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ON THE NATURE OF THE APV EFFECT IN SEMICONDUCTOR FILMS

1. The effect of anomalously large photovoltages (the APV effect) in semiconductor films has in recent years been the subject of numerous and diverse studies (1–20). However, the theory of the APV effect still remains at the level of more or less reliable hypotheses. The totality of these hypotheses, in a systematized form convenient for survey, may be represented by the following scheme:

```
                                 APV effect
                                     |
                  --------------------------------------------
                  |                                          |
         Microphotobattery (17)                        Photoelement (15)
                  |                                          |
         ------------------------------                ---------------
         |              |              |               |
External        Dember effect      p—n junctions     Gradient of trap
photoeffect     (3,21)             (8,21)            concentration (15)
(21)                               |
                    ------------------------------
                    |                             |
                Potential barriers            Packing defects
                at grain boundaries           at phase boundaries
                (1,5)                          (4,7)
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Theoretical consideration and direct experiments carried out in work (17) made it possible substantially to narrow the range of possibilities within which the physical cause of the APV effect should be sought. The inconsistency of the concepts and calculations of Brandkhorst and Potter (15), who attempted to interpret APV films as single photoelements with a complex distribution of adhesion levels, was shown, and a theorem was proved on the multielement (

Figure 1

Figure 1: Figure 1

“battery”) nature of the APV effect. In addition, it was established experimentally that the APV effect is not connected with the external photoeffect.

As a result, the question of the nature of the elementary processes underlying the APV effect has been reduced to a dilemma—either the photovoltaic effect in microscopic p—n junctions, or the diffusion (Dember) effect in microregions homogeneous in conductivity type. As is seen from the scheme given, models based on ideas of potential barriers at phase boundaries, grain boundaries, etc., should be treated not as something fundamentally different from a system of p—n junctions, but as definite concretizations of the p—n-junction hypothesis.

2. In Fig. 1 the structure of an APV film is shown schematically, corresponding to the p—n-junction (a) and Dember (b) models. In the first of these models, a high-voltage photovoltage V_{APV} arises as a result of summation of elementary photovoltages generated at junctions of one type (for example, p—n^{-}), whereas junctions of the other type (n—p^{-}) remain unilluminated (see Fig. 1a):

$$V_{\mathrm{APV}} = \frac{kT}{q} \sum_{i=1}^{N} \ln\left(1 + \frac{J_{fi}}{J_{si}}\right) = \frac{kT}{q} \ln \prod_{i=1}^{N} \left(1 + \frac{J_{fi}}{J_{si}}\right) = N \frac{kT}{q} \ln\left[1 + \left(\widetilde{\frac{J_{fi}}{J_{si}}}\right)\right]. \tag{1}$$

Here J_{si} and J_{fi} are the saturation current and photocurrent in the i-th p—n junction.

The Dember model (Fig. 1b) consists of photoconducting regions separated by interlayers that prevent exchange of free carriers between these photoconducting regions. In this case

$$V_{\mathrm{afn}} = \frac{kT}{q}\frac{b-1}{b+1} \sum_{i=1}^{N} \ln \frac{\sigma_{2i}}{\sigma_{1i}} = \frac{kT}{q}\frac{b-1}{b+1} \ln \prod_{i=1}^{N} \frac{\sigma_{2i}}{\sigma_{1i}} =$$

$$= N \frac{kT}{q}\frac{b-1}{b+1} \ln\left(\overline{\frac{\sigma_{2i}}{\sigma_{1i}}}\right). \tag{2}$$

Here $\sigma_{1i} = \sigma_0 + \Delta\sigma_{1i}$ and $\sigma_{2i} = \sigma_0 + \Delta\sigma_{2i}$ are the values of the total conductivity (dark plus photo) respectively at the left and right boundaries of the i-th microregion.

Let us note that in the Dember model of the afn effect the interlayers between the photoconducting regions may be either high-resistance or low-resistance.

Figure 2

Figure 2: Figure 2

Fig. 1. Model of an afn film: *a*—from *p*-*n* microjunctions; *b*—from photodiffusion microregions

Fig. 2. Dependence of V_{afn} on the illumination angle for afn germanium films

3. Consideration of the entire set of known experimental facts from the standpoint of the dilemma concerning the nature of the elementary processes underlying the afn effect shows that many characteristics are not critical for its solution. Let us consider, for example, the inversion of the sign of V_{afn} when changing from illumination of afn films with short-wavelength light to illumination with long-wavelength light (see, for example, (^{6})). From the point of view of the *p*-*n*-junction hypothesis this is explained by the fact that deeply penetrating long-wavelength light generates nonequilibrium carriers not only at *p*-*n* junctions but also at *n*-*p* junctions (see Fig. 1a), which, as λ increases, should lead to a weakening of the afn effect and, if the *n*-*p* junctions are sufficiently effective, to inversion of the sign of V_{afn}.

For the photodiffusion model (see Fig. 1b), inversion of the sign of V_{afn} with increasing λ is explained by the concept of the anomalous Dember effect (^{22}). At a high rate of surface recombination at the illuminated face, the photodiffusion flux in a Dember element changes its sign when going from short-wavelength light to long-wavelength light.

4. More definite conclusions seem possible on the basis of a physical discussion of the dependence of V_{afn} on the light intensity. Let us consider the expression for the photovoltages generated by photovoltaic and photodiffusion elements

$$v_{p-n} = \frac{kT}{q} \ln\left(1 + \frac{J_f}{J_s}\right), \qquad v_{\text{demb}} = \frac{kT}{q}\frac{b-1}{b+1} \ln \frac{1 + \Delta\sigma_2/\sigma_0}{1 + \Delta\sigma_1/\sigma_0}. \tag{3}$$

Deviation from linearity of the lux-voltage characteristic in the photodiffusion effect occurs when the photoconductivity becomes

comparable with the dark conductivity:

$$\Delta\sigma \equiv q\mu(1+b)\Delta n \sim \sigma_0 \equiv q\mu n \quad , \tag{4}$$

i.e., when $\Delta n \sim n$. Violation of the linearity of the lux-voltage characteristic in the photovoltaic effect at a p—n junction occurs at

$$J_f \equiv qD\,\Delta n/L \sim J_s \equiv qDn \quad /L, \tag{5}$$

i.e., when $\Delta n \sim n$.

It follows from (4) and (5) that, in the case of photovoltaic microphotocells, the linearity of the lux-voltage characteristic must be violated considerably earlier than in the case where the film consists of photodiffusion microregions.

Turning to Fig. 1a, given in (^{12}), we see that afn films of Si, Ge, and GaAs have linear or nearly linear lux-voltage characteristics up to $I = 300\,000$ lx, whereas in afn films of CdTe a sharp nonlinearity is observed already at $I = 20\,000$ lx. This suggests that in Si, Ge, and GaAs the afn effect is due to the photodiffusion mechanism, while in CdTe it is due to the occurrence of photovoltages at p—n junctions.

A final conclusion about the mechanism of the afn effect on the basis of an analysis of lux-voltage characteristics can, however, be drawn only with independent measurements of n, since in films of different materials the values of n may differ by several orders of magnitude.

5. It seems to us that a critical experiment for resolving the question of the nature of the physical processes in afn films can be the study of the dependence of the magnitude and sign of V on the angle of incidence of light.

If the afn effect is due to the summation of photovoltages at electron-hole junctions, then changing the angle of illumination of the film within the range from 0 to 180° cannot lead to an inversion of the sign of V, since at any angle of incidence of light the p—n junctions will be illuminated better than the n—p junctions (see Fig. 1a). A change in the sign of V can occur only when the film is illuminated at angles greater than 180°. If, however, the afn effect is due to the Dember mechanism, then it should be expected that the direction in which the afn film was deposited may correspond to an inversion of the sign of V, since upon passing from illumination of one face of a microelement of the afn film to the other, in the normal Dember effect the direction of diffusion of the current carriers generated by the light changes, and consequently so does the sign of V. In the anomalous Dember effect, i.e., if on one of the faces of the microelement the rate of surface recombination is much greater than on the other, the direction of photodiffusion will be independent of the direction of illumination, i.e., inversion of the sign of V when the angle of incidence of light passes through the angle of film deposition should not occur.

From the above considerations it follows that the fact of inversion of the sign of V within illumination angles from 0 to 180° unambiguously indicates a photodiffusion (Dember) mechanism of the afn effect, whereas the absence of inversion does not make it possible to draw an unambiguous conclusion.

6. Figures 2, 3, and 4 show, in polar coordinates, the results of experiments on measuring the angular dependences of V for films of Ge, GaAs, and CdTe. The dependence of the film illumination on the angle of incidence of light was calculated according to the cosine law; the measured values of the photovoltages were normalized to unit illumination. The dotted circumference in these figures denotes the zero level of V; passage of

Fig. 3. Dependence of V_{afn} on the illumination angle for afn films of gallium arsenide

Figure 3: Fig. 3. Dependence of V_{afn} on the illumination angle for afn films of gallium arsenide

Fig. 4. Dependence of V_{afn} on the illumination angle for afn films of cadmium telluride

Figure 4: Fig. 4. Dependence of V_{afn} on the illumination angle for afn films of cadmium telluride

> the experimental curve through the dotted circumference corresponds to a change in the sign of V . The values of V are plotted along the radii in relative units. The arrows indicate the directions in which the afn films were deposited.

Experimental polar diagrams $V_{\text{afn}}(\varphi)$ for Ge and GaAs films show, for most samples, a reversal of the sign of V_{afn} at illumination angles close to the deposition angles of the films (see Figs. 2 and 3). Similar results were obtained for afn films of Si. By contrast, in none of the 30 CdTe films studied was a reversal of the sign of V_{afn} found. Typical diagrams $V_{\text{afn}}(\varphi)$ for CdTe are shown in Fig. 4.

Fig. 3. Dependence of V_{afn} on the illumination angle for afn films of gallium arsenide

Fig. 4. Dependence of V_{afn} on the illumination angle for afn films of cadmium telluride

These experiments show that the afn effect in Ge, Si, and GaAs films is due to a photodiffusion mechanism, while in CdTe films it is due to micro-p—n junctions.

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