If we assume that a second neutral meson, having the same mass as the π^0 meson, exists but is capable, unlike the other, of decaying into three γ quanta, then we obtain from our data the following maximum estimates for the relative probability of production and decay of such a meson: 6×10^{-8} at an average lifetime $\tau_{3\gamma} < 10^{-10}$ sec, 1.3×10^{-5} ($\tau_{3\gamma} < 5 \times 10^{-10}$ sec), 2×10^{-5} ($\tau_{3\gamma} < 10^{-9}$ sec), and 1.5×10^{-4} ($\tau_{3\gamma} < 10^{-7}$ sec).

The method used in the present paper to register the $\pi^0 \to 3\gamma$ decay allows us, in our opinion, to advance into a region of even lower values of λ.

In conclusion, we take the opportunity to thank L. I. Lapidus, L. B. Okun', I. Ya. Pomeranchuk, and B. Pontecorvo for useful discussions.

[1] Christenson, Cronin, Fitch, and Turlay, Phys. Rev. Lett. 13, 138 (1964).

[2] Dunaitsev, Petrukhin, Prokoshkin, and Rykalin, JETP 47, 84 (1964), Soviet Phys. JETP 20, 58 (1965); V. I. Petrukhin and Yu. D. Prokoshkin, Nuovo Cimento 28, 99 (1963).

[3] A. F. Dunaitsev, PTE no. 6, 77 (1964).

[4] Dunaitsev, Petrukhin, Prokoshkin, and Rykalin, PTE no. 2, 114 (1965).

[5] F. A. Berends, Phys. Rev. Lett. 16, 178 (1965).

[6] R. P. Ely and D. H. Frisch, Phys. Rev. Lett. 3, 565 (1959).

[7] Vasilevskii, Vishnyakov, Dunaitsev, Prokoshkin, Rykalin, and Tyapkin, Proc. Internat. Conf. on High-energy Physics, Dubna, 1964.

[8] D. Cline and R. Dowd, Phys. Rev. Lett. 13, 530 (1965).

[1)] Reported at the June Session of the Nuclear Physics Division of the USSR Academy of Sciences.

FEATURES OF OPTICAL ABSORPTION OF METALLIC FILMS IN THE REGION WHERE THE METAL TURNS INTO A DIELECTRIC

V. N. Lutskii
Institute of Radio Engineering and Electronics, USSR Academy of Sciences
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1. It is well known that the character of the conductivity of many metals is governed by the overlapping of the valence and conduction bands. Any cause which leads to elimination of this overlap transforms the metal into a dielectric (at 0°K). In particular, the transformation of a metal into a dielectric in a quantizing electric field was discussed in [1].

A similar result is expected in the case of thin metallic films, in which conditions for size quantizations of the energy spectrum of the carriers is realized. The quantization of the energy spectrum, as is well known, leads to a shift of the bottom of the conduction band and of the top of the valence band by an amount $\Delta\epsilon = \pi^2\hbar^2/2md^2$ (in the approximation where $\epsilon = p^2/2m$), where d is the thickness of the film and m the effective mass of the carriers in the band in question. With decreasing d, the energy corresponding to the bottom of the con-

duction band increases, and that corresponding to the top of the valence band decreases. The thickness-dependent change in the width of the forbidden band of semiconductor films was first noted by V. B. Sandomirskii [2].

For metals with small effective carrier mass, the value of d at which the overlap of the bands is eliminated is quite large. For Bi, for example, it amounts to $\sim 10^{-5}$ cm. It must be noted that for Bi films $\lesssim 10^{-5}$ thick the experimentally observed temperature dependence of the conductivity is similar to that of a semiconductor [3].

2. Metals in which the extrema of the overlapping bands occur at different values of the wave vector $\vec{k}$ should exhibit singularities of light absorption in the region where the metal is transformed into a dielectric. Let us consider the band scheme usually given for Bi [4] (Fig. 1). The direction of $\vec{k}$ is chosen such that the plane of the figure crosses the minimum of the conduction band ϵ_c. The maximum of the valence band V_1 is arbitrarily located at the origin. The energy is measured from an arbitrary deep-lying level in a bulk sample.

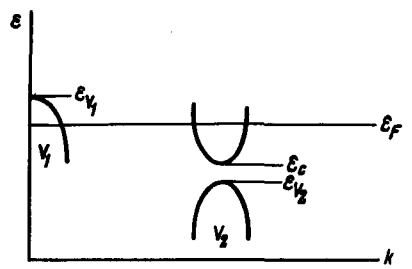

Fig. 1.

We consider optical transitions from the band V_2 to the conduction band. We define the red boundary ($h\nu_{red}$) of such transitions as the distance from the maximal of the V_2 band to the Fermi level (ϵ_F) for large film thicknesses (metal), or the distance between the extrema of the V_2 and conduction bands for films with thickness $d < d_0$, where d_0 is the thickness at which the metal turns into a dielectric.

Let us determine the relation $h\nu_{red} = f(d)$. We assume that the dispersion law is quadratic and isotropic, that the effective mass of the carriers does not depend on the thickness of the film, and that $T = 0°K$. The position of the Fermi level, as usual, is determined from the neutrality condition

$$\sum_{n=1}^{N_{p_1}} \int_{\epsilon_F}^{\epsilon_{V_1 0} - \frac{\pi^2\hbar^2 n^2}{2m_{p_1} d^2}} f(\epsilon) g_{V_1}(\epsilon)\, d\epsilon = \sum_{n=1}^{N_e} \int_{\epsilon_{c0} + \frac{\pi^2\hbar^2 n^2}{2m_e d^2}}^{\epsilon_p} f(\epsilon) g_c(\epsilon)\, d\epsilon \qquad (1)$$

The integration is carried out here within the limits of a single subband, corresponding to a fixed value of the transverse component of the wave vector. The summation is over the number of filled subbands. We use the following notation: $f(\epsilon)$ - Fermi distribution function; $g_{V_1}(\epsilon) = m_{p_1}/\pi\hbar^2$, $g_c(\epsilon) = m_e/\pi\hbar^2$ - state density in the subband for the V_1 and conduction band, respectively; m_{p_1} and m_e - effective masses of the carrier in the V_1 and conduction bands, respectively; $\epsilon_{V_1 0}$ - energy corresponding to the maximal of the V_1 band in the bulk sample; ϵ_{c0} - energy corresponding to the bottom of the conduction band in the bulk sample; n = 1, 2, 3, ...; N_{p_1}, N_e - number of filled subbands in V_1 and in the conduction band, respectively ($N_{p_1} = E([2m_{p_1}(\epsilon_{V_1 0} - \epsilon_F)]^{1/2}/\pi\hbar)d$; $N_e = E([2m_e(\epsilon_F - \epsilon_{c0})]^{1/2}/\pi\hbar)d$; E(x) - whole-number part of x).

From (1) we get

$$\epsilon_F = \frac{N_{p_1} m_{p_1} \epsilon_{V_1 0} + N_e m_e \epsilon_{c0}}{N_{p_1} m_{p_1} + N_e m_e} + \frac{\pi^2 \hbar^2 [N_e(N_e + 1)(2N_e + 1) - N_{p_1}(N_{p_1} + 1)(2N_{p_1} + 1)]}{12 d^2 (N_{p_1} m_{p_1} + N_e m_e)} ,$$

$$(N_{p_1} \text{ and } N_e = f(\epsilon_F)).$$

We consider two particular cases.

1. We put $N_{p_1} = N_e = 1$.

This condition imposes limitations on the thickness of the film. The Fermi level should be located within the limits of the first subband for the electrons and the holes, from which it follows that

$$d \leq [2\pi^2 \hbar^2 (1/m_e + 1/m_{p_1})(\epsilon_{V_1 0} - \epsilon_{c0})^{-1}]^{1/2} .$$

In addition, for reasonable values of d, the masses of the electrons and of the holes should not differ greatly.

Under these conditions, the dependence of $h\nu_{red}(d)$ takes the form

$$h\nu_{red} = \left(\frac{m_{p_1} \epsilon_{V_1 0} + m_e \epsilon_{c0}}{m_{p_1} + m_e} - \epsilon_{V_2 0} \right) + \frac{\pi^2 \hbar^2}{2 m_{p_2} d^2} \qquad \text{for} \quad d > d_0 \tag{2}$$

and

$$h\nu_{red} = (\epsilon_{c0} - \epsilon_{V_2 0}) + \frac{\pi^2 \hbar^2}{2 d^2} \left(\frac{1}{m_e} + \frac{1}{m_{p_2}} \right) \qquad \text{for} \quad d < d_0 . \tag{2a}$$

Here: $\epsilon_{V_2 0}$ is the top of the valence band V_2 in the bulk sample and m_{p_2} is the effective mass of the holes in the band V_2.

A qualitative plot of $h\nu_{red} = f(1/d^2)$ is shown in Fig. 2. The curve is characterized by a kink at the point $d = d_0$, indicating the transition of the metal into a semiconductor. The intercepts $\epsilon' = \epsilon_{c0} - \epsilon_{V_2 0}$ and $\epsilon'' = (m_{p_2} \epsilon_{V_1 0} + m_e \epsilon_{c0})/(m_{p_1} + m_e) - \epsilon_{V_2 0}$ of the lines $h\nu_{red}(1/d^2)$ with the ordinate axis give respectively the width of the forbidden band and the position of the Fermi level relative to the top of the valence band V_2 in the bulk sample (for $N_{p_1} = N_e = 1$ and $\epsilon_F = (m_{p_1} \epsilon_{V_1 0} + m_e \epsilon_{c0})/(m_{p_1} + m_e)$).

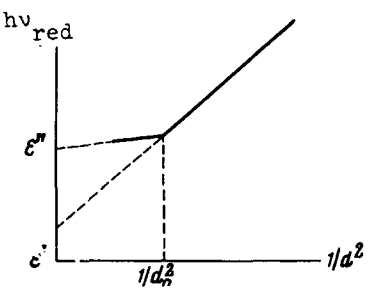

Fig. 2.

At the point $d = d_0$, equating (2) and (2a), we have $\epsilon'' - \epsilon' = \pi^2 \hbar^2 / 2 m_e d_0^2$, from which we can determine the effective mass of the electrons. We note in this connection that it is possibly more important not so much to determine the parameters of the band scheme by this method, as to check on the assumptions made concerning the dispersion law and the independence of the carrier effective mass of the thickness, by comparing the derived expressions with experimental results. [1)]

2. We consider the case when $m_{p_1} \gg m_e$. This situation is apparently realized in bismuth. In this case $\epsilon_F \approx \epsilon_{V_1 0}$. Thus, for $d > d_0$ we get

$$h\nu_{red} = (\epsilon_{V_1 0} - \epsilon_{V_2 0}) + \frac{\pi^2 \hbar^2}{2m_{p_2} d^2} \tag{3}$$

and for $d < d_0$

$$h\nu_{red} = (\epsilon_{c0} - \epsilon_{V_2 0}) + \frac{\pi^2 \hbar^2}{2d^2} \left(\frac{1}{m_e} + \frac{1}{m_{p_2}}\right). \tag{3a}$$

Qualitatively, the form of $h\nu_{red}(1/d^2)$ remains the same as in Fig. 2, but ϵ' and ϵ'' are now defined as $\epsilon' = \epsilon_{c0} - \epsilon_{V_2 0}$ and $\epsilon'' = \epsilon_{V_1 0} - \epsilon_{V_2 0}$, i.e., we determine, besides the forbidden band of the bulk samples, also the distance between the valence band maxima at different values of $\vec{k}$. At the point $d = d_0$, in analogy with the preceding case, we determine the value of m_e. We note finally that, in the thickness range in question, singularities should also be observed for the transitions from the V_2 band to the conduction band.

[1] M. Ya. Azbel' and N. B. Brandt, JETP 48, 1206 (1965), Soviet Phys. JETP 21, 804 (1965).

[2] V. B. Sandomirskii, JETP 43, 2309 (1962), Soviet Phys. JETP 16, 1631 (1963).

[3] Yu. F. Ogrin, Diploma Thesis, Physics Institute, Academy of Sciences, 1962; M. Green, Bull. Amer. Phys. Soc., ser. II 10, 111 (1965).

[4] B. Lax, Revs. Modern Phys. 30, 122 (1958).

[1)] I am deeply grateful to V. B. Sandomirskii who expressed this opinion.

TRANSITION OF SEMICONDUCTORS TO A SUPERCONDUCTING STATE UNDER THE INFLUENCE OF THE FIELD EFFECT

V. B. Sandomirskii

Institute of Radio Engineering and Electronics, USSR Academy of Sciences

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In superconducting semiconductors the transition to the superconducting state sets in at a carrier density small compared with that in metals, and the transition temperature T_c depends on the carrier density. In p-type GeTe, T_c changes from 0.1 to 0.3°K as the hole density is changed from 8.5×10^{20} to 1.5×10^{21} cm^{-3} [1]. In n-type $SrTiO_3$, T_c changes from 0.1 to 1.0°K as the density of the normal electron is changed from 10^{18} to 10^{21} cm^{-3}, going through a maximum at $T_c \simeq 0.5$°K and at $n \simeq 10^{20}$ cm^{-3} [2]. In either n- or p-type PbTe, $T_c \simeq 5$°K at an excess of Pb (n-type) density or Tl (p-type) impurity density ~1 wt.% [3]. Such carrier densities can be produced in a narrow region near the surface of a superconductor by means of the field effect. To avoid misunderstanding we emphasize that we are referring here not to the surface superconductivity considered by V. L. Ginzburg and D. L. Kirzhnits [4], but to superconductivity in a space-charge layer near the surface.

Let us make a few estimates for a semiconductor having the parameters of $SrTiO_3$. Assume that a degenerate layer of such a superconductor serves as one electrode of a capacitor in which the dielectric is a ferroelectric material. (It is obvious that to increase the capac-