

## ELECTRET EFFECT IN CdTe THIN FILMS

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In the paper the effect of persistent internal polarization in the thin films structures metal — CdTe — metal is described. In these structures a *dc* voltage  $\leq 1$  V was measured in darkness. The voltage has been registered more than two years after the deposition of the samples. The observed phenomena are explained by the existence of the persistent polarization, i.e. the electret effect in the CdTe film. It is supposed that the CdTe film is a pseudo-electret created by the implantation of the charge into the film during its deposition time by the cathode sputtering. A simple model with the charge built into the CdTe film is proposed. This model is in a qualitative agreement with the measured results.

### I. INTRODUCTION

The following effect in the metal—CdTe—metal thin film structures was observed. Using a voltmeter with the input resistance greater than  $10^{15}$  Ohm a value  $\leq 1$  V of *dc* voltage was measured in darkness. The first results are summarized by us in paper [1]. In this paper the detailed description of the experiments is given. Furthermore, there is introduced a simple model which qualitatively explains the dependence of the measured voltage on temperature and time, its polarity and its dependence on the thickness of the CdTe film.

### II. PREPARATION OF SAMPLES

Samples were prepared in gap (Fig. 1a) and sandwich (Fig. 1b) configurations. The distance between the inner edges of contacts was 1 to 4 mm for the gap sample. The contacts were evaporated in a vacuum of  $1.33 \times 10^{-3}$  Nm<sup>-2</sup> ( $10^{-5}$  torr). All combinations of Al, Ag, Cu and Au were prepared. This represents ten possibilities for each configuration. The CdTe film was prepared in two ways:

- a. By a cathode diode sputtering in spectral-pure argon gas at a pressure

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of  $1.33 \text{ Nm}^{-2}$  ( $10^{-2}$  torr). The distance between target and substrate was 3 cm, the voltage between these electrodes was about 5 kV and the current density on the target had the value of  $2 \text{ mA/cm}^2$ .

b. By flash evaporation in a dry vacuum of  $1.33 \times 10^{-6} \text{ Nm}^{-2}$  ( $10^{-8}$  torr). It was possible to create an electric field of  $2 \text{ kV/cm}$  near the substrate surface.

In both cases we started with a polycrystalline CdTe material. During the preparation of films with a thickness of  $0.1-2 \text{ }\mu\text{m}$  the temperature of substrates did not exceed the value of  $70^\circ \text{C}$ .

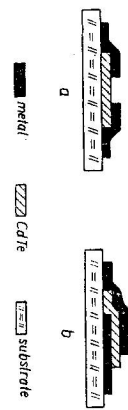


Fig. 1. Samples in gap (a) and sandwich (b) configurations.

### III. RESULTS OF MEASUREMENTS

The structure of the CdTe samples was checked by the aid of X-ray diffraction using a TTR M 62 apparatus. Since no reflections were observed we suppose the films were amorphous or microcrystalline. By X-ray luminescence spectroscopy a value of  $\pm 3\%$  [2] was observed for the deviation of the composition of films from the stoichiometric ratio. The resistivity of the sputtered films was  $10^9$  to  $10^{11} \text{ Ohm cm}$ , the resistivity of the evaporated layers was by two orders smaller [2].

The voltage measurements were performed in darkness. The samples were screened against external fields. An electrometer VA-J-51 (RFT) with an input resistance greater than  $10^{15} \text{ Ohm}$  was used for the measurement. The samples were measured at temperatures from  $20^\circ \text{C}$  to  $150^\circ \text{C}$ .

Table 1 shows the mean values of the voltage  $U$  and the corresponding standard deviation  $\delta$  in the 2-nd and 3-rd columns, respectively. These values were obtained measuring the sets of ten gap samples with various combinations of contacts at a temperature of  $20^\circ \text{C}$ . The thickness of the sputtered CdTe film was approximately  $1 \text{ }\mu\text{m}$ . For contacts from the same material a zero or almost vanishing voltage was observed. A voltage of  $U \geq 0.5 \text{ V}$  was measured in samples with different contacts, when an aluminum contact was used (Al—Ag, Au—Al). Here, for Al and Ag a positive polarity was observed. For the Al—Ag combination the Al contact had a positive polarity.

In the 4-th and 5-th columns of Table 1 the values of the voltage  $U$  and the standard deviations  $\delta$  measured for sets of ten sandwich samples for various contacts combinations are summarized. The samples were measured at  $20^\circ \text{C}$ , the thickness of the sputtered CdTe film again being approximately

Table 1  
The mean values of the voltage and the standard deviations for the sets of ten samples in gap and sandwich configurations for various contact combinations

Contacts	Gap configurations		Sandwich configurations	
	$U$ [V]	$\delta$ [V]	$U$ [V]	$\sigma$ [V]
Au—Au	0.00	0.04	0.01	0.01
Au—Al	0.82	0.08	0.03	0.03
Al—Al	0.02	0.08	0.61	0.18
Ag—Al	0.22	0.03	0.09	0.03
Ag—Ag	0.00	0.01	0.00	0.01
Ag—Au	0.08	0.03	0.03	0.04
Cu—Cu	0.00	0.02	0.00	0.01
Ag—Cu	0.00	0.02	0.00	0.01
Al—Cu	0.09	0.03	0.00	0.01
Au—Cu	0.00	0.02	0.00	0.02

$1 \text{ }\mu\text{m}$ . At the bottom electrode (in Table 1 always the first) a negative polarity was observed. A voltage of  $U > 0.01 \text{ V}$  was measured for samples where at least one of the Ag, Al metals was employed. For samples with Al—Al contacts a voltage of  $U \geq 0.5 \text{ V}$  was observed.

In Table 1 all values are measured with two valid digits only. By measuring a voltage of about  $1 \text{ mV}$  some disturbances caused by thermovoltages in the measuring circuit occurred. The scatter of the measured values of the order of  $10 \text{ mV}$  (c.f. Table 1) was due to discrepancies in sputtering conditions in various experiments. For a single experiment one or two samples with the same contact combination were prepared. The voltages of these two samples were mostly identical (except when the contacts or the CdTe films were damaged).

For the CdTe films prepared by evaporation in a vacuum with or without an electric field a zero voltage was observed.

The dependence of the measured voltage upon the CdTe sputtered film thickness is shown in Fig. 2. Line 1 corresponds to the Al—CdTe—Al sample with an arrangement according to Fig. 1b. Line 2 is valid for the sample Au—CdTe—Al with an arrangement according to Fig. 1a.

Some typical temperature dependences of voltage are shown in Figs. 3 and 4. For the gap structure of Ag—CdTe—Al at a slow heating from  $20^\circ \text{C}$  to  $40^\circ \text{C}$  the voltage  $U$  reaches a maximum and then slowly decreases (Fig. 3). At a fast heating (Fig. 4) the voltage after passing the maximum decreases almost to a zero value. After cooling the voltage increases again but it reaches a value lower than the original one. After several temperature cycles the

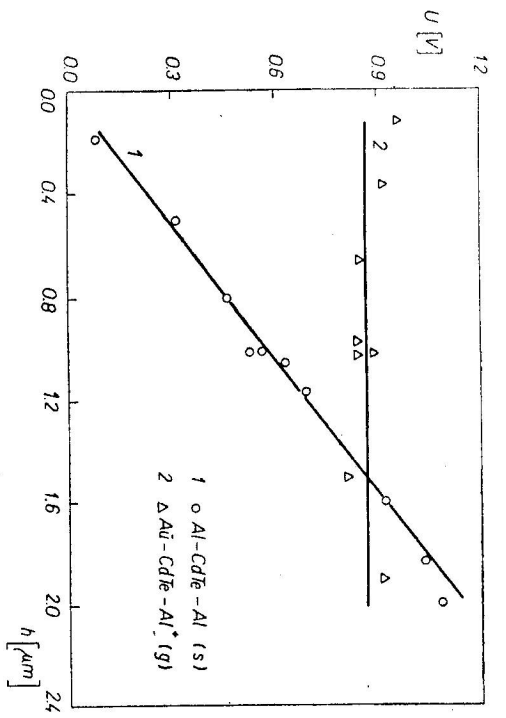


Fig. 2. The dependence of the voltage measured with samples in sandwich configuration (line 1) and in gap configuration (line 2) upon the thickness of the CdTe thin film.

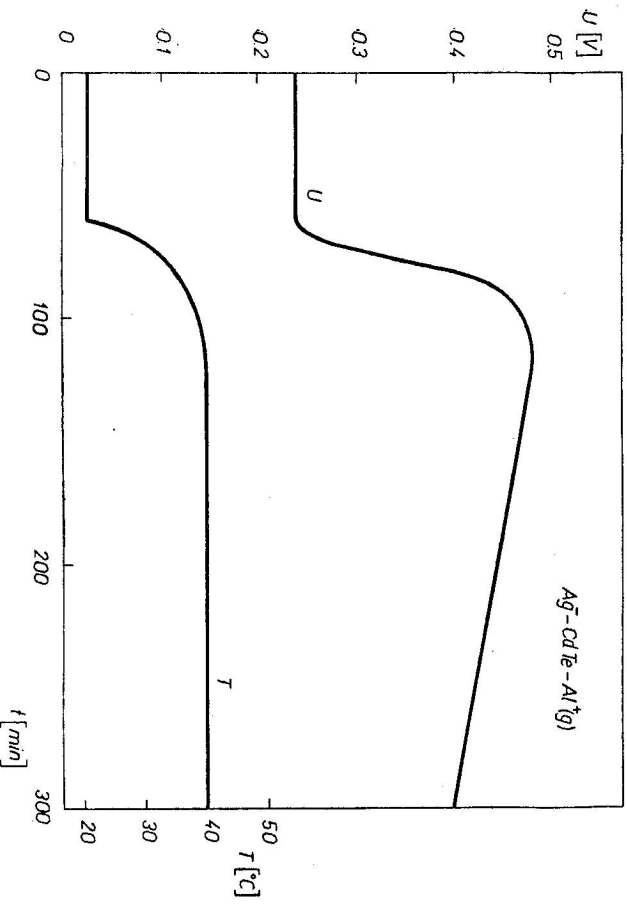


Fig. 3. The temperature dependence of the voltage measured with a gap Ag-CdTe-Al sample at slow heating.

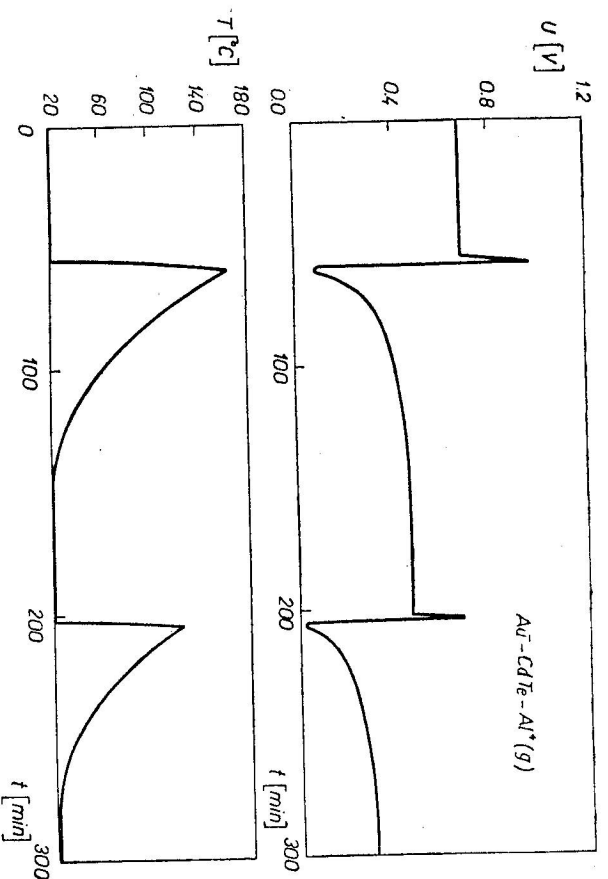


Fig. 4. The temperature dependence of the voltage measured with a gap Au-CdTe-Al sample at fast heating.

voltage may vanish. The measurement at temperatures higher than  $150^{\circ}\text{C}$  is rather complicated since here is a CdTe film recrystallization danger.

#### IV. DISKUSSION

To explain the observed phenomena it is reasonable to employ a hypothesis of the existence of a persistent polarization, i.e. the electret effect in the CdTe films. The temperature dependence of the measured voltage is similar to the usual depolarization characteristics of electrets (Fig. 4). Especially the inorganic-ceramic electrets resemble by their properties (e.g. the value of resistivity) to the CdTe films. Similarly as in some ceramic electrets a persistent polarization after a time longer than two years after the preparation was observed in our samples, supposing the storing at common atmospheric conditions without short-circuiting of the contacts.

The common way of electrets (the so-called thermoelectrets) preparation consists of the heating or the melting followed by the cooling of a material in an electrostatic field of 5 to 10 kV/cm (Gubkin [3]). This mechanism of the

persistent polarization origin in the case of our samples can be excluded. By evaporating the samples in an electric field a zero voltage was found. By sputtering the samples there exists in the glow discharge an electric field sufficiently large to originate the electret properties, however, it is located around the cathode in the dark space (Neu [4]). Near the anode where the sample is located, the field is usually by several orders smaller. It seems therefore that the technology of sputtering and not only the presence of an electric field represents the substantial factor for the creation of the observed voltage.

It is possible to explain the origin of the electret phenomena in CdTe by bombarding a condensating film by electrons or negative ions from the discharge. Such electrets are called pseudoelectrets. Usually, they are prepared by bombarding a dielectric plate by electrons with an energy of  $\approx 1$  MeV. The bombarding implies a charge implantation under the surface and an amorphisation or a disordering, i.e. a formation of structural defects into which the charge can be trapped (Fig. 5a). On the opposite surface of the plate a compensating positive charge is induced.

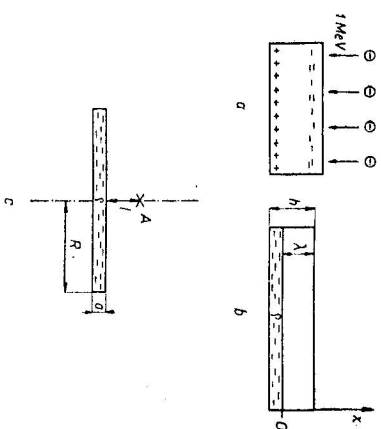


Fig. 5. a. A model of pseudoelectret formation due to the bombardment of a bulk insulator by electrons.  
 b. Model of a charge implantation during the CdTe film growth. ( $h$ ,  $\lambda$ ,  $\rho$  denote the thickness of the film, the depth of the implantation and the density of the implanted charge, respectively).  
 c. The replacement of the charged part of the film by a disk with the radius  $R$  and the thickness  $a$ . The electric field is calculated in the point  $A$  on the axis of the disk in the distance  $l$  from the disk surface.

In the case of sputtering a CdTe film the amorphous structure necessary for the formation of deep traps and defects in the film is obtained during the process of the film deposition. Therefore, considering also the small thickness of the film, the energy necessary for the implantation of the charge can be substantially smaller. In our conditions of the CdTe film sputtering in the glow discharge the mean free path of electrons is approximately 2 cm, i.e. it is comparable to the distance between the target and the substrate. Therefore, there are almost no electron collisions between the electrodes of the sputtering apparatus and the electrons reach the film surface having the energy of

$\approx 5$  keV. Their penetration into the amorphous CdTe layer can be (from comparison with other materials) estimated as  $\lambda = 50$  nm to 100 nm [6, 7]. This distance is at beginning of the growing of the film comparable to its thickness. Therefore the charge will be buried at the bottom of the film and the compensating positive charge will occur at the upper surface. The source of this compensating charge can be the contact or the vicinity of the sample. This explains the polarity of the voltage measured in the sandwich samples where the bottom contact was always negative.

We explain in these samples the dependence of the voltage on the material of the electrodes in such a way that by using metals with a fast diffusion ability (Au, Cu, Ag) the metal can penetrate into the sputtered film and partially or totally short-circuit the inner electric field. This assumption follows from an analogic experience with contacts of amorphous switching devices, amorphous Ge and InSb, where a diffusion of the metal contacts into the film already at room temperatures was observed e.g. by Morgan and Jonscher [5].

Next, we give a qualitative explanation of the dependence of the sandwich samples thickness on the measured voltage. Let us start with a simplified model shown in Fig. 5b. There a beam of monoenergetic electrons is trapped at the depth  $\lambda$  in the film. Considering a film of the thickness  $h$ , a layer of the thickness  $h - \lambda$  with the space charge density  $\rho$  is originated in the bottom part of the film during the sputtering. We choose an approximate solution in which the charged part of the film is replaced by a disc with the radius  $R$  and thickness  $a$  (Fig. 5c). The following formula can be derived for the absolute value of the electric field in the point  $A$  located on the axis of the disc at the distance  $l$ :

$$E_A = q \{ a + (R^2 + l^2)^{1/2} - [R^2 + (l + a)^2]^{1/2} \} / 2\epsilon. \quad (1)$$

The formula is obtained by the integration of the relation

$$E_\sigma = \frac{\sigma}{2\epsilon} \left[ 1 - \frac{\xi}{(R^2 + \xi^2)^{1/2}} \right], \quad (2)$$

which gives the electric field at the distance  $\xi$  from a disc with the surface charge density  $\sigma$  (see e.g. [8]). The integration is to be performed in limits the  $l$ ,  $l + a$ , replacing  $\sigma = qd\xi$ .

For the CdTe film one must put into (1)  $a = h - \lambda$ ,  $l = \lambda$  and consider  $\epsilon$  as the permittivity of the film material. Then

$$E = q[h - \lambda + (R^2 + \lambda^2)^{1/2} - (R^2 + h^2)^{1/2}] / 2\epsilon. \quad (3)$$

This relation has a physical meaning for  $h > \lambda$ . For thin films it is  $R \gg \lambda$ ,

$R \gg h$ . Expanding (3) a power series and taking the first two terms only we obtain

$$E \doteq q(h - \lambda)/2\epsilon. \quad (4)$$

This electric field produces the compensating positive charge on the film surface. We assume a surface charge distribution with the density  $q(h - \lambda)$ . As inside the film the direction of the electric field from both kinds of charge is identical, the total electric field reads

$$E_t \doteq q(h - \lambda)/\epsilon. \quad (5)$$

The voltage across the film is given by the integral from 0 to  $\lambda$  (Fig. 5b)

$$U \doteq \int_0^\lambda E_t dx = E_t \lambda = q(h - \lambda)\lambda/\epsilon. \quad (6)$$

Thus, in the first approximation neglecting the edge effects the voltage is a linear function of the film thickness. This is in a qualitative agreement with line 1 in Fig. 2.

Let us next consider the gap samples (Tab. 1). We assume the charge to be buried analogously to that of the sandwich samples.

As both contacts are located on the same surface of the sample one can expect that  $U = 0$  (the case of the Al—CdTe—Al sample). However, the situation changes if one of the contacts penetrates into the sample volume (by diffusion or solution) and therefore it reaches a different equipotential level. Then the measured voltage increases with the increasing diffusion depth differences of the used metals. The voltage is greatest in the combinations Au—Al and Ag—Al. For a metal with a similar diffusion character (Au—Cu, Cu—Ag) and for identical contacts (Au—Au, Cu—Cu, Ag—Ag) it becomes  $U \doteq 0$ . As the dept of the contact penetration into the bulk is independent of the film thickness one can expect the voltage  $U$  to be independent of the film thickness. This is in a good agreement with line 2 in Fig. 2.

The higher value of the voltage for the gap samples in comparison with the sandwich samples may be due to different conditions of their preparation. In the first case the CdTe film is sputtered onto glass, in the second it is sputtered onto a bottom metallic contact. Therefore, in the first case especially in the initial stages of the growth of the film beginning, there are probably better conditions for the trapping of an implanted charge.

#### V. CONCLUSION

In the paper a qualitative explanation of the origin of voltage measured on thin film structures metal—CdTe—metal is suggested. The proposed model

is based on several assumptions. These assumptions cannot be supported by a more exact theory with regard to the present state of knowledge of amorphous substances.

So far we have not investigated other amorphous films with a high resistance prepared by the cathode sputtering. However, effects similar to those in CdTe may exist also in some other materials. There might even be a general property of thin films prepared under conditions where an electric charge implantation is possible. In practical applications of such films in microelectronic circuits these effects may cause an unwanted long-time instability of thin film devices.

On the other hand the possibility of the practical application of the mentioned films as the source of a bias voltage in microelectronics should be further investigated.

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