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MECHANISM OF THE SO-CALLED "ANOMALOUS" PHOTOCONDUCTIVITY

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I. Results of an investigation of the photoconductivity of amorphous selenium suitably t reated in mercury vapor were presented in 1961 in [1]. It was found that the characteristics of the photoconductivity of this substance differ radically from all the previous data, and on this basis the observed photoconductivity was called "anomalous." The main features of the anomalous conductivity reduce to the following: 1) The stationary photoconductivity does not depend on the light intensity in a very wide range (many orders of magnitude) of the intensity and is determined only by the wavelength of the employed light. The maximum of the sensitivity is shifted in this case to the long-wave side relative to the intrinsic absorption edge. 2) The photoconductivity relaxation time is inversely proportional to the light intensity and is therefore very large (practically unmeasurable) after the light is turned off.

Detailed quantitative characteristics of anomalous photoconductivity are described in Korsunskii's 1972 monograph [2], where he presents also an interesting phenomenological model. This model, however involves the artificial assumption that certain local centers (called U-centers) having distinct properties are present in the forbidden band of the semiconductor.

We propose here an anomalous-photoconductivity model based on a perfectly realistic structure. All the features of anomalous photoconductivity follow from this model in natural fashion.

II. The anomalous photoconductivity should set in when light is absorbed by the free carriers (say, electrons) if there exist in the semiconductors two regions with different electron densities, separated by a potential barrier (Fig. 1)[1)].

Indeed, the measured conductivity between contacts 1 - 1' or 3 - 3' placed on any of the electronic regions should change after illumiation, since the electrons of regions I and III can, after absorbing the light, overcome the potential barrier, as shown by the arrows of Fig. 2. As a result, since the electron transitions from left to right and from right to left are in general not equal in intensity, the conductivities of regions I and III will change, and furthermore in opposite directions, i.e., positive photoconductivity is produced in one region and negative in the other. This photoconductivity has the above-mentioned characteristics of the "anomalous" photoconductivity.

Indeed, the change in the number N_1 of the electrons, say in region I, is determined by oppositely directed flows of electrons above

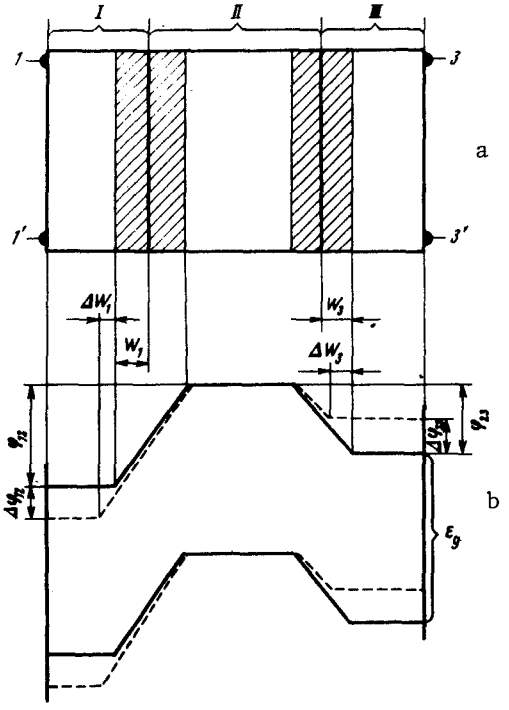

Fig. 1. Model of "anomalous" photoconductor: a) geometry; b) level scheme. Solid lines - prior to illumination, dashed - changes due to illumination.

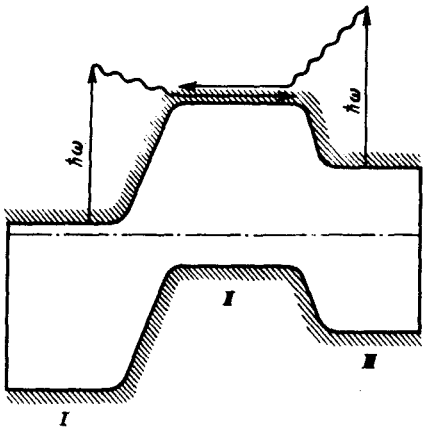

Fig. 2. Scheme of electron transitions above the barrier following absorption of photons of energy exceeding the barrier height.

the barrier, each proportional to the light intensity I

$$-\frac{dN_1}{dt} = \alpha_1(\lambda)\, n_1 q I - \alpha_3(\lambda)\, n_3 q I \qquad (1)$$

Here q is the cross section for photon capture by a free electron; n_1 and n_3 are the electron densities on the left and right of the barrier, respectively; $\alpha_1(\lambda)$ and $\alpha_2(\lambda)$ are coefficients that depend on the wavelength and are independent of the light intensity, and characterize the probability that an electron will go over the barrier into the neighboring region after absorbing a photon.

It follows from (1) that the stationarity condition $\alpha_1 n_1 = \alpha_2 n_2$ does not contain the light intensity.

III. To calculate the magnitude and time constant of the photoconductivity we start from the fact that the electron excesses or shortages produced in region I or III cause the charge to change in these regions, thus resulting in jumps of the potential energies ϕ_{12} and ϕ_{23} on the boundaries with the p-region II (see Fig. 1). This changes also the thicknesses of the space-charge layers, W_{12} and W_{23}, at these boundaries. The change of conductivity between contacts 1 - 1' (or 3 - 3') in the case of a pure semiconductor without deep impurities is determined by just this effect of narrowing (or broadening) of the conducting "channel" between contacts, due to the change of the thickness W_1 (or W_2) of the nonconducting space-charge region[2].

For the case when the interaction between the electrons is week and the only electrons that can pass above the barriers are those excited to states of energy higher than the energy of the top of the barrier ("external photoeffect" from region I to region III or back), calculation in the linear approximation yields for the stationary photoconductivity

$$\Delta\sigma_I = \frac{h}{\ell} e\mu \frac{\beta_3 n_3 - \beta_1 n_1}{\frac{\gamma_1}{w_1} + \frac{\gamma_3}{w_3}} \neq f(I) \qquad (2)$$

and for the time constant

$$\tau = \frac{d_2\theta}{D_2 q I\left(\frac{\gamma_1}{w_1} + \frac{\gamma_3}{w_3}\right)} \sim \frac{1}{I} \qquad (3)$$

where

$$\beta_1 = (\hbar\omega - \phi_{12}) \exp\left(-\frac{W_{12}}{L_1}\right); \qquad \beta_3 = (\hbar\omega - \phi_{23}) \exp\left(-\frac{W_{23}}{L_3}\right);$$

$$\gamma_1 = \left(2\phi_{12} + \hbar\omega \frac{W_{12}}{L_1}\right) \exp\left(-\frac{W_{12}}{L_1}\right); \quad \gamma_3 = \left(2\phi_{23} + \hbar\omega \frac{W_{23}}{L_3}\right) \exp\left(-\frac{W_{23}}{L_3}\right)$$

ℓ is the distance between electrodes, h is the sample dimension perpendicular to the plane of the drawing, e is the elementary charge, μ is the mobility, D_2 is the diffusion coefficient in region II, d_2 is the thickness of region II, θ is the rate of energy loss by the hot carriers, and L_1 and L_3 are the effective rate of cooling of the optically-excited carriers to the top of the barrier.

The remaining notation is clear from Fig. 1.

The stationary photconductivity is thus independent of the light intensity, while τ is inversely proportional to it.

An estimate of τ for an n-p-n germanium structure at T = 77°K, $d_2 = 10^{-4}$ cm, $n_1 = 1.1$ cm^{-3},

$n_3 = 10^{15}$ cm^{-3}, $I = 10^{16}$ photon/sec-cm^2 leads to a value $\sim 10^2$ sec.

IV. In principle, anomalous photoconductivity can be possessed not only by a three-layer system (e.g., n-p-n or p-n-p), but also by a system made up of two layers in contact, but of different materials, i.e., a heterojunction or even a junction of a semiconductor with a metal (Fig. 3). The role of the third (barrier) layer is played in such a "twolayer" system by the space-charge region at the boundary. It is possible that the material used in [1, 2] is a system of this kind (e.g., Se-HgSe heterojunction or mercury-semiconductor junction).

It follows from the foregoing, however, that the phenomenon of anomalous photoconductivity, first observed and known so far only in the Se + Hg system, can be deliberately produced also with other semiconducting materials.

We note in conclusion that, as shown by analysis, in the case of the usual n-p homojunction the absorption of light by free carriers in one of the regions and their transfer to the other region where they recombine with the majority carriers (a process inverse to that considered in detail in [3]) also leads to unique phenomena that are close to "anomalous" photoconductivity (inverse proportionality of to the light intensity and independence of the stationary photoconductivity of the intensity). In this case, however, the conductivity changes only on going to illumination with light of shorter wavelength, whereas the anomalous photoconductivity does not depend on the "direction" of the change of the wavelength.

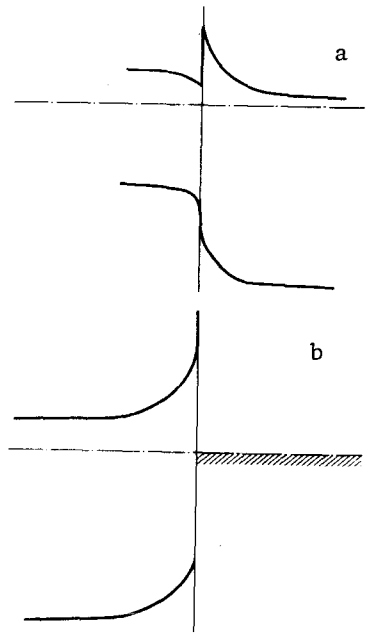

Fig. 3. Two-layer model of "anomalous" photoconductor (level scheme): a - semiconductor-semiconductor system, b - semiconductor-metal system.

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[1] We assume for concreteness that the barrier region II is of the p-type, although it can in principle be also a high-resistance n- or i-region.

[2] In analogy with the situation in field-effect transistors.

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EFFECTIVE INTERACTION OF ELECTRONS WITH SOUND ON CYLINDRICAL AND FLAT SECTIONS OF FERMI SURFACE

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It is shown that absorption and dispersion of the spped of sound has a sharp maximum when the wave vector of the sound is inclined an angle $\sim s/v$ from the axis of the cylinder or from the plane. This phenomenon is analogous to the tilt effect.

In view of the large velocity difference, $s \ll v$, the electrons actively interacting with sound are those from a narrow strip on the Fermi surface, for which $\vec{k}\cdot\vec{v} = \omega$ (or $\vec{k}\cdot\vec{v} \simeq 0$ if $\omega \ll \nu$), and which move in phase with the wave. The fraction of these electrons is small, so that the relative absorption at $k\ell \gg 1$ reaches only a value $\sim s/v$, and the sound velocity dispersion is $\sim (s/v)^2$ [1].

On cylindrical and flat sections of the Fermi surface, however, if the sound wave vector $\vec{k}$ is directed along the cylinder axis or in the plane, all the electrons of these sections