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Dynamic gamma irradiation effects on mid-wavelength HgCdTe photovoltaic detectors

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Abstract: The dynamic current-voltage (*I-V*) characteristics of mid-wavelength HgCdTe photovoltaic detectors under steady-state gamma irradiation have been measured as a function of gamma dosage. Two obvious effects were observed due to gamma radiation. One is the ionization effect demonstrated by the generation of the photocurrent in the diodes. The other is the displacement damage effect reflected by the increased resistivity in the neutral region. Both effects showed dosage dependence. Qualitative analysis showed that the photo electron yield became small with increasing gamma dosage, which meant the radiation-induced defects played a significant role in large dosage range.

Key words: gamma irradiation, dynamic irradiation effect, photovoltaic detector, HgCdTe
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中波碲镉汞光伏探测器的实时 gamma 辐照效应

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摘要: 对中波碲镉汞光伏探测器进行了实时 gamma 辐照效应研究. 通过在辐照过程中对器件的电流—电压特性曲线进行测试, 得到了器件电学性能随着 gamma 辐照剂量的变化. 研究发现器件在辐照过程中表现出两种典型的辐照效应: 电离效应和位移效应. 电离效应可以通过辐照过程中类似光电流的产生来表现出来, 而位移效应则通过辐照过程中器件串联电阻的增加来体现. 两种效应都表现为总剂量效应. 分析认为, 由于位移效应引入的辐照损伤随着辐照剂量的增加越来越多, 辐照电离效应产生的自由载流子产额随之逐渐降低, 说明随着辐照剂量增加, 电离效应逐渐降低, 而位移效应则逐渐增强, 导致器件性能衰退.

关 键 词: gamma 辐照; 实时辐照效应; 光伏探测器; 碲镉汞

中图分类号: TN21 **文献标识码**: A

Introduction

Irradiation effect of photonic sensors has been one of the necessary research issues since the early years of their applications[1]. It will be very beneficial for people to understand the degradation mechanisms induced by different kinds of radiations, for example, it has helped to protect the photo devices operating in a radiation environment. Gamma radiation is one of the practical and universal methods to study the irradiation effect of infrared detectors. HgCdTe photovoltaic detector is one of the most important infrared detectors up to now, and current-voltage (*I-V*) characteristic is a direct and efficient tool to study its electrical performance[2-4]. Several papers have been issued on the topic of gamma radiation effects for HgCdTe materials and photo detectors[5-9]. In this paper, the dynamic irradiation effects of mid-wavelength HgCdTe photodiodes have been evaluated by measuring current-voltage curves during gamma irradiation.

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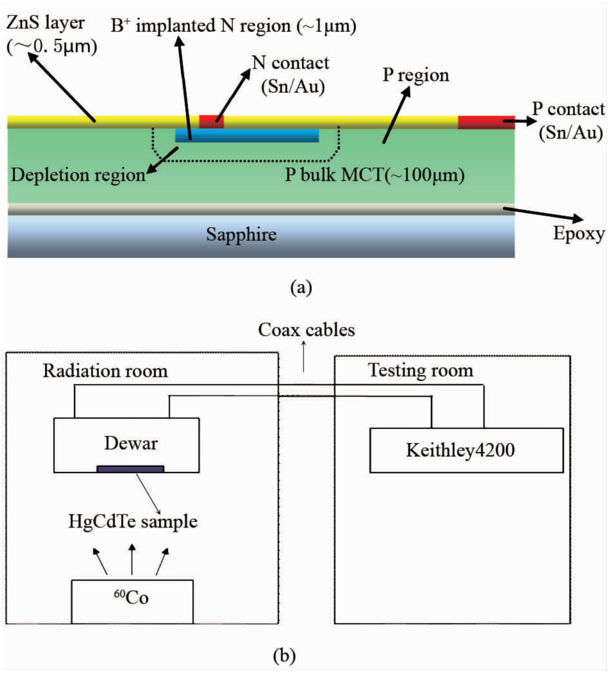
1 Experimental details

Photovoltaic detectors used in the study were fabricated by vacancy doped p-type HgCdTe wafer grown by Travelling Heater Method (THM) with a Cadmium fraction of 0.301. The Hall hole concentration and mobility of the material were 1.1×10^{16} cm^{-3} and 580 $cm^2V^{-1}sec^{-1}$ at 77 K, respectively. The wafer was first mounted to a sapphire with epoxy and then thinned to around 100μm by chemical-mechanical polishing with 0.5% bromine/methanol mixture. The photodiodes were planar n-on-p homojunction structure with implanted area of 400 μm × 400 μm, as shown in Fig. 1(a). Since the minority diffusion length is only several tens of micrometers, so the enlarged active area due to minority diffusion can be neglected. The p-n junction was formed by B^+ implantation through a ZnS layer of 100nm, and the depth of the junction is about 1.5 μm[10-11]. Then the ZnS layer was removed and another ZnS layer of about 500 nm was thermally deposited at a rate of 1.5 Å/sec for the purpose of surface passivation. Then a metal layer of Sn/Au was deposited as ohmic contacts for both p and n type regions. The fabricated detectors were mounted in a vacuum dewar for gamma irradiation. The attenuation of the gamma rays by the dewar window can be omitted. The gamma irradiation was performed using ^{60}Co source with a dose rate of 50 rad(Si)/sec, and the total dosage was 1×10^6 rad(Si). The gamma radiation setup is shown in Fig. 1(b). The distance between the ^{60}Co source and HgCdTe sample is 75 cm. The temperature of the detectors during gamma irradiation was held at 80 K. The current-voltage curve measurements were performed before and during the irradiation.



(a)

(b)

Fig. 1 The experimental details for the gamma irradiation of HgCdTe photodiodes, (a) schematic structure of the irradiated HgCdTe detectors, and (b) gamma irradiation setup

图 1 碲镉汞光伏器件 gamma 辐照实验细节.(a)辐照实验用的碲镉汞器件结构,(b)gamma 辐照实验过程示意图

2 Results and discussions

The representative *I-V* characteristics of HgCdTe photodiodes before and during gamma irradiation are shown in Fig. 2. It can be seen that an increased current was generated by the gamma rays. Here this current would be called photocurrent. The differential dynamic resistance-voltage (*R-V*) characteristics are also given for comparison as shown in the inset. It can be seen apparently that magnitude variation happened to the photocurrent during gamma irradiation, however the dynamic resistance almost kept the same except for small fluctuations. This meant that the increased current was not a leakage current but a gamma radiation induced photocurrent similar to the one in photovoltaic solar cells.

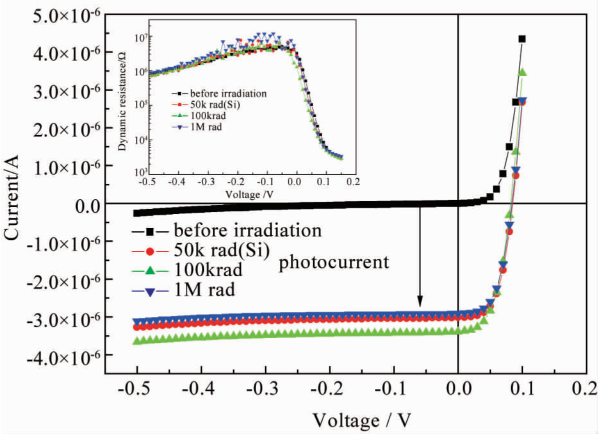


Fig. 2 Variation of current-voltage and dynamic resistance-voltage characteristics

图 2 器件电流—电压和动态电阻—电压特性随着辐照剂量的变化

The variation of photocurrent during irradiation is shown in Fig. 3. It can be seen that the photocurrent is dependent on the total dosage of irradiation. The current increases near linearly at first, then its slope reduces slowly. When the dosage exceeded around 3×10^5 rad (Si), the photocurrent began to decrease as the dosage of radiation continued to increase.

There are usually two main mechanisms for irradiation effect: ionization and displacement. The ionization effect may cause a current in the diode by generating extra carriers in the depletion region. Some researchers also showed that surface leakage current could be generated[1,12]. As discussed in Ref. [13], the surface leakage current is closely related with shunt resistance of the diodes. Yet as shown in Fig. 2, the shunt resistance is not affected obviously by gamma radiation. So it can be inferred that the influence on the detectors by gamma irradiation is dominated by the bulk effect. This can be easily understood since gamma ray is a kind of penetrating radiation. Therefore the main result of ionization effect is to generate a photocurrent in the depletion region where there is a high electric filed. When the hole-electron pairs are generated in the depletion region and its

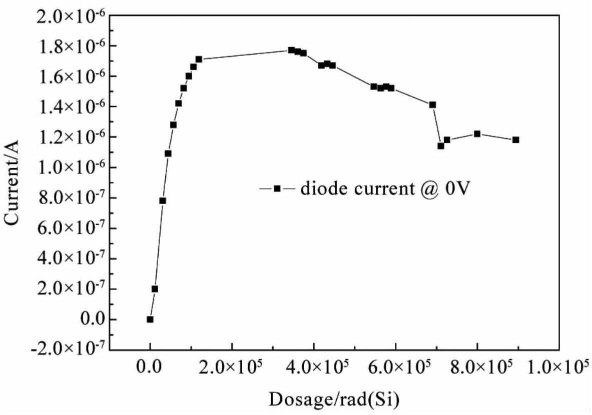


Fig. 3　Variation of photocurrent for HgCdTe photodiode with increasing gamma dosage
图3　碲镉汞光伏器件的光电流随着 gamma 辐照剂量的变化

adjacent region within the diffusion length, the hole-electron pairs can be separated and accelerated by the electric field and contribute to the current in the outer circuit. In general, the number of electron-hole pairs generated varies as[12]

$$N_{\mathrm{ion}} = \frac{E_{\mathrm{deposited}}}{\Delta E} \quad , \quad (1)$$

where $E_{\mathrm{deposited}}$ is the deposited energy in the material, ΔE is the energy needed to create an electron-hole pair. Typically ΔE is about 3 ~ 5 times of the intrinsic bandgap[12], hence for $\mathrm{Hg_{0.7}Cd_{0.3}Te}$ it is about 0.8 eV. The deposited energy in the material can be described by mass-energy absorption coefficient μ_{en}/ρ[14], where μ_{en} is energy absorption coefficient and ρ is the density. According to the energy spectrum of ^{60}Co gamma radiation [15], the average energy of photons emitted by ^{60}Co can be deemed as 1.25 MeV. According to Nation Institute of Standards and Technology (NIST) XCOM database, μ_{en}/ρ is about 2.55×10^{-2} cm^2/g for $\mathrm{Hg_{0.7}Cd_{0.3}Te}$[16]. So the deposited energy in the material can be estimated as

$$E_{\mathrm{deposited}} = E_{\mathrm{ph}}[1 - \exp(-\mu_{\mathrm{en}}x)] \quad , \quad (2)$$

where E_{ph} is the photon energy, x is the thickness of the detector.

Accordingly the number of electron-hole pairs created by one incident 1.25 MeV photon is calculated to be about 58. For the dose rate of 50 rad(Si)/s, the flux of gamma photons is about 1×10^{11}/s · cm^2, therefore the photo electron yield for different gamma dosages can be obtained, as shown in Fig. 4. It can be seen that the photo electron yield decreases slowly from the beginning 50 (very close to 58) with increasing gamma dosage, which means that the ionization effect is dominant at the beginning.

The interaction of gamma rays with semiconductors can be manifested in three different ways: photoelectric effect, Compton scattering and pair production, depending on the gamma photon energy[17]. Electron-hole pairs can be generated in each of these processes. According to the energy spectrum of ^{60}Co gamma ray, the Compton scattering mechanism is the main attenuation process in this case. The emitted high energy Compton electrons can interact with HgCdTe by Coulomb scattering and cause displacement damage to the crystal lattice. These radiation-induced defects can act as scattering centers and reduce the mobility of carriers in the semiconductor. Then, additional energy levels can be introduced in the forbidden band by these defects. According to Ref. [18], n type defects can be created by electron irradiation in p type HgCdTe materials, so similar defects can also be produced by high energy Compton electrons. As a result, the concentration of the hole in the materials is reduced by the compensation effect accordingly. Some of these defect levels can act as carrier trapping centers which also leads to a decrease of the carrier concentration. According to Ref. [17], the noticeable change in mobility of carriers can only be observed by high energy electron irradiation with flux larger than 10^{15}/cm^2. However, in this study, the total fluence of gamma photons is about 3×10^{12}/cm^2, so the carrier concentration is mainly affected by displacement effect which will result in the increase of material resistance.

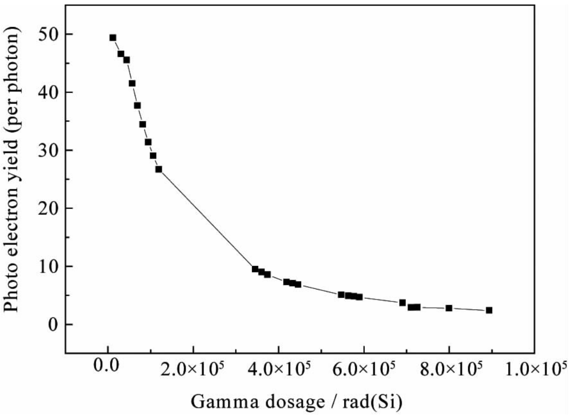


Fig. 4　Variation of photo electron yield with gamma dosage
图4　光电子产额随着辐照剂量的变化

Series resistance of a photodiode arises from the resistance of the contacts and the resistance of the neutron region. In the case of this paper, it is mainly due to the neutral p type HgCdTe region between the junction and p contact. The n type region with a high density of electrons is thin and its contribution to the series resistance can be neglected. So the series resistance can reflect the electrical properties of bulk p material. The series resistance of the photodiode has been obtained by the linear fitting of I/g_{d}-I curves under large forward biases, where I is the current in the photodiode and g_{d} is the conductance[19]. In Fig. 5, the variation of series resistance is given with increasing gamma dosage. It can be observed clearly that the series resistance shows a near linear increase. So it can be inferred that there are two competing mechanisms in the material during the process of steady state gamma irradiation, which are the generation of extra carriers by ionization effect and trapping/compensation of carriers by displacement defects. At the very beginning, the former is dominant. With more defects being generated, the latter mechanism becomes more important, leading to the decrease of photocurrent and the increase of series resistance, as shown in Figs. 3 and 5.

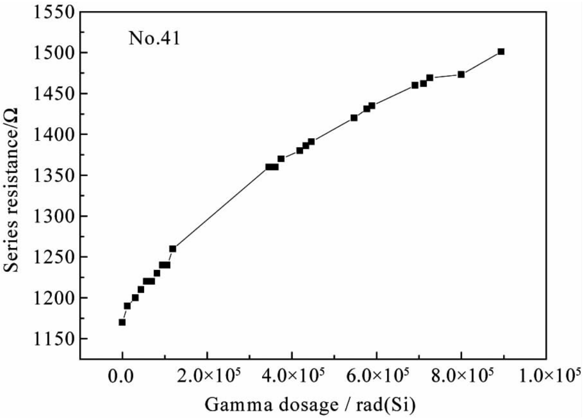


Fig. 5 Change of series resistance with gamma dosage
图5 串联电阻随着辐照剂量的变化

3 Conclusion

The dynamic irradiation effects on the mid-wavelength HgCdTe photodiodes caused by steady state gamma radiation were studied. It was found that the degradation of the devices is due to bulk effect and shows a total dosage effect which is manifested in two ways. For the depletion region with a high electric filed, a photocurrent is generated due to the ionization effect. This additional photocurrent is then reduced by displacement damage with increasing dosage. For the neutral p region between the depletion zone and p contact without an electric filed, the displacement damage is demonstrated by the increase of series resistance which can be interpreted by the trapping of excited electrons and removal of majority carriers via compensation.

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