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Quantitative evaluation of germanium displacement induced by arsenic implantation using germanium isotope superlattices

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ABSTRACT

The displacement of germanium (Ge) atoms induced by arsenic (As) ion implantation at room temperature was investigated using Ge isotope superlattices grown by molecular beam epitaxy. The depth profiles of ^{74}Ge isotopes in the ^{70}Ge/^{nat}Ge isotope superlattices before and after ion implantation were obtained by secondary ion mass spectrometry. By representing the experimental data using a conventional integral model, Ge atomic displacement as a function of depth was obtained, from which we determined that 0.75 nm is the critical displacement necessary to make the structure appear amorphous under examination by cross-sectional transmission electron microscopy. However, we found that the amorphous Ge layers were recrystallized due to a local elevation of temperature caused by the implantation, which indicates that the samples should be cooled down during implantation to avoid the regrowth of amorphous Ge layers for this analysis.

1. Introduction

Ion implantation technology has been extensively employed for the fabrication of shallow junctions for silicon (Si) MOSFETs. Recently, interest in ion implantation into germanium (Ge) has increased because Ge has higher carrier mobilities than Si. This fact is important for the next generation of higher performance computers. However, our level of understanding of Ge behaviours such as amorphization induced by ion implantation and recrystallization during post-implantation annealing is much less advanced than that of Si. Si atomic displacement induced by ion implantation at room temperature was previously investigated by utilizing a convention integral model [1,2], and it was shown that the critical displacement of Si atoms that makes the structure amorphous by cross-sectional transmission electron microscopy (XTEM) is 0.5 nm. In this study, we investigated Ge atomic displacement induced by room temperature ion implantation of arsenic (As), which is one of the most important dopants for the formation of shallow junctions for n-type devices, using the same model as the previous work. We employed Ge isotope superlattices grown by solid-source molecular beam epitaxy (MBE) [3–5] for the evaluation of Ge atomic displacement.

2. Experiment

Naturally available Ge (^{nat}Ge) is composed of the five stable isotopes in a fixed ratio: ^{70}Ge (20.5%), ^{72}Ge (27.4%), ^{73}Ge (7.8%), ^{74}Ge (36.5%), and ^{76}Ge (7.8%). We grew ^{nat}Ge/^{70}Ge isotope superlattices, which are composed of alternating layers of ^{nat}Ge and isotopically pure ^{70}Ge (^{70}Ge: 96.3%, ^{74}Ge: 0.2%), by using MBE on ^{nat}Ge (1 0 0)-oriented substrates. First, a ~100 nm-thick ^{nat}Ge buffer layer was formed on the substrates to achieve an atomically flat and smooth surface prior to the epitaxial growth of the Ge isotope superlattices. Then, ^{75}As^{+} ions were implanted into the superlattices at an energy of 90 keV, which corresponds to the projected range of 40.5 nm, and with doses between 1×10^{14} and 1×10^{15} cm^{-2}. The ion implantation was performed at room temperature under a 7° tilt angle to avoid channeling of the ions and the beam current striking the wafers was 20 μA. Depth profiles of ^{74}Ge isotopes in the ^{70}Ge/^{nat}Ge superlattices and those of the implanted ^{75}As ions were obtained by secondary ion mass spectrometry (SIMS) (PHI ADEPT1010), using a Cs^{+} primary ion beam at 1.0 kV. The sputtering rate was assumed to be constant. XTEM observations were performed with the TECNAI F12 electron microscope operating with an accelerating voltage of 200 kV.

3. Result and discussion

Fig. 1(a)–(d) show the depth profiles of ^{74}Ge in the Ge isotope superlattices before and after implantation with ^{75}As^{+} ions at

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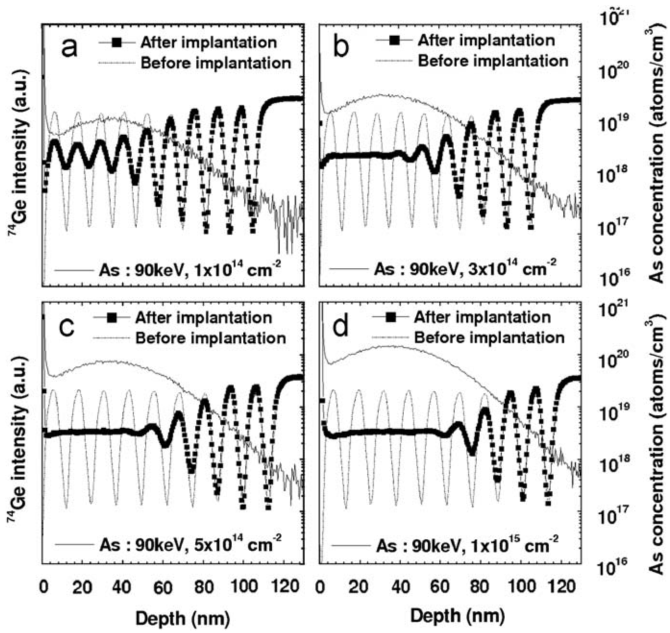

Fig. 1. Depth profiles of ^{74}Ge (solid symbols) and ^{75}As (solid lines) measured by SIMS after As ion implantation at the energy of 90 keV and with the doses of (a) 1×10^{14}, (b) 3×10^{14}, (c) 5×10^{14} and (d) $1\times10^{15}\,\text{cm}^{-2}$, respectively. Dashed lines show the profiles of the as-grown samples.

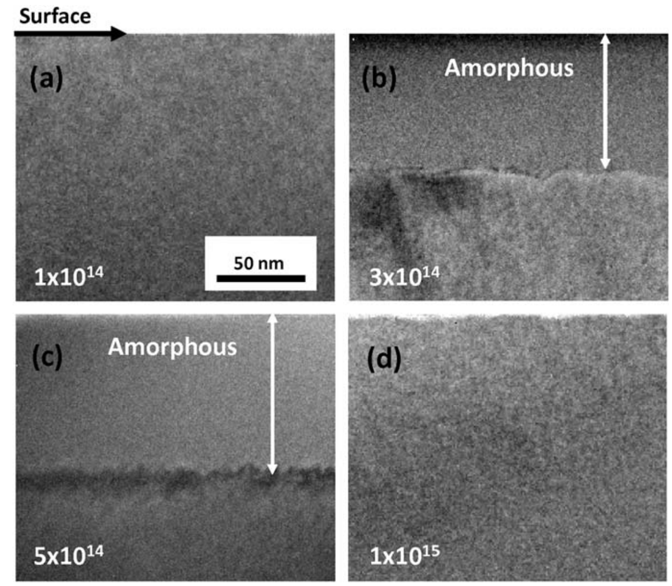

Fig. 2. XTEM images of As-implanted samples at the energy of 90 keV with the doses of (a) 1×10^{14}, (b) 3×10^{14}, (c) 5×10^{14} and (d) $1\times10^{15}\,\text{cm}^{-2}$, respectively.

90 keV with doses of 1×10^{14}, 3×10^{14}, 5×10^{14} and $1\times10^{15}\,\text{cm}^{-2}$, respectively, and the profiles of ^{75}As in each case. In addition, XTEM images of the Ge substrates implanted under the same conditions as the superlattice samples are shown in Fig. 2(a)–(d). From these SIMS data, it is found that the mixing degree of Ge atoms after implantation becomes larger with increasing implant doses. However, no amorphous layer was observed in the As-implanted samples with the lowest ($1\times10^{14}\,\text{cm}^{-2}$) and highest doses ($1\times10^{15}\,\text{cm}^{-2}$) although amorphous layers with the thicknesses of about 80 and 90 nm were observed in the samples with the middle implant doses of 3×10^{14} and $5\times10^{14}\,\text{cm}^{-2}$, respectively. This difference indicates that the amorphous Ge layers formed by the implantation were recrystallized by a so-called solid phase epitaxial (SPE) regrowth due to a local elevation of temperature caused by the implantation. Epitaxial regrowth of ion-implanted amorphous Ge on the underlying crystal substrate occurs between 300 and 400 °C with an activation energy of 2.0 eV and a rate of $10\,\text{nm}\,\text{min}^{-1}$ on (1 0 0) Ge at 350 °C [6]. On the other hand, the rate of ion-implanted amorphous Si is $10\,\text{nm}\,\text{min}^{-1}$ on (1 0 0) Si at 550 °C [7]. The regrowth temperature of Ge is 200 °C lower than that of Si at the same rate, which shows that recrystallization of amorphous layers more easily occurs in Ge than in Si. Moreover, the XTEM images that we observed in this experiment suggest that amorphous Ge layers formed by the implantation were recrystallized by a local elevation of temperature caused by the implantation as we mentioned above, and besides, the recrystallized Ge regions were amorphized again due to the implanted ions with time. Consequently, we reproduced the depth profiles of ^{74}Ge in the Ge superlattices implanted with the middle doses where amorphous Ge layers remain by employing the following model based on the convolution integral to obtain the average length of Ge displacement due to ion implantation as a function of the depth x.

$$C_{aft}(x) = \int C_{bef}(x')g(x-x')\,dx' \tag{1}$$

Here $C_{bef}(x)$ and $C_{aft}(x)$ indicate the concentrations of ^{74}Ge in the Ge isotope superlattices before and after As implantation, respectively. $g(x)$ is the Gaussian function:

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{2}$$

$\sigma(x)$ is the distance of the Ge displacement as a function of the depth x:

$$\sigma(x) = k\exp\left[-\frac{(x-c)^2}{2d^2}\right] \tag{3}$$

where k, c, and d are the parameters of peak amplitude, peak position, and peak width, respectively. It is known that except for the tails, the distribution of the displacement of atoms in solids by ion implantation can be approximated by a Gaussian [8]. We obtained good agreement between the depth profile experimentally measured by SIMS in the sample implanted with $3\times10^{14}\,\text{cm}^{-2}$ and the profile predicted by the model as shown in Fig. 3(a). The Ge displacement predicted by the simulation and the XTEM image of the $3\times10^{14}\,\text{cm}^{-2}$ implanted sample is shown in Fig. 3(b) and (c), respectively. By comparing the Ge displacement to the position of the amorphous/crystalline interface in the XTEM image, we found that the displacement that makes the structure amorphous by XTEM is 0.75 nm, which is 1.5 times larger than that of Si [1,2]. This difference can be attributed to the fact that the Ge–Ge bonding energy is smaller than that of Si. Specifically, Ge atoms which recoil from lattice points due to implantation are more easily reallocated on other lattice points, which makes the critical displacement longer. As mentioned above, however, we found that As implantation at room temperature can cause the SPE regrowth of amorphous Ge layers due to a local elevation of temperature caused by the implantation even though the implantation was performed with the beam current of 20 μA which would not be expected to cause significant wafer heating. Moreover, the SPE regrowth may move the amorphous/crystalline interface towards the sample surface even if the amorphous layer is not completely recrystallized, which would result in increasing the critical value. Therefore, recrystallization of amorphous Ge layers should be taken into account for this analysis. In order to avoid this phenomenon, the samples should be cooled down (by liquid nitrogen, etc.) during ion implantation.

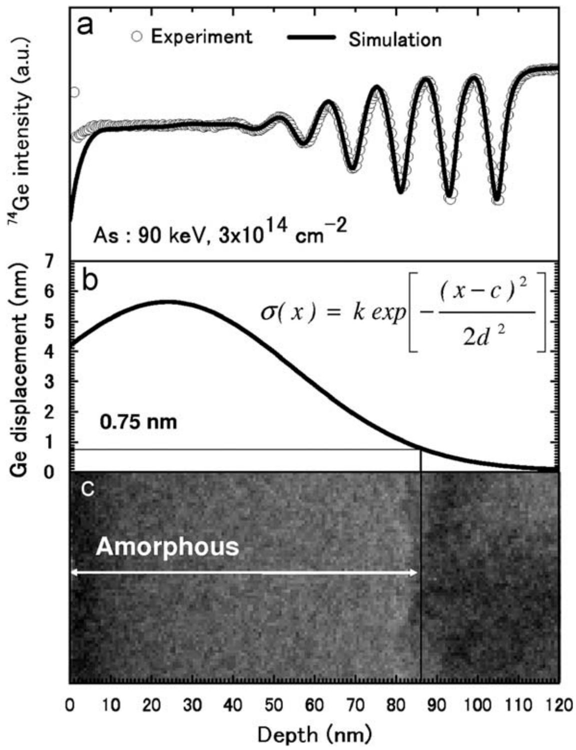

Fig. 3. (a) Profiles of ^{74}Ge in the ^{70}Ge/^{nat}Ge superlattice after As implantation at the energy of 90 keV with the dose of $3\times10^{14}\,cm^{-2}$ that were experimentally measured by SIMS (open circles) and simulated by using the convolution integral model (solid line) described in this text. (b) The depth dependence of Ge atomic displacement $\sigma(x)$ induced by the implantation. (c) XTEM image of the sample under the same implant condition.

4. Conclusion

In conclusion, we have investigated Ge atomic displacement induced by As implantation at room temperature using Ge superlattices. We reproduced SIMS data using the convolution integral model and obtained good agreement between experimental data and simulation results. We obtained 0.75 nm as the critical displacement of Ge that makes the structure appear amorphous by comparing Ge displacement deduced by the simulation to XTEM images. However, we found that amorphous layers formed by the implantation were recrystallized again due to a local elevation of temperature caused by the implantation and therefore the samples should be cooled down during ion implantation in order to avoid the SPE regrowth of amorphous Ge layers.

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