In addition, the effect can be further increased by using thin-layer nonmagnetic dielectric coatings.

The frequency dependence of $\delta(\omega)$ of the investigated iron garnets is characterized in the main by the presence of a strong positive maximum at $\hbar\omega = 2.85$ eV for $\phi = 70°$, and also of two positive maxima ($\hbar\omega = 2.55$ and 2.75 eV) and two negative maxima ($\hbar\omega = 2.95$ and 3.15 eV) for $\phi = 65°$. It can be assumed that this structure is due to the two lowest-energy transitions $t_1(\pi) \rightarrow e(\pi)$ (A) and $t_2(\pi_1\sigma) \rightarrow e(\pi)$ (B) in the tetrahedral FeO_4 complexes. These are two allowed electric-dipole transitions from the oxygen orbitals of the $2p(\pi, \sigma)$ type to the Fe^{3+} ion orbitals of the 3d(e) type [2]. The fact that the magneto-optical transitions in the region 2 - 3.4 eV are due mainly to the tetrahedral iron ions was established for europium garnets in [3] by replacing the tetrahedral Fe^{3+} ions with nonmagnetic Ga^{3+} ions, but the transitions for the iron garnets were not identified there. The δ curve for the yttrium garnet at $\phi = 65°$ (Fig. 2) can be represented in the 2.5 - 3.3 eV region as a superposition of two dispersion-type curves with natural frequencies 2.75 and 2.95 eV and half-widths of the order of 0.2 eV, and the δ curve for $\phi = 70°$ can be represented by a superposition of similar curves of the absorption type.

The last circumstance is apparently connected with the fact that according to our estimates the main contribution to δ at $\phi = 70°$ and in the 2 - 3.4 eV region is made by the absorption part of the nondiagonal component of the dielectric tensor. Thus, the indicated maximum of δ at $\phi = 70°$ and $\hbar\omega = 2.85$ eV is due to the maximum of the losses at the magneto-optical transitions A and B, and the values obtained for the natural frequencies of these transitions are 2.75 and 2.95 eV.

The δ curves for the terbium and europium garnets are in the main analogous to the corresponding curves for the yttrium garnet, but there are some significant differences. In the europium garnet, and particularly in the terbium garnet, the amplitudes of the 2.55 and 2.75 eV maxima are lower at $\phi = 65°$, and the shape of the positive 2.85-eV maximum at $\phi = 70°$ is altered. In the europium garnet the amplitude of the 2.55-eV negative peak at $\phi = 70°$ is lower, and in the terbium garnet this peak is shifted to the region of positive δ. The change observed in the $\delta(\omega)$ curves in the rare-earth terbium and europium garnet is apparently connected not directly with the optical transitions in the rare-earth Tb^{3+} and Eu^{3+} ions, but with the indirect influence of the rare earth sublattice on the character of the formation of the molecular orbitals in the FeO_4 complexes and on the intensity of the optical transition.

[1] G.S. Krinchik and V.S. Gushchin, Zh. Eksp. Teor. Fiz. 56, 1833 (1969) [Sov. Phys.-JETP 29, 984 (1969)].
[2] C.J. Ballhausen and A.D. Liehr, J. Mol. Spectrosc., 2, 342 (1958).
[3] F.J. Kahn, P.S. Pershan, and J.P. Remeika, Phys. Rev. 186, No. 3 (1969).

INVESTIGATION OF THE METAL-DIELECTRIC TRANSITION IN Ge AND Si BY A MICROWAVE METHOD

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There are at present two points of view concerning the dielectric-metal transition in the exciton system in Ge and Si at low temperatures. A number of workers believe that the excitons condense into metallic drops already at a low exciton density, $n_e \sim 10^{12}$ cm^{-3}, and it is precisely the appearance of the drops

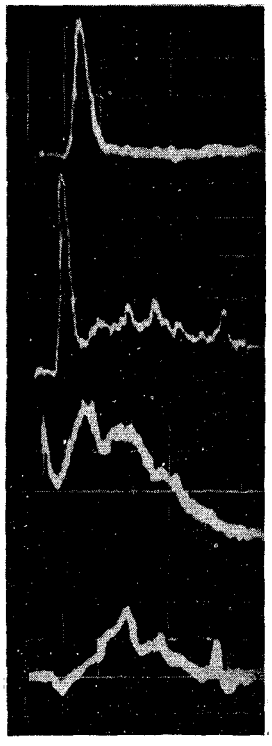

Fig. 1. Oscillogram of microwave absorption pulse in Ge. The pump increases in the downward direction. The time scale is 140 nsec/square in the first frame, and 350 nsec/square in the second, third, and fourth frames.

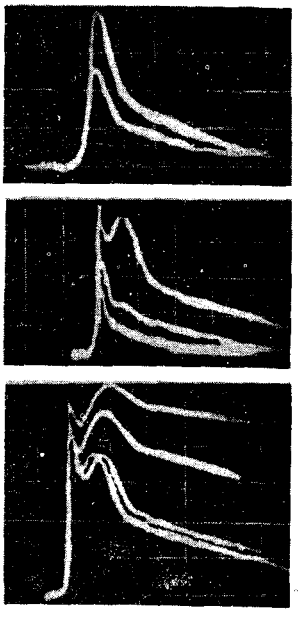

Fig. 2. Oscillograms of the absorption pulse in Si at 4.2°K. The time scale is 140 nsec/square in the first frame and 350 nsec/square in the second and third frames.

which leads to the excitation of a broad long-wave recombination-radiation line [1 - 3]. On the other hand, it is believed that the excitons first form biexcitons, the latter produce this emission line [4], and condensation of biexcitons into drops occurs when the density of the latter is appreciable, $\sim 10^{15}$ cm^{-3} [5]. One of the effective mechanisms of biexciton recombination may be Auger recombination that occurs when the biexciton annihilation is accompanied by ejection of a free electron and a free hole.

A study of the conductivity at microwave frequencies is the most direct method of detecting the appearance of metallized regions (drops) in an exciton system. The high sensitivity of the method also raises hopes of observing the conductivity due to Auger electrons.

The data obtained here by measuring microwave absorption in Ge and Si specimens excited by laser light apparently favor the existence of biexcitons and their condensation into metallic drops.

This raises the question of the behavior of an electron-hole drop at microwave frequencies. The drop can either absorb or reflect the microwave radiation, depending on its parameters (shape, dimensions, and conductivity). Our preliminary experiments [6] have shown that the drops mainly absorb the microwave radiation. The measurement procedure is described in [6].

Figure 1 shows oscillograms of an absorption pulse at 2.5°K. At low pumps, this pulse duplicates the shape of the exciting-light pulse. In this case the free carriers exist only during the time of action of the light pulse, after which they are rapidly bound into excitons and there is no microwave absorption. At a pump corresponding to[1)] $n \sim 1 \times 10^{16}$ cm^{-3}, a slow conductivity

[1)] The concentration was estimated from the generation rate, accurate to within a factor of 2.

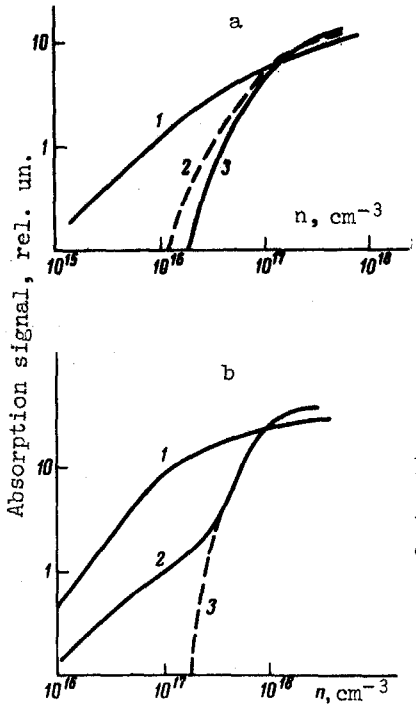

Fig. 3. Dependence of the absorption signal on the average density of the electron-hole pairs: a) Ge: 1 - amplitude of absorption signal at 4.2°K; 2 - absorption signal 300 nsec after the termination of the light pulse at 4.2°K; 3 - the same at 2.5°K; b) Si: 1 - amplitude of absorption signal; 2 - absorption signal 300 nsec after the termination of the light pulse; 3 - extrapolation of the section of absorption by the drops, T = 2.4°K.

component is produced and its content increases rapidly with increasing pulse (Fig. 3a); it is accompanied by abrupt and irregular jumps of conductivity [6]. A similar picture is observed at T = 4.2°K, but the pulse has a smoother waveform.

The picture in Si is somewhat different (Fig. 3b). Here, too, a slow kinetics sets in (Fig. 2), but its fraction in this case increases smoothly with the pump. The time of decrease of the slow kinetics greatly exceeds the lifetime in the drops. In the case of even stronger pumps, however, an additional absorption comes sharply into play, and its characteristic decay time is $\sim$300 nsec, which is close to the measured [7] lifetime of the condensed in Si[2)].

We investigated simultaneously the recombination radiation under the same conditions. At small pumps, $n \sim 10^{15}$ cm^{-3}, we observed in both Ge and Si a broad long-wave emission line [1, 3, 7]. Its shape remained unchanged, and its intensity increased linearly with increasing pump, up to $n \sim 2 \times 10^{17}$ cm^{-3} for Ge and $n \sim 3 \times 10^{18}$ cm^{-3} for Si. At large pumps, the emission line started to broaden and to shift somewhat. This instant is apparently connected with the filling of the sample with drops, and with the increased density in the electron-hole plasma.

Thus, the abrupt threshold increase of the microwave absorption sets in at concentrations that are lower by more than one order of magnitude than the particle density in the drops, and consequently the drops occupy in this case a volume not exceeding 10% of the excited volume. The presence of a steep growth of the microwave absorption signal under these conditions (Fig. 3) points to the existence of a threshold for the formation of conducting electron-hole drops. The sharp bursts of microwave conductivity are also evidence of the start of the condensation process, for they are due to the creation and

[2)] The exciton lifetime exceeds 1 μsec [7].

annihilation of a small number of drops, for in this case the conductivity of the system should vary jumpwise.

It follows from these experiments that the condensation process in Ge and Si sets in only at high density. We note, however, that the broad emission line sets in long before that instant. As shown in [4, 5], at low concentrations this line can be due to biexciton recombination.

Important evidence favoring the assumption that at $n \sim 10^{16}$ cm^{-3} the system consists mainly of biexcitons is afforded by the following facts:

The number of free electron-hole pairs present in the Ge specimen at 4.2°K and pumps $\sim 10^{14} - 10^{15}$ cm^{-3} after the light is turned off does not exceed the sensitivity of the circuit ($\sim 1 \times 10^{12}$ cm^{-3}). Such a small number of free carriers indicates that the latter are in equilibrium with the excitons and the biexcitons, and not with the excitons alone [8].

Another important proof of the existence of biexcitons is the observation of the Auger electrons produced upon annihilation of the biexcitons in Si. It is precisely these Auger electrons which determine the main slow component of the microwave absorption signal in the Si (Fig. 2). Indeed, the dependence of the amplitude of this absorption-signal component on the pump, the shape of the absorption fall-off curve, and the sensitivity of the fall-off time to the lifetime of the excitons in the sample, are all well described by the model of Auger recombination of biexcitons. We note that the picture in question should be similar to Auger recombination of bound excitons [9]; indeed, the shape of the observed conductivity fall-off curve is similar to the relaxation of the conductivity of the Auger electrons investigated in [9] in samples of strongly doped silicon[3]. After the biexcitons reach a certain density, they condense into drops. Since such drops have a lifetime of $\sim$300 nsec, they contribute to the conductivity only during this time (Figs. 2 and 3b).

Thus, apparently, at low pumps the excitons in Ge and Si become bound into biexcitons, and in the case of Si, where the Auger recombination in the biexciton is much more intense than in Ge, owing to the high effective density, conductivity of the Auger electrons is clearly observed. At sufficiently high pumps, the biexcitons condense into metallic drops. We note that the average concentration at which the condensation of the biexcitons sets in should apparently depend strongly on the experimental conditions, mainly on the character of the pump (stationary or nonstationary). Therefore the concentration region where the biexcitons can exist in the main can vary. However, great importance attaches to the result obtained here that the system goes through a biexciton stage, and that the lines of the biexciton emission and the emission of the electron-hole drops are not separated spectrally.

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[1] Ya.E. Pokrovskii and K.I. Svistunova, ZhETF Pis. Red. 9, 435 (1969) [JETP Lett. 9, 261 (1969)].
[2] In: Eksitony v poluprovodnikakh (Excitons in Semiconductors), Nauka, 1971.
[3] C. Benoit a la Guillaume, M. Voos, and F. Salvan, Phys. Rev. B5, 3079 (1972).
[4] J.R. Haynes, Phys. Rev. Lett. 17, 860 (1966).
[5] V.M. Asnin, A.A. Rogachev, and N.I. Sablina, Fiz. Tverd. Tela 14, 399 (1972) [Sov. Phys.-Solid State 14, 332 (1972)].

[3] We investigated undoped specimens with $\sim$100 ohm-cm and observed only the biexciton line in their emission spectrum.

[6] B.M. Ashkinadze and V.V. Rozhdestvenskii, ZhETF Pis. Red. 15, 371 (1972) [JETP Lett. 15, 261 (1972)].
[7] B.M. Ashkinadze, I.P. Kretsu, S.M. Ryvkin, and I.D. Yaroshetskii, Zh. Eksp. Teor. Fiz. 58, 507 (1970) [Sov. Phys.-JETP 31, 264 (1971)].
[8] L.V. Keldysh, in: Eksitony v poluprovodnikakh (Excitons in Semiconductors), Nauka, 1971.
[9] J.D. Cuthbert, J. Appl. Phys. 42, 747 (1971).

MAGNETIC ORDERING IN GARNETS WITH DIVALENT NICKEL AND COBALT IONS IN AN OCTAHEDRAL LATTICE

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A number of garnets in which the 3d-metal ions occupy only one (octahedral) position have been synthesized recently [1]. Some of these garnets exhibit antiferromagnetic properties at low temperatures. Compounds of this type are of interest as systems in which the magnetic cations are separated by at least two oxygen ions and consequently cannot be coupled by the usual superexchange interaction. The magnetic structures of garnets with Mn^{3+} and Fe^{3+} ions were determined in [2 - 4]. The difference between the types of magnetic ordering in these compounds has induced us to carry out neutron-diffraction investigations of garnets with other magnetic ions, namely

$$\{NaCa_2\}[Ni_2^{2+}](V_3)O_{12}$$

and

$$\{NaCa_2\}[Co_2^{2+}](V_3)O_{12}.$$

The neutron-diffraction patterns were obtained by the powder method from a cylindrical specimen at room and liquid-helium temperatures. Figure 1 shows the measurement results for nickel garnet. All the reflections obtained at room temperature correspond to the garnet lattice. At 4.2°K, the neutron-diffraction pattern reveals the additional magnetic peaks 200 and 222 and a noticeable contribution to the nuclear peak 420. These three magnetic reflections suffice to determine uniquely the magnetic structure (Fig. 2).

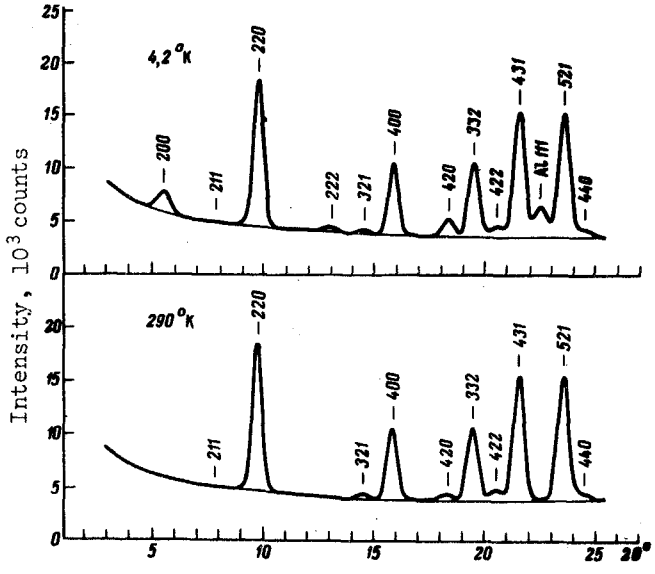

Fig. 1. Neutron diffraction pictures of nickel garnet at 3.2 and 290°K.