The article presents results of systematic investigation on annealing of radiation defects introduced into n-type oxygen-rich float-zone silicon by single (7 MeV) and double energy (7 and 7.6 MeV) alpha-particle irradiation with fluences from $8.5 \times 10^8$ to $1 \times 10^{12}$ cm$^{-2}$. Effect of isochronal anneal in the temperature range from 100 to 500°C on introduced defects and their interaction was studied by deep level transient spectroscopy. Shallow donor levels arising during annealing were investigated by C-V profiling. It is shown that formation of thermal donors (TDs) in the temperature range from 375 to 500°C is significantly enhanced by radiation damage (vacancy-oxygen clusters) produced by alpha-particle irradiation.

1. Introduction

Nowadays, irradiation of silicon with high energy swift ions is irreplaceable tool for arbitrary lifetime control in silicon power devices. The irradiation introduces recombination centers locally and turn-off of irradiated device speeds-up without significant deterioration of static parameters. It is usually assumed that irradiation with alpha-particles, in contrast with protons, has no negative doping effects on irradiated device. Application of alphas therefore allows to maintain high blocking capability of irradiated devices and increase their safe operation area. However, irradiation has to be completed by annealing to stabilize introduced defects and remove undesirable defects, generation centers, which increase device leakage [1]. The annealing leads to formation of new centers in silicon band gap and also activates thermal donors (TDs) [2] if annealing temperature exceeds 350°C. The aim of this paper is to show a systematic investigation of defect interaction in silicon irradiated with high energy alphas using isochronal annealing in range from 100 to 500°C. The main emphasis is put on properties and evolution of new recombination centers, as well as enhanced formation of thermal donors.

2. Experimental

Recombination centers were investigated on commercial 100A/1700V planar p$^+nn^+$ chip diodes. The diodes were fabricated from the low-doped <100>-oriented float zone n-type silicon using field ring technology. Long thermal diffusion, which was required for production of deep anode (p$^+$) and cathode (n$^+$) emitters, enhanced concentration of oxygen in the samples. Radiation damages were introduced by single- (7 MeV) and double-energy (7 and 7.6 MeV) alpha-particle irradiation. The fluences of alphas ranged from $8.5 \times 10^8$ to $1 \times 10^{12}$ cm$^{-2}$. Isochronal (30 minutes) annealing in temperature range form 100 to 500°C was applied after irradiation. Deep levels resulted from irradiation and the subsequent isochronal annealing
were monitored by deep level transient spectroscopy using DLS-82 E spectrometer. Profiles of shallow levels were characterized using HP 4280 1MHz capacitance analyzer at temperature 85°C to eliminate influence of ionized deep acceptors. High level lifetime was calculated using open circuit voltage decay measurement (OCVD). Leakage current of samples was monitored at 85°C and reverse voltage of 300V.

2. Results and Discussion

Deep levels. Spectra corresponding to radiation defects appearing after irradiation with 7 MeV alphas to a fluence of $8.5 \times 10^8$ cm$^{-2}$ and their evolution during isochronal annealing up to 450°C are shown in Fig.1. DLTS spectrum of not annealed sample (n.a.) shows three major peaks that correspond to different deep levels in silicon bandgap which are attributed to the following defects: the vacancy-oxygen pair VO$^{(-/0)}$ at $E_C-0.163$eV (E1), the double charge state of divacancy $V_2^{(=/=)}$ at $E_C-0.252$eV (E2) and the single negative state of divacancy $V_2^{(-/0)}$ at $E_C-0.436$eV (E3) with a contribution the acceptor level of vacancy-phosphorous pair (VP$^{(-/0)}$). The spectrum also contains levels labeled as T1 and T2 which originate from diode fabrication since they were also detected in unirradiated samples. The dependence of the DLTS peak amplitude versus annealing temperature, which was received from spectra shown in Fig.1, is plotted in Fig.2.a. Figure shows that all deep centers are stable up to 150°C when VP pair (E–center) anneals out ($VP \leftrightarrow V+P$). The peak E3$^+$ at $E_C-0.425$ eV (see Fig.1) then can be attributed to pure divacancy $V_2^{(-/0)}$. During annealing of VP centers, part of free vacancies is being captured by interstitial oxygen and participates to formation of VO ($V+O \leftrightarrow VO$). This can explain slight reverse annealing of A-center (see Fig.2a). Annealing at 250°C shifts divacancy related peak E2 and E3$^+$ to A1 located at $E_C-0.238$ eV and A2 at $E_C-0.454$ eV. This shift is attributed to annealing of divacancy and formation of a new center $V_2O$ with two charge states $V_2O^{(-/0)}$ and $V_2O^{(=/=)}$ lying close to $V_2^{(=/=)}$ and $V_2^{(-/0)}$, respectively [3]. The new center forms as a result of reaction of divacancy with interstitial oxygen ($V_2+O_i\rightarrow V_2O$). This reaction facilitates annealing out of divacancy in oxygen rich silicon. Fig.2a shows that annealing above 350°C removes both VO and $V_2O$ centers.

Fig. 1. Majority carrier DLTS spectra of diode irradiated with alphas to a fluence of $8.5 \times 10^8$ cm$^{-2}$ measured after irradiation (n.a.) and subsequent isochronal annealing in range from 100 to 450°C (a). Two spectra recorded after annealing at 350 and 430°C for sample irradiated with alphas to fluence of $2 \times 10^{11}$ cm$^{-2}$ (b). Rate window of 260 s$^{-1}$ was used in both cases.
Fig. 2. Amplitude of DLTS signal of dominant deep levels after irradiation with 7 MeV alphas to fluence $8.5 \times 10^8 \text{ cm}^{-2}$ and consequent isochronal annealing (a). Proposal defect identification is shown in brackets. Normalized inverse lifetime for sample irradiated to fluence of $8.5 \times 10^8 \text{ cm}^{-2}$ and leakage current for samples irradiated to fluence $3 \times 10^{11} \text{ cm}^{-2}$ (b).

At higher temperatures, new defects are formed as a result of dissociation or reaction of VO and $V_2$ centers. This is evidenced by appearing of deep levels $A3$ at $E_C-0.181$ eV and $A4$ at $E_C-0.211$ eV. According to DLTS measurement, all new centers are localized in the defect peak maximum. Evolution of radiation defects and formation of the new centers is strongly influenced by irradiation fluence. Fig.1.b shows new peaks labeled as $A5$ ($E_C-0.248$ eV) and $A6$ ($E_C-0.44$ eV) in DLTS spectrum of sample irradiated to a fluence of $2 \times 10^{11} \text{ cm}^{-2}$ and subsequently annealed at 350 and 430°C, respectively. Both levels $A5$ and $A6$ are probably related to complexes consisting of multi-vacancies and oxygen $V_n$ and $VO_m$. Influence of defect thermal stability on normalized inverse lifetime and generation current is shown in Fig.2b for samples irradiated with low- and high-fluence of alphas. Decreasing of leakage current in temperature range from 85 to 200°C and corresponding increase of the carrier lifetime can be explained by annealing of unstable VP pairs. Between 200 and 275°C, the inverse lifetime increases due to additional formation of VO centers. Since these centers have negligible influence on carrier generation, the increase of VO concentration does not affect diode leakage. In agreement with results of DLTS measurement, for samples irradiated with low fluences, lifetime recovers after annealing at 425°C. In samples irradiated with higher fluences of alphas, new centers ($A5$, $A6$) remain after annealing at 400°C and contribute to increased leakage of diodes. In this case, the recovery of the carrier lifetime is also prolonged.

**Shallow levels.** At higher annealing temperatures (> 350°C), majority of the vacancy related defects is annealed out if lower irradiation fluences are applied ($5 \times 10^9 \text{ cm}^{-2}$). At these temperatures, C-V profiling shows enhanced formation of shallow donors at the depth close to the projected range $R_p$ of alphas. One can conclude that the enhanced formation of thermal donors is caused by an easier transformation of $O_i$ configuration supported by vacancies from annealed vacancy-related defects. At higher radiation fluences, temperatures exceeding 400°C are necessary to anneal more stable vacancy-oxygen complexes and to stimulate TDs formation. Since for higher fluences of alphas, the distribution of vacancy-related defects is shifted closer to the irradiated surface, the TDs distribution develops with temperature in a different way. This is depicted in Fig.3 where evolution of donor doping with temperature is compared for irradiation with 7 MeV (a) and for double irradiation with 7 and 7.6 MeV alphas.
Fig. 3. Evolution of excess donor doping with annealing temperature in FZ silicon irradiated with single 7 MeV (a) and double 7 and 7.6 MeV (b) energy of alphas to fluence of $1 \times 10^{11}$ cm$^{-2}$. Distributions of primary vacancies for 7 and 7.6 MeV irradiation are also shown.

(b) to fluence of $1 \times 10^{11}$ cm$^{-2}$. Higher annealing temperatures spread-out distribution of TDs well behind projected range of projectiles and make it more complex compared with single irradiation. It is clear from the Fig.3a and Fig.3b that TDs achieved their maximum concentration $1.3 \times 10^{14}$ cm$^{-3}$ at 475°C. This TDs saturation level was observed in all samples irradiated with high fluences of alphas and a finite concentration $O_i$ is found to be a limiting factor for TDs formation.

Conclusions

New recombination centers were investigated after isochronal annealing of FZ silicon irradiated with alpha-particles (7 and 7.6 MeV) in wide range of fluences. It is shown that annealing leads to formation of variety of new centers with energetic levels in silicon band gap. Their appearing is attributed to interaction of radiation defects created by alphas with intrinsic defects originated from FZ silicon. Results show that radiation damage (increased formation of vacancy-related defects) stimulates thermal donor formation during annealing at temperatures from 375 to 500°C. The evolution of the donors depends on alpha particle’s fluence and temperature of subsequent annealing. The maximum enhancement of TD’s formation is observed at 475°C. For higher fluences, the TD formation at the defect peak saturates due to the limited amount of interstitial oxygen.

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