Photoconductivity of CdTe Semiconductor Radiation Detectors

Ondrej SIK, and Lubomir GRMELA

***Abstract*—**This paper presents the results of experimental studies of transport and noise characteristics of CdTe deterctors. The current – voltage (*I-V*) characteristics and noise spectral densities were measured at the room temperature in dark and illumination through the contact area. We found that in this sample are good ohmic contacts and then measured noise corresponds volume noise sources only. The dominant noise source is 1/*f* type. One sample met the criteria to assumed bz the Hooge model. The Hooge constant for this sample was found: α = 5.5x10^{-2}. This value is higher than α_H = 2x10^{-3} proposed by the Hooge theory due to the contact noise sources. Nevertheless, this value is very close to the theoretical.

***Keywords*—**CdTe, noise, transport characteristics.

I. Introduction

DETECTOR technology based on the semiconductor materials is a strategically important area of interest in the field of international research and industrial applications for radiation sensing. In order to achieve a significant improvement, the next generation of sensor devices will be based on the II –VI compounds and its alloys, especially Cadmium telluride (CdTe) is a very promising materials for semiconductor radiation detectors of a small dimensions. The physical quantities of a material that is suitable for high quality detector are high direct band gap (CdTe = 1.5 eV, Si = 1.1 eV), high effective atom number (CdTe = 48, 52, Si = 14) and high density (CdTe = 5.85 g/cm^3, Si = 2.33 g/cm^3,) [1]. As can be seen from the mentioned comparsion, the most appropriate material is CdTe. Even though II-VI compounds have a long evolutionary history, the development of high purity (with defect concentration reduced to orders of ppb) and high uniformity crystals is a very much slower process than in the case of traditional materials. The manufacturing technology of CdTe crystal growth is still far from perfect. The process of impurity compensation (by doping of oppositely charged defect centres) is very hard to control [2]. This fact results to difficulty of reaching semi-insulating state (ρ >10^9 Ωcm) of semiconductor, which is the key prequirements to obtain a good quality radiation detector. Improper compensation of defects is connected with the requirement of low carrier trapping. Another essential device property is high signal-noise ratio. So far, most effort has been concentrated to maximize the signal, while much less attention was paid to the analysis of additive noise of the detector system noise and its suppression.

Ondrej Sik is with the Department of Physics, Faculty of Electrical Engineering and Comunication, Brno, 61600 Czech Republic (corresponding author's phone: +420 541 143 256; fax: +420 541 143 133; e-mail: xsikon00@stud.feec.vutbr.cz).

Lubomir Grmela Sik is with the Department of Physics, Faculty of Electrical Engineering and Comunication, Brno, 61600 Czech Republic (corresponding author's phone: +420 541 143 207; fax: +420 541 143 133; e-mail: grmela@feec.vutbr.cz).

II. Measuring Setup

The schematic diagram of the apparatus dedicated for the transport characteristics measurements is shown in Fig. 1.Samples with a load resistor are placed into the cryostat. The cryostat allows controlling operating temperature in the range from 77 K to 400 K by a heating spiral and liquid nitrogen dosing. The programmable digital-analog converter Agilent E34401A is used for the *IV* characteristics measurements. Measuring instruments are interconnected by the data acquisition unit Agilent 34970A with the plug-in module Agilent 34902A, which is used for data conversion and is connected with a PC via GPIB / IEEE488 interface.

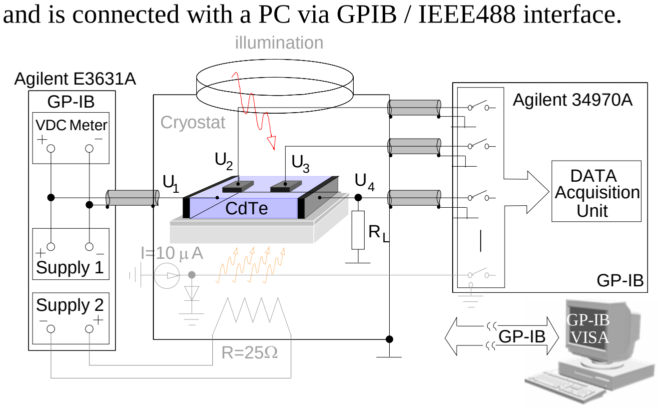

Fig.1 Scheme of the transport characteristics measuring system

Fig. 2 shows block diagram of the noise measuring setup. The sample is fed from the dry cells, which proved to exhibit a low own noise, negligible with respect to the background noise of the measurement system. The sample voltage was measured by a selective nano-voltmeter, the noise voltage by a sampler and transformed into the corresponding current noise spectral density using the Fast Fourier Transform - a method similar to that described in [3]. In some experiments an analog noise measurement method in the range from 1 Hz to 100 kHz was used [4]. Our set-up allows us to measure the sample current and noise voltage simultaneously without any effect on the noise. The whole set-up (with exception for instruments) was placed in a double shielded cryostat, which als works as unwanted electromagnetic field screening. The measured values were recorded and analyzed in a personal computer.

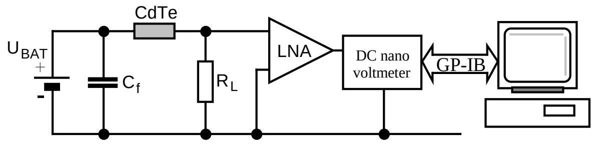

Fig.2:

Fig. 2 Scheme of the low frequency noise measuring system

III. Measurements results and discussion

CdTe sample B39D1H with semi-transparent contacts and semi-insulating sample with non-transparent contacts, B39D1G will be presented. CdTe crystals were grown by the traveling heater method (THM) and are doped with Chlorine. Sample volume is V = 0.152 cm^3. From Hall measurements, we recetived the total number of charge curriers is 1.8x10^{14}. These samples are manufactured at Institute of Physics at the Charles University.

A. Spectral Sensitivity of theDetector

In Figure 3 are plotted of detector resistance change characteristics depending on wavelength of monochromatic light. Measurement of ΔR / R = $f(\lambda)$ is based on samples resistance measurements under constant bias voltage in the dark R_0 and illuminated R_{meas} by monochromatic light with certain wavelength. Values describing the detector resistance change after illumination were obtained by using formula

$$\frac{\Delta R}{R} = \frac{R_{\text{meas}} - R_0}{R_0}. \qquad (1)$$

So, it is an absolute value of the detector resistance change, related to the reference value of resistance of unilluminated detector.

As we expected, the wavelength of light for which is the sample most sensitive, was found at λ = 845 nm. This value was measured for both samples. The photon energy of that monochromatic light is 1.468 eV, which corresponds to the theoretical of CdTe energy gap. At wavelength 827 mn (photon energy $E = hc/\lambda$ = 1.5 eV), which is a shallow defect energy level. We can notice local maximum for both samples. This energy level was identified in [5] as chlorine A-center. The presence of chlorine was expectable, due to chlorine is the dopant used for donor – acceptor forming to neutralize defects in the crystal. Furthermore, solution of $AuCl_3$ was used for contacts deposition and some relicts of Chlorine are expectable.

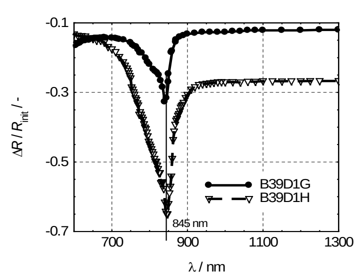

Fig. 3 Plot of resistivity change of analyzed detectors after illumination by the monochromatic light with specific wavelengths.

Even though both samples were cut from the same crystal, we observed higher resistance drop for sample B39D1H. Compared with the other analyzed sample B39D1G, the resistance decrease was significantly higher. At wavelength λ = 845 nm, the resistance drop was ΔR / R = - 0.32 for the detector B39D1G, whereas the in case of the detector B39D1H we measured resistance decrease ΔR / R = - 0.65. The interaction of monochromatic which has λ < 700 nm is absorbed on the detector surface and did not affect resistance of the detectors system. In case of light with λ > 950 nm, both detectors behaved as transparent and no impurities can be activated by light of these photon energies.

B. Current – Voltage Characteristics

In Fig. 4, the first sets of *I-V* characteristics are demonstrated. These characteristics were measured at room temperature and samples were illuminated by monochromatic light with wavelengths of 700 nm, 830 nm and 950 nm. The *I-V* characteristics in Fig. 4 left shows obviously higher influence of irradiation for sample with semi-transparent contacts. Also, the *I-V* characteristic curve non-linearity is remarkable that at applied bias voltage from 7 V to 16 V, the shape of characteristics reminds power function. The *I-V* characteristic of the sample with non-transparent contacts (fig. 4 right) shows less significant characteristics change, because of higher absorbance of non-transparent contacts. Beside the non-linearity observed at the whole measurement range, this detector showed higher leakage currents.

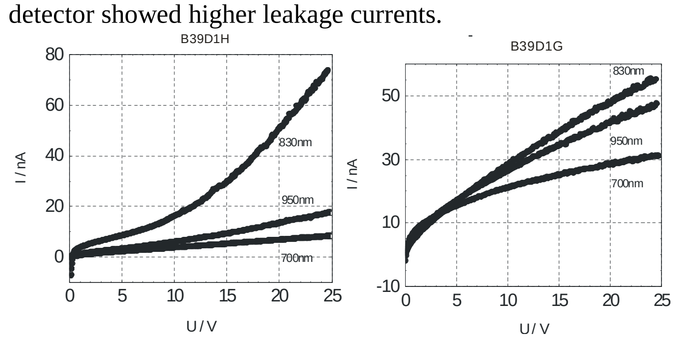

Fig. 4 The *I-V* caracteristics of detector with semi-transparent contacts (left) and non-transparent contacts (right) at the room temperature, illuminated by monochromatic light with wavelengths of 700 nm, 830 nm and 950 nm

The non-linearity of the *I-V* curves under bias voltage below 5 V was caused by less effective rectification efficiency of the reverse biased contacts and points to higher bias voltage necessary for detector full depletition. From this fact we conclude worse technological quality of non-transparent contacts deposition. From the first sight, the power character, as shown in Fig. 4 left for λ = 845 nm, of the *I-V* curves seems to be the effect the of interaction of photons in whole sample bulk, but further measurements showed that at higher intensity of illumination this effect disappears and the shape of *I-V* characteristics become similar to characteristics of the sample with semi-transparent contacts (Fig 4 right). For the *I-V* characteristics plotted in Fig. 5, the sample was directly illuminated by the 20 W tungsten bulb.

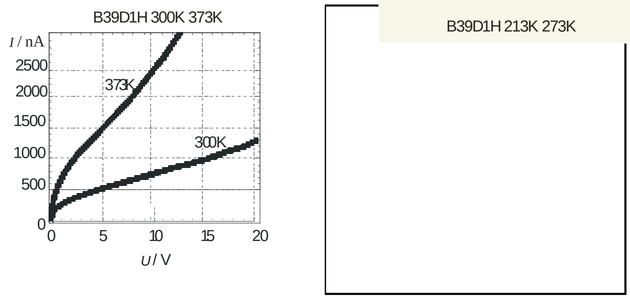

Fig. 5 *I-V* caracteristics of detector with semi-transparent contacts in the dark at temperatures 213K, 273 K, 300K and 373K

The *I-V* characteristics of illuminated sample with light of higher intensity (Fig. 4), shows from approximately U = 3 V nearly linear characters at room temperature. At temperature 373 K, the power character of *I-V* curve is apparent again. These findings lead us to conduct further measurements at lower temperatures. The last measurement was carried out at temperature 273 K and 213 K. These measurements proved the power character disappearance at lower temperatures. From this experiment, we can see that illumination has similar impact on the detector *I-V* characteristics as in case of thermal generation of charge carriers in the detector bulk.

C. Noise Measurement

1) Noise Spectra of Unilluminated Detectors

As can be seen from Figure 6, the noise spectral densities of both samples have similar shape. Two different frequency regions with the same corner frequency of 30 Hz for both samples appear.

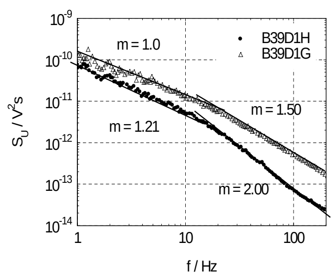

Fig. 6 The Low frequency noise spectra of unilluminated detectors. Bias voltage was 24 V.

The first region - the low frequency part of investigated frequency band has slope of 1/*f* noise m = 1.0 (sample B39D1H) and m = 1,2 (sample B39D1G). At higher frequencies than 30 Hz, we have observed an increase of the m parameter to m = 2.0 (detector B39D1H) and m = 1.50 (detector B39D1G) As a result of higher values of the slope m in both areas, the ratio of noise spectral densities magnitudes between each detector increase. At f = 100 Hz, the sample B39D1G showed one order higher magnitude of power spectral density. This ratio is continuously decreasing with frequency lowering. At f = 1 Hz, the detectors showed nearly the same values of the noise spectral densities of both detectors. We can assume that at frequencies of tenths Hz, values would become exactly the same. Unfortunately, due to the limitation of high-pass filter of used amplifier, which was set to cut-off frequency 0.3 Hz. we are not capable to proof this statement experimentally. The difference of the m parameter, which is higher for the sample B39D1H, is caused by presence of more defect levels in band gap. At frequencies below 30 Hz the sample B39D1G showed „ideal“ 1/*f* noise behavior. The increased magnitude was caused by higher concentration of traps at the same energy levels [6].

Fig. 7 show dependence of noise spectral density on applied voltage at frequency f = 10 Hz. Analyzed sample was fed with applied voltage U = 24V, 43V and 76 V. The measurement was carried out at the room temperature in the dark.

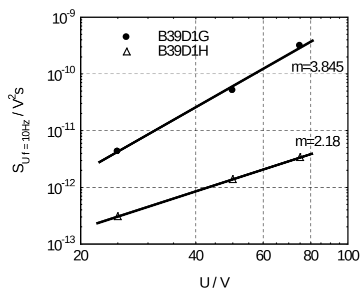

Fig. 7 Dependence of noise spectral density on applied voltage at frequency f = 10 Hz. Analyzed sample was fed with applied voltage U = 24V, 43V and 76 V.

According to the experimental Hooge model, the voltage noise spectral density is by described by formula [6]

$$S_U = \frac{\alpha U^2}{Nf}, \tag{2}$$

Where α is Hooge constant, *N*-total number of free curriers. Voltage noise spectral density is proportional to the square of applied voltage. It‘s apparent this presumption was met in the case of the detector B39D1H. The value of exponent was found m = 2.18 and the Hooge constant, given by eq. 2 is $\alpha = 5.5\mathrm{x}10^{-2}$. This value is slightly higher than $\alpha_H = 2\mathrm{x}10^{-3}$ proposed by Hooge [6]. The difference between theoretical and experimental value lies upon the quality of contacts, which are significant sources of the detector additional noise. Detector B39D1G showed rise of the noise spectral density with exponent m = 3.845. This value is in disrespect with expected value m = 2. This apparently higher value is caused by improper quality of contacts.

2) Noise of Illuminated Detectors

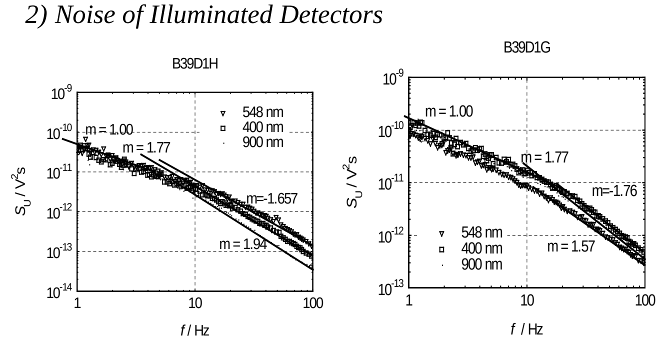

Fig. 8: The low frequency noise spectra of illuminated detectors. Bias voltage was 24 V, wavelengths of were 700 nm, 830 nm and 950 nm.

Fig. 8 represents the low frequency noise spectra of the investigated detectors when illuminated. From the first sight, compared the noise spectra from Fig. 6, we can see higher similarity of the spectra of both detectors. Illumination of detector caused the same detector additive noise at frequencies below 10 Hz. At this frequency range, we observed generic $1/f$ noise with the slope $m = 1$. The lower corner frequency of the $1/f$ spectra with the parameter $m = 1$ is caused by strengthened generation recombination processes due to the crystal illumination.

More interesting behavior of noise spectra were observed at frequencies higher than 10 Hz. Monochromatic light with photon energy equal to measured gap energy, 1.48 eV (λ = 837 nm), shows the same, lowest spectrum slope $m = 1.57$ (B39D1G) and $m = 1.58$ (B39D1H). Exactly the same value of $m = 1.77$ was measured for the light with $E = 3.10$ eV (λ = 400 nm). A variation of the spectrum was found after illumination of the crystal by light with $E = 1.37$ eV (λ = 900 nm). For the sample B39D1G m was 1.80 and for the sample B39D1H we received the value of $m = 1.94$. The difference of the m for the case of light with $E = 1.37$ eV is apparent, but, on the other hand, it was the highest value of spectra slope from all used wavelengths. As reported for unilluminated detectors, the detector B39D1G showed higher noise spectral density than the detector B39D1G.

IV. Conclusion

The recent measurements showed the necessity of higher illumination intensity, because low intensity interacted only with swallow area bellow detector contacts. Illumination with light of wide spectra has advantage of complex interaction of CdTe sample with light. Spectral compounds with higher wavelength than 830 nm passes through whole crystal, the 830 nm compound generates photoelectrons and compounds below 830 nm are absorbed and cause thermal generation of charge carriers [7]. Nevertheless, it's crucial to take into account that also impurities, which cause parasite energy levels in the band gap of CdTe, are activated. But still, for exact description of charge transport properties of illuminated CdTe radiation it's necessary to illuminate samples by light of certain energies. For this reason, it's necessary to explain the influence of light at various photon energies on CdTe material.

From the *I-V* measurement we carried out, we can estimate that the power shape of characteristics, which appear above inflexion point (at applied voltage 5÷7 V) is caused by thermal generation of charge carriers. To prove this assumption, further measurements on more samples with semi-transparent contacts will be carried out. To get better information qualities of measurements, we find necessary use light source with balanced spectrum of emitted light to assure constant intensity of illuminating light at various wavelength.

Low frequency spectral density measurements further proved worse contacts manufacturing quality of the detector B39D1G. This sample showed not only higher leakage current, but also higher value of additional noise. One one hand, higher value can be explained as a result of higher leakage current of the detector, but order of increase of power spectral density with applied voltage proved deteriorating noise properties if this detector with increasing bias voltage. Furthermore, this sample did not meet the requirements given by frequently used Hooge model.

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