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Electron bistability and switching effects in Mo/p-CdTe/Mo structure

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Abstract
It has been experimentally shown that in a simple metal–semiconductor-metal structure with ohmic contacts, a reversible transition from a high-resistance state to a state with high electrical conductivity is possible under the influence of short current pulses of 80-ns duration with a peak voltage of more than 20 V. It was established that after the breakdown under static voltage, the structure irreversibly goes into a state with high electrical conductivity. At the same time, sections with negative differential resistance and negative differential conductivity appear on its low-frequency current–voltage characteristics at voltages less than 1 V. The most probable physical mechanisms that can provide such current–voltage characteristics are considered.

1 Introduction

Among the instrumental structures based on cadmium telluride thin films, solar cells have the greatest application [1] due to the CdTe base layer band gap that is optimal for the photoelectric conversion of solar energy under earth conditions. At the same time, the use of this material in other electronics products is not so widely represented. However, the potential of this material for electronics can be as high as for the traditionally used compounds of the A3B5 group, since they have similar band structures with the presence of light and heavy carrier zones [2]. It has long been shown that structures using *n*-CdTe:Cl single crystals can have bistable S-type current–voltage characteristics (CVCs) with a switching voltage of several tens of volts [3–5]. In the most of works, crystals with *n*-type conductivity were investigated, and we know only one work in which crystals with *p*-type conductivity were studied [6].

In [7], it was theoretically shown that for a structure with *n*-CdTe:Cl, a region with negative differential conductivity should follow after a region with negative differential resistance. Non-linear static CVCs are observed in film structures based on cadmium telluride [8]; these can serve as the basis for the creation of a new class of electronic devices based on cadmium telluride if such CVCs are realized under high-frequency pulsed action.

For example, it was theoretically shown in [9] that during generation–recombination process into thin semiconductor films, in the case of multiplication of charge carriers, a dynamic phase transition is possible [10], in which the threshold voltage is controlled by the generation-recombination parameters of the film. For small thicknesses, this voltage becomes comparable with the values of the semiconductor device operating voltages, which makes it possible to use this type of structures in the devices for recording and processing information. In addition, the high radiation resistance of cadmium telluride makes the material promising for use in the construction of radiation sensors [11].

Therefore, the aim of this work is experimental studies of the low-frequency electrical properties of the Mo/CdTe/Mo structure with a thin CdTe film.

2 Sample preparation procedure

The samples studied were Mo/*p*-CdTe/Mo structures. The functional layer of the cadmium telluride film was formed on the surface of the Mo foil with a thickness of 0.15 mm by the method of thermal vacuum deposition. The temperature of the evaporator was 700 °C, and the temperature of the substrate was 330 °C. The thickness of the cadmium

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telluride layer of 5–7 µm was set by the deposition time. To measure the CVCs, a measuring cell was constructed (Fig. 1), in which the studied sample as a disk with a diameter of 2 mm was placed. The upper spherical Mo contact with a radius of curvature of 10 mm was pressed to the surface of CdTe layer. The force in the contact zone between CdTe and the clamping electrode was set by an elastic element (spiral spring) (Fig. 1 in circle).

To ensure the possibility of soldering conductors to the Mo contact, a copper layer was preliminarily deposited on its back surface. The sphericity of the contact surface was ensured by mechanical molding between the punch and the die of the corresponding shape and followed by grinding. The calculated contact radius was ~ 85 µm and the contact area was ~ 2.27 10^{-4} cm^2, respectively.

The Mo contact is electrically connected to the output of the measuring cell by a bundle of three copper conductors passed through the steel spring and soldered to the back side of the Mo contact. Thus, the clamping contact was a composite structure with the following calculated electrical parameters: inductance $L = 30$ nH, intrinsic capacitance $C = 0.12$ pF, intrinsic resonance frequency $f_r = 2594.68$ MHz, and design quality of the coil $Q = 588$. The CVCs were measured using a parameter meter of semiconductor devices L2-56 (characteriscope).

To measure the voltage–time characteristics of the experimental samples in a pulsed mode, a measuring bench based on a cable generator (CG) was used, which was a forming line in the shape of a coaxial cable with an impedance of 50 Ohms. A transistor operating in the avalanche breakdown mode was used as a CG switch, which made it possible to obtain a rise time of the voltage pulse of 3 ns. The CG cable was charged from a direct current source to a voltage equal to the avalanche breakdown voltage of the transistor, which was about 90 to100 V. During the discharge of the CG cable to the matched load, the pulse amplitude was half the charge voltage of the cable.

The charge of the cable was controlled using the G5-54 generator, which made it possible to obtain both single voltage pulses and periodically repeating pulses with a frequency of 10 Hz at the output of the CG. The test sample (TS) was connected to the output of the cable generator through a delay line (DL) of 40-ns duration, and a potentiometer which made it possible to smoothly change the pulse amplitude to the TS.

The use of the DL of 40 ns made it possible to avoid the reflected signals from the potentiometer getting to the pulse front when the TS was activated. The control of voltage pulses was carried out using a Rigol DS1204B digital storage oscilloscope which was connected to the DL sending end through a broadband voltage divider 1:100 with one channel, and directly to the TS with the other. The amplitude of the pulses was controlled using two matching resistors, which made it possible to obtain amplitudes of 23 V, 42 – 46 V, and 84 – 92 V. The time delay between the beginning of the pulse signals at the input (Ch1) and the output (Ch2) was 30 ns, and between the beginning of Ch2 and the arrival of reflection (the beginning of the step) to Ch1 are 50 ns.

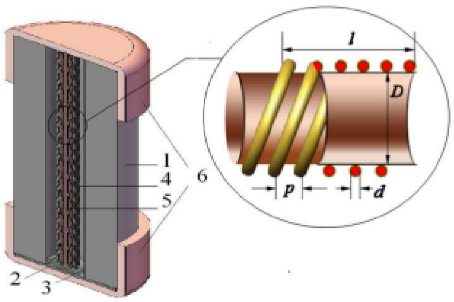
This is due to the fact that the channel of the oscilloscope Ch1 is connected through a voltage divider with an electrical length of 10 ns, and the oscilloscope channel Ch2 is connected directly to the output of the DL. The TS was connected to the end of the DL using a coaxial connector, which ensured a low intrinsic inductance and uniformity of the wave impedance of the entire coaxial system.

3 Measurement results

3.1 Low-frequency CVC

It was experimentally found that the electrical resistance of the Mo/*p*-CdTe/Mo samples in the initial state was 10–20 MΩ. With a resistance of 10 MΩ for 5 µm thickness of *p*-type cadmium telluride film and a frontal contact area of

Fig. 1 Design of the measuring cell



1 – ceramic case; 2 – CdTe/Mo structure of; 3 – clamping Mo contact; 4 – spring; 5 – copper wire; 6 – external contacts, case diameter: $D = 0.8$ mm; wire diameter: $d = 0.2$ mm; pitch of turns: $p = 1$ mm; number of coil turns: 10

2.27×10^{-4} cm^2, the resistivity of the CdTe layer is 5×10^6 Ω cm. Taking into account the literature data on the characteristic hole mobility values of 30 cm^2/V·s in undoped cadmium telluride films [10], the concentration of the majority charge carriers is $4\cdot10^{10}$ cm^{-3}.

Typical experimental low-frequency CVCs of the studied Mo/CdTe/Mo structures is shown in Fig. 2.

When measuring the CVC, after inserting the sample into the measuring circuit, the voltage on it gradually increased. The experimental CVC was symmetric and linear with high resistance. The currents flowing through the sample in this mode did not exceed 1 μA. When the voltage reached approximately 15–20 V corresponding to electric field strength ~ 30 kV/cm, breakdown occurred and the structure turned into a state with high electrical conductivity. After removing the voltage and setting lower voltage limits, a linear CVC was again observed (Fig. 2a).

Some time after the sample was left at a voltage of 1.5 V, the shape of the CVC changed, and it successively took the form shown in Fig. 2b, c. The CVC shown in these figures are S-shaped with a stall voltage of $0.7-1$ V; a stall current in Fig. 2c is at a level of 2 mA or less, and in Fig. 2b it is about 25 mA. At high currents, sections of negative differential conductivity can be seen on the CVC (Fig. 2g). After disconnecting the sample, its resistance remained low. Repeated measurements after several days showed that the CVC behavior was identical to that shown in Fig. 2; i.e., at first, the CVC looked straight at voltages of 1–1.5 V, but after a while it also began to transform to a shape similar to Fig. 2g. During the measurement of the CVC, the temperature of the sample increased, as evidenced by heating of the case. An increase in the surface temperature of the ceramic casing by 8 °C was recorded. With a current of 2 mA and a voltage of 1 V, a power of 2 mW is released in the current flowing region, while the power flux density is ~ 19 W/cm^2. If we assume that all this power is ultimately dissipated by the surface of the casing through an external terminal directly in contact with the sample, then the estimate gives the temperature of this terminal ≈ 37 °C. Given the additional heat loss from the external terminal directly to the atmosphere (ambient temperature 12.5 °C), it can be expected that the terminal temperature was actually higher. This suggests that the temperature of the CdTe film in the current flow region could exceed 100 °C.

To determine the breakdown effect on the state of the contact, several samples after breakdown and several samples that did not pass the breakdown stage were disassembled. A typical optical image of the surface of a contact needle (spherical Mo contact) after disassembling is shown in Fig. 3. This type of surface of the contact

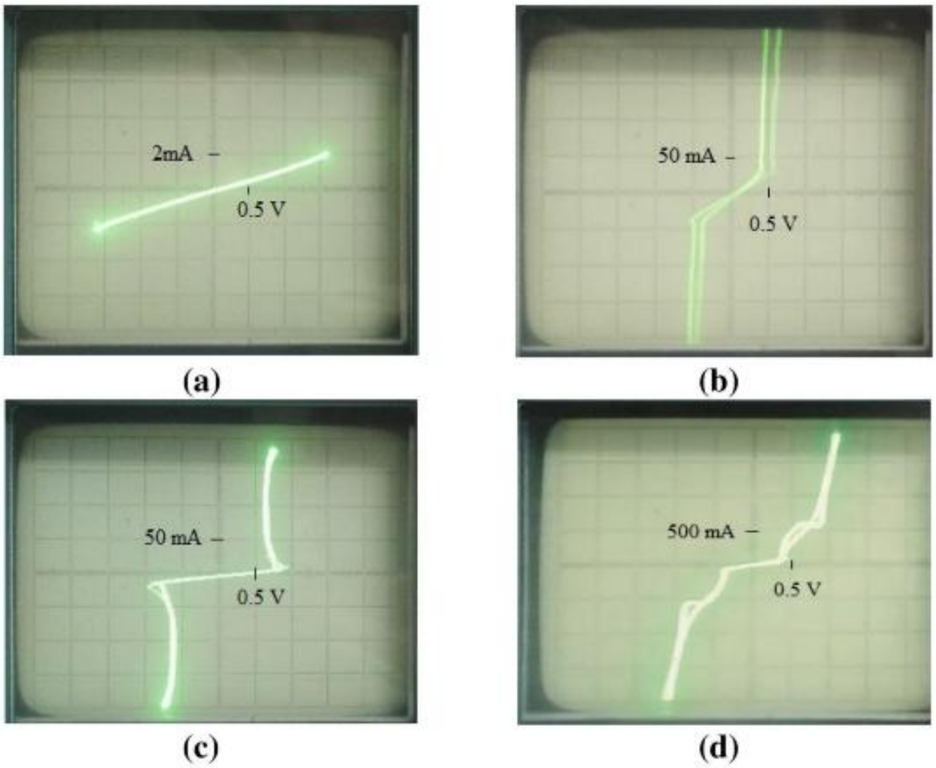


Fig. 2 Typical low-frequency CVC structures after breakdown

a) CVC of the structure immediately after breakdown and a decrease in the limits of the applied voltage;

b), c), d) sequential CVC evolution of the Mo/CdTe/Mo structure after breakdown.

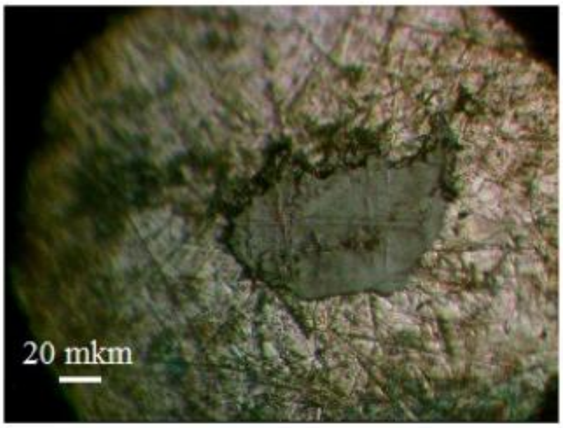


Fig. 3 Optical image of the contact surface of the contact needle with the working area of the CdTe film

needle was characteristic both for samples that passed the breakdown stage and for samples that were not subjected to breakdown.

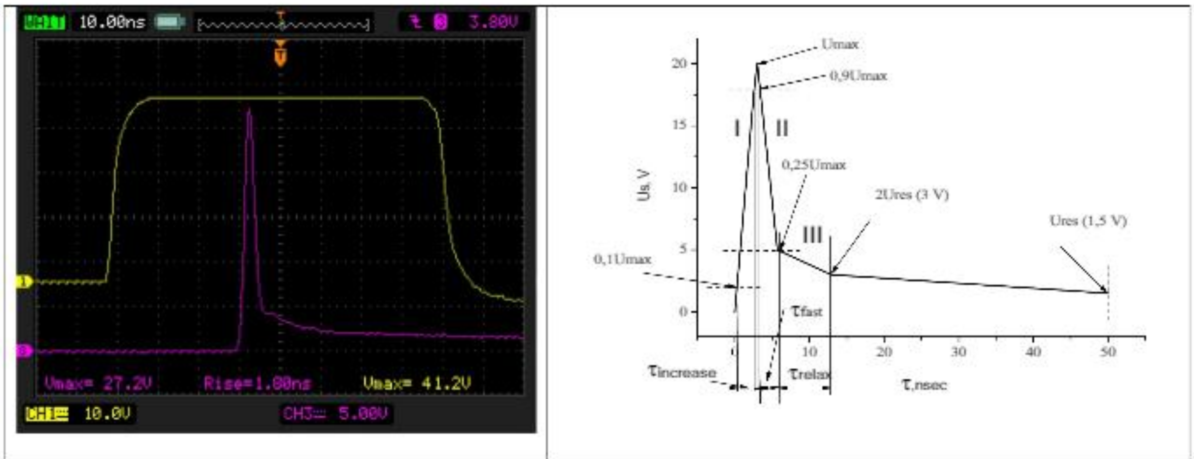
On the clamping needle (Fig. 3), one can see a part of the CdTe film with a size of $\sim 100 \times 67\ \mu m^2$ ($S \sim 0.67\ 10^{-4}\ cm^2$) which remained on the needle after disassembling.

Such a picture is typical both for the samples that have passed the breakdown stage and for the samples that have not passed the breakdown stage. It was this region of the CdTe film that ensured the operation of the structure under study. Therefore, it is expected that a small volume of the CdTe film section ($V \sim 4.7 \cdot 10^{-8}\ cm^3$) can be heated to a significant temperature during a long flow of current. The transition of the investigated structure from a high-resistance state to a low-resistance state with a long-time supply of voltage close to the breakdown voltage is irreversible. Therefore, after studying the structure in the low-frequency mode, we studied its electrical properties in the pulsed mode with pulse durations of the order of tens of nanoseconds.

3.2 Voltage–time characteristics

To study the voltage–time characteristics, high-resistance samples were used that were not subjected to breakdown. Single voltage pulses of 23 V, 46 V, and 76 V and duration of 80 ns were applied to these samples. The waveform of the pulse, the response of the sample (voltage–time characteristic), and the schematic typical voltage–time characteristic of the test samples are presented in Fig. 4. Such voltage–time characteristic allows to conclude that this MSM structure is perspective for use as transient-voltage-suppression (TVS) diode.

As can be seen from the figure, the voltage–time characteristic has four clearly pronounced time intervals: I—"rise time" of voltage on the sample; II—"time of rapid decline"; III—"relaxation time" or time of slow voltage decrease; IV—period of asymptotic decline (50 ns after operating) to some residual voltage *U*. It was found that the manufactured samples operate at voltages at the level of 1/3 of the magnitude of the supplied pulse. The timing of the response depends on the magnitude of the electrical voltage of the supplied pulse. With an increase in the applied voltage pulse, the fast fall time decreases, and the relaxation time increases. The pulse rise time (Sect. I, Fig. 4) and the fast fall time (Sect. II, Fig. 4) decrease with increasing pulse voltage from 3.1 ns to 2.4 ns and from 3.9 ns to 2.3 ns, respectively, and the spread of these values for different samples amounted to no more than 0.5 ns. At the same time, for a slow decline (Sect. III, Fig. 4), on the contrary, an increase in time is observed, its maximum value was 9 ns, and the spread for



(a)

(b)

Fig. 4 The waveform of the pulse, the response of the sample (voltage–time characteristic), (**a**) and a typical schematic voltage–time characteristic of the structure of Mo/CdTe/Mo (**b**) different samples was 6 ns. Further, 50 ns after operation, a certain residual voltage $U_{\text{res}} = 1.5$ V is maintained in the film, which is the same for all samples and ensures that a pulse current flows through it. It is interesting to note that the residual voltage coincides with the band gap of CdTe, as well as the maximum voltage after breakdown at which the transition to the S-shaped CVC occurs.

4 Discussion

The CVCs obtained after breakdown can correspond to the characteristics of a thermistor or for a *p*–*n* junction in the initial section of an avalanche breakdown or CVC of an S-diode. If the symmetric form of the CVC is traditional for a thermistor, then for the *p*–*n* junction the CVC must be asymmetric. Based on the band diagram of the contact between Mo (work function 4.3 eV) and intrinsic CdTe (work function ~ 5.0 eV), it can be expected in theory that for the Mo/CdTe/Mo structure at the contacts, we obtain a potential difference of about 0.8 eV and layers enriched with electrons. The width of these layers can be estimated as ≈ 0.1 µm or less. In this case, at the boundary, the Fermi level will practically coincide with the bottom of the conduction band, i.e., a very thin layer of a weakly degenerate semiconductor with an electron concentration of the order of the density of states ~ $10^{17} - 10^{18}$ cm^{-3} should appear. The layers of space charge at the contacts of the structure will not give a rectifying effect, since they are enrichment layers. Since films of thermal CdTe, as a rule, have a weak, but *p*-type conductivity, we can assume the formation of an n^+–p–n^+ structure with inverse layers. Nevertheless, due to the very thin regions of the space charge at the contacts and the large resistance of the neutral volume of the cadmium telluride base layer, the initial current–voltage characteristics are linear.

Therefore, it can be assumed that in the initial state, the main mechanism of current flow in the structure under study is the mechanism of currents limited by the spatial (volume) charge (SCLC). In this case, before the breakdown, the CVC does not go beyond the first linear section of the SCLC. However, after the breakdown, the sample undergoes irreversible changes associated with the formation of a channel with high electrical conductivity. Most likely, this channel is formed along the grain boundaries. Subsequently, at low voltages, this channel shunts a high-resistance volume of grains, which as a result leads to the appearance of S-shaped CVCs. One can propose the following physical mechanism of current flow in this structure. At low voltages, current flows mainly through a high electrical conductivity channel formed by breakdown. Since this channel has a small cross section, with increasing voltage and the magnitude of the flowing current, part of this current begins to flow through the high-resistance CdTe regions adjacent to the channel. This leads to a heating of the semiconductor and an increase in the carrier concentration. As a result, the electrical conductivity of high-resistance regions and the magnitude of the current flowing through them increase.

It is known [2] that for the formation of an NDR region (negative differential resistance), the conductivity must grow superlinearly as function of current, and then in current controlled mode the CVC will be S-shaped. Such a superlinear increase in the conductivity of the CdTe film can be ensured as follows. Since the CdTe film in the initial state has a *p*-type conductivity with a carrier concentration close to intrinsic, then even with slight heating it passes into the intrinsic conductivity region. In this case, the "majority" charge carriers that determine the magnitude of the electrical conductivity are electrons, because their mobility is an order of magnitude greater than the mobility of holes. In addition, electrons are also injected into the film from the enrichment layers at the contacts. An increase in the mobility of charge carriers in addition to an increase in their concentration upon film heating also provides a superlinear increase in electrical conductivity and the appearance of the NDR section. The additional mechanism of the appearance of S-shaped CVC, which is connected with the heating up of charge carriers in the electric field, was discussed in [12, 13], where also was shown that the CVC form depends on inelastic scattering of electrons on the surface [14].

After heating the film, the structure under consideration acquires the character of an n^+–n–n^+ structure in which the appearance of an N-shaped CVC in voltage controlled mode is possible. In this case, the conductivity as a function of voltage should grow superlinearly, for example, by the mechanism of Gunn's diodes. This is due to the fact that, in CdTe, intervalley transitions are possible [2], which lead to the formation of a negative differential conductance region on the CVC. Thus, the breakdown leads to the appearance of non-linear characteristics in the simple structure of Mo/*p*-CdTe/Mo.

At the same time, as shown by experiments on the effect of single voltage pulses, in the case of short pulses, irreversible breakdown does not occur, even when the pulse voltage is significantly higher than the breakdown voltage. Moreover, the structure is able to repeatedly switch between states with low and high levels of electrical conductivity. According to estimates of the pulse energy ($W = t\ U^2 / R = 80\ 10^{-9}\ \ 42^2/50 \approx 2.76$ µJ, R is the line resistance), this energy is sufficient to heat the CdTe film in the contact region to a temperature of ~ 50 °C ($W = m\ c\ \Delta T \Rightarrow \Delta T = 2.76\ 10^{-6}/205/2.9\ 10^{-10} \approx$ 46 °C). For a film that has not passed the breakdown stage, this temperature, as well as the pulse duration, is not enough to provide high electrical conductivity due to heating. Therefore, a mechanism associated with the injection of electrons from the contact seems to be a more likely mechanism for the film to transition to a state with high electrical conductivity under the action of a short strong current pulse.

At voltages corresponding to the transition to a state with high electrical conductivity (~ 20 V), the drift velocity of the injected electrons (assuming the electron mobility in the CdTe film is ~ 100 $cm^2/V \cdot s$) reaches ~ $3 \cdot 10^6$ cm/s, and their transit time through the film is ~ $2 \cdot 10^{-10}$ s, which is shorter than their lifetime, which for films made by vacuum methods is usually ~ 1 ns [15]).

Thus, for the lifetime of the electrons, the film is filled with injected electrons and passes into a state with high electrical conductivity, after which the film returns to its original high-resistance state.

5 Conclusion

Preliminary electrical molding of the Mo/*p*-CdTe/Mo film structure by applying a voltage greater than a certain threshold value allows reproducible CVCs that have S- and N-shaped regions at low voltages < 1 V. The appearance of the S-shaped portion is most likely due to a gradual increase in the temperature of the conductive channel, which is formed as a result of the molding. This leads to the transition of the sample from the state of impurity conductivity to the state of intrinsic conductivity, while electrons are effectively the majority carriers due to greater mobility. The additional mechanism of the appearance of S-shaped CVC is connected with the heating up of charge curriers in electric field.

An increase in the concentration and mobility of charge carriers also leads to the appearance of a section of the NDR. The N-shaped portion of the CVC is formed according to the mechanism known for Gunn's diodes. Experimental studies of device structures based on film layers of cadmium telluride showed that when exposed to electromagnetic pulses, they limit the voltage in the circuit due to the restored sharp drop in the electrical resistance of the CdTe layer.

Moreover, compared with industrial samples of TVS diodes, structures based on film layers of cadmium telluride have a simpler design and have almost the same speed as TVS diodes. A more probable mechanism for the film to transition to a state with high electrical conductivity under the action of a short strong current pulse is the mechanism associated with the injection of electrons from the contact.

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