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Unexpected Irreversible Changes of Photodiode Structure due to Multiple Gamma Irradiation

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Abstract: We have studied the influence of gamma radiation on the structure of the photodiode and its current. Fifty-five photodiodes have been irradiated twice, the first dose of 2000 Gy and then a dose of 5000Gy. U-I characteristics of each photodiode have been measured several times, before the radiation, between the radiation and after radiation and presented on the same diagram. These diagrams show the influence of gamma radiation on photodiodes. The results show that gamma irradiation reduces the current of photodiode. After some time photodiodes have been recovered from the effects of radiation, but not completely. Some time after the second irradiation some unusual changes in photodiode current have been observed. Because of these two doses of radiation, the current of photodiodes have been reduced by 14-17 %.

Keywords: photodiode; gamma radiation; U-I characteristic; irreversible changes

1 Introduction

Due to the wide field of use, photodetectors are very often exposed to various forms of radiation in the enviroment where they are (natural cosmic enviroment, the upper layers of the atmosphere, military and civilian nuclear enviroment, etc.). Optoelectronic devices in which the active elements are semiconductors are frequently sensitive to radiation because the absorption or generation of light in a solid medium is influenced by the defect structure of that medium [1-5]. For this reason, extensive research has been undertaken to develop semiconductor devices that can operate in conditions of increased radiation. Typical representatives of the semiconductors used as photodetectors are photodiodes.

The aim of this study is to assess the impact of multiple gamma radiation on the U-I characteristic of photodiode. It is known that exposure of semiconductor to gamma radiation causes irreversible damage of their structure which decreases the photocurrent. It is also known that after the exposure to radiation comes to partial recovery (relaxation) of semiconductors when their properties, which were disturbed by radiation, are re-established

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in certain percentage. In this study we wanted to examine how much the current of photodiodes decreases under the influence of gamma radiation as well as what percentage of these semiconductor manage to restore their disturbed properties.

2 Theoretical analysis

Silicon PIN photodiodes have stable gain, require less than 100V power supplies, are insensitive to magnetic fields, have high quantum efficiency (50 - 80 % in the visible spectrum), can be made in small sizes (minimum dimension of the optical surface is approximately 100μm, minimum depth is approximately 2 mm including substrate), are relatively inexpensive and can be made in close packed arrays with small dead area and crosstalk. However, PIN photodiodes are unity gain devices and have low quantum efficiency at violet and ultraviolet wavelengths, which makes them very sensitive to electronic noise and limits the energy and timing resolution when measuring gamma radiation with scintillators.

When gamma rays interact with the material, the primary effects, depending on the energy of radiation, are: photoelectric effect and Compton effect, which leads to the creation of electron-hole pairs and the creation of recombination centers. Creation of recombination centers in the energy gap in the interface areas is particulary important because their density may even be equal to the density of surface atoms. Number of recombination centers is proportional to the energy, ie. dose radiation. These recombination centers will attract the free electrons, ie. reduce minority carrier lifetime. Because of that the current is smaller after irradiation. Of course, the higher dose of radiation should create more recombination centers and thus smaller current.

3 Experimental procedure

In this experiment were used a number of photodiodes (55 photodiodes). Photodiodes are silicon PIN photodiodes BPW34. U-I characteristics of these photodiodes at different light intensities are shown in Fig. 1.

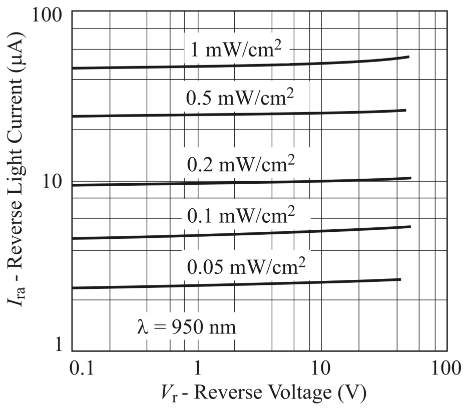

Fig. 1. U-I characteristics of photodiodes BPW34

U-I characteristics of these components have been measured in the following way. Semiconductor element was located in a sealed tube where was illuminated by light from light sources. A red light bulb (25W power), as the BWP34 are most sensitive to red light, was used as a light source. DC power source with a potentiometer to adjust the voltage (0-25V) was used as an electrical source. The tube in which there was semiconductor element was sealed to disable the external light to enter inside. Voltage was changed from 0 to 4V.

Five characteristics have been measured. The first characteristic was measured on the new elements before irradiation. Then the phototransistors were exposed to irradiation dose of 2000 Gy. Immediately after irradiation (in the first 12 hours after radiation) the second characteristic was measured. Then the elements were given a period of 15 days to recover. After that the third characteristic was measured. Then again there was performed gamma radiation by a dose of 5000 Gy and during the first 12 hours after the radiation, the fourth characteristic was measured. The last, fifth characteristic was measured after 2 months of repairs.

All 5 characteristics for each photodiode were represented in one diagram, so we finally get the 55 diagrams.

These diagrams were the starting point for the conclusions.

4 Results and discussion

Observing these diagrams it is obvious that some photodiodes have similar diagrams. We will form groups of photodiodes, based on the similarity of diagrams, and we will analyze each group particulary. Since all photodiodes in one group have a similar diagram, each group will be presented with one diagram as its representative.

Considering the diagrams, all 55 photodiodes can be divided into 6 groups, which we will denote with I, II, III, IV, V and VI. U-I characteristics of certain groups are shown in the following pictures.

Fig. 2. shows that the first irradiation influenced the structure of the photodiodes resulting in the decrease of the photocurrent. Fifteen days later after the recovery of the photodiodes resulted in the increase of the diode current. Second irradiation let to larger structure damages and smaller current. The decrease of current after irradiation is caused by the creation of recombination centers in the structure of the material. Some charge carriers will recombinate in these recombination centers and that will decrease the minority carrier lifetime. If we take into consideration only the first four U-I characteristics we can say the photodiodes have exactly the same behavior according the textbooks. However, there were some photodiodes whose behavior significantly deviated from the expected (Fig. 3. to 7.). Fig. 2. also shows that photodiodes don't recover two months after the second irradiation. On the contrary, its characteristics worsen and they conduct even smaller current. This drastic reduction of photodiode conductivity is quite unexpected.

Fig. 3 - 7 shows that all photodiodes conduct smaller current after 2 months. It is known that gamma rays consist of gamma quanta that is of photons of great energy. During the interactions with photodiodes gamma rays give a large amount of energy to

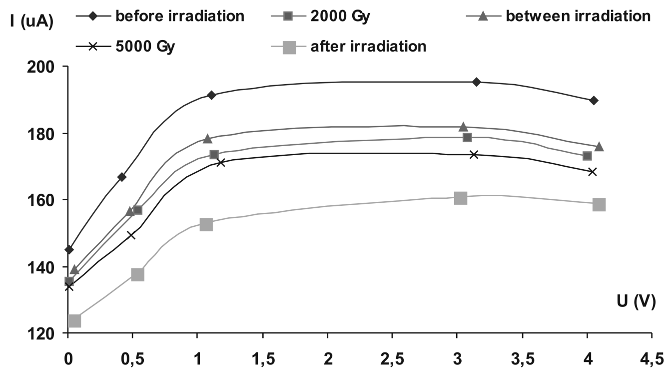

Fig. 2. U-I characteristics of photodiodes from the group I

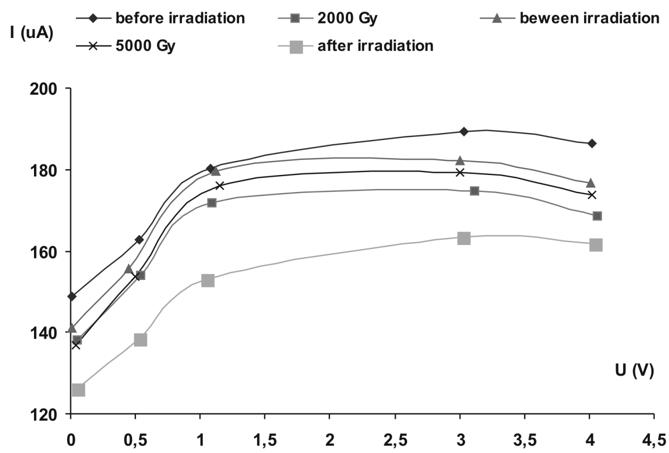

Fig. 3. U-I characteristics of photodiodes from the group II

the electrons. Under the influence of that energy some of valence electrons will come out of atoms and become free thus creating recombination centres. Minority carriers would later recombinate in these recombination centres, which will result in the current reduction. During the period of recovery the concentration of the recombination centres should be partially reduced due to the diffusion motion of free electrons and their recombination. Therefore, the current should increase. However, this does not happen, but, on the contrary, the current decreases a lot.

Possible cause of this could be noise, probably low frequency 1/f noise, generation-recombination noise or diffusion noise. It is known that low frequency noise (1/f and burst noise) is manifested as random fluctuation of the output current or voltage, leading to lowering of the efficiency of the device. Various experiments suggests [6, 7, 8, 9] that the origin of this noise is fluctuation of the number free charge carriers connected to existence of the traps located in the vicinity or directly in the junction area, or fluctuation of the mobility of

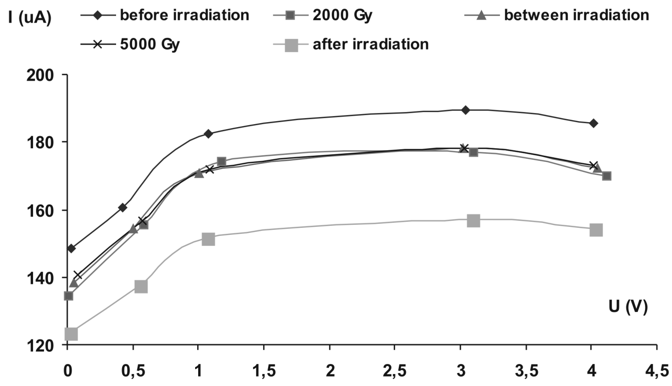

Fig. 4. U-I characteristics of photodiodes from the group III

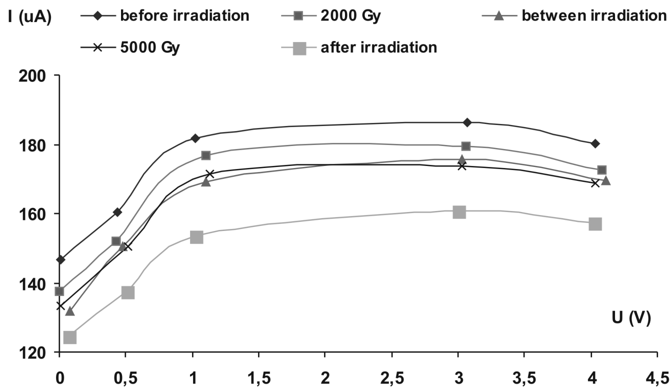

Fig. 5. U-I characteristics of photodiodes from the group IV

charge carriers. In both cases these fluctuations arise from the interactions of carriers with defects, surface states and impurities, that are either introduced during manufacturing of the device, or as a consequence of the hostile working conditions (radiation, high temperature, humidity). In our case, radiation is a key factor. The main effect of the radiation is an increase of the saturation current generated within or at the surface of the depletion region. The permanent damage the photodiodes is caused by collisions of the incident radiation particles with the atoms in the crystalline lattice, which are displaced from their positions. These defects degrade the transport properties of the material and particularly the minority carrier lifetime [10, 11, 12, 13, 14]. Spontaneous fluctuations in the rates of generation, recombination and incidence of charge carriers cause the fluctuations in the density of charge carriers, which produces generation-recombination noise. Diffusion noise also arise as a result of localized fluctuations in the density of charge carriers but also due to fluctuations in the rate of diffusion. In any case, each of these noises affect the density of free charge carriers and thus the level of current of photodiode.

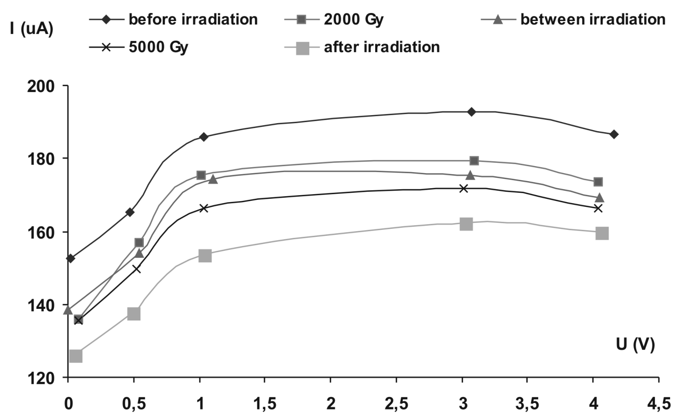

Fig. 6. U-I characteristics of photodiodes from the group V

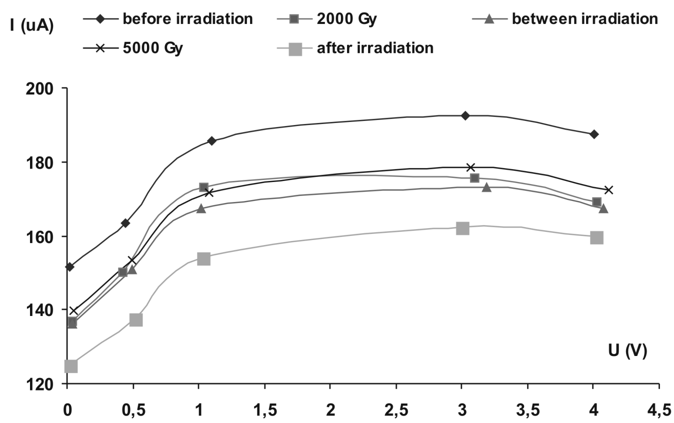

Fig. 7. U-I characteristics of photodiodes from the group VI

Another reason for the drastic decrease of the photodiode current could be the amount of energy introduced into the material. The dose of second radiation was more than two times higher than the first. This radiation has introduced a large amount of energy into the photodiodes. Both the electrons in atoms as well as the free electrons have received that energy. We assume that, during the period of recovery after the second irradiation, due to this energy, the diffusion motion of free electrons became very strong. Due to this diffusion motion, a number of electrons has been recombinated in the recombination centres, much more than after the first radiation when their energy was lower. As a result, the concentration of the majority and minority charge carriers significantly reduced. The reduction of the concentration of minority charge carriers is especially important, since they are the ones who provide current through the photodiode. The photodiode current reduced in proportion to the reduction of the concentration of minority charge carrier.

Also, regardless of quality of production, none crystal semiconductor is pure (there are always more or less impurities and defects in the structure of the material). This energy can cause strain in the crystal structure of the diodes and lead to activation of existing defects and impurities that can serve as recombination centers, especially if they are in the energy gap in the interface areas.

Some diodes indicated such behavior after the first irradiation (groups IV, V and VI). Fig. 5., 6. and 7. show that the photocurrent of this diodes is smaller after 15 days of recovery than it was immediately after the first irradiation.

Photodiodes from the groups II and III also show interesting behavior (Fig. 3. and 4.). These diodes have more stable structure. Photodiodes from the group III show no changes in current level immediately after the first irradiation, after 15 days and immediately after the second irradiation. Diodes from the group II even show reversible behavior thus the current after the second irradiation is higher than the current after the first irradiation which indicates that there was a stable recovery between the two irradiations.

If we summarize all these previous results we can say that the current of photodiodes, after the multiple radiation and recovery, has approximate values showed in Table 1. (I_p is the current through new unirradiated photodiode).

Table 1. Photodiodes current

Radiation	2000 Gy	Recovery	5000 Gy	Recovery
BPW34	$0,9293I_p$	$0,9366I_p$	$0,9165I_p$	$0,8394I_p$

Table 1 shows that the current level of all photodiodes is approximately equal immediately after the first irradiation, after 15 days of recover and immediately after the second irradiation. It is obvious that there is not come immediately to major damages in the structure of the diode either after the first or after the second irradiation, but it happened much later, which can be attributed to the delayed effect of irradiation.

5 Conclusion

Previous analysis has shown that it is not a rule that the recovery after the first irradiation would bring the stabilization of the photodiode structure and give higher current (although this happens at photodiodes from groups I and II). Photodiodes from groups III, IV, V and VI show interesting behavior, their current is lower after the recovery than before. Also, for all photodiodes, two months of recovery after the second irradiation didn't bring stabilization but the current drasticly decreased (14 to 17 %). This points to the possible further deterioration of the characteristics of photodiode, even in a long time after the irradiation. This means that such photodiodes after the irradiation are no longer reliable, even if their current immediately after the irradiation has not changed much.

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