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Amplitude-time Characteristics of Switching in Thin Films of Cadmium Telluride

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The amplitude-time characteristics of switching in thin films of cadmium telluride were investigated when single impulses of 1 μs duration are applied. It has been experimentally established that with an increase in the thickness of the cadmium telluride layer from 3 μm to 8 μm, an increase in the operating threshold from 70 V to 105 V is observed. The maximum residual sample voltage varies from 12 V to 40 V, the minimum – from 5 V to 20 V. The switching time of the samples was no more than 2 nanoseconds; the interelectrode capacity of the samples was no more than 2 pF. All the test samples were operated without failure 20 times. The structural studies of cadmium telluride films by the method of X-ray diffractometry and scanning electron microscopy have made it possible to propose a mechanism for realizing the monostable switching of the columnar structure of cadmium telluride films oriented in the form of melted high-conductivity channels in grains oriented in the [111] direction

Keywords: Cadmium Telluride films, Amplitude-time characteristics, X-ray diffractometry, Scanning electron microscopy, Melted high-conductivity channel.

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1. INTRODUCTION

One of the main requirements for modern radio-electronic equipment (REE) is the high reliability of its operation under the conditions of external factors. In recent years, more attention has been paid to electromagnetic stability, which implies the property of preserving operating parameters during and after the action of electromagnetic impulses (EMI) of various origins [1]. The problem of ensuring the electromagnetic stability of REE is due to the fact that under the influence of EMI, overvoltage impulses are induced in the circuits of the circuits, the amplitude values of U_{imp}, the time rise and the duration of which can vary within wide limits due to the nature of the EMI, the distance from the EMI source to the location of the REE, geometric features of individual components of the hardware complex (antennas, communication lines), as well as other factors. EMI-induced impulse overvoltage's can have a serious damaging effect on the elements of the equipment (primarily input devices), which is manifested in the violation of galvanic coupling due to the melting of conductors, in the appearance of areas of increased conductivity not provided for by the REE design due to the deposition of arc discharge products on the dielectric between metal sections, a catastrophic increase in the leakage current of capacitors and field diodes with an isolated gate in the dielectric layer breakdown. Semiconductor devices are particularly susceptible to damaging effects of EMI. This is due both to the properties of the *p-n* junction and to the specific heat conductivity of semiconductor materials. When the reverse bias voltage of the transition is sufficient for the onset of avalanche breakdown, a large amount of warm energy can be released in the transition. Therefore, in local avalanche breakdown areas, due to the progressive accumulation of heat, the temperature can reach values corresponding to the melting point of the semiconductor material, which causes the *p-n* junction to be shunted. With a decrease in the size of semiconductor instrument structures, the level of their damage is reduced and for integrated circuits is from 10^{-3} J to 10^{-7} J [2]. If the energy released is insignificant and is not capable of causing thermal breakdowns, the transient processes associated with the impulse overvoltage can cause the appearance of false signals, malfunctions, switching and a number of other negative effects from the point of view of the normal functioning of the elements of the REE. For computing devices operating in real time, such short-term failures in operation lead to a complete loss of computational efficiency.

To ensure the protection of electrical circuits, the elements of protection of REE from impulse overvoltage's are used. The most important property of the protection elements: gas discharges, semiconductor Zener diodes, varistors and limiting diodes, is their ability to reduce their resistance Re from 5 10^4-10^{10} Ω for a short time τ_{sw} (switching time or response time) to a value significantly lower than the value of the input resistance of the protected element REE, when the voltage U_i in the circuit exceeds the value of the threshold voltage U_t, called the switching threshold or the pick-up threshold [3]. If such protection elements are connected in parallel to the protected device, then for $U_i > U_t$ during a time τ_s the amplitude value of the voltage on the protected device is reduced to the value U_t (zener diodes, varistors, limiting diodes) or to a value significantly lower than U_t (gas discharges). The most widely used restrictive silicon diodes, since they have high speed (τ_s at 1 nanosecond) [4]. However, they can shunt a limited amount of energy and have an interelectrode capacitance at a level of 20 pF, which limits their application for the protection of microwave REE.

Therefore, in order to create protection elements for microwave REE in this work, studies were made of the amplitude-time characteristics of switching in thin films of cadmium telluride.

2. TECHNIQUE OF THE EXPERIMENT

In order to obtain the base layers of cadmium telluride by the method of thermal vacuum deposition, an industrial vacuum unit УВН67 was used. The installation has a size of the 0.12 m^3 work zone and allows the deposition of cadmium telluride films on 10 cm × 10 cm substrates.

The initial vacuum was $6 \cdot 10^{-6}$ mm Hg, the working pressure in the vacuum chamber during the deposition was maintained at $1 \cdot 10^{-5}$ mm Hg. For evaporation of cadmium telluride films, a graphite evaporator with indirect heating from two electrically insulated heaters made of molybdenum wire with a diameter of 1,2 mm (Fig. 1). The evaporation temperature was controlled by a thermocouple installed in the volume of the heater immediately below the sample area, which was a batch of 99.999 % cadmium telluride with a particle size of 10 mm. The heating time of the evaporator to evaporation temperatures (700 ± 750) °C was 260 to 275 sec. To achieve these speeds and the uniformity of heating, the spatial uniformity of the vapor flow to the graphite evaporator, a hole cricket was made. The accuracy of maintaining the temperature of the evaporator was not more than 5 °C.

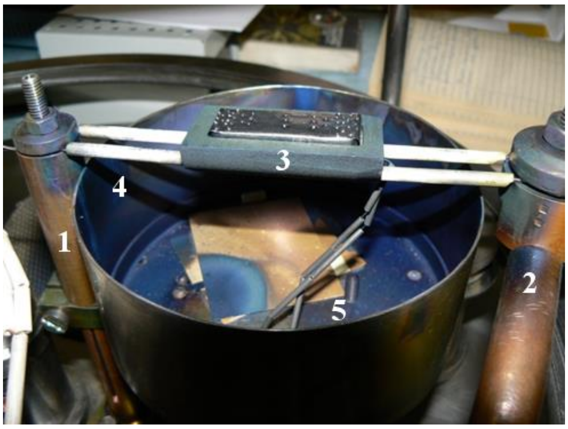

Fig. 1 – Graphite evaporator of cadmium telluride: 1, 2 – current inputs; 3 – graphite crucible with a hole cricket; 4 – heating elements; 5 – thermocouple

To monitor the temperature of the thermocouples of the cover and the evaporator, a digital multimeter MS8040 was used, which was connected via a mechanical switch.

Deposition of cadmium telluride films was carried out on molybdenum foil. Electrolytic polished molybdenum strips 1.5 mm in width and 50 mm in length were placed under a mask with a hole diameter of 2 mm in the substrate holder, which was then attached to the manipulator in a vacuum installation above the crucible. The thickness of the deposited layers of cadmium telluride, which was set by the deposition time, was 3-10 μm.

The crystalline structure of cadmium telluride layers was investigated by X-ray diffractometry. X-ray diffraction patterns were recorded by the θ-2θ method using a ДРОН-4 X-ray diffractometer with a step of 0.01 degrees in the radiation of the copper anode.

The control of the initial electrical resistance of cadmium telluride film layers was carried out at a temperature of 20 °C in the housings of microwave diodes using a digital ampere-voltmeter Щ300. Along with the initial electric resistance of the samples to a direct current, at a frequency of 10^7 Hz at a temperature of 20 °C, their electrical capacitance was measured by the device Л2-28.

The switching characteristics of the samples were studied on a special test bench, which included a voltage impulse generator, a generator control unit, and a set of measuring equipment. The inhomogeneity introduced into the coaxial line by samples at a frequency of 5 GHz, according to the reflectometry obtained with the instrument P5-11, did not exceed 30 %. At an ambient temperature of 20 °C, the samples were subjected to stress impulses of amplitude U_i from 100 V to 1400 V with a duty ratio of $2 \cdot 10^7$. The rise time of the pulse to the amplitude value was 2.5 nanoseconds. Then, the impulse voltage decreased exponentially to 0.5 in a time of 100 nanoseconds. The amplitude-time characteristics of the process of sample switching were determined by experiment. The amplitude-time characteristics of the switching process of the samples were determined from experimental oscillograms obtained with the help of the oscillographs C8-12 and C7-19.

3. DEVELOPMENT OF THE SECURITY ELEMENT DESIGN

To connect to a coaxial line with a wave impedance of 50 Ohm by soldering, film samples of cadmium telluride were placed in modified bodies of microwave diode type Д403Б. As shown by capacitance measurements made with the capacitance meter of p-n junctions of low power transistors Л2-28, the interelectrode capacitance of such bodies without fillings at 10^7 Hz is only 0.2 pF. For these cases, a specific design of a clamping counter electrode was used, which was made of molybdenum.

The specificity of the counterelectrode was that it should gently pressurize to the surface of the cadmium telluride film and be able to freely move along the direction of the perpendicular surface of the layer to track changes in film thickness caused by its heating and cooling during the forward and backward switching stages. To ensure such mechanical properties of the clamping counterelectrode, a blind drilling was performed at one of the hull terminals from its inner end. The cylindrical cavity created served to house the molybdenum base against the electrode and the element of counter-electrode spring.

The molybdenum counter electrode was a rod of cylindrical shape with an outer diameter of 1,65-1,70 mm and a length of 4,5 mm.The counter-electrode portion contacting the switching layer had a hemispherical surface which was polished with diamond pastes. The end face of the counter electrode contacting the spring-biasing element was flat. An additional element of the filling of the case was a fluoroplastic insert of a cylindrical shape, which was used as a guide for the molybdenum counter electrode. A schematic illustration of the assembled case with a thin-film layer is shown in Fig. 2.

4. STUDIES OF THE CRYSTAL STRUCTURE AND ELECTRICAL PROPERTIES OF CADMIUM TELLURIDE FILM LAYERS IN THE INITIAL STATE

Using X-ray diffractometry it was found that at deposition temperatures of less than 300 °C, a two-phase cadmium telluride film is formed, which contains, along

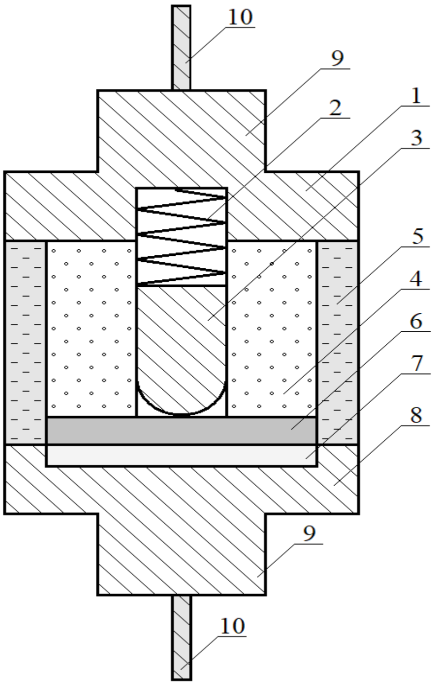

Fig. 2 – The casing scheme with cadmium telluride film layer installed in it. 1 – pin with internal cavity, 2 – spring, 3 – counter-electrode, 4 - fluoroplastic insert, 5 – ceramic tube, 6 – CdTe layer, 7 – substrate, 8 - inner end of the output, output, 9 – technological part of the output, 10 – soldering zone

with a stable cubic modification, a metastable hexagonal phase. At substrate temperature above 350 °C, the growth rate of the CdTe layer sharply decreases. Therefore, the substrate temperature when depositing cadmium telluride films for switched layers (320-330) °C. Film layers were made which had a thickness (d) of 3 μm to 8 μm. Investigations of the crystal structure showed that all the layers have a stable cubic modification, as is unambiguously confirmed by the presence of reflections from the (111), (200) (311), (400), (331), and (422) planes (Fig. 3). The intensity ratio of the detected peaks differs from the theoretical ones and indicates the advantage of the orientation of the films in the [111] direction. The morphology of the surface of cadmium telluride films, studied with the Philips CM30 raster microscope, indicates that the grain size in the layer of cadmium telluride is 1 μm (Fig. 4).

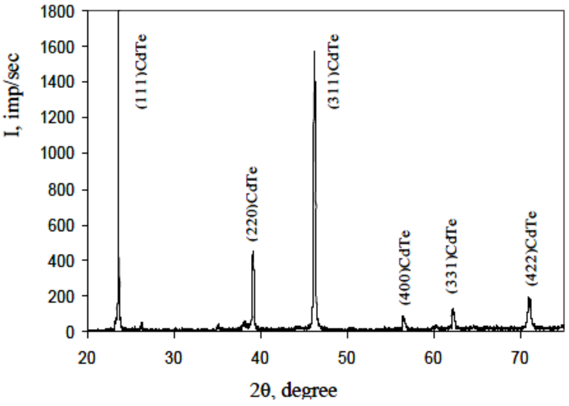

Fig. 3 – X-ray diffractogram of Cadmium Telluride layer of 4 μm thick

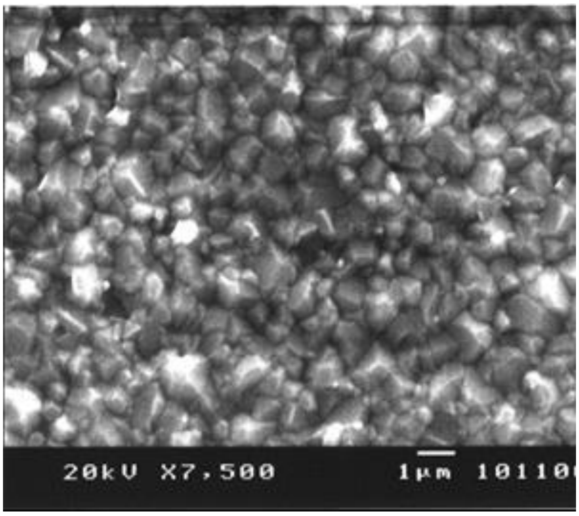

Fig. 4 – Surface of CdTe films of 4 μm thick

According to the literature data [5, 6], cadmium telluride films oriented in the [111] direction have a columnar structure. In the initial state, the electrical resistance R_c of the samples exceeded 10^9 Ohms and did not depend on the thickness of the layer of cadmium telluride. For the initial electrical capacitance, the value of which was from $0.4 \cdot 10^{-12}$ F to $1.2 \cdot 10^{-12}$ F, there was also no dependence on the thickness of the layer. The absence of dependence of the electrical resistance and capacitance on the thickness of the layer of cadmium telluride from our point of view is due to the variation of the electrode contact area with the switching layer of cadmium telluride.

5. STUDY OF THE SWITCHING AMPLITUDE-TIME CHARACTERISTICS

Experimental oscillograms were used to study the amplitude-time characteristics (ATC) of the switching process in the resulting thin films of cadmium telluride. The qualitative form of a typical oscillogram of the experimental stress diagram on film samples is shown in Fig. 5 (curve 1). This figure also gives a qualitative view of a typical oscillogram of the voltage impulses acting on the samples.

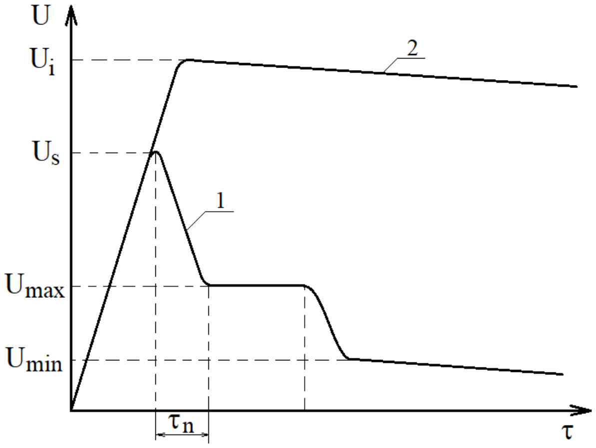

Fig. 5 – Typical oscillogram of the experimental stress diagram on film samples of Cadmium Telluride

The determination of the ATC of the switching process was preceded by the determination of the pickup threshold, which was carried out by feeding the forming impulse to the samples. The shaping impulse had the amplitude, which was minimum necessary for the first operation. Then several measuring impulses were fed with the minimum amplitude necessary for the next trips, which was identified with the value of the threshold voltage U_t. The results of ATC research are given in Table 1. The table shows the threshold voltage U_t, the maximum voltage on the samples U_s, the maximum residual voltage on the samples $U_{\max}$, the minimum residual voltage on the samples $U_{\min}$, the time of switching to the low-resistance state τ_s.

Table 1 also gives the electrical resistivity of the samples to the direct current R_e after a 20-fold impulse action with amplitude U_i. It was found that the values of ATC do not depend on the polarity of the current impulses acting on the film samples.

Table 1 – Results of studies of the amplitude-time characteristics of the thin-film cadmium telluride samples switching and the electrical resistivity of these samples to a direct current after a series of impulsed effects

d, μm	U_t, V	U_s/U_i, V	$(U_{\max}-U_{\min})/U_i$, V	τ_s, sec	R_e, Ohm
3	75	42/285	(20-10)/285	< 2	$1.7 \cdot 10^5$
3	75	38/271	(20-10)/271	< 2	$2.0 \cdot 10^5$
4	70	40/214	(13-5)/214	< 2	$1.3 \cdot 10^6$
4	70	50/211	(12-5)/211	2	$7.7 \cdot 10^6$
6	70	52/216	(15-7)/216	2	$5.6 \cdot 10^6$
6	75	51/225	(15-7)/225	2	$5.6 \cdot 10^6$
7	80	55/240	(20-10)/240	< 2	$1.5 \cdot 10^6$
7	70	53/219	(20-10)/219	2	$1. \cdot 10^6$
8	105	120/316	(40-20)/316	2	$2.3 \cdot 10^6$

Analysis of Table 1 shows that with an increase in thickness from 3 μm to 8 μm, an increase in the operation threshold from 70 V to 105 V is observed. The maximum residual voltage on the sample varies from 12 V to 40 V, the minimum – from 5 V to 20 V. The switching time of the samples was no more than 2 nanoseconds. All the test samples were operated without failure 20 times.

We believe that in the investigated films of cadmium telluride, the effect of a monostable switching from a low-conducting state to a high-conducting state is observed, which is realized due to the appearance of a reversible instability in the ionic subsystem. The instability in the ionic subsystem occurs when the semiconductor layer melts. The source of heat for monostable switching is the Joule layer heating of cadmium telluride by high-density current, which occurs in the initially high-resistance material. According to the literature data, when heating to 800 °C [7], the specific electrical conductivity of cadmium telluride films increases exponentially. According to [8], melting of cadmium telluride due to the rearrangement of the crystal structure leads to an abrupt increase in the electrical conductivity by more than an order of magnitude of its electrical conductivity. When the temperature exceeds 120 °C, the coefficient of the temperature dependence of the electrical conductivity increases noticeably due to the inclusion of the dissociation process [9]. Since the dissociation of cadmium telluride occurs congruently, when both elements pass to the gas phase simultaneously and the stoichiometry of the remaining layer does not change, the samples showed stability at 20 times the impulse action.

It should be noted that at the present time, calculations of the ATC theoretical parameters in the monostable switching caused by the melting of layers have not been carried out in the literature. Nevertheless, the fixed short switching times, which do not exceed 2 nanoseconds, which limits the amount of Joule heat released, suggest that the switching does not occur simultaneously over the entire layer, but due to the appearance of the channels of the liquid phase in the polycrystalline film layer.

Moreover, taking into account the columnar structure of the cadmium telluride layer, it can be assumed that the dimensions of the channels correspond to the grain sizes, which according to the results of structural studies are 1 μm. Indeed, according to the results of X-ray diffraction studies, the obtained cadmium telluride films are predominantly oriented in the [111] direction.

According to [10], biphasic, twinning and high concentration of packing defects are characteristic of cadmium telluride films predominantly oriented in the [111] direction (see, for example, in [6]), which is caused by errors in the stacking sequence of close-packed planes to which the (111) plane refers to.

The above structural defects are easily formed due to a slight (about 1 %) difference in the formation energies of the sphalerite and wurtzite crystal lattices and the low energy of formation of packing defects in cadmium telluride. It is quite obvious that the defective grains of cadmium telluride films oriented in the [111] direction will melt first of all, forming highly conducting channels of molten cadmium telluride.

6. CONCLUSIONS

It has been experimentally established that layers of cadmium telluride with a thickness of 3 to 7 μm can be used to create protection elements for ultrahigh-frequency radioelectronic equipment since samples representing the cadmium telluride film layers placed in the body of microwave diodes when electric impulses of 1 μm duration were applied to them had a switching time at a level of 2 nanoseconds and had a capacity of not more than 2 pF. In this case, the value of the residual voltage could be reduced to 5 V, and the value of the operating voltage can be adjusted by the thickness of the base layer.

Investigations of the crystal structure have made it possible to propose a mechanism for monostable switching in film layers of cadmium telluride films, which is the formation of molten high-conductivity channels in grains oriented in the [111] direction, which have a columnar structure under the action of an electromagnetic impulse.

The fixed failure-free operation of the protection elements on the basis of film layers of cadmium telluride for 20 cycles of impulse action is due to the congruent melting of cadmium telluride films, which ensures the preservation of the stoichiometry of the switching layer after the action of a high-frequency electric impulse with a high amplitude.

Амплитудно-временные характеристики переключения в тонких пленках теллурида кадмия

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Были исследованы амплитудно-временные характеристики переключения в тонких пленках теллурида кадмия при подаче одиночных импульсов длительностью 1 мкс. Экспериментально установлено, что с ростом толщины слоя теллурида кадмия от 3 мкм до 8 мкм наблюдается увеличение порога срабатывания от 70 В до 105 В. Максимальное остаточное напряжение на образце изменяется от 12 В до 40 В, минимальное – от 5 В до 20 В. Время переключения образцов составляло не более 2 нсек, межэлектродная емкость образцов не более 2 пФ. Все исследуемые образцы сработали без отказа 20 раз. Проведенные структурные исследования пленок теллурида кадмия методом рентгеновской дифрактометрии и растровой электронной микроскопии позволили предложить механизм реализации моностабильного переключения, обусловленного образованиям расплавленных высокопроводящих каналов в зернах столбчатой структуры пленок теллурида кадмия, ориентированных в направлении [111].

Ключевые слова: Пленки теллурида кадмия, Амплитудно-временные характеристики, Рентгеновская дифрактометрия, Растровая электронная микроскопия, Расплавленный высокопроводящий канал.

Амплітудно-часові характеристики перемикання в тонких плівках телуриду кадмію

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Були досліджені амплітудно-часові характеристики перемикання в тонких плівках телуриду кадмію при подачі одиночних імпульсів тривалістю 1 мкс. Експериментально встановлено, що з ростом товщини шару телуриду кадмію від 3 мкм до 8 мкм спостерігається збільшення порогу спрацьовування від 70 В до 105 В. Максимальна залишкова напруга на зразку змінюється від 12 В до 40 В, мінімальна – від 5 В до 20 В. Час перемикання зразків не більше 2 нсек, міжелектродна ємність зразків не більше 2 пФ. Всі досліджувані зразки спрацювали без відмови 20 разів. Проведені структурні дослідження плівок телуриду кадмію методом рентгенівської дифрактометрії та растрової електронної мікроскопії дозволили запропонувати механізм реалізації моностабільного перемикання обумовленого утворенням розплавлених високопровідних каналів в зернах стовпчатої структури плівок телуриду кадмію, орієнтованих в напрямку [111].

Ключові слова: Плівки телуриду кадмію, Амплітудно-часові характеристики, Рентгенівська дифрактометрія, Растрова електронна мікроскопія, Розплавлений високопровідний канал.

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