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Effects of Fluences of Irradiation with 107 MeV Krypton Ions on the Recovery Charge of Silicon p^+n-Diodes

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The diodes manufactured on the wafers of single-crystalline silicon uniformly doped with phosphorus are studied. The wafer resistivity was 90 Ω cm. Krypton ions are implanted to the side of the p^+-region of diodes (energy 107 MeV, fluence Φ from 5×10^7 to 4×10^9 cm^{-2}). It is shown that recovery charge $Q_{\rm rr}$ is inversely proportional to the square root of the irradiation fluence value Φ. When the fluence increases, the part of the recovery charge $Q_{{\rm rr}A}$, due to the high reverse conductance phase, decreases faster than the value $Q_{\rm rr}$.

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1. Introduction

Irradiation with protons or alpha rays enables formation of layers with the increased irradiation-induced defect content, which is used in the fabrication of fast recovery diodes [1–6]. In this case the irradiation fluences are usually larger than 10^{11} cm^{-2}. Implantation with heavy ions with the fluences of 10^9–10^{12} cm^{-2} [7, 8] also leads to a considerable decrease in reverse resistance recovery time (recovery charge). A possibility to reduce the reverse resistance recovery time by an order of magnitude for the diodes implanted with Au ions with the energy 350 MeV and the fluence 10^8 cm^{-2} is shown in [9]. In work [10] silicon diodes irradiated with krypton ions with energy of 250 MeV and three fluence values (10^8; 5×10^8; 10^9 cm^{-2}) were studied. The main problem is to define optimal fluence values of irradiation with high-energy ions and to determine the dependence of the recovery charge on the ion fluence. The aim of the work is to study effects of the irradiation fluence with 107 MeV krypton ions on the recovery charge of diodes.

2. Experimental technique

Diodes are manufactured on wafers (thickness of 460 μm, plane (111)) of silicon grown by the crucibleless floating-zone technique. Silicon wafers were uniformly doped with phosphorus. Wafer resistivity was 90 Ω cm, phosphorus concentration was 5×10^{13} cm^{-3}. Region of the p^+-type was created by implantation of boron ions with energy of 60 keV and fluences of 5.6×10^{14} cm^{-2} on the apparatus "Vezuviy-3M" followed by annealing of defects and dopant drive-in in oxidizing atmosphere at temperature of 1150 ℃ during 50 min. The active area of the p^+n-junction is 4.41 mm^2. The profile of the difference of acceptor and donor concentrations $|N_{\rm A}-N_{\rm D}|$ plotted according to the results of the modeling of the technological process of diode manufacturing is shown in Fig. 1 (curve *1*). In order to create an ohmic contact to the base of diodes, implantation of phosphorus ions (energy of 75 keV, fluences of 3.1×10^{15} cm^{-2}) into the non-planar side (n-region) was performed. Contacts were formed by aluminium sputtering followed by burn-in at temperature 475 ℃ in nitrogen atmosphere (aluminium layer thickness at contact to p^+-region is 1.5 μm).

Diodes are irradiated with krypton ions at cyclotron U-400. The irradiation energy E is 107 MeV, fluence Φ varies from 5×10^7 to 4×10^9 cm^{-2}. Implantation is performed to the side of the p^+-region. The average projected range of krypton ions in the double-layer structure Al/Si according to the results of modeling in the TRIM program [11] is equal to $R_{\rm p}\approx16.5$ μm. Figure 1 (curve *2*) shows the calculated profiles of the distribution of primary vacancies. The distance between the metallurgical border of the p^+n-junction (where $N_{\rm A}=N_{\rm D}$ — defined neglecting n-Si compensation by radiation-induced defects) and the maximum of the distribution of primary vacancies is found to be $\delta\approx11.5$ μm.

Static current–voltage characteristics are registered according to a standard procedure using the program-

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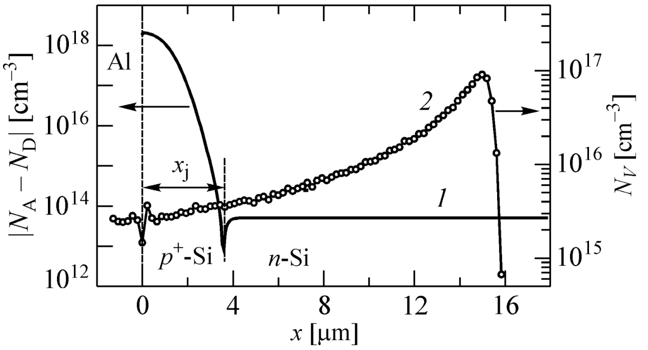

Fig. 1. Calculated profiles of the absolute value of the difference of acceptor and donor concentrations (curve *1*) in the virgin diode, and the distribution of the primary vacancies (curve *2*), formed by irradiation of the diodes with krypton ions with the fluence $\Phi = 10^9$ cm^{-2}. N_A is the concentration of acceptors, N_D is the concentration of donors, N_V is the concentration of primary vacancies, x is the depth, x_j is the depth of pn-junction.

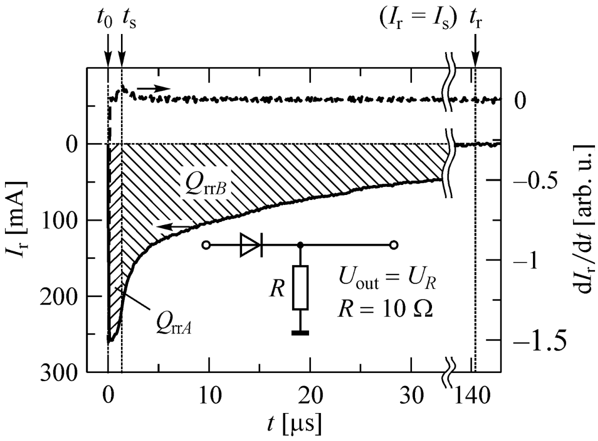

Fig. 2. Dependences of the reverse current I_r and the rate of current change $\mathrm{d}I_\mathrm{r}/\mathrm{d}t$ on time t for the switching of a diode irradiated with krypton ions with the fluence $\Phi = 10^8$ cm^{-2}. $Q_{\mathrm{rr}A}$ is the part of the switching charge corresponding to the phase of the high reverse conductivity, $Q_{\mathrm{rr}B}$ is the part of the switching charge corresponding to the phase of the reverse resistance recovery. The border between phases is taken by the instance of time $t = t_\mathrm{s}$, when the maximum is observed in derivation $\mathrm{d}I_\mathrm{r}/\mathrm{d}t$ corresponding to the inflection in the dependence $I_\mathrm{r}(t)$.

-analytical complex HP 4156B. Transient processes in diodes are studied by switching from the forward (forward current $I_\mathrm{f} \leq 1$ A) to the reverse bias (voltage $U_\mathrm{r} = 2$ V). The dependences of the reverse current $I_\mathrm{r}(t) = U_R(t)/R$ passing through the diode are calculated on the basis of voltage oscillograms $U_R(t)$ at the load resistor ($R = 10\ \Omega$). All measurements are carried out at room temperature. Figure 2 presents the scheme of the diode connection in the measuring circuit and the examples of the dependence of current I_r on time t when diodes are switched and its derivative $\mathrm{d}I_\mathrm{r}/\mathrm{d}t$. There are also marked instants of time: $t = t_0$ (when the polarity of the current is changed) and $t = t_\mathrm{r}$ (when the current through the diode I_r decreases to the value of the reverse current of the diode in stationary conditions I_s under the same reverse voltage on the diode U_r), and also the moment of time $t = t_\mathrm{s}$ (when a maximum on the derivative $\mathrm{d}I_\mathrm{r}/\mathrm{d}t$ and a bend on the dependence $I_\mathrm{r}(t)$ are observed). The value of recovery charge Q_rr, being the sum $Q_{\mathrm{rr}A} + Q_{\mathrm{rr}B}$ (see Fig. 2), is assessed by a numerical integration of the reverse current I_r of the diodes

$$Q_\mathrm{rr} = Q_{\mathrm{rr}A} + Q_{\mathrm{rr}B} = \int_{t_0}^{t_\mathrm{r}} I_\mathrm{r}(t)\,\mathrm{d}t\,, \qquad (1)$$

where $Q_{\mathrm{rr}A}$ is the part of recovery charge corresponding to the high reverse conductance phase, $Q_{\mathrm{rr}B}$ is the part of recovery charge corresponding to the reverse resistance recovery phase. The boundary between the A and B phases is chosen to be $t = t_\mathrm{s}$.

3. Experimental results and discussion

Figure 3 shows the dependences of the differential conductance $G = -\mathrm{d}I_\mathrm{r}/\mathrm{d}U_\mathrm{r}$ of the diodes on the reverse bias voltage U_r. The $G(U_\mathrm{r})$ dependences are calculated by differentiation of the current–voltage characteristics represented in the inset in Fig. 2. For the diodes irradiated with krypton ions with the fluences of 5×10^7–10^9 cm^{-2} there is a section of a differential conductance where an increase on the $G(U_\mathrm{r})$ dependence occurs. According to [1] this can be considered as confirmation of the spatial separation of the irradiation defect maximum and the space charge region under equilibrium conditions (at $U = 0$). For the diodes irradiated with the fluences of 4×10^9 cm^{-2} the section of differential conductance increase is not observed. This issue is connected to the propagation of the space charge region into the irradiation defect layer even when there is no bias voltage.

Figure 4 shows the dependences of current I on time t for the switching of virgin diodes (Vir), and the diodes irradiated with krypton ions. The inset represents the initial part of $I_\mathrm{r}(t)$ dependence for the diodes irradiated with the fluences of 4×10^8, 10^9 and 4×10^9 cm^{-2}. It is seen that an increase in the fluence of krypton ion irradiation leads to a change in $I_\mathrm{r}(t)$, which consists in a considerable decrease in the length of the high reverse conductance phase and the transformation of dependence $I_\mathrm{r}(t)$ for the reverse conductance recovery phase. Such behaviour of the $I_\mathrm{r}(t)$ dependence during the switching of the diodes irradiated with krypton ions with the energy of 250 MeV has been considered earlier [10] and has been connected with the inhomogeneous distribution of injected charge carriers over the bulk of the base which contains clusters of irradiation-induced defects. At fluences of 10^8 cm^{-2} dependences $I_\mathrm{r}(t)$ for diodes irradiated with krypton ions with energies $E = 250$ MeV (for the diodes with $\delta \approx 26.4\ \mu$m) and $E = 107$ MeV (for the diodes with

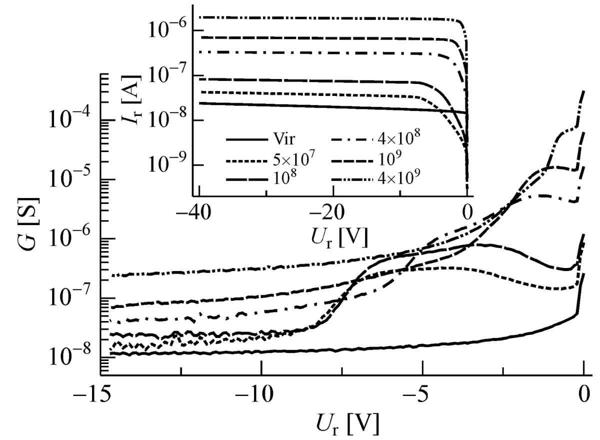

Fig. 3. Dependence of the differential conductance of the diodes G on the reverse bias voltage U_{r} for the virgin (Vir) diode and the diodes irradiated with krypton ions with the energy of 107 MeV. The inset shows the current–voltage characteristics of the diodes at a reverse bias. The values of irradiation fluences are shown in cm^{-2}.

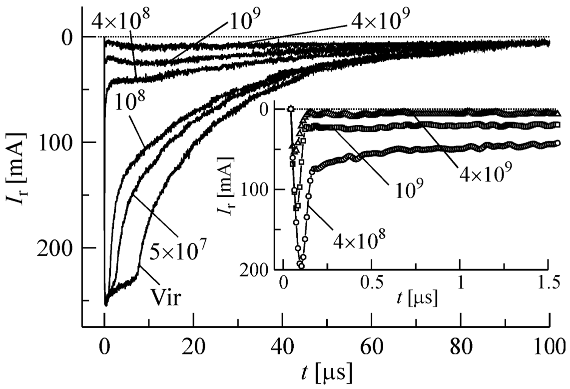

Fig. 4. Dependences of the reverse current I_{r} on time t for switching of the virgin diode (Vir), and the diodes irradiated with krypton ions with the energy of 107 MeV. The values of irradiation fluences are shown in cm^{-2}. The dependences are obtained at the injection current density of 1.5×10^5 $\mathrm{A/m^2}$ and the duration of a rectangular injecting pulse of 500 μs.

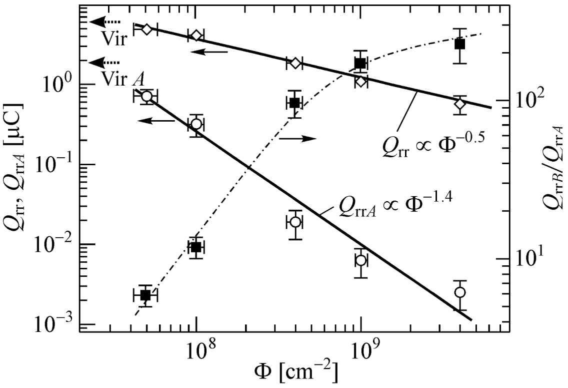

Fig. 5. Dependences of recovery charges on the fluence of krypton ions: open rhombs stand for the recovery charge Q_{rr}; open circles indicate the fraction $Q_{\mathrm{rr}A}$ of the recovery charge accounted for the phase of the high reverse conductance; filled squares are the ratio $Q_{\mathrm{rr}B}/Q_{\mathrm{rr}A}$ of the recovery charges for the phases of the reverse resistance recovery (index B) and of the high reverse resistance (index A). The dependences are obtained with the injection current density of 1.5×10^5 $\mathrm{A/m^2}$ and the duration of a rectangular injecting pulse of 500 μs.

$\delta \approx 11.5$ μm) are similar to each other, i.e., a considerable portion of charge corresponds to the reverse resistance recovery phase (phase B). An increase of irradiation fluence for krypton ions with the energy $E = 250$ MeV to 10^9 cm^{-2} leads to a considerable decrease in $Q_{\mathrm{rr}B}$ (unlike to irradiation with $E = 107$ MeV). Irradiation with energy of 250 MeV caused (for comparable injection currents and irradiation fluences) a more essential decrease in switching charge. For instance, at injection current density of about 10^5 $\mathrm{A/m^2}$ for $E = 250$ MeV and $\Phi = 10^8$ cm^{-2} reverse recovery charge $Q_{\mathrm{rr}} \approx 1.8$ μC is observed, but for $E = 107$ MeV and $\Phi = 10^8$ cm^{-2} it is $Q_{\mathrm{rr}} \approx 4$ μC. Comparison of the results obtained in [10] with the ones presented in this paper suggests that an increase of irradiation energy of krypton ions to 250 MeV affects $I_{\mathrm{r}}(t)$ dependences due to the increased irradiation-induced defect concentration as well as due to the larger δ distance.

Figure 5 represents the dependences of the recovery charge Q_{rr}, the fraction $Q_{\mathrm{rr}A}$ of recovery charge accounted for the high reverse conductance phase, and the ratio $Q_{\mathrm{rr}B}/Q_{\mathrm{rr}A}$ of recovery charges for phases of the high reverse conductance and reverse resistance recovery on the fluence of irradiation with krypton ions. As it follows from the results of integration of experimental curves $I_{\mathrm{r}}(t)$, the dependences $Q_{\mathrm{rr}A}(\Phi)$ and $Q_{\mathrm{rr}}(\Phi)$ may be approximated by a power function. The total recovery charge depends on the fluence as $Q_{\mathrm{rr}}(\Phi) \propto \Phi^{-0.5}$. The fraction of recovery charge accounted for the phase of the high reverse conductance depends on the fluence as $Q_{\mathrm{rr}A}(\Phi) \propto \Phi^{-1.4}$. Thus, when the fluence of irradiation with krypton ions increases, $Q_{\mathrm{rr}A}$ decreases much stronger than Q_{rr}.

As it follows from Figs. 4, 5 irradiation with krypton ions leads to a substantial decrease in the recovery charge of the diodes even when the fluences are $< 10^{12}$ cm^{-2}. For example, irradiation with krypton ions with the fluence of 4×10^8 cm^{-2} causes a decrease by more than three times in the recovery charge. In the first approximation the ratio $Q_{\mathrm{rr}B}/Q_{\mathrm{rr}A}$ of recovery charges for the phases of the reverse resistance recovery and the high reverse conductance determines the softness of the reverse resistance recovery. A faster decrease in the charge $Q_{\mathrm{rr}A}$ helps to "preserve" a soft reverse conductance recovery when the irradiation fluence increases, at least for $\Phi < 10^9$ cm^{-2}. Although an increase in leakage currents at the given irradiation fluences may be considerable (by more than an order of magnitude), it can likely be minimized by annealing. It is known that in the case of large local concentrations of irradiation-induced defects annealing can cause formation of vacancy and interstitial clusters [12, 13]. Because of issues indicated above, annealing experiments on optimization of leakage currents and reverse resistance recovery time of diodes irradiated with high-energy heavy ions require careful preparation and electron microscope studies which are beyond the scope of the current work.

4. Conclusions

It is shown that the use of high energy ion implantation with krypton ions with the fluences $\leq 10^9$ cm^{-2} allows to decrease the recovery charge of diodes considerably (by up to an order of magnitude). The recovery charge Q_{rr} of the diodes is found to be inversely proportional to the square root of the irradiation fluence value Φ. The fraction of reverse recovery charge $Q_{\mathrm{rr}A}$ (which accounts for the phase of the high reverse conduction) is found to decrease faster than Q_{rr} value with the increasing fluence. Thus, irradiation with high energy ions can be considered as one of the possible ways of creation of the Si-based fast diodes with the soft recovery.

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References

[1] A.M. Ivanov, N.B. Strokan, V.B. Shuman, *Semiconductors* **32**, 325 (1998).

[2] F. Fizzotti, E. Colombo, A. Lo Giudice, C. Manfredotti, Z. Medunic, M. Jaksic, E. Vittone, *Nucl. Instrum. Methods Phys. Res. B* **260**, 259 (2007).

[3] R. Siemieniec, F.-J. Niedernostheide, H.-J. Schulze, W. Südkamp, U. Kellner-Werdehausen, J. Lutz, *J. Electrochem. Soc.* **153**, G108 (2006).

[4] V.A. Kozlov, V.V. Kozlovski, *Semiconductors* **35**, 735 (2001).

[5] P. Hazdra, V. Komarnitskyy, *Microelectron. J.* **37**, 197 (2006).

[6] P. Hazdra, J. Vobecký, H. Dorschner, K. Brand, *Microelectron. J.* **35**, 249 (2004).

[7] P. Sathyavathi, P.S. Bhave, V.N. Bhoraskar, *Solid State Commun.* **106**, 755 (1998).

[8] P.S. Bhave, V.N. Bhoraskar, *Nucl. Instrum. Methods Phys. Res. B* **127/128**, 383 (1997).

[9] N.A. Poklonski, N.I. Gorbachuk, S.V. Shpakovski, A.V. Petrov, S.B. Lastovskii, D. Fink, A. Wieck, *Nucl. Instrum Methods Phys. Res. B* **266**, 5007 (2008).

[10] N.A. Poklonski, N.I. Gorbachuk, S.V. Shpakovski, V.A. Filipenia, V.A. Skuratov, A. Wieck, *Physica B* **404**, 4667 (2009).

[11] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, *Nucl. Instrum Methods Phys. Res. B* **268**, 1818 (2010).

[12] S. Dannefaer, V. Avalos, D. Kerr, R. Poirier, V. Shmarovoz, S.H. Zhang, *Phys. Rev. B* **73**, 115202 (2006).

[13] S. Libertino, S. Coffa, C. Spinella, J.L. Benton, D. Arcifa, *Mater. Sci. Eng. B* **71**, 137 (2000).