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A MODEL FOR FAILURE IN THE CONTACT SYSTEM OF A SEMICONDUCTOR DEVICE ON TEMPERATURE CYCLING

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A physical model is proposed for the failure in a multilayer contact system for a semiconductor device on temperature cycling.

The following expression [1] is a formal definition of the thermal-expansion coefficient of a structure formed of plane-parallel layers with different thermal, mechanical, and geometrical characteristics:

$$\alpha = \Big(\sum_{i=1}^{n} \alpha_i \bar{E}_i \bar{z}_i\Big) \Big/ \Big(\sum_{i=1}^{n} \bar{E}_i \bar{z}_i\Big). \tag{1}$$

Then the elastic modulus averaged over a layer $\bar{E}_i$ may differ substantially from the value of Young's modulus $E_{0,i}$ (e.g., for a platy material) because the usual definition for the elastic modulus

$$\bar{E}_i = \bar{\sigma}_i / \bar{\varepsilon}_i \tag{2}$$

takes the following form in the case of an idealized loading curve for material i:

$$\bar{E}_i = \begin{cases} E_{0,i}, & |\bar{\varepsilon}_i| \leqslant \varepsilon_{0,i}; & (3.1) \\ \bar{\sigma}_i/\bar{\varepsilon}_i, & \varepsilon_{0,i} < |\bar{\varepsilon}_i| < \varepsilon_{i,\,\mathrm{cr}}, & (3.2) \\ 0, & |\bar{\varepsilon}_i| \geqslant \varepsilon_{i,\mathrm{cr}}, & (3.3) \end{cases}$$

and the value of the equivalent layer thickness $\bar{z}_i$ in (1) for an unchanged geometrical thickness z_i is defined by the thermal-stress distribution in the layer

$$\bar{z}_i = \frac{1}{\sigma_i} \int_i \sigma_i dz_i \tag{4}$$

and can be established by methods from the theory of material resistance.

One can examine the thermal stresses in a multilayer contact system that includes a layer of metal of thickness about 1 μm deposited on a semiconductor (for example, silicon) of thickness $\geqslant$100 μm (Fig. 1), and it can be shown that there is substantial plastic strain in the metal zones in contact with the semiconductor when the temperature changes by only a few tens of degrees. The curve for temperature cycling of the metal then takes a hysteresis form (1), and the area of the loop is assumed proportional to the specific energy dissipated, which initiates the formation of reversible defects in the metal lattice. A defect is formed in the latter at the stage of plastic stretching when the system cools, and vanishes (at least partially) on subsequent temperature rise.

The semiconductor in contact with the layer of plastically deformed metal is subject to tensile stresses on heating (and the magnitude of these may be at the critical level for the semiconductor at the points of localization of the defects in the metal), and it senses the defect, and transforms it by virtue of its brittleness into an irreversible one.

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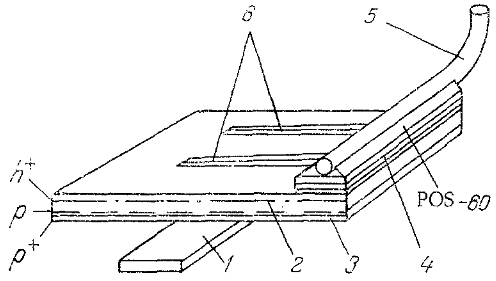

Fig. 1. Design of a $n^+ - p^- - p^+$ photoelectric structure: 1) planar rear current lead; 2) semiconductor substrate; 3) continuous rear contact; 4) multilayer contact system on working surface; 5) wire lead; 6) projecting components on ridged contact system.

Therefore, the thickness relationship and the thermal stresses in the contacting layers may mean that the defects are localized either in the plastic metal or in the surface of the semiconductor, and this determines the form of the curve and the onset of failure on thermal cycling.

In accordance with [1], the relative area of the defective region arising in the plastic metal in unit thermal cycle is proportional to the square of the plastic strain:

$$\bar{\varepsilon}_{\text{pl},i} = \bar{\varepsilon}_i(T_{\min}) - \bar{\varepsilon}_i(T_{\max}) - 2\varepsilon_{0,i}, \tag{5}$$

i.e., the relative contact area between the mechanically damaged layers varies in accordance with

$$s_i(N)/s_i(0) \sim (1 - \bar{\varepsilon}^2_{\text{pl},i})^N, \tag{6}$$

where N is the number of thermal cycles, and this in fact determines the form of the failure curve for the multilayer structure by reference to the different electrophysical parameters.

The multilayer contact system in a real device (for example, a photoelectric one [2]) takes the form of a ridge on the working side (in plan), which constitutes the collecting lead, and during thermal cycling this is subject to thermal loads that are different from those on the electrically parallel parts of the contact. Then one gets the situation (for substantial metal thickness on the collecting electrode) where the thermal defects are formed and localized directly in the surface layer of semiconductor, and their total area may substantially exceed $\bar{\varepsilon}^2_{\text{pl},i}$. The change in area in the ohmic contact between these layers occurs as before in accordance with (6), but with the replacement of $\bar{\varepsilon}^2_{\text{pl},i}$ by the equivalent parameter f characterizing the relative area of the defective region formed in the semiconductor on a single thermal cycle.

On the basis of the contact resistances between the damaged parts of the system, we get the relative conductivity as a function of the number of thermal cycles:

$$G(N) = \frac{g(N)}{g(0)} = \left[1 - \frac{1}{\sum\limits_{\text{K}} G_{\text{c},i}} + \frac{1}{\sum\limits_{\text{K}} G_{\text{c},i}(1-f_i)^N}\right]^{-1}. \tag{7}$$

The relative initial conductivity of the contact c-i-$G_{\text{c},i}$ is determined by the relation between the effective geometrical area of the contact $s_{\text{c},i}(0)$ (referred to the total surface of the device s) and the specific resistance in the damage zone $R_{i,\text{c}}$:

$$G_{\text{c},i} = s_{\text{c},i}(0)/sR_{i,\text{c}} \tag{8}$$

Reduction in the contact surface between the damaged layers continues up to some critical value $(1 - f_i)^{N_{\text{cr}}}$ at which the work of damage to this boundary (for example, in the metal $f_i = \bar{\varepsilon}^2_{\text{pl},i}$) is

$$A_{\text{cr},i} = \sigma_{T,i}[\varepsilon_{\text{cr},i} - \bar{\varepsilon}_i(T_{\min})](1 - \bar{\varepsilon}^2_{\text{pl},i})^{N_{\text{cr}}}\bar{z}_i \tag{9}$$

and is reduced to a value equal to the energy of the dissipative forces deposited throughout the defective region in a cycle:

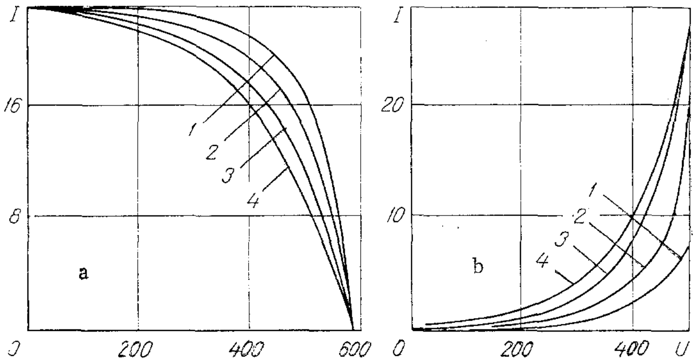

Fig. 2. Changes in charging VCC (a) and dark-current characteristic (b) for a photoelectric structure on cycling from −150 to +70°C with an average rate of temperature change of 100 deg/min (N is the number of cycles): 1) N = 0; 2) 45; 3) 145; 4) 205. I, mA; U, mV.

$$A_{\text{dis}} = 2\sigma_{T,i}\bar{\varepsilon}_{\text{pl},i}\left[1-(1-\bar{\varepsilon}^{2}_{\text{pl},i})^{N_{\text{cr}}}\right]\bar{z}_i, \tag{10}$$

where $\bar{\varepsilon}_i(T_{\min}) = \varepsilon_{\max,i}$ and $\bar{\varepsilon}_{\text{pl},i}$, $\bar{z}_i$ are values averaged over the layer.

Here it is assumed that the loading parameters attain the critical values in the material at the moment of failure ($\varepsilon_{\text{cr},i}$, $\sigma_{\text{cr},i}$), whereas for example in the plastic metal the stresses remain equal to the yield point $\sigma_{T,i}$; for example, if the boundary fails in the brittle material (e.g., in the semiconductor, which is not very resistant in compression), then the specific work of failure takes the form

$$A_{\text{cr},i} = \frac{1}{2}\left[(\overline{\sigma\varepsilon})_{\text{cr},j} - (\overline{\sigma\varepsilon})_{j,T_{\min}}\right](1-f_j)^{N_{\text{cr}}}z_j, \tag{11}$$

where $(\overline{\sigma\varepsilon})_{j,T_{\min}} \equiv (\overline{\sigma\varepsilon})_{j,\max} \equiv \overline{\sigma\varepsilon}_{j,\max}$.

Similar expressions can be drawn up for the failure in the boundary between two plastic materials each of which is incapable of absolute relaxation for the thermally induced defects. In the corresponding expressions, one then incorporates only the direction in the layer deformation diagrams, i.e., the relation between the relative areas of the defective regions and the work done by the dissipative forces in the contacting layers.

Since the mechanical failure in the contact occurs on the weakest link in the successive set of layers, the equation for the critical number of cycles preceding failure in a certain zone k takes the form

$$N^{k}_{\text{cr}} = \min\begin{cases} \dfrac{\log\left[2\bar{\varepsilon}_{\text{pl},i}/(\varepsilon_{\text{cr},i} - \varepsilon_{\max,i} + 2\bar{\varepsilon}_{\text{pl},i})\right]}{\log(1-\bar{\varepsilon}^{2}_{\text{pl},i})}; & (12.1)\\[2ex] \dfrac{\log\left\{2\sigma_{T,i}\bar{\varepsilon}_{\text{pl},i}\Big/\left[\dfrac{1}{2}(\overline{\varepsilon\sigma}_{\text{cr},j} - \varepsilon\sigma_{j,\max})\bar{z}_j + 2\sigma_{T,i}\bar{\varepsilon}_{\text{pl},i}z_i\right]\right\}}{\log(1-f_i)}; & (12.2)\\[2ex] \dfrac{\log\dfrac{2\left[(\overline{\sigma_T\varepsilon_{\text{pl}}})_m\bar{z}_m - (\sigma_T\varepsilon_{\text{pl}})_l\bar{z}_l\right]}{\sigma_{T,m}(\varepsilon_{\text{cr},m} - \varepsilon_{\max,m})\bar{z}_m + 2\left[(\overline{\sigma_T\varepsilon_{\text{pl}}})_m\bar{z}_m(\overline{\sigma_T\varepsilon_{\text{pl}}})_l\bar{z}_l\right]}}{\log\left[1-(\bar{\varepsilon}_{\text{pl},m} + \bar{\varepsilon}_{\text{pl},l})^2\right]}; & (12.3)\\[2ex] \dfrac{\log\dfrac{2\left[(\sigma_T\varepsilon_{\text{pl}})_m\bar{z}_m + (\overline{\sigma_T\varepsilon_{\text{pl}}})_l z_l\right]}{\sigma_{T,m}(\varepsilon_{\text{cr},m} - \bar{\varepsilon}_{\max,m})\bar{z}_m + 2\left[(\overline{\sigma_T\varepsilon_{\text{pl}}})_m + (\overline{\sigma_T\varepsilon_{\text{pl}}})z_l\right]}}{\log\left[1-(\bar{\varepsilon}_{\text{pl},m} - \bar{\varepsilon}_{\text{pl},l})^2\right]}, & (12.4) \end{cases}$$

where (12.1) and (12.2) describe the typical failure of a multilayer structure along the boundary between the plastic metal i and the brittle semiconductor j. The latter equations in (12) reflect the failure of the boundary between the plastic materials m and *l*, in particular on m for various directions of the thermal deformation: (12.3) when the condition is

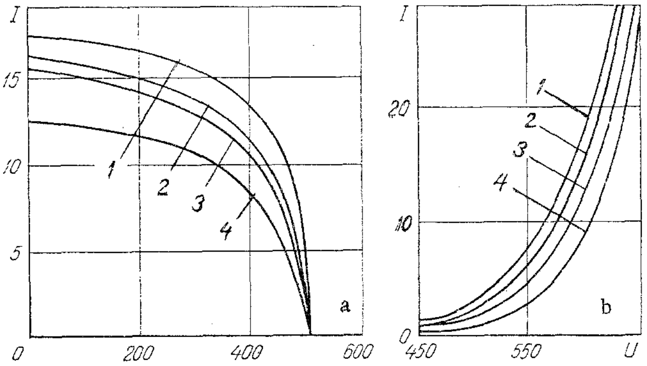

Fig. 3. Change in the charging VCC (a) and dark-current curve (b) for photoelectric structures with a wire switching line on thermal cycling from −100 to +70°C with an average rate of temperature change of ±70 deg/min (N is the number of cycles): 1) N = 0; 2) 10; 3) 40; 4) 80.

$$\frac{[\bar{\varepsilon}(T_{\min})-\bar{\varepsilon}(T_{\max})]_m}{[\bar{\varepsilon}(T_{\min})-\bar{\varepsilon}(T_{\max})]_l}<0, \tag{13}$$

and (12.4) when

$$\frac{[\bar{\varepsilon}(T_{\min})-\bar{\varepsilon}(T_{\max})]_m}{[\bar{\varepsilon}(T_{\min})-\bar{\varepsilon}(T_{\max})]_l}>0. \tag{14}$$

Failure to obey the latter conditions indicates that the boundary is absolutely resistant to thermal cycling.

Therefore, cyclic temperature change in a multilayer contact system in accordance with (7) produces local change in the conductivity and related changes in the electrophysical characteristics of the device, and the working life is essentially restricted by the onset of mechanical failure in accordance with (12).

Experiments indicate that the rate of temperature change has a marked effect on the degradation rate, which is explained within this model as the loading diagram being dependent on the strain rate. In fact, if we incorporate the dynamic component, the thermal stresses under the conditions of (3.1) and (3.2) become

$$\sigma_{T,i}=\begin{cases}E_{D,i}\bar{\varepsilon}_i, & \bar{\varepsilon}_i\leqslant\varepsilon_{v,i}(\dot{\varepsilon}_i),\\ \sigma_{T,i}+\delta(\bar{\varepsilon}_i;\ \dot{\varepsilon}_i), & \bar{\varepsilon}_i>\varepsilon_{v,i}(\dot{\varepsilon}_i),\end{cases} \tag{15}$$

where $\varepsilon_{v,i}(\dot{\varepsilon}_i)$ is the strain in material i, which characterizes the onset of yield on the idealized loading curve in relation to the loading rate $\dot{\varepsilon}_i$.

The specific work in a cycle is

$$A_{\text{dis},i}=2\bar{\varepsilon}_{\text{pl},i}[\sigma_{T,i}+\delta(\varepsilon_i\dot{\varepsilon}_i)][1-(1-\bar{\varepsilon}^2_{\text{pl},i})]^{N}\bar{z}_i \tag{16}$$

and this exceeds the static work of the dissipative forces and therefore facilitates more rapid degradation when there are high rates of temperature change.

Therefore, the incorporation of rheological effects means that the equivalent and true plastic strains are related by

$$\bar{\varepsilon}^{\text{eq}}_{\text{pl},i}=\bar{\varepsilon}_{\text{pl},i}\left[1+\frac{\delta(\bar{\varepsilon}_i;\ \dot{\varepsilon}_i)}{\sigma_{T,i}}\right], \tag{17}$$

which follows from equality of the work done in a cycle.

Figures 2 and 3 show curves for the effects of thermal cycling on the voltage–current characteristics (VCC) in the light (a) and in the dark (b) for a silicon photocell made by the technology of [2] with a ridged configuration for the contact system on the working surface. Typical VCC are shown for a group of specimens in Fig. 3, and this group differs from the group shown in Fig. 2 in that there is a copper line (∅0.3 mm) on the working surface

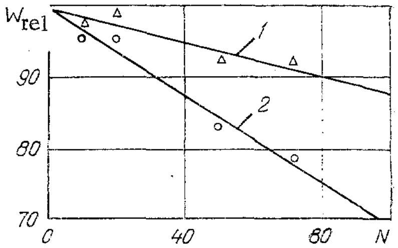

Fig. 4. Measured (points) changes in photocell power with local (1) and continuous (2) contacts with the switching line on thermal cycling. W_{rel}, %.

soldered with POS-60 alloy to the current-collecting lead. The number of specimens in each group was 15. The VCC were recorded with an LKDP XY pen recorder.

The results show that the intensity (temperature difference and rate of change) and the design features of the contact (thickness, material, and configuration) result in two superficially different failure mechanisms. The first (Fig. 2) is predicted by the above theory of cyclic aging and is due to increase in the contact resistances between the relatively thin layers in the contact system. The second (Fig. 3) is that of few-cycle fatigue, and in addition to the first case there is mechanical failure in the contact surface of the device, i.e., microcracks extending from the comparatively thick collecting contact into regions of the active surface.

For example, if we describe the relationships from the VCC equation for the photocell

$$U = \frac{AkT}{q}\ln\left(\frac{I_p - I}{I_s} + 1\right) - IR_s, \tag{18}$$

then in the first there is a change only in the series resistance R_s, whereas in the second there are also marked changes in the recombination parameter A, the reverse saturation current I_s, and the photocurrent I_p.

When the thermal cycling intensifies, the probability of few-cycle fatigue becomes greater no matter what the design of the device, particularly if the temperature difference extends into the cryogenic region.

The simultaneous action of the two failure mechanisms makes itself felt at the local contact between the wire switching line and the collecting electrode in the photocell. The region of the contact free from the line degrades at a substantially lower rate and provides much higher fatigue strength in the joint (Fig. 4). This effect is of practical significance, since it enables one to combine adequate mechanical strength in the contact of the device with the switching line and to improve the stability under thermal cycling.

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