Typical cross sectional SEM images obtained from Ge layers on Si formed by (a) sputter and (b) GS-MBE.

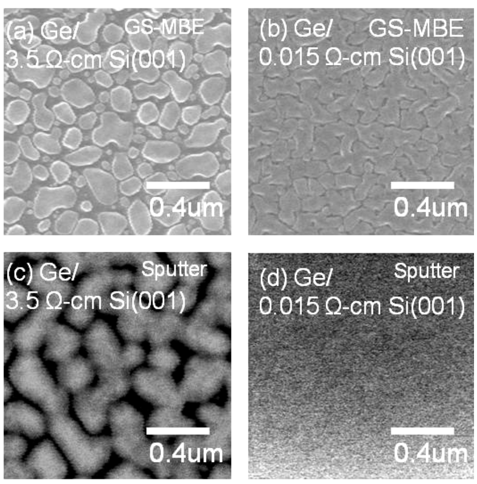

Fig. 2 Typical SEM images obtained from Ge layers formed by GS-MBE on (a) 3.5 and (b) 0.015 Ω cm Si, and formed by Sputter on (c) 3.5 and (d) 0.015 Ω cm Si.

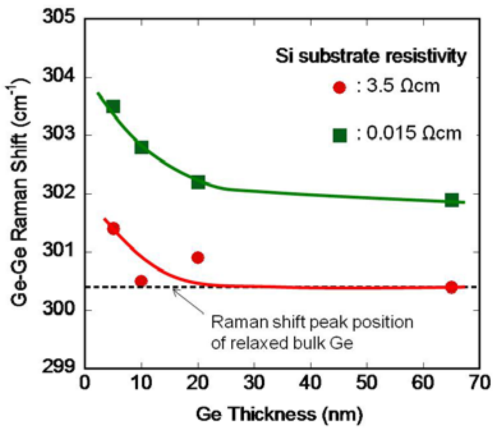

Fig. 3 Ge-Ge Raman shift peak positions, as function of Ge thickness, obtained from samples after Ge growths by 5, 10, 20 and 65 nm on 3.5 and 0.015 Ωcm Si substrates.

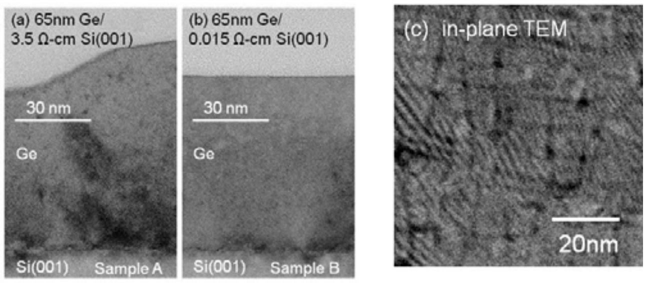

Fig. 4 TEM images obtained from Ge layers on (a) 3.5 Ωcm and (b) 0.015 Ωcm Si substrates and (c) in-plane TEM image of interface of Ge and Si 0.015 Ωcm Si substrate.

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