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INCREASE OF THE SURFACE RECOMBINATION VELOCITY AT HIGH BIAS VOLTAGE IN SILICON IRRADIATED BY NEUTRONS TO EXTREMELY HIGH FLUENCES

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The upgrading of ionizing radiation detectors is an actual problem especially related to the high energy physics and space research experiments. The simplest way to restore the signal of the irradiation degraded detector is the increase of the detector bias voltage. This method is widely used worldwide, including high energy physics experiments in ATLAS and CMS. This work presents an effect, which was caused by increased bias voltage in detectors irradiated to extreme high neutron fluence at low temperature. The effect could be related to the increase of surface recombination velocity.

The intrinsic photoconductivity spectra were exploited in order to investigate the properties of highly irradiated silicon as this effect depends on parameters that are important in radiation detectors. Two characteristic effects were observed in such highly irradiated samples: the increase of photoconductivity quantum yield and the enhancement of surface recombination at higher bias voltages. The increase of the quantum yield was analyzed in Ref. [1]. The increase of the surface recombination with bias electric field was analyzed in this work as an extension of the performed investigation in the same samples as in Ref. [1]. The investigated silicon samples were irradiated by neutrons to wide range fluence up to 10^{17} n/cm^2.

The origin of this effect was analyzed and related to the radiation clusters, which decrease the free carrier lifetime.

Keywords: radiation detectors, silicon, photoconductivity, CERN

1. Introduction

Silicon is the dominating material for high energy physics (HEP) detectors. The challenges of its application in HEP are related to the necessity to increase the range of fluence at which radiation detectors retain the required sensitivity. This can be realized by increasing the bias voltage, adjusted to the irradiation fluence [2] or by the novel design and engineering of sophisticated detectors such as, e.g. a low gain avalanche detector (LGAD) [3–5], in which an implanted layer of ions creates an effective multiplication of the non-equilibrium carriers. The simplest and widely used method to increase the detector signal is to increase the operational voltage, as realized for all HEP experiments at LHC at CERN [6]. We have investigated such detectors and met the effect of increasing surface recombination velocity with bias voltage, and this work presents the analysis of this phenomenon.

It is well known [7, 8] that the photoconductivity depends on the absorption of incident photons, the mechanism of the generation of electron–hole pairs and the carrier transport (diffusion and drift). To cause the charge carrier excitation, the incident photons must have energy exceeding the band gap of the semiconductor, or to excite the impurities within the band gap. The increase of electrical conductivity depends on the number of photogenerated electron–hole pairs, being dependent on the quantum yield, as well as on the carrier mobility and lifetime. All these factors are also dependent on the presence of recombination centres in a bulk and at the surface of crystals. It is well known that the surface passivation by the SiO_2 layer, which reduces the surface conductivity, is important for radiation detectors. Moreover, the increase of detector bias voltage is used for highly irradiated detectors, which enables the hole injection by a peripheral electric field that can change properties of charge trapping and/or recombination in the SiO_2 layer [9].

In this paper, we present the analysis of the spectral dependences of photoconductivity in the silicon, irradiated by neutrons to a very high fluence (10^{15}–10^{17} n/cm^2). The main attention is paid to the intrinsic photoconductivity region. We report a significant increase of the surface recombination velocity in the samples with the applied higher bias voltage and irradiated by the highest fluence and discuss a possible nature of the phenomenon. Also, the increase of quantum yield data is presented in the samples that were analyzed in Ref. [1], but in this paper we present data only in the samples that are biased with a high voltage.

2. Methods and samples

We have investigated the same Si samples as in Ref. [1]. They were fabricated by the magnetic Czochralski (MCZ) method. Measurements were performed on two types of samples: strip sensors (0.3 mm thick, with 8 mm gap between 6 mm wide contacts) and microstrip sensors (0.3 mm thick, 10 microstrips on each sample, 43 μm between the strips) (Fig. 1).

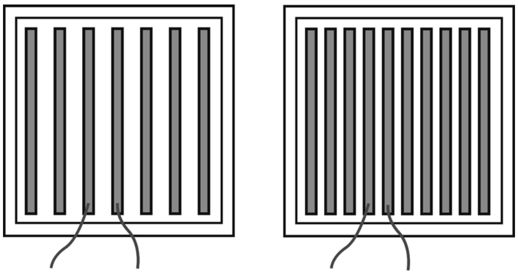

Fig. 1. The sketch of the investigated samples with 7 (left) or 10 (right) microstrips. The connection of sample bias electrodes is also shown.

The microstrip samples were RD50-20 n-type MCZ. They were produced by *CNM*, Barcelona, Spain in 2006 on 4-inch n-type MCZ wafers produced by *Okmetic*, Finland. The measurements were performed between the neighbouring microstrips.

The samples were irradiated in the Ljubljana University TRIGA reactor by reactor neutrons with fluence ranging from 10^{15} up to 10^{17} n/cm^2 (1 MeV neutron equivalent fluence). The time elapsed between the irradiation and the beginning of the experiments was usually one week. However, during the transportation, the samples were kept for two days in a ‘cold box’, the temperature of which at the delivery was −10°C, and we want to stress that all the time when the samples were not investigated, they were stored in a freezer at about −20°C in order to prevent the thermal annealing of the created defects. The displacement damage originates from the fast neutrons, which have a NIEL (non-ionizing energy loss), which is several orders of magnitude higher than the thermal neutrons. The sample surfaces were passivated by a SiO_2 layer, with a thickness of 800–1000 nm.

The main attention of this research is paid to the intrinsic photoconductivity region, where the photocurrent spectral dependence can be approximated by the expression in the thick sample (thickness $d \gg L$, where L is diffusion length) [8]

$$I_{\mathrm{ph}} = \frac{eqwLJ\tau q(1-R)E}{L+S\tau} \times \left(1+\frac{S\tau}{L+\alpha L}\right), \qquad (1)$$

where e is the electron charge, q is the quantum yield, w is the sample width, J is the density of photons/cm^2, τ is the electron lifetime, μ is the electron mobility, R is the coefficient of reflection, S is the recombination at surface velocity, and α is the light absorption coefficient. According to this dependence, the quantum yield dependence on photon energy is the main factor that defines the photocurrent spectral dependence in the samples with a passivated surface ($s = 0$) if all photons are absorbed in the sample.

The samples were placed in a closed-cycle helium cryostat (ARSCryo), the temperature was controlled by a Scientific Instruments 9700. The photocurrent was measured by an electrometer HP4140B. The samples were optically excited using a double prism monochromator DMR-4. The measurements were performed keeping the same photon density of 7.8×10^{13} photons/cm^{2}s at all photon energies. The data were processed by a PC with the GPIB interface. The main measurements in the homogeneous Si strip samples (8 mm distance between contacts) were performed at 50 V bias. In the microstrip samples (23 μm gap between strips), the bias was varied between 0.1 and 10 V.

The I–V characteristics of the samples were nearly linear. The measurements were performed first by increasing the energy of photons and afterwards by decreasing it to avoid the pre-excitation of the samples. The difference of these results showed a role of the non-equilibrium carrier-induced persistent current, which was observed in the extrinsic region.

3. Results

The spectral dependences of photoresponse have demonstrated a classical behaviour in the pristine (non-irradiated) and in the irradiated to a relative low neutron irradiation fluence samples with the passivated surface: the contribution of deep levels was observed below the band gap. In the intrinsic excitation region, the photoresponse used to grow up to the maximum value, where, due to the increasing light absorption coefficient and the influence of the surface recombination, it started to decrease slightly.

A significant change of the spectral dependences of photoresponse was observed in the samples irradiated by neutrons to and above 1×10^{15} n/cm^2 (Fig. 2). If the photoresponse was measured between the microstrips, where a much higher electric field could be created (as already mentioned, the sample surface was passivated by SiO$_2$), the new feature was observed: the increase of the applied bias leads to the increase of surface recombination. Instead of the saturation, the increase of the photoresponse at photon energies above the band gap of Si was observed. In those samples, the increase of quantum yield was also observed with its dependence on the bias.

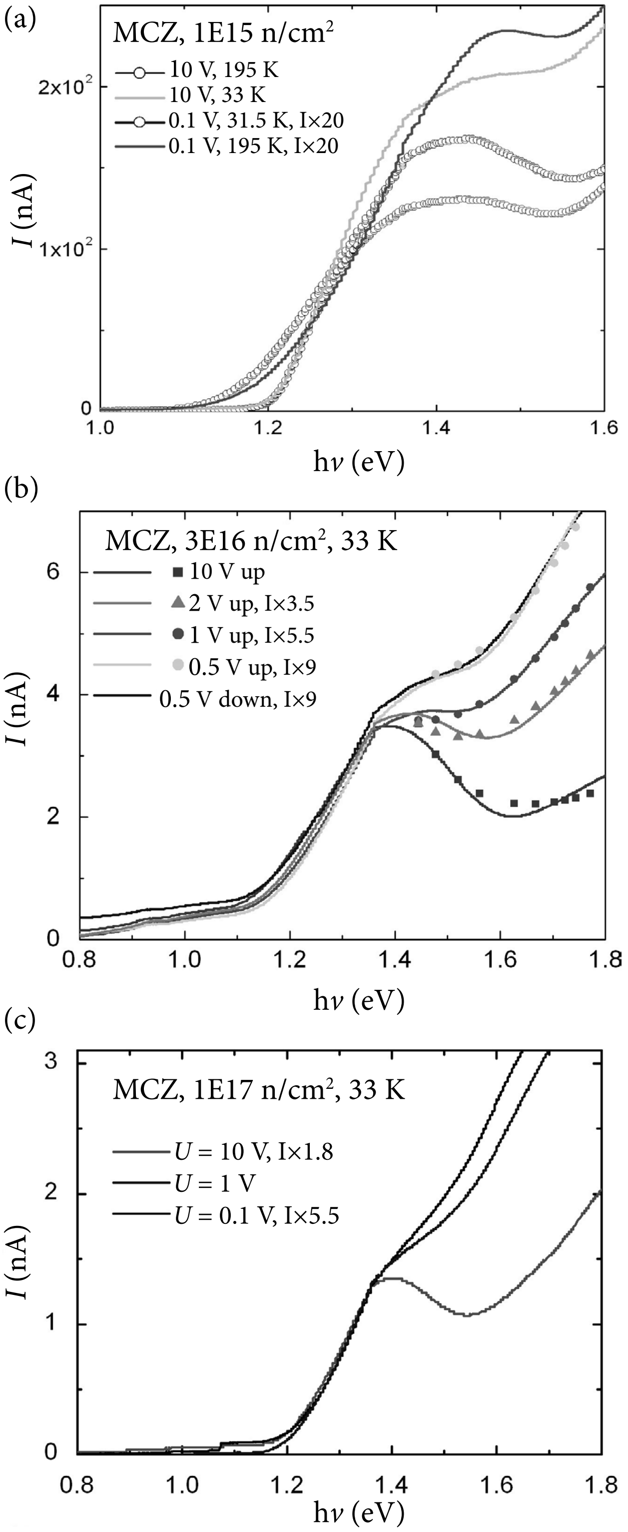

Fig. 2. Spectral dependences of the photocurrent in the microstrip samples irradiated by neutrons to different fluences: a) 1×10^{15} n/cm^2, b) 3×10^{16} n/cm^2 and c) 1×10^{17} n/cm^2. Dotted curves are simulations to find the surface recombination rate.

Thus, to evaluate the surface recombination rate, we have modelled the data with the classical photocurrent spectral dependence approximation [8]

$$I_{ph}/I_{ph\infty} = 1 + (S\tau/L)/(1 + \alpha L), \quad (2)$$

where I_{ph} is the photocurrent, $I_{ph\infty}$ is the photocurrent, assuming that the optical absorption coefficient $\alpha = \infty$, S is the surface recombination rate, $L = (D\tau)^{1/2}$ is the diffusion length, D is an ambipolar diffusivity, and τ is the carrier lifetime. S, τ and $I_{ph\infty}$ were used as parameters to fit the experimental data. The optical absorption coefficient spectrum of Si was used as reported in Ref. [10] with a correction to the temperature of the experiment. The diffusivity value $D = \mu kT/e$ of 6.77 cm^2/s was obtained by using the electron (μ_e) and hole (μ_h) mobility data presented in Ref. [11]. We have assumed that the defect concentration is about 10^{17} cm^{-3}. At 33 K, the following values were used: $\mu_h \cong 1620$ cm^2/sV, $\mu_e = 4500$ cm^2/sV and $D = 2D_pD_n/(D_p + D_n) = 6.77$ cm^2/s.

The fit of this model and the experimental data are presented in Fig. 2(c) as the dotted curves. By the fitting procedure, the values of surface recombination velocity and lifetime were evaluated. The surface recombination velocity was obtained to be: $S = 0.1$ cm/s at 23 V/cm bias, $S = 60$ cm/s at 236 V/cm bias, $S = 400$ cm/s at 472 V/cm bias and $S = 3000$ cm/s at 2360 V/cm bias. The lifetime determined by the fitting was evaluated to be 0.1 ms.

The increase of photoconductivity in the intrinsic absorption region of the highly irradiated samples could be related to the increase of quantum yield, and it did not depend on the bias (Fig. 3).

As the increase of photocurrent at low bias voltages followed a nearly linear dependence on the photon energy only in the samples irradiated by neutrons to extreme high fluences, this dependence was related to the increase of quantum yield. Its value was evaluated by photocurrent normalization to the photocurrent at the beginning of the linear dependence on the photon energy (Fig. 4).

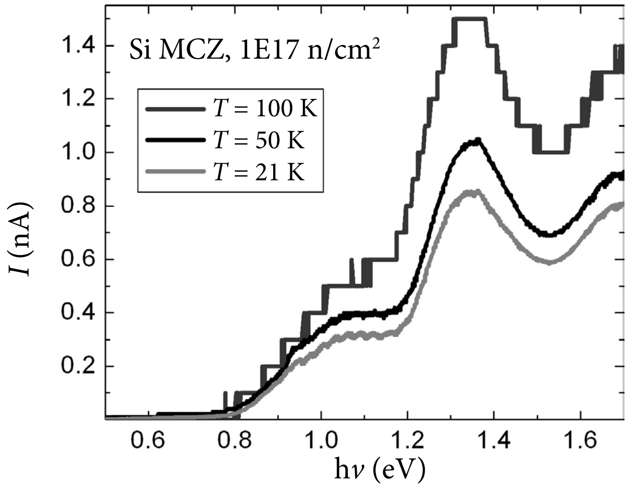

Fig. 3. Dependence of the photocurrent spectra on the temperature at 10 V bias voltage.

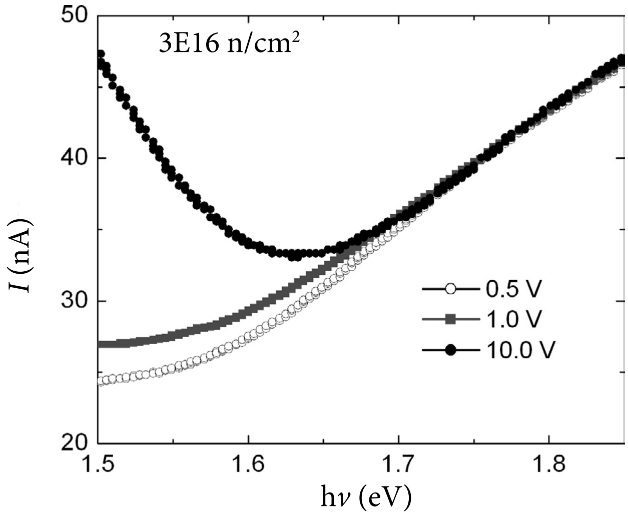

Fig. 4. Dependence of the photocurrent spectra on the bias voltage.

4. Discussion

The observed threshold of the quantum yield increase with the photon energy took place at much lower energy than it was observed earlier; therefore, it was necessary to develop a new model of the impact multiplication of free electrons [1, 12–13], and this effect was observed only in the samples irradiated by neutron fluence above 10^{15} neutron/cm^2. It was proposed that it was related to the properties of the cluster created by high energy hadrons [14, 15]. These clusters also set the free carrier lifetime [16–18].

Characteristically, the effect of the applied bias voltage is also well pronounced. The applied model of the photoconductivity spectral dependence [8] (see above) fitted to the experimental data quite well (Fig. 2(c)). The evaluated free carrier lifetime value being the tenths of milliseconds corresponded to the lifetime that followed the one obtained in Refs. [16–18] in similar samples if it was adjusted to the measurement temperature. In order to discuss the free carrier lifetime dependence on semiconductor parameters, it is clear that the standard Shockley–Read–Hall model [19–20], which is suitable for microelectronics, cannot be applied. Despite the fact that it has been applied [21], in order to explain the avalanche effect in heavily irradiated Si detectors, we have to admit that it does not fulfill the main requirement of this theory that the concentration of local levels should be low. The application of Shockley–Read–Hall theory is analyzed in detail in Ref. [22], and we have pointed out its limitations [23].

Therefore we used the Rose model that can be applied for any concentration of local levels and provide a possibility to discriminate between levels serving as recombination centres or traps. As found experimentally, the lifetime followed the relation found in Refs. [16–18] in the samples irradiated to the hadron fluence in a very wide fluence range and the reciprocal lifetime followed the linear dependence, therefore we approximated it by the following formula

$$1/\tau = v_{\mathrm{thermal}}\,\sigma M, \qquad (3)$$

where v_{thermal} is the electron thermal velocity that in the case of silicon at 300 K equals 10^7 cm/s [24], σ is the capture of free carrier cross-section, and M is the concentration of recombination centres.

The applied bias created the electric field that did not change the electron mobility [11] therefore the carrier recombination changes had been responsible for the observed dependences. It was shown in Ref. [16] that the lifetime depends on the presence of clusters, which reduces the lifetime in the sample. The carrier has to reach the recombination centre by diffusion, which can depend on the bias created electric field and a distance between recombination centres. The concentration of clusters, expressed in cm^{-3}, has been evaluated in the silicon samples irradiated by fast neutrons and the approximate value equals the fluence value expressed in cm^{-2} [24–25]. It was proposed [18] that only the clusters that had an electric dipole feature could act as fast recombination centres. Only a third part of clusters had the dipole feature on its surface. It means that in the analyzed case, i.e. in the sample irradiated by neutrons to 3×10^{16} n/cm^2 fluence, the mean distance between the clusters would be equal to 3.22×10^{-6} cm. Thus, it could be proposed that the lifetime is defined by the clusters, but in the rest part of the sample the contribution to the recombination is dependent on the surface properties.

$$D = \mu kT/e \qquad (4)$$

was obtained to be 6.77 cm^2/s by using the electron (μ_{e}) and hole (μ_{h}) mobility, the data of which is presented in Ref. [11]. We have assumed that the defect concentration is about 10^{17} cm^{-3}. At 33 K, the following values were used: $\mu_{\mathrm{h}} \cong 1620$ cm^2/sV, $\mu_{\mathrm{e}} = 4500$ cm^2/sV and $D = 2D_{\mathrm{p}}D_{\mathrm{n}}/(D_{\mathrm{p}} + D_{\mathrm{n}}) = 6.77$ cm^2/s. The thermal velocity of electrons was equal to 7.6×10^6 cm/s and the lifetime was obtained by fitting of the experimental data according to Eq. (1), and it was found equal to 9.4×10^{-5} s.

The experimental results are interpreted in terms of the dominant physical mechanisms responsible for mobility degradation at the Si/SiO$_2$ interface [26], i.e. an effective enhancement in the rate of electron scattering with the Si/SiO$_2$ surface roughness, as well as other types of defects, caused the lower mobility of the carriers.

The applied bias voltage caused a drift of carriers to the clusters, and it led to the change of the carrier recombination rate. As the mobility of electrons is lower at the surface, it causes a greater decrease of the carrier recombination rate if the carriers are generated near the surface. The possibilities of modelling could be illustrated by Fig. 5 that confirms the model.

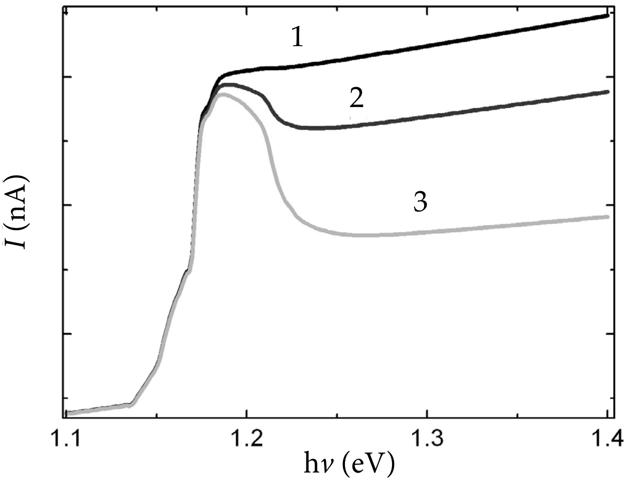

Fig. 5. Modelling of photocurrent spectral dependence with different mobility in the bulk and at the surface (1 is a homogeneous sample, 2 is the surface mobility 2 times smaller than in the bulk, and 3 is the surface mobility 100 times smaller than in the bulk).

Therefore, the dependence of the photocurrent on light absorption in the sample could be similar to the classical photocurrent spectral dependence [7], but a nature of the surface recombination velocity S change was different.

Conclusions

The quantum yield enhancement was observed in the Si irradiated by neutrons to the fluence of 10^{15} cm^{-2} and above and it was independent of the bias voltage.

The increase of surface recombination rate was proposed to be attributed to the recombination at the clusters and the mobility decrease at the interface of Si/SiO$_2$.

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PAVIRŠINĖS REKOMBINACIJOS GREIČIO AUGIMAS DIDINANT ĮTAMPĄ SILICYJE PO ŠVITINIMO GREITAISIAIS NEUTRONAIS YPAČ DIDELIU ĮTĖKIU

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Santrauka

Didelių energijų dalelių fizikos eksperimentuose (pvz., ATLAS, CMS) dėl švitinimo poveikio degraduoja detektoriai ir silpsta iš jų gaunami signalai. Vienas populiariausių būdų atkurti nykstantį signalą yra kelti maitinimo įtampą. Šiame darbe nagrinėjamas reiškinys, kai silicio detektoriaus fotolaidumo spektre keliant įtampą stebimas pokytis po švitinimo greitaisiais neutronais įtėkių srityje nuo 10^{15} iki 10^{17}n/cm^2. Atlikus teorinių fotosrovės matematinių išraiškų priderinimus prie eksperimentinių duomenų, buvo nustatyti paviršinės rekombinacijos greičiai, kurie tendencingai keitėsi priklausomai nuo pridėtos įtampos. Šio greičio kitimo intervalas apima ribas nuo 0,1 iki 3 000 cm/s, keičiant įtampą, lemiančią elektrinio lauko kitimo ribas nuo 23 V/cm iki 2,4 kV/cm. Tokio stiprumo elektrinis laukas nekeičia krūvininkų judrio, o krūvininkų tankio kitimas yra nulemtas rekombinacijos kitimo. Iš kitų tyrimų žinoma, kad greitaisiais neutronais paveiktame Si kuriasi defektų klasteriai, iš kurių 1/3 yra elektrinių dipolių pavidalo ir tik jie lemia krūvininkų gyvavimo trukmę. Taigi, likusią įtaką rekombinacijai daro medžiagos paviršiaus savybės. Todėl eksperimentiniams rezultatams paaiškinti šiame darbe buvo pasiūlytas modelis, pagal kurį bandinio paviršiuje dėl nelygumų ar kitų defektų yra mažesnis krūvininkų judris. Pridėta įtampa krūvininkus efektyviau nukreipia link defektų klasterių, dėl kurių mažėja gyvavimo trukmė, tačiau paviršiuje generuotų krūvininkų rekombinacijos greitis yra mažesnis dėl mažesnio judrio. Apibendrinant rezultatus, daromos tokios išvados: Si, švitintame greitaisiais neutronais įtėkiu 10^{15}n/cm^2 ir didesniu, stebimas kvantinės išeigos padidėjimas, kuris nepriklauso nuo pridėtos įtampos; manoma, kad paviršinės rekombinacijos greičio padidėjimas yra susijęs su defektų klasteriais ir krūvininkų judrio sumažėjimu ties paviršine Si/SiO$_2$ sandūra.