SCIENTIFIC PUBLICATIONS OF THE STATE UNIVERSITY OF NOVI PAZAR
SER. A: APPL. MATH. INFORM. AND MECH. vol. 3, 1 (2011), 27-34.

Photodiode Behavior in Radiation Environment

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Abstract: Possibilities of application of photodetectors based on photodiodes are very high, primarily because of their relatively low cost, small size and high speed response (among the highest in comparison to all other types of detectors). However, like all other types of photodetectors, photodiodes have certain limitations and disadvantages, too. If the photodiode is powered by the constant voltage, its response (current) is practically identical to the technical information provided by the manufacturer even if it has previously been subjected to the radiation (in that case the current is only a bit weaker). On the other hand, if the voltage is not constant and the photodiode is located in the areas with strong gamma radiation, then its response varies from the one that is expected. Therefore, the improvement of the electrical properties of photodetectors based on photodiodes is very important. The aim of this study was to research the behavior of photodiodes in nonideal conditions (variable voltage power supply and the environment with strong gamma radiation).

Keywords: Photodiode, time-varying voltage, gamma radiation, I-V characteristics, antiresonance, high harmonics of current

1 Introduction

Photodiodes are some of the most used photodetectors. Silicon PIN photodiodes have stable amplification, 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 100m, minimum depth is approximately 2mm including substrate), are relatively inexpensive and can be made in close packed arrays [2]. Very important facts that determine the quality of photodiodes used as photodetectors are the response of photodiodes (form of I-V characteristics ie. whether the current is constant) and the behavior of photodiodes exposed to radiation. This is important because the photodetectors are widely used and thus often exposed to various forms of radiation in the enviroment where they are found (natural cosmic enviroment, the upper layers of the atmosphere, military and civilian nuclear enviroment, etc.)

Manuscript received October 3 2010; accepted January 21 2011

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Photodetectors (photodiodes) are typically used in reverse bias. In the dark, current dependence on voltage (I-V characteristics) of photodiodes are as the same as the characteristics of rectifier diodes. In that case, only the leakage current flows through the photodiode. When the photodiode is exposed to the effects of light, then the photon energy is used to break the covalent bond releasing electrons and creating a hole in the process. If the generation of electrons and holes occurred in the depletion area, then the existing electric field removes them from that area before they get a chance to recombine. As a result, the reverse current (photocurrent) occurs. Photocurrent grows in proportion to the intensity of light. For larger values of reverse bias voltage photocurrent does not depend on the applied voltage but is practically constant. The speed of electron-hole pairs generation under the influence of light limits the photocurrent. The number of generated electron-hole pairs increases only with the increasing of the light intensity [17]. Also, the number of collisions of electrons with phonons in the semiconductor crystal lattice increases at the higher reverse bias voltage, so the speed of directional movement of charge carriers less depends on electric field. The speed of moving carriers through the crystal is limited. When the moving carriers reach the highest speed, further increasing of the electric field does not increase the speed of directional movement of carriers but only their kinetic energy [18]. This means that the voltage at which the photodiode is connected doesn't need to be constant. If it is DC voltage and its RMS is high enough, the current that flowing through the photodiode will be constant.

On the other hand, optoelectronic devices in which the active elements are semiconductors are usually sensitive to radiation because the absorption or generation of light in solids is influenced by the defect in the structure of that medium [1-5]. For this reason, extensive research has been undertaken to develop semiconductor devices that can operate under conditions of increased radiation.

The aim of this study is to assess the response of the photodiode to the connected variable DC voltage while it is simultaneously exposed to gamma radiation.

2 Experimental procedure

A large number of photodiodes (40 photodiodes) have been used in this experiment Photodiodes are silicon PIN photodiodes BPW34, with high speed and high radiant sensitivity in miniature, flat, top view, clear plastic package. It is sensitives to visible and near infrared radiation, produced by VISHAY. Some of the characteristics of these diodes are: dimensions $5.4 \times 4.3 \times 3.2$ mm, radiant sensitive area 7.5 mm^2, angle of half sensitivity $\varphi = \pm 65^0$. The data about these photodiodes can be found at www.vishay.com. The photodiodes are first connected to stabilized DC voltage (constant) and their I-V characteristics (photocurrent) have been measured. Then they are connected to variable DC voltage at 50Hz frequency (as in Fig. 1.) and their I-V characteristics have been measured again.

After that the photodiodes were exposed to irradiation dose of 2000 Gy and the I-V characteristic (with the attached voltage as in Fig 1.) was measured immediately after the irradiation (within the first 12 hours after the radiation). Radioactive source for irradiation

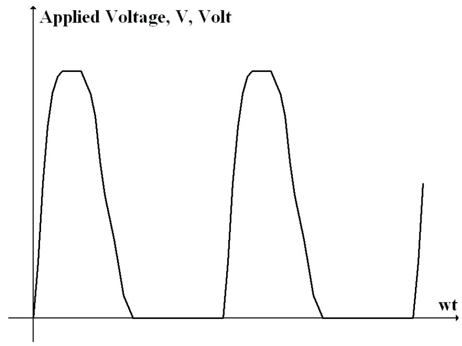

Fig. 1. Voltage connected to photodiode

was a Co-60, with the energy of 1.17 MeV, and half-life time of 5.27 years (this energy is sufficient for the creation of electron-hole pairs). The strength of the dose was 100 Gy/h at a distance of 150 mm away from the radioactive source. The strength of the dose was measured by electrometer UNIDOS with ionization chamber TW 30012-0172, produced by PTW, Germany. Measurement uncertainty of the system is less than 1.2%. The components were irradiated in the air at a temperature of 21 C and relative humidity of 40% to 70%.

The professional digital multimeter AMPROBE 33XR was used for the current measurement. The accuracy of this instrument (for DC current) is $\pm1\%$ of reading. Taking this into account, the combined measurement uncertainty was less than 1,2% for all measurements performed within the experiment.

Also, an oscilloscope was used for the waveform current measurement.

3 Results and discussion

3.1 Response of the non-irradiated photodiodes

Figure 2. shows I-V characteristic of photodiodes when they are connected to a constant voltage of the stabilized source and to a variable voltage from the unstabilized source (as in Fig. 1).

Photodiode response at a constant voltage power supply is almost identical as in the technical information provided by the manufacturer, while the photodiode response has an unusual shape at a variable voltage power supply. The kind of shape of I-V characteristic in this case depends on two factors, frequency of supply voltage and photodiode capacitance. Since the reverse biased PIN photodiode can be equivalently represented as in Fig. 3 [19], it will act as a resonant circuit if we connect it to the voltage as in Fig. 1

Not that the capacitance of the PIN photodiode is very small because of the depletion layer but it even decreases with the increasing voltage (due to the increase of potential barrier width), while the conductivity increases [19]. Due to capacitance and conductance changes, an antiresonance will happen at one moment and the current will have a minimum value (Fig. 2) [20]. Waveform of photocurrent for different voltage RMS is shown in Fig.

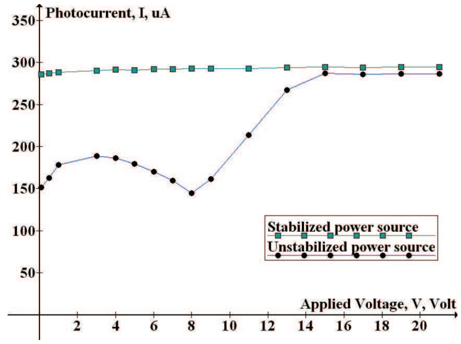

Fig. 2. I-V characteristic of the photodiode connected to a stabilized and unstabilized power source

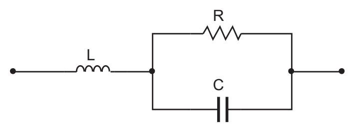

Fig. 3. Equivalent circuit of reverse biased PIN photodiode

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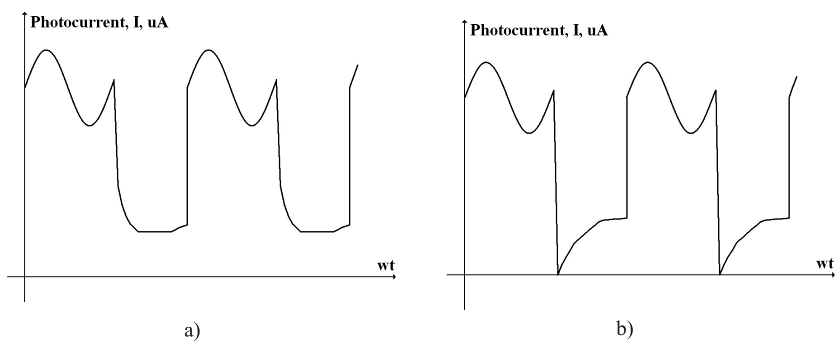

Figure 4(b) shows the voltage at which the photocurrent gets a negative value ie. the moment when the diode begins to oscillate (about 6V). Figure 4(c) shows the voltage at which photocurrent has the largest negative peak, ie. the moment when the antiresonance appears (8V). Figure 4(d) shows the moment when the oscillations of photodiode stop. The capacitance of photodiode is this big at higher voltages that it acts as a filter capacitor stabilizing current through the diode (Fig. 4(f)). Practically, the photocurrent has more or less pronounced higher harmonics up to the voltage of 15V, while the photocurrent is sinusoidal for larger values of voltage.

It is obvious that the photodiode acts as a resonant circuit at voltages of about 6V to about 11V. It is also worth noting that changes of the current are linear (Fig.2) at the voltage range from 9V to 13V, which means that the impedance (admittance) of the photodiode is

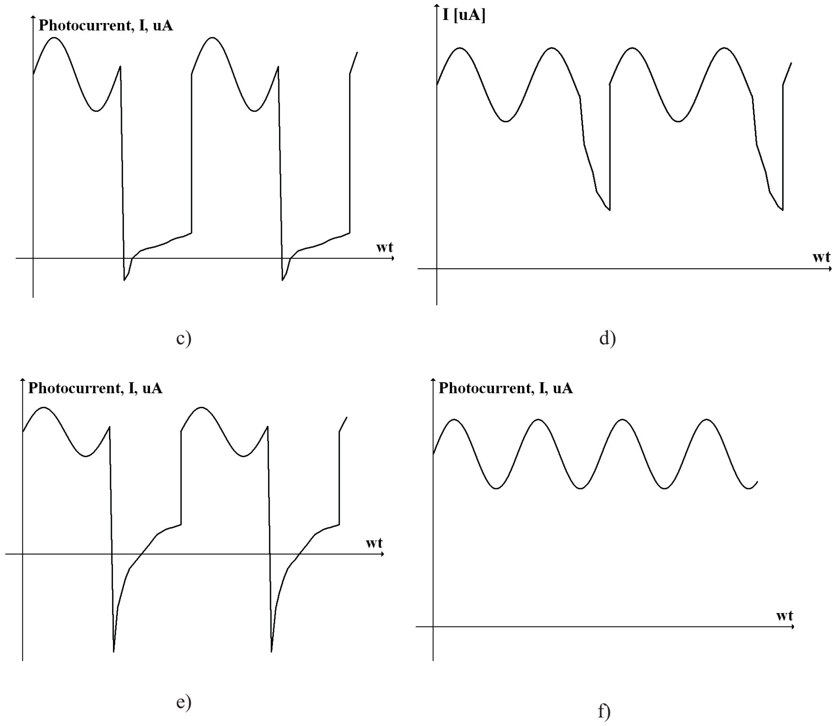

Fig. 4. Waveform of photocurrent for different voltage RMS (a) $V = (0-5)V$; (b) $V = 6V$; (c) $V = 8V$; (d) $V = 11V$; (e) $V = 13V$; (f) $V = 15V$

constant at that voltage range (Y=const). We can write

$$I = Y \cdot V \tag{1}$$

where I and V are RMS of current and voltage of photodiode and Y is the RMS of photodiode admittance. If equation (1) is differentiated by V, we get:

$$\frac{dI}{dV} = \frac{dY}{dV} \cdot V + Y \cdot \frac{dV}{dV} \tag{2}$$

Since $Y = const$, we can write

$$\frac{dI}{dV} = Y \tag{3}$$

and

$$Y = \tan \alpha \tag{4}$$

where α is the angle between I-V characteristic and the x-axis (within the voltage range where the change of photocurrent is linear). In that way, the RMS of admittance or impedance of the photodiode can be determined within this voltage range (from 9V to 13V).

3.2 Response of the irradiated photodiodes

The I-V characteristics of photodiodes have been measured after the exposure to gamma radiation. Figure 5. shows a reduction of photodiode current after irradiation, as expected. It is known that gamma rays consist of gamma quanta that is of photons of great energy. During the interactions with the photodiode, gamma rays give a large amount of energy to the electrons (in this case 1.17 MeV).

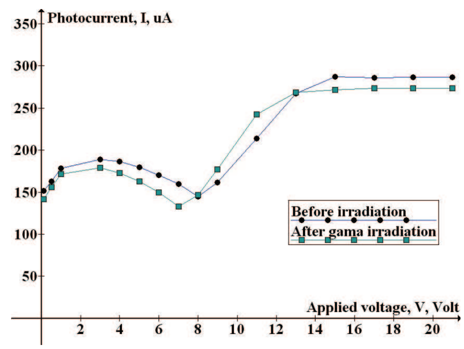

Fig. 5. I-V characteristics of photodiodes before and after irradiation

Gamma ray (high energy photons) interact with orbital electrons via photoelectric and Compton effects. If the energy of gamma ray is high enough (above several hudred keV) the pair generation occurs. The energy spectrum of the energetic electrons is called ”slowing spectrum”. The energetic electron interacts with a lattice atom. As a result, the lattice atom is displaced from lattice site. This is so called Primary Knock on Atom (PKA) [14, 15]. Interstitial (PKA), vacancy, and complex of them form a deep level in bandgap. This is so-called the generation-recombination centre. The recombination centres in bulk region cause the reduction of carrier lifetime. In addition the deep levels compensate the donor or acceptor levels resulting in the reduction of effective carrier concentration (Carrier Removal CR effect). Because of this, the depletion layer width become long. The depletion layer width strongly affects the photocurrent so the photocurrent decreases.

What is not expected is that the photocurrent found in resonant range is higher after irradiation (Fig. 5). This can be explained by the fact that the photocurrent has negative value in some periods during the oscillation of the photodiode, i.e. in these periods it is flowing in the opposite direction. Due to constant changes of motion direction the charge carriers don’t have enough time to recombine, their lifetime is increasing and thus the current is higher.

4 Conclusions

Previous results have shown several things. Photocurrent through the photodiode connected to the variable DC voltage is also variable. Because of its structure and characteristics, photodiode will act as the real resonant circuit. If the RMS voltage increases, as a result of changes in photodiode capacitance and a constant frequency of voltage, the antiresonance will appear at a certain voltage and photocurrent will have a minimal value. With further increasing of the voltage, as long as oscillation of photodiode lasts, changes in capacitance and conductance of photodiode are such that its admittance is constant. When the photodiode capacitance is reduced enough, the photocurrent will stabilize and become sinusoidal. Also, it is noted that gamma radiation strongly afects the oscillatory mode of photodiodes, so thE photodiodes then conduct a larger photocurrent The photodiode oscillation is the main cause of RMS current increasing because during the oscillation there are time intervals in which the photocurrent is negative.

Acknowledgment The Ministry of Science and Technological Development of the Republic of Serbia supported this work under contract 171007.

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