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Enhanced Carrier Activation by B and Sb/P Doping for Ge CMOSFET

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1. Introduction

Ge is an attractive candidate for new channel material due to its high electron and hole mobilities and excellent compatibility with Si CMOS integration. However, Ge material still has potential issues on obtaining high dopant activation above $1x10^{20}$ cm^{-3} especially for NMOS, which makes a big impact on not only SD diffusion resistance but contact resistance by affecting Schottky barrier thickness.

Thareja *et al* [1] adopted melt laser annealing to obtain high n-type dopant activation over $1x10^{20}$ cm^{-3} but the dopant diffusion was largely enhanced and the melting condition could lead to destroy pattern layouts in device wafers.

In this paper, we systematically studied mechanisms of carrier activation enhancement both for p- and n-type dopants using mass-production worthy methods, which enabled a world record carrier activation of no less than $7x10^{20}$ cm^{-3} and an enhanced dopant activation of $8x10^{19}$ cm^{-3} for p- and n-type dopants, respectively.

2. Experimental

Boron ions (35 keV, $1.0x10^{16}$ cm^{-2}, 7ºoff) were implanted for p-type dopant with three conditions: (i) implant at room temperature (RT), (ii) implant at liquid nitrogen temperature (LN_2T), and (iii) implant after Ge preamorphization (PAI) at RT. P/Sb coimplants were applied at 90 keV/65 keV with $6.0x10^{14}$ cm^{-2}/$6.0x10^{14}$ cm^{-2} for n-type dopant activation at RT and LN_2T. All experiments were performed using ~30 ohm-cm Ge (100) substrates.

Furnace annealing (FA) and rapid thermal annealing (RTA) were used for dopant activation at low temperatures of 400-525ºC, suppressing dopant diffusion. After the processes, samples were analyzed by SIMS, spreading resistance profile (SRP) analysis, RBS, and TEM.

3. Results and Discussion

Ion implantation into Ge substrate has been reported to easily cause large surface roughing which hinders appropriate evaluation on carrier activation in Ge [2]. We carefully reduced beam current to less than 50 μA to suppress excessive substrate temperature elevation during implantation. Therefore we obtained smooth surfaces even after implantation for all samples (**Fig. 1**).

In Fig. 2, for the first time, we compare a systematic B activation profile variation among the three conditions: Implant (i) at RT, (ii) at LN_2T, and (iii) after Ge PAI at RT. All the samples were annealed by FA at 400ºC for 1 hour. B diffusion after annealing was not observed for all the samples by SIMS. SRP shows B activation range gets deeper using Condition (i) RT, (iii) Ge PAI, and (ii) LN_2T in that order. The maximum activation density also increases in the same order as $3.6x10^{20}$ cm^{-3}, $7.0x10^{20}$ cm^{-3}, and $7.8x10^{20}$ cm^{-3}. The activated B densities of LN_2T and Ge PAI samples are much higher than $2\text{-}3x10^{20}$ cm^{-3} in Silicon [3] and even higher than reported values of $4.7x10^{20}$ cm^{-3} and $5.7x10^{20}$ cm^{-3} in Germanium [4,5].

The depth of high dopant activation area is reported to be determined by critical dose of implanted ion [4], which is an ion dose to create a continuous amorphous layer in crystal. LN_2T drastically decreases B critical dose and easily makes a deeper amorphous layer compared to RT [6]. Ge PAI also can assist to reduce B critical dose. **Figure 2** shows the PAI profile simulated with TRIM clearly coincides with the enhanced carrier portion. Therefore Ge PAI is expected to realize deeper activation when higher implant energy is applied.

Figure 3 shows a systematic illustration of amorphization conditions before anneal by TEM among the three above. The observation gives clear evidence why a systematic carrier activation variation occurred. The amorphous layer depths have a direct correlation with the highly activated carrier profiles. LN_2T and Ge PAI samples show very smooth interfaces between amorphous and crystal in contrast with rough interface of RT sample. So electrical and physical studies prove both LN_2T and Ge PAI methods have an equivalent capability to obtain high carrier activation.

We also applied the enhanced amorphization techniques to Phosphorous (**Fig. 4**). Unfortunately those approaches still show conventionally obtained carrier concentrations of $3\text{-}4x10^{19}$ cm^{-3}. RBS analyses in **Fig. 5** explain that all RT, LN_2T and Ge PAI conditions for P implant do not show significant differences in amorphization. The results indicate only P can make a complete amorphous layer in contrast with B due to its heavier mass.

P/Sb coimplant, which is reported by Kim *et al* [7] to enable $1x10^{20}$ cm^{-3} carrier activation for n-dopant, was evaluated (**Fig. 6**). It is worth noting that the activation mechanism has not been clarified yet. Only P or only Sb has not been reported to surpass $3x10^{19}$ cm^{-3} in carrier activation. **Figure 6** shows RTA can greatly increase activated carrier density to $8x10^{19}$ cm^{-3} which is more than double that of FA. We first proved that carrier enhancement in P/Sb system is caused by not only specific combination of P and Sb atoms but also kinetic control by RTA.

4. Conclusion

We systematically studied enhanced carrier activation mechanisms for both p- and n-type dopants in Ge and obtained a world record carrier concentration of $7.8x10^{20}$ cm^{-3} and a high carrier density of $8x10^{19}$ cm^{-3} for p- and n-doping, respectively. Boron activation was found to be clearly governed by amorphization status before annealing and Ge PAI technique, which is an already proven method in Si LSI, showed a comparable capability to LN_2T implant. Enhanced electron activation in P/Sb coimplanted Ge was also found to be greatly due to kinetic control by RTA.

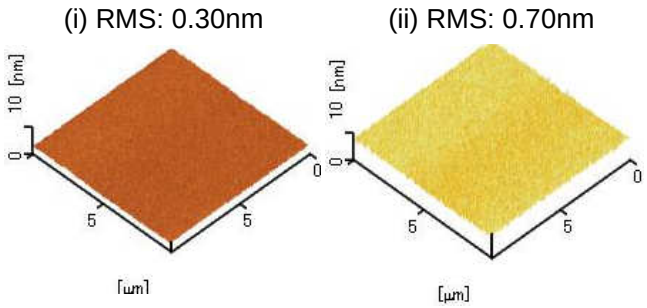

Fig. 1 AFM scan images of (i) B implanted Ge sample and (ii) P/Sb coimplanted Ge sample before annealing. Both RMS roughness values are much smaller than a reported value of ~4 nm for Sb implanted Ge with 60keV [2].

References

[1] Thareja *et al*., IEDM Tech. Dig., pp. 245 (2010)
[2] Janssens *et al*, JVST **B24**, 510 (2006)
[3] Pawlak *et al*, APL **86**, 101913 (2005)
[4] Chao *et al*, APL **87**, 142102 (2005)
[5] Mirabella *et al*, APL **92**, 251909 (2008)
[6] Impellizzeri *et al*, APL **105**, 063533 (2009)
[7] Kim *et al*, ESL **13** H12 (2010)

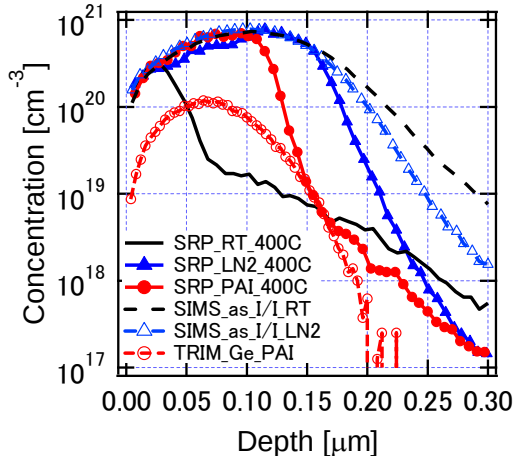

Fig. 2 SRP and SIMS profiles of B (35keV, $1x10^{16}cm^{-2}$) for RT, LN_2T and Ge PAI samples. SRP shows a systematic trend of activated portion by implant condition.

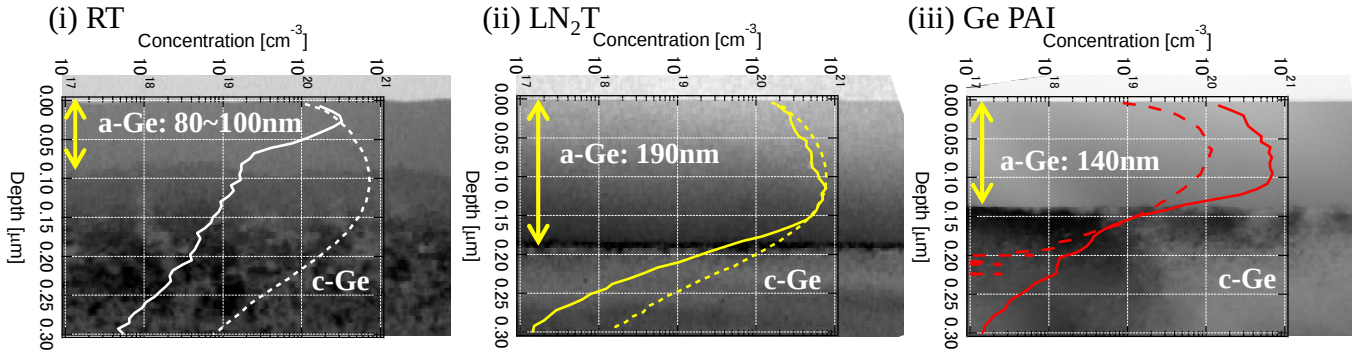

Fig. 3 XTEM micrographs overlapped with SRP profiles of (i)RT, (ii)LN_2T, and (iii)Ge PAI samples before thermal annealing. Amorphous-crystal interfaces are clearly observed. The each activated carrier density is closely correlated with each top amorphous area before annealing, enhancing activated carrier density more than one order of magnitude compared to crystal portion.

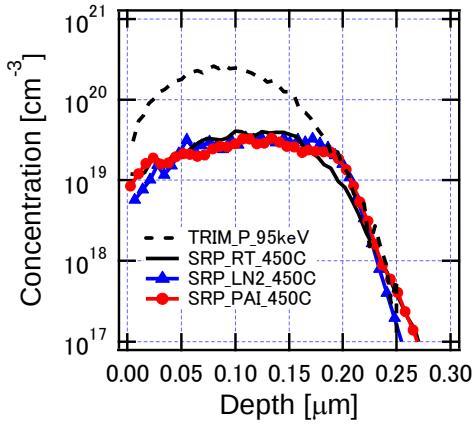

Fig. 4 SRP profiles of P (95keV, $3x10^{15}$ cm^{-2}) for RT, LN_2T, and Ge PAI samples. A simulated P profile is also included.

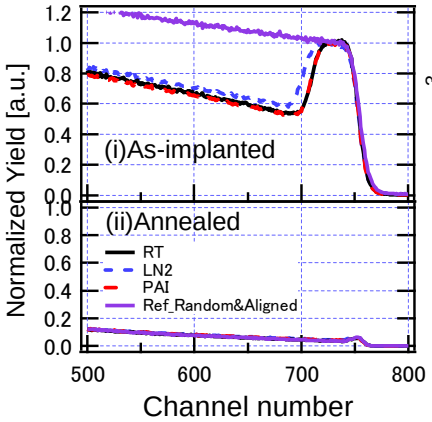

Fig. 5 RBS spectra for samples in Fig. 4. The yields around channel number 730 are 0.99-1.00 for all samples in (i).

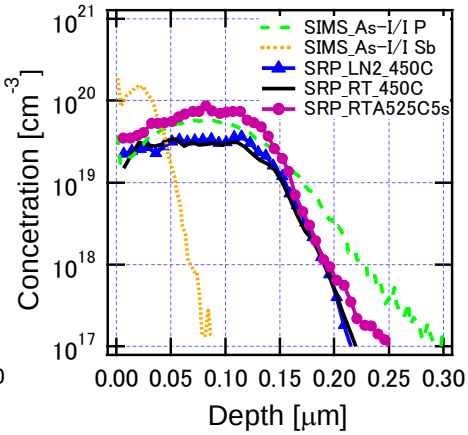

Fig. 6 SRP and SIMS profiles of P/Sb for no-annealed, 450ºC/1hour FA, and 525ºC/5s RTA samples.