Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Effects of Irradiation Dose and Post-Irradiation Annealing Temperature on Minority Carrier Lifetime of Proton-Irradiated P-type Silicon

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1. Introduction

Power semiconductor devices such as IGBT, BJT, and Tyristor are used as a switch or rectifier in power electronics. High switch speed with a low energy loss is required for these devices. The tail current during turn-off limits the switch speed and generates energy loss. The tail current can be suppressed; i.e. the switch speed can be increased by creating recombination centers in devices. These centers promote the recombination of the remaining carriers during turn-off with majority carriers.

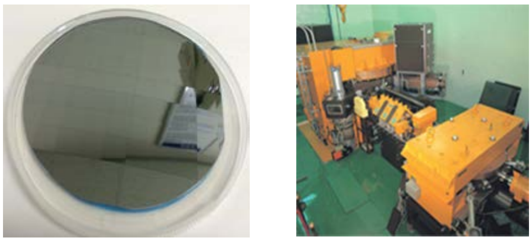
High-energy protons can recoil lattice atoms once injected into a silicon wafer, and generate radiation defects. The vacancy-related defects, i.e. vacancies combine with other vacancies or impurity atoms, have been found to act as the recombination centers. Hence proton irradiation has been used to increase the performance of power semiconductor devices [1]. The density and types of recombination centers influence the performance. In order to establish optimum irradiation conditions, the irradiation dose effect on the creation of the recombination centers have been a subject of a number of research papers [2-5]. The thermal stability of created recombination centers is also of interest for establishing optimum annealing processes.

In this study, we evaluate the irradiation dose and annealing temperature effects on a proton-irradiated silicon wafer by measuring minority carrier lifetime. The result of this study is expected to provide valuable information for developing power semiconductor devices with a high switch speed.

2. Methods and Results

2.1 Proton irradiation

A p-type silicon wafer with a thickness of 525 μm was diced into pieces with a size of 10×10 mm^2 as shown in Fig. 1(a). The square pieces were divided into eight groups. Each group was irradiated by protons using MC-50 cyclotron at Korea Institute of Radiological Medical Sciences (Fig. 1(b)). The acceleration energy of protons was set to be 10 MeV. Beam direction was perpendicular to wafer surface, which is (100). SRIM calculation showed that protons pass through the silicon wafer; hence the number of protons implanted inside silicon is negligible. The silicon pieces were irradiated inside a vacuum chamber at nominal room temperature. The dose levels of each group are listed in Table 1.



(a) (b)

Fig. 1 (a) Diced silicon wafer, (b) MC-50 Cyclotron

Table 1 Dose levels

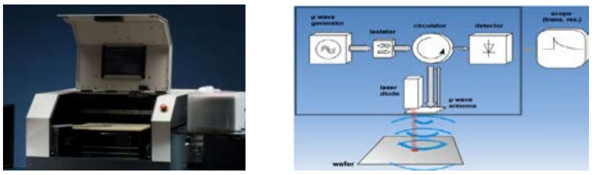
Group	Fluence (cm^{-2})	Annealing Temperature (K)
A	0	423, 523, 573, 623, 673, 723, 773
B	$1\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
C	$5\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
D	$10\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
E	$50\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
F	$100\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
G	$500\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773
H	$1000\cdot10^{10}$	423, 523, 573, 623, 673, 723, 773

2.2 Annealing of proton-irradiated specimens

Proton-irradiated silicon specimens in each group were annealed for 15 minutes at seven different temperatures. The annealing temperatures are listed in Table 1. In order to avoid excess surface oxidation during annealing, the specimens were put in a tube filled with Ar gas.

2.3 Carrier lifetime measurement

Minority carrier lifetime was measured using micro-wave PCD (photoconductivity decay) method (WT-2000, Semilab). The WT-2000 equipment and the schematic principle of micro-wave PCD technique are shown in Fig. 2. Electron-hole pairs are generated inside a specimen by laser source. The equipment then measures the change in the microwave reflectivity by the generated electron-hole pairs. From the time evolution of the measured reflectivity, the carrier lifetime is estimated.



(a) (b)

Fig. 2 (a) Semilab WT-2000, (b) The schematic of micro wave photoconductivity decay method

3. Result and discussion

3.1 Carrier lifetime

Fig. 3 shows the measured carrier lifetime from the specimens irradiated at different dose levels. The carrier lifetime decreases with increasing the irradiation dose significantly; the carrier lifetime of unirradiated silicon is decreased by 97% at a fluence of 10^{13} cm^{-2}. The decrease in lifetime may be induced by the increased density of radiation-induced defects which act as the recombination centers.

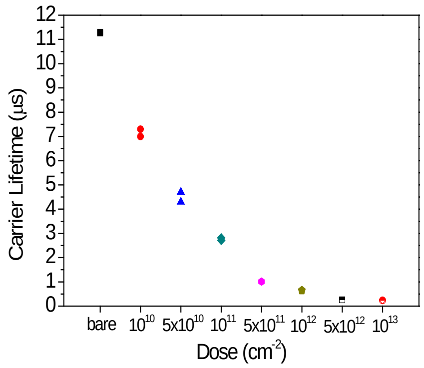


Fig.3 Change in carrier lifetime with irradiation dose

Fig.4 shows the change in carrier lifetime with annealing temperature for each irradiation dose level. Up to the annealing temperature of 573 K, the carrier lifetime slightly increases, and at the range between 573 and 673 K, the lifetime decreases sharply. The carrier lifetime then slightly increases at annealing temperatures larger than 673 K. The variation in carrier lifetime shown in Fig. 4 can be explained as follows

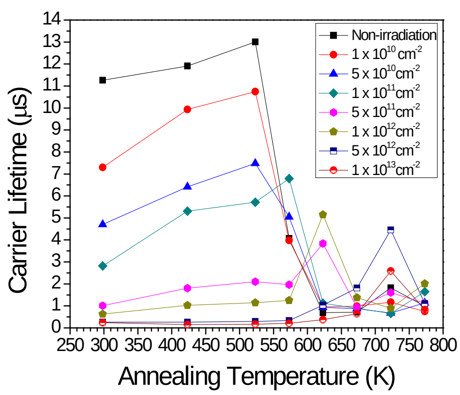


Fig.4 Change in the carrier lifetime with annealing temperature

Various vacancy-related radiation defects in proton-irradiated silicon reported in the literature are listed in Table 2. Thermal stability and electron/hole capture cross-section of each recombination center is different. For example thermal stability of V_2O_2 is the highest among the recombination centers listed in Table 2. In the annealing temperature range less than 573K, the thermal dissociation of V_2 and the associated increase in VO and V_2O decrease the overall electron capture cross-section. Carrier lifetime may increase consequently. In the temperature range between 573 and 673 K, the number of VO decreases and that of V_2O and V_2O_2 increases, which may result in the increase in electron capture cross-section. Hence carrier lifetime decreases. At annealing temperature higher than 673K, all the other recombination centers are dissociated and only V_2O_2 exists, which may result in slight increase in the carrier lifetime.

Table 2 Vacancy-related recombination centers

Recombination Center	Thermally unstable temperature (K)	Electron Capture Cross-section (cm^2)	Hole Capture Cross-section (cm^2)
$V_2^{+/0}$	473	$400\cdot10^{-15}$	$10\cdot10^{-15}$
VO	573-773	$130\cdot10^{-15}$	$1000\cdot10^{-15}$
$V_2O^{2-/-}$	623	$310\cdot10^{-15}$	$90\cdot10^{-15}$
$V_2O_2^{-/0}$	723	$140\cdot10^{-15}$	$10\cdot10^{-15}$

4. Conclusion

We investigated the effects of dose and post-irradiation annealing temperature on the carrier lifetime of proton-irradiated p-type silicon. Carrier lifetime was found to decrease significantly by increasing dose level. Subsequent annealing of the irradiated specimens showed that carrier lifetime changed with annealing temperature. The trend in the change of the carrier lifetime could be explained by using thermal stability data and electron capture cross-section reported in the literature.

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