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Critical Displacement of Host-Atoms for Amorphization in Germanium Induced by Arsenic Implantation

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We evaluated quantitatively the germanium (Ge) displacement induced by arsenic (As) implantation as a function of the depth from the sample surface both in the amorphous and single-crystalline regions using ^{70}Ge/$^{\mathrm{nat}}$Ge isotope superlattices (SLs). The profiles of ^{74}Ge in the Ge isotope SLs were measured by secondary ion mass spectrometry and the sample structure along the depth was observed by cross-sectional transmission electron microscopy. The critical Ge displacement for amorphization induced by As implantation is found to be 0.75 nm, which is independent of the implantation doses. This value is 50% larger than 0.5 nm for Si.

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A renewed interest in germanium (Ge) as a substrate material of metal–oxide–semiconductor field-effect transistor is increasing because carrier mobilities in Ge are higher than those in silicon (Si).[1–3] While arsenic (As) implantation both into Si and Ge are important processes for the formation of the n-channel transistors, they induce radiation damage that can significantly affect redistribution of the dopants during post-implantation annealing.[4–6] Therefore, the As implantation process into Si has been studied extensively from various perspectives.[7–11] Specifically, the critical displacement of Si atoms, which is the average Si displacement along the depth to make the structure appear uniformly amorphous by cross-sectional transmission electron microscopy (XTEM) observation, was reported to be 0.5 nm for the case of Si.[7] In this study, we have evaluated quantitatively the average distance of Ge displacement induced by As implantation as a function of the depth from the implanted surface both in the amorphous and single-crystalline regions using Ge isotope superlattices (SLs).[12–15] The critical Ge displacement for amorphization is found to be 0.75 nm, which is 50% larger than 0.5 nm for Si.[7]

Naturally available Ge ($^{\mathrm{nat}}$Ge) is composed of 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%). In this study, ^{70}Ge (5 nm)/$^{\mathrm{nat}}$Ge (5 nm) isotope SLs which are composed of the alternating layers of $^{\mathrm{nat}}$Ge and isotopically pure ^{70}Ge (^{70}Ge: 96.3%, ^{72}Ge: 2.1%, ^{73}Ge: 0.1%, ^{74}Ge: 1.2%, ^{76}Ge: 0.3%) were grown by solid-source molecular beam epitaxy on a (100) $^{\mathrm{nat}}$Ge substrate. A ~100-nm-thick $^{\mathrm{nat}}$Ge buffer layer was formed prior to the growth of the Ge isotope SLs in order to achieve an atomically smooth surface. The temperature of the substrates during the growth was 250 °C and the sample was rotated with a consistent speed. ^{75}As$^+$ ions were implanted into the Ge isotope SLs at an energy of 90 keV, which corresponded to the projected range of 40.5 nm, and with the doses in the range between 5×10^{13} and 5×10^{14} cm^{-2}. The implantation was performed with a 7° tilt angle to avoid channeling of the ions and the beam current striking the samples was ~50 μA. The implantation was initially performed at room temperature (RT). However, it was found in our initial study that RT implantation of As ions into Ge led to inconsistent results.[15] The amorphous Ge layers formed by implantation were recrystallized by a so-called solid phase epitaxial regrowth due to a local elevation of temperature even during the RT implantation.[15] This result can be considered consistent with a report showing that amorphous Ge layers formed by implantation can be recrystallized by annealing at 300 °C.[16,17] Therefore the implantation temperature of 77 K was chosen in this study by attaching the sample directly to a holder cooled down using liquid N$_2$. The depth profiles of ^{74}Ge in the Ge isotope SLs and ^{75}As were obtained by secondary ion mass spectrometry (SIMS), PHI ADEPT1010, using a Cs$^+$ primary ion beam at 1.0 kV. XTEM observations were performed with the TECNAI F12 electron microscope operating at 200 kV. By comparing the XTEM samples prepared by argon (Ar) ion milling at room- and liquid-N$_2$-

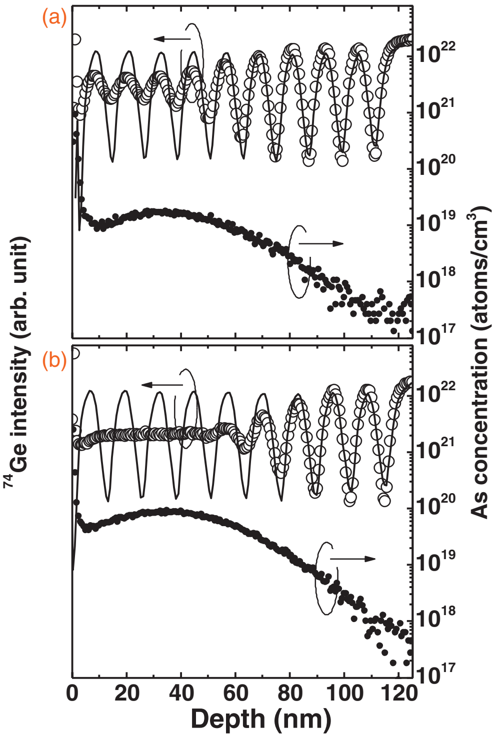

Fig. 1. Depth profiles of ^{74}Ge (upper profiles) and ^{75}As (lower profiles) in ^{70}Ge/$^{\mathrm{nat}}$Ge isotope SLs implanted with ^{75}As$^+$ at 90 keV and with doses of (a) 1×10^{14} and (b) 5×10^{14} cm^{-2}, respectively. In the upper profiles, the solid line and the solid symbols represent ^{74}Ge SIMS intensity before and after As implantation, respectively.

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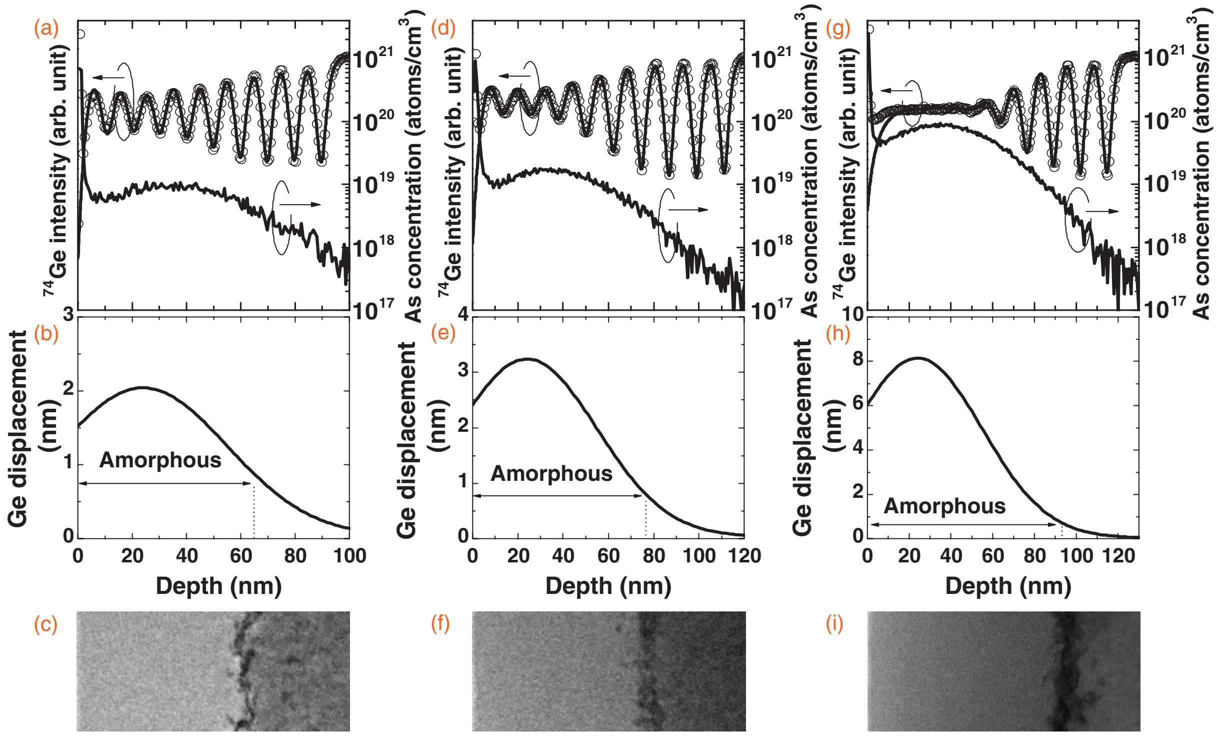

Fig. 2. (a) Depth profiles of ^{74}Ge (upper profiles) and ^{75}As (lower profile) in the ^{70}Ge/$^{\mathrm{nat}}$Ge isotope SLs implanted with ^{75}As$^+$ at 90 keV and with the dose of 5 x 10^{13} cm^{-2}. In the upper profiles, the solid symbols represent the SIMS data and the solid line represents the simulation result. (b) The displacement of Ge atoms induced by As implantation as a function of the depth from the sample surface with the same scale as in (a). (c) XTEM image of the sample with the same condition with the depth scale same as (a) and (b). The same set of figures for the samples implanted at 90 keV with the dose of 1 x 10^{14} and 5 x 10^{14} cm^{-2} are shown in (d)–(f) and (g)–(i), respectively.

temperatures, we confirmed that no recrystallization occurred during Ar ion milling performed at RT.

Figure 1 shows the depth profiles of ^{75}As and ^{74}Ge in the Ge isotope SLs before and after As implantation at 90 keV with the doses of (a) 1×10^{14} and (b) 5×10^{14} cm^{-2}. As expected, the ^{74}Ge periodicity in the SLs after implantation was perturbed compared to the profiles before implantation. The degree of Ge atom mixing in the SLs increases with increasing the implantation doses. In order to reproduce such perturbed depth profiles of ^{74}Ge in the SLs with the characteristic length of Ge atomic displacement as a function of the depth x from the surface, the following simulation model based on a convolution integral[7] was employed;

$$C_{\text{after-implant}}(x) = \int C_{\text{before-implant}}(x') \cdot g(x - x')\,dx'. \quad (1)$$

Here, $C_{\text{after-implant}}(x)$ and $C_{\text{before-implant}}(x)$ correspond to the concentration distribution of ^{74}Ge in the SLs after and before implantation, respectively. $g(x)$ is a Gaussian function described by

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

where $\sigma(x)$ is the displacement of Ge atoms due to implantation as a function of the depth x;

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

where k, p, and d are the parameters of peak amplitude, peak position, and peak width, respectively. It is known that the distribution of the displacement of atoms by ion implantation can be approximated well by a Gaussian except for the tails.[18] In parallel, unavoidable artificial smearing of the ^{74}Ge depth periodicity known as the SIMS artifacts was corrected by employing the mixing, roughness, and information-depth (MRI) model.[19] This model considers atomic mixing (w) and surface roughing (s) that occur during the SIMS measurement. The degree of the SIMS mixing can be described by the difference between the concentration measured by SIMS, $C(x)$ and the true concentration profile $C(x + w)$ where w is a small distance away from x;

$$\frac{dC(x)}{dx} = \frac{C^0(x+w) - C(x)}{w}. \quad (4)$$

The roughness is considered by superposition of a normalized Gaussian broadening as described by

$$C(x) = \frac{1}{\sqrt{2\pi}s} \int_{x-3s}^{x+3s} C^0(x') \exp\left[-\frac{(x-x')^2}{2s^2}\right] dx', \quad (5)$$

where s is the standard deviation.

First we determined the parameters w and s in eqs. (4) and (5) by fitting the depth profile of ^{74}Ge measured by SIMS before implantation, i.e., in the as-grown SLs. Then the ^{74}Ge SIMS profiles after implantation are reproduced by appropriately perturbing the originally rectangular profiles of ^{74}Ge using eqs. (1)–(3) and broaden them by the MRI model using the set of w and s already determined. Figure 2(a) shows the SIMS depth profiles of ^{74}Ge in the Ge isotope SLs implanted with 5×10^{13} cm^{-2} along with calculated profile using $k = 2.0$, $p = 24$, and $d = 31$ nm. This allows us to plot the distribution of the Ge displacement with the maximum of 2.0 nm situating at 24 nm from the surface [Fig. 2(b)]. The XTEM image of the same sample is shown in Fig. 2(c). The XTEM image shows that amorphization due to the As implantation occurred between the surface and ~66 nm in depth, while the deeper region of $x > 66$ nm remained single-crystal. Note that smeared but clearly existing periodicity of ^{74}Ge is observable even in the amorphous region. By comparing the displacement of Ge atoms shown in Fig. 2(b) with the XTEM image shown in Fig. 2(c), we find that the region where $\sigma(x)$ is larger than 0.75 nm appears "uniformly amorphous" in the XTEM image. Therefore, we define $\sigma_C = 0.75$ nm as the critical value of the Ge displacement for amorphization. Figures 2(d)–2(i) show similar results for the samples implanted with the doses of 1×10^{14} and 5×10^{14} cm^{-2}. We find $k = 3.2$, $p = 24$, and $d = 31$ nm for the 1×10^{14} cm^{-2} dose, and $k = 8.1$, $p = 24$, and $d = 31$ nm for the 5×10^{14} cm^{-2} dose. The XTEM images shown in Figs. 2(f) and 2(i) indicate that amorphization takes place between the surface and ~77 nm in the sample with the 1×10^{14} cm^{-2} dose, and ~92 nm in the sample with the 5×10^{14} cm^{-2} dose. Here the critical displacement of Ge atoms for amorphization $\sigma_C = 0.75$ nm remains the same and does not depend on the doses. Therefore, amorphization occurs when Ge atoms are displaced in the direction of the depth by average 0.75 nm and more. This $\sigma_C = 0.75$ nm is 50% larger than $\sigma_C = 0.5$ nm for Si.[7] This difference may be attributed to the fact that Ge–Ge bonding energy in Ge is smaller than that of Si–Si in Si. Therefore, Ge atoms are more easily displaced but at the same time also more easily brought back to the substitutional sites than Si.

In conclusion, we found that the critical displacement of Ge atoms necessary to make the structure appear amorphous is 0.75 nm and this value is independent of the implantation doses.

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