



## DLTS spectra of silicon diodes with $p^+$ - $n$ -junction irradiated with high energy krypton ions<sup>☆</sup>

Nikolai A. Poklonski<sup>a,\*</sup>, Nikolay I. Gorbachuk<sup>a</sup>, Sergey V. Shpakovski<sup>b</sup>, Viktor A. Filipenia<sup>b</sup>, Arkady S. Turtsevich<sup>b</sup>, Sergey V. Shvedov<sup>b</sup>, Nha Vo Quang<sup>a</sup>, Nguyen Thi Thanh Binh<sup>a</sup>, Vladimir A. Skuratov<sup>c</sup>, Andreas D. Wieck<sup>d</sup>

<sup>a</sup> Belarusian State University, 4 Nezavisimosti Ave., Minsk 220030, Belarus

<sup>b</sup> JSC «INTEGRAL» - Holding Management Company, 121 A Kazintsya I. P. Str., Minsk 220108, Belarus

<sup>c</sup> Joint Institute for Nuclear Research, 6 Joliot-Curie, Dubna 141980, Russia

<sup>d</sup> Ruhr-Universitaet Bochum, 150 Universitaetsstrasse, Bochum D-44780, Germany

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### ABSTRACT

$p^+$ - $n$ -Diodes have been studied. The diodes were manufactured on wafers (thickness 460  $\mu\text{m}$ , (111) plane) of uniformly phosphorus doped float-zone-grown single-crystal silicon. The resistivity of silicon was 90  $\Omega\text{ cm}$  and the phosphorus concentration was  $5 \times 10^{13}\text{ cm}^{-3}$ . The diodes were irradiated with 250 MeV krypton ions. The irradiation fluence was  $10^8\text{ cm}^{-2}$ . 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  $-19\text{ V}$  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  $E_t = E_c - (0.5 \pm 0.02)\text{ eV}$  and an electron capture cross section of  $\sim 4 \times 10^{-13}\text{ cm}^2$ .

### 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

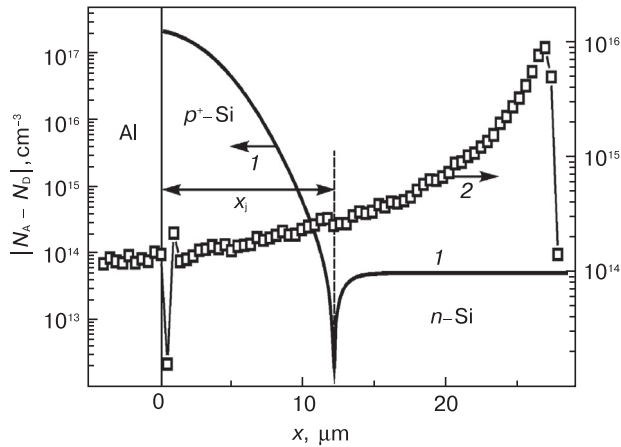
The diodes were synthesized on wafers (thickness 460  $\mu\text{m}$ , (111) plane) of homogeneously phosphorus doped float zone melt grown single crystal silicon. The material resistivity was 90  $\Omega\text{ cm}$  (KOF-90), and the phosphorus concentration was  $5 \times 10^{13}\text{ cm}^{-3}$ . The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

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<sup>☆</sup> Corresponding author.

E-mail address: [Poklonski@bsu.by](mailto:Poklonski@bsu.by) (N.A. Poklonski).

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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  $10^8 \text{ cm}^{-2}$ .

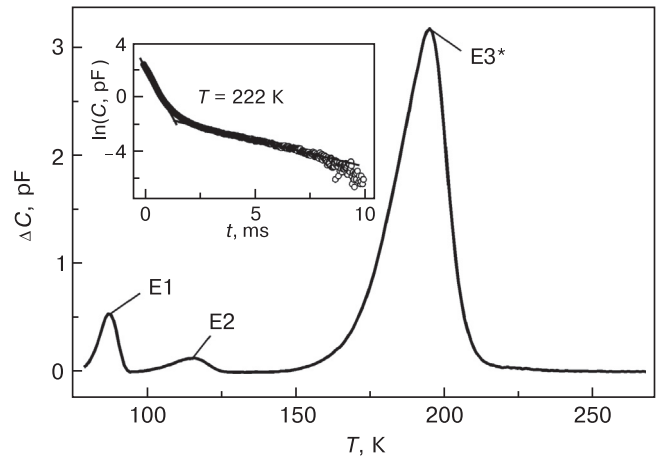
depth of the  $p^+-n$  junction as per ball grind chemical etching data was  $x_j = 12 \mu\text{m}$ . This agrees well with boron diffusion simulation results obtained using Process Wizard 1D software based on earlier models [10]. In Fig. 1, curve 1 shows the acceptor/donor difference profile  $|N_A - N_D|$  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  $\approx 4.5 \mu\text{m}$ . An ohmic contact to the base was made by phosphorus ion implantation into the non-planar silicon wafer side (energy 75 keV, dose  $500 \mu\text{C}/\text{cm}^2$  ( $3.1 \times 10^{15} \text{ cm}^{-2}$ )). The contacts were formed by Al sputtering followed by annealing at  $475^\circ\text{C}$  in an nitrogen atmosphere (the Al layer thickness on the contact to the  $p^+$  region was  $4.5 \mu\text{m}$ ).

As-fabricated diodes were irradiated with krypton ions (Kr) on a U-400 cyclotron at the Joint Institute for Nuclear Research in Dubna. The energy was 250 MeV, and the fluence was  $10^8 \text{ cm}^{-2}$ . 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  $R_p \approx 31 \mu\text{m}$ . 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  $\approx 14.5 \mu\text{m}$ .

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  $-16 \text{ V}$ . The  $V$ - $C$  curves were recorded at reverse bias ranging from 0 to  $-19 \text{ V}$  with a  $0.1 \text{ V}$  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  $10^8 \text{ cm}^{-2}$  recorded at  $U_p = 0$  and  $U_e = -6 \text{ V}$ . 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  $E_t = E_c - (0.20 \pm 0.02) \text{ eV}$ , and for the E2 peak,  $E_t = E_c - (0.25 \pm 0.02) \text{ eV}$ . 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,  $\text{V-O}^{(-/0)}$ ) and the E2 peak is formed by the divacancies in the  $-2$  charge state ( $\text{V}_2^{(=/-)}$ ). The inset in Fig. 2 shows in

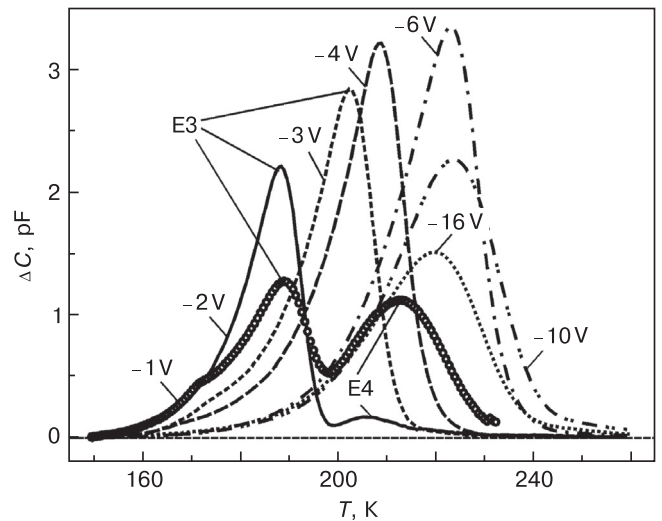


**Fig. 2.** DLTS spectrum of diodes for krypton ion irradiation at 250 MeV, fluence  $10^8 \text{ cm}^{-2}$ . Trap filling pulse  $t_p = 5 \text{ ms}$ , capacity relaxation (emission) pulse  $t_e = 10 \text{ ms}$ . Inset: transient capacity of the irradiated diode  $C$  as a function of time  $t$ .

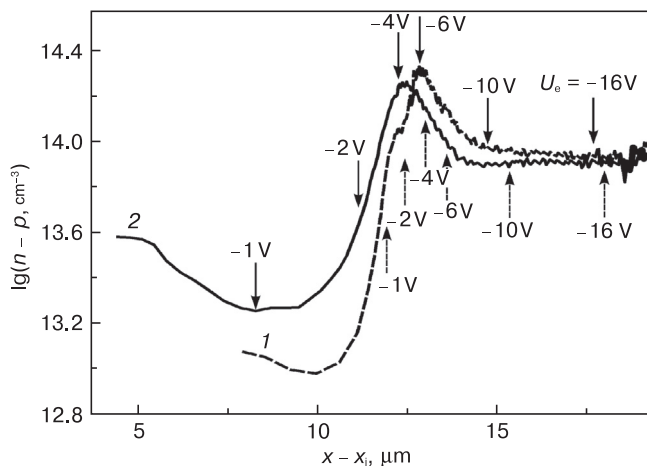
semilogarithmic scale transient capacity of the diode  $C$  as a function of time  $t$  (counted from emission pulse start). The  $C(t)$  curve has at least two discernable linear portions. Multiexponential capacity relaxation may suggest that the  $\text{E3}^*$  peak is a superposition of signals from several centers.

To check this assumption we recorded a series of DLTS spectra for the diodes at  $150$ – $260 \text{ K}$  for  $U_p = 0$  and  $U_e$  varying from  $-1$  to  $-16 \text{ V}$ . These spectra are shown in Fig. 3. It can be seen that at  $U_e = -1 \text{ V}$  and  $U_e = -2 \text{ V}$  the spectra have two peaks: E3 and E4. The energy level calculated for the E3 peak was  $E_t = E_c - (0.40 \pm 0.02) \text{ eV}$ , and for the E4 peak,  $E_t = E_c - (0.50 \pm 0.02) \text{ eV}$ . At emission voltage  $|U_e| \geq 3 \text{ V}$  the spectra have only the  $\text{E3}^*$  peak. For  $U_e$  variation the energy level calculated for the  $\text{E3}^*$  peak ranged from  $E_t = E_c - (0.39 \pm 0.02) \text{ eV}$  to  $E_t = E_c - (0.46 \pm 0.02) \text{ eV}$ . According to [13–15], the E3 and  $\text{E3}^*$  DLTS peaks are formed by complexes of phosphorus atoms and vacancies ( $\text{V-P}^{(-/0)}$ , the E-center) and divacancies in the  $-1$  charge state ( $\text{V}_2^{(-/0)}$ ).

The presence of two peaks in the DLTS for  $|U_e| \leq 3 \text{ V}$  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  $2 \times 10^{12} \text{ cm}^{-3}$ ). 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  $10^8 \text{ cm}^{-2}$ . Trap filling pulse  $t_p = 10 \text{ ms}$ , capacity relaxation (emission) pulse  $t_e = 15 \text{ ms}$ . 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  $\sigma_n$  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  $\sigma_n = 4.6 \times 10^{41}$  cm $^2$ . Our estimation of the parameters of the E4 peak gave  $E_t = E_c - (0.50 \pm 0.02)$  eV and  $\sigma_n = 4 \times 10^{-13}$  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  $\mu$ m thick layer at an average projection path depth. It was shown in another study [18] that the trivacancy  $V_3^{(C/O)}$  has the energy level  $E_t = E_c - 0.46$  eV and the trivacancy-oxygen complex  $V_3-O^{(C/O)}$  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.  $4 \times 10^{-13}$  cm $^2$ .

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