OPTIMIZATION OF ION IMPLANTATION USING TRIM SOFTWARE FOR THE FORMATION OF SHALLOW N+/P JUNCTION IN GERMANIUM SUBSTRATE

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ABSTRACT

Silicon (Si) device down-scaling is facing a big challenge to maintain its high drive current capability along with lower leakage current. Due to its similarities with Si, the interest has been focused on Germanium (Ge) as a substitute for device substrate. However, there are major problems in fabricating complementary metal-oxide semiconductor (CMOS) devices i.e. poor dopant solubility, low dopant activation and large dopant diffusion coefficient. These required further optimization on fabrication parameters involving ion implantation process. This paper reports the optimization of ion implantation parameters such as energy and dose. Co-implantation technique employing two atoms with different size will be adopted for forming the shallow n^+/p junction in Ge. The stress associated with atomic size is expected to be introduced into the Ge lattice. This stress will be manipulated to enhance dopant activation while controlling the diffusion. Low energy of dopant-ion implantation is selected to achieve high dopant concentration near the surface. The simulation parameters of two atoms were arranged to get such result where the effect of stress from co-implantation process can be manipulated.

***Keywords* —** co-implantation, dopant distribution, amorphous layer, defect vacancies, germanium, np junction

1. INTRODUCTION

According to the International Technology Roadmap for Semiconductors (ITRS) 2010, it is reported that the traditional scaling of planar Si-CMOS devices is becoming difficult due to the physical limit in down-scaling dimension. Germanium (Ge) and III-V compound have been pointed out as a new material candidate for pMOS and nMOS devices, respectively. This is due to the material properties that could improve the density, energy efficiency and reliability of the devices. However, the utilization of the same material for both nMOS and pMOS devices is important in order to reduce the process complexity and cost in manufacturing process. The interest has been focused on Ge due to similarities with Si and its higher carrier mobility (i.e. two times higher mobility for electrons and four times for holes compare to Si) [1–5].

One of the process involve in manufacturing CMOS devices is the fabrication of the pn junction. Two major processes that will be employed in the fabrication of pn junction are ion implantation and thermal annealing. However, unlike Si, there are many problems related to the dopant electrical activation and diffusion behaviour in Ge substrate during the fabrication process [5-9]. Since dopant activation and diffusion are controlled by the interactions between dopant and defects, it is important to control the defects introduced in the substrate by ion-implantation process. Aggressive change or uncontrollable processing parameter can enhance these dopant-defect interactions which result in anomalous characteristics of the devices.

Previous studies have revealed that fabrication of nMOS is facing severe problem compare with pMOS [9]. This is due to the heavy dopant ions i.e. arsenics (As) or antimony (Sb) is widely used for n-type dopant ion implantation results in more damages/defects. Furthermore, Ge easily forms unstable oxide on the surface which also can induce defects into the substrate [10]. Consequently, these damages/defects give substantial effect on the dopant electrical activation and diffusion during the thermal annealing process. Therefore, it is important to select appropriate atoms and process parameter to reduce the damages/defects introduced by ion-implantation during the formation of n^+/p junction.

Co-implantation is a technique where two atoms with different sizes are implanted together in the substrate. The

stress associated with atomic size will be introduced into the Ge lattice which subsequently contributes to the enhancement of dopant activation level [11]. Therefore, in regard to this background, this study will demonstrate the optimization of ion-implantation parameters by adopting co-implantation technique. The optimization will be done by varying the ion implantation process parameters i.e. ion implantation energy and dose concentration using Transport of Ion in Matter (TRIM) software. The finding of the optimization will also be discussed.

2. EXPERIMENTAL DETAILS

The co-implantation process was consisted of the crystalline Ge substrate that was ion implanted with two different sizes of atoms. Tilt angle of 7° was selected to minimize the channelling effect [12-13]. This process was modelled using the ion implantation software of TRIM. TRIM is Monte Carlo computer program that calculates the interactions of energetic ions with target. It consists of a group of programs called Stopping and Range of Ion in Matter (SRIM); which calculate the stopping and range of ions into matter using a quantum mechanical treatment of ion-atom collisions [14].

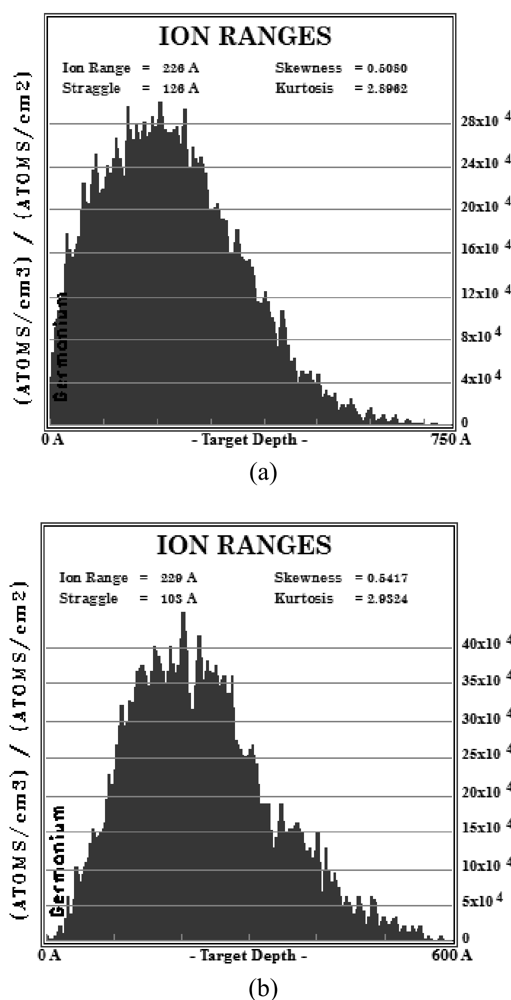
Phosphorus, P (atomic radius of 98 pm) and tin, Sn (atomic radius of 145 pm) were selected as a dopant and non-dopant atoms, respectively. P was selected as an n-type dopant due to its light properties. The simulations were firstly performed by varying the implantation energy and dose concentration of dopant atom (i.e. P atom). Low energy at the series of 20 keV, 30 keV, and 40 keV were selected in order to form a shallow junction. Dose concentration was varied between 3.0E14 – 6.0E14 cm^{-2} to achieve maximum dopant concentration level of 1E20 cm^{-3} [11]. Ion projected ranges (R_p) of P were simulated using SRIM. The simulation of non-dopant ion (i.e. Sn) was then performed based of the results of dopant TRIM simulation. The implantation energies of Sn were adjusted so that the projected range of Sn ion implantation will be similar to those of P ion implantation. Dose concentrations of Sn were then manipulated to achieve maximum dopant concentration level of 1E20 cm^3 [11]. From TRIM simulation of both ions, damage event for vacancies were observed and raw data from TRIM simulation were analyzed to get information related to the damage layer and concentrations.

3. RESULTS AND DISCUSSION

Table 1 shows projected ranges and ion implantation energy of P and Sn co-implantation calculated from SRIM simulation. Projected ranges of Sn were manipulated by varying the implantation energy so that it will be similar to those of P. It is important to overlap the profile to fully utilize the effect of stress associated with atomic size. From Table 1, it is found that the projected range, R_p for P and Sn are between 210 – 438 Å. It is also confirmed that the projected range increased with implantation energy.

Table 1 Projected range, R_p and co-implantation energy of P and Sn ions

P Implantation	R_p		Sn Implantation	R_p
20 keV	210 Å		58 keV	238 Å
30 keV	310 Å		90keV	310 Å
40 keV	400 Å		130keV	438 Å



(a)

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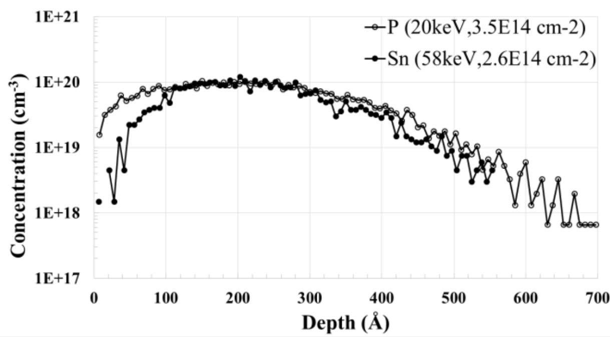
FIGURE 1 TRIM simulation result of ion ranges distribution at (a) P: 20 keV and (b) Sn: 58 keV

Figure 1 shows the TRIM simulation results of ion range distribution for the 20-keV P ion implantation and 58-keV Sn ion implantation. Projected ranges calculated from this profile are in a good agreement with those of SRIM calculation; with calculation error of ±10%. The same results were also obtained for (30-keV P/90-keV Sn) and (40-keV P/130-keV Sn) profiles.

Dopant ion concentration profiles can be achieved by multiplying the ion range results of Figure 1 with the implantation dose. Implantation dose were manipulated to achieve maximum dopant concentration of 1E20 cm^{-3}. The calculation was performed using Equation (1). The result is shown in Figure 2 and Table 2.



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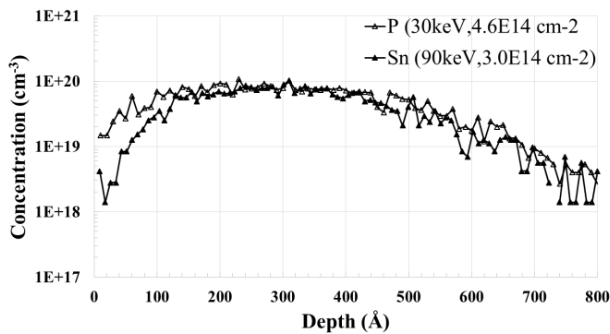

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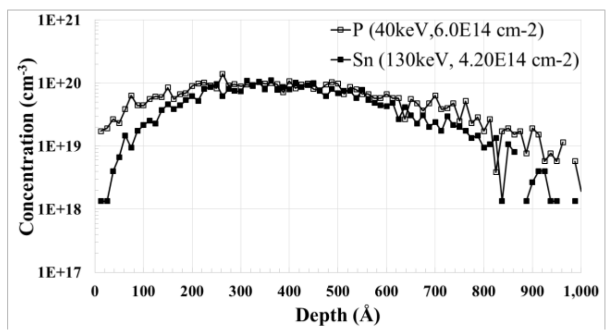

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Figure 2 Dopant distribution profile for co-implantation in Ge by the combination of (a) P: 20 keV/ Sn: 58 keV
(b) P: 30 keV/ Sn: 90 keV (c) P: 40 keV/ Sn: 130 keV

$$\textit{Impurity Concentration (Atoms/cm}^3\textit{)} = \textit{Ion Distribution Profile (Atoms/cm}^3\textit{) / (Atoms/cm}^2\textit{)} \times \textit{Implantation Dose (Atoms/cm}^2\textit{)} \quad \text{Eq. (1)}$$

From these results, it is shown that the dose concentration for each parameter needs to be varied from 2.6E14 cm^{-2} – 6.0E14 cm^{-2} in order to achieve similar maximum dopant profile of 1E20 cm^{-3}. It is also confirmed that dose concentration increased with implantation energy. It is due to implantation of higher energy will result in the deeper profile. Consequently, higher dose concentration is required in order to occupy the lattice site to the deeper range.

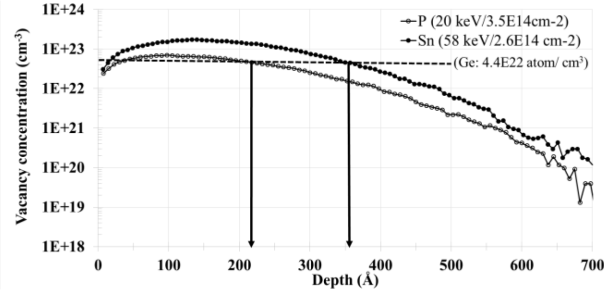
Table 2 Dose concentration for P and Sn co-implantation

P (keV)	Dose (cm^{-2})	Sn (keV)	Dose (cm^{-2})
20	3.5E14	58	2.6E14
30	4.0E14	90	3.0E14
40	6.0E14	130	4.2E14

As previously stated, damages and defects will be introduced into the substrate during the ion implantation process. Figure 3 shows the damage layer (i.e. amorphous layer) created during the ion-implantation process. It is assumed that the amorphous layer was produced when the displacement atom density (vacancies concentration) exceeds the single-crystal's atomic density of Ge (i.e., 4.4E22 atom/cm^3). The calculation was performed using Equation (2). From the results, the depth of amorphous layer varied from 218 – 738 Å. The depth is increased with the energy as higher implantation energy results in more damage to the target substrate. The same tendency can also be observed from the damage concentration shown in Figure 4. The calculation for damage concentration was performed using Equation (3). The results for these calculations were summarized in Table 3 and 4.

$$\textit{Vacancy Concentration (vacancy/cm}^3\textit{)} = \textit{Vacancy Dose (Vacancy/ Å-cm}^2\textit{) / }10^8\textit{ Å} \quad \text{Eq. (2)}$$

$$\textit{Defect Dose (cm}^{-2}\textit{)} = \textit{Ge Vacancy (Å-ion) / Implantation Dose (cm}^2\textit{)} \quad \text{Eq. (3)}$$



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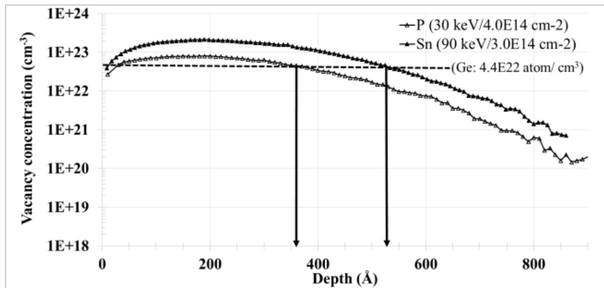

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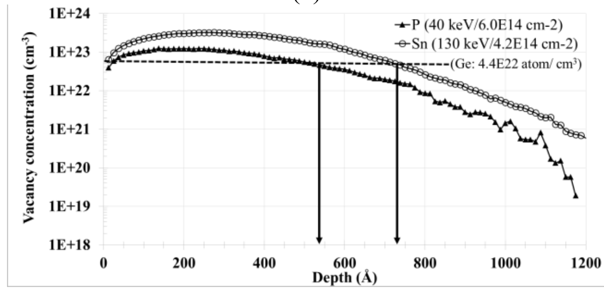
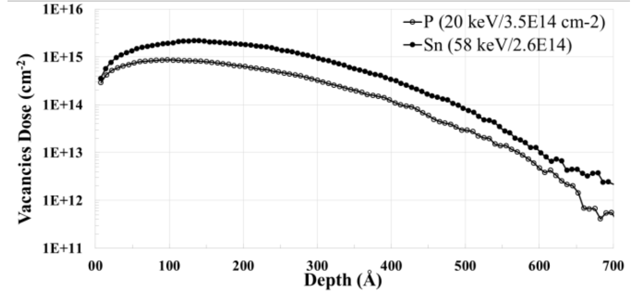


(c)

Figure 3 Amorphous layer created by P and Sn co-implantation in Ge with energy of (a) P: 20 keV/ Sn: 58keV (b) P: 30keV/ Sn: 90KeV (c) P: 40 keV/ Sn: 130 keV

Table 3 Amorphous layer of P and Sn co-implantation in Ge

P (keV)	Amorphous layer (Å)	Sn (keV)	Amorphous layer (Å)
20	218	58	357
30	380	90	525
40	538	130	738



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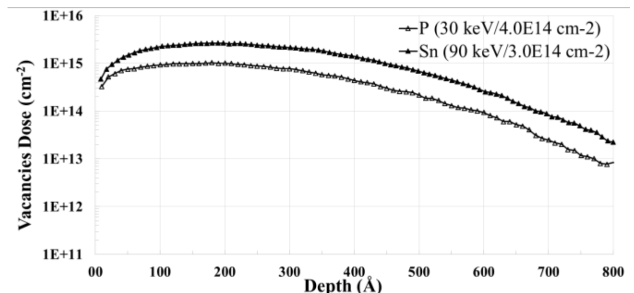

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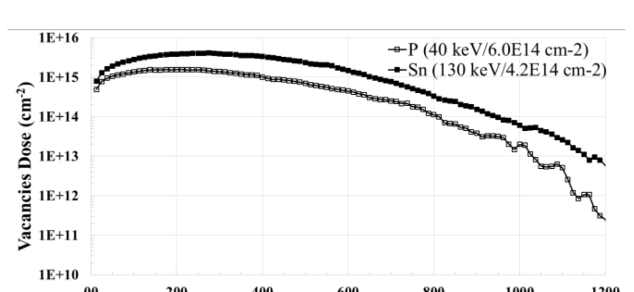

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Figure 4 Defects vacancies dose distribution of P and Sn implantation in Ge with energy of (a) P: 20 keV/ Sn: 58keV (b) P: 30keV/ Sn: 90KeV (c) P: 40 keV/ Sn: 130 keV

Table 4 Peak vacancies dose concentration for P and Sn co-implantation in Ge

P (keV)	Dose (cm^{-2})	Sn (keV)	Dose(cm^{-2})
20	8.72E14	58	2.19E15
30	1.15E15	90	2.66E15
40	1.55E15	130	4.04E15

4. SUMMARY

The optimization of ion implantation parameter for the formation of shallow n^+/p junction in Ge substrate was demonstrated using TRIM software. Co-implantation technique using two different size of dopant ions i.e. P and Sn was introduced as n-type dopant and non-dopant; respectively. The stress associated with atomic size is

expected to be introduced into the Ge lattice during the co-implantation process. Ion implantation parameters such as energy and dose were varied in order to attain an overlap profile of P and Sn with maximum dopant concentration of 1E20 cm^{-3}. This is important in order to fully utilize the effect of stress for enhancing the dopant activation level while controlling the diffusion during the fabrication process.

5. ACKNOWLEDGEMENT

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