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Current–Voltage Characteristic Features of Diodes Irradiated with 170 MeV Xenon Ions

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Diodes manufactured on the wafers of single-crystalline silicon uniformly doped with phosphorus are studied. The wafer resistivity was 90 Ω cm. Xenon ions were implanted into the diodes from the side of the p^+-region (implantation energy 170 MeV, fluence Φ from 5×10^7 to 10^9 cm^{-2}). It is shown that the formation of a continuous irradiation damaged layer with the thickness of the order of magnitude of the average projective range creates prerequisites for the negative differential resistance in the current–voltage characteristics of the irradiated diodes.

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1. Introduction

It is known that the presence of point defects with deep energy levels within the energy gap of high-resistance materials can lead to the S-shaped current–voltage (I–V) characteristics with a section of the negative differential resistance [1]. The features of such current–voltage characteristics are determined both by the space charge limited current and by double injection of the charge carriers (both electrons and holes) [2, 3]. During irradiation of silicon diodes with high energy heavy ions a region of high concentration of the irradiation-induced defects is formed along the ion trajectory. This region can be tentatively considered as a "track" due to its parameters differing significantly from those of unimplanted semiconductor material [4, 5]. Foremost, this fact is related to the free charge carrier concentration that can be considerably lower in the track region due to compensation of the irradiation-induced defects by the dopant impurity. Thus, the formation of a section associated with the negative differential resistance in the current–voltage characteristics of irradiated diodes is expected.

The purpose of this paper is to study the silicon p^+–n-diodes irradiated with the high energy xenon ions and to determine the possibility for appearance of the negative differential resistance section in the current–voltage characteristics.

2. Experimental technique

The diodes under study were manufactured on the uniformly phosphorous doped single-crystalline silicon wafers with the resistivity of 90 Ω cm and the thickness of 460 μm. The p^+-type anode region was formed by boron ion implantation. The active area of the p^+–n-junction was 4.41 mm^2. From an analysis of chemical etching of the spherical metallographic section, the location of the p^+–n-junction was found at $x_j = 3.5$ μm. The calculated distribution profile of the difference $|N_A - N_D|$ is shown in Fig. 1 (curve 1). The space charge region thickness of the p^+–n-junction in the as-manufactured diodes was found to be ≈ 4.5 μm. The contacts were formed by Al (1.5 μm) sputtering.

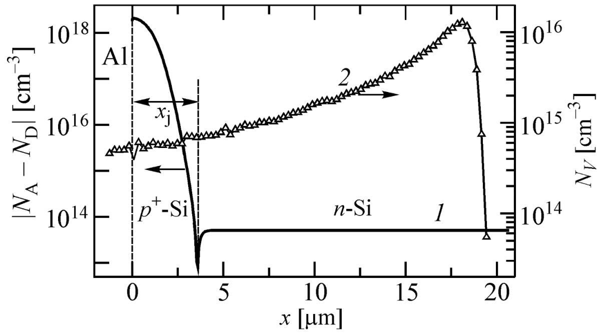

Fig. 1. Calculated distribution profiles: the difference $|N_A - N_D|$ in acceptor and donor concentrations in the initial diode (curve 1) and primary vacancies formed by irradiation of diode with 170 MeV xenon ions (curve 2). The irradiation fluence $\Phi = 10^8$ cm^{-2}.

The diodes were irradiated with xenon ions having the energy of 170 MeV. Implantation was performed from the side of the p^+-region. The irradiation fluence Φ was 5×10^7, 10^8, 10^9 cm^{-2}. Computational results for the distribution profile of the primary vacancies formed due to xenon irradiation with the fluence of 10^8 cm^{-2} are shown in Fig. 1 (curve 2).

Dependences of the forward current I_f through the diodes on the voltage U_f were measured in the current generator mode, while those of the reverse current I_r on

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the voltage U_{r} — in the voltage generator mode. An HP 4156B semiconductor parameter analyzer was used in measurements of I–V-characteristics. Measurements of the real Z' and imaginary Z'' parts of the impedance $Z = Z' + \mathrm{i}Z''$ with respect to the frequency f were performed with the use of an Agilent E4980A LCR-meter at room temperature.

3. Experimental results and discussion

Figure 2 shows the current–voltage characteristics both for the initial diode and for those irradiated with 170 MeV xenon ions with the fluences of 5×10^7, 10^8, 10^9 cm^{-2}. Contrary to the diodes irradiated with the fluences of 5×10^7 and 10^8 cm^{-2}, in the current–voltage characteristics of the diode irradiated with the fluence of 10^9 cm^{-2} the section associated with negative differential resistance is clearly observed.

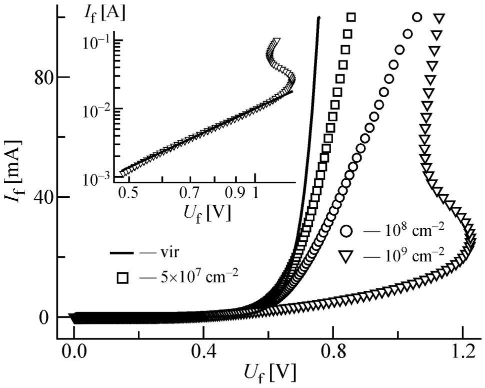

Fig. 2. Current–voltage characteristics of diodes. Irradiation fluences are indicated in the figure. The inset shows in a double logarithmic scale the section of the current–voltage characteristic of the diode irradiated with xenon ions with the fluence of 10^9 cm^{-2}.

The appearance of the negative differential resistance section only at $\Phi = 10^9$ cm^{-2} may point to a threshold nature of changes in the current–voltage characteristics of the diodes with an increase in the irradiation fluence. In this case the most probable cause of such a significant change in the current–voltage characteristics can be the formation of an irradiation damaged layer in silicon when the regions of the irradiation-induced defects formed along the ion pass trajectory (track regions) are merging.

The formation of an irradiation damaged layer in the diodes irradiated with xenon ions with the fluence of 10^9 cm^{-2} may be confirmed by the measurement results for the frequency dependences of impedance. During the experimental data analysis it is convenient to use the quantity M^* (instead of Z) that is proportional to the complex electric module M and is defined as follows:

$$M^* = M/C_0 = \omega(-Z'' + \mathrm{i}Z'), \tag{1}$$

where C_0 is the geometrical capacitance of a vacuum capacitor having the geometry identical to that of the examined sample.

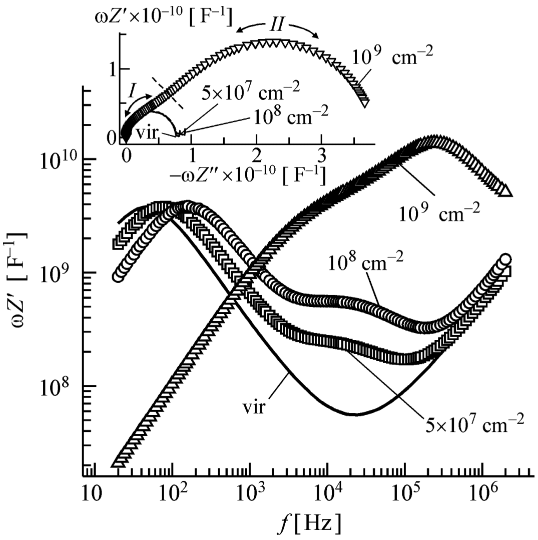

Fig. 3. The imaginary part of the complex electric module as a function of the frequency. The inset shows plots of the electric module M/C_0 in a complex plane. Values of the irradiation fluences are indicated in the figure.

From the point of view of physics, M^* is the quantity inverse to the diode capacity [6]. For short, the quantity M^* is further referred to as the complex electric module. The inset in Fig. 3 shows the plots of M^* in a complex plane. It is seen that the plot of the complex electric module for the diodes irradiated with xenon ions with the fluence of 10^9 cm^{-2} differs significantly from both the plots of the initial diodes and those of the diodes irradiated with the fluences below 10^9 cm^{-2}. Two arcs in the inset of Fig. 3 (marked by numbers I and II) have comparable "diameters". The presence of several arcs in the plots of complex electric quantities (impedance, admittance, etc.) indicates the multilayer structure [6]. The changes observed in the structure of the irradiated diodes can be distinctly traced in the curves of the imaginary part of the complex electric module $\omega Z'$ as a function of the frequency f (see Fig. 3). Only one maximum at $f \approx 45$ Hz can be observed in the dependence $\omega Z'(f)$ for the initial diodes. Irradiation of the diodes with xenon ions with the fluence of 5×10^7 cm^{-2} results in the shift of this maximum to $f \approx 80$ Hz and leads to the saddle point at the frequencies of about 5 kHz. An increase in the fluence up to 10^8 cm^{-2} is accompanied by a further shift of the low frequency maximum to $f \approx 150$ Hz and by the appearance of the second maximum at $f \approx 12$ kHz. As the irradiation fluence is increased up to 10^9 cm^{-2}, the dependence $\omega Z'(f)$ changes drastically: the first maximum is shifted to the region of the frequencies $f > 30$ kHz acting only as an additional saddle point in the dependence $\omega Z'(f)$, whereas the second one is observed at the frequency $f \approx 240$ kHz.

The additional indirect evidence for the formation of a continuous layer with the irradiation-induced defects may be derived from the current–voltage characteristics of the reversely biased diodes. Figure 4 shows the dependences of the differential conductivity G for the initial and the xenon ion irradiated diodes with respect to the reverse bias voltage U_r. The dependences are derived by means of differentiation of the reverse current–voltage characteristics. As for the diodes irradiated with the fluences of 5×10^7, 10^8 cm^{-2}, the dependences $G(U_\mathrm{r})$ are non-monotonic. There is a minimum in the interval of the reverse bias voltages from 0 to -3 V. As it was shown previously, for the diodes irradiated with 107 MeV krypton ions [7] and 130 MeV xenon ions [8], such dependence $G(U_\mathrm{r})$ is possible under equilibrium conditions (i.e. at $U = 0$) when the maximum of the irradiation-induced defects is located outside the space charge region. There is no minimum in the dependence $G(U_\mathrm{r})$ of the diode irradiated with the fluence of 10^9 cm^{-2}. Under equilibrium conditions, this corresponds to the capture of the major part of the irradiation damaged layer by the space charge region, which is possible in the case of considerable compensation of silicon located in the vicinity of the boundary of the space charge region.

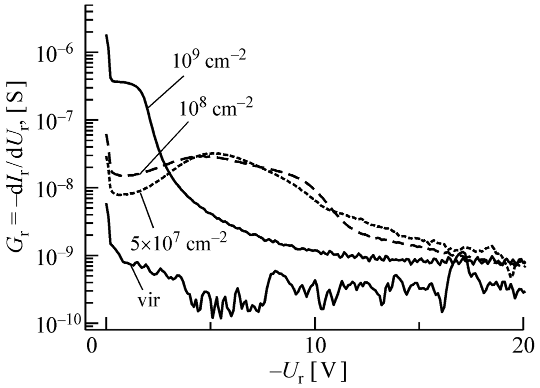

Fig. 4. The differential conductivity of the diodes G as a function of the reverse voltage U_r for the initial (vir) diode and for those irradiated with 170 MeV xenon ions.

Thus, we can state that, under irradiation of diodes with 170 MeV xenon ions with the fluence of 10^9 cm^{-2}, the triple-layer structure (heavily doped p^+-region — region of the compensated n^--silicon — n-base) is formed instead of the double-layer structure (heavily doped p^+-region — weakly doped n-base). There is a possibility for double injection into the region of compensated n^--silicon: holes from the p^+-region and electrons from the n-region. Filling the traps extends the life time of the nonequilibrium charge carriers, and hence larger current values are possible at smaller voltages. It should be noted that the current–voltage characteristics of the diodes irradiated with the fluence of 10^9 cm^{-2} are determined not only by effects related to the current limitation by space charge (of the injected free carriers and those captured by the irradiation-induced defects), but also by the generation-recombination processes in the space charge region close to the p^+–n-junction. Therefore, the current–voltage characteristics of the diode can be similar to that typical of space charge limited current at voltages greater than the contact potential difference. The inset in Fig. 2 shows (in a double logarithmic scale) the section ($U_\mathrm{f} > 0.5$ V) of the current–voltage characteristics of the diode irradiated with xenon ions with the fluence of 10^9 cm^{-2}. Along with the experimental data, the inset also shows the result of the current–voltage characteristic approximation over the voltage interval from 0.6 to 1.2 V in the form of $I_\mathrm{f} \propto U_\mathrm{f}^a$, with $a \approx 2.9 \pm 0.1$. The experimental and computed data are in good agreement. The obtained value of $a \approx 2.9 \pm 0.1$ is close to three, corresponding to the cubic law of current increase, which is typical of the case of the injection plasma in the high-resistance materials [2].

4. Conclusions

It is established that the presence of the section associated with negative differential resistance in the current–voltage characteristics of the diodes, irradiated with the high energy xenon ions, is possible provided a continuous irradiation damaged layer is formed. At the irradiation fluence of 10^9 cm^{-2}, due to compensation of silicon by the irradiation-induced defects, the p^+–n^-–n-structure is formed. Thus, the injection into n^--Si of holes from p^+-Si and of the electrons from n-Si becomes possible, whereas filling the traps by nonequilibrium charge carriers results in the formation of the section associated with negative differential resistance in the current–voltage characteristics.

Acknowledgments

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