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Lifetime control in silicon power P-i-N diode by ion irradiation: Suppression of undesired leakage

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Abstract

The irradiation with high-energy (7.35 MeV) protons through a set of energy degraders was used to suppress leakage of the silicon power diodes subjected to local lifetime control. The aim was to modify the profile of recombination centers and to reduce production of vacancy complexes. The high-energy proton irradiation was compared with standard local lifetime killing by high-energy alphas. Recombination centers arising from irradiation were characterized after irradiation and subsequent annealing at 220 and 350 °C by deep level transient spectroscopy and I–V profiling. Static and dynamic parameters of irradiated diodes were also measured and compared. Results show that the applied irradiation with protons provides 3–10 times lower leakage compared to standard alphas for equivalent reduction of the reverse recovery current maximum. On the other hand, the excessive formation of hydrogen donors at high proton fluences and their diffusion during annealing at 350° decreases diode blocking capability.

Keywords: Lifetime control; Silicon; Irradiation; Protons; Alphas; Power diodes

1. Introduction

Nowadays, the irradiation with alphas in combination with high-energy electrons is a dominant technique for setting the carrier lifetime in silicon P-i-N diodes [1]. It is widely accepted that the optimum position of the narrow and heavily damaged region produced by alphas, where carrier recombination is enhanced locally, is close to the anode junction [2,3]. Unfortunately, if high irradiation fluences are necessary, high concentration of defects (vacancy complexes) produced in this region drastically increases device leakage [4] and causes parasitic doping [3]. One way to eliminate this drawback is to modify the shape of the lifetime profile within the device. The goal may be, for example, decreasing of the peak defect concentration or/and placement of the majority of the defects to the position where they are not harmful, e.g. outside the space charge region (SCR) of the anode junction. Another possibility is the suppression of vacancy complexes generation using local irradiation by lighter projectiles (low energy electrons) [5,6] or application of lifetime killing based on more appropriate recombination centers, e.g. platinum atoms. However, in this case, an adequate method capable of axial profile shaping comparable to irradiation techniques should be developed [7–9].

In this paper, we compare the traditional local lifetime reduction by alpha-particle irradiation with lifetime killing using a wide defect peak (or its part) produced by proton irradiation with relatively high-energy (>7 MeV). The impact of both techniques on device parameters is evaluated for two types of post-irradiation annealing, which were used for radiation defect stabilization: the low temperature annealing at 220 °C, which is usually applied on wafer devices, and annealing at 350 °C which is used for chip devices soldered into modules.

2. Experimental

The device under test was a planar 100 A/1700 V $P^+PN^-N^+$ chip diode produced on the low-doped ⟨100⟩-oriented FZ n-type silicon substrate. The diode contact area was $11\times5.2\,mm^2$. The doping profile of the diode and concentration profiles of recombination centers, which were introduced for lifetime reduction, are shown in Fig. 1. The reference local lifetime reduction was done by standard irradiation with alphas at fluences ranging from 2×10^{10} to $1\times10^{12}\,cm^{-2}$. The alpha's range was set into two qualitatively different regions, the anode emitter (region A) and the n-base side of the anode p–n junction (region B) covering the most important locations from the point of application. A wide Gaussian peak of recombination centers was introduced by the high-energy (7.35 MeV) proton irradiation with fluences from

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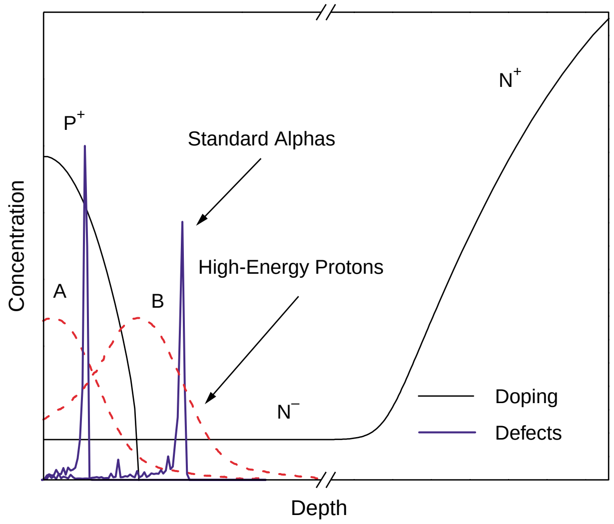

Fig. 1. Doping profile of the $P^+PN^-N^+$ diode with concentration profiles of recombination centers which were introduced by alphas and high-energy protons. Two locations of the damage peak, the anode (A) and the base side of the anode junction (B), were used for both projectiles.

1.4×10^{10} to 2×10^{12} cm^{-2}. Different sets of aluminum foils were placed on the front side of the diodes during irradiation. This allowed us to change the position of the peak relatively to the anode junction. The first, thickest foil set produced a sloping profile consisting only of the deeper side of the Gaussian peak. This profile was placed in the anode (region A) to coincide with anode doping (see Fig. 1). The second set located the defect peak directly into the anode PN junction (region B), and the third one, which placed the defect peak into the N-base, served only for characterization of defect distribution. After irradiation, diodes were annealed for 40 min in furnace at 220 or 350 °C.

Defects produced by irradiation and subsequent annealing were characterized by capacitance deep level transient spectroscopy (C-DLTS), high-voltage current transient spectroscopy (HVCTS) [10], I–V [11] and C-V profiling. Static and dynamic parameters of modified diodes were recorded and compared to those measured before irradiation. The forward I–V characteristics were measured in a four point arrangement at 30±0.1 °C under constant loading to minimize effect of contact resistance variation. To minimize self-heating effects, a pulse measurement principle was applied. The static reverse I–V curves were registered at 30 and 60 °C. The reverse recovery waveforms were measured at room temperature under the conditions of resistive switching where the commutation di/dt is controlled by the active switch. The diodes were switched from the ON-state operation with the forward currents $I_F=25$ A and $I_F=2$ A to the OFF-state condition with $V_{DC}=500$ V.

3. Results and discussion

3.1. Recombination centers

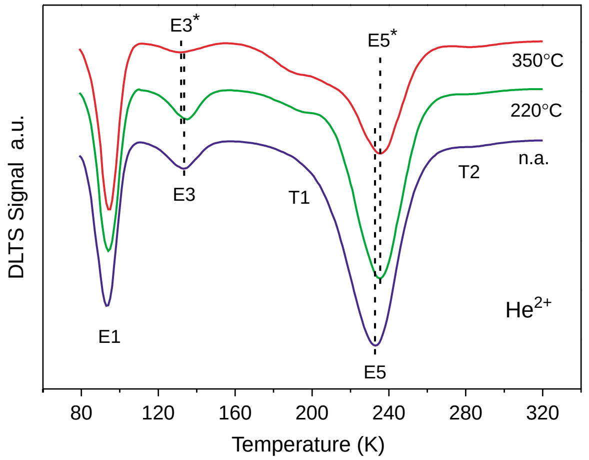

Fig. 2. Majority carrier DLTS spectra of $P^+PN^-N^+$ diode irradiated with 7 MeV alphas measured after irradiation (n.a.), and isochronal 40 min annealing at 220 and 350 °C, rate window 260 s^{-1}.

C-DLTS spectra of majority carrier (electron) traps measured on diodes irradiated with alpha particles and protons into region B are shown in Figs. 2 and 3, respectively. The figures contain spectra recorded after irradiation on not annealed (n.a.) samples, and on diodes which were subsequently annealed at 220 and 350 °C. Table 1 collects the identification parameters of resolved levels labeled E1–E7, T1, T2 and their attribution to particular lattice defects. Only deep levels given by pure radiation defects, the divacancy (E3, E5) and the vacancy-oxygen pair (E1), are clearly resolved in the spectrum measured on the diode irradiated with alphas prior to annealing. Two minor peaks labeled as T1 and T2, which were already registered in the spectra of unirradiated diodes, are supposed to be given by deep traps induced by diode fabrication. For carrier recombination, the most significant deep level is the acceptor level of the vacancy-oxygen pair $VO^{-/0}$ at $E_C-0.167$ eV (E1) and the single-acceptor level of divacancy $V_2^{-/0}$ at $E_C-0.436$ eV (E5) [2,3]. Their actual influence on carrier lifetime is given by their concentration ratio. Lighter projectiles, protons and especially low-energy electrons [6], produce simple radiation defects, intersitials and vacancies, which subsequently pair with impurities giving rise

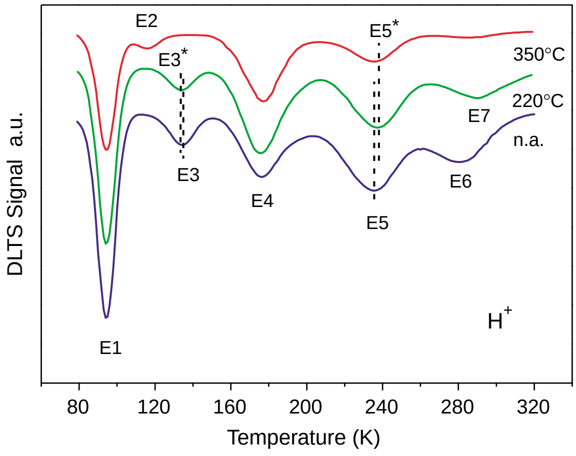

Fig. 3. Majority carrier DLTS spectra of $P^+PN^-N^+$ diode irradiated with 7.35 MeV protons measured after irradiation (n.a.), and isochronal 40 min annealing at 220 and 350 °C, rate window 260 s^{-1}.