

# Germanium *In Situ* Doped Epitaxial Growth on Si for High-Performance n<sup>+</sup>/p-Junction Diode

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**Abstract**—We demonstrate an abrupt and box-shaped n<sup>+</sup>/p junction in Ge with a high level of activation of n-type-dopant phosphorus (P) using *in situ* doping during epitaxial growth. The temperature dependence of dopant activation was investigated associated with the shallower and abrupt junction formation. In addition, we have fabricated high-performance Ge n<sup>+</sup>/p-junction diodes at 400 °C–600 °C, based on the *in situ* doping technique. Excellent diode characteristics having a  $1.1 \times 10^4$  on/off ratio and a high forward current density (120 A/cm<sup>2</sup> at 1 V) are obtained in an n<sup>+</sup>/p diode at 600-°C *in situ* doping.

**Index Terms**—Doping, germanium, *in situ*, phosphorus, shallow.

## I. INTRODUCTION

AS SCALING of silicon MOSFETs for higher performance is approaching fundamental limits, germanium (Ge) has appeared to be an attractive material because of its higher carrier mobility than Si. Since p-type dopants in Ge could be activated below 400 °C with minimum redistribution, mobility-enhanced p-channel Ge MOSFET has not been an issue. [1]–[3] On the contrary, relatively low n-type-dopant solubility [4], [5] and fast n-type-dopant diffusion [6] during activation in Ge make it difficult to fabricate the source and drain (S/D) in n-channel Ge MOSFETs.

Normally, ion implantation with postannealing has been used to form shallow junctions for MOSFET applications. However, in fabricating shallower junctions, the challenge is to minimize the redistribution of dopants during postannealing since the ion implantation damage results in fast diffusion, particularly for n-type dopants in Ge [7], [8]. Recently, the laser annealing method has been investigated for the Ge n<sup>+</sup>/p junction due to its short annealing time to prevent diffusion [9]. In order to avoid transient enhanced diffusion (TED), channeling effects, and extended defect formation, solid- and gas-phase diffusion techniques are also very attractive alternatives to form shallow junctions without any damage. However, because the solid-source diffusion technique requires high-temperature annealing (> 800 °C) for n-type-dopant diffusion, the shallow-n<sup>+</sup>/

p-junction formation in Ge would be more challenging [10]. In addition to these techniques, *in situ* doping of Ge has recently gained interest due to the potential to form an ultrashallow junction with high level of dopant activation without any ion implantation damage and subsequent dopant deactivation [11]–[15].

In this letter, we demonstrate an abrupt and box-shaped n<sup>+</sup>/p junction in Ge with a high level of activation of n-type-dopant phosphorus (P) using *in situ* doping during the epitaxial growth of Ge.

## II. EXPERIMENT

A p-type (100) Si wafer was cleaned according to the standard Si wafer cleaning process and was immediately loaded into an Applied Materials Centura RP-CVD epitaxial reactor. A hydrogen bake at 900 °C was carried out to ensure that no native oxide remained on the Si surface. The initial Ge film was grown at 400 °C and 8 Pa, yielding a 400-nm-thick film. This was followed by annealing in H<sub>2</sub> ambient for 30 min at 825 °C. The growth temperature was increased to 600 °C at 8 Pa for the second Ge layer. Finally, a 15-min H<sub>2</sub> bake at 750 °C completed the intrinsic Ge epitaxial process. This intrinsic Ge epitaxial layer showed p-type  $4 \times 10^{15}$  cm<sup>-3</sup> of electrically activated concentration. Before *in situ* doped layer growth, the dopant-gas baseline is purged with diluted 1% phosphine to avoid the dopant cross-contamination at the stabilization step. Finally, an *in situ* doped n-type Ge layer with diluted 1% phosphine doping was grown at 400 °C–600 °C at 8 Pa on the intrinsic Ge layer for 1 min to form an n<sup>+</sup>/p-junction diode. Mesa diode structures with 200 μm in diameter were patterned by HBr/Cl<sub>2</sub> reactive ion etching of 1 μm of Ge layer in depth, followed by a 20-nm-thick SiO<sub>2</sub> layer deposition for surface passivation.

## III. RESULTS AND DISCUSSION

Fig. 1 shows the resistivity measured by the four-point probe technique in P-doped Ge layers grown at different temperatures on the intrinsic Ge epitaxial layer for 10 min. This sheet resistance is a measure of electrical activation. The resistivity of the grown P-doped Ge layer decreases monotonously until reaching a minimum value and finally increases due to the formation of polycrystalline Ge as the F(PH<sub>3</sub>)/F(GeH<sub>4</sub>) mass-flow ratio increases. We also measured the P-doped Ge-layer growth rate at different growth temperatures as a function of F(PH<sub>3</sub>)/F(GeH<sub>4</sub>) mass-flow ratio. The growth rate is relatively independent of the mass-flow ratio used and mainly depends on the growth temperature with 65, 53.5, and 43 nm/min at

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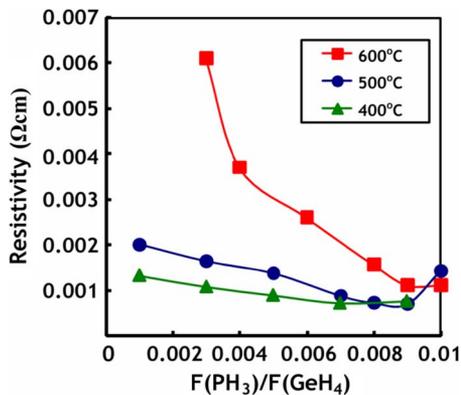


Fig. 1. Resistivities for phosphorus-doped Ge layer as a function of  $F(\text{PH}_3)/F(\text{GeH}_4)$  mass-flow ratio after 10-min *in situ* doped P-layer growth.

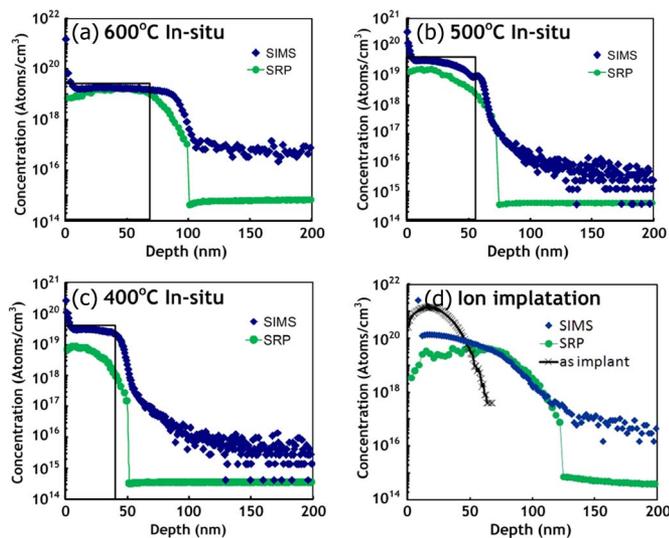


Fig. 2. SIMS and SRP depth profiles of P in (a) 600 °C, (b) 500 °C, and (c) 400 °C *in situ* doped Ge-layer growth for 1 min (the box indicates the *in situ* layer thickness), and (d) ion-implanted Ge ( $\text{P}^{31}$ , 18 keV, and  $4 \times 10^{15} \text{ cm}^{-2}$ ) after 600-°C/1-min RTA.

the growth temperatures of 600 °C, 500 °C, and 400 °C, respectively.

Fig. 2 shows the depth profiles of P-doped Ge layers grown at temperatures of 400 °C–600 °C for 1 min to form  $n^+$ /p junctions. Both secondary-ion mass spectrometry (SIMS) and spreading resistance profiling (SRP) data are presented. Fig. 2(d) shows both SIMS and SRP data of the conventional ion implantation sample P ( $\text{P}^{31}$ , 18 keV, and  $4 \times 10^{15} \text{ cm}^{-2}$ ) in the intrinsic Ge layer with post-RTA annealing at 600 °C for 1 min for a comparison. As the deposition temperature increases, deeper phosphorus diffusion was observed. Phosphorus diffused into the intrinsic Ge grown layer up to 35 nm due to 600 °C *in situ* deposition for 1 min [Fig. 2(a)] from the initial interface. However, at lower temperatures ( $\leq 500$  °C), the diffusions were within 15 and 10 nm (Fig. 2(b) and (c), respectively).

The electrical concentration profiles are also shown in Fig. 2 at different deposition temperatures. At 600 °C growth temperature, the resultant  $n^+$ /p junction has a junction depth of 97 nm and a peak electrically activated concentration of  $2 \times 10^{19} \text{ cm}^{-3}$  [Fig. 2(a)]. A shallower junction depth (97 nm) is

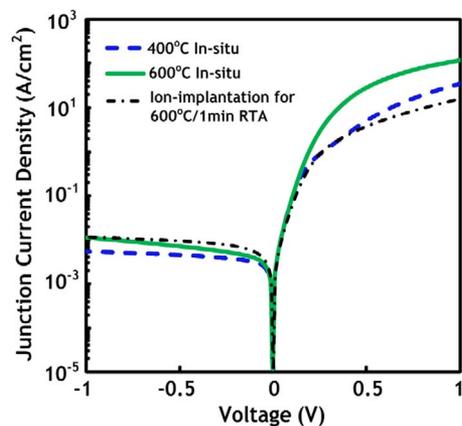


Fig. 3. Junction current density of  $n^+$ /p-junction diodes using 1-min *in situ* doping and ion implantation with 600 °C/1-min RTA.

obtained than for the ion-implanted sample (122 nm) annealed at 600 °C for 1 min. This *in situ* doped profile also exhibits an abrupt edge near the  $n^+$ /p junction from the SRP data, yielding a slope for the decay of the phosphorus concentration of 13 nm/decade. A sharper profile is observed at this 600 °C *in situ* doping than for the ion-implanted sample (24 nm/decade), as shown in Fig. 2(a) and (d). The SIMS and SRP data confirm an  $\sim 100\%$  dopant activation without any postannealing step after 600 °C 1-min *in situ* doped Ge-layer growth [Fig. 2(a)]. The peak electrically active concentration decreases as the growth temperature decreases because a lower temperature condition does not have enough thermal energy to activate the high level of dopants during 1-min deposition.

In Fig. 3, the  $n^+$ /p-junction diode formed by *in situ* doping at 600 °C shows a better diode characteristic having a  $1.1 \times 10^4$  on/off ratio and a high forward current density ( $120 \text{ A/cm}^2$  at 1 V) than a conventional junction diode fabricated by using ion implantation and 1-min post-RTA annealing ( $1.37 \times 10^3$  on/off ratio and  $15\text{-A/cm}^2$  forward current density at 1 V). The ideality factors of three  $n^+$ /p-junction diodes are extracted. At low forward bias, the ideality factors are found to be around one. This means that the diffusion current component is dominant at low forward bias due to the small band gap of Ge. Also, the ideality factor increases as the forward bias increases. The shallower and more abrupt junction in the 600 °C *in situ* sample with  $\sim 100\%$  dopant activation provides higher forward current than the ion-implanted sample, even though it has lower peak electrically active dopant ( $2 \times 10^{19} \text{ cm}^{-3}$ ) than the ion-implanted sample ( $5 \times 10^{19} \text{ cm}^{-3}$ ). This result confirms that the 600 °C *in situ* doped diode sample has high performance without damage such as TED, defect formation, etc. To the best of our knowledge, this is one of the highest forward current densities and on/off ratios [16]–[18]. Even at lower growth temperature (400 °C), the *in situ* doped sample shows a higher forward current ( $33.8 \text{ A/cm}^2$ ) and a higher on/off current ratio ( $6.47 \times 10^3$ ).

#### IV. CONCLUSION

We have examined temperature dependence associated with abrupt  $n^+$ /p-junction formation and the activation of n-type P dopant in Ge. The abrupt and box-shaped junctions (less

than 100 nm) with high-level activation of P were accomplished using the *in situ* doping technique at 400 °C–600 °C growth temperatures. This process will be feasible for making an ultrashallow junction. In addition, we have fabricated high-performance Ge n<sup>+</sup>/p-junction diodes with excellent characteristics having a  $1.1 \times 10^4$  on/off current ratio and a high forward current density (120 A/cm<sup>2</sup> at 1 V).

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