and discussion.

[1] H. Benard, Ann. Chim. et phys. 23, 62 (1901).

[2] R. Schmidt and O. Saunders, Proc. Roy. Soc. 165, 216 (1938).

[3] S. Mal, Beitr. Z. Physik d. fr. Atm. 17, 40 (1931).

[4] D. Q. Brunt, J. Roy. Met. Soc. 63, 277 (1937).

[5] K. Chandra, Proc. Roy. Soc.(London) 164A, 231 (1938).

[6] V. K. Liapidevskii, J. Exptl. Theoret. Phys.(U.S.S.R.) 27, 103 (1954).

[7] V. K. Liapedevskii, J. Exptl. Theoret. Phys.(U.S.S.R.) 29, 263 (1955).

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Metal-to-Semiconductor Contact Resistance at High Contact Potential Differences

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IT is well known that at the interface between a metal and a semiconductor under certain condi-

tions[1] there appears a layer with additional resistance R_k which is related to the contact potentail difference (cpd) by Davydov's equation[2]

$$R_k = (2\varkappa / \sigma)(\exp\{eV_k / kT\} - 1),$$

where R_k is the supplementary resistance, $1/\varkappa$ is the Debye screening thickness, σ is the conductivity of the semiconductor, and V_k is the cpd between the semiconductor and the metal. This equation is applicable for small V_k (when there is no intersection of the Fermi level and the impurity level), but it does not take into account a number of secondary phenomena: screening of the field by the space charge, tunnel effect, etc. For large V_k, when the above mentioned intersection takes place, Davydov's equation is entirely unacceptable, since a layer with reversed resistivity now appears on the surface of the semiconductor and thus dependence of R_k on V_k is different than in the case of small V_k. The degree to which the surface levels are filled with electrons must also affect the magnitude of the contact resistance

We have measured the dependence of R_k on the cpd V_k by the method of clamped contacts for different degrees of filling of the surface levels of
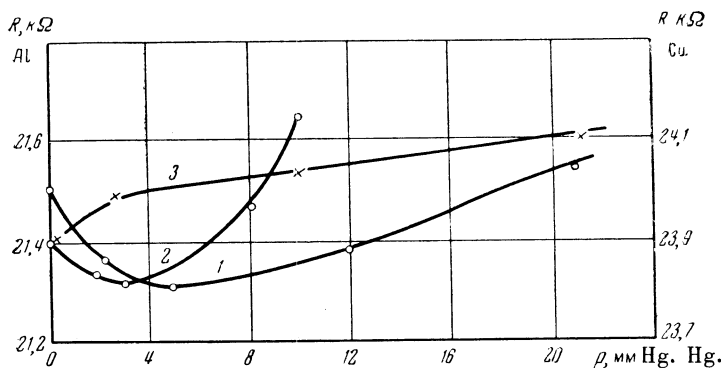

FIG. 1. Change of metal-to-semiconductor contact resistance with air pressure: *1* and *2* — copper oxide — aluminum ($V_k = 1.18$ v), two samples; *3* — copper oxide — copper ($V_k = 0.22$ v).

samples of copper oxide[3]. The copper oxide was prepared by the standard method of heating in a high-temperature furnace followed by quenching in boiling water. The copper oxide was not separated from the copper base in order to increase the strength of the sample. Different metals were deposited on the same sheet of nickel, measuring $10 \times 15 \times 0.05$

mm. The measurements were taken at room temperature. The contact potential difference was measured by the vibration method with an accuracy to within 0.005 v; R'_k was measured by a direct current bridge with an accuracy to within 0.5%.

The filling of the surface levels was changed through adsorption on the semiconductor surface of water, alcohol, acetone and benzene vapors (as

in Ref. 4). The *cpd* then changed by 0.04 − 0.06 v and the resistance changed as a function of the *cpd* and the pressure of the adsorbed vapor. For small V_k (Au, Cu, Ni) the resistance increased as the vapor pressure was raised, and decreased again as the pressure dropped. However, beginning at approximately $V_k = 0.50$ v (Ni) the behavior of the samples changed sharply: the resistance at first dropped very slightly with adsorption and began to rise only at considerable pressures. It was especially easy to observe this effect at evacuation or with slow admission of the vapors or of atmospheric air (which always contained water vapor (Fig. 1): the sample had a slightly smaller contact area with Cu than with Al). The most

appreciable effect was observed with aluminum and zinc (*cpd* with samples of Cu_2O in vacuum, 1.06 and 0.88 v, respectively). With nickel ($V_k = 0.50$ v) transition effects were observed − during evacuation the resistance changed quite slowly and irregularly.

We have explained the above phenomena as follows. The normal effect, i.e., the increase of resistance with the rise of vapor pressure, can be explained by the reduction of negative surface charge due to adsorption and, consequently, to the decreased positive space charge of the semiconductor contact layer. As a result of this change the deformation of the hole semiconductor zone is increased, the potential barrier is raised and the contact resistance increases.
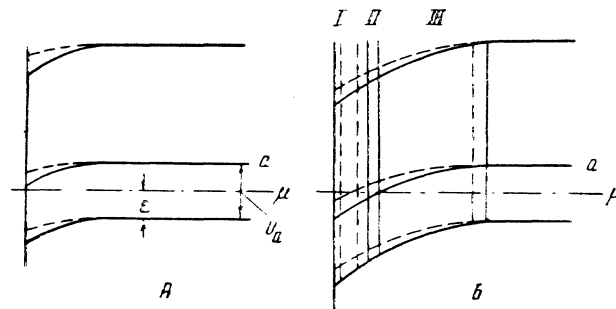

FIG. 2. Change of thickness of barrier layer of hole semiconductor with adsorption for different V_k: *A* − normal effect; *B* − anomalous effect; *a* − impurity level, μ − Fermi level, *I* − electron semiconductor, *II* − barrier layer, *III* − hole semiconductor; - — — — in vacuum; — — — with adsorption.

The anomalous effect, i.e., the decrease of R_k with rising pressure, is associated with the above-mentioned formation of a layer of an electron semiconductor (Fig. 2). With adsorption the resistance at first decreases, since the deformation of the zone narrows the barrier layer at the interface between the electron and hole semiconductors (region II). In addition with adsorption there is an increase of the number of current bearers in region I. However when the surface levels are largely filled the predominant increase of contact resistance is due to the curvature of the filled zone (resistance increase of region III), and there is also a decrease of *cpd* screening by the contact charge. The total resistance of the sample increases. The fact that the intersection of the chemical potential level with the impurity level takes place at $V_k = 0.50$ v, but theoretically should occur at 0.15 v (the hole activation energy is $\varepsilon = U_a 2$ and $U_a = 0.30$ v for copper oxide, as follows from the

temperature dependence of the resistivity of the sample), shows that the entire *cpd* field does not penetrate into the semiconductor, but that a considerable portion of it falls in the space between the semiconductor and the metal, and also is screened by the contact charge.

Thus the above experiments show that: 1) in the study of contact resistances it is necessary to take into consideration the filling of the surface levels; 2) with clamped contacts it is easy to produce intersection of the chemical potential level with the impurity level.

When our work had been completed and was being prepared for publication there appeared a report by Kalashnijov and Iunovich[5] concerning a similar layer on the surface of germanium.

[1] A. V. Ioffe. J. Exptl. Theoret. Phys. (U.S.S.R.) 15, 721 (1945).

[2] B. I. Davydov, J. Exptl. Theoret. Phys. (U.S.S.R.) 9, 451 (1939).

[3] N. A. Gozhenko, Scientific Symposium of the Uzhgorod State University (in press).

[4] V. E. Lashkarev and V. I. Liashenko, Symposium in Commemoration of the 70th Birthday of A. F. Ioffe, 1950, p. 535.

[5] S. G. Kalashnikov and E. A. Iunovich, J. Tech. Phys. (U.S.S.R.) 25, 952 (1955).

Investigation of NaCl-AgCl Trapping Centers by a Method of Thermo-Optical Bleaching

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TO investigate trapping centers in a crystal, a method could be applied which is based on the measurement of the change $\Delta \varkappa$ of the absorption coefficient of the trapping centers as a function of the temperature T when the crystal is excited by heat at a constant rate β. The theory and some of its applications are explained in the following [1-3]. The dependency of $\Delta \varkappa(T)$ was investigated under conditions such that electrons released from the trapping centers by optical excitation were small compared to the thermal excitation during the measurement of $\Delta \varkappa$. Perhaps conditions can be treated such that the optical system which releases electrons from the trapping centers will be of a secondary nature. This discloses a supplementary method for investigation of trapping centers. Usually the probability of direct optical ionization of the trapping centers for the release of electrons is smaller than that of the optical release of electrons from trapping centers of thoroughly warmed crystals [4].

Let us suppose a crystal contains a single type of electron trapping center; the change of the numbers of electrons n of the thermally excited crystal would then be proportional to the condition of continuous illumination of the light flux B, and determined by the equation

$$-\frac{dn}{dT} = \beta_0^{-1}(p + \alpha B p^*) n \frac{\sigma_p n}{\sigma_p n + \sigma_3(N - n)}. \quad (1)$$

Here σ_r and σ_t are the effective crosssections of recombination and trapping N, the number of trapping levels, $p = p_0 \exp(-E_T / kT)$ and $p^* = p_0^* \exp(-E_T^* / kT)$ — the laws of probability of thermal ionization of the trapping centers of the stable and excited states. (It would be convenient to designate the value of E_t as the thermal ionization energy of the trapping center, although this is not strictly correct. See, for example, Ref. 2. Since $\Delta \varkappa = An$, the coefficient A is slightly dependent on the temperature ($A \sim T^{-0.5}$). Equation (1) determines not only $n(T)$ but also the dependence of $\Delta \varkappa(T)$.

If $p \gg \alpha B p^*$, which has been previously pointed out [3], the temperature T_k at which $n = 0.5\, n_0$, is connected with the thermal ionization energy of the trapping centers by the relation

$$T_k = \frac{E_T}{k} \left\{ \ln \left[\frac{p_0}{\beta_0} \delta_k \left(1 + \frac{2\sigma_3 N}{\sigma_p n_0} - \frac{\sigma_3}{\sigma_p}\right)^{-1}\right]\right\}^{-1} \quad (2)$$

If $p \ll \alpha B p^*$, then most of the electrons would be liberated from the trapping centers due to optical bleaching. It is easily shown that, in this case,

$$(3)$$

$$T_k = \frac{E_T^*}{k} \left\{ \ln \left[\alpha B \frac{p_0^*}{\beta_0} \delta_k \left(1 + \frac{2\sigma_3 N}{\sigma_p n_0} - \frac{\sigma_3}{\sigma_p}\right)^{-1}\right]\right\}^{-1}.$$

Thus, when B is small (the region of thermal bleaching) $T_k \neq T_k(B)$. When B is large (the region of optical bleaching) $T_k^{-1} = kE_T^{-1}\ln B + \text{const}$.

For measuring the bleaching curve $\Delta \varkappa(T)$ it is necessary to maintain control of the light flux for the investigation. It is possible to determine E_T from the rate of the thermal bleaching, which is dependent on $\Delta \varkappa(T)$. [2,3] From the rate of the optical bleaching, which is dependent on $\Delta \varkappa(T)$ as well as T_k for B, it is possible to determine the thermal ionization energy E_T of the excited trapping centers.

A method of thermo-optical bleaching was used by us in the investigation of trapping centers of single crystals of NaCl-AgCl. Simultaneous experiments were made of the spectral absorption of the trapping centers $\Delta \varkappa(\lambda)$ and thermal curve $I(T)$.

The quantities $\Delta \varkappa(T)$ and $\Delta \varkappa(\lambda)$ were measured on the SF-4 and SF-2M spectrophotometers. Curve $I(T)$ was recorded with the aid of an electron multiplier, amplifier, and self-recording potentiometer EPP-09. In all runs, $\beta_0 = 0.14$ deg./sec.

In accordance with literature [5-8], we found the $F-$ and $M-$ bands (460 and 720 mμ) in x-rayed