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

Choong Hyun Lee, Toshiyuki Tabata, Tomonori Nishimura, Kosuke Nagashio, Koji Kita, and Akira Toriumi

Department of Materials Engineering, The University of Tokyo
JST-CREST
7-3-1 Hongo, Tokyo 113-8656, Japan
Phone: +81-3-5841-1907 E-mail: lee@adam.t.u-tokyo.ac.jp

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 Y_2O_3 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 $1x10^{15}$ cm^{-2} with 30 kV, and $1x10^{15}$ cm^{-2} with 30 kV and $1x10^{14}$ cm^{-2} with 150 kV through 10 nm SiO_2 buffer layer, respectively. The dopant activation was carried out at 400 ~ 700 ^oC for 30 sec in N_2 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 (R_p) 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 ($1x10^{15}$ cm^{-2}, 30 kV), where dopant activation was carried out at 400^{o}C to 650^{o}C. The n^+/p junctions annealed above 600^{o}C only show good diode properties with the on/off ratio of 10^4. 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 H_2O_2 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 R_p 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^{o}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 phosphorous diffusion in Ge doesn't occur below 500^{o}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 $1x10^{15}$ cm^{-2} with 30 kV and $1x10^{14}$ 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^oC to 650^oC. It shows good rectifying diode properties and much lower reverse current even annealed at 400^oC, 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 $1x10^{14}$ cm^{-2} was fully recovered above 500^oC 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.

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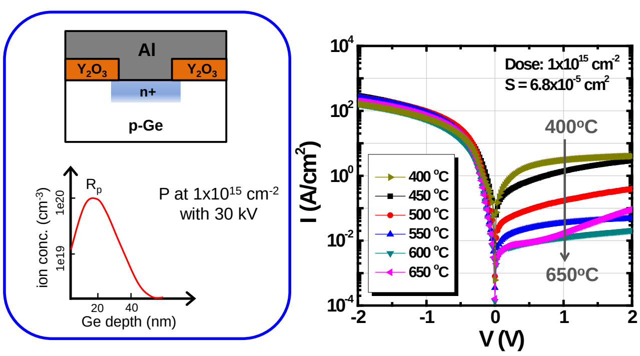
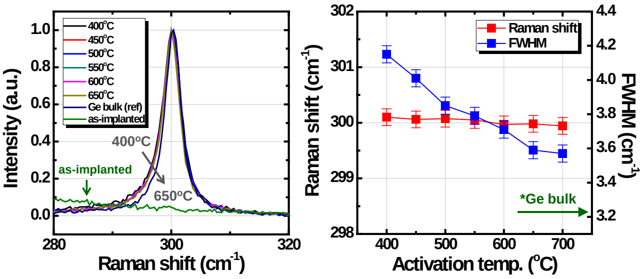


(a) (b)

Fig. 1 (a) Schematics of n^+/p diode and phosphorus concentration as a function of Ge depth. **(b)** *I-V* characteristics of n^+/p junctions formed by a conventional ion implantation ($1x10^{15}$ cm^{-2}, 30 kV), where dopant activation was carried out at 400^oC to 650^oC.



(a) (b)

Fig. 2 (a) Raman spectra for Ge wafers implanted with phosphorus as a function of dopant activation temperature. **(b)** Both position and full width at half maximum (FWHM) of Raman peak as a function of activation temperature.

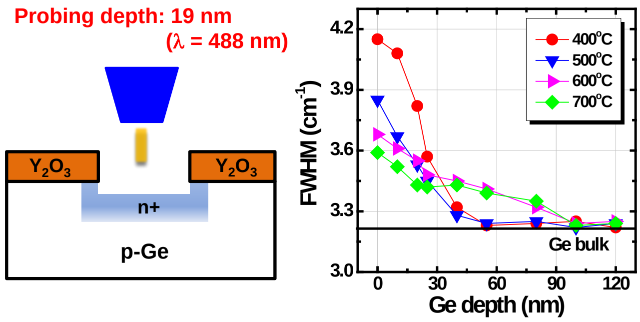
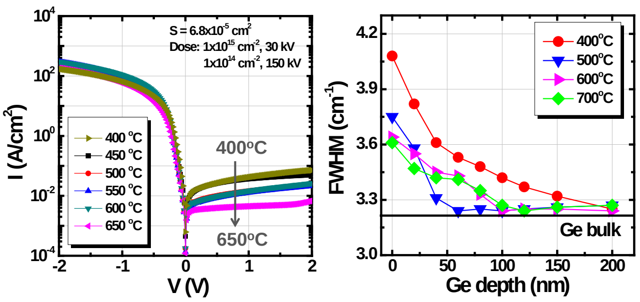


Fig. 3 Ge depth profile of FWHM in phosphorus implanted region after dopant activation annealing. It is worth noting that laser wavelength of Raman spectroscopy is 488 nm and probing depth in Ge is around 19 nm.



(a) (b)

Fig. 4 (a) *I-V* characteristics of n^+/p junctions, where dopant activation was carried out at 400^oC to 650^oC. It shows good rectifying diode properties and much lower reverse current even annealed at 400^oC, compared to Fig. 1(b). **(b)** Ge depth profile of FWHM in phosphorus implanted region after dopant activation annealing.

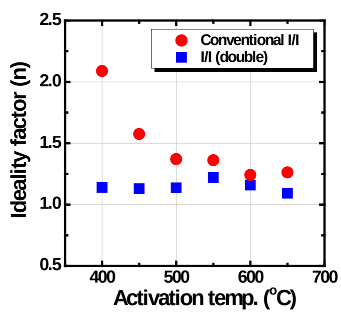


Fig. 5 Ideality factor of n^+/p junction as a function of activation temperature. The value of *n* is a range of 1.1 to 1.2 for ion implantation with a double acceleration voltage and dose, regardless of the activation temperature.