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INVESTIGATION IN TEMPERATURE AND FREQUENCY DEPENDENCES FOR CONDUCTIVITY IN BARRIER REGION OF NONIDEAL HETEROJUNCTION

The described experimental data indicate the tunnel-jumping character of carriers transport through space-charge region (SCR) of heterojunction CdS—Cu_2S. The conductivity caused by this mechanism essentially depends on the barrier parameters which can vary under illumination. This conductivity has the determinative influence on photo-electric properties of CdS—Cu_2S heterophotoelements. Rather low efficiency values of these elements, small U_{oc} values and, in many cases, the rectification factor of volt-current characteristics (VCC) are caused by junction external shunting as in the case the element conductivity would not find out the listed above features. In spite of similar VCC, the elements with various shunting mechanisms their character (tunnel-jumping transport on the located levels through a barrier or external with respect to junction transport) can be easy determined experimentally.

It is known, that for many nonideal heterojunctions, including heterostructures CdS—Cu_2S, the slope of VCC either does not depend on T or depends but not by such way as it should be expected from Shockly—Anderson model. The temperature dependences of current-voltage characteristics of our heterophotoelements made on the basis of CdS—Cu_2S are shown in fig. 1. As can be seen in the investigated temperature interval (at voltages less than diffusion potential) the closest for approximation of received VCC is the general empirical formula $j \sim \exp(\alpha U)$. As the factor α does not depend on T it indicate the defining influence of tunnel processes in carriers transport.

As can be seen in fig. 1, the slope of the curves plotted in coordinates $\ln j \div U$ does not depend practically on temperature (α does not depend on T), but it is not strictly constant along all bias interval, i.e. current—voltage characteristics are not exponential.

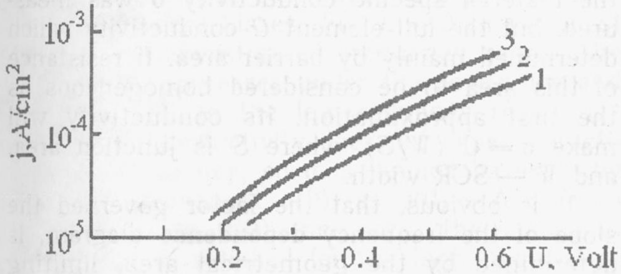

Fig. 1. CdS—Cu_2S heterojunctions VCC, measured at temperatures 150, 250, 300 K (curves *1*, *2*, *3* — respectively)

The investigation of the current character dependence on a temperature can add the information on a nature of current transport can. Such curves measured at several fixed biases of direct polarity, plotted in Arhenius coordinates, are shown in fig. 2.

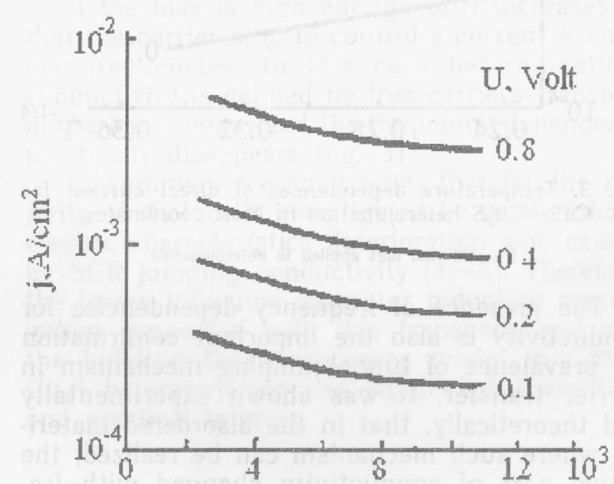

Fig. 2. Temperature dependencies of direct current for CdS—Cu_2S heterojunction in Arenius coordinates:
U — the external bias applied to heterojunction

One can see, that the obtained dependences in the specified coordinates are not straightened well. Temperature dependence is rather weak, that also can point out the realization of tunnel current transport mechanism. Direct tunneling in investigated junctions ($\varphi_0 = 1$ eV, $W \sim 1$ micron) is impossible, and expressions for current temperature dependence at thermoactivative tunneling at the top of potential barrier are the similar to classical and do not describe the curves obtained by us. The given results do not explain well also by the model of Riben and Feucht for multistage tunneling, as in this case the current temperature dependence would be defined by very weak dependence $E_g(T)$ and would be exponential [1] (as dependence $E_g(T)$ is linear). At the same time it is obvious, that at tunnel-jumping carrier transfer are dominating, the specific conductivity σ may often be describe satisfactorily by Mott formula:

$$\sigma = \sigma_0 \exp[-(T_0/T)^{1/4}],$$

where σ_0 and T_0 — constants which does not depend on temperature. It means, that at the realization of tunnel-jumping mechanism for transfer through barrier, current temperature dependence should be straightened in characteristic Mott coordinates: $\ln j \div T^{-1/4}$. Really, curves $j = j(T)$, replotted in such coordinates, as can be seen in fig. 3, are linear in the whole investigated temperature interval, at all biases, smaller than the magnitude of diffusion potential.

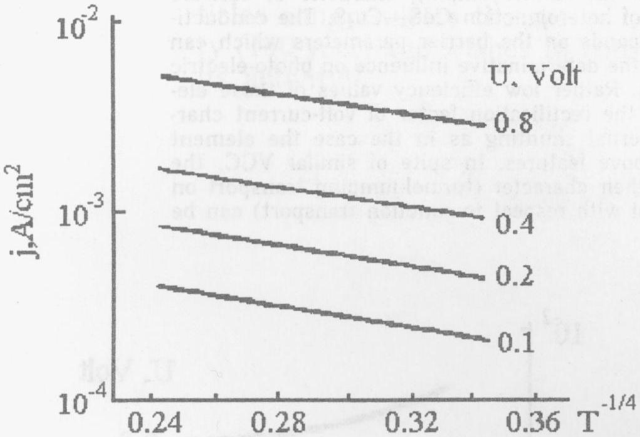

Fig. 3. Temperature dependences of direct current for $CdS—Cu_2S$ heterojunction in Mott coordinates:

U — external bias applied to heterojunction

The presence of frequency dependencies for conductivity is also the important confirmation for prevalence of tunnel-jumping mechanism in carrier transfer. It was shown experimentally and theoretically, that in the disordered materials where such mechanism can be realized, the active part of conductivity changed with frequency under the power law, and the power as calculations showed, poorly depended on frequency and in the vicinity of 10^4 Hz it approached to 0.8, that is often observed experimentally, for example, at investigation of impurity conductivity in crystalline silicon [2]. For many amorphous semiconductors on the basis of chalcogen glasses, the power is closer to 1 [3]. Such frequency dependence of conductivity strongly differs from the predicted kinetic theory for current transport by free carriers, for which at $\omega\tau \ll 1$ (where $\tau \sim 10^{-14}$ — time for impulse Maxwell relaxation) conductivity does not depend on frequency [3]. Thus, the detection of frequency conductivity dependence of power character can be considered as the serious ground to assume the dominant role of tunnel-jumping mechanism of transport.

The constant component of conductivity can be caused by free carriers movement, and jumping conductivity, not equal to zero, on the located levels under direct current.

In fig. 4, the frequency dependencies of active conductivity component for our heterophotoelement on a basis of heterojuncton CdS—

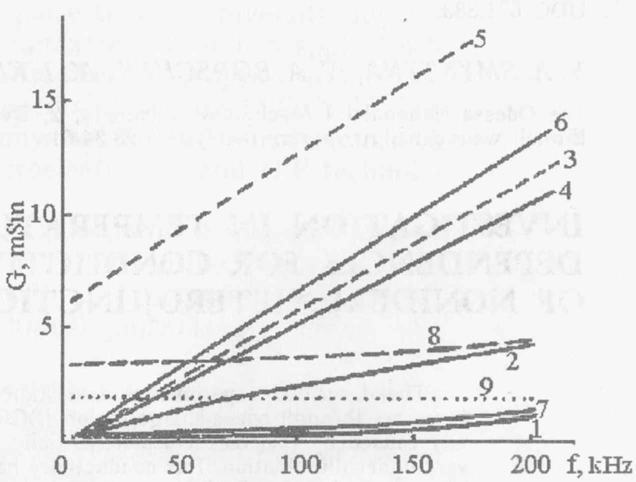

Fig. 4. Frequency dependencies for conductivity heterojunction $CdS—Cu_2S$:

1 — in the darkness, *2*—*4* — under two illumination levels with $\lambda < 520$ nm (*2* — corresponds to low level, *3* and *4* correspond to high level), *5* and *6* — under illumination by white light, *7* and *8* — under illumination with $700 < \lambda < 1200$ nm. Full curves correspond to the short-circuit condition, dash curves — to open-circuit. The dotted curve (*9*) shows frequency characteristic for Germanium homojunction

Cu_2S, measured at various external conditions and, for comparison — germanium homojunction, are given.

As one would expect, the conductivity of the latter, determined only by the free carriers transfer, does not depend on the frequency of the measuring signal (fig. 4, curve *9*). The heterojunction $CdS—Cu_2S$ conductivity, measured at darkness and at two illumination intensities with $\lambda < 520$ nm (modulating SCR junction width), increases with frequency raise in whole investigated range (1—200 kHz), and all obtained dependencies look like close to linear (fig. 4, curves *1*, *2*, *4*). These curves were measured at conditions of element short circuit by a constant component, that is at unchanged height of the barrier for all illumination conditions. It is well seen, that as, at increase of stimulating light intensity, the angle slope of the frequency dependence raises essentially. This becomes clear if one takes into account, that not the material specific conductivity σ was measured, but the full element G conductivity which determined mainly by barrier area. If resistance of this area to be considered homogeneous as the first approximation, its conductivity will make $\sigma = G\ (W/S)$, where S is junction area, and W — SCR width.

It is obvious, that the factor governed the slope of the frequency dependence diagram, is determined by the geometrical area, limiting conductivity value. The junction area S does not depend on external conditions. At the photo cell illumination by the light stimulating wideband CdS, the width of SCR junction W will decrease, and in conditions of short circuit the height of barrier remains unchanged. It results in increase of the angle slope for frequency dependence curve, that one can see experimentally. So, when the samples were illuminated by light with $\lambda < 520$ нм, U_{oc} of the opened elements was not too large, therefore a small distinction in curve slope for frequency dependence and in the constant component for short-circuit and opened-circuit conditions becomes appreciable only at the greatest intensity of stimulating light (which generates $U_{oc} = 159$ mV, fig 4, curve *3*).

Frequency characteristics in darkness and at small illumination intensity (generating $U_{xx} = 17$ mV) for short-circuit and opened-circuit conditions coincide, as the barrier height varies slightly. The change of barrier width connected with the bias presence (but not with the effect of light modulation) is rather insignificant in this case too. At the element illumination by white light, the difference between frequency characteristics for opened and short-circuit conditions is very essential (fig. 4, curves *5—6*). At practically identical curve slopes in opened condition ($U_{oc} = 375$ mV), the element displays the higher conductivity constant component $G(0)$, than in the short-circuit one. The appearance of such shift at transfer of element from short circuit mode in open- circuit mode is not enough to change significantly the barrier width W (and, hence, the slope of frequency characteristics), however, the barrier lowering may increase essentially its conductivity for a direct current which obviously has tunnel-jumping character too because such displacement to occur significant thermoactivation transport connected with the free carrier over-barrier emission, is not enough, nevertheless.

The illumination of element by light with $\lambda > 520$ nm, which does not cause change in the barrier width in short circuit current mode, does not influence the form of frequency characteristics (fig. 4, curve *7*). For the open-circuit element, such illumination (generating $U_{oc} = 376$ mV) results in displacement without slope change (fig. 4, curve *8*). As well as in the case of illumination by white light, it indicates the essential raise of conductivity constant component.

In fig. 5, the conductivity frequency dependences of the non-illuminated element plotted in double logarithmic coordinates are presented at various external biases. For $U = 0$ in the most part of the investigated frequency range, the conductivity increases under the power law and $s \sim 0.8 \div 1.0$. In the low-frequency region (at $f < 2$ kHz) conductivity does not depend practically on frequency, so σ is defined basically by constant component $\sigma(0)$, as $\sigma(0) \gg A\omega^s$. With the bias raise $\sigma(0)$ increases, the condition $\sigma(0) \gg A\omega^s$ is satisfied for the high frequencies and the initial horizontal part is extended. At

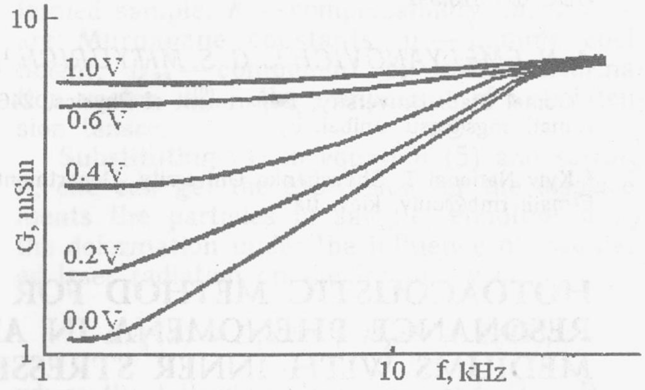

Fig. 5. Frequency dependence of conductivity for heterojunction CdS—Cu_2S at various constant biases

high enough frequencies (~ 200 kHz) the curves tend to some constant value caused by series resistance of base layer (at rather high frequency the barrier conductivity becomes so high, that heterostructure resistance will be defined by a base layer).

If the bias is high enough $\sigma(0)$ increases so that the barrier stop to control a current even at low frequencies. In this case heterojunctions conductivity is defined by free carriers transport in the base region and the frequency dependence practically disappears (fig. 5).

In summary we shall note, that for the majority of photocells investigated by us the photoelectric characteristics deterioration was caused by SCR jumping conductivity [4—5]. Therefore, the losses influence character reduction investigation connected with this transport, and also the building these processes model in CdS—Cu_2S heterojunction has significant theoretical and practical interest.

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