Lithuanian Journal of Physics, Vol. **48**, No. 4, pp. 325–331 (2008) doi:10.3952/lithjphys.48403

ANNEAL-INDUCED VARIATIONS OF THE RECOMBINATION CHARACTERISTICS IN 2 MeV PROTON IRRADIATED Si STRUCTURES

J. Višniakov, T. Čeponis, E. Gaubas, and A. Uleckas

Institute of Materials Science and Applied Research, Vilnius University, Saulėtekio 10, LT-10223 Vilnius, Lithuania
E-mail: j.visniakov@post.skynet.lt, eugenijus.gaubas@ff.vu.lt

Received 17 July 2008; revised 25 September 2008; accepted 4 December 2008

Comparative study of the carrier recombination and generation lifetime as well as reverse recovery durations, dependent on proton irradiation fluence and annealing regimes, has been performed on FZ silicon PIN diodes and wafer structures. The samples were irradiated by 2 MeV protons with fluences in the range of $7{\cdot}10^{12}$–$7{\cdot}10^{14}$ p/cm^2. Carrier decay constituents and values of recombination lifetime have been evaluated by employing a microwave probed photoconductivity transient technique, while deep level spectra ascribed to variations of generation lifetime have been examined by exploiting capacitance deep level transient spectroscopy (DLTS). Variations of six DLTS peaks are examined under 24 h isochronal annealings in the range of temperatures from 80 to 320 °C, to clarify threshold of annealing out of the specific traps. Fluence-dependent variations of the effective carrier recombination lifetime in wafer samples after isochronal annealing indicate a weak change in density of the recombination centres. The latter can be ascribed to cluster defects. Fluence-dependent variations of the reverse recovery time (RRT) in diodes after isochronal annealing imply the rearrangement of the recombination and trapping centres, probably within a space charge region (SCR) of clusters.

Keywords: carrier lifetime, reverse recovery time, microwave probed photoconductivity, deep level transient spectroscopy, proton irradiations, radiation defects

PACS: 61.72.J-, 61.82.Fk, 72.40.+w

1. Introduction

The reverse recovery time of PIN diodes directly depends on the carrier recombination lifetime in vicinity of the device active layers [1]. It is desirable to coordinate an introduction of the recombination centres into the diode base region, responsible for the reverse recovery time (RRT) from the on-state conduction modulation regime within i-layer, with inevitable creation of the generation traps, which determine a leakage current of PIN diode [2–7]. This issue can be partially solved when technological handling of the type of recombination / generation defects and position of levels within band gap, associated with these defects, is feasible. Actually, different traps usually compete within processes of carrier generation and recombination. Also, it can be that different defects determine carrier recombination lifetime at low and high injection level [5]. Therefore, only a trade-off between the densities of recombination and generation centres can be optimized by combining procedures of defect introduction and annealing out. The reverse recovery pulse shape significantly pertains to location and distribution of the fast recombination centres. To avoid inductance effects by implementing a soft diode switching regime, a ratio between a distance of the enhanced recombination layer from junction and the thickness of i-layer should be increased. However, this leads to a necessity of the base thickness shortening. The latter condition comes into contradiction with requirement of a rather thick base region to keep the high voltage of diode reverse breakdown [1]. Complementarily, introduction of fast recombination centres increases the resistivity of diode base material and, consequently, the on-state voltage drop (V_F) [4]. Thus, additional contradiction between dynamic and static diode parameters appears. In general, only partial optimization within multi-factor task can be achieved by trade-off between the dynamic and static parameters in technology of fast high power diodes. The modern technologies [2–6] of the improved reverse recovery and voltage drop of the on-state junction characteristics are based on elaborated radiation and heat treatment techniques [1–6] for industrial fabrication of the commercial high-voltage high-frequency diodes.

© Lithuanian Physical Society, 2008
© Lithuanian Academy of Sciences, 2008
ISSN 1648-8504

In this work, a study of the carrier lifetime as well as reverse recovery time constants (RRT) has been performed on float zone (FZ) silicon PIN diodes and wafer structures to identify the optimal technological steps for formation by irradiations of δ-layer of the enhanced recombination and to suppress generation centres by annealings. To determine the dominant radiation defects and to reveal the optimal their depth distribution, the concerted investigations have been performed by employing a microwave probed photoconductivity transient technique (MW-PC), capacitance deep level transient spectroscopy (C-DLTS), and RRT as well as V_F measurements. Depth distribution of the recombination lifetime has been controlled by the cross-sectional scans of the excess carrier lifetime by using MW-PC technique. Fluence dependent variations of the reverse recovery time and recombination lifetime after 24 h isochronal annealings in the range of temperatures of 80–320 °C imply the rearrangement of the trapping centres, probably, within space charge region (SCR) surrounding the clusters, while a relatively small increase of the recombination lifetime has been obtained.

2. Samples, irradiations, and annealings

Two sets of samples, namely, industrial n–n^+ substrates and the standard industrial PIN diodes have been examined. Samples were irradiated with different fluences of 1.9–2 MeV protons. Substrate wafer samples were used to examine lifetime variations by contactless technique of MW-PC. To examine lifetime variations with irradiation fluence and to compare with such characteristics obtained for Si material irradiated with penetrative particles, the n-layer depth integrated carrier lifetime values have been examined on wafer samples. The diodes were exploited for investigations of the C-DLTS, RRT, and diode on-state voltage drop V_F characteristics in the as-irradiated and heat treated FZ Si structures.

The proton irradiations were performed by using a proton accelerator at Helsinki University. The irradiations were arranged to form a δ-layer of the enhanced recombination within either n-layer of substrates or n-base, i. e. i-layer of PIN diodes. A depth-position of the δ-layer relatively to a p^+–n junction was varied by changing the energy of proton beam. Position of the δ-layer was controlled by MW-PC cross-sectional scan profiling of carrier lifetime after irradiation. Density of radiation defects was varied by changing irradiation fluence in the range of $7 \cdot 10^{12}$–$7 \cdot 10^{14}$ p/cm^2.

To suppress carrier generation centres, the isochronal annealings for 24 h were performed by varying heat treatment temperature in the range from 80 to 320 °C. Characteristics of the recombination and carrier trapping were examined after each step of heat treatment.

3. Measurement techniques and instruments

Excess carrier decays were examined by MW-PC technique [7, 8]. Excess carriers were generated by a laser operating at 1062 nm wavelength with pulses of 500 ps. A single-mode fibre excitation beam with cross-section diameter of 3–10 μm was exploited for excitation in a cross-sectional scan regime. A pulsed excited area of the sample was probed with microwaves at 22 GHz by using either a slit of 120 μm, for depth-integrated lifetime measurements, or a needle-tip antenna for cross-sectional scans, in order to obtain a high spatial resolution. The excess carrier decay transients were recorded by a digital oscilloscope TDS-5104 with time resolution of 1 ns.

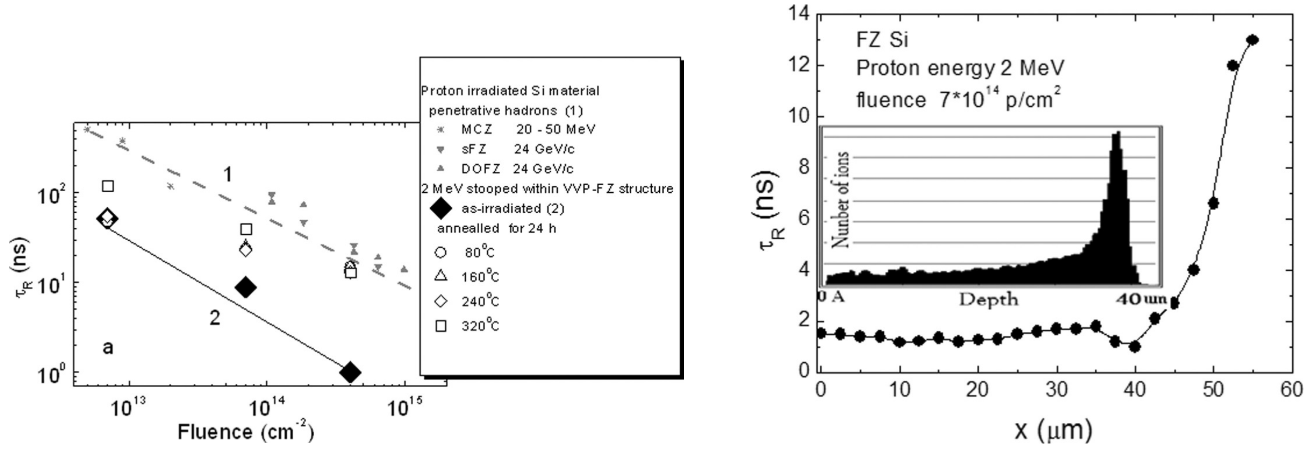
C-DLTS measurements were performed to identify carrier trapping centres [7, 9, 10]. The DLTS spectra were recorded by employing a commercial spectrometer DLS-82E.

Measurements of RRT and V_F were carried out by an industrial TD2050 tester. Reverse recovery time τ_{RR} in diodes is determined at 10 or 25% level of the reverse recovery current I_{RRmax}. A forward current with pulse duration of 30 μs can be varied in the range of 0.5–15 A. Current drop rate dI/dt is varied in the range of 10–50 A/μs. This tester is designed to measure the τ_{RR} values in the range from 10 ns to 4 μs.

4. Results and discussion

Carrier decays containing several components within the depth-integrated transients have been observed in n-Si wafer substrates. Transients containing a short initial stage together with a convex shape constituent in the carrier density relaxation mid-stage and exponential asymptote indicate that carrier diffusion towards δ-layer of enhanced recombination is significant. Carrier lifetimes ascribed to the initial and asymptotic single-exponential decay components decrease with proton irradiation fluence [7].

The recombination lifetime values extracted from these transients are plotted in Fig. 1(a) as a function of 2 MeV proton irradiation fluence. Fluence-dependent lifetime variations for 2 MeV protons are compared in



(a) (b)

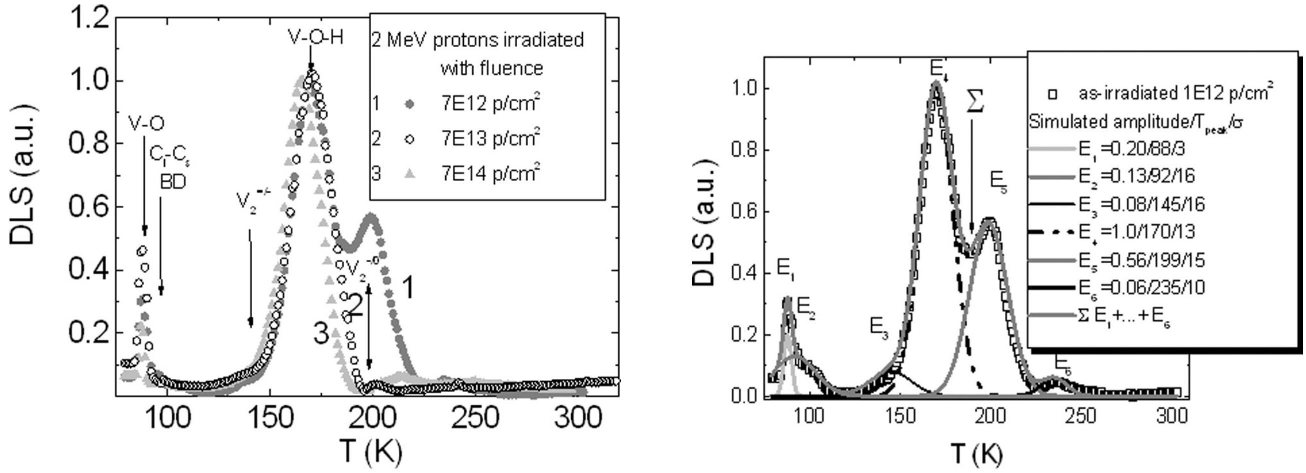
Fig. 1. (a) Carrier recombination lifetime in different n-Si materials as a function of the irradiation fluence. MCZ are magnetic field applied Czochralski grown, sFZ are CERN standard float zone, DOFZ are diffusion oxygenated float zone, FZ (VVP) are float zone moderately doped materials. The MCZ, sFZ, and DOFZ samples were irradiated by penetrative (20 MeV – 24 GeV) protons. 2 MeV protons were stopped within diode base of moderately doped VVP-FZ material. The as-irradiated and isochronally annealed at temperatures of 80, 160, 240, and 320 °C, respectively, samples of the VVP-FZ material were examined. (b) Recombination lifetime depth-profile in the as-irradiated material is compared with TRIM simulated defect distribution induced by 2 MeV protons of fluence of $7\cdot10^{14}$ cm^{-2}.

Fig. 1(a) with such a nearly linear dependence obtained for the FZ n-Si samples of the same thickness irradiated with penetrative protons of 50 MeV – 24 GeV energies. Values of the excess carrier recombination lifetime, τ_R, in the FZ n-Si as-irradiated with 2 MeV protons are significantly decreased relatively to those in the same non-irradiated sample. These values exhibit also a nearly linear decrease with enhancement of fluence. However, lifetime in the latter dependence is considerably shorter compared to those measured after irradiation with penetrative protons and neutrons [8] of the same fluence. This result confirms that radiation damage is more efficient within a stopping range of 2 MeV protons than that obtained under irradiation with penetrative hadrons.

A depth-profile of recombination lifetime variations, measured by MW-PC cross-sectional scans, within depth of 2 MeV proton irradiated n-Si wafer is illustrated in Fig. 1(b) for irradiation fluence of $7\cdot10^{14}$ p/cm^2. This profile correlates rather well with that of defect introduction profile simulated by TRIM (TRansport of Ions in Matter) program. A sharp step behind the stopping range of 2 MeV protons indicates a position of δ-layer a little bit smoothed by the excess carrier diffusion towards a range of enhanced recombination. The recombination lifetime profiling proves a possibility to design rather well a positioning of δ-layer within diode structure by varying the energy of proton beam. There is some uncertainty due to a simultaneous action of several radiation induced emission / recombination centres which differ respectively in their introduction rates and type.

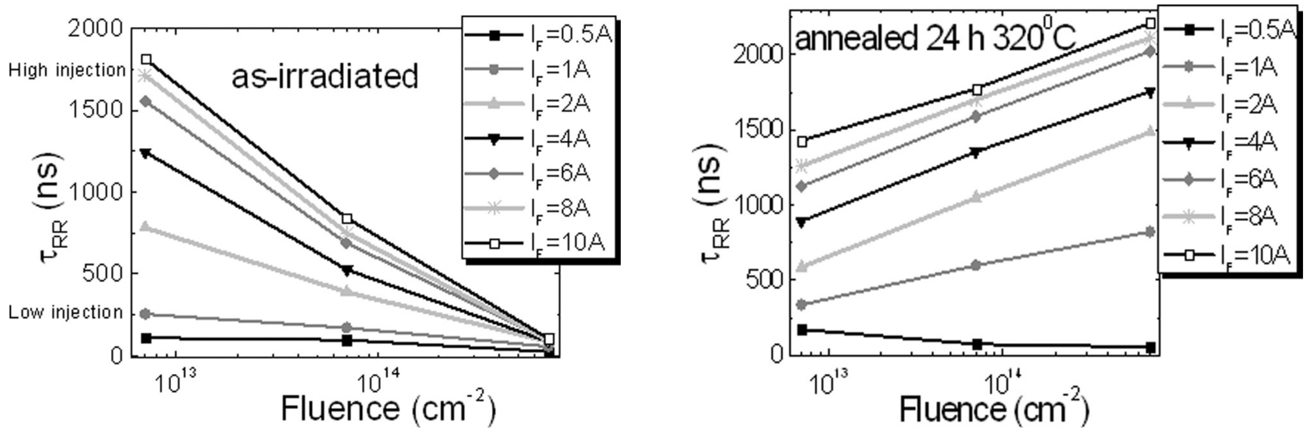
A comparison of parameters of the dominant generation centres in the as-irradiated structures, determined from the C-DLTS, is presented in Fig. 2. Three main DLTS peaks at 90, 140, and 250 K have been obtained at the same lock-in filtering and carrier injection parameters. These peaks are well-known in literature [9, 10] as caused by radiation defects and ascribed to vacancy related centres. The peaks are denoted by a widely accepted signature in Fig. 2, namely, as manifestation of a vacancy-oxygen complex and divacancy of =/− as well as −/0 charged states, respectively. Activation energy of the latter centres has been evaluated from the Arrhenius plots and found to be close to values published in literature. The DLTS peak at around 170 K was observed in the hadron heavily irradiated Si detectors [11] and debated as a feature of either inter-centre recombination [12], or cluster type defects [3, 13–15] and VOH complex [5, 6]. A position of the latter peak in between of $V_2^{=/-}$ and $V_2^{-/0}$ peaks within a DLTS spectrum and the strongest amplitude hint at vacancy ascribed clusters.

To follow evolution and transforms of the DLTS spectra dependent on fluence and isochronal annealings, a spectrum was simulated by using up to six peaks shown in Fig. 2(b). The simulated distribution of emission rates enables one to separate a shift of peaks, possible due to incomplete filling of traps, from emergence of the additional and complex traps under either increased radiation damage with fluence or defect transforms due to heat treatments. It can be clearly observed that amplitude of peaks, attributed to $V_2^{=/-}$ and $V_2^{-/0}$ defects,



(a) (b)

Fig. 2. (a) Evolution of the DLTS spectra in diodes, irradiated by 2 MeV protons, with enhancement of irradiation fluence (*1–3*). Amplitudes within a single spectrum are normalized to the strongest peak at 170 K. (b) Simulated distribution of composed DLTS peaks.



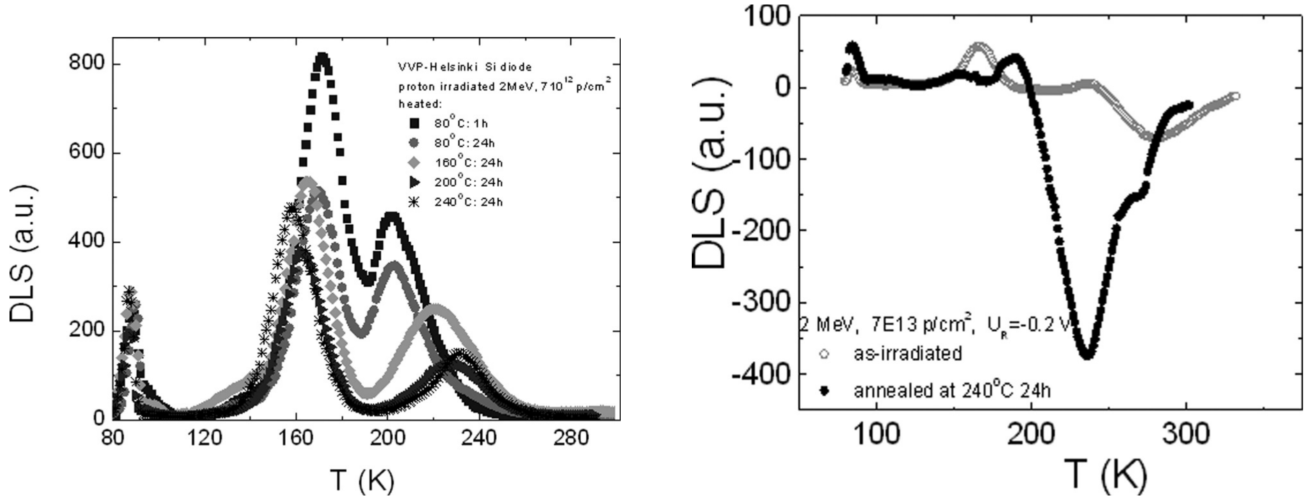
(a) (b)

Fig. 3. Fluence-dependent variations of the reverse recovery time in diodes of VVP-FZ Si (a) after irradiation with 2 MeV protons and (b) under annealing at 320 °C for 24 hours.

decreases significantly with enhancement of proton fluence while impact of a peak at 170 K grows within carrier capture / emission processes. This implies a conglomeration of the point defects, when their density increases and distances among them shorten with enhancement of fluence. Alternatively, a 170 K DLTS peak can be also ascribed to hydrogen attributed (VOH) defects with an increase of implantation fluence [16].

Fluence and on-stage current I_F dependent variations of the diode reverse recovery time τ_{RR} decrease with fluence at low carrier injection level (Fig. 3(a)). The absolute τ_{RR} values correlate with carrier recombination lifetime (Fig. 1) only in diodes irradiated with the highest fluences for all the I_F's range. Enhanced τ_{RR} values are obtained at high injection level ($\sim I_F$) for relatively low and moderate irradiation fluences. This can be explained by carrier diffusion gradients towards a δ-layer within a diode base and by an increase of the excess carrier recombination lifetime with carrier density within frame of a simple Shockley–Read–Hall (S–R–H) statistics through a dominant centre. After isochronal annealings, the τ_{RR}–I_F characteristics change their behaviour as a function of irradiation fluence, as shown in Fig. 3(b), namely, τ_{RR} decreases with fluence only for the lowest injection levels (I_F), while it behaves conversely for higher injection levels. This straightforwardly indicates the change of the dominant recombination / trapping centres within diode base.

A partial annealing of recombination centres is also confirmed within fluence dependences of recombination lifetime measured after heat treatments, shown in Fig. 1(a). However, variation of values of the recombination lifetime with isochronal annealing temperature does not exceed several times, and these changes dif-



(a) (b)

Fig. 4. (a) Variation of DLTS spectra for majority carrier traps with temperature of the 24 h isochronal annealing in $7{\cdot}10^{12}$ cm^{-2} fluence irradiated diode. (b) Comparison of the DLTS spectra for minority carrier traps in the as-irradiated and 24 h isochronally annealed sample.

fer for various irradiation fluences. This result hints on more complicated transforms of the defect structure under heat treatments.

The anneal-induced transforms of a structure of deep level spectrum and density of electrically active emission traps are corroborated within evolution of DLTS spectra, illustrated in Fig. 4(a), for $7{\cdot}10^{12}$ cm^{-2} fluence irradiated diode.

An amplitude of DLTS peaks associated with majority carrier traps, dominant in the as-irradiated material, decreases with enhancement of annealing temperature indicating a seemingly shift of peaks within spectrum, excepted VO centre. This visible shift of the DLTS peaks can be composed by simulating a change in relative amplitudes of additional traps, as illustrated in Fig. 2(b). In more precise simulations, a small shift of peaks ascribed to specific traps within temperature scale should be also involved, which can be attributed to trap filling effects discussed in literature [9, 14, 16]. A range of temperature shifts of the specific peaks is denoted in the legend of Fig. 5. Then, annealing of the specific traps can be examined via variations of their amplitude as a function of a heat treatment temperature. The latter dependences are shown in Fig. 5 for $7{\cdot}10^{13}$ cm^{-2} fluence irradiated diode.

It can be noticed that the density of VO centres (E_1) is nearly independent of annealings. Double-charged divacancy ($V_2^{=/-}$, E_3) shows a small increase in density. Densities of centres ascribed to the single-charged divacancy ($V_2^{-/0}$, E_5) and VOH (E_4) defects feature the annealing out for temperatures above 160 °C. Density of the deepest emission centre (E_6), associated with V_n complexes [14–16], behaves non-monotonically with

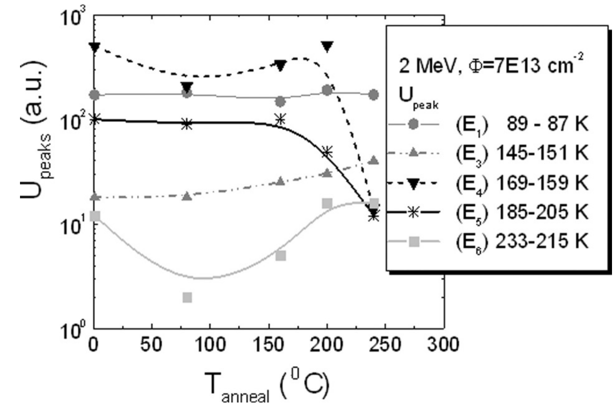


Fig. 5. Variation of relative amplitudes of simulated distribution of peaks in the DLTS spectra, shown in Fig. 4(a), with annealing temperature. A range of temperature shifts of specific peaks is denoted in the legend.

increase of the heat treatment temperature. The E_2 centre, which appears in the DLTS spectra as a broad pedestal for a VO peak, seems to be caused by bistable thermodonors (BD) and carbon (C_i-C_s) attributed centres [17, 18], while it is omitted from consideration in Fig. 5.

Together with transforms of the DLTS spectra for majority carrier traps, a significant increase in density of deep minority carrier traps appears under isochronal annealing, as shown in Fig. 4(b) for $7{\cdot}10^{13}$ cm^{-2} fluence irradiated diode. The spectra of minority carriers were recorded by using forward injection pulses in vicinity of zero voltage of reverse biasing. There, DLTS peaks of inverse polarity and of low amplitude, attributed to majority carrier traps, are also visible in Fig. 4(b). The traps of holes, as minority carriers, manifested by a DLTS peak of large amplitude can be tentatively ascribed to the Γ centre, characterized by the same temperature range of the peak location, revealed in the spectra of thermo-stimulated currents (TSC) [17].

Qualitatively, the same anneal-induced transforms of DLTS spectra were obtained for samples irradiated by various fluences in the examined range, while absolute densities of the specific traps vary with irradiation fluence. However, density of VO and E_2 centres changes only few times over the entire range of fluences examined.

The observed variations of the recombination characteristics in FZ n-Si structures hint on creation and interplay of the point and extended defects within projectile range of the 2 MeV protons. On the one hand, carrier recombination lifetime in wafer samples after 24 h isochronal annealing out at temperatures in the range from 80 to 320 °C indicates only a rather weak annealing of the recombination centres (Fig. 1(a)). The latter feature additionally depends on the proton irradiation fluence. On the other hand, a drastic change is obtained in DLTS spectra under isochronal annealing (Fig. 4(a, b)) for both majority and minority carrier trapping centres, which interact, however, only with a subsystem of one (either valence or conductivity) band. Heat treatment induced transformations of the DLTS traps, which determine the carrier generation lifetime and leakage current, seem to make a rather weak influence on redistribution of carrier recombination flows. Changes of the RRT characteristics (Fig. 3), induced by heat treatments, imply competition between the recombination and trapping centres. The effective diode switching time depends on filling and, probably, dynamic screening of barriers around these complex defects. Based on the models of radiation created clusters [15, 16], it can be assumed that recombination centres are attributed to cluster core states while generation traps are ascribed to the space charge regions (SCR) around the extended defects.

5. Summary

Recombination lifetime decreases from hundreds to few of ns in the proton as-irradiated FZ n-Si with increase of fluence from $7\cdot10^{12}$ to $7\cdot10^{14}$ $\mathrm{p/cm^2}$. Recombination lifetime depth-profile correlates with TRIM simulated defect creation profile within stopping range of 2 MeV protons. Inhomogeneous depth distribution of recombination lifetime satisfies a formation of the δ-layer of enhanced recombination in vicinity of the p^+–n junction of PIN diodes. These characteristics correlate rather well with reverse recovery time constants measured in the as-irradiated PIN diodes at low injection level.

Spectra of deep levels ascribed to generation lifetime contain up to six peaks for majority carriers and a peak for minority carrier traps in the as-irradiated diodes. DLTS spectra show an increase of the amplitude of a DLTS peak at 170 K with irradiation fluence for majority carrier traps. Fluence-dependent variations of the effective carrier recombination lifetime in wafer samples after 24 h isochronal annealing at temperatures ranging from 80 to 320 °C indicate a weak annealing of the recombination centres. The latter can be ascribed to cluster defects. Fluence dependent variations of the reverse recovery time in diodes after 24 h isochronal annealings in the range of temperatures from 160 to 320 °C imply the rearrangement of the recombination and trapping centres, probably within SCR of clusters.

Acknowledgement

This work was partially supported by the Lithuanian State Science and Studies Foundation.

References

[1] B.Y. Baliga, *Power Semiconductor Devices* (PWS Publishing Company, Boston, 1995).

[2] J. Vobecký and P. Hazdra, Radiation-enhanced diffusion of palladium for a local lifetime control in power devices, IEEE Trans. Electron Devices **54**, 1521–1526 (2007).

[3] R. Siemieniec, H.-J. Schulze, F.-J. Niedernostheide, W. Sudkamp, and J. Lutz, Compensation and doping effects in heavily helium-radiated silicon for power device applications, Microelectron. J. **37**, 204–212 (2006).

[4] J. Vobecký, P. Hazdra, and V. Záhlava, Helium irradiated high-power P-i-N diode with low ON-state voltage drop, Solid-State Electron. **47**, 45–50 (2003).

[5] P. Hazdra and V. Komarnitskyy, Lifetime control in silicon power P-i-N diode by ion irradiation: Suppression of undesired leakage, Microelectron. J. **37**, 197–203 (2006).

[6] S.M. Kang, T.J. Eom, S.J. Kim, H.W. Kim, J.Y. Cho, and Chongmu Lee, Reverse recovery characteristics and defect distribution in an electron-irradiated silicon p-n junction diode, Mater. Chem. Phys. **84**, 187–191 (2004).

[7] J. Višniakov, E. Gaubas, T. Čeponis, A. Uleckas, J. Raisanen, and S. Vayrynen, Comparative investigation of recombination characteristics in proton and electron irradiated Si structures, Lithuanian J. Phys. **48**, 137–144 (2008).

[8] E. Gaubas, A. Kadys, A. Uleckas, and J. Vaitkus, Investigation of carrier recombination in Si heavily irradiated by neutrons, Acta Phys. Pol. A **113**, 837–840 (2008).

[9] J.H. Bleka, L. Murin, E.V. Monakhov, B.S. Avset, and B.G. Svensson, On the identity of a crucial defect contribution to leakage current in silicon particle detectors, Appl. Phys. Lett. **92**, 132102 (2008).

[10] M. Mikelsen, J.H. Bleka, J.S. Christensen, E.V. Monakhov, B.G. Svensson, J. Harkonen, and B.S. Avset, Annealing of divacancy-oxygen and vacancy-oxygen complexes in silicon, Phys. Rev. B **75**, 155202 (2007).

[11] S. Watts, Radiation induced defects in silicon, in: *High Purity Silicon V*, Eds. C.L. Claeys, P. Rai-Choudhury, M. Watanabe, P. Stallhofer, and H.J. Dawson, Proc. Electrochem. Soc. **PV 98-13**, Boston, Massachusetts, Fall 1998.

[12] S.J. Watts, J. Matheson, I.H. Hopkins-Bond, A. Holmes-Siedle, A. Mohammadzadeh, and R. Pace, A new model for generation-recombination in silicon depletion regions after neutron irradiation, IEEE Trans. Nucl. Sci. **43**, 2587–2594 (1996).

[13] K. Gill, G. Hall, and B. MacEvoy, Bulk damage effects in irradiated silicon detectors due to clustered divacancies, J. Appl. Phys. **82**, 126–136 (1997).

[14] R.M. Fleming, C.H. Seager, D.V. Lang, P.J. Cooper, E. Bielejec, and J.M. Campbell, Effects of clustering on the properties of defects in neutron irradiated silicon, J. Appl. Phys. **102**, 043711 (2007).

[15] P.F. Ermolov, D.E. Karmanov, A.K. Leflat, V.M. Manankov, M.M. Merkin, and E.K. Shabalina, Neutron induced effects conditioned by the divacancy clusters with the tetravacancy core in a float zone silicon, Semiconductors 36, 1114–1122 (2002).

[16] P. Pellegrino, P. Lévêque, J. Lalita, A. Hallén, C. Jagadish, and B.G. Svensson, Annealing kinetics of vacancy related defects in low-dose MeV self-ion-implanted n-type silicon, Phys. Rev. B **64**, 195211 (2001).

[17] I. Pintilie, E. Fretwurst, G. Lindström, and J. Stahl, Results on defects induced by ^{60}Co gamma irradiation in standard and oxygen-enriched silicon, Nucl. Instrum. Methods A **514**, 18–24 (2003).

[18] V. Boisvert, J.L. Lindström, M. Moll, L.I. Murin, and I. Pintilie, Characterization of oxygen dimer-enriched silicon detectors, Nucl. Instrum. Methods A **552**, 49–55 (2005).

REKOMBINACIJOS CHARAKTERISTIKŲ KITIMAI IŠKAITINANT 2 MeV PROTONAIS ŠVITINTUS Si DARINIUS

J. Višniakov, T. Čeponis, E. Gaubas, A. Uleckas

Vilniaus universiteto Medžiagotyros ir taikomųjų mokslų institutas, Vilnius, Lietuva

Santrauka

Ištirti rekombinacijos būdingųjų dydžių kitimai Si padėkluose ir dioduose, apšvitintuose 2 MeV protonais ir izochroniškai 24 val. iškaitintuose, keičiant temperatūrą 80–320 °C ruože. Rekombinacijos parametrai tirti kombinuojant giliųjų lygmenų talpinę spektroskopiją, mikrobangų sugerties relaksacijos ir diodų perjungimo trukmės matavimų metodikas. Aptiktas rekombinacijos trukmės didėjimas po iškaitinimų, kai pokyčių vertės priklauso nuo apšvitos integrinio srauto, o šiluminės emisijos, nulemiančios krūvininkų tankio relaksacijos generacinę trukmę bei nuotėkio sroves, spektre aptikti žymūs pokyčiai, sietini su taškinių defektų, priskirtinų vakansijoms ir jų kompleksams, transformacijomis.