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PHOTOELECTRIC PROPERTIES OF SELENIUM DOPED p^+–n–n^+ SILICON STRUCTURE

V. M. ARUTYUNYAN, R. S. BARSEGHYAN, G. E. GRIGORYAN,
V. A. MKHIKYAN and B. O. SEMERDJIAN
Department of Radiophysics, State University, Yerevan, Armenian SSR, U.S.S.R.

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Abstract—The photoelectric properties of selenium doped p^+–n–n^+ silicon structures were investigated. Impurity absorption range illumination influence on current–voltage and spectral characteristics of the device were considered. The photoresponse magnitude dependences on electric intensity, current and radiation power at the sample were observed. It was shown that the current-sensitivity of these structures at forward-directed biases is rather higher than that of photoresistors. The threshold photosensitivity and the detectivity were up to $(2/7) \times 10^{-15}\,\mathrm{W \cdot Hz^{-1/2}}$ and $2 \times 10^{11}\,\mathrm{cm\,Hz^{1/2}\,W^{-1}}$ respectively.

INTRODUCTION

The parameters determining the non-equilibrium carrier distribution in the base region in structures made on the base of semiconductors compensated with deep levels depends on current. Such distribution usually leads to the formation of S-type negative resistance region on current–voltage characteristic (CVC).[1,2] The additional modulation of parameters takes place at impurity illumination in bipolar injection conditions which insert a certain specification on the electron–hole plasma properties.[2,3] Particularly, the effects associated with impurity gradients are added to the ordinary current modulation photoresistive effect which leads to high sensitivity of such diodes.[2,4]

The high photosensitivity of the silicon p^+–n–n^+ and p^+–p–n^+ structures has been reported in Refs (2, 4–7).

In the present paper the results of the investigation of 3–5 μm illumination influences on silicon p^+–n–n^+ structure doped with selenium are presented. It is shown that an effective injection amplification might be realized in the case of the illumination from impurity range.

The photodiode (PL) properties have been compared with Si ⟨Se⟩ photoresistors (PR) which have the same geometrical sizes.

THE SAMPLES AND EXPERIMENTAL METHODS

The silicon was doped with selenium in evacuated hermetic tubes. The detailed account of technology of Si ⟨Se⟩ is presented in Ref. (8), as well as the results of investigation of electrophysical and optical properties of silicon doped with selenium.

The concentration of B residual atoms in initial silicon was $\sim 10^{11}$–$10^{12}\,\mathrm{cm^{-2}}$. The concentration of electroactive selenium atoms in silicon after doping was $\sim 6 \times 10^{16}\,\mathrm{cm^{-3}}$. The maximal photoresponse at the temperature of liquid nitrogen was observed at $\lambda_p \approx 3.8\,\mu$m and the longwave boundary level corresponding to 50% relative spectral characteristics ($\lambda_{1/2}$) was $\approx 4.2\,\mu$m. The optic ionization energy level of selenium was $\Delta E_{\mathrm{opt}} \approx 0.301$ eV. The experimental data obtained agree with those presented in Refs (9, 10).

The PD had a tablet form of 0.4–0.5 mm thickness and 1.5–2 mm in dia on which contacts were made: the ohmic ones by alloying of Au + 1% Sb and rectifying ones—Al powder layer. The illumination fell on p–n junction. The samples were deposited in cryostat with saphire side windows and frozen by liquid nitrogen. The illumination was realized with the help of a looking-glass monochromator with NaCl prisma. A globar was used as an illumination source. The illumination energy current equalization over wavelength was achieved by changing the entrance and exit hole size of SPM-2 monochromator. The illumination current power was measured by a thermoelectric column Vth-2, calibrated against the black body illumination ($T = 500$ K). To determine the integral sensitivity in terms of weak light registration a Plank distribution illumination source was taken ($T = 500$ K). The noise measurements were realized by U2-8 selective voltmetre with preamplifier.

A silicon filter was used to take the illumination characteristics. The time characteristics were measured by photoresponse frequency dependence and mechanical modulation with a disk was used for this purpose and the disk rotation velocity had been varying by changing the feeding voltage frequency, and also by transition characteristics at giving rectangular light signals. To get CVC a two-coordinate PDP self-writer was used. The measurements were carried out in generator voltage region.

The samples CVC at $T = 300$ K had the usual low power rectifier form. At $T = 77$ K an S-type negative differential resistance region on CVC was formed in the forward direction (Fig. 1). An ohmic region was observed when illumination was absent and injection was low and increasing the voltage the region changes into a $J \sim V^{3/2}$ region. The dependence $J \sim V^{3/2}$ changed into a superlinear one with a power 2–3 at large injection levels. After this an impact ionization began,

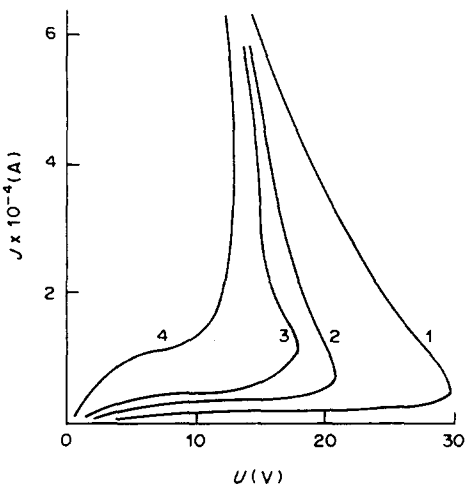

Fig. 1. CVC illumination dependencies of Si ⟨Se⟩ PD structures. $1 - \Phi = 0$; $2 - \Phi = \Phi_1$; $3 - \Phi = \Phi_2$; $4 - \Phi = \Phi_3$. $\Phi_1 < \Phi_2 < \Phi_3$.

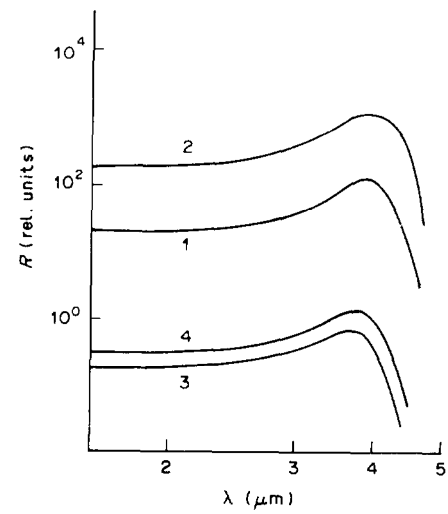

Fig. 2. Spectral characteristics vs voltage of PD (1, 2) and its equivalent PR (3, 4). The voltage, V: 1,3–4; 2,4–25.

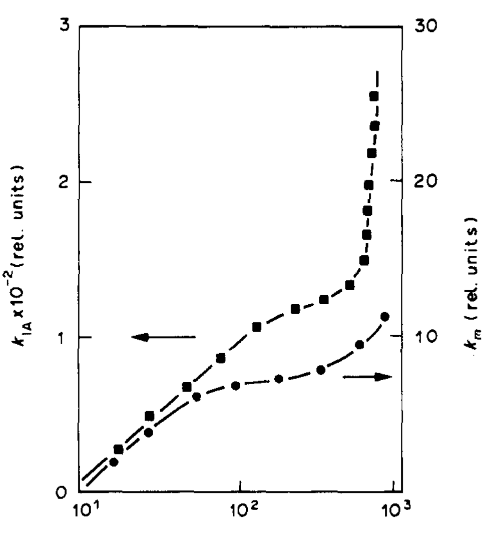

Fig. 3. Electric intensity dependence of injection amplification and conductivity modulation of base injection with current.

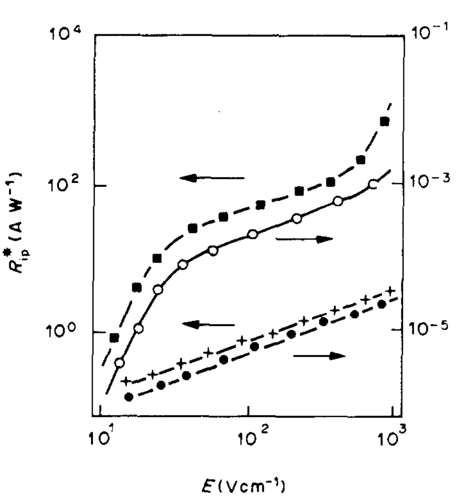

Fig. 4. Current sensitivity and dark current density dependences upon the electric intensity for PD (1, 2) and equivalent PR (3, 4).

and then for most of the diodes a CVC region was observed in which the voltage did not depend on current. When illumination presented CVC before the breakdown was highly deformed. The small ohmic region changed into a slow current increasing one (sublinear dependence of I on V) which then changed into linear dependence. The motions of the curves (Figs 2–4) correspond with one another which is evidence of the amplification mechanisms.[4] A sharp sensitivity growth of particular samples was observed at distribution point. Sensitivity increased for several times in this region. Evidently the sensitivity increase before the breakdown is explained by a strong increase of injection multiplication coefficient before the breakdown.[3] R_i and j_T current sensitivities and dark current densities dependence upon the electric field intensities for PD was linear up to the intensity $2 \times 10^3\ V \cdot cm^{-1}$. At lower E ($50\ V \cdot cm^{-1}$) the samples had a sensitivity of $20\ A \cdot W^{-1}$. If

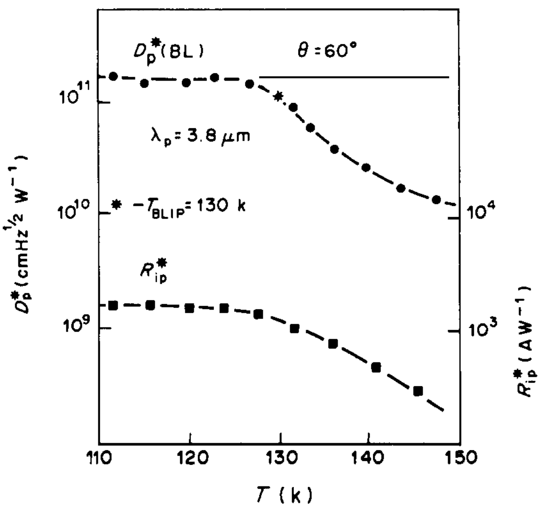

Fig. 5. The detectivity D_{max} and current sensitivity R_{ip} vs temperature T for the Si ⟨Se⟩ photodiode.

one takes into account that the noise current density at a frequency at which the signal registered without lighting was $10^{-11}\ A \cdot Hz^{-1/2}$, the threshold sensitivity defined by:[2,11,12]

$$P_{min} = \frac{i_n}{S_i\sqrt{\Delta f}},$$

was equal to $5 \times 10^{-13}\ W \cdot Hz^{-1/2}$. Most PD had high photosensitivity, amounting to $1560\ A \cdot W^{-1}$ at $\lambda = 3.8\ \mu m$, near the breakdown point (Fig. 5), corresponding to the quantum efficiency of about 300 electron/photon, the noise in a single band being $\sim 10^{-11}\ A \cdot Hz^{-1/2}$ and hence $P_{min} \approx 5 \times 10^{-15}\ W \cdot Hz^{-1/2}$. Voltage sensitivity was mentioned at $\approx 2 \times 10^9\ V \cdot W^{-1}$ ($R = R_{PD}$). PD detectivity was also measured. Modulated radiation of the thermal source ($T = 500$ K) at the receiver temperature 77 K and at the field view on the background 60° was also used. For the applied field $E \sim 100\ V \cdot cm^{-1}$ they were D^* (500; 200; 1) $\approx 8 \times 10^9\ cm \cdot Hz^{1/2} \cdot W^{-1}$. Practically at fields $E \sim (5\text{–}6)\ 10^2\ V \cdot cm^{-1}$ D^* was not changed, although such a sensitivity increased abruptly but in that case noise-level also increased.

An idealized curve of relative spectral sensitivity with a peak wavelength of 3.8 μm was used to define the absolute spectral detectivity and further D^*_{max}/D^*_{500} was calculated.

In this case the relation was equal to ≈ 12.5 and D^*_{max} (3,8; 570; 1) $\approx 10^{11}\ cm\ Hz^{1/2}\ W^{-1}$ at a field of view of 60°.

The magnitude of sensitivity and detectivity did not depend upon frequency in the range 200 kHz. Detectivity increased with a decrease in the field of view on a background up to 30° was registered equal to $D^*_{max} \approx 2 \times 10^{11}\ cm\ Hz^{1/2}\ W^{-1}$. Hence, silicon diode structures doped with selenium can successfully be used as effective radiation photoreceivers in the atmospheric window 3–5 μm.

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