MOTT TRANSITION IN THE EXCITON SYSTEM IN GERMANIUM

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The exciton gas of a semiconductor is a convenient object for the study of the transition of a many-electron system into a state with metallic conductivity. Since the Bohr radius of the Wannier-Mott excitons in semiconductors is quite large, an appreciable overlap of the wave functions is attained at relatively low densities. Another important factor is that it is possible to study the conductivity in this case while the density is gradually varied.

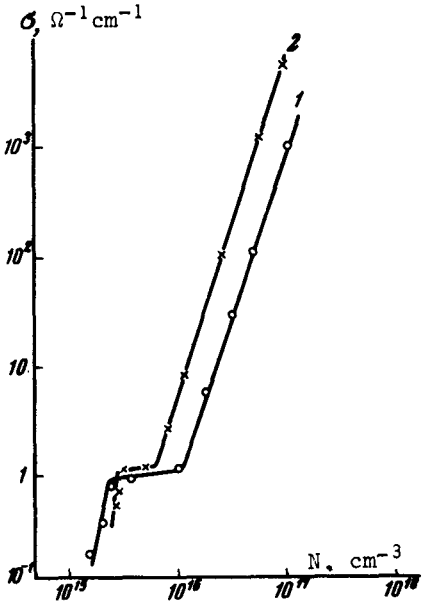
The laws governing the transition of a many-electron system into a state with metallic conductivity were investigated theoretically by Mott [1], who presented, in particular, arguments indicating that the transition should be in the nature of an abrupt jump of the conductivity with a smooth increase of the density. For a system of hydrogenlike centers, the criterion for the transition into the metallic state is [1]

$$r_{\hbar} n^{1/3} \geq 0.25, \tag{1}$$

where $r_{\hbar} = \epsilon\hbar/e^2 m^*$ is the Bohr radius of the center.

Preliminary results given in [2] indicate that at densities satisfying (1) and at 4.2°K the electrons and holes produced in germanium by light have a high mobility, the density dependence of which is evidence of the presence of metallic conductivity.

The present communication is devoted to a further investigation of this question by a somewhat better procedure. The improvement consists essentially of performing the measurements soon after the termination of the light pulse, within a time interval that is short compared with the carrier lifetime. This eliminates the influence of the heating of the electron-



Germanium conductivity vs. density of electron-hole pairs at 4.2°K (1) and 1.7°K (2) (the conductivity was measured with an electric field of 0.04 V/cm applied to the sample).

hole plasma, occurring when the carriers produced by the light are thermalized.

We investigated the photoconductivity of n- and p-type germanium with a doping-impurity density from 3×10^{13} to 6×10^{13} cm^{-3} at temperatures 1.7 and 4.2°K. The electron-hole pairs were produced by a pulsed light source with a flash duration 0.25 - 2 μsec. We chose for the measurements samples in which the lifetime of the electron-hole pairs in the entire range from room temperature to 1.7°K was much larger than the light-pulse duration. This made it possible to use the method described in [2] to determine the density.

The results of the experiments were independent of the dark conductivity of the samples (at 77°K).

The figure shows typical plots of the conductivity against the density of the electron-hole pairs at T = 1.7 and 4.2°K. At densities lower than 2×10^{15} cm^{-3}, there is no conductivity, thus evidencing that practically all the carriers are bound into excitions. That excitons are indeed produced can be readily verified by applying to the sample a field of intensity larger than 3.5 V/cm, when a sharp increase of the conductivity is produced by the shock ionization of the excitons [3].

When the excitation level is increased and the density reaches $\sim 2 \times 10^{15}$ cm^{-3}, the conductivity of the crystal increases jumpwise. On this section of the curve, a change of density by a factor 1.5 increases the conductivity tenfold. Such an abrupt jump of the conductivity can be attributed to a sharp rise in the number of free carriers as a result of the transition of the system of excitons into the metallic state. With decreasing temperature, this section becomes less steep and shifts towards larger densities, in accordance with the expected temperature dependence of the Mott transition. An important proof of the metallic character of the conductivity beyond the transition point is the absence of a noticeable temperature dependence of the conductivity.

The density at which the metallization of the exciton states takes place satisfies the condition $r_{\text{ex}} n^{1/3} \geq 0.2$, where the exciton Bohr radius r_{ex} is assumed equal to 140 Å [4]. This inequality should be compared with the Mott criterion (1) given above [1)].

With further increase of the density, a section is observed in which the increase of the conductivity is faster than linear and in which the total mobility of the electrons and the holes increases with increasing density and with decreasing temperature like

$$(\mu_n + \mu_p) \sim n^2/T^2. \qquad (2)$$

At T = 1.7°K and $n = 2 \times 10^{17}$ cm^{-3} the mobility reaches a value $\sim 10^6$ $cm^2 V^{-1} sec^{-1}$, which is much higher than the value expected theoretically for scattering by charged centers in either a classical plasma or a degenerate one in the case of immobile scattering centers.

The observed regularities can be understood by recognizing that the gas is degenerate. In this case only a small part of the carriers, in a strip of width ~kT near the Fermi sur-

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1) The Mott transition was observed earlier for hydrogenlike impurity centers in germanium, and the experimentally obtained transition condition also has the form $r_{\text{H}} n^{1/3} \geq 0.2$, where r_{H} is the Bohr radius of the impurity center [1].

face can take part in the scattering of carriers of opposite sign, since by virtue of the Pauli principle the particles situated deep under the Fermi level cannot change their energy by the amount ~kT which is transferred by carrier collision. In addition, the scattered carrier should also remain in the strip ~kT after the collision. Allowance for these limitations leads to the following dependence of the mobility on the density and on the temperature [5]

$$\mu \sim n^{4/3} T^2. \qquad (3)$$

This expression describes correctly the temperature dependence, but leads to a somewhat weaker dependence on the density. Formula (3) has been derived under the assumption that the density is so high that $r_n n^{1/3} \gg 1$, whereas at the highest densities attained in the present experiments $r_n n^{1/3} \approx 1$. This is why the discrepancy between the experimental results and the theory is not unexpected.

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GENERATION IN POLYMETHINE DYE SOLUTIONS EXCITED BY NEODYMIUM-GLASS LASER EMISSION (λ = 1.06 μ)

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The feasibility of generation by organic dyes has uncovered new possibilities for effective frequency conversion of the emission of powerful lasers in a wide spectral interval. So far, dyes were used for frequency conversion of ruby-laser emission [1-4] and of the harmonics of the emission of ruby and neodymium-glass lasers [5]. There is no published report of direct conversion of neodymium laser emission at λ = 1.06 μ. Yet the conversion of this emission with the aid of dyes is of undisputed scientific and practical interest, since the neodymium-glass laser is one of the most powerful solid-state lasers. In addition, the use of lasers of this type can extend the spectral range of the converted radiation towards longer wavelenths (λ > 1.06 μ). We therefore attempted to convert the 1.06-μ neodymium-laser

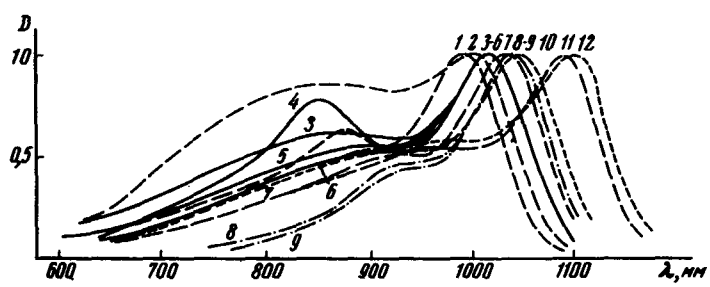

Fig. 1. Absorption spectra of dye solutions in nitrobenzene.