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Dopants behavior in polycrystallization of heavily doped $Ge_{1-x}Sn_x$ layer using pulsed laser annealing in water

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Abstract

We have investigated dopant dependence of heavy doping behavior for poly-$Ge_{1-x}Sn_x$ layer formed on insulator using pulsed laser annealing in water. We found that the resistivity of poly-$Ge_{1-x}Sn_x$ layer clearly depends on kind of dopants. It is also observed that the reduction of the dopant density after the annealing depends on kind of dopants. We consider that out-diffusion behavior from $Ge_{1-x}Sn_x$ layer during laser annealing is different among dopants, which means differences of the diffusion coefficient in melting $Ge_{1-x}Sn_x$.

1. Introduction

Polycrystalline-Ge (poly-Ge) layer on insulator is one of the most attractive semiconductor materials for advanced three-dimensional integrated circuits (3D-ICs) because of its high carrier mobility and low crystallization temperature compared with poly-Si [1]. To fabricate high performance CMOS circuits with poly-Ge on insulators, heavy doping technique for both n- and p-type poly-Ge with low thermal budget process is required to enhance a driving current of MOSFETs.

Recently, we are focusing on the pulsed laser annealing (PLA) in water for this requirement. Our group previously found that using this method for a 2%-Sn-incorporated amorphous Ge (a-Ge) layer effectively suppresses the ablation of layers even for the high-energy-density laser, and as a result, the large grain growth was achieved [2]. We also achieved high-quality heavy n- and p-type doping for poly-$Ge_{1-x}Sn_x$ layers with Sb and Ga, respectively, using this method [3].

In this study, we investigated the dopant dependence of heavily doping behavior for poly-$Ge_{1-x}Sn_x$ layer prepared with PLA in water. It is well known that equilibrium segregation coefficient (k) and maximum solubility limit depend on kind of dopants [4]. On the other hand, we found that, in the case of PLA in water for poly-$Ge_{1-x}Sn_x$ layer, out-diffusion of dopants form melted $Ge_{1-x}Sn_x$ is an important factor to achieve heavy doping without the reduction of dopant density.

2. Experiment

N-type Si(001) wafer covered with a 1-μm-thick SiO_2 layer was used as substrate. A 50-nm-thick a-$Ge_{0.98}Sn_{0.02}$ layer was deposited on the substrate at room temperature (RT) using molecular beam deposition system. We introduced various dopants into a-$Ge_{0.98}Sn_{0.02}$ layer by ion-implantation technique or in-situ doping during a-$Ge_{0.98}Sn_{0.02}$ deposition. Details of the dopant introduction are summarized in **Table I**. The a-$Ge_{0.98}Sn_{0.02}$ layers were crystalized with the irradiation of a KrF excimer laser (pulse duration: 55 ns, wavelength: 248 nm) in pure water at RT. The laser energy density (E) was set in range of 90−320 mJ/cm^2, and the laser beam was pulsed 20 times at an irradiated area.

3. Results and discussion

Figures 1(a) and **(b)** shows the resistivity of poly-$Ge_{1-x}Sn_x$ layer with n- and p-type dopants, respectively, as a function of the laser energy density. In the n-type doping case, at $E \leq 110$ mJ/cm^2, the resistivity is higher than that of the undoped poly-$Ge_{1-x}Sn_x$ layer, which suggests the carrier compensation of electrons from activated n-type dopants and holes from electrically activated vacancies. Increasing E, the resistivity of As- and Sb-doped samples decreases, which indicates that the electron density and/or mobility is increased by PLA with a high E. Actually, we already found that the Hall electron density and mobility increase with irradiation of high-energy-density laser for a Sb-doped a-$Ge_{0.98}Sn_{0.02}$ layer [3]. In contrast, the resistivity of P-doped sample increases at $E > 190$ mJ/cm^2 and it is similar to that of an undoped poly-$Ge_{1-x}Sn_x$ layer, which suggests that P atoms introduced into an a-$Ge_{0.98}Sn_{0.02}$ layer don't contribute to electrical properties of the polycrystallized $Ge_{1-x}Sn_x$ layer. As shown in **Fig. 1(b)**, the resistivity of all poly-$Ge_{1-x}Sn_x$ layers with p-type dopant at $E \leq 190$ mJ/cm^2 is lower than that of the undoped poly-$Ge_{1-x}Sn_x$ layer, which suggests that there are additional holes related to p-type dopants. Increasing E, the resistivity of Al- and In-doped samples increases like the P-doped sample.

To clarify the reason of the dopant dependence of the resistivity, we carried out hard x-ray photoelectron spectroscopy (HAXPES; SPring-8 BL47XU and BL09XU) and SIMS measurements to investigate the dopant density in poly-$Ge_{1-x}Sn_x$ layers. **Figure 2(a)** shows the ratio of the dopant density after PLA with various energies and that before PLA. As, Ga, and Sb densities don't depend on the laser-energy density. In contrast, Al and P densities are drastically reduced by PLA with a high-energy density of E>170 mJ/cm^2. Thus, it can be considered that the dopant reduction affects the resistivity increase. Because the equilibrium segregation coefficients of As and Sb are lower than those of P and Al and the maximum solubility limits of Al and P are also higher than that of Sb [4], it is difficult to explain the dopant reduction by the segregation phenomena or differences of the maximum solubility limit. We consider that one of the possible reasons is out-diffusion of dopant atom from melting $Ge_{1-x}Sn_x$ layer. **Figure 2(b)** shows the schematic illustration of dopant distributions with different diffusion coefficients (D) after annealing. As shown in **Fig. 2(b)**, in the case of a large D, out-diffusion reduces the dopant density at not only surface but also deep region of $Ge_{1-x}Sn_x$ layer. Thus, it is suggested that Al and P atoms in a melting $Ge_{1-x}Sn_x$ layer has a higher D than Ga, Sb, and As atoms. It is noted that, in the case of melting Si, the similar trend of D has been reported [5]. These results suggest that the diffusion coefficient in melting $Ge_{1-x}Sn_x$ is one of the keys for achieving heavy doping using PLA in water.

4. Conclusions

We examined the heavy doping for poly-$Ge_{1-x}Sn_x$ layer with various dopants using PLA in water. We found that Al and P densities after PLA are drastically reduced compared with other dopants. This result suggests that out-diffusion occur by large diffusion coefficient in Al and P cases compared with other dopants.

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References

[1] K. Toko *et al.*, Solid-State Electron. **53**, 1159 (2009).
[2] M. Kurosawa *et al.*, Appl. Phys. Lett. **104**, 061901 (2013).
[3] K. Takahashi *et al.*, Ext. Abstr. ICSI-10, p. 125.
[4] F. A. Trumbore, Bell Syst. Tech. J. **39**, 205 (1960).
[5] H. Kodera, Jpn. J. Appl. Phys. **2**, 212 (1963).

Table I Summary of dopant introduction method and density.

	Dopant	Method, energy, dose	Average density (cm^{-3})
n-type	Phosphorus	ion-implantation, 25 keV, 6×10^{14} cm^{-2}	1×10^{20}
	Arsenide	ion-implantation, 50 keV, 6×10^{14} cm^{-2}	1×10^{20}
	Antimony	in-situ	2×10^{20}
p-type	Aluminum	ion-implantation, 20 keV, 6×10^{14} cm^{-2}	1×10^{20}
	Gallium	in-situ	3×10^{19}
	Indium	ion-implantation, 55 keV, 5×10^{14} cm^{-2}	1×10^{20}

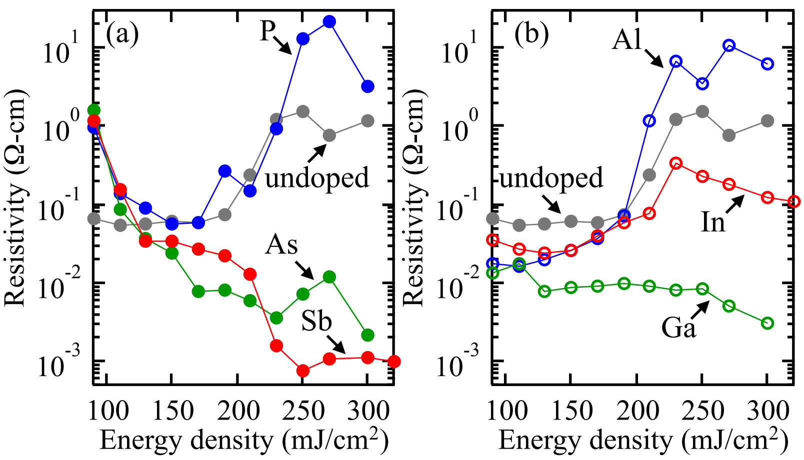

Fig. 1 The resistivity of poly-$Ge_{1-x}Sn_x$ layer with (a) n- and (b) p-type dopants as a function of the laser energy density.

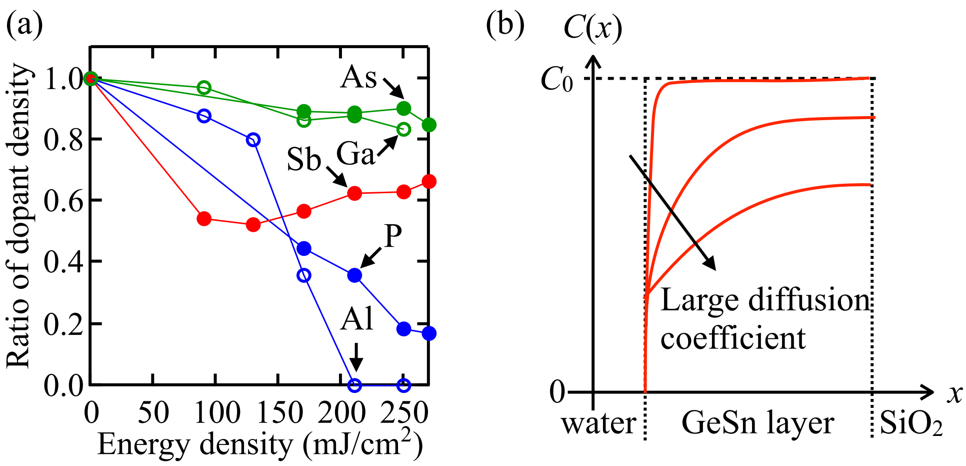

Fig. 2 (a) The ratio of the dopant density after and before PLA as a function of the laser energy density. (b) The schematic illustration of dopant distribution with different diffusion coefficients in $Ge_{1-x}Sn_x$ layer.