Indian J. Phys. **70A** (2), 219–224 (1996)

IJP A
— an international journal

Influence of irregularly distributed localized states on the photoconductivity of InSe

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Received 19 September 1995, accepted 14 November 1995

Abstract : The influence of irregular distribution of localized states on the photoconductivity of InSe crystals has been investigated experimentally Depending upon the position of the locally illuminated point by the supplementary light and also its intensity, the effect of either sensitization or quenching of the photoresponse signal is observed The obtained experimental results have been explained by a model based on the existence of trapping centers and two kinds of recombination centers namely fast *s*-centers and irregularly distributed slow *r*-centers in InSe crystals.

Keywords : Optoelectronics, photoconductivity, InSe

PACS Nos. : 71 35 +z, 72 40 +w

1. Introduction

Wide band gap semiconductors possess a large number of localized states due to the existence of defects and impurity centers within their band gap. These localized states influence strongly the electric and optical properties of these crystals. These defects and impurities are mainly distributed irregularly within the volume of the crystal, such that the parameters of the crystal may change considerably from a micro-region to another one. Such changes occurred by the influence of locally absorbed radiation were observed by the investigation of electro-optical properties of a number of crystals having cubic symmetry [1–3]. In these works, an increment of electrooptical coefficient was observed with both positive and negative signs depending upon the choice of locally illuminated places on the crystal surface. Such kind of changes were also observed when the photoconductivity was investigated in compensated chromium semi-insulating GaAs crystals [4]. In these crystals under locally absorbed radiation, a photoconductivity rise was observed. The absorbed radiation was of a low power (~ 10^{-3} W) type having a wavelength in the intrinsic or impurity region of the spectrum.

Amongst the wide band gap semiconductors, the layered crystals essentially have a large number of irregularities due to the presence of structural defects, impurity centers accumulated in the layers and also within the interlayer spaces [5]. It is not accidental to interpret certain experimental results using a model involving different groups of recombination and trapping centers [6–8]. However, the distribution character of these centers have not been definitely established so far. This can be established particularly by measuring the photoelectric properties of these crystals under locally illuminated radiation which concerns the present work.

2. Experimental methods

The block diagram of the experimental set-up is shown in Figure 1. A beam of an incandescent lamp was focused on the input slit of a monochromator (JOBIN–YVON, model HR 320). The monochromatized beam being modulated by a mechanical chopper

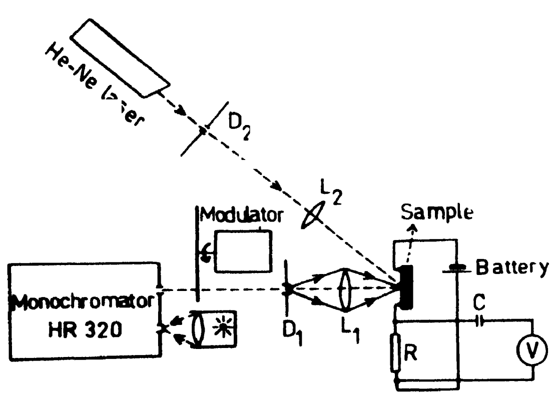

Figure 1. Block diagram of the experimental set-up

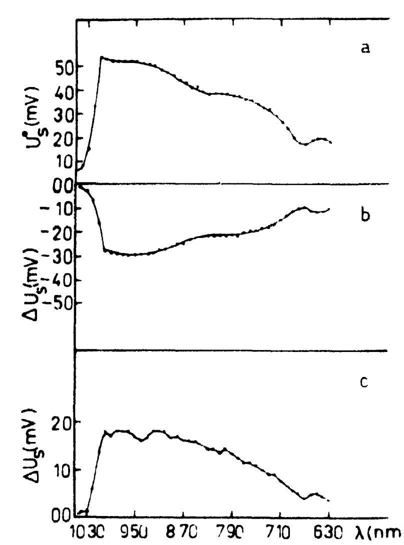

Figure 2. Spectral dependence of photoresponse signal for an InSe crystal (a) photoresponse signal U_s^0 without the supplementary illumination, (b) in the case where the photoresponse signal increment ΔU_s is quenched. (c) in the case where the photoresponse signal increment ΔU_s is increased.

with a frequency of 250 Hz was passed through the diaphragm D_1 and was focused by lens L_1 on the sample. The diameter of the light spot was not greater than 0.5 mm. The photoresponse voltage U_s^0 which is proportional to the intensity of the incident beam was measured through a resistance R and was registered by a selective voltmeter. The sample was mounted on a holder which could permit the sample to shift on the focal plane in two directions.

To affect the generation-recombination processes, a He-Ne laser beam having wavelength of 632.8 nm and power ~ 1 mW was used as a supplementary illumination source. The laser beam passing through the diaphragm D_2 and lens L_2 was fallen on to the sample continuously and was focused to a spot having the same diameter as the modulated beam. The laser set, diaphragm D_2 and lens L_2 were settled on a platform, allowing to scan the beam spot on the sample surface. To illuminate the sample by infra-red light, the laser source could be replaced by an incandescent lamp having an infra-red filter. After registration of the photoresponse voltage U_s^0, the surface of the sample was irradiated by the supplementary light. By scanning the supplementary light, attempts were made to find the points at which the radiation influenced the value of the photoresponse voltage, which was either increased or decreased.

The investigated n-type InSe crystals having high quality surfaces were grown by the Bridgman method. The Ohmic contacts to the samples were made by indium and disposed on the illuminated side of the sample. The investigated samples had high resistivities with $\rho \sim 10^6\ \Omega$ cm.

3. Experimental results and discussion

In Figure 2a is given a typical spectral dependence of photoresponse signal U_s^0 for an InSe crystal. As it is seen, the photoconductivity spectrum stretches in the energy range from 1.23 upto 1.97 eV (the absorption edge of InSe is ~ 1.27 eV at 300 K [9]).

At local illumination by He-Ne laser, a point was observed at which the value of photoresponse signal was decreased. The spectral dependence of photoresponse increment $\Delta U_s = U_s^1 - U_s^0$ is given in Figure 2b, where U_s^1 is the value of photoresponse at the presence of supplementary illumination. As it is clear from the figure, the highest change in photoresponse signal occurs near the absorption edge. The spectral dependence of ΔU_s for the point at which the illumination causes the photoresponse to increase is shown in Figure 2c. Here, also ΔU_s has a maximum value near the absorption edge. It should be mentioned that a number of the investigated samples could cause the value of the photoresponse signal totally to diminish or to increase its value more than an order of magnitude.

Dependence of ΔU_s (in cases where the photoresponse signal is increased) on the illumination power P_L for a number of different locally illuminated points, using a calibrated incandescent lamp having an infra-red filter is given in Figure 3.

As it is seen from the figure, by increasing the illumination power P_L, ΔU_s rises smoothly first and then begins to fall down. At some points, ΔU_s changes its sign by the increase of P_L, so the illumination transforms ΔU_s from increasing to quenching case. It should be noted that at the quenching points, the inversion of increment sign was not observed by the increase of P_L.

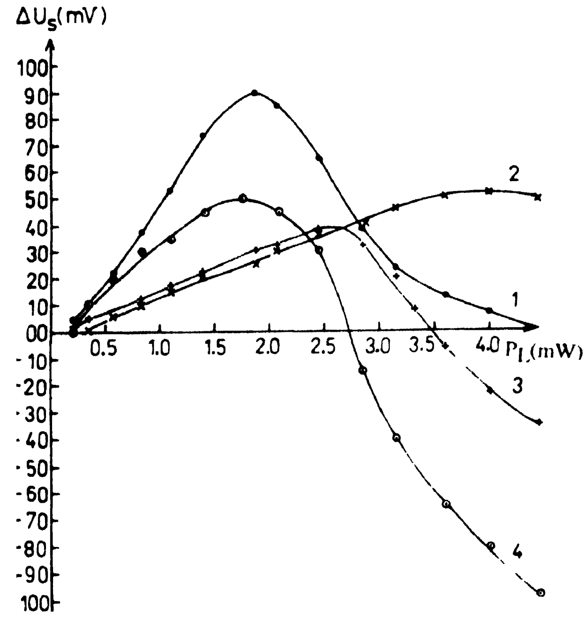

Figure 3. Dependence of the photoresponse signal increment ΔU_s (in cases where the photoresponse signal is increased) on the illumination power P_L for 4 different locally illuminated points

The obtained results can be qualitatively explained on the basis of a model suggested by Rose which proposes the existence of two kinds of recombination centers and also some trapping centers which are distributed exponentially from energy view point within the band gap of semiconductors [10]. This model has widely been used to account for the photoelectric processes in wide band gap and as well as layered semiconductors such as InSe [6–8]. According to these works, within the band gap of InSe crystal, are situated *r*-slow and *s*-fast recombination centers with bedding depths $E_{vr} = 0.46$ eV and $E_{cs} = 0.34$ eV, respectively. Contrary to the concentration of *r*-centers ($N_r \sim 10^{16}$ cm^{-3}) which is greater than that of the *s*-centers ($N_s \sim 10^{15}$ cm^{-3}), the electron capture cross section of the *r*-centers ($C_{nr} \sim 10^{-19}$ cm^2) is rather less than that of the *s*-centers ($C_{ns} \sim 10^{-16}$ cm^2). Existence of the trapping centers *t* which are distributed exponentially from energy view point in InSe crystals is given in reference [11].

To explain the experimental results, it is supposed that *r*-recombination centers which play a sensitizing role in InSe are distributed irregularly in the crystal. According to this idea cited in reference [5], InSe single crystal is an inhomogenous semiconductor in which high resistance defects are supposed to exist in a low resistance matrix. It is shown that, *r*-recombination centers are essentially accumulated in the boundaries of disordered regions. The model used for explaining the experimental results is given in Figure 4. At low excitation intensities, and in the absence of the supplementary laser light, the quasi-Fermi level for electrons E_{fn} lies below the trapping centers, while the quasi-Fermi level for holes E_{fp} lies above the r-centers. In this case, r-centers act as hole trapping centers (Figure 4a).

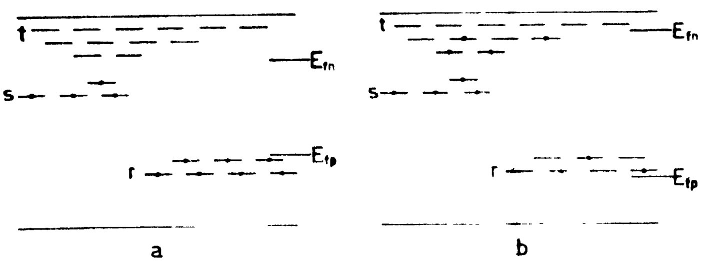

Figure 4. Relevant band schemes for an InSe crystal based on the Rose model (a) at low excitation intensities (b) at high excitation intensities

At high excitation intensities where the supplementary laser light is present, the quasi-Fermi levels for electrons and holes are displaced towards the corresponding band edges (Figure 4b). Consequently, the trapping centers for electrons which are exponentially distributed, partially become recombination centers. Irradiating the laser light onto a part of the crystal where the r-centers are absent, causes the photoresponse signal to decrease (see Figure 2b). However, irradiating the laser light on to the crystal where the r-centers are present, the shift of E_{fp} towards the valence band causes the r-centers (which were first playing the role of trapping centers) to become recombination centers which can act as sensitizing centers. Since the InSe crystal possesses n-type conductivity, the displacement rate of E_{fp} is rather larger than that of the E_{fn}, leading to the sensitization of the photoresponse signal at relatively low intensity scanned light. However, since the concentration of r-centers is limited, at relatively high intensities when all the r-centers become recombination centers, the electron trapping centers start to function, causing the photoresponse signal to decrease (see Figure 3). This gives the possibility to estimate the concentration of r-centers from the position of the observed photoresponse maxima in Figure 3. Taking the absorption coefficient $\alpha \sim 10^3$ cm^{-1} and lifetime of the photocarriers $\tau \sim 10^{-7}$ s for InSe, the calculated value of local concentration of r-centers is $N_r \sim$ (2–5) 10^{15} cm^{-3} which is in a good agreement with the literature data [6,7]. It should be noted that, the position of the observed maxima in Figure 3 which are occurred at different illuminated points correspond with different values of the photoresponse signals, giving an evidence for the inhomogenous distribution of the r-centers in InSe.

In conclusion, it should be mentioned that the nature of r-centers in InSe is not completely known yet. In reference [5], it is proposed that these centers possess the surface nature and are formed in the boundaries where a group of layers are accidentally ruptured, while in references [6,7], they are supposed to be proper defects of the lattice itself. These defects can be entered into the composition of r-centers in the form of neutral bivacancies $(V_{\text{In}}V_{\text{se}})$.

4. Conclusions

1) It is shown that, the behaviour of photoresponse signal in InSe crystals at the presence of local supplementary irradiation depends on the position of the illuminated spot : at some points, the photoconductivity is sensitized, while at some other points, it is quenched.

2) The obtained results can be explained on the basis of the Rose model by which two kinds of recombination centers (*r* and *s* centers) and also trapping centers which are distributed exponentially from energy view point are supposed to exist in our presently investigated crystals.

3) It is shown that the sensitizing *r*-centers are distributed irregularly in InSe crystals.

4) The obtained data give possibility to suppose that, this effect may also be observed in other high resistivity wide band gap crystals with irregular distribution of impurities and defects.

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