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Spectroscopic studies of Ni/CdTe/Au Schottky diode X/γ-ray detectors

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Abstract

This research is devoted to spectroscopic studies of Ni/CdTe/Au diode detectors with a high barrier Schottky contact at the Ni-CdTe interface and near Ohmic contact at the Au-CdTe interface. Both contacts were formed on the opposite sides of high resistivity CdTe(111) crystals after preliminary chemical and ion etchings. The detectors had low dark current (2-3 nA at 1000 V) and were tested using ^{137}Cs, ^{57}Co and ^{241}Am isotopes as radiation sources. Quite high energy resolution (0.9%@662keV at 800 V) was obtained in the ^{137}Cs spectrum at room temperature. In the spectra of ^{57}Co and ^{241}Am isotopes an increase in bias voltage resulted in competing processes: efficient collection of photogenerated charge carriers and harmful increase in reverse current. There were optimal values of bias voltages to achieve sufficient detection efficiency and energy resolution of every detector for radiation of different isotopes. The most interesting and important feature of the developed Ni/CdTe/Au Schottky diode detectors was the absence of degradation of the parameters with time. Moreover, the optimization of the spectroscopic characteristics (FWHM, peak counts, peak to valley ratio, peak channel position, etc.) of the Ni/CdTe/Au diode biased and subjected to irradiation from a ^{137}Cs isotope was observed under long time detector operation.

Keywords: CdTe semiconductor, Schottky diode, X/γ-ray detector, Radioisotope spectra, Spectroscopic characteristics

1. Introduction

Optimal physical characteristics of semi-insulating CdTe semiconductor continue to make this material effective and attractive for compact solid-state X/γ-ray detectors operating at room temperature which are used in many application fields. [1-3] Depending on the CdTe crystal surface state and metal electrode, essentially three kinds of detection structures have been developed: with both Ohmic contacts (in fact, quasi-Ohmic ones), with Ohmic contacts and a built-in electrical junction (*p*-*n*, *n*-i, *p*-i, *n*-i-*p*, etc.), and when one contact is Ohmic and the second one is a blocking contact (Schottky barrier). [1-17]

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To achieve efficient characteristics of CdTe-based detectors, rather high bias voltages should be applied to decrease charge losses caused by incomplete collection of nonequilibrium carriers. However, there is the problem of an increase in dark current. This problem can be overcome if CdTe-based X/γ-ray detectors are developed as a diode structure with a Schottky barrier that has been employed since the end of 1990s. [4-6]

Excellent electrical properties and promising electrical and spectroscopic characteristics were achieved in CdTe-based Schottky diode detectors when high quality semi-insulating CdTe single crystals grown by THM were used. [4-16] The need for high energy resolution X/γ-ray imaging detectors for application in astrophysics, medicine, security, environment monitoring, etc. has caused intense development of technologies to fabricate CdTe-based diode-type detectors either as Schottky diodes [1-14] or rectifying structures with an electrical junction (*p*-*n*, *p*-i-*n* and M-*p*-*n* structured diodes). [1, 13-16]

Various metals for creation of electrical contacts in development and fabrication of CdTe-based detectors are used: In, Al, Ni, Cr, Pt, Au, etc. [1-17] The application of this or that metal for contact formation depends on the intention to create an Ohmic or rectifying (blocking, Schottky) contact. In general, In (Al) and Au (Pt) are commonly used for high-resistivity detector grade *p*-like CdTe crystals to create a blocking and Ohmic contact, respectively. [2-10]

The main task of this research was to obtain diode structures with low dark current even at high bias voltage that provides full collection of photogenerated charge carriers. Super high voltage Schottky diodes with low dark current (< 50 nA/cm^2 at 2000 V), which demonstrated high energy resolution (FWHM = 0.42 % at 662 keV), were obtained using the technique of Schottky barrier formation based on Ar-ion bombardment of the surfaces of THM-grown (111) oriented single-crystal CdTe wafers before electrode deposition. [11-13] The Ni/CdTe/Au structures with a high barrier Schottky contact at the Ni-CdTe interface and near Ohmic contact at the Au-CdTe interface have been fabricated employing this technique and these diodes are the subject of the present study.

The choice of Ni for creation of a Schottky contact was due to the suitable parameters of the metal and semiconductor. Along with appropriate electronic characteristics (high work function ~ 4.7 eV, etc.), Ni is a chemically low-active, ductile and hard metal. Ni contacts (electrodes) are mechanically strong and not corroded during long time operation in various environment conditions. Both the high work function of Ni and particular surface processing of CdTe(111)B surface by Ar-ion bombardment with certain parameters provide the conditions at the metal-semiconductor interface to form a high barrier (1.1-1.2 eV from the metal side) Schottky contact and thus, obtaining Ni/CdTe/Au diodes with low reverse dark current. These Ni properties, in particular high corrosion resistivity are great advantages of Ni over In, which is commonly used for Schottky contacts in the manufacture of CdTe diode-type detectors. [2-8]

In the present work, the spectrometric characteristics of the obtained Ni/CdTe/Au diode-type detectors with a high barrier Schottky contact at the Ni-CdTe interface and near Ohmic contact at the Au-CdTe interface both formed by preliminary chemical and ion etchings of high resistivity *p*-like CdTe crystals have been studied and briefly analyzed.

2. Experimental details

2.1. Schottky diode fabrication

Schottky diode detectors were fabricated using semi-insulating Cl-compensated (111) oriented CdTe single crystals produced by Acrorad Co., Ltd. [8] The crystals showed weak *p*-type conduction with the resistivity ρ = 4-6 × 10^9 Ω·cm (indicated by the manufacturer) that was close or a little higher than the intrinsic value. [10] Parallelepiped-like CdTe wafers with the surface area of 5 × 5 mm^2 and thickness of 0.75 mm, polished by the manufacturer, were used.

The technological processes of the creation of Ni/CdTe/Au diode detectors are schematically shown in Fig. 1. The procedure of formation of both the Schottky and near Ohmic contacts included preliminary chemical treatment (washing, polishing etching and cleaning) of the CdTe crystal surface, using a Br-methanol solution as a polishing enchant and methanol for washing and rinsing of the samples as well as Ar-ion bombardment etching and deposition of the contact metals (electrodes). [11, 12]

A Schottky contact was created by evaporation of Ni onto the CdTe(111)*B* crystal surface (Te-terminated) in vacuum without heating the samples using a Mo mask of the sizes of 3.5 × 3.5 mm^2 (Fig. 1(c)). A near Ohmic contact was formed on the opposite side, i.e. CdTe(111)*A* surface (Cd-terminated), by chemical deposition of Au from a gold chloride solution (Fig. 1(e)). This procedure was simple to cover the entire front surface of the CdTe crystals and required less time and material (gold) to form an electrode in comparison with Au evaporation in vacuum. Just prior to the deposition of metal contacts, both the CdTe(111) crystal surfaces were subjected to treatment with an Ar plasma at different regimes (ion energy, beam density and processing duration) for the *B*- and *A* faces, respectively (Fig. 1(b, d)).

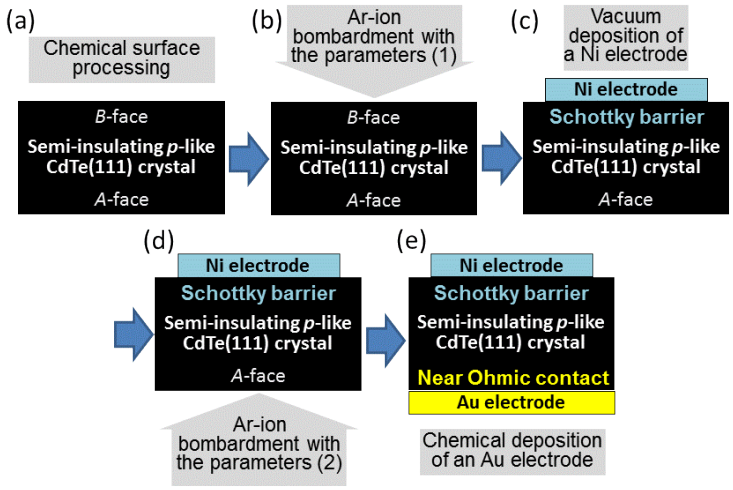

Fig. 1. Schematic illustration of the fabrication technology of Ni/CdTe/Au diode detectors: chemical surface processing of the CdTe crystal (a); etching of the CdTe(111)B surface by Ar-ion bombardment with certain parameters (1) (b); vacuum deposition of a Ni electrode and formation of a Schottky barrier (c), etching of the CdTe(111)A surface by Ar-ion bombardment with certain parameters (2) (d); chemical deposition of an Au electrode and formation of a near Ohmic contact (e).

The area of the Ni electrode (rectifying contact) and Au electrode (near Ohmic contact) was around 0.1 cm^2 and 0.25 cm^2, respectively. No any guard ring was used however, certain passivation of the lateral faces of Ni/CdTe/Au diodes was used to eliminate leakage current. The thickness of both the electrodes was around 0.5 μm. Electrical connection to the measurement electronic device was provided by clamping contacts using a conductive polymer tape or rubber. It was established by Fowler's method measurements that the barrier height of the Ni/CdTe Schottky contact from the metal side equaled 1.1-1.2 eV.

The developed Ni/CdTe/Au Schottky diode detectors were examined by electrical and spectroscopic measurements. The *I-V* characteristics measured in dark condition at room temperature evidenced high rectification properties. The forward current was measured when the Ni contact was biased negatively with respect to the Au contact. Diode detectors operated in reverse bias mode, therefore it was important that the fabricated Ni/CdTe/Au diode structures demonstrated low reverse (dark) current (a few nA) even at high (1000-1500 V) bias voltage. This can allow increasing bias voltage to extend the depletion region up to the whole thickness of the CdTe crystal and thus, to achieve better or even full collection of photogenerated charge carriers while avoiding electrical breakdown. There is a certain optimal value of bias voltage for each detector to obtain the best energy resolution.

2.2. Spectroscopic measurements

Quite low dark (a few nA at 1000 V) current and sufficient hole transport characteristics of the fabricated Ni/CdTe/Au Schottky diodes were indicators to expect fine spectroscopic properties of the detectors. The spectroscopic performance of the Ni/CdTe/Au detectors was tested using radiation of ^{137}Cs, ^{57}Co and ^{241}Am isotopes in dark at room temperature.

The schematic illustration of the spectroscopic measurement experimental setup is shown in Fig. 2. The Ni/CdTe/Au Schottky diode detector was enclosed into a shielded box to avoid daylight illumination and eliminate or reduce electrical noise. The positively biased Ni electrode and negatively biased Au electrode were connected with coaxial connectors to the signal line and shield, respectively. To apply bias voltage of 400-800 V, a power supply source High Voltage Standard HSX-3R5 (Matsusada Precision Inc.) was used. The detector was exposed to radiation of ^{137}Cs, ^{57}Co and ^{241}Am isotopes from the Ni electrode side (Fig. 2). The signal was collected by the Preamplifier 5102 (CLEAR-PULSE Co., Ltd.). The output signal from the preamplifier was delivered to the Pulse Shaping Amplifier 4419 HI (CLEAR-PULSE Co., Ltd.) through the 10 dB attenuator. The constant for the shaping amplifier was chosen as 2 μs. Faster shaping time could cause some errors due to ballistic deficit but too long shaping time increased electrical noise.

If the rise time of the signal (carrier drift time in CdTe) was higher than the shaping time in 10 times and more, an impact of ballistic deficit could be avoided. The rise time for *p*-type CdTe depended on the electric field strength, hole mobility and thickness of the CdTe crystal. It was estimated from the well-known expression [18] and equaled about 150 ns that was more than 10 times higher than the shaping time. An obtained pulse was sent to the Multichannel Analyzer MCA 7700 (Seiko EG&G) (Fig. 2.). The measurements were started after 5 minutes keeping the detector in the dark under high bias voltage. The electronic equipments were adequately calibrated to provide correct channel positions in isotope spectra taken by the detectors.

Different bias voltages were applied to the detectors to find the optimal values which provided better detection efficiency and higher energy resolution. The spectra of ^{137}Cs, ^{57}Co

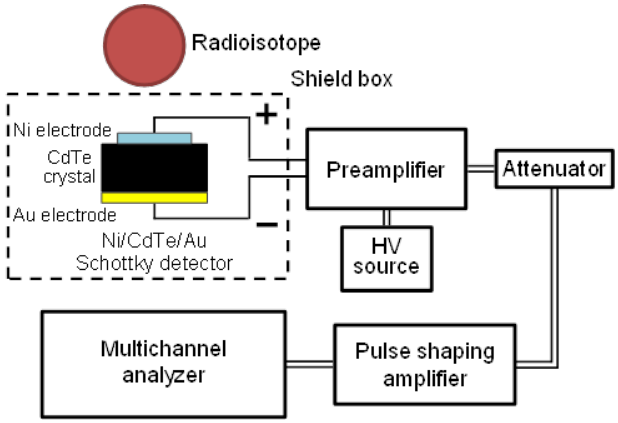

Fig. 2. Schematic diagram of the experimental setup of the spectroscopic measurements with the Ni/CdTe/Au Schottky diode detector.

and ^{241}Am isotopes were taken by the Ni/CdTe/Au detector at applied bias voltage of 400 V, 600 V and 800 V with the measurement time of 2 min. The distance between the radiation source and detector was fixed during the spectral measurements. To study time stability of the developed Ni/CdTe/Au detectors, the spectra of a ^{137}Cs isotope were measured during 10 min at bias voltage of 600 V and measurements were repeated after 6 hours, 9 hours and 12 hours while the detector remained biased and under radiation. The ^{137}Cs spectra were also measured after the bias was switched off and when voltage was re-applied again and also after the detector was illuminated by day light.

3. Results and discussion

The typical energy spectra of ^{137}Cs, ^{57}Co and ^{241}Am radioisotopes taken by the Ni/CdTe/Au Schottky diode detector at applied bias voltages of 400 V, 600 V and 800 V are shown in Fig. 3. The detector demonstrated high sensitivity to γ-ray radiation, compared with industrial Acrorad detectors (In/CdTe/Au Schottky diodes) [8] however, the spectrum profile and number of counts depended on applied bias voltage. In the case of the ^{137}Cs isotope spectra, the highest number of counts for the 662 keV line was observed at V = 800 V (Fig. 3(a)).

A broad shoulder or low-energy tail due to incomplete of charge collection was apparent in the spectra obtained at bias voltages below 600-700 V. The tail, extending toward the low-energy side from the 662 keV peak, was due to the fact that a part of photogenerated carriers (holes) was trapped in the detector, in particular at lower biases V = 600 V and V = 400 V (Fig.3(a)).

Perhaps, these bias voltages were not sufficient for the full charge collection for 662 keV γ-rays at the CdTe thickness of 0.75 mm. [4-7] It should be noted that the energy position of the maximum of the spectra at V = 400 V and V = 600 V was shifted from the peak channel position of the 662 keV line from a ^{137}Cs isotope. The peak channel position for that line was found to reach its maximum at V = 800 V.

The spectrum at V = 800 V showed better energy resolution (FWHM = 0.9 %) than in the cases of V = 400 V (FWHM = 2.3 %) and V = 600 V (FWHM = 2.1 %). The number of counts

at the 662 keV peak for V = 800 V was higher than that for V = 400 V and V = 600 V that demonstrated more complete collection of photogenerated charge carriers despite of some increase in dark current (Fig.3(a)). Thus, not sufficiently high mobility-lifetime product of holes, which should be transported to the cathode (Au electrode), required higher bias voltage for achieving higher spectral performance. It was considered that the features of the electronic devices, used in the experiments, did not have a remarkable unwanted influence on the measurement results.

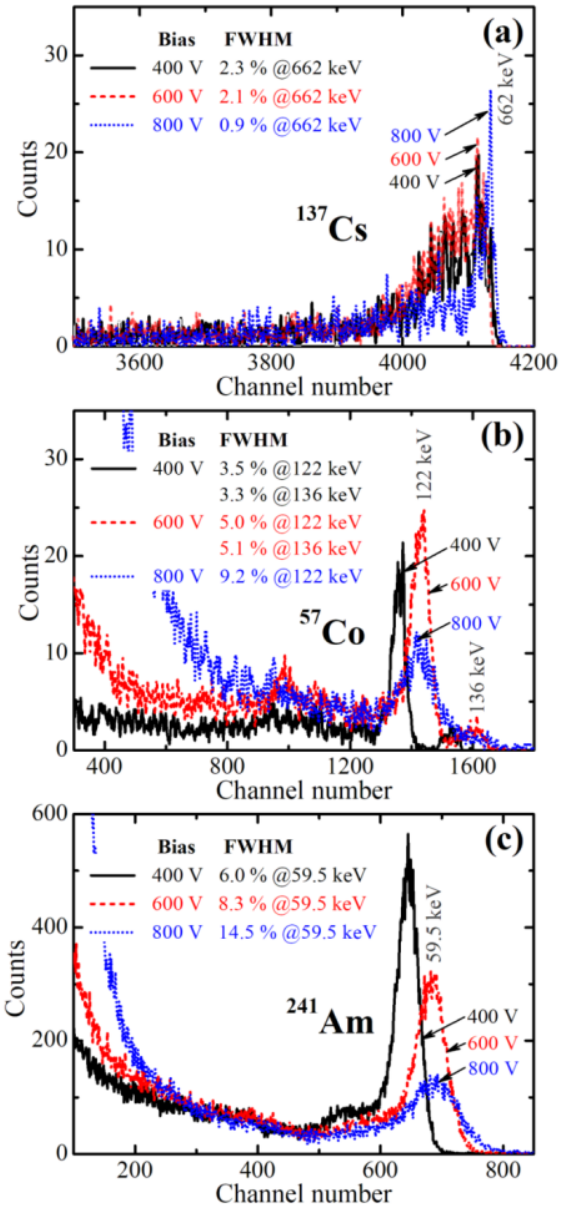

Fig. 3. Spectra of ^{137}Cs (a), ^{57}Co (b) and ^{241}Am (c) radioisotopes taken with the Ni/CdTe/Au Schottky diode detector at applied bias voltages V = 400 V, V = 600 V and V = 800 V.

In the case of electric field strength dependence of the ^{57}Co isotope energy spectrum, the peak channel position of the 122 keV line reached its maximum at V = 600 V and V = 800 V (Fig. 3(b)). However, the energy resolutions of both the 122 keV and 136 keV lines at these bias voltages were worse than the corresponding values at V = 400 V. Deterioration in energy resolution and decreased number of counts in the spectra at V = 800 V was caused by increased the total reverse current, i.e. photocurrent (charge packet) and leakage current, that could meet limitations in the detector or electronics (Fig. 3(b)). The symmetric shape of the 122 keV line in the spectra for all applied bias voltages indicated that the full charge collection is complete even with V = 400 V. An increase in bias voltage (V = 600 V) resulted in that the peak channel position for the 122 line reached its maximum. However, at V = 800 V, dark current more significantly influenced the electronic processes in the Ni/CdTe/Au diode and it resulted in a decrease of the number of counts (Fig. 3(b)).

Figure 3(c) shows the typical electric field strength dependence of the energy spectra of a ^{241}Am isotope. The situation, related to the peak channel position in the energy spectrum, was similar to that of the ^{57}Co isotope spectrum. The peak channel position corresponded to the main line (59.5 keV) of the spectrum was obtained at V = 600 V and V = 800 V (Figure 3(c)). At bias V = 400 V, the peak channel was shifted toward the lower-energy side that could be due the reduction in charge collection efficiency at lower voltage as well as the influence of the Compton scattering component from the surrounding CdTe material. [7, 8] Compton scattering along with incomplete charge collection because of photogenerated carrier loss due to trapping were usually considered as the reasons of an excess tail structure in the lower energy region of isotope spectra, especially for not high energy radiation. [4-8] Probably, this was also the reason that the peak channel positions at V = 400 V did not correspond to the lines at 122 keV and 59.5 keV in the ^{57}Co and ^{241}Am isotope energy spectra, respectively (Fig. 3(b, c)). A decrease in the intensity of the 59.5 keV line and increase in its FWHM at V = 600 V and V = 800 V compared with the corresponding values at V = 400 V was attributed to the larger electronic contribution of the total reverse current, i.e. photocurrent and leakage currents, and corresponding limitations in the detector or electronics (Fig. 3(c)).

The distortion in the isotope spectra, attributed to Compton scattering of γ-rays, can also be resulted from not high enough mobility-lifetime product of charge carriers in CdTe. [7] Since the interaction depth of γ-rays was deeper for higher energies, the 122 keV line had a larger tail structure (Fig. 3(b)) in comparison with the 59.5 keV line (Fig. 3(c)). The peak position and peak counts usually increased when bias voltage was raised. [4-7] However, if leakage current in detectors increased at increasing applied voltage, its contribution to the total reverse current became more significant that resulted in a decrease in number of counts and energy resolution (Fig. 3(b), V = 800 V and Fig. 3(c), V = 600 V and V = 800 V).

In order to decrease the effect of the incompleteness of the hole collection in CdTe-based detectors, in addition to reducing the CdTe crystal thickness and increasing bias voltage, different methods have been employed including irradiation with γ-rays (usually not high energy) from a radioactive source on the cathode (negative electrode), special configuration of electrodes (stacks, strips, pixels, etc.), electronic correction, etc. [2-7] Certainly, the various electrode configurations in detector fabrication technologies have also been used to provide visualization, image formation, data collection rate, leakage current decrease, detection efficiency increase etc.

In our case, the obtained Ni/CdTe/Au diodes with a Schottky contact had sufficient low dark current (0.5-1 nA at 500 V and 2-3 nA at 1000 V) and showed quite high efficiency to

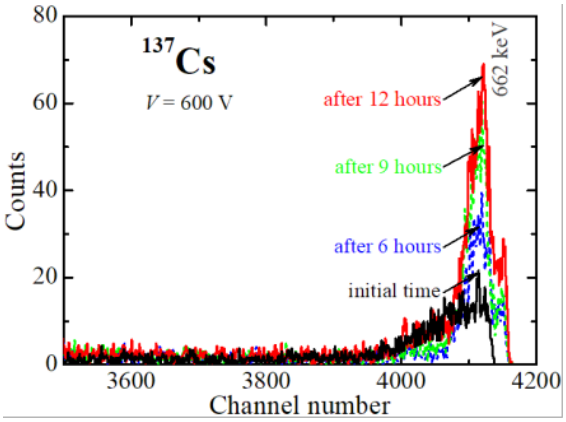

Fig. 4. Spectra of a ^{137}Cs radioisotope taken with the Ni/CdTe/Au Schottky diode detector just after applying bias voltage (V = 600 V) and after operation (biased and γ-ray irradiated) during 6 hours, 9 hours and 12 hours.

detect X/γ-rays in a wide energy range (Fig. 3). However, there were the optimal bias voltage values for each Ni/CdTe/Au diode that provided better detection efficiency (number of counts), truer peak channel position and highest energy resolution (FWHM) for spectra of ^{137}Cs, ^{57}Co and ^{241}Am isotopes.

The long term stability is one of the key requirements for practical application of room temperature CdTe-based X/γ-ray detectors, particularly fabricated as diode structures[1-14]. The capabilities of the fabricated Ni/CdTe/Au Schottky diode detectors to operate for long time without deterioration of its functional parameters were studied by measurements of the spectra of a ^{137}Cs isotope just after the detector was biased (V = 600 V) and after operation during 6 hours, 9 hours and 12 hours (Fig. 4). The interesting and quite important feature was found that the detection efficiency of the diode increased with operation time. The number of counts measured for the 662 keV peak in the spectra gradually increased after operating during 6 hours, 9 hours and 12 hours, respectively (Fig. 4). Moreover, the peak channel position better corresponded to the main line (662 keV) in the ^{137}Cs isotope spectrum when the biased detector was operating longer (Fig. 4, after 9 hours and 12 hours).

This was different from the general results obtained for diode-type detectors where degradation in charge collection efficiency and energy resolution were discussed as an inevitable effect caused by the polarization phenomenon. This phenomenon is peculiar to both kinds of CdTe diodes: with a Schottky contact, formed using various metals [4, 5, 9, 14], and barrier structures with a *p-n* junction. [14]

The polarization is associated with the non-uniform electric field due to the charge accumulation in the CdTe diode detector. Generally, this effect appears when the internal electric field generated by accumulated charge carriers becomes comparable to the electric field of external applied bias, and this leads to a decrease in radiation spectrum peak amplitude, degradation of energy resolution and shifting the peak toward lower energies with time after applying bias voltage that was clearly observed in both Schottky diodes and M-*p-n* structures fabricated using the same CdTe semiconductor[14]. Therefore, the application of the strong electric field, i.e. higher bias voltage, is the key condition to obtain the long-term stability of CdTe diode detectors operating at room temperature. To suppress the polarization

effect in CdTe Schottky diode detectors a pulse bias voltage shutdown technique was applied. [8]

Nevertheless, at the present time, functional characteristics of most CdTe-based diode-type detectors both with rectifying contacts and electrical junctions are not sufficiently stable under bias voltage applied for long time and suffer from progressive degradation with time due to the polarization effect and hole trapping and detrapping from deep acceptors levels. [1-16]

The absence of such undesirable features in the ^{137}Cs isotope spectra, measured after long-term operation of the detector, as low energy shifting of the peak channel, broadening of the 662 keV line and decreasing of the number of counts evidenced a negligible effect of the polarization phenomenon. It became possible owing to the properties of the deposited contacts providing more uniform electric field in the diode and optimal choice of bias voltage for that kind of samples. [12, 17]

The evolution of the characteristics obtained from the analysis of the ^{137}Cs isotope spectra taken by the Ni/CdTe/Au detector (Fig. 4) is shown in Fig. 5. As seen, the best value of energy resolution (FWHM = 0.8 % at 662 keV) was reached in 9 hours of operation of the detector at bias voltage V = 600 V at room temperature. The larger number of counts, truer peak channel position and better peak-to-valley ratio were observed after 12 hours operation of the detector (Fig. 5).

The detection efficiency sufficiently increased in 6-12 hours when the bias voltage was applied to the detector. The time-dependence characteristics of the Ni/CdTe/Au detector calculated from the ^{137}Cs isotope spectra (Fig. 3) and presented in Fig. 5 (FWHM, peak counts, peak to valley ratio and peak channel position) have allowed us to evaluate the detector performance. Thus, we can conclude that the developed technological approaches and technique of fabrication of Ni/CdTe/Au Schottky diodes are quite efficient and promising for creation of X/γ-ray detectors for identification of radioactive sources and image formation. [15]

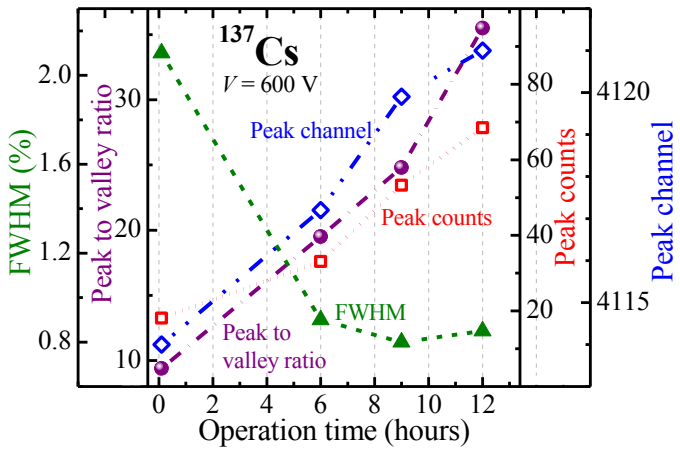

Fig. 5. Dependences of energy resolution (FWHM), peak counts, peak channel position and peak-to-valley ratio on the operation time for the Ni/CdTe/Au Schottky diode detector under the measurements of the ^{137}Cs radioisotope spectra (Fig. 4).

The increased signal in the ^{137}Cs isotope spectra, after a few hours keeping of the biased detector in the dark during measurements (Fig. 4), decreased to its initial value when bias voltage was turned off and detector was illuminated by daylight for 1 min. The recovery of spectral characteristics was usually observed when the bias was switched off for a few minutes [12] or after the bias voltage was re-applied to a detector. [4, 5] Further investigations are needed to study the time-dependence features of the spectroscopic characteristics of the fabricated Ni/CdTe/Au Schottky diode detectors.

4. Conclusion

In Spectroscopic studies of Ni/CdTe/Au diode detectors with a Schottky contact at the Ni-CdTe interface and near Ohmic contact at the Au-CdTe interface, both formed using the Ar-ion bombarding technique, demonstrated the following peculiarities. Quite low dark current (0.5-1 nA at 500 V and 2-3 nA at 1000 V) in the fabricated detectors allowed us to apply high bias voltages, extend the depletion region and thus, improve the carrier charge collection. As a result, the spectra of ^{137}Cs, ^{57}Co and ^{241}Am isotopes with relatively high energy resolution (0.9-2.0 %@662 keV, 3.5 %@122 keV, 3.3 %@136 keV and 6.0 %@59.5 keV, respectively) and correct peak channel position at room temperature were obtained.

The energy resolution (FWHM) in the ^{57}Co and ^{241}Am isotope spectra taken with the Ni/CdTe/Au detectors was comparable with that of In(Al)/CdTe/Au Schottky diode detectors produced by Acrorad Co., Ltd, but for a ^{137}Cs isotope, the Ni/CdTe/Au detectors showed better resolution than commercially available Acrorad's detectors. [19] It should be noted that Acrorad's detectors had a guard ring. Certainly, using a guard ring for the Ni/CdTe/Au detectors would significantly decrease dark current and improve the resolution detector performance.

However, the spectra obtained with the developed Ni/CdTe/Au Schottky diode detectors contained tail structures which extended to the lower pulse height region from the photopeak of incident γ-rays that mostly resulted from the effect of slow mobility and short lifetime of carriers, especially for holes. Mobility-lifetime product of holes determines the amount of the tail component while mobility-lifetime product of electrons affects the peak channel more in a spectrum. [7]

An increase in bias voltage (up to 800 V) resulted higher energy resolution (FWHM = 0.9 %) in the ^{137}Cs isotope spectrum. However, in the spectra of ^{57}Co and ^{241}Am isotopes, the resolution at V = 800 V was lower than that at lower voltages. This was attributed to the competing processes: (i) an increase in the electric field strength in the semiconductor crystal and thus, more efficient collection of photogenerated charge carriers and (ii) harmful increase in reverse current that caused decreasing number of counts and lowering energy resolution.

The most important feature of the developed Ni/CdTe/Au Schottky diode detectors was the improving the spectroscopic characteristics (FWHM, peak counts, peak to valley ratio and peak channel position) with time under operation of the detector. The detector biased and subjected to radiation from a ^{137}Cs isotope was tested during 12 hours and demonstrated higher detection efficiency and energy resolution. The Ni/CdTe/Au diode detectors with Schottky and Ohmic contacts, formed on the opposite surfaces of CdTe(111) crystals pretreated with chemical etching in a Br-methanol solution and Ar-ion bombardment, have shown promise for spectroscopic application.

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