

Higher Voltage Ni/CdTe Schottky Diodes With Low Leakage Current

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Abstract—A significant improvement in electrical characteristics of Schottky diodes designed for X- and γ -ray detectors has been achieved using semi-insulating CdTe single crystals and unified technology, where both Schottky and near-ohmic contacts were formed by the deposition of the same metal (Ni) on the opposite surfaces of the crystal pre-treated by chemical etching and Ar ion bombardment with different parameters. Reduction of injection of minority carriers from the near-ohmic contact in the neutral part of the diode and high Schottky barrier for holes provides low leakage current even at high bias voltage ($< 50 \text{ nA/cm}^2$ at 2000 V and at room temperature). The current-voltage characteristics of the detectors with Ni/CdTe/Ni electrode configuration in the low-voltage range are described by the generation-recombination Sah-Noyce-Shockley theory. The results of the reproducibility and time stability of the fabricated diodes are reported.

Index Terms—Charge carrier processes, leakage currents, Schottky diodes, X- and gamma-ray detectors.

I. INTRODUCTION

THE main advantages of semi-insulating CdTe semiconductor (such a high atomic number and large band gap) provide its application in room temperature X- and γ -ray detectors widely used in medicine, industry, power engineering, space physics, and other areas. However, limitations in resistivity and charge transport properties, caused by structural imperfections and residual impurities in CdTe crystals, have imposed restrictions on its effective use. In particular, CdTe detectors suffer from leakage (dark) current which is a source of electrical noise and deteriorates the electrical characteristics, decreases the energy resolution and causes detector degradation [1]–[3].

Recently, significant progress in the growth technology of semi-insulating CdTe has already made possible to decrease a number of accidental impurities, native point and extended defects and obtain high quality single crystal wafers suitable for high energy radiation detectors [4]–[10]. In order to obtain high charge collection and low leakage current, CdTe detectors have

been developed as diodes with a blocking contact (Schottky barrier, $p-i-n$ or $p-n$ junction) instead of one of ohmic contacts [1]–[12].

Nowadays, one of the bottlenecks in technology of producing CdTe detectors is formation of electrical contacts. The ability to create metal-semiconductor contacts with desired properties (ohmic or blocking contact) and which are mechanically sound and electrically stable is a key requirement in fabrication of CdTe-based detectors [5]–[12]. The most widely used CdTe diode detectors are constructed as a combination of a Schottky barrier and ohmic contact on the opposite surfaces of the crystal and they exhibit much lower leakage current than detectors with two ohmic contacts. Two different metals and two technology procedures are commonly used to form Schottky and ohmic contacts, respectively [1]–[8], [11], [12]. The In/CdTe/Pt Schottky diode X- and γ -ray detectors differ from those with ohmic contacts in that for an increase in the charge collection efficiency and the width of the active region, they allow to raise the applied voltage at low dark currents [5], [6]. The reverse current in detector with In/CdTe Schottky contact of $2 \times 2 \text{ mm}^2$ area and 0.5 mm crystal thickness is equal to $\sim 1 \text{ nA}$ at voltage 1000 V and room temperature. Such low reverse current is considered to be the special property of a Schottky contact itself. However, the current-voltage characteristics of such type of detectors exhibit unusual behavior [5], [6]. It would be expected that due to existing the high resistance of the bulk part of the detector, the rectifying properties of the diode structure should disappear as soon as the forward voltage V is in excess of the built-in potential ($< 0.5\text{--}0.6 \text{ V}$). In fact, at the lowest voltages rectifying is not observed and, to the contrary, the forward current steeply increases as far as V exceeds a few volts. The Al/CdTe Schottky contacts have also similar properties and can be explained by modulation of the conductivity of the bulk part of the CdTe crystal as a result of injection of minority carriers at higher forward voltage [12], while at low voltages, rectifying properties of a Schottky contact is masked by series high resistance of the CdTe crystal [8].

In this paper, we report new results in the development of high-voltage Schottky diode structures based on high quality semi-insulating (semi-intrinsic) p -like CdTe single crystals [4]. The fabricated CdTe diodes with Ni electrodes have attractive electrical properties to be used as X- and γ -ray detectors. A number of advanced innovations were used to obtain Schottky CdTe diodes which for the first time exhibit well-defined rectifying behavior at low bias voltages and very low leakage currents at extremely high reverse bias voltages (up to 1500–2000 V). (i) The effective procedure, including ion bombardment, was developed to intentionally modify the surface state of the

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CdTe crystals and form a Schottky contact. (ii) The electrical characteristics of a Schottky contact were improved using electrode metals with high work functions, such as Ni (the use of Au and Pt is also possible) instead of recently used In and Al with low work functions. (iii) The same experimental setup and technological procedure (but with different parameters), and also the same metal (Ni) were used to form a near-ohmic contact on the opposite side of CdTe wafers hindering injection of minority carriers in the bulk of the crystal.

The fabricated high-quality CdTe Schottky diodes with low leakage current at higher bias voltage in comparison with the best samples described in the literature show great promise as X- and γ -ray radiation detectors.

II. FABRICATION AND ENERGY DIAGRAM OF Ni/CdTe/Ni DIODE STRUCTURES

In an ideal case, the work function of a metal should be lower than that of a semiconductor to obtain a Schottky contact to *p*-type semiconductor, i.e., to form a depletion layer at the semiconductor surface. From this standpoint, the use of the above mentioned metals In and Al with relatively low work functions for fabrication of CdTe-based Schottky diode detectors is quite grounded. The formation of an ohmic contact to a *p*-type CdTe crystal faces obstacles because in this case, it is necessary to use a metal with a too high work function. In fact, the work function of a semiconductor is equal to the electron affinity plus the energy distance between the conduction band bottom and the Fermi level. Assuming the electron affinity of CdTe equal to 4.3 eV, one finds the work function in the range of 5–5.7 eV ($E_g = 1.46$ eV) [13], [14]. There is no available metal with the work function higher than these values. However, due to high concentration of surface states in CdTe single crystals, it seems not necessary that the work function of a *p*-type semiconductor should exceed the work function of a metal to form a non-rectifying ohmic contact. By varying technological conditions, it is possible to change bands bending at the surface of a CdTe crystal, and hence to modify properties of the contact. In the case of a small band bending, a metal with a high work function can form a contact with electrical properties close to an ohmic one. The below presented results are evidence that, by varying technological conditions, it is possible to use Ni for both Schottky and near ohmic contacts.

The single-crystalline CdTe wafers of the area of 5 mm \times 5 mm and thickness of 0.5 mm produced by ACRORAD Corporation were used for the diode fabrication [4]. The crystals showed weak *p*-type conduction of the material with a resistivity $\rho = 4 \times 10^9 \Omega \cdot \text{cm}$ at $T = 293$ K. The procedure of formation of both ohmic and Schottky contacts included chemical etching of the crystals in the $\text{K}_2\text{Cr}_2\text{O}_7 + \text{HNO}_3 + \text{H}_2\text{O}$ solution during 20–30 s, de-ionized aqueous cleaning, argon ion etching (500 eV) and deposition of the metal in the vacuum of 10^{-5} Torr. As mentioned above, Ni was used as the contact metal. This provided good adhesion of the metal film to the crystal surface and the procedure did not need high temperature of the substrate during deposition of the film ($< 100^\circ\text{C}$). The use of Ni ensured also a certain unification of the technology because the procedures of formation of ohmic and Schottky contacts differed by only the ion beam parameters and duration of the

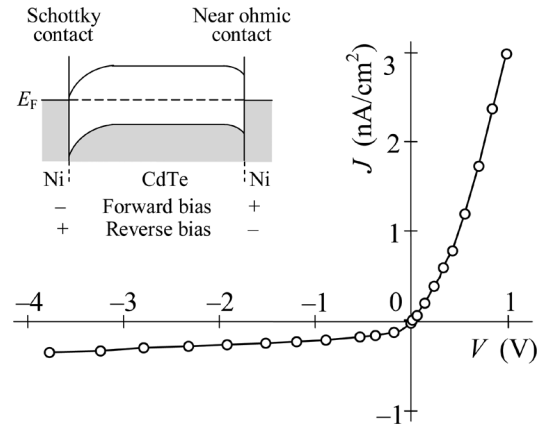


Fig. 1. Room-temperature J - V characteristic of the Schottky diodes with Ni/CdTe/Ni electrode configuration plotted in linear coordinates: (circles) experiment and (solid line) calculation. The insert shows an energy diagram of the diode structure.

processing of the crystal surface. “Ohmic” (hereafter referred to as near-ohmic) contacts were obtained at the ion beam density 10–15 mA/cm² and ion energy 400–500 eV, while Schottky contacts were formed at the ion beam density 2–5 mA/cm² and ion energy 700–800 eV. In the both cases, the etching time was about 10 min and the substrate was not intentionally heated. The measurements showed that the temperature of the crystal increased less than 2–3°C (it was due to efficient heat removal). Our study has shown that just the heightened energy of Ar ions apparently resulted in an increase in the density of surface states and, hence led to a larger band bending at the surface of a CdTe crystal.

The difference between the properties of the two contacts is explained by the modification of the system of electronic state at the CdTe(111)A and CdTe(111)B surfaces caused by argon ion etching at different conditions. It has long been known that the Fermi level pinning at the CdTe/metal interface takes place at different position depending on the surface treatment prior to metal deposition [11]. The Fermi level position at the CdTe/metal interface determines the barrier height and thus mainly influences the electrical properties of the contact.

Fig. 1 shows the low-voltage parts of the current-voltage (J - V) characteristics of a Ni/CdTe/Ni diode structure plotted in linear coordinates. The forward current was measured when the Schottky contact was biased negatively with respect to the ohmic one. For the first time, pronounced rectifying properties of the diode based on semi-intrinsic CdTe are observed starting from the lowest voltages that distinguishes it from the diodes described in both [5], [6] and our previous paper [8]. This was possible due to an essential decrease in the reverse (leakage) current (more than one order of magnitude in comparison with that in [8]) using the technological procedure described above. Thanks to the improvement of the electrical characteristic of the diode structure, the voltage drop across the neutral part of the crystal R_s , which masked the diode characteristic, became much lower.

Indeed, assuming the thicknesses of the crystal and its neutral part as the same (0.5 mm), the voltage drop on R_s is equal only to 0.04 V at reverse bias of 1 V. The high quality of the

diodes is supported by good agreement of the experimental and calculated results for the J - V characteristics of samples. The calculations are presented in Section III.

To construct the energy diagram of the diode structure, the energy distance $\Delta\mu$ of the Fermi level E_F from the top of the valence band is usually calculated using the hole concentration in the valence band p as $kT \ln(N_v/p)$, where k is the Boltzmann constant, $N_v = 2(m_p kT/2\pi\hbar^2)^{3/2}$ is the effective state density in the valence band and m_p is the effective hole mass. The value p for a nondegenerate p -type semiconductor is determined as $1/q\mu_p\rho$, where q is the electronic charge and μ_p is the hole mobility in CdTe equal to $80 \text{ cm}^2/(\text{V} \cdot \text{s})$ at $T = 293 \text{ K}$.

However, for the calculation of $\Delta\mu$ in a semi-intrinsic semiconductor it is necessary to use the more exact formula which takes into consideration the presence of both holes in the valence band and electrons in the conduction band. This formula can be easily obtained by solving equation for $\rho = 1/(q\mu_n n + q\mu_p p)$ relative to $\Delta\mu$:

$$\Delta\mu = kT \ln \left(\frac{1 - \sqrt{1 - 4q^2\mu_n\mu_p n_i^2 \rho^2}}{2q\mu_n n_i^2 \rho} \right). \quad (1)$$

Here μ_n is the electron mobility in CdTe single crystal equal to $1000 \text{ cm}^2/(\text{V} \cdot \text{s})$ and $n_i = (N_c N_v)^{1/2} e^{E_g/2kT}$ is the intrinsic carrier concentration equal to $5.5 \times 10^5 \text{ cm}^{-3}$ (both at $T = 293 \text{ K}$), $E_g = 1.605 - 4.9 \times 10^{-4} T \text{ eV}$ is the semiconductor band gap, $N_c = 2(m_n kT/2\pi\hbar^2)^{3/2}$ is the effective state density in the conduction band, m_n is the effective electron mass and N_v is the value defined above.

The temperature dependence of the resistivity ρ measured on the crystal and the temperature dependences of the Fermi level energy $\Delta\mu$ calculated by (1) are shown in Fig. 2. It is known that in CdTe single crystals of high structural quality, scattering by optical phonons is dominant at $T > 200 \text{ K}$ and the mobility of electrons μ_n and holes μ_p decreases with temperature proportionally to $T^{-3/2}$ [16], [17] according to expressions:

$$\mu_n = 5.715 \times 10^6 T^{-3/2} \quad (2)$$

$$\mu_p = 5.197 \times 10^5 T^{-3/2} \quad (3)$$

which yield $\mu_n = 1100 \text{ cm}^2/(\text{V} \cdot \text{s})$ and $\mu_p = 100 \text{ cm}^2/(\text{V} \cdot \text{s})$ at $T = 293 \text{ K}$ [4].

Since the effective densities of states in the conduction and valence bands are proportional to $T^{-3/2}$, the temperature dependence of the resistivity is determined only by an exponential function. Therefore, the dependence $\rho(T)$ in the coordinates $\log(\rho)$ vs $1000/T$ is represented by a straight line whose slope directly yields the activation energy for the material conductivity E_a (Fig. 2(a)).

Fig. 2(b) shows the temperature dependence of the Fermi level energy $\Delta\mu$ calculated by (1) using (2) and (3) (it was accepted $m_n = 0.11m_0$ and $m_p = 0.35m_0$, where m_0 is the free electron mass). One can see that the value $\Delta\mu$ is equal to 0.66 eV over the whole temperature range, i.e., the Fermi level is distant from the midgap by 0.07 eV ($E_g/2 = 0.73 \text{ eV}$).

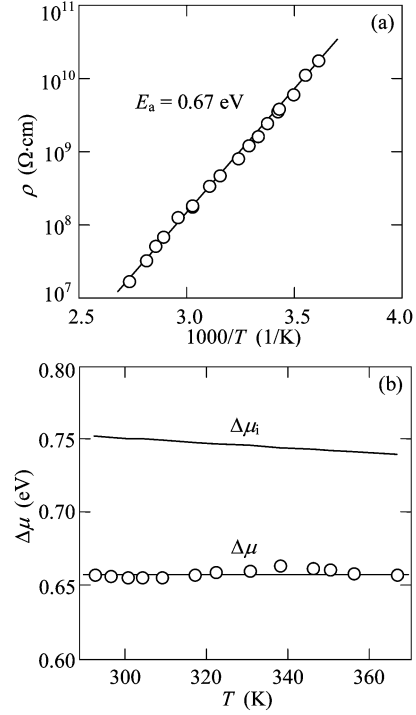


Fig. 2. Temperature dependences of (a) resistivity ρ and (b) Fermi level energy $\Delta\mu$ of the CdTe crystals. The position of the Fermi level in intrinsic CdTe μ_i is also shown in (b).

It should be borne in mind that the Fermi level in intrinsic CdTe is shifted from the midgap towards the conduction band by $kT \ln(m_p/m_n)^{3/4}$ because of the difference in the effective masses of electrons and holes. As a result, the Fermi level in the investigated crystals is shifted relative to that in the intrinsic semiconductor by $\sim 0.1 \text{ eV}$ (the hole concentration in the valence band at $T = 293 \text{ K}$ $p = 2.1 \times 10^7 \text{ cm}^{-3}$ exceeds the intrinsic carrier concentration $n_i = 5.5 \times 10^5 \text{ cm}^{-3}$ by approximately two orders of magnitude).

Thus, the obtained results show that in the case of band bending towards the valence band, a depleted layer with free carriers is formed at the CdTe surface, i.e., a Schottky contact with an n -type inversion layer at the CdTe surface arises. The electron concentration at the CdTe surface strongly depends on band bending, i.e., on the Schottky barrier height. In the case of significant band bending and applying forward bias, electrons can be injected in the bulk part of the crystal and even can reach the contact on the opposite side if the electron lifetime is sufficiently long. Evidently, such an injecting contact cannot operate as ohmic one.

However, it is possible to assume that at small band bending, the injecting and rectifying properties of the contact are weakened and the electrical behavior of a contact can be close to ohmic (see Section IV).

III. TRANSPORT PROPERTIES OF NI/CdTe/Ni DIODES AT LOW BIAS VOLTAGES

It is known that even purest and perfect CdTe single crystals still contain a significant amount of intrinsic point defects and residual impurities with concentration up to $10^{15} - 10^{16} \text{ cm}^{-3}$ and even 10^{17} cm^{-3} [18], [19]. Therefore, it can be assumed

that in a Schottky diode based on this material, carrier generation-recombination in the space charge region is the dominant charge transport mechanism [20]. According to the Sah-Noyce-Shockley theory, the generation-recombination current density is described by expression [21]:

$$J = q \int_0^W \frac{n(x, V)p(x, V) - n_i^2}{\tau_{p0}[n(x, V) + n_1] + \tau_{n0}[p(x, V) + p_1]} dx \quad (4)$$

where τ_{n0} and τ_{p0} are the effective lifetimes of electrons and holes in the space charge region, $n(x, V)$ and $p(x, V)$ are the electron and hole concentrations in the conduction and valence bands, respectively [20]:

$$n(x, V) = N_c e^{-E_g - \Delta\mu - \varphi(x, V) - eV/kT} \quad (5)$$

$$p(x, V) = N_v e^{-\Delta\mu + \varphi(x, V)/kT}. \quad (6)$$

In (5) and (6), the energy $\varphi(x, V)$ is measured downward from the top of the valence band and the coordinate x measured from the surface towards the bulk of the semiconductor.

In the Shockley-Read-Hall statistics, the values of n_1 and p_1 in (4) are respectively equal to the equilibrium concentrations of electrons and holes under the condition that the Fermi level coincides with the considered level, i.e., $n_1 = N_c e^{-(E_g - E_t)/kT}$ and $p_1 = N_v e^{-E_t/kT}$, where E_t in our reference system is the energy spacing between the generation-recombination energy level and the top of the valence band. In the space charge region of a Schottky diode, the function $\varphi(x, V)$ in (5) and (6) is equal to [22]:

$$\varphi(x, V) = (\varphi_0 - eV) \left(1 - \frac{x}{W}\right)^2. \quad (7)$$

The calculation results of the current density by (4) and using (5)–(7) are shown in semi-logarithmic coordinates in Fig. 3 by the solid line (circles are experimental results). The uncompensated acceptor concentration $N_a - N_d$ in the expression for the space charge region width

$$W = \sqrt{\frac{2\varepsilon\varepsilon_0(\varphi_0 - qV)}{q^2(N_a - N_d)}} \quad (8)$$

is accepted equal to 10^{14} cm^{-3} , where ε and ε_0 are the dielectric constants of the semiconductor ($\varepsilon = 10.6$ for CdTe) and vacuum, respectively, and $\varphi_0 = qV_{bi}$ is the barrier height from the semiconductor side (V_{bi} is the built-in potential). For the best coincidence of calculated and experimental results, the effective carrier lifetime in the space charge region $\tau = (\tau_{n0}\tau_{p0})^{1/2}$ was accepted equal to $1.5 \times 10^{-8} \text{ s}$ and the value E_t , which determines the rectification coefficient, becomes equal to 0.69 eV.

In the case of a diode based on a semi-insulating semiconductor, the voltage drop across the bulk part of the crystal V_s should be taken into account as the product ρdJ , where J is the current density and d is the crystal thickness ($d = 0.5 \text{ mm}$). It should be noted that consideration of the voltage drop V_s has strongly modified the shape of the forward J - V characteristic of the studied diode structure.

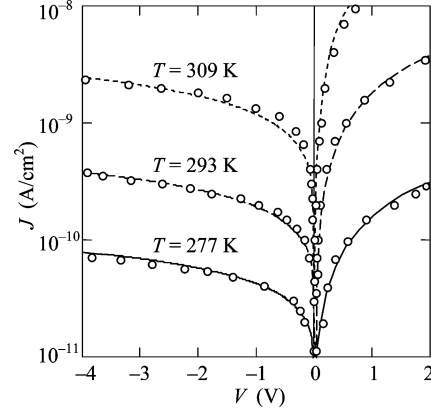


Fig. 3. Room-temperature J - V characteristic of the Ni/CdTe/Ni diode structures at different temperatures plotted in semi-logarithmic coordinates: (circles) experiment, (solid line) calculation by (2).

It should be noted that in the Sah-Noyce-Shockley theory, the effective carrier lifetime $\tau = (\tau_{n0}\tau_{p0})^{1/2}$ and uncompensated acceptor concentration $N_a - N_d$ appear as a product $\tau(N_a - N_d)^{1/2}$. Thus, if one accepts $N_a - N_d = 10^{12} \text{ cm}^{-3}$ (rather than the value 10^{14} cm^{-3} above) as it is assumed in some papers, we will obtain the same J - V characteristic taking $\tau = 1.5 \times 10^{-7} \text{ s}$ (rather than $1.5 \times 10^{-8} \text{ s}$).

As seen from Fig. 3, the applied charge transport mechanism leads to a very good agreement of the calculated results with the experimental data for both forward and reverse connections of the investigated Ni/CdTe/Ni diode. The Sah-Noyce-Shockley theory also describes the temperature variations of the J - V characteristic of the diode structure. Note that in calculations of curves at the $T = 277 \text{ K}$, 293 K and 309 K , only the temperature T and resistivity ρ changed whereas the other parameters were the same. Attention is also drawn to the fact that the effective carrier lifetime in the space charge region $\tau = (\tau_{n0}\tau_{p0})^{1/2}$ was taken equal to $1.5 \times 10^{-8} \text{ s}$ whereas the electron lifetime τ_n in the ACRORAD crystals is in the range of several microseconds [4]. Such a significant difference between τ and τ_n appears reasonable since τ_n is proportional to $1/N_t f$, where N_t is the concentration of recombination centers and f is the probability that a center is empty. Both of the values τ_{n0} and τ_{p0} in the Sah-Noyce-Shockley theory are proportional to $1/N_t$. Since the probability f in the bulk part of the diode can be much less than unity, the electron lifetime τ_n can be far in excess of the effective carrier lifetime τ in the space charge region.

The obtained results also show that *over-barrier diffusion currents* play an insignificant role in the transport properties of the studied samples. The density of over-barrier current is given by the well-known expression [22]:

$$J_d = qA^* e^{-\varphi_0 + \Delta\mu/kT} (e^{eV/kT} - 1) \quad (9)$$

where $A^* = qm_p k^2 / 2\pi^2 \hbar^3$ is the effective Richardson constant. Substitution of $m_p = 0.35m_0$, $\Delta\mu = 0.64 \text{ eV}$ and $\varphi_0 = 0.4 - 0.5 \text{ eV}$ into (9) gives for the reverse current density $J_d = 10^{-12} - 10^{-14} \text{ A/cm}^2$ at $T = 293 \text{ K}$ (at $|V| \gg kT$). Thus, the hole over-barrier current is 2–4 orders of magnitude smaller than the measured reverse currents.

Expression (9) is known to be applied to the so-called *diode* approximation where the electron free path l is much greater than the space charge region width W , or more exactly, under fulfillment of the condition [22]:

$$\frac{l}{W} \frac{\varphi_0}{kT} \gg 1. \quad (10)$$

Taking for assessment $l = 10^{-6}$ cm, $\varphi_0 = 0.5$ eV and $W = 0.1 \times 10^{-4}$ cm, we obtain $l\varphi_0/(WkT) \approx 1$, i.e., the inequality (10) does not hold. Hence, it is possible to suggest that the *diffusion* model of the carrier transport (rather than the diode model) is applicable for the studied contacts. It follows from the diffusion equation for the barrier region that in this case, the expression for the over-barrier current density differs from that described by (9):

$$J_{diff} = qu_{dr}n_s e^{qV/kT} - 1 \quad (11)$$

where u_{dr} is the electron drift velocity and n_s is the equilibrium electron concentration at the semiconductor surface ($V = 0$). The value of u_{dr} is equal to the product of the mobility μ_n and the electric field strength at the surface $E_0 = 2(\varphi_0 - qV)/qW$. The electron concentration at the semiconductor surface n_s is equal to . Therefore,

$$J_{diff} = q\mu_n \frac{2(\varphi_0 - qV)}{qW} N_c e^{-\varphi_0 + \Delta\mu/kT} \left(e^{qV/kT} - 1 \right). \quad (12)$$

Substituting the above parameters into (12), we obtain the reverse current density $J_{diff} = 10^{-12} - 10^{-13}$ A/cm² at $T = 293$ K and $V = -1$ V. Thus, the obtained current is also much smaller than the measured reverse currents. It is worth noting that the pre-exponential factor for the over-barrier diffusion current in (12) depends on the bias voltage ($\sim (\varphi_0 - qV)^{1/2}$) in contrary to the hole over-barrier current which is voltage independent.

Consider also the over-barrier current of minority carriers (electrons) in the studied Schottky diode. We can suggest that the flowing of such a current is identical to that in a $p-n$ junction and for the density current we can write [22]:

$$J_n = q \frac{n_p L_n}{\tau_n} \left(e^{qV/kT} - 1 \right) \quad (13)$$

where n_p is the electron concentration in the *bulk* part of the p -CdTe crystal which is equal to $N_c e^{-(E_g - \Delta\mu)/kT}$, where $L_n = \sqrt{\tau_n D_n}$ is the electron diffusion length, and D_n is the electron diffusion coefficient related to the electron mobility μ_n by the Einstein relationship $qD_n/kT = \mu_n$. Substitution of the above values of $\Delta\mu$, τ_n and μ_n gives the reverse electron over-barrier current $J_n = 3 \times 10^{-12}$ A/cm² ($|V| \gg kT$ and $T = 293$ K). Thus, the obtained value is approximately two orders of magnitude smaller than the measured reverse currents.

The insignificance role of over-barrier diffusion currents in the studied diodes is supported not only by their low values but also their much weaker rise with increasing reverse voltage.

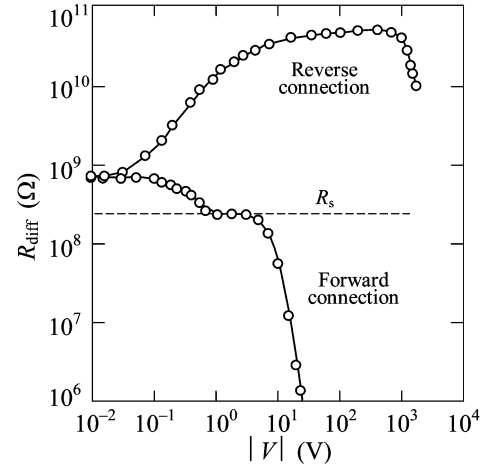


Fig. 4. Differential resistance of the Ni/CdTe/Ni diode structures in a wide range of forward and reverse biases. The dashed straight line shows the resistance R_s of the bulk part of the diode structure.

IV. J - V CHARACTERISTICS OF NI/CdTE/Ni DIODES AT HIGHER VOLTAGES

From the standpoint of the elucidation of the transport mechanism at higher bias voltages, it seems to be very informative the voltage dependence of the differential resistance R_{diff} of the studied diode structures (Fig. 4). As is usually for a semiconductor diode, the value of R_{diff} at *forward* connection decreases with increasing V in the low-bias region (Fig. 4). In the range $V = 1 - 3$ V, the differential resistance saturates, which means that the energy barrier is practically compensated by applied voltage V and further voltage drop takes place across the bulk part of the diode structure. In this voltage region, the value of R_{diff} evidently coincides with the above mentioned resistance of the bulk part of the diode $R_s = \rho d = 2 \times 10^8 \Omega$ shown by the horizontal dashed line in Fig. 4.

With further increasing the forward bias voltage, a sharp decrease in R_{diff} is observed. The value of R_{diff} becomes 2–3 orders of magnitude less than R_s . Thus, a decrease in the crystal resistance is quite significant so that the current in the external circuit can be higher in comparison with the current with ideal ohmic contacts of the same area. Such lowering of R_{diff} is explained by injection of electrons (minority carriers) from the forward-biased Schottky contact into the bulk part of the crystal and modulation of its resistance (Fig. 5(a)).

Indeed, at higher forward voltage the barrier φ_0 lowers and electron injection in the bulk part of the crystal is increasingly enhanced. Direct determination of the electron lifetime τ_n from the decay curve of photoconductivity gave for the investigated CdTe crystals $\tau_n = 5 \times 10^{-6}$ s. Thus, the electron diffusion length is equal to approximately 117 μm (the diffusion coefficient $D_n = 27.8$ cm²/s at the mobility $\mu_n = 10^3$ cm²/(V s) and $T = 293$ K), i.e., this value is a few times less than the thickness of the CdTe crystal.

Consequently, only a small part of the crystal is subjected to modulation by the *diffusion* way. However, this process is enhanced due to the electrical field acting in the base. For example, the forward current density at $V = 1$ V is equal to $\sim 3 \times 10^{-9}$ A/cm² at $T = 293$ K, the voltage drop across the

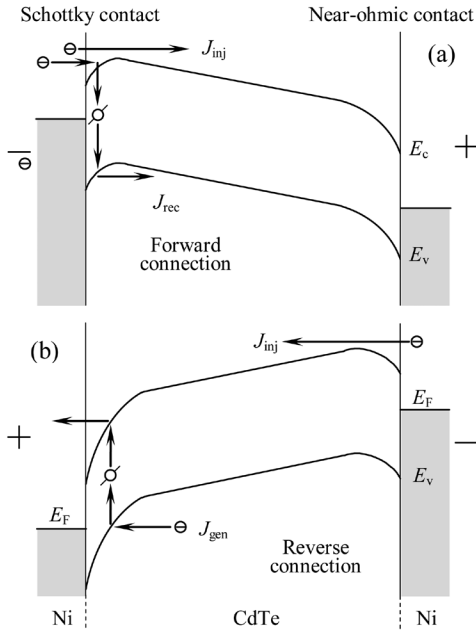


Fig. 5. The energy diagram of the (a) forward and (b) reverse biased Ni/CdTe/Ni diode structures. The recombination (J_{rec}), generation (J_{gen}) and injection (J_{inj}) currents are shown by arrows.

resistance $R_s = 2 \times 10^8 \Omega$ equals 0.6 V and the electrical field strength V/d is 12 V/cm ($d = 0.05$ cm). It follows from this that the mean drift length of electrons $L_{drift} = \mu_n \tau_n V/d$ at $V = 1$ V is equal to 0.06 cm, i.e., an order of magnitude comparative with the crystal thickness. Thus, as the forward voltage increases, the role of minority carrier injection is enhanced because of both increasing the amount of injected electrons and their more effective drift.

Let us now analyze the *reverse* J - V characteristic at high bias voltages that is most important and interesting in the application of CdTe diodes as X- and γ -ray detectors. The reverse current through the diode structure is controlled by the reverse-biased Schottky contact. A sublinear rise in the current (it is typical for the generation charge transport mechanism) at $V < 600$ – 700 V corresponds to a gradual increase in the differential resistance (Fig. 4). However, on exceeding 600–700 V, the differential resistance decreases increasingly and then steeply decays at $V > 1000$ V similarly to that at forward connection of the diode at voltages higher than a few volts. It can be explained by injection of electrons from the near-ohmic contact into the bulk of the crystal (Fig. 5(b)).

With an increase in the current, a fraction of the applied voltage, likely in the forward-connected diode, drops across the neutral part of the crystal and only its small fraction drops across the near-ohmic contact on the opposite side of the crystal. As mentioned above, by changing the technological procedure, we have succeeded in lowering the reverse current whose density reaches the above indicated value of 3×10^{-9} A/cm² at voltages higher than ~ 100 V instead of $V = 1$ V at forward connection (Fig. 6). In addition, the special technological treatment allowed us to weaken injection properties of the near-ohmic contact. As a result, the injection of electrons reveals itself at higher currents compared to the

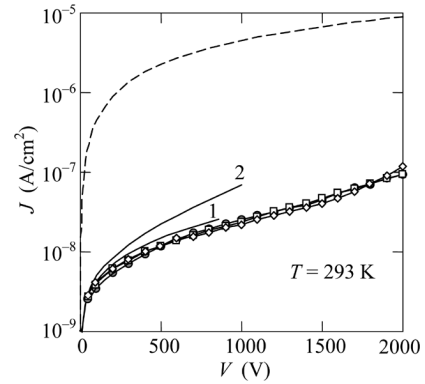


Fig. 6. Room-temperature reverse J - V characteristics: (circles, squares and diamonds) three Ni/CdTe/Ni diode structures with Schottky and near-ohmic contacts obtained under different technological conditions; (curves 1 and 2) best results for Schottky diode detectors taken from [5], [6], respectively; (dashed line) 0.5 mm thick crystal of 1 cm² square with ohmic contacts assumed as ideal ones.

case of forward connection of the diode. At reverse connection, it occurs at $V = 600$ – 700 V when the potential barrier of the near-ohmic contact in the long run lowers and this results in injection of electrons into the neutral part of the diode.

As in the case of forward connection, some amount of injected electrons reaches the reverse-biased Schottky contacts on the opposite side of the crystal by the diffusion way. With increasing current, this process is enhanced due to the electrical field in the neutral part of the crystal. As a result, the current in the external circuit begins to increase.

Thus, we have come to the nontrivial conclusion that at relatively high reverse currents, the processes in the near-ohmic contact influence the reverse-biased Schottky contact on the opposite side of the crystal. At low reverse voltages this effect is practically not observed. It should be pointed out that electron injection from the near-ohmic contact at *forward* connection of the diode is excluded and the current through the Schottky contact is described by the Sah-Noyce-Shockley theory but only at low bias voltages. At higher forward voltages, a dramatic increase in the current caused by effective injection electrons from the forward-biased Schottky contact takes place. The processes in a forward-biased Schottky diode detector are not so interesting from the practical point of view.

It is necessary to emphasize that in case of an *enriched* (but not depleted) near-ohmic contact, injection of carriers in the bulk part of the reverse-biased Ni/CdTe/Ni structure and the effects described above are impossible. Thus, the above results testify that the near-ohmic contact in the investigated diodes is an inefficient Schottky contact and the assumption made in our previous paper [8] that such contact is enriched is most likely incorrect.

In Fig. 6, along with J - V characteristics (circles, squares and diamonds) of the investigated Ni/CdTe/Ni diode structures, analogous curves 1 and 2 for detectors with In/CdTe/Ti electrode configuration taken from the literature ([5], [6], respectively) and the J - V characteristic (dashed line) of the CdTe crystal with ohmic contacts of the same area are shown. A comparison of the data confirms once more the fact that the leakage currents in Schottky diode detectors are approximately

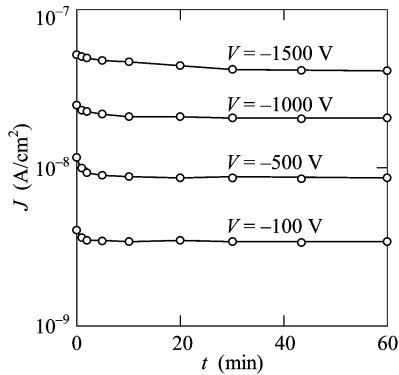


Fig. 7. Room-temperature time dependences of the reverse (leakage) current in the Ni/CdTe/Ni structures after switching on the voltage at different bias voltages.

two orders of magnitude lower as compared to that in the detector with two ohmic contacts (at room temperature). The currents in the best In/CdTe/Pt (Fig. 6, curves 1 and 2) and Ni/CdTe/Ni (circles) detectors are almost equal at reverse bias voltage V lower than ~ 200 V. However, due to a weaker voltage dependence, the leakage current in the Ni/CdTe/Ni diodes at $V \sim 1000$ V is 1.5–2 times smaller than that in In/CdTe/Pt diode detectors. A no less important result is that the Ni/CdTe/Ni diode detector allows us to increase the operating voltage from 1000 V to 1500 V or even 2000 V with a relatively small increase in the leakage current.

Thus, a decrease in carrier injection from the near-ohmic contact in the Schottky diode detectors with Ni/CdTe/Ni electrode configuration is an important way to reduce the leakage current and improve the performance of CdTe based X- and γ -ray detectors. An increase in the operating voltage at low leakage current allows us to enhance the detection efficiency of Schottky diode detectors especially in the high energy photon region.

The reproducibility of the electrical characteristics of the Ni/CdTe/Ni diode structures can be judged from Fig. 6 where the measured curves for the three samples are shown (about 10 samples were studied). As is seen, the J - V dependences of the samples are distinguished insignificantly over the whole voltage range. Finally, the results illustrated the long-term stability of the Ni/CdTe/Ni diode structures are shown in Fig. 7.

It should be pointed out that the reverse current in the investigated Ni/CdTe/Ni diode structure decreases with time in contrast to that reported in some works [23]. The time variations of the current in the Ni/CdTe/Ni diode structures are as follows. If reverse voltage V was applied across the sample, the current decreased by $\sim 10\%$ for 1–2 min at $V < 500$ V and by $\sim 20\%$ for 20–30 min at $V > 1000$ V. With ongoing operation of the diode structure, the current was practically unchanged during 6–8 hours and longer time. Repeated switching on of the diode showed reproducibility of the reported time variations of the current.

It still remains to be investigated how these time dependent changes of the electrical properties are related to current pulses and energy resolution of X- and γ -ray detectors based on such diode structures.

V. CONCLUSION

The Ni/CdTe/Ni Schottky diode structures fabricated on the base of semi-insulating CdTe single crystals have electrical properties improved in comparison with CdTe Schottky X- and γ -ray detectors known from the literature. The J - V characteristics which are typical for a semiconductor diode at low bias voltages have been obtained in semi-insulating CdTe-based Schottky diodes for the first time. In addition, the electrical properties of the fabricated diodes are analytically described by the generation-recombination Sah-Noyce-Shockley theory. An important result of this work is that we have succeeded in developing the technology of fabrication of near-ohmic contacts to semi-insulating CdTe which provides a low enough level of minority carrier injection into the neutral part of the diode structure. It allows us to provide the reverse current in the Schottky diode detectors with Ni/CdTe/Ni electrode configuration at $V = 800 - 1000$ V to be about two times lower in comparison with the best In/CdTe/Pt detectors and a steeper increase in the leakage current starts at higher voltages (at $V > 1000$ V instead of $V > 200 - 300$ V). It turns out to be possible to raise the operating voltage up to 1500–2000 V. The developed technological procedures and fabricated Ni/CdTe/Ni Schottky diodes are promising for application in X- and γ -ray detector performance.

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