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A. Zozime, C. Vermeulin. Properties of sputtered mercury telluride contacts on p-type cadmium telluride. *Revue de Physique Appliquée*, 1988, 23 (11), pp.1825-1835. 10.1051/rphysap:0198800230110182500 . jpa-00246011

HAL Id: jpa-00246011

<https://hal.science/jpa-00246011>

Submitted on 1 Jan 1988

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Classification
Physics Abstracts
73.40 — 79.20

Properties of sputtered mercury telluride contacts on p-type cadmium telluride

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(Reçu le 12 avril 1988, révisé le 29 juillet 1988, accepté le 16 août 1988)

Résumé. — La valeur élevée du travail de sortie du composé semi-métallique HgTe ($q\phi_m \sim 5.9$ eV) a conduit à utiliser ce matériau pour réaliser des contacts ohmiques de faible résistance spécifique ρ_c ($\Omega \text{ cm}^2$) sur le composé semi-conducteur II-VI CdTe de type p, dans la gamme des résistivités $70 \Omega \text{ cm} < \rho_B < 45 \text{ k}\Omega \text{ cm}$. Les couches de HgTe ont été déposées par pulvérisation cathodique en atmosphère de mercure à des températures de l'ordre de 150°C . Les contacts ont été réalisés en technologie planar et leur résistance spécifique déterminée à l'aide des modèles TLM (Transmission Line Model) et ETLM (Extended TLM). La méthodologie de la mesure est développée. Pour les résistivités élevées ($\rho_B = 1,45 \text{ k}\Omega \text{ cm}$; $13 \text{ k}\Omega \text{ cm}$; $16 \text{ k}\Omega \text{ cm}$; $45 \text{ k}\Omega \text{ cm}$), le rapport ρ_c/ρ_B est de l'ordre de 10^{-2} cm, et les caractéristiques $J(V)$ sont sensiblement linéaires. Pour $\rho_B = 70 \Omega \text{ cm}$, ρ_c/ρ_B est de l'ordre de 10^{-1} cm, et les caractéristiques $J(V)$ ne sont plus linéaires. L'ensemble de ces résultats n'est pas affecté par l'attaque préalable par pulvérisation du CdTe. La nature chimique et/ou les désordres structuraux de la surface de CdTe expliquent les déviations observées par rapport à la théorie de l'effet thermoionique.

Abstract. — Because of the high value of its work function ($q\phi_m \sim 5.9$ eV), the semimetallic compound HgTe has been used to realize ohmic contacts of low specific resistance ρ_c ($\Omega \text{ cm}^2$) on the II-VI semiconductor compound p-type CdTe, in the bulk resistivity range $70 \Omega \text{ cm} < \rho_B < 45 \text{ k}\Omega \text{ cm}$. The HgTe films were deposited by cathodic sputtering in a mercury vapour, at about 150°C . Planar contacts were carried out and their specific resistance determined from the Transmission Line Model (TLM) and the Extended Transmission Line Model (ETLM). The methodology of the measurement is developed. For high values of the bulk resistivity ($\rho_B = 1.45 \text{ k}\Omega \text{ cm}$; $13 \text{ k}\Omega \text{ cm}$; $16 \text{ k}\Omega \text{ cm}$; $45 \text{ k}\Omega \text{ cm}$), the ratio ρ_c/ρ_B is about 10^{-2} cm, and the $J(V)$ characteristics show a quasi linear shape. For $\rho_B = 70 \Omega \text{ cm}$, ρ_c/ρ_B is about 10^{-1} cm, and the $J(V)$ characteristics are no more linear. The sputter etching of the CdTe surface before HgTe deposition does not affect these results. The chemical nature and/or the structural disorder of the CdTe surface account for the observed deviations to the thermo-ionic effect theory.

1. Introduction.

The manufacturing of CdTe optoelectronic devices (solar cells, electroluminescent diodes, nuclear detectors), the measurement of transport properties of CdTe (Hall effect, $J(V)$, $C(V)$, DLTS, ...) require low-resistance ohmic contacts compared to the serie resistance of the material, in a large range of values of the bulk resistivity, from $1 \Omega \text{ cm}$ to $10^9 \Omega \text{ cm}$. A lot of work deal with CdTe contacting [1], which remains a serious problem, in particular for p-type CdTe. We will first precise the fundamental problems of the p-type CdTe contacting.

Practically, the contact is made of a metallic film deposited on the semiconducting material. The speci-

fic contact resistance ρ_c is defined from the current density-voltage characteristic $J(V)$:

$$\rho_c = (dJ/dV)^{-1}|_{V=0} \quad (1)$$

According to the thermoionic emission theory, an expression of ρ_c for a Schottky contact is the following [2] :

$$\rho_c = (k/qAT) \exp(q\phi_b/kT) \quad (2)$$

k : Boltzmann constant ; A : Richardson constant ; q : electron charge ; T : absolute temperature ; ϕ_b : barrier height. Equation (2) shows that a low specific contact resistance is obtained for small barrier heights.

For the ideal band structure at the interface gold-p-type CdTe (without oxide film or interface states), one has $q\chi_s = 4.5$ eV for the electron affinity of CdTe [3]. For a doping concentration of 10^{17} cm^{-3} , the distance from the conduction band to the Fermi level is ~ 1.4 eV, and the work function $q\phi_s$ of the semiconductor is ~ 5.9 eV (this value becomes ~ 5.7 eV for a doping concentration of 10^{14} cm^{-3}).

The work function of gold $q\phi_m \sim 4.58$ eV [4] yields the relation $\phi_m < \phi_s$ and the following theoretical barrier height :

$$q\phi_b = E_g - q(\phi_m - \chi_s) = 1.44 \text{ eV} ,$$

with $E_g = 1.52$ eV for the band gap energy of CdTe. This calculation does not take into account the Schottky effect which lowers $q\phi_b$ to [5] :

$$q\phi_b = 5.78 - q\phi_m = 1.20 \text{ eV} ,$$

but shows that the work function of gold, although one of the highest one of the usual metals, gives a large barrier height and subsequently a rectifying contact. Ponpon *et al.* [5] have determined, from measurement of the photoresponse, the barrier heights of thirteen metals deposited on the chemically etched surface of p-type CdTe, and found out $q\phi_b = 0.64$ eV for gold. These measurements confirm the occurrence of a rectifying barrier.

The theoretical values of ϕ_s which would give an ohmic contact [6] are given by the relation :

$$\phi_m > \phi_s$$

$$\text{or : } q\phi_m > 5.9 \text{ eV} .$$

Unfortunately, no metal has such a high work function, but the semimetallic compound HgTe whose work function $q\phi_m$ is about 5.9 eV [7] can be used. Janik and Triboulet [8] carried out HgTe-CdTe contacts by close spacing isothermal deposition of HgTe at 550 °C [9]. They obtained ohmic contacts of specific resistance $\rho_c = 0.1 \Omega \text{ cm}^2$ at room temperature, for p-type CdTe crystals resistivity 10-15 $\Omega \text{ cm}$.

However, Janik and Triboulet pointed out that the thermal deposition process they used alters the characteristics of the as-grown crystals. This observation is valid particularly in the case of our studies on extended defects in CdTe (dislocations, grain boundaries, ...). Indeed, the nature and the properties of these defects can be strongly affected by annealing. That is the reason why we developed a contacting method at lower temperature. We used the triode cathodic sputtering technique, where the substrate made of the material to be contacted can be maintained below 150 °C.

In this paper we will report the condensation conditions of HgTe thin films by triode cathodic sputtering. To simplify the manufacturing process,

we opted for the planar technology, which required a film deposit only on one side of the substrate. We describe the Transmission Line Model (TLM) and the Extended Transmission Line Model (ETLM) with their respective validity domains, used to characterize the planar contacts. The specific contact resistances that we obtained for materials of different bulk resistivities are discussed and compared to values given in the literature.

2. Modelisation of the planar contact. Determination of the specific contact resistance.

The contacts of the transverse type used by Anthony *et al.* [10] in which the streamlines are perpendicular to the interface, and uniformly distributed under this interface, allow in most of the cases a direct measurement of the specific contact resistance :

$$\rho_c = A_c R_{cv} \quad (3)$$

with :

$R_{cv} = dV/dI|_{V=0}$: resistance of a pure vertical type contact,

$A_c = wd$: contact area (w : contact width ; d : contact length). The voltage V across the contact and the current I through it can be directly measured.

The determination of the specific resistance of contacts of the horizontal type (planar) is no more

Fig. 1. — Constant current streamlines for $d/h = 1$ and three values of $\eta = \rho_c / h\rho_B$. The number on the streamline gives the percentage of current contained between the streamline and the top surface of the substrate. Normalized contact resistance $R_c = R_c w / \rho_B$ and its components $R_{cb} = R_{cb} w / \rho_B$, $R_{ci} = R_{ci} w / \rho_B$ are shown (see Eq. (7)).

straightforward and requires a modelisation. This is due to the non uniform distribution of the streamlines under the interface. Figure 1 gives the streamlines distribution calculated by S. B. Schuldt [11] from the Laplace's equation for $\tau = d/h = 1$ and three values of the ratio $\eta = \rho_c/h\rho_B$ (d : contact length; h : thickness of the semiconductor substrate; ρ_B : resistivity of the substrate). The equipotentials distribution has been measured by Woelk *et al.* [12], for five values of η . No equipotential surrounding the contact is parallel to the substrate surface. As a result, the voltage drop distribution $V(x)$ across the contact is not uniform [12], and yields the following definition of the contact resistivity:

$$\rho_c = \frac{w}{I} \int_0^d V(x) dx.$$

Berger [13] proposed the Transmission Line Model (TLM) to account for the voltage distribution $V(x)$ across the contact. Figure 2 shows this model for direct current operation. The resistance of the semiconductor substrate corresponds to the series resistance $R' dx = (R_s/w) dx$ ($R_s = \rho_B/h$ is the sheet resistance of the substrate under the contact, supposed equal to that of the bulk material). The contact resistance corresponds to the parallel shunt line resistance $R dx = (\rho_c/w) dx$. The line equations describe the current and voltage distribution along the contact:

$$V(x) = V(0) \cosh \sqrt{R_s/\rho_c} x - I(0) \sqrt{R_s \rho_c}/w \cdot \sinh \sqrt{R_s/\rho_c} x \quad (4)$$

$$I(x) = I(0) \cosh \sqrt{R_s/\rho_c} x - V(0) w / \sqrt{R_s \rho_c} \cdot \sinh \sqrt{R_s/\rho_c} x. \quad (5)$$

From the measurement of $V(0)$ and $I(0)$ we deduce the horizontal contact resistance R_c :

$$R_c = V_c/I|_{I(d)=0} \quad (6)$$

where $V_c = V(0)$ and $I = I(0)$.

R_c can be written as the sum of two components:

$$R_c = R_{ci} + R_{cb} \quad (7)$$

where R_{ci} is the contribution of the metal semiconductor interface itself ⁽¹⁾ and R_{cb} the contribution due to the effect of current crowding in the semiconductor. Schuldt has shown (cf. Fig. 1) that for high values of $\eta = \rho_c/h\rho_B$ (for example $\eta = 10$), the contribution of R_{cb} in (7) is negligible, and the measurement of R_c is actually that of the contact resistance. On the contrary, measurement of R_c done for small values of η (for $\eta = 10^{-3}$) do not give any information about the interface, because R_{ci} is negligible. Therefore, the choice of the value of η is fundamental in the problem of the determination of ρ_c from R_c measurements. For this determination, we will use the expression derived from relations (4), (5) and (6) by Berger for the TLM:

$$R_c = R_{cv} \alpha d \coth \alpha d = (\rho_B/w) \sqrt{\eta} \coth \tau/\eta \quad (8)$$

with $\alpha = \sqrt{R_s/\rho_c}$.

(8) gives a relation between the contact resistances of the horizontal (R_c) and the vertical (R_{cv}) contacts. However, the TLM is useful only for $\eta \gg 0.2$. To increase the application field in the model, Berger

⁽¹⁾ Let us point out that R_{ci} from (7) and R_{cv} from (3) have the same physical meaning. Nevertheless these parameters are not equal, because Schuldt took for R_{ci} a definition based on the power dissipation in the interface, different from that of R_{cv} .

Fig. 2. — The Transmission Line Model (TLM) of a contact, for direct current.

introduced the Extended Transmission Line Model (ETLM) in which a part of the semiconductor material is taken into account in the definition of the contact.

With this new supposition, R_c can be written :

$$R_c = (\rho_B/w) \sqrt{\eta + 0.2} \coth \tau / \sqrt{\eta + 0.2} . \quad (9)$$

The ETLM establishes a transition between the TLM ($\eta \rightarrow \infty$) and the model proposed by Kennedy *et al.* [14] which gives the streamlines distribution in the vicinity of the contact when $\rho_c = 0$ ($\eta = 0$) (see also [15] and [16]). For practical use Woelk *et al.* gave the validity ranges of both models :

$2 < \eta < \infty$ for the TLM and $0.2 < \eta < 2$ for the ETLM. For $0.2 < \eta < 2$ the ETLM accounts better for the spreading resistance (R_{cb}).

However, for $\eta < 0.2$, the spreading resistance is the main contribution to R_c , the contribution caused by the contact resistivity fades, and the ETLM does not allow anymore statement about ρ_c .

Another way to determine the specific contact resistance is to measure the contact end resistance R_e , defined in figure 2 in the following way :

$$R_e = Ve/I|_{I(d)=0} \quad (10)$$

with $Ve = V(d)$.

From (4) and (5) we obtain for the TLM :

$$R_e = R_{cv} \alpha d / \sinh \alpha d = (\rho_B/w) \sqrt{\eta} / \sinh \tau / \eta \quad (11)$$

$$(\alpha = \sqrt{R_s/\rho_c}; \tau = d/h; \eta = \rho_c/h\rho_B).$$

The ETLM yields the following expression of R_e :

$$R_e = (\rho_B/w) \sqrt{\eta + 0.2} / \sinh \tau / \sqrt{\eta + 0.2} . \quad (12)$$

The validity ranges of (11) and (12) are the same respectively as that of (8) and (9).

The curves $R_c w/R_s h = f(\eta)$ drawn from (8) and (9), and the curves $R_e w/R_s h = f(\eta)$ drawn from (11) and (12) for different values of τ are given respectively in figure 3 and 4, with their corresponding validity ranges. These curves allow the determination of ρ_c from measurements of R_c (R_e), ρ_B , h , d and w .

3. Experimental.

3.1 DEPOSITION OF HgTe THIN FILMS. — The stoichiometry of HgTe films condensed from the vapour phase is related to the mercury vapour pressure p_{Hg} and to the temperature T_{HgTe} at the surface of these films during deposition. In our triode sputtering system, at the thermal equilibrium, the substrate temperature is about 150 °C. A maximum pressure $p_{Hg} \sim 10^{-4}$ torr is required to con-

Fig. 3. — Calculated curves of the TLM (solid lines) and the ETLM (dashed lines) with their respective validity ranges. Our experimental values for the contact resistance R_c (▲).

Fig. 4. — Calculated curves of the TLM (solid lines) and the ETLM (dashed lines) with their respective validity ranges. Our experimental values for the contact end resistance R_e (▲).

dense the stoichiometric material in our experimental conditions [17]. To achieve that condition, mercury is used as atmosphere (plasma) of the triode sputtering system already described elsewhere [18-20].

The water-cooled double-walled chamber of this system is kept at a temperature of ~ 30 °C. A

mercury diffusion pump is used to reduce contamination of the film by organic impurities. The single crystal HgTe target is cooled down to $\sim 15^\circ\text{C}$ to prevent its thermal decomposition. A mercury tank with a shutter monitored by a regulator system controls the mercury flux in the chamber and so far the mercury pressure in the sputtering chamber. A 600 l s^{-1} pumping speed allows a permanent sweeping of the chamber with gas mercury, minimizing the impurities concentration in the target-substrate space.

Single crystals of p-type CdTe substrates were used to deposit HgTe thin films on $\langle 111 \rangle$ oriented planes. The substrates were mechanically polished with a $5\text{ }\mu\text{m}$ diamond paste over a $300\text{ }\mu\text{m}$ thickness to eliminate the damages due to the cutting of the sample [21]. Then the samples were etched during 2 min in a 3 % Br-CH₃OH solution. Before HgTe deposition the targets were sputter etched to remove the surface contamination.

The $\sim 1\text{ }\mu\text{m}$ thick films were deposited at a rate of $\sim 80\text{ }\text{\AA min}^{-1}$. The chemical composition was measured with an electronic microprobe. A typical surface composition profile is given in figure 5. Taking account of the measurement precision (1 %), we conclude that HgTe films are homogeneous and stoichiometric in composition.

In some cases the CdTe substrate was sputter etched with mercury ions prior to HgTe deposition, in order to remove the surface contamination. The drawback of this surface pretreatment, as already observed for other semiconductors [22], is to create structural damages of the surface. We limited this surface degradation using low energy ions ($\sim 40\text{ eV}$) for which the sputtering yield of the substrate was $\sim 100\text{ }\text{\AA min}^{-1}$ in the experimental conditions described above. In such a way a $\sim 500\text{ }\text{\AA}$ thickness was removed from samples Ib and III 2 (see further Tab. II and III).

The design of the contacts was realised manually with a mask and a resin.

3.2 MEASUREMENT OF THE CONTACT RESISTANCE R_c .

— The geometry of the contacts for R_c measure-

ments is shown in figure 6a. The four middle narrow contacts allow the control of the sample homogeneity, by checking that the points $V_i(\ell_i)$ for $i = 1$ to 4 in figure 6b lie on a straight line. The extrapolation of this straight line to $\ell_i = 0$ ($\ell_i = \ell_5$) gives the contact resistances $R_c = V_c/I$ of the contacts at each extremities of the sample. To simplify this procedure, we used an expression of V_c derived from figure 6b :

$$V_c = (\lambda V_1 - V_4)/(\lambda - 1) \text{ (for contact 0) (13)}$$

$$\text{with } \lambda = (V_4 - V_c)/(V_1 - V_c) = \ell_4/\ell_1.$$

Fig. 6. — a) Arrangement used for the measurement of the contact resistance R_c . b) Potentials distribution at the surface of the sample.

In (13) the streamlines are supposed parallel to the substrate surface, and uniformly distributed between the contacts travelled by the current. Results of calculation presented in figure 1 show that these assumptions are satisfied.

Fig. 5. — Profile of the surface atomic composition of a HgTe film.

The uncertainty on the V_c determination can be derived from (13) :

$$\Delta V_c/V_c = (\lambda + 1)(2 + \beta) \Delta \ell / (\lambda - 1) \ell_1. \quad (14)$$

$\beta = (V_4 - V_c)/V_c$ is the ratio of the substrate resistance between contacts 0 and 1 to the contact resistance.

$\Delta \ell$: uncertainty on ℓ_1 .

From (14), $\Delta V_c/V_c$ is a decreasing function of ℓ_1 and λ . In order to minimize the uncertainty on V_c , we took the largest possible values for ℓ_1 and λ , taking into account the dimensions of the available single crystal samples, that is : $\ell_1 = 1.8$ mm and $\lambda = 4.33$ (distance of 2 mm between the axes of two neighbouring contacts). For an estimated mean value $\Delta \ell = 0.2$ mm, Table I gives the values of $\Delta V_c/V_c$ calculated for the smallest and the largest

Table I. — Calculated error $\Delta V_c/V_c$ for $\Delta \ell = 0.2$ mm and $\ell_1 = 1.8$ mm.

$\beta \backslash \lambda$	2.11	4.33
0.1	65 %	37 %
3	155 %	89 %
6	249 %	142 %

values of λ corresponding to our specimens (the value $\lambda = 2.11$ is also suited for small samples where only four contacts could be manufactured), and for three values of β representative of our measurements (cf. Tab. II). Table I shows that $\Delta V_c/V_c$ reaches 249 % for low ohmic contacts (that is to say $V_4 - V_c > V_c$). This uncertainty becomes equal to 373 % for $\Delta \ell = 0.3$ mm.

Table II. — Parameters of HgTe-CdTe contacts in the case of measurements of the contact resistance R_c . Sample Ib was sputter etched before HgTe deposition.

Sample	Temp. (°C)	ρ_B (Ω cm)	R_s ($\Omega/\square$)	$\tau = d/h$	$R_c wd$ (Ω cm ²)	$\frac{R_c w}{R_s h}$	$\eta = \frac{\rho_c}{h\rho_B}$	ρ_c/ρ_B (cm)	ρ_c (Ω cm ²)	β
Ia	22	70	547	0.38	17	4.95	1.5	1.9×10^{-1}	13.3	0.18
Ib (sp. etched)	22	70	769	0.53	31	9.03	4.2	3.8×10^{-1}	26.7	0.09
II	22	1.45×10^3	1.29×10^4	0.43	22.9	0.33	—	$<1.6 \times 10^{-2}$	<22.9	2.7
	-40	1.6×10^4	1.43×10^5	0.43	238	0.31	—	$<1.5 \times 10^{-2}$	<238	2.9
III 1	22	1.3×10^4	5.65×10^5	2.13	840	1.32	1	2.3×10^{-2}	299	5.5

Fig. 7. — Picture of a sample.

On the other hand, the contacts 1 to 4 are not infinitely narrow. Figure 7 shows a typical sample for which $d \sim 0.3$ mm. As a result, the perturbation of the equipotentials in the vicinity of these contacts yields an uncertainty in the measurement of R_c . However, the good agreement of the resistivity measurements done on our samples (cf. (15) here after) with that done with the Van der Pauw method, shows that we can neglect this uncertainty.

The voltage V_c from (13) was calculated by an analog electronic circuit. When excited with a 50 Hz sinus wave generator, this circuit allowed the direct visualization of the $I(V)$ characteristic on an oscilloscope screen, and so far the determination of R_c after (6). This type of measurement gave the same results as in direct current.

With the suitable connexions, the whole contacts in figure 6a can be characterized. Our measurement method of R_c does not suppose contacts with identical characteristics. As a matter of fact, a certain spreading of these characteristics can be observed on a sample.

Finally, the arrangement of the contacts in figure 6a allows the determination of the substrate resistivity :

$$\rho_B = \frac{V_4 - V_1}{I} \frac{wh}{\ell_4 - \ell_1}. \quad (15)$$

3.3 MEASUREMENT OF THE END CONTACT RESISTANCE R_c . — The end contact resistance of middle contacts 1 to 4 in figure 6a can be measured according to the circuit shown in figure 8.

Fig. 8. — Connexions used for the measurement of the contact end resistance $R_c = V_c/I$ (here for contact 3).

3.4 MANUFACTURING OF Au-p TYPE CdTe CONTACTS. — Measurements on transverse and planar type contacts were performed in order to test the validity of the method. In this purpose a chemical deposition technique of the contact, well adapted to the realization of vertical structures, was used. The CdTe samples were mechanically polished and chemically etched as for the HgTe deposition. Gold was deposited by electroless deposition from a AuClH_4 : CH_3OH (4 gr : 20 cc) solution during 1 min immersion. The geometry of Anthony *et al.* [10] was used for the measurement of R_{vc} .

4. Results and discussion.

4.1 RESULTS. — Experiments were carried out on p-type CdTe grown by the Bridgman method. The substrates I were cut in an ingot which was not doped ⁽²⁾, whose resistivity $\rho_B = 70 \Omega \text{ cm}$ and carrier concentration $p = 3.6 \times 10^{15} \text{ cm}^{-3}$.

⁽²⁾ Grown by F. Gelsdorf, Cristallabor, Universität Göttingen, FRG.

The substrates II ($\rho_B = 1.45 \text{ k}\Omega \text{ cm}$;
 $p \sim 8 \times 10^{14} \text{ cm}^{-3}$),
 III 1 ($\rho_B = 13 \text{ k}\Omega \text{ cm}$;
 $p \sim 9 \times 10^{13} \text{ cm}^{-3}$),
 III 2 ($\rho_B = 45 \text{ k}\Omega \text{ cm}$;
 $p \sim 3 \times 10^{13} \text{ cm}^{-3}$)
 and
 IV ($\rho_B = 125 \Omega \text{ cm}$;
 $p \sim 4 \times 10^{15} \text{ cm}^{-3}$)

comes from phosphorus doped ingots ⁽³⁾. The samples III 1 and III 2 were cut in different places of the same ingot. The non uniform phosphorus distribution in this ingot is responsible for the different resistivities.

The method described in paragraphe 3.2 was used to test the homogeneity of the samples. The results concerning the ρ_c measurements are reported in tables II and III for HgTe-CdTe contacts (the contacts of the samples Ia and Ib were made on the substrate I), and in tables IV and V for the Au-CdTe contacts. The measurements are plotted in figures 3 and 4 from which η was determined, and subsequently ρ_c . The two values of the ratio $R_c w/R_s h$ (0.33 and 0.31) obtained at 22 °C and - 40 °C for the sample II (Tab. II) were not reported in figures 3 and 4 because of the corresponding low values of η (< 0.2) for which the TLM and the ELTM are useless. In these particular cases we simply wrote $\rho_c < R_c w d$.

The measurement method was tested on sample IV (Tabs. IV and V) with R_c , R_c and R_{vc} measurements. The three values of ρ_c determined from these measurements are in good agreement, and attest of the validity of the measurement method. Let us remark that the largest discrepancy between the values of ρ_c determined from R_c and

⁽³⁾ Grown by R. Triboulet, Laboratoire de Physique du Solide de Bellevue, CNRS, Meudon-Bellevue, France.

Table III. — *Parameters of HgTe-CdTe contacts in the case of measurement of the contact end resistance R_c . Samples Ia, Ib and III 1 are those reported in table II. Samples Ib and III 2 were sputter-etched before HgTe deposition.*

Sample	Temp. (°C)	ρ_B ($\Omega \text{ cm}$)	R_s ($\Omega/\square$)	$\tau =$ d/h	$R_c w d$ ($\Omega \text{ cm}^2$)	$\frac{R_c w}{R_s h}$	$\eta = \frac{\rho_c}{h\rho_B}$	ρ_c/ρ_B (cm)	ρ_c ($\Omega \text{ cm}^2$)
Ia	22	70	547	0.38	21.3	6.21	2.47	3.2×10^{-1}	22.1
Ib (sp. etched)	22	70	769	0.53	6.2	1.81	0.9	8.19×10^{-2}	5.7
III 1	22	1.3×10^4	5.65×10^5	2.13	30	4.71×10^{-2}	0.2	4.6×10^{-3}	59
II 2 (sp. etched)	22	4.5×10^4	1.45×10^6	2.19	525	0.17	0.6	1.86×10^{-2}	836

Table IV. — *Parameters of Au-CdTe contacts in the case of measurement of the contact resistance R_c .*

Sample	ρ_B (Ω cm)	R_s ($\Omega/\square$)	$\tau = d/h$	$R_c wd$ (Ω cm ²)	$\frac{R_c w}{R_s h}$	$\eta = \frac{\rho_c}{h\rho_B}$	ρ_c/ρ_B (cm)	ρ_c (Ω cm ²)	β
IV	125	887	0.52	16	1.75	0.65	9.2×10^{-2}	11.5	0.36

Table V. — *Parameters of Au-CdTe contacts in the case of measurement of the contact end resistance R_c , for the sample of the table IV.*

Sample	ρ_B (cm)	R_s ($\Omega/\square$)	$\tau = d/h$	$R_c wd$ (Ω cm ²)	$\frac{R_c w}{R_s h}$	$\eta = \frac{\rho_c}{h\rho_B}$	ρ_c/ρ_B (cm)	ρ_c (Ω cm ²)	$R_{cv} wd$ (Ω cm ²)
IV	125	887	0.52	11.8	1.5	0.7	9.87×10^{-2}	12.3	12.1

R_c measurements occurred for the sample III 1 (Tabs. II and III) : 299Ω cm² and 59Ω cm². The study in paragraphe 3.2 accounts, with the existence of a spreading between the different contacts, for this discrepancy.

Tables II and III show that, in the case of non sputter etched samples, that the ratio ρ_c/ρ_B is about 10^{-1} cm for the least resistive material (sample Ia at 22 °C, $\rho_B = 70 \Omega$ cm) and decreases to 10^{-2} cm for the most resistive materials (sample II at 22 °C, $\rho_B = 1.45$ k Ω cm ; sample III 1 at 22 °C, $\rho_B = 13$ k Ω cm ; sample II at -40 °C, $\rho_B = 16$ k Ω cm). Table II gives the values of the parameter β introduced in paragraphe 3.2.

The characteristics current-density voltage $J(V)$ of the contacts of sample Ia ($\rho_B = 70 \Omega$ cm) are curved, as shown in figure 9 corresponding to

Fig. 9. — Current density-voltage characteristic for one contact at the extremity, respectively of the samples Ia and Ib ($\rho_B = 70 \Omega$ cm for both of them), drawn from V_c measurements Ia : without sputter etching of the material ; Ib : with sputter etching of the material.

V_c measurements on a contact at an extremity. The sputter etching of the material prior to deposition does not change basically neither the form of the $J(V)$ characteristics (cf. curve Ib in Fig. 9) nor the values of the specific contact resistance ρ_c (cf. samples Ib and III 2 on Tabs. II and III).

A linearization of the $J(V)$ characteristics comes out for most resistive samples (samples II, III 1, III 2) as shown for the sample III 1 ($\rho_B = 13$ k Ω cm) in figure 10 corresponding to V_c measurements on the two contacts at the extremities.

Let us note finally that the $J(V)$ characteristics of a sample are not always identical. Figure 10 shows an example of spreading of these characteristics.

Fig. 10. — Current density-voltage characteristics for the two contacts of the extremities of the sample III 1 ($\rho_B = 13$ k Ω cm) drawn from V_c measurements.

4.2 DISCUSSION. — For a bulk resistivity $\rho_B = 70 \Omega$ cm we found the relation $\rho_c/\rho_B \sim 10^{-1}$ cm,

identical to that found by Anthony *et al.* [10] for CuAu contacts evaporated on a p-type CdTe surface etched by a $K_2Cr_2O_7 : H_2SO_4$ solution, but for values of ρ_B lying between 0.4 and 4 Ω cm, which are between one to two order of magnitude smaller than our value of ρ_B .

For gold contacts deposited by electroless deposition from a $AuClH_4$ solution on a p-type CdTe surface etched by a $Br-CH_3OH$ (10 %) solution, in the resistivity range 100-500 Ω cm close from our value of ρ_B (70 Ω cm), A. Musa *et al.* [23] found the relation $\rho_C = 1.45 \rho_B^{1.13}$ (with ρ_C in Ω cm² and ρ_B in Ω cm). This relation corresponds to values of ρ_C about one order of magnitude larger than that we found.

On the other hand E. Janik and R. Triboulet [8] found the relation $\rho_C/\rho_B \sim 10^{-2}$ cm. For HgTe films deposited by close spacing isothermal deposition on p-type CdTe whose resistivity lies between 10 and 15 Ω cm. With the sputtering method we found the same relation, but for higher values of the resistivity, lying between 1.45 k Ω cm and 45 k Ω cm.

The non-ohmic behaviour of the contacts manufactured on low resistive CdTe (70 Ω cm) means that a potential barrier subsists at the CdTe-HgTe interface, although the choice of HgTe should have theoretically suppressed this barrier. This fact can be explained through the existence of interface states [24]. When the density of interface states is very large, the barrier height is no more determined by the work function of the metal and the electron affinity of the semiconductor, but it is pinned by these interfaces states to the value

$$q\phi_b = Eg - q\phi_0,$$

where ϕ_0 is the neutral level of the interface states. Between this limit case (the Bardeen limit) and the case where the density of interface states is null, the barrier height varies with the density of states.

The interface states are related to the chemical and/or structural nature of the interface. Surface studies on CdTe give informations about the physical origin of these states. According to Hage-Ali *et al.* [25], bromine in methanol etching produces on CdTe a 10-20 Å thick oxide film of TeO, and the surface remained contaminated with various impurities, mainly Br, O, CH_n , ... Furthermore the structure of the material is damaged [26]. The SIMS spectra that we recorded on a sputtered HgTe-CdTe contact (Fig. 11) shows a Cd peak that we correlate to the existence of the TeO film. The sputter etching of the substrate over a 500 Å depth removes this TeO film, what the disappearance of the Cd peak on the corresponding SIMS spectra (Fig. 12) confirms. However, according to Courreges *et al.* [27], the band bending increases for a sputter etched surface. Although we used smaller energies (~ 40 eV) as that used by these authors (0.6-2.0 keV) it seems that the structural disorder introduced by ion bombardment is enough to limit the expected efficiency of this surface treatment. A contamination of the CdTe surface in the sputtering system is also not to exclude.

The experimental conditions of the HgTe film deposition can influence the nature and the density of the surface states. For example, the treatment at high temperature (550 °C) of the CdTe substrate in the case of the close spacing isothermal deposition method relaxes the structure defects created during the preparation of the substrate. The interdiffusion

Fig. 11. — SIMS profile recorded on a HgTe-CdTe contact deposited by HgTe sputtering, without sputter etching of the CdTe substrate. The full erosion depth is about 1.4 μ m.

Fig. 12. — SIMS profile recorded on a HgTe-CdTe contact deposited by HgTe sputtering, with sputter etching of the CdTe substrate. The full erosion depth is about 1 μm .

of HgTe into CdTe over a length of a few 10 μm [28] can also account for a decrease of the interface states density, for example through diffusion of the oxide film and other impurities in the volume. In the case of a deposition at low temperature (150 $^{\circ}\text{C}$), an extrapolation of the results given by F. Bailly [29] for HgTe-CdTe interdiffusion yields an estimation of a few 100 $\text{\AA}$, confirmed by the SIMS spectra in figure 11 and 12. So far, in the case of sputtering, where the structure defects of the substrate are not annealed, and the interdiffusion length is three order of magnitude lower as for deposition at 550 $^{\circ}\text{C}$, the nature and the density of the surface states undergo much less transformations as in the case of close spacing isothermal deposition. It follows, for sputtered films, a barrier height giving the non-ohmic contacts observed, while Janik and R. Triboulet obtained, at 550 $^{\circ}\text{C}$ ohmic contacts and low contact resistivity.

The high resistive materials ($1.45 \text{ k}\Omega \text{ cm} < \rho_B < 45 \text{ k}\Omega \text{ cm}$) show a strong compensation which can influence the density of the surface states. The linearization of the $J(V)$ characteristics and the decreasing of the ratio ρ_c/ρ_B observed for these materials account for a lowering of the potential barrier due to the lowering of the interface state density.

5. Conclusion.

The deposition by cathodic sputtering of the semi-metal compound HgTe whose work function has a high value ($\sim 5.9 \text{ eV}$) yields low ohmic contacts ($\rho_c/\rho_B \sim 10^{-2} \text{ cm}$) on p-type CdTe in the resistivity range $1.45 \text{ k}\Omega \text{ cm} < \rho_B < 45 \text{ k}\Omega \text{ cm}$. However, for these materials, and still more for low resistive p-type CdTe ($\rho_B = 70 \Omega \text{ cm}$), the electrical properties of the contact strongly depend on the properties of the interface: chemical nature (oxide film TeO_2 , surface contamination, ...), structural disorder (coming from mechanical treatment, chemical etching, sputter etching, ...).

We think that it would be worthwhile to apply the sputtering method to the contacting of CdTe thin films the surface of which is not damaged by mechanical and chemical treatment, that is to say that it contains a smaller state density than in the case of bulk material.

Acknowledgments.

We are very grateful to Dr. R. Triboulet for providing CdTe crystals, technical assistance and very helpful discussions. We also thank C. Bahezre for microprobe analysis of the HgTe thin films, and M. Miloche for SIMS analysis.

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