Characterization of phosphorus-implanted n⁺/p Ge junctions by reversely biased leakage current and Raman spectroscopy

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1. Introduction
Recent progress of Ge n-MOSFETs with proper interface passivation has attracted a great deal of interest for Ge CMOS [1]. However, to achieve high drive current and good switching properties of devices, n⁺/p junction formation for source/drain in n-MOSFETs is highly required. Although ion implantation is a conventional technique for source/drain formation, n⁺/p junction in Ge has less studied because the activation of n-type dopants and the recovery of implantation damage are more problematic compared to p⁺/n junction [2-5]. In this work, we investigate the n⁺/p junction formation by ion implantation and focus on the origin of the reverse current in Ge diodes. Since the reverse current of junction is mainly determined by the generation and recombination current at junction edge, we used Raman scattering measurement to evaluate the residual implantation damage after dopant activation annealing. Furthermore, ion implantation with a double acceleration voltage and dose is proposed to reduce reverse current of n⁺/p junction.

2. Experimental Details
p-type Ge (100) wafers with resistivity of 0.4 – 0.5 Ω cm were used in this study. To fabricate n⁺/p diodes in Ge, 50 nm Y₂O₃ was deposited on Ge surface as a passivation layer and photoresist was used for blocking layer of implantation. Two types of samples were prepared, where phosphorus was implanted at a dose of 1x10¹⁵ cm⁻², 30 kV, and 1x10¹⁵ cm⁻² with 30 kV and 1x10¹⁴ cm⁻² with 150 kV through 10 nm SiO₂ buffer layer, respectively. The dopant activation was carried out at 400 ~ 700 °C for 30 sec in N₂ atmosphere. Al was deposited by the vacuum evaporation for the gate electrode and ohmic contact of diodes. Current-voltage (I-V) characteristics were measured at room temperature (RT). To investigate the relation of ion implantation damage and reverse current in n⁺/p Ge junctions, the samples were analyzed by Raman scattering measurements at RT. The Ar laser at 488 nm, the laser penetration depth into Ge is about 19 nm, was used as an excitation source to analyze the Ge crystallinity and residual stress in the depth direction.

3. Results and Discussion
Fig. 1(a) shows the schematics of n⁺/p Ge diode and phosphorus concentration as a function of Ge depth, which was simulated by SRIM [6]. The projected range (Rₚ) is targeted to 20 nm for shallow junction formation. Fig. 1(b) shows I-V characteristics of n⁺/p junctions formed by a conventional ion implantation (1x10¹⁵ cm⁻², 30 kV), where dopant activation was carried out at 400°C to 650°C. The n⁺/p junctions annealed above 600°C only show good diode properties with the on/off ratio of 10⁴. It is found that the reverse current of n⁺/p junction decreases monotonically with increase of dopant activation temperature possibly due to the recovery of implantation damage with recrystallization. It indicates that high temperature process is needed to activate phosphorus dopant for good rectifying properties of n⁺/p Ge diode.

To investigate the relation of phosphorus implantation damage and reverse current in n⁺/p Ge junction, the samples were analyzed by Raman scattering measurements at RT. Fig. 2(a) shows Raman spectra for Ge wafers implanted with phosphorus as a function of dopant activation temperature. In case of an as-implanted sample, no Raman peaks at 300 cm⁻¹ was observed indicating that Ge is amorphousized by phosphorus implantation damage. Fig. 2(b) summarizes both position and full width at half maximum (FWHM) of Raman peak as a function of activation temperature. FWHM of Ge bulk measured before phosphorus implantation is inserted as a reference. It is interesting that Ge bulk crystallinity is not fully recovered from the implantation damage despite the dopant activation of high temperature. Fig. 3 shows the depth profile of FWHM in phosphorus implanted region after dopant activation annealing. Ge is etched by dilute H₂O₂ solution and etching rate (~1 nm/sec) was estimated using 100 nm-thick GeOI wafer measured by spectroscopic ellipsometry. It clearly shows that Ge bulk crystallinity in depth direction becomes better as etching time increases, indicating that phosphorus implanted region is all etched out. These results are well consistent with implantation simulation that Rₚ of phosphorus is around 20 nm, as shown in Fig. 1(b). It can be inferred that n⁺/p junction edge is highly damaged by ion implantation and it is not recovered by low temperature annealing (below 500°C). This is why we observed large reverse current of n⁺/p junction annealed at low temperature as shown in Fig. 1(b). On the other hand, the high temperature annealed samples show the worse crystallinity between 30 to 60 nm regions possibly due to the defects diffusion and/or phosphorus clusters. Fast indiffusion of phosphorus deeper into Ge could make n⁺/p junction edge far from the damaged layer and it shows good rectifying diode properties. We confirmed that phosphorus diffusion in Ge doesn’t occur below 500°C of activation annealing by SIMS (data not shown).
On the basis of above results, we examined phosphorus implantation with different acceleration voltage at a dose of $1 \times 10^{15}$ cm$^{-2}$ with 30 kV and $1 \times 10^{14}$ cm$^{-2}$ with 150 kV for avoiding implantation damage at junction edge. Fig. 4(a) shows $I-V$ characteristics of $n^+/p$ junctions, where dopant activation was carried out at 400$^\circ$C to 650$^\circ$C. It shows good rectifying diode properties and much lower reverse current even annealed at 400$^\circ$C, compared to Fig. 1(b). We also investigated depth profile of these samples by Raman scattering as shown in Fig. 4(b). Interestingly, the implantation damage at the second ion implantation of $R_p$ (150 nm) with a dose of $1 \times 10^{15}$ cm$^{-2}$ was fully recovered above 500$^\circ$C of activation annealing. Thus, it is reasonable that junction edge of $n^+/p$ diode is defect-free and low reverse current is achieved. Fig. 5 shows ideality factor ($n$) of $n^+/p$ junction as a function of activation temperature. The value of $n$ is very stable from 1.1 to 1.2 for ion implantation with a double acceleration voltage regardless of the activation temperature, while that of a conventional ion implantation is highly dependent on activation temperature. These results indicate that it is possible to reduce $n^+/p$ junction formation temperature, which is highly desired for gate-first Ge n-MOSFETs. Finally, to achieve damage-free $n^+/p$ junction in Ge, multiple ion implantation process at a low dose should be required for avoiding implantation damage and improving dopant activation.

4. Conclusion

We investigated origin of reverse current in $n^+/p$ junctions in Ge and revealed that implantation damage is not fully recovered by dopant activation annealing, which mainly determined reverse current of $n^+/p$ junction. To avoid residual damage by implantation, we examined ion implantation with a double acceleration voltage and dose. It shows that the reverse current is dramatically reduced by forming a damage-free junction edge.

References