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DLTS spectra of silicon diodes with p^+-n-junction irradiated with high energy krypton ions☆

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ABSTRACT

p^+-n-Diodes have been studied. The diodes were manufactured on wafers (thickness 460 μm, (111) plane) of uniformly phosphorus doped float-zone-grown single-crystal silicon. The resistivity of silicon was 90 Ω cm and the phosphorus concentration was 5×10^{13} cm^{-3}. The diodes were irradiated with 250 MeV krypton ions. The irradiation fluence was 10^8 cm^{-2}. Deep-level transient spectroscopy (DLTS) was used to examine the defects induced by high energy krypton ion implantation. The DLTS spectra were recorded at a frequency of 1 MHz in the 78–290 K temperature range. The capacity-voltage characteristics have been measured at a reverse bias voltage from 0 to −19 V at a frequency of 1 MHz. We show that the main irradiation-induced defects are A-centers and divacancies. The behavior of DLTS spectra in the 150–260 K temperature range depends essentially on the emission voltage U_e. The variation of U_e allows us to separate the contributions of different defects into the DLTS spectrum in the 150–260 K temperature range. We show that, in addition to A-centers and divacancies, irradiation produces multivacancy complexes with the energy level $E_t = E_c-(0.5 \pm 0.02)$ eV and an electron capture cross section of ~4×10^{-13} cm^2.

Introduction

Irradiation with high-energy heavy ions is a tool for optimizing parameters of high-speed high-power diodes. It provides for the same operation speed as electron irradiation but with a smaller increase in the base resistance and hence forward voltage drop [1–4]. In some cases this may compensate for the high costs of high-energy implantation. Unlike light ion irradiation, irradiation with high-energy heavy ions leads to the formation of radiation defect clusters (multi-vacancy and multi-interstitial atom complexes) [5,6]. To develop optimum process modes for high-speed diodes one needs data on the composition of radiation defects and their depth profile. Capacitance spectroscopy is widely used for the analysis of defect-impurity composition of barrier structures. The most information valuable method is deep-level transient spectroscopy (DLTS). Under high-energy ion irradiation, radiation-induced defects have an inhomogeneous depth profile. Their peak concentration is at a distance slightly smaller than the average ion projection path. Therefore the free carrier concentration distribution is also inhomogeneous and hinders the treatment of capacitance spectroscopy data [7–9].

The aim of this work is to study DLTS spectra of silicon-based diodes containing a highly defective layer formed by irradiation with 250 MeV krypton ions.

Experimental

The diodes were synthesized on wafers (thickness 460 μm, (111) plane) of homogeneously phosphorus doped float zone melt grown single crystal silicon. The material resistivity was 90 Ω cm (KOF-90), and the phosphorus concentration was 5×10^{13} cm^{-3}. The p^+ region was formed by boron implantation with a 60 keV energy and a 20 μC/cm^2 dose (1.3×10^{14} cm^{-2}) on a Vezuvii-3M instrument followed by defect annealing and impurity homogenization in an oxidizing atmosphere at 1200 °C for 9 h. The active area of the p^+-n junction was 9.43 mm^2. The

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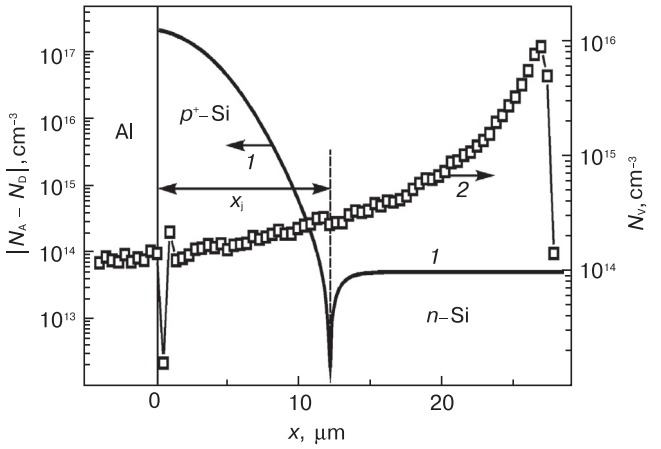

Fig. 1. (*1*) Simulated acceptor/donor difference profiles $|N_A–N_D|$ in the as-fabricated diode and (*2*) primary vacancy profiles for krypton ion irradiation at 250 MeV, fluence 10^8 cm^{-2}.

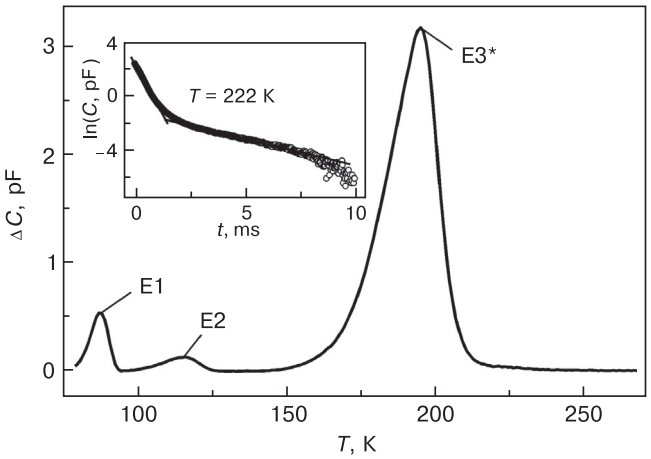

Fig. 2. DLTS spectrum of diodes for krypton ion irradiation at 250 MeV, fluence 10^8 cm^{-2}. Trap filling pulse t_p = 5 ms, capacity relaxation (emission) pulse t_e = 10 ms. Inset: transient capacity of the irradiated diode *C* as a function of time *t*.

depth of the p^+-*n* junction as per ball grind chemical etching data was x_j = 12 μm. This agrees well with boron diffusion simulation results obtained using Process Wizard 1D software based on earlier models [10]. In Fig. 1, curve *1* shows the acceptor/donor difference profile $|N_A–N_D|$ plotted based on diode technology simulation. The thickness of the double electric layer of the p^+-*n* junction in the as-fabricated diodes estimated from *V*-*C* measurements for *U* = 0 was ≈ 4.5 μm. An ohmic contact to the base was made by phosphorus ion implantation into the non-planar silicon wafer side (energy 75 keV, dose 500 μC/cm^2 ($3.1×10^{15}$ cm^{-2}). The contacts were formed by Al sputtering followed by annealing at 475 °C in an nitrogen atmosphere (the Al layer thickness on the contact to the p^+ region was 4.5 μm).

As-fabricated diodes were irradiated with krypton ions (Kr) on a U-400 cyclotrone at the Joint Institute for Nuclear Research in Dubna. The energy was 250 MeV, and the fluence was 10^8 cm^{-2}. The wafers were implanted at the p^+ region side. The average projection path of krypton in the Al/Si bi-layered structure as simulated with TRIM [11] was R_p ≈ 31 μm. Curve *2* in Fig. 1 shows simulated primary irradiation-induced vacancy profiles. The distance between the metal boundary of the p^+-*n* junction (N_A = N_D without allowance for doping impurity compensation by irradiation-induced defects) and the primary vacancy peak was ≈ 14.5 μm.

The DLTS spectra were recorded at 1 MHz on a CE-6 spectrometer (Scientific and Production LLC OMNITEL, Minsk, Belarus). The electron trap filling pulse length was at least 5 ms, and the trapped electron emission pulse length was at least 10 ms. The trap filling voltage (hereinafter U_p, the filling voltage) was 0 V. The capacity relaxation measurement voltage (during trapped electron emission) (hereinafter U_e, the emission voltage) was varied in the range from −1 to −16 V. The *V*–*C* curves were recorded at reverse bias ranging from 0 to −19 V with a 0.1 V step. Based on the *V*–*C* curves and using a conventional method [12] we calculated the free electron and hole concentration difference profiles in the diode base depth.

Results and discussion

Fig. 2 shows DLTS spectrum of diodes after krypton ion irradiation at 250 MeV, fluence 10^8 cm^{-2} recorded at U_p =0 and U_e = −6 V. The sampling time t_1 and t_2 forming the so-called emission rate window were 5 and 10 ms, respectively. The spectrum contains three peaks. The Arrhenius equation calculated energy levels of the traps in the band gap for the E1 peak were $E_t = E_c–(0.20 ± 0.02)$ eV, and for the E2 peak, $E_t = E_c–(0.25 ± 0.02)$ eV. Comparison with reported data [13–15] suggests that the E1 peak is formed by the A-centers (i.e. complexes of oxygen atoms and vacancies, V-O$^{(-/0)}$) and the E2 peak is formed by the divacancies in the −2 charge state ($V_2^{(=/-)}$). The inset in Fig. 2 shows in semilogarithmic scale transient capacity of the diode *C* as a function of time *t* (counted from emission pulse start). The *C*(*t*) curve has at least two discernable linear portions. Multiexponential capacity relaxation may suggest that the E3* peak is a superposition of signals from several centers.

To check this assumption we recorded a series of DLTS spectra for the diodes at 150–260 K for U_p = 0 and U_e varying from −1 to −16 V. These spectra are shown in Fig. 3. It can be seen that at U_e = −1 V and U_e = −2 V the spectra have two peaks: E3 and E4. The energy level calculated for the E3 peak was $E_t = E_c–(0.40 ± 0.02)$ eV, and for the E4 peak, $E_t = E_c–(0.50 ± 0.02)$ eV. At emission voltage $|U_e|$≥3 V the spectra have only the E3* peak. For U_e variation the energy level calculated for the E3* peak ranged from $E_t = E_c–(0.39 ± 0.02)$ eV to $E_t = E_c–(0.46 ± 0.02)$ eV. According to [13–15], the E3 and E3* DLTS peaks are formed by complexes of phosphorus atoms and vacancies (V-P$^{(-/0)}$, the E-center) and divacancies in the −1 charge state ($V_2^{(-/0)}$).

The presence of two peaks in the DLTS for $|U_e| ≤ 3$ V can be caused not only by intrinsic irradiation-induced defects. For example, it was shown [16] that spurious DLTS peaks may occur in p^+-*n*-n^+ structures based on highly ohmic silicon (free carrier concentration $2×10^{12}$ cm^{-2}). As the metallic contact to the p^+ region covered part of the oxidized silicon surface, the spurious DLTS peaks were attributed to capacity relaxation in metal–insulator–semiconductor structure [16]. In our

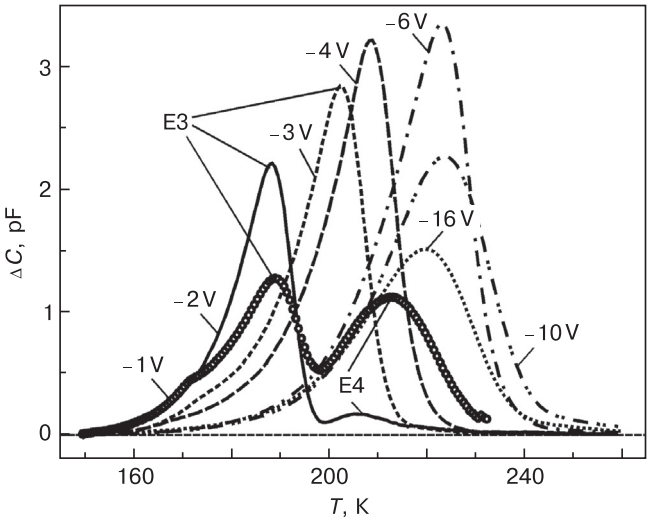

Fig. 3. DLTS spectra of diodes for krypton ion irradiation at 250 MeV, fluence 10^8 cm^{-2}. Trap filling pulse t_p = 10 ms, capacity relaxation (emission) pulse t_e = 15 ms. Trap filling voltage U_p = 0. U_e are shown in the figure.

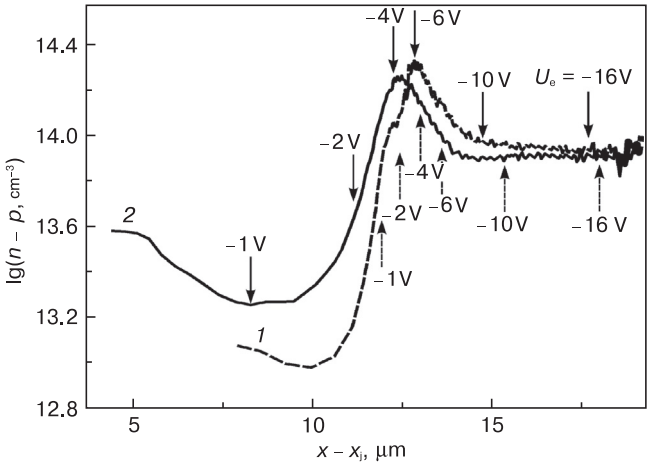

Fig. 4. Free electron and hole concentration difference profiles based on *V–C* curves for (*1*) 160 K and (*2*) 250 K. Arrows show spatial charge area boundaries for voltage U_e.

case this would cause DLTS peaks to appear on both the irradiated and as-fabricated diodes, which was not the case.

It is well-known that inhomogeneous depth profiles of free carriers may also distort [7] DLTS spectra and cause additional peaks [8]. For the implantation of high-energy heavy ions the carrier depth profiles are inhomogeneous due to the inhomogeneous distribution of irradiation-induced defects compensating the doping impurity in the diode base. Fig. 4 shows in semilogarithmic scale free electron and hole concentration difference profiles ($n - p$) based on *V–C* curves for 160 K and 250 K. For each temperature, the arrows show space charge area boundaries for the voltage U_e used in the experiment. It can be seen that an increase in temperature of DLTS spectrum recording the spatial charge area boundary shifts towards p^+ silicon and may distort the spectra.

Similar observations of inhomogeneous carrier depth profile were also made earlier [7,8]. DLTS spectra calculations were reported for GaAs [7] containing centers with the energy level $E_t = E_c - 0.35$ eV in which the free carrier profile was described by Gauss or Lorentz functions. It was shown there that nonmonotonic variations of amplitude, halfwidth and peak position in the DLTS spectrum are possible. A linear carrier depth profile ranging from 10^{16} to 10^{15} cm^{-3} was considered for GaAs [8] containing centers with the energy level $E_t = E_c - 0.4$ eV. It was shown that such concentration change may cause an additional DLTS peak. Trapping cross-section σ_n and level depth estimations based on Arrhenius equations for the spurious peak observed in [8] gave unrealistic results: $E_t = E_c - 2.7$ eV and $\sigma_n = 4.6\times10^{41}$ cm^2. Our estimation of the parameters of the E4 peak gave $E_t = E_c - (0.50 \pm 0.02)$ eV and $\sigma_n = 4\times10^{-13}$ cm^2. The trapping cross-section estimate seems to be too large but still realistic if the defect is a multivacancy complex. Other authors [17] studied boron ion irradiated silicon (14 MeV, 10^{11} cm^{-2}) and observed defects with the energy level $E_t = E_c - 0.57$ eV and the electron trapping cross-section $\sigma_n = 10^{-12}$ cm^2. The authors assumed that these defects are of vacancy nature and their highest concentration is localized in an approx. 5 μm thick layer at an average projection path depth. It was shown in another study [18] that the trivacancy $V_3^{(-/0)}$ has the energy level $E_t = E_c - 0.46$ eV and the trivacancy-oxygen complex V_3-$O^{(-/0)}$ has the energy level $E_t = E_c - 0.455$ eV which is sufficiently close to our results. Thus, the most probable hypothesis is currently that the E4 peak in the DLTS spectra is caused by irradiation-induced defects, possibly, multivacancy complexes, whose formation probability at the end of path of high-energy ions is quite high [5,6]. Our results agree in general with earlier conclusions [9] based on a study of DLTS spectra caused by inhomogeneous distribution of defects in neutron irradiated GaAs.

Summary

We show that at < 150 K DLTS the spectra have peaks corresponding to oxygen-vacancy complexes and −2 charge divacancies. The pattern of the DLTS spectra in the 150–260 K range depends largely on emission voltage. Varying emission voltage in the course of the experiment allows separating the contributions from different defects to the DLTS spectra in the 150–260 K temperature range. Along with A-centers and divacancies, irradiation produces multivacancy complexes with the energy level $E_t = E_c - (0.50 \pm 0.02)$ eV and an electron trapping cross-section of approx. 4×10^{-13} cm^2.

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References

[1] N.A. Poklonski, N.I. Gorbachuk, S.V. Shpakovski, V.A. Filipenia, V.A. Skuratov, A. Wieck, Kinetics of reverse resistance recovery of silicon diodes: The role of the distance the metallurgical p$^+$n-junction-defect layer formed by 250 MeV krypton implantation, Physica B 404 (23–24) (2009) 4667–4670. http://dx.doi.org/10.1016/j.physb.2009.08.129.

[2] N.A. Poklonski, N.I. Gorbachuk, S.V. Shpakovski, A.V. Petrov, S.B. Lastovskii, D. Fink, A. Wieck, Electrical properties of silicon diodes with p$^+$n junctions irradiated with $^{197}Au^{+26}$ swift heavy ions, Nucl. Instrum. Methods B 266 (23) (2008) 5007–5012. http://dx.doi.org/10.1016/j.nimb.2008.09.001.

[3] P. Sathyavathi, P.S. Bhave, V.N. Bhoraskar, Irradiation effects of 35 MeV lithium and 70 MeV oxygen ions on the hole lifetime and the forward current of silicon diodes, Solid State Commun. 106 (11) (1998) 755–758. http://dx.doi.org/10.1016/S0038–1098(98)00116–1.

[4] P.S. Bhave, V.N. Bhoraskar, Irradiation effects of high energy heavy ions on the switching characteristics of p-n junction diodes, Nucl. Instrum. Methods B 127/128 (1997) 383–387. http://dx.doi.org/10.1016/S0168-583X(96)00962-7.

[5] M. Nastasi, J.W. Mayer, Ion Implantation and Synthesis of Materials, Springer, Berlin, 2006, p. 263.

[6] A.R. Chelyadinskii, F.F. Komarov, Defect-impurity engineering in implanted silicon, Phys. Usp. 46 (8) (2003) 789–820. http://dx.doi.org/10.1070/PU2003v046n08ABEH001371.

[7] A. Ito, Y. Tokuda, Deformation of a deep-level transient spectroscopy spectrum by an inhomogeneous carrier concentration depth profile, Solid-State Electron 46 (9) (2002) 1307–1313. http://dx.doi.org/10.1016/S0038-1101(02)00077-1.

[8] A. Ito, Y. Tokuda, Effects of inhomogeneous carrier concentration depth profile on deep-level transient spectroscopy measurements, J. Cryst. Growth. 210 (1–3) (2000) 384–387. http://dx.doi.org/10.1016/S0022-0248(99)00716–2.

[9] V.A. Novikov, V.V. Peshev, Effect of nonuniform distribution of radiation defects in GaAs on the DLTS spectra, Semiconductors 32 (4) (1998) 366–371. http://dx.doi.org/10.1134/1.1187397.

[10] ULSI technology / Ed. by C. Y. Chang, S. M. Sze. NY: McGraw-Hill, 1996. 726 p.

[11] J.F. Ziegler, SRIM-2003, Nucl. Instrum. Methods B 219–220 (2004) 1027–1036. http://dx.doi.org/10.1016/j.nimb.2004.01.208.

[12] S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley, New York, 2001, p. 568.

[13] V. Eremin, E. Verbitskaya, Z. Li, Effect of radiation induced deep level traps on Si detector performance, Nucl. Instrum. Methods A 476 (3) (2002) 537–549. http://dx.doi.org/10.1016/S0168-9002(01)01640-0.

[14] M. Moll, E. Fretwurst, M. Kuhnke, G. Lindstroem, Relation between microscopic defects and macroscopic changes in silicon detector properties after hadron irradiation, Nucl. Instrum. Methods B 186 (1–4) (2002) 100–110. http://dx.doi.org/10.1016/S0168-583X(01)00866-7.

[15] P. Hazdra, V. Komarnitskyy, Lifetime control in silicon power p-i-n diode by ion irradiation: Suppression of undesired leakage, Microelectron. J. 37 (3) (2006) 197–203. http://dx.doi.org/10.1016/j.mejo.2005.09.010.

[16] V.K. Eremin, A.M. Ivanov, A.M. Strokan, False peaks in DLTS spectra of planar diode structures, Sov. Phys. Semicond. 26 (3) (1992) 269–271.

[17] I.V. Antonova, S.S. Shaĭmeev, S.A. Smagulova, Transformation of electrically active defects as a result of annealing of silicon implanted with high-energy ion, Semiconductors 40 (5) (2006) 543–548. http://dx.doi.org/10.1134/S106378260605006X.

[18] V.P. Markevich, A.R. Peaker, B. Hamilton, S.B. Lastovskii, L.I. Murin, J. Coutinho, V.J.B. Torres, L. Dobaczewski, B.G. Svensson, Structure and electronic properties of trivacancy and trivacancy-oxygen complex in silicon, Phys. Status Solidi A 208 (3) (2011) 568–571. http://dx.doi.org/10.1002/pssa.201000265.