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Khusainov

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CHARGE COLLECTION IN M-S-M CADMIUM TELLURIDE DETECTORS

A. T. AKOBIROVA, L. V. MASLOVA, O. A. MATVEEV, S. M. RYVKIN
and A. Kh. KHUSAINOV

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad, USSR

Résumé. — On a étudié la structure métal-semiconducteur-métal (MSM) sur le tellure de cadmium découpé chimiquement ou rodé mécaniquement. Cette structure est souvent mise en œuvre pour la réalisation de détecteurs nucléaires. La courbure des bandes aux interfaces a été évaluée en étudiant la dépendance de la tension photovoltaïque en fonction de la longueur d'onde d'excitation et en analysant les caractéristiques I - V du dispositif. On a par ailleurs observé que le champ électrique était plus faible que dans une structure p-i-n, ce qui conduit à une dégradation de la résolution en énergie du détecteur. Il apparaît que le courant d'obscurité est déterminé uniquement par la résistivité de l'échantillon et non pas par une barrière de potentiel.

Abstract. — The metal-semiconductor-metal (MSM) structure often used for cadmium telluride radiation detectors has been studied for etched and mechanically polished material. The band bending at the interfaces has been determined by looking at the spectral dependence of the photovoltage and the I - V characteristics. An analysis of the electric field for a MSM, CdTe device shows that slower charge collection and, hence, poorer resolution than expected for a p-i-n detector, is obtained. Also the dark current is at best determined only by the resistivity of the material rather than by a barrier.

The shape of the pulse produced by nuclear radiation is determined primarily by the charge collection processes of the induced nonequilibrium electron-hole pairs. In detectors with a p-i-n structure, charge collection occurs by the drift of nonequilibrium carriers in a uniform electric field without the participation of carriers coming from the electrodes, making it similar to the process of charge collection in an ionization chamber. In structures with injecting or nonrectifying contacts, the pulse shaping process is more complicated because of the nonuniform electric field distribution and the participation of equilibrium carriers [1].

It is important, therefore to investigate the charge collection in metal-semiconductor-metal (MSM), cadmium telluride detectors. First consider the nature of a real metal-cadmium telluride contact.

Our studies showed that irrespective of the actual metal deposition technique used (chemical precipitation or vacuum evaporation), the height of the potential barrier at the M-p_i-CdTe contact and the direction of band bending are determined by the presence of the oxide or the disordered layer on the crystal surface (Fig. 1a). If the crystals are etched with a solution which does not leave tellurium and cadmium oxides until the disordered layer (produced as a result of mechanical treatment of the surface) is completely removed, the band bending at the metal-cadmium telluride contact is in qualitative agreement with the model of Mead and Spitzer [2]. The Fermi level

FIG. 1. — Band diagram for the Au-(p_i-CdTe) contact : (a) chemically etched surface ; (b) mechanically polished surface.

position at the interface is fixed by surface states and lies 0.35 eV above the valence band irrespective of the metal used.

When a metal is deposited on to a polished surface,

two barriers of opposite sign are formed (Fig. 1b), of which the first is at the interface between the metal and the disordered cadmium telluride surface layer, and the second lies at the interface between the unperturbed semi-insulating cadmium telluride which is p-type and the disordered layer.

This model for potential barriers at the metal-cadmium telluride contact is supported by the spectral dependence of the photovoltage (Fig. 2) and the specific features of the I - V characteristics (Fig. 3).

FIG. 2. — The photo-emf spectral response for an Au-(p-CdTe)-Au structure. Curve 1 is for an etched surface and curve 2 for a polished surface.

FIG. 3. — The I - V characteristic of an Au-(p-CdTe)-Au structure ($p = 1 \times 10^8 \text{ cm}^{-3}$). Curve 1 is for metal deposited on etched surface; and curve 2 is metal deposited on polished surface. n —the slope of the linear regions.

As seen from figure 2, the photo-emf at the barrier formed by depositing gold on an etched surface (curve 1) is of negative polarity (the semiconductor minus). Extrapolating the dependence of the photo-

emf on radiation energy into the long wavelength region yields for the barrier height 1.15 eV which corresponds to the Fermi level position at the surface of $E_v = 0.35 \text{ eV}$ (see Fig. 1a). The photo-emf at the contact obtained by gold deposition on the polished surface (curve 2) is negative in the long wavelength region (similar to the etched surface) but reverses polarity at shorter wavelengths and passes through a maximum at a wavelength of $0.82 \mu\text{m}$ which corresponds to interband optical transitions. The photo-emf in this spectral region is determined by carrier separation at the disordered layer-unperturbed crystal surface.

Presented in figure 3 are the I - V characteristics of the Au-CdTe-Au structure where curve 1 is for gold deposited on the etched surface of a p-type cadmium telluride crystal with a hole concentration of $1 \times 10^8 \text{ cm}^{-3}$, and curve 2, gold deposited on a polished surface of the same crystal.

In a structure with an etched surface the current is carried by equilibrium holes, with the slope of the I - V curve determined by the ohmic resistance of the crystal, which means that the current flow is limited by the space charge produced by the trapped holes. The sharp increase of the current at high bias voltages is associated with the total filling of the traps [3]. The current in the structure with a polished surface is transported by electrons injected from the surface n -layer. The I - V characteristic has a linear part corresponding to the resistivity of intrinsic cadmium telluride, a quadratic part for the space-charge limited current, and a cubic part representing the double injection current. The observed characteristic can be interpreted within the framework of the *relaxation* model of injection of minority carriers (in our case, electrons) developed by van Roosbroeck and Casey [4].

In our nuclear radiation detectors we make use mainly of the etched surface structures since they ensure lower currents at high bias voltages (curve 1 in figure 3) and thinner windows which is very important in X-ray and charged particle spectrometry. Therefore we will only consider here some features of collection of the nuclear radiation induced charge for structures produced by metal deposition on the etched surface of a semiinsulating p-CdTe. When an external bias is applied to such a structure, a specific field distribution is obtained which results in the time needed by the carriers to traverse such a structure being substantially different from that of a solid ionization chamber with similar parameters.

We will determine the electric field distribution in the M-(p-CdTe)-M structure based on the model developed by Lampert and Mark [3]. With an external bias applied to such a structure, one can roughly divide it into four regions with markedly different values of electric field (Fig. 4). Using reference [3] and taking into account that the current flowing through the sample is ohmic and limited by the space charge of

FIG. 4. — The electric potential and field distribution in an M-(p-CdTe)-M structure. (a) Potential distribution in the presence of external bias. $F(x)$ is the quasi Fermi level position and E_t is the energy level of the traps. (b) Electric field distribution; Region I, $0 < x < x_1$; Region II, $x_1 < x < x_2$; Region III, $x_2 < x < x_3$; and Region IV, $x_3 < x < d$. I and IV contact regions about $1 \mu\text{m}$ thick.

the deeply trapped holes, we obtain the electric field, $E(x)$ for regions II and III :

region II :

$$E(x) = \frac{eN_t}{\epsilon} x$$

region III :

$$E(x) = \frac{V - \int_{x_1}^{x_2} E(x) dx}{d - x_2} \cong \frac{V}{d} = E_0 \quad (1)$$

where N_t is the concentration of the traps which are not filled at equilibrium, ϵ the dielectric constant, V the bias voltage, and d the crystal thickness.

A numerical evaluation shows that it is these regions where the motion of carriers should be taken into account when estimating the carrier transit time, since in real cadmium telluride crystals the thickness of contact regions I and IV is very small ($\sim 1 \mu\text{m}$) and, hence, does not markedly contribute to pulse shaping.

For the transit time of the carriers generated near one electrode and collected on the other electrode of the M-(p-CdTe)-M structure one obtains

$$t_{dr} = \frac{d}{\mu E_0} + \frac{1.3 \epsilon}{e \mu N_t} \quad (2)$$

where μ is the mobility of the carriers swept through the total thickness of the detector. Note that the integration in region II was performed from point x_1 to point x_2 where the field drops to $0.1 E_0$.

As can be seen, the transit time of the charge carriers in a structure with nonrectifying contacts will be

larger than that in a p-i-n structure which is $t_0 = d/\mu E_0$ by the amount

$$\Delta t = \frac{1.3 \epsilon}{e \mu N_t}.$$

The effect of this term will be particularly important for thin detectors. At trap concentrations of 10^{12} cm^{-3} , corresponding to presently produced cadmium telluride crystals, Δt is 10^{-7} sec for the collection of electrons, which results in substantially slower charge collection in detectors.

Figure 5 presents the dependence of the electron transit time on crystal thickness at a fixed field (E_0)

FIG. 5. — The relative electron transit time t_{dr}^e/t_0 vs crystal thickness in an Au-(p-CdTe)-Au structure.

obtained with a Au-(p-CdTe)-Au structure at room temperature. Nonequilibrium electrons were excited by alpha-particles from a ^{244}Cm source (5.798 MeV). The value of t_{dr} was derived from the rise time of the voltage pulse in a charge-sensitive preamplifier. It is seen that for sample thicknesses less than 1.5 mm the transit time differs markedly from t_0 , this difference increasing with decreasing thickness in accordance with eq. (2). The value of mobility derived from this plot was 1050 to $1100 \text{ cm}^2/\text{V} \cdot \text{s}$ for the plateau region which agrees with the values obtained by other techniques for very good, low resistivity crystals [5, 6].

These results show that the charge collection process in the M-(p-CdTe)-M structure occurs in accordance with the model considered. Taking into account these specific features of charge collection is quite important when determining the mobility and lifetime of carriers from measurements of the rise time and amplitude of pulses induced by nuclear particles.

Thus it follows that the MSM structure is not optimal for spectrometric detectors for two reasons : (1) The dark current of the structure is at best determined by the resistivity of the crystals which limits the possibility of increasing the electric field in the sensitive region of the detector. For the highest possible resistivity of cadmium telluride the maximum possible

electric field will still be an order of magnitude less than that required to saturate the electron drift velocity (2). The electric field at the anode of the anode of the structure is weakened because of the presence of a positive space charge due to trapped holes. This results in slower charge collection and, hence, in a poorer resolution compared to the p-i-n detectors.

The effect of these phenomena on the behavior of cadmium telluride detectors will be even more pro-

nounced for purer crystals (with trap concentrations less than 10^{11} cm^{-3}). The production of type MSM spectrometric detectors with fairly good characteristics achieved at present [7, 8] indicates that in a p-i-n structure based on the same crystals these detectors would still be better.

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