EMI protection elements on cadmium telluride thin films

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Abstract. The amplitude-time characteristics of cadmium telluride thin films switching were investigated at the influence of single impulses duration 1 μs. It has been founded that with an increase of cadmium telluride layer thickness from 3 μm up to 8 μm, an increase of the operating threshold from 70 V to 105 V is established. The maximum residual sample voltage was change in the range from 12 V to 40 V, the minimum - from 5 V to 20 V. Samples switching time was no more than 2 nanoseconds; the samples interelectrode capacity does not exceed 2 pF. All test samples were operated without failure up to 20 times. Based on the results of cadmium telluride films structural studies by X-ray diffractometry and scanning electron microscopy we proposed a mechanism of cadmium telluride films with columnar structure monostable switching based on the formation of melted high conductivity channels in cadmium tel-luride grains oriented in the [111] direction.

1. Introduction
The problem of ensuring radio-electronic equipment (REE) electromagnetic stability is because under the influence of electromagnetic impulses (EMI), overvoltage impulses are induced in the circuits, which can have a serious damaging effect on the elements of the REE [1]. Semiconductor devices are particularly susceptible to damaging effects of EMI thankfully to properties of the p-n junction and to the specific heat conductivity of semiconductor materials. With a decrease of semiconductor device structures size, the level of their damage is reduced and for integrated circuits is from $10^{-3}$ J to $10^{-7}$ J.

To ensure the protection of electrical circuits, practically the REE protection elements from EMI are used. The most important property of them, is their ability to reduce resistance $R_e$ from $10^4$ - $10^{10}$ Ω for a short time $\tau_{sw}$ (switching time or response time) to a value significantly lower than input resistance of the protected REE, when the voltage $U_i$ in the circuit exceeds the threshold voltage $U_t$, called the switching threshold [2]. The most widely used restrictive silicon diodes, since they have $\tau_s$ at a level of 1 nanosecond. 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 microwave REE protection. Therefore, in order to create protection elements for microwave REE should be perspective, to carry out research aimed to creation EMI protected elements on the base of cadmium telluride thin films.

2. Experimental technique
For deposition base layers of cadmium telluride on 10cm × 10cm substrates from electrolytic polished molybdenum foil, we used industrial vacuum unit (Fig.1a) and method of thermal vacuum deposition (Fig.1b) from 99.999% purity powder with a particle size of 10 mm. The initial vacuum was $6\times10^{-6}$ mm Hg, the working pressure in the vacuum chamber during the deposition was maintained at $1\cdot10^5$
mm Hg. For thermal evaporation of cadmium telluride we use a graphite evaporator with indirect heating from two electrically insulated heaters (Fig. 1b).

![Image](image1.jpg)

**Figure 1.** Overall view of vacuum chamber (a) and graphite evaporator of cadmium telluride (b).

The evaporation temperature was controlled by a thermocouple installed in the volume of the heater, the time of evaporator heating to working temperature \((700 \pm 750) ^\circ C\) was 260 to 275 sec. The accuracy of evaporator working temperature control was not more than 5 °C. The thickness of the deposited layers of cadmium telluride, which was set by the deposition time, was 3-10 μm. To control the cadmium telluride films thickness we used a quartz thickness meter KKT-40.

The crystalline structure of cadmium telluride layers was investigated by X-ray diffractometry by the 0-20 method with a step of 0.01 degrees in the radiation of the copper anode.

The control of cadmium telluride film layers initial electrical resistance was carried out at a temperature 20 °C using a digital ampere-voltmeter MS8040. Along with the initial electric resistance of the samples to a direct current, at a frequency of 107 Hz and temperature of 20 °C, their electrical capacitance was measured by the L2-28 capacitance meter device.

The switching characteristics of the samples were studied on a test bench with subsequent stress impulses parameters: amplitude \(U_i\) from 100 V to 1400 V with a duty ratio of 2-107, rise time of the pulse to the amplitude value was 2.5 nanoseconds, impulse voltage decreased exponentially to 0.5 in a time of 100 nanoseconds. The amplitude-time characteristics of samples switching process were determined from experimental oscillograms obtained on the digital oscilloscopes.

To connect to a coaxial line with a wave impedance of 50 Ohm, film CdTe samples were placed in modified bodies of microwave diode D403B type (Fig.2) with interelectrode capacitance at 10^1 Hz is only 0.2 pF.

![Image](image2.jpg)

**Figure 2.** The microwave diode bodies prepared for installing cadmium telluride films.

The specificity of the electrodes design was that it should gently pressurize to the cadmium telluride film surface and should be able to freely move along the perpendicular direction of layer to
track changes in film thickness caused by its heating and cooling during the forward and backward switching stages. A schematic illustration of the assembled case with a thin-film layer is shown on Fig. 2.

3. Results and their discussion
Using X-ray diffractometer it was found that when deposition temperatures less than 300 °C, a two-phase cadmium telluride film was formed, which contains, along with a stable cubic modification, a metastable hexagonal phase. At substrate temperature above 350 °C, the CdTe layer growth rate sharply decreases. Therefore, the substrate temperature during depositing cadmium telluride films for switched layers was (320-330) °C. Film layers were made which had a thickness (d) from 3 μm up to 8 μm. Investigations of the crystal structure shown 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. 3a). The intensity ratio of the detected peaks differs from the theoretical ones and indicates the advantage of [111] direction of the films orientation. The morphology of cadmium telluride films surface, studied with the Philips CM30 raster microscope, indicates that the grain size in cadmium telluride layer of is about 1 μm (Fig. 3b).

![Figure 3. X-ray diffractograms (a) and surface (b) of 4 μm thick cadmium telluride layer](image)

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 $R_e$ of the samples exceeds $10^7$ Ohms and did not depend on the thickness of cadmium telluride layer. For the initial electrical capacitance, the value of which was from $0.4\cdot10^{-12}$ F to $1.2\cdot10^{-12}$ F, there was also no dependence from the layer thickness. The absence of electrical resistance and capacitance dependence from the cadmium telluride layer thickness on our opinion is due to the variation of the electrode contact area with the cadmium telluride switching layer.

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. 4a (curve 1). This figure also gives a qualitative view of a of the voltage impulses acting on the samples typical oscillogram (curve 2). On the Fig.4b represents the typical electromagnetic pulse shapes which are acting on real semiconductor devices and caused by nature or human influence.
The determination of the ATC for switching processes 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 $U_{max}$, 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 $\tau_s$.

Also in Table 1 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 from the polarity of the current impulses acting on the film samples.

![Oscillogram of the experimental stress diagram on cadmium telluride film samples](image)

**Figure 4.** Typical oscillogram of the experimental stress diagram on cadmium telluride film samples (a) and typical electromagnetic pulse shapes (b).

**Table 1.** – Main switching parameters of thin-film cadmium telluride samples and their electrical resistivity to a direct current after the 20 impulses influence

| $d$ (μm) | $U_i$ (V) | $U_s$ (V) | $U_{max}$ (V) | $U_{min}$ (V) | $\tau_s$ (sec) | $U_i$ (V) | $R_e$ (Ohm) |
|---------|-----------|-----------|---------------|---------------|---------------|-----------|------------|
| 3       | 75        | 42        | 20            | 10            | <2            | 285       | 1.7 $\cdot 10^5$ |
| 3       | 75        | 38        | 20            | 10            | <2            | 271       | 2.0 $\cdot 10^5$ |
| 4       | 70        | 40        | 13            | 5             | <2            | 214       | 1.3 $\cdot 10^6$ |
| 4       | 70        | 50        | 12            | 5             | 2             | 211       | 7.7 $\cdot 10^5$ |
| 6       | 70        | 52        | 15            | 7             | 2             | 216       | 5.6 $\cdot 10^6$ |
| 6       | 75        | 51        | 15            | 7             | 2             | 225       | 5.6 $\cdot 10^6$ |
| 7       | 80        | 55        | 20            | 10            | <2            | 240       | 1.5 $\cdot 10^6$ |
| 7       | 70        | 53        | 20            | 10            | 2             | 219       | 1.7 $\cdot 10^6$ |
| 8       | 105       | 120       | 40            | 20            | 2             | 316       | 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 think that in the investigated cadmium telluride films, 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 heating of cadmium telluride layer 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 from its electrical conductivity. When the temperature exceeds 120 °C, the coefficient of electrical conductivity temperature dependence 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 liquid phase channels 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 about 1 μm. According to the results of X-ray diffraction studies, the obtained cadmium telluride films are predominantly oriented in the [111] direction and in [10] has been noted that biphasic, twinning and high concentration of packing defects are characteristic for 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. 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.

4. Conclusion
We have found that CdTe layers with a thickness from 3 to 7 μm placed in the body of microwave diodes under the action of electric impulses duration up to 1 μs had a switching time no more than 2 nanoseconds and capacity up to 2 pF. As a result such films can be used as a base layers in order to creation EMI protection elements for ultrahigh-frequency radioelectronic equipment.

Investigations of the crystal structure have made it possible to propose a mechanism for monostable switching in CdTe films by 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 protection elements on the CdTe films basis for 20 cycles of impulse action is due to the congruent melting of CdTe films, which ensures the preservation of switching layer stoichiometry after the action of a high-frequency electric impulse.

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