*Journal of Nano- and Electronic Physics*
Vol. **9** No 3, 03035(4pp) (2017)

*Журнал нано- та електронної фізики*
Том **9** № 3, 03035(4cc) (2017)

# CdTe Based $X/\gamma$-ray Detector with $MoO_x$ Contacts

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(Received 12 April 2017; revised manuscript received 20 April 2017; published online 30 June 2017)

The electrical characteristics of the Mo-$MoO_x$/$p$-CdTe/$MoO_x$-Mo heterostructures, manufactured by magnetron sputtering of molybdenum oxide thin films on CdTe semi-insulating crystals produced by Acrorad Co. Ltd were studied. Optimization of substrate conditions pretreatment and contacts deposition allowed to reduce the dark current of the detectors compared with earlier analogs and, consequently, to improve its spectrometric characteristics. The charge transport mechanisms for ensuring the low values of reverse currents in the structures were determined: the generation-recombination in the space charge region (SCR) at relatively low voltages and currents limited by the space charge at high voltages. It is shown that the heterostructure Mo-$MoO_x$/$p$-CdTe/$MoO_x$-Mo can be used for practical applications in the $X$- and $\gamma$-ray detectors.

**Keywords**: CdTe, $MoO_x$, Radiation detector, Schottky diodes, Charge transport, Space-charge-limited currents

DOI: 10.21272/jnep.9(3).03035 PACS numbers: 71.55.Gs, 73.30. + y

## 1. INTRODUCTION

The potential of $X$- and $\gamma$-ray ($X/\gamma$) detectors based on cadmium telluride (CdTe) is now recognized in security systems, space industry, medicine and other fields. The high atomic number of the materials gives a high quantum efficiency suitable for a detector operating in the energy range above 30-50 keV. A large band-gap energy allows us to operate these detectors at room temperatures without cryogenic cooling [1, 2]. The significant progress in the technology of producing high quality semi-insulating CdTe crystals with high lifetime and mobility of electrons and holes has achieved [3].

The full charge collection during the absorption of high-energy photons provides the operating of CdTe-detector in spectrometric mode. Therefore in order to avoid trapping of charge carriers in the CdTe detector, a high bias voltage is required. However a rapid growth of the leakage current with increasing bias is often observed due to the currents limited by the space charge. The origin of the excess charge carriers can be either tunneling of charge carriers through a thin insulating film between the crystal and the metal contact [4] or injection of minority carriers from imperfect Ohmic contact on the opposite face of the crystal [5]. Therefore, the problem of forming noninjecting contacts to CdTe is actual scientific and technical problem.

Commercially available $p$-CdTe detectors use high work-function metal such as Au or Pt to form Ohmic contacts. A low work-function metal such as In or Al are usually used for obtaining a high Schottky barrier to p-CdTe [6 – 9]. As high concentration of surface states affects on the bands bending it is possible to modify properties of the surface of a CdTe crystal by varying technological conditions and to use the same metal (Ni) for both Schottky and near Ohmic contacts [10].

Nevertheless, despite the progress in technology, some issues concerning the physics of the processes governing the detection efficiency in semi-insulating CdTe crystals with a Schottky diode remain unrevealed. In particular, CdTe-detectors with high energy resolution demonstrate time instability at prolonged voltage applying. It is known as a polarization effect. This phenomenon is mainly related to the accumulation of negative charge on deep acceptor levels during the application of the bias voltage [11, 12]. Polarization effect can be avoided either changing contact barrier or periodically removing the applied bias voltage [11]. This is the reason that the study of the detectors characteristics and the search for the new contact materials remains relevant scientific and technical problem. In this work we continue the investigation of the gamma response of $MoO_x$/p-CdTe/$MoO_x$-Mo detectors studied in Ref. [5]. Using different methods of ion etching of CdTe crystals prior deposition of $MoO_x$ contacts the dark current of the detectors has reduced and, as a consequence, its spectrometric properties have significantly improved.

## 2. EXPERIMENTAL DETAILS

### 2.1 Samples Preparation and Spectra Measurements

The single-crystalline CdTe(Cl) (111) wafers produced by Acrorad Co. Ltd. [3] of the area of $5 \times 5$ мм$^2$ and thickness of 0.5 mm were used for the heterostructures fabrication. The crystals showed weak p-type conduction of the material with a resistivity $\rho = (1.4 - 2) \times 10^9$ Ohm·cm at room temperature, i.e. $\rho$ is close to the value in CdTe with intrinsic conductivity $\rho_i = 4 \times 10^9$ Ohm cm. The procedure of formation of both Ohmic and Schottky contacts included chemical etching of the crystals in the solution for 20-30 s. The $MoO_x$ films were deposited on the heated surface of CdTe substrates in a Leybold-Heraeus L560 universal vacuum system by means of DC reactive magnetron sputtering of a pure molybdenum target in the atmosphere of a mixture of argon and oxygen. During the deposition process, the partial pressures of argon and oxygen in the vacuum chamber were 0.24 and 0.034 Pa, re-

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spectively. The magnetron power was ~ 120 W.

The spectra were measured at room temperature and the bias voltage – up to 60 V using a charge-sensitive amplifier in combination with a multichannel analyzer MCA527L.

## 3. RESULTS AND DISCUSSION

### 3.1 Characterization of Detectors

Fig. 1 shows the current-voltage (*J-V*) characteristics of a Mo-$MoO_x$/p-CdTe/$MoO_x$-Mo heterostructure fabricated by reactive magnetron sputtering of molybdenum oxide for ~ 300 s at substrate temperature of ~ 373 K (detector 1). After the deposition of the $MoO_x$ layer, the oxygen supply was closed and the deposition of the pure molybdenum film was carried out for ~ 60 s. Prior the deposition of the $MoO_x$ film the surface of the *p*-CdTe substrates were subjected to the long term bombardment by argon ions (ion beam intensity ~ 15 mA/cm$^2$, the processing time ~ 10 min) to form a $p^+$-layer, which improves the quality of the Ohmic contact. Due to the optimal ratio of the work function p-CdTe and $MoO_x$, as well as the presence of *p* + – layer with an increased concentration of uncompensated acceptors the Mo-$MoO_x$/*p*-CdTe/$MoO_x$-Mo heterostructure with a minimum potential barrier was formed. As seen, *J-V* characteristic of the detector 1 is linear at both polarities of applied voltage from 1 to 80 V (filled and blank circles respectively).

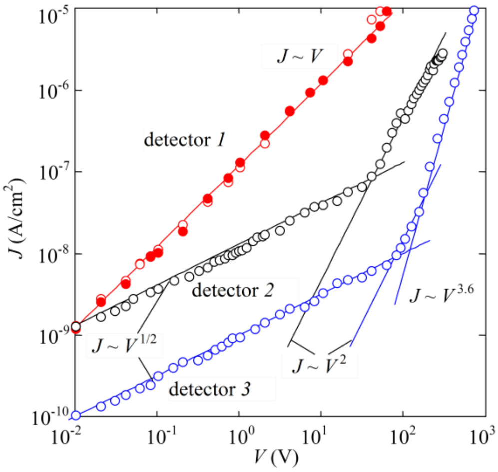

**Fig. 1** – *J-V* characteristics of the Mo-$MoO_x$/*p*-CdTe/ $MoO_x$ -Mo detector 1 (with two Ohmic contacts) at both polarities of applied voltage (filled and blank circles) and reverse branches of *J-V* characteristics of detector 2 and detector 3 (with Schottky contact)

However, detecting characteristics of the Mo-$MoO_x$/*p*-CdTe/$MoO_x$-Mo detector were so poor that the emission spectra of isotopes $^{137}$Cs (662 keV) and $^{241}$Am (59 keV) were hardly detected against the background of electrical noise (Fig. 2, detector 1).

Changing in conditions of argon ions bombardment of the CdTe wafer from the A(Cd) face (the intensity of the ion beam was about ~ 5 mA/cm$^2$, the processing time ~ 300 s) led to obtain the structures with lower reverse current density at bias voltage of 40-60 V (more than an order of magnitude compared to heterostructure with two Ohmic contacts) (Fig. 1, detector 2). Due to such lowering of the dark current of detector 2 $^{241}$Am (59.5 keV) isotope spectra were taken (Fig. 2, detector 2). The full width at half maximum (FWHM) of the peak amounts to 6.58 keV, which corresponds to 11.05 % of the photon energy of radiation emitted with a $^{241}$Am isotope [5].

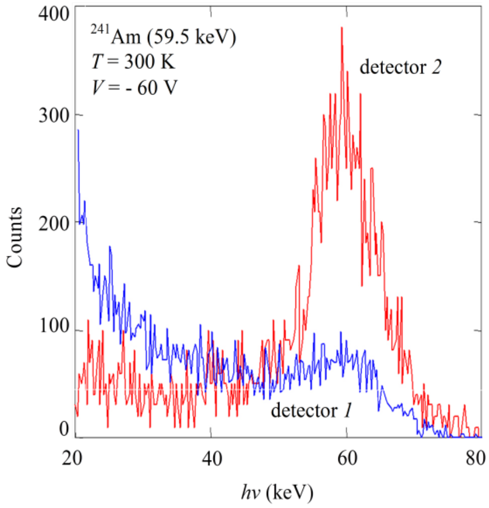

**Fig. 2** – Spectra of the $^{241}$Am isotope taken with the Mo-$MoO_x$/*p*-CdTe/$MoO_x$-Mo detector 1 (with two Ohmic contacts) and detector 2 (with Schottky contact).

Further optimization of the $MoO_x$ film deposition conditions, namely, changing the stoichiometric composition of the film and the sputtering time (partial pressure of argon and oxygen in the vacuum chamber were 0.24 and 0.024 Pa, respectively, and the processing time of ~ 60 s), led to a decrease by an order of magnitude the reverse current density at bias voltage of 40 – 60 V (Fig. 1, detector 3). It has allowed to measure the isotope $^{137}$Cs (662 keV) spectra. The FWHM of the $^{137}$Cs peak presented at Fig. 3 amounts ~ 6 %.

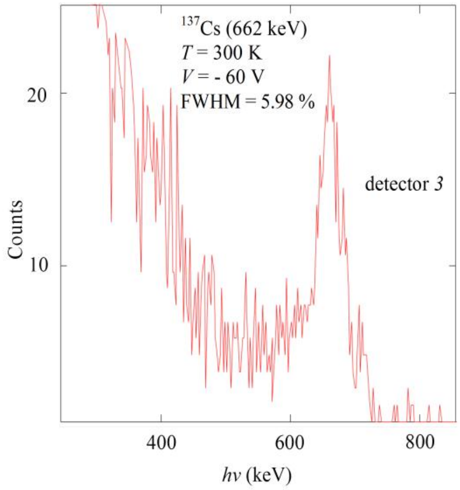

**Fig. 3** – Spectra of the $^{137}$Cs (662 keV) isotope taken with the Mo-$MoO_x$/*p*-CdTe/$MoO_x$-Mo detector 3 (with Schottky contact)

### 3.2 Charge Transport Mechanisms

As can be seen (Fig. 1) *J-V* characteristic of the detector 1 in double logarithmic coordinates is linear and symmetric in the entire range of the voltage which confirms the formation of a high quality MoO$_x$ Ohmic contact to $p$-CdTe. One can see that a root dependence is clearly observed in the dependence $J(V)$ at the bias voltages $0.02 < V < 50$ V for the detector 2 and at $0.02 < V < 100$ V for the detector 3. It is quite clear, because, according to the Sah-Noyce-Shockley theory of generation-recombination in the space-charge region, if the reverse voltage satisfies the condition $qV > kT$, the multiplier $[\exp(qV/2kT) - 1]$ does not reveal itself and the dependence of $J$ on $V$ becomes root-like ($J \sim V^{1/2}$) [13, 14]. However, at further increase of reverse bias voltage the mechanism of conductivity in heterostructures with Schottky diode changes. The dependences $J(V)$ in the detectors 2 and 3 become proportional to the squared voltage ($I \sim V^2$), i.e. the Mott-Gurney law is obeyed, which is typical for semi-insulating material [15]. The observed rapid increasing of current can be explained by the peculiarities of the charge transport at high voltage when intensive injection of electrons from the "Ohmic" contact occurs, and their concentration is much greater than the equilibrium concentration in the conduction band. In addition, at $V > 125$ V dependence $J(V)$ in the detector 3 becomes $I \sim V^{3.6}$, i.e. according to the Mott-Gurney theory trap-filled limit regime with a presence of deep carrier trap in the crystal occurs [15, 16].

## 4. CONCLUSIONS

The current-voltage characteristics of the Mo-MoO$_x$/$p$-CdTe/MoO$_x$-Mo heterostructures fabricated by magnetron sputtering of molybdenum oxide thin films onto semi-insulating p-like CdTe crystals ($\rho = (1.4 - 2)\cdot 10^9$ Ohm cm). The distinction of electric and spectrometric properties of Mo-MoO$_x$/$p$-CdTe/MoO$_x$-Mo detectors is caused by different regimes of treatment of CdTe crystals prior to deposition MoO$_x$ contacts. The charge transport mechanisms in the Mo-MoO$_x$/$p$-CdTe/MoO$_x$-Mo structures are well described in the framework of the well-known theoretical models.

## ACKNOWLEDMENT

This research was supported by the NATO Science for Peace and Security Programme (Project SENERA SfP-984705).

## CdTe детекторы $X/\gamma$ излучения с MoO$_x$ контактами

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Исследованы электрические характеристики гетероструктур Mo-MoO$_x$/p-CdTe/MoO$_x$-Mo, изготовленных методом магнетронного напыления пленок оксида молибдена на полуизолирующие кристаллы CdTe производства Acrorad Co. Ltd. Оптимизация условий предварительной обработки подложек и нанесения контактов позволила уменьшить темновой ток детектора по сравнению с ранее полученными аналогами и, как следствие, улучшить его спектрометрические характеристики. Проанализированы механизмы переноса заряда, обеспечивающие низкие значения обратных токов в исследуемых структурах: генерация-рекомбинация в области пространственного заряда (ОПЗ) при относительно низких напряжениях и токи, ограниченные объемным зарядом, при высоких напряжениях. Показано, что гетероструктуры Mo-MoO$_x$/$p$-CdTe/MoO$_x$-Mo могут быть использованы для практического применения в детекторах $X$- и $\gamma$-излучения.

**Ключевые слова**: CdTe, MoO$_x$, Детекторы излучения, Диоды Шоттки, Перенос заряда, Токи ограниченные пространственным зарядом.

## CdTe детектори $X/\gamma$ випромінювання з MoO$_x$ контактами

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Досліджено електричні характеристики гетероструктур Mo-MoO$_x$/p-CdTe/MoO$_x$-Mo, виготовлених методом магнетронного напилення плівок оксиду молібдену на напівізолюючі кристали CdTe виробництва Acrorad Co. Ltd. Оптимізація умов попередньої обробки підкладинок і нанесення контактів дозволила зменшити темновий струм детектора у порівнянні з раніше отриманими аналогами і, як наслідок, покращити його спектрометричні характеристики. Проаналізовано механізми переносу заряду, які забезпечують низькі значення зворотного струму в досліджуваних структурах: генераціярекомбінація в області просторового заряду (ОПЗ) при відносно низьких напругах і струми, обмежені просторовим зарядом, при високих напругах. Показано, що гетероструктури Mo-MoO$_x$/$p$-CdTe/MoO$_x$-Mo можуть бути використані для практичного застосування в детекторах $X$- и $\gamma$-випромінювання.

**Ключові слова**: CdTe, MoO$_x$, Детектори випромінювання, Діоди Шотткі, Перенос заряду, Струми обмежені просторовим зарядом.

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