In the same range of pressure variation, there appears a strong linear polarization of exciton radiation, increasing to 50 - 60% at stresses lower than 200 kg/cm^2. The polarization direction was parallel to thepressure axis, corresponding to a ground state with $J_z^h = 1/2$, i.e., $\Delta_c > 0$ [5].

Such a behavior of the lumnescence polarization demonstrates once more that the 0.709-eV line is due to exciton molecules at low excitation levels. In the case of the electron-hole condensate one should expect a negligibly low polarization of the radiation at such a small deformation of the crystal.

It was shown in [1, 6, 7] that condensation of the biexciton gas in germanium occurs at concentrations close to 5×10^{15} cm^{-3}. This agrees with the decrease we observed in the degree of polarization radiation when such excitation levels are reached. At non-equilibrium electron-hole concentrations larger than 2×10^{16} cm^{-3}; the luminescence was almost completely depolarized at pressures lower than 500 kg/cm^2. Simultaneously, a slight broadening of the 0.709-eV line was observed; this broadening, as shown in [7], is the consequence of formation of a condensed state in the sample.

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1) According to [2], the electron-hole pair concentration in the condensed phase is equal to 2.6×10^{17} cm^{-3}, corresponding to an approximate Fermi energy 5×10^{-3} eV.

2) Strong radiation polarization was observed in some of the investigated samples in the absence of external deformation. This phenomenon is apparently due to strains existing inside the crystal. These strains, however, are so small, that the hardly affect the position of the exciton emission line, which was shifted less than 0.25 meV in such samples.

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POLARIZATION OF EXCITON AND BIEXCITON RECOMBINATION RADIATION IN DEFORMED GERMANIUM

G. L. Bir and G. E. Pikus
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences
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Results of calculations of the degree of polarization of exciton and biexciton radiation in germanium are presented. It is shown that at low deformations that disturb the equivalence of the electronic extrema this radiation can be strongly polarized.

The investigation of the polarization dependences of recombination radiation may serve as an effect-ve method of distinguishing, in principle, between the radiation of excitons, biexcitons, or drops, and of obtaining information concerning their structure.

Strong polarization of exciton absorption in deformed germanium was observed by Balslev [1]. Recently Asnin, Lomasov, and Rogachev have observed that exciton radiation of deformed germanium and the radiation in the band ascribed to biexcitons or drops is strongly polarized [2]. In this paper we give results of calculations showing that biexciton luminescence in deformed crystals cal, like exciton luminescence, be strongly polarized. In the case of drops one can expect an appreciable luminescence polarization only at large deformations, when the corresponding deformation splitting comes close to the Fermi energy of the electrons or holes.

If the main channel of the indirect recombination is the passage of the electron through the Γ extremum with emission of a longitudinal phonon, as is the case in Ge, then the selection rules for the indirect L - Γ excitons are determined by the selection rules for the direct Γ - Γ excitons [3]. The essential difference between the indirect and direct excitons is that the ground state of the former is fourfold degenerate with respect to the projections of the hole angular momentum J_z^h, and as a result of the effective-mass anisotropy this state splits into two terms with $J_z^h = \pm 1/2$ and $J_z^h = 3/2$ (z 111), the radiation of which is strongly polarized. This splitting $\Delta_c = E_{3/2} - E_{1/2}$ will be called crystalline splitting.

In the spherical approximation, the ground state of a biexciton, like that of a double acceptor [4], is split by the hole exchange interaction into two terms, D_0 and D_2, with total hole angular momentum $J_h = 0$ and $J_h = 2$, and with an energy difference $\Delta_{ex} = E_0 - E_2$. The anisotropy of the electron masses leads, just as for the exciton, to an additional crystalline splitting of these states, which is different (a) when both electrons are in one valley and (b) when they are in different valleys.

We consider here a simplified model of the biexciton, in which it is assumed that each of the wave functions of the ground state is a product of corresponding combinations of Bloch functions of electrons and holes by one S-type smooth function, the concrete form of which is immaterial. A similar assumption is made also concerning the wave function of the exciton remaining after the recombination.

In this model, the ground sixfold degenerate state corresponding to each of the possible states of the electrons splits, as a result of the exchange, crystalline, and defformation splitting, into three terms. One of the terms, coming from the states D_2, is fourfold degenerate, is not shifted, and its radiation is not polarized. The positions of the two other non-degenerate terms are altered by the deformation (Fig. 1), and their radiation is polarized even in the absence of external deformation. The non-equivalence of the electronic extrema, which sets in upon deformation, leads, just as for the exciton, to polarization of the crystal radiation.

We present below the final formulas for sufficiently low temperatures, when only the lower of the split levels of the exciton or biexciton is filled, for cases when this lower level is a level of the biexciton (a) or biexciton (b). We consider separately the case of small deformations, when the deformation splitting Δ_ε for holes is small in comparison with Δ_c, and the case of large deformations, when Δ_ε exceeds both Δ_c and Δ_{ex} (but is small in comparison with the binding energy).

1. Deformation along the 111 axis, light propagates perpendicular to this axis.

<u>Small deformations</u>: exciton and biexciton (a)

$$\mathscr{P}_{lin} = 3d_1\{1 - \exp[-\gamma(\Delta E_e/T)]\}/\{4 + d_1 + (12 - d_1)\exp[-\gamma(\Delta E_e/T)]\}.$$

For exciton: $d_1 = \Delta_c/|\Delta_c|$, $\gamma = 1$,

For biexciton (b): $d_1 = \Delta_c/\sqrt{(\Delta_{ex}/2)^2 + \Delta_c^2}$, $\gamma = 2$.

For biexciton (a):

$$\mathscr{P}_{lin} = 3d_3[1 - \exp(-\Delta E_e/T)]/[4\sqrt{3} + d_3 + (4\sqrt{3} - d_3)\exp(-\Delta E_e/T)],$$

where $d_3 = \Delta_c/\sqrt{(3/4)\Delta_{ex}^2 + \Delta_c^2}$. Here E_e is the difference between the deformation displacements of the valeys (11$\bar{1}$), (1$\bar{1}$1), ($\bar{1}$11), and the valley (111): $\Delta E_e = E_{11\bar{1}} - E_{111}$. At sufficiently large deformations, when $|\Delta E_e|/T \gg 1$ (but $\Delta_\varepsilon \ll \Delta_c$), as seen from (1) and (2), $\mathscr{P}_{lin}$ saturates. At $\Delta E_e > 0$ and $\Delta_c > 0$ we have for the exciton $\mathscr{P}_{lin}^{sat} = 3/5$, and $\mathscr{P}_{lin}^{sat} = -1$ at $\Delta_c < 0$. (Positive $\mathscr{P}_{lin}$ corresponds to predominant polarization

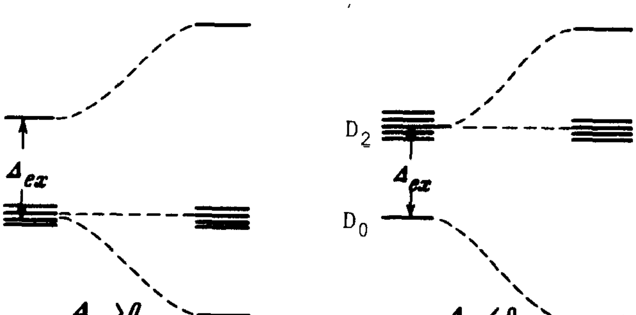

Fig. 1

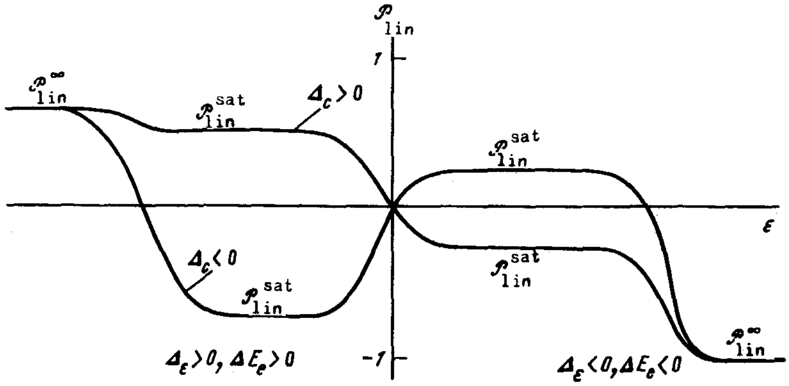

Fig. 2

in a plane passing through the deformation direction, i.e., to π polarization). It is seen from (1) and (2) that in the considered biexciton model the polarization depends strongly on the ratio of the crystalline and exchange splittings, viz., at $\Delta_c \ll \Delta_{ex}$ the polarization is small and is equal to $\mathcal{P}^{sat}_{lin} = (3/2)(\Delta_c/|\Delta_{ex}|)$ (a) or $\mathcal{P}^{sat}_{lin} = (1/2)(\Delta_c/|\Delta_{ex}|)$ (b), whereas at $\Delta_c > \Delta_{ex}$ it approaches the same value as for the exciton in the case of biexciton (a), but for biexciton (b) $\mathcal{P}^{sat}_{lin} = 0.38$ at $\Delta E_e > 0$ and $\Delta_c > 0$, and $\mathcal{P}^{sat}_{lin} = -0.51$ at $\Delta_c < 0$.

Large deformations. At $\Delta_\varepsilon \gg \Delta_c$, Δ_{ex} the radiation polarization for excitons and biexcitons is the same as for direct interband absorption [3] and is equal to $\mathcal{P}^{\infty}_{lin} = 3/5$ for $\Delta_\varepsilon > 0$ and $\mathcal{P}^{\infty}_{lin} = -1$ at $\Delta_\varepsilon < 0$. The schematic course of $\mathcal{P}^{\infty}_{lin}(\varepsilon)$ for the exciton and for the biexcitons is shown in Fig. 2 for deformation along [111]. Account is taken here of the fact that for Ge at $\varepsilon > 0$ (compression) we have $\Delta E_e > 0$ and $\Delta_\varepsilon = (2/\sqrt{3})d\varepsilon'_{11} > 0$ (since the deformation-potential constants for Ge are $d < 0$ and $b < 0$ [3]). It is seen from Fig. 2 that at the indicated signs of the deformation-potential constants, at $\Delta_c > 0$ the polarization increases monotonically with increasing deformation, whereas at $\Delta_c < 0$ it passes through zero and reverses signboth in compression and in tension. It follows from (1) and (2) that the experimental data [2] can be explained with the aid of our model if it is assumed that the lower level belongs to the biexciton (a) and that $\Delta_{ex} \leq \Delta_c$ (with $\Delta_c > 0$ [2]).

2. Deformation along [001].

In this case all the electron valleys are equivalent and the polarization is due only to splitting of the valence band. Saturation sets in therefore at large deformation, when the deformation splitting for holes is $\Delta\varepsilon = 2b\varepsilon'_{00\omega}$ exceeds Δ_0 and Δ_{ex}. At sufficiently low temperatures we have

$$\mathcal{P}_{lin} = 3d_5 / (4 + d_5), \tag{3}$$

for the exciton:

$$d_5 = \Delta_\varepsilon / \sqrt{\Delta_\varepsilon^2 + \Delta_0^2},$$

for the biexciton (a):

$$d_5 = \Delta_\varepsilon / \sqrt{(\Delta_{ex}/2)^2 + \Delta_0^2 + \Delta_\varepsilon^2},$$

for the biexciton (b):

$$d_5 = \Delta_\varepsilon / \sqrt{(\Delta_{ex}/2)^2 + (\Delta_0^2/3) + \Delta_\varepsilon^2}.$$

Under these conditions, the values of $\mathcal{P}^{\infty}_{lin}$ are the same as for deformation along [111].

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