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# Influence of radiation defects on formation of thermal donors in silicon irradiated with high-energy helium ions

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ABSTRACT

Isothermal annealing at temperatures from 370 to 410 °C was used for investigation of radiation enhanced formation of thermal donors in oxygen-rich FZ silicon irradiated with 7 MeV helium ions. Results show that formation of these defects is caused by hydrogen atoms which are diffusing from the anode contact. Hydrogen enhances diffusivity of interstitial oxygen and allows it to react with radiation defects containing vacancies and oxygen to form a new type of thermal donors. Their distribution is then given by concentration profile of radiation damage and diffusion length of hydrogen atoms. This effect occurs only in oxygen-rich silicon annealed in air and is absent in oxygen–lean silicon and samples annealed in vacuum.



## 1. Introduction

Nowadays, irradiation with helium ions is widely used for local reduction of carrier lifetime in silicon power devices [1,2]. To stabilize radiation defects acting as recombination centers, devices must be annealed for several hours at temperatures from 200 to 350 °C. Annealing at higher temperatures, which is required for increasing of radiation defect stability, discovered that helium irradiation also introduces shallow donors generated at damage maximum. This negative side effect deteriorating blocking capability of power devices was first reported on oxygen enriched float-zone (FZ) silicon irradiated with helium and subsequently annealed at 430 °C [2]. Recently, we showed that thermal donor (TD) formation is significantly stimulated by helium irradiation and annealing at temperatures from 375 to 500 °C [3]. For lower fluences of helium ions ($<10^{11}$ cm$^{-2}$), concentration of these radiation enhanced TDs (RETDs) is proportional to helium fluence and follows distribution of radiation damage. At higher fluences, concentration of RETDs saturates and their distribution becomes more complex.

In this paper, we used isothermal annealing at temperatures from 370 to 410 °C to investigate formation of RETDs in more detail and disclose reasons of their origin.

## 2. Experimental

The effect of helium irradiation on TDs production was studied on the oxygen-rich low-doped ⟨1 0 0⟩-oriented FZ *n*-type silicon substrate forming the *n*-base of planar $p^+nn^+$ power diodes. Diodes were irradiated from the anode side with 7 MeV $He^{2+}$ ions (fluences from $1 \times 10^{10}$ to $3 \times 10^{11}$ cm$^{-2}$) to place damage maximum beyond the deep anode junction. The evolution of TDs was investigated during isothermal annealing at temperatures from 370 to 410 °C in air. Similar experiment was also performed on diodes fabricated on Czochralski (CZ) and oxygen-lean FZ silicon. Some samples were also annealed in vacuum. Deep and shallow levels produced by irradiation and subsequent annealing were studied by capacitance DLTS and *C*–*V* profiling.

## 3. Results and discussion

Evolution of RETDs in the sample irradiated with a low-fluence ($1 \times 10^{10}$ cm$^{-2}$) of 7 MeV alphas during isothermal annealing in air at 370 °C is shown in Fig. 1. Profiles obtained from *C*–*V* measurement clearly show that RETDs evolve from the irradiated surface and consequently cover the profile of radiation damage produced by helium ions. The RETD peak is localized at the damage maximum and its width is close to that of radiation defects [1]. For annealing time $T_a > 100$ min, the localized formation of RETDs is already finished and the donor doping uniformly grows in the whole volume of the sample as a result of generation of ordinary TDs. Final shape of the RETD profile ($T_a = 110$ min) is identical with the distribution of point defects generated by helium ions. We did not register RETDs

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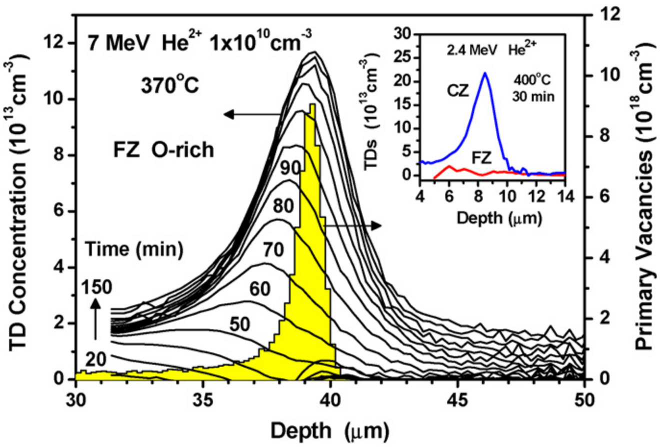


**Fig. 1.** Evolution of the excess donors in FZ oxygen-rich silicon irradiated with 7 MeV alphas to a fluence of $1 \times 10^{10}$ cm$^{-2}$ during isothermal annealing on air at 370 °C. The simulated profile of primary defects (vacancies) also is shown for reference. The inset shows profiles of excess donors in CZ and oxygen-lean FZ silicon irradiated with identical fluence of 2.4 MeV alphas (annealed on air at 400 °C for 30 min).

formation in helium irradiated oxygen-lean FZ silicon, while, in CZ silicon, RETDs were substantially enhanced (see the inset in Fig. 1). This indicates that RETDs are oxygen related TDs [4] and the level of RETD doping depends on concentration of oxygen interstitials ($O_i$).

Annealing of radiation defects (their deep levels) at 370 °C in the sample irradiated to a fluence of $1 \times 10^{10}$ cm$^{-2}$ is shown in Fig. 2 where DLTS spectra originating from electron traps are presented for identical $T_a$ as RETD profiles in Fig. 1. Since DLTS measurement covered full depth of the irradiated region, the height of DLTS peaks is proportional to average concentration of particular defects. Several peaks corresponding to radiation defects E1–E3 and defects arising during annealing A1–A6 were resolved and identified (see Table 1). The as irradiated sample contains only deep

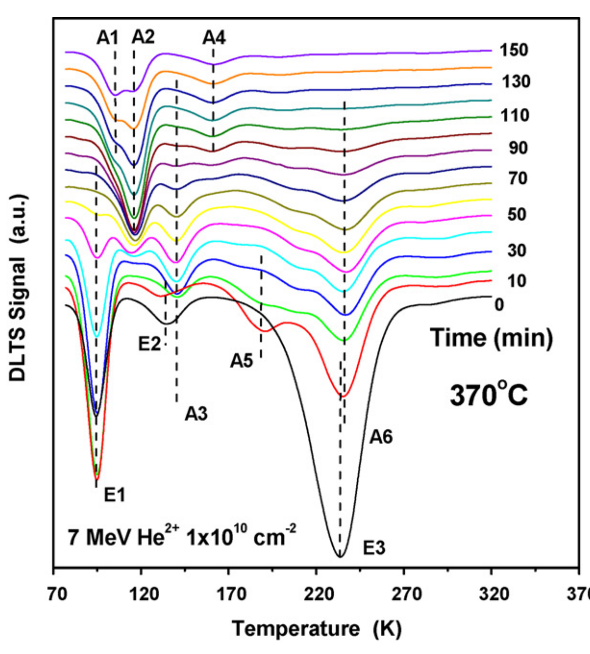


**Fig. 2.** Evolution of majority DLTS spectra of diodes irradiated with 7 MeV alphas to a fluence $1 \times 10^{10}$ cm$^{-2}$ with annealing time during isothermal anneal in air at 370 °C, rate window 260 s$^{-1}$.

**Table 1**
Survey of identified electron traps.

| Level | Bandgap position (eV) | Capture cross section (cm$^2$) | Identity |
|---|---|---|---|
| E1 | $E_C - 0.167$ | $4 \times 10^{-15}$ | $VO^{(-/0)} + C_i - C_s^{(-/0)}$ |
| E2 | $E_C - 0.252$ | $7 \times 10^{-15}$ | $V_2^{(=/-)}$ |
| E3 | $E_C - 0.436$ | $3 \times 10^{-15}$ | $V_2^{(-/0)}$ |
| A1 | $E_C - 0.181$ | $5 \times 10^{-15}$ | ? |
| A2 | $E_C - 0.211$ | $1 \times 10^{-14}$ | ? |
| A3 | $E_C - 0.238$ | $4 \times 10^{-15}$ | $V_2O^{(=/-)}$ |
| A4 | $E_C - 0.248$ | $3 \times 10^{-15}$ | ? |
| A5 | $E_C - 0.337$ | $2 \times 10^{-15}$ | ? |
| A6 | $E_C - 0.454$ | $7 \times 10^{-15}$ | $V_2O^{(-/0)}$ |

levels related to pure radiation defects, the vacancy-oxygen pair VO (acceptor level E1–$VO^{-/0}$) and the divacancy $V_2$ (the single- and double-acceptor levels E3 and E2–$V_2^{-/0}$ and $V_2^{=/-}$). First, divacancies anneal out by transformation to VO and divacancy-oxygen pairs (see new levels A6 and A3 corresponding to the single- and double-acceptor levels $V_2O^{-/0}$ and $V_2O^{=/-}$ of this center [5]). Next, VO pairs also anneal out either by transformation to electrically inactive $VO_2$ complex [6] or other defects (see level A2). Within this period ($T_a$ < 60 min), RETD generation is still not fully resolved, while, in the next 50 min, it substantially grows and finally ceases. This is accompanied by gradual disappearing of $V_2O$ centers. Simultaneously, new defects (see levels A1, A2, and A4), probably $V_n$ and $VO_n$ complexes, are appearing. They do not contribute to RETD formation since they anneal after creation of RETDs ($T_a$ > 100 min). Annealing of radiation defects in samples irradiated with higher fluences proceeds in similar way.

Time evolution of RETDs in sample irradiated to a fluence of $1 \times 10^{11}$ is shown in Fig. 3. To accelerate annealing of radiation defects, the annealing temperature was raised to 380 °C. This increased uniform generation of TDs for $T_a$ > 85 min (see the vertical shift of the profile). Again, RETDs evolve from irradiated surface and follow the distribution of radiation defects between irradiated surface and defect maximum. However, in the peak region, the RETD generation is limited by concentration of $O_i$ in the wafer. Therefore, the peak of the profile is cut and profile broadens. Higher fluences also imply a non-negligible amount of unannealed defects (deep acceptor centers [1]) making a drop on the measured C-V profiles close to damage maximum. This is evidenced in Fig. 4 which compares C-V profiles measured at 358 K (standard measurement)

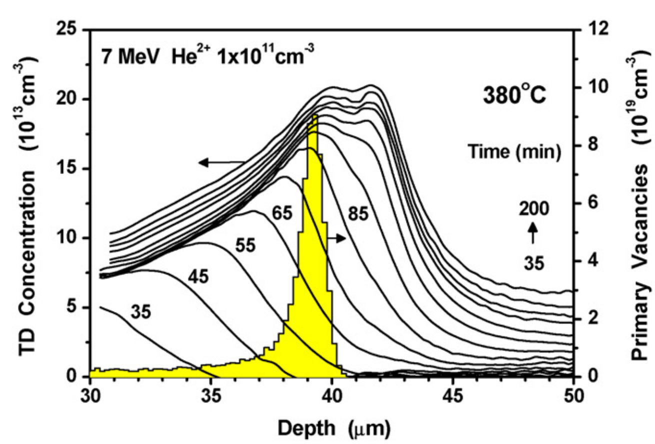


**Fig. 3.** Evolution of the excess donors in sample irradiated with 7 MeV alphas to a fluence of $1 \times 10^{11}$ cm$^{-2}$ during isothermal annealing in air at 380 °C.

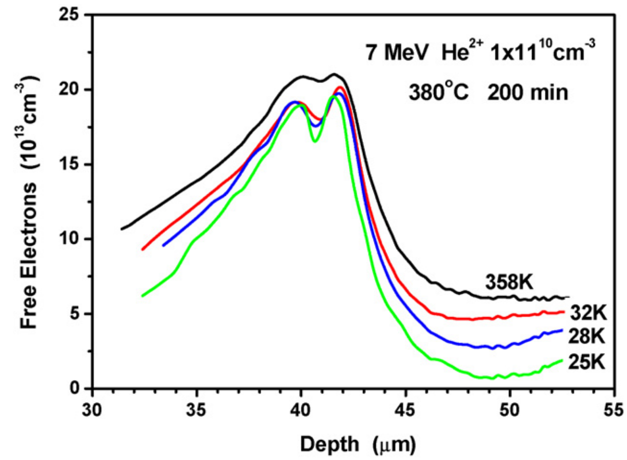


**Fig. 4.** Profiles of excess donors in sample irradiated with 7 MeV alphas to a fluence of $1 \times 10^{11}$ cm$^{-2}$ and annealed at 380 °C for 200 min (C-V profiles measured at 358, 32, 28, and 25 K).

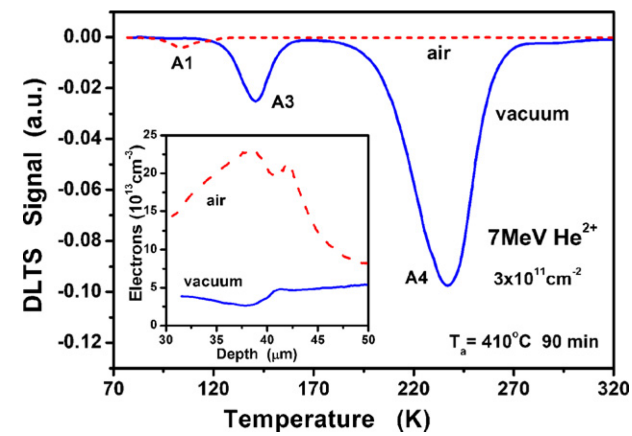


**Fig. 6.** DLTS spectra of samples irradiated with 7 MeV He$^{2+}$ ions to a fluence of $3 \times 10^{11}$ cm$^{-2}$ measured after annealing in air (dashed) or vacuum (solid) at 410 °C for 90 min. The corresponding profiles of free electrons obtained from C-V measurement are shown in the inset.

and 32, 28, and 25 K. Decreasing of temperature shifts Fermi level towards the conduction band. This ionizes acceptor levels A1, A2, and A4 and increases the noticeable drop on profile of free electrons at the depth of 41 μm. The donor concentration also uniformly drops between 32 and 25 K while the RETD profile remains unchanged. This indicates that RETDs are formed by different defects with shallower donor levels than bulk TDs .

Isochronal annealing at 410 °C of sample irradiated to a fluence of $3 \times 10^{11}$ cm$^{-2}$ (Fig. 5) confirms the conclusions presented above. RETD profile again evolves from the surface and saturates at the level of $1.5 \times 10^{14}$ cm$^{-3}$. Profile apparently broadens since the profile of radiation defects is cut closer to its foothill. For $T_a > 80$ min, the uniform generation of TDs again lifts up the measured profile and the drop in the damage peak caused by deep acceptors is now more pronounced.

Evolution of REDT profiles presented in Figs. 1, 3 and 5 clearly show that RETD generation is controlled by a catalyst diffusing from the surface. Position of the falling edge of the RETD profile is then given by its penetration depth (diffusion length). We analyzed time dependences of RETD penetration obtained on different samples and compared them with models corresponding to the diffusion from constant or limited source. The best fit was achieved for Gaussian distribution of the catalyst which well approximates

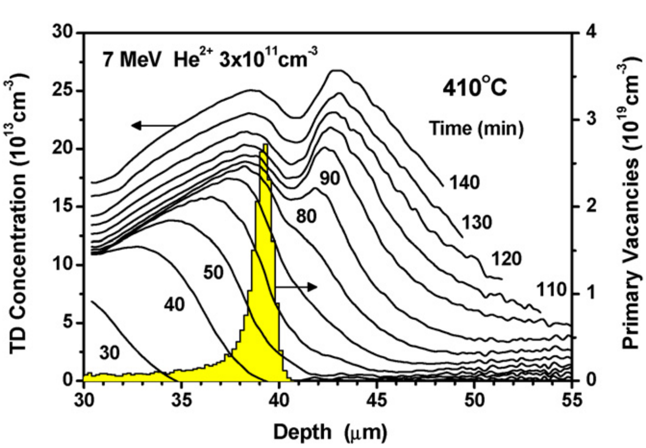


**Fig. 5.** Evolution of the excess donors in sample irradiated with 7 MeV alphas to a fluence of $3 \times 10^{11}$ cm$^{-2}$ during isothermal annealing in air at 410 °C.

the diffusion from approximately 5-μm thick sub-surface layer into silicon bulk with a diffusivity of 0.5 to $1.0 \times 10^{-9}$ cm$^2$ s$^{-1}$ (for annealing temperatures 370–410 °C). These magnitudes are substantially (about several orders) higher than those reported for oxygen or hydrogen-enhanced oxygen diffusion [7], but they are very close to values of hydrogen diffusivity measured in plasma-hydrogenated silicon annealed between 270 and 450 °C [8]. It is very probable, that hydrogen, which can be accumulated in the deep boron-doped anode layer in the form of hydrogen–boron pairs (either as a result of chemical etching or sintering of aluminum contacts) diffuses into silicon bulk and, within its penetration depth, enhances diffusivity of oxygen interstitials. This enables $O_i$ to react with radiation damage and generate RETDs at lower temperatures than those necessary for formation of ordinary TDs. Possible scenario may be enhanced generation of $VO_2$ centers by reaction $VO + O_i \rightarrow VO_2$ with subsequent formation of oxygen dimers $O_{2i}$ ($Si_i + VO_2 \rightarrow O_{2i}$) [9] what is the first step of oxygen agglomeration preceding TD formation [4]. The damaged layer is then a source of VO centers which also arise as a product of $V_2O$ dissociation ($V_2O \rightarrow VO + V$) [6]. However, we cannot exclude other mechanisms involving direct interaction of hydrogen with other radiation defects.

To confirm these conclusions, we also annealed helium-irradiated diodes in vacuum. In this case, we expected that hydrogen will out-diffuse from the diode and the RETD formation will be suppressed. Results are presented in Fig. 6 which compares DLTS spectra and C-V profiles of identically irradiated diodes annealed at 410 °C for 90 min in vacuum (solid) and air (dashed). Fig. 6 clearly shows that annealing in vacuum suppresses introduction of RETDs and annealing of $V_2O$ centers (see levels A3 and A4). This is in agreement with our hypothesis that hydrogen moderates transformation of radiation defects into TDs.

## 4. Conclusions

Irradiation of oxygen-rich silicon with helium ions followed by annealing in air at temperatures from 350 to 500 °C introduces a new type of TDs following the distribution of radiation defects. Their origin and evolution is moderated by hydrogen atoms diffusing from anode contact into silicon bulk. Hydrogen stimulates diffusion of oxygen interstitials and allows them to react with radiation defects to form RETDs. Therefore, the origin of RETDs in silicon is conditioned by simultaneous presence of hydrogen, interstitial oxygen and radiation defects containing vacancies and oxygen. At higher irradiation fluences or in the peak of radiation damage, concentration these centers and, consequently, RETDs growth saturates. As a result, profiles of RETDs are broader and flatter.

## Acknowledgements

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