Exciton and electron-hole-drop radiation polarization induced in germanium by uniaxial compression

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The dependence of the spectral distribution and of the degree of polarization of recombination radiation of excitons and electron-hole drops on the uniaxial compression applied to germanium crystals in the [111] direction is investigated. It is found that the polarization of drop radiation develops from the long-wave edge of the LA and TO radiation bands. With increase of pressure the polarization increases and reaches saturation at pressures corresponding to splitting of the conduction band or valence band, the splitting being close to the Fermi energy of the nonequilibrium carriers in the condensed phase. The results are compared with data by others.

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1. INTRODUCTION

A number of recent communications[1-4] have been devoted to the investigation of the polarization of the radiation of collective states of carriers[5] and excitons in germanium, due to uniaxial compression of crystals. The relations obtained in[1-4] between the degree of polarization of this radiation and the applied pressure do not agree even qualitatively with one another. Nonetheless, the authors arrive on the basis of these experiments at mutually-exclusive deductions concerning the physical nature of the collective states, which they identify either with exciton molecules (biexcitons[1-3]) or with electron-hole drops (EHD).[4] In view of the contradictory character of the experimental results, it seemed necessary to investigate in greater detail the influence of uniaxial compression on the polarization of exciton and EHD radiation in germanium and primarily on the spectral distribution of the polarization of this radiation.

2. EXPERIMENTAL PROCEDURE

We investigated germanium samples measuring $15 \times 2.5 \times 1.7$ mm and having the intrinsic conductivity 300°K and an exciton lifetime of about 5 μsec at 4.2°K. The samples were cut along the [111] axis and ground down to points on the ends. This sample shape ensured high homogeneity of the deformation in the central part, as evidenced by the slight decreases of the EHD emission intensity even at pressures exceeding 1000 kgf/cm^2.[6] The sample surface was polished, first mechanically and then chemically. The compression in the [111] direction was effected in apparatus similar to that described in[7]. The pressure was transmitted to the samples placed in the helium bath of the metallic cryostat with the aid of a moving rod balanced between two bellows that communicated with the working cavity of the cryostat. This prevented additional pressure from being produced on the sample when the helium was pumped off.

The photoexcitation was produced by modulated radiation from an 80-mw argon laser, focused either in the form of a spot of $\approx$0.5 mm diameter or in the form of a strip measuring 8×0.5 mm. Although the excitation density in these two cases differed by more than one order, no differences were observed in the polarization of the EHD radiation. As noted in[4], the recombination radiation emerging from the samples through the side faces is strongly polarized as a result of the large-angle refraction. To prevent such radiation from entering the spectrometer slit, the samples were placed in a screen that covered the side faces and edges of the samples and had slits for the entry of the exciting radiation and the exit of recombination radiation.

The polarization of the recombination radiation was analyzed with a film polarizer which was rotated 90° every 10 seconds automatically in such a way that its axis was alternately either parallel or perpendicular to the sample compression direction. The apparatus polarization was canceled out by synchronous variation of the photoresponse gain, the value of which was chosen such that the radiation signal of the undeformed germanium remained unchanged when the polarizer was rotated. The control spectra recorded in the absence of deformation have shown that this cancellation took place in the entire required spectral range with accuracy of at least 1%. When the strain-induced polarization appeared, the cancellation was disturbed and the emission spectra corresponding to the two different polarizer positions were recorded in the form of two successive segments for one pass over the spectral interval. The spectra were analyzed with an MDR-2 monochromator. The radiation receiver was a cooled copper-doped n-type germanium photoresistor.[8] The spectra were recorded with an approximate resolution 0.5 meV at a signal integration time constant 0.5–1 sec and with the signal exceeding the noise by two orders of magnitude.

3. EXPERIMENTAL RESULTS

Figure 1 shows the spectral distribution of the LA and TO components of the recombination radiation of electron-hole drops in germanium; the spectra were recorded for two polarization directions and for several values of the pressure P applied to the sample. It is seen from the figure that when the sample is compressed the polarization appears on the long-wave edges of the LA and TO emission bands. With increasing pressure, the polarization increases and gradually covers these bands. In the TO band the radiation is polarized predominantly perpendicularly, and in the LA band it is parallel to the direction of the pressure **P**.

Figure 2 shows the dependence of the degree of polarization α of the integrated EHD and exciton radiation. For the EHD it was assumed that

$$\alpha = \left(\int I_\perp d\nu - \int I_\parallel d\nu\right) \Big/ \left(\int I_\perp d\nu + \int I_\parallel d\nu\right),$$

where $I_\perp(\nu)$ and $I_\parallel(\nu)$ are the spectral densities in the

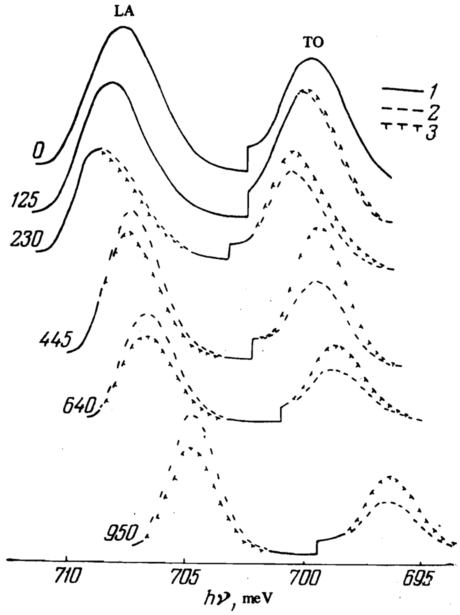

FIG. 1. Emission spectra of electron-hole drops in germanium, recorded for two polarization directions at 2°K. The pressure P along [111] (in kgf/cm²) is indicated on the left of each curve. The radiation intensity corresponds to the absence of polarization (1), to a polarization E‖P (2), or to polarization E⊥P (3). The TO component was recorded with the gain increased by six times.

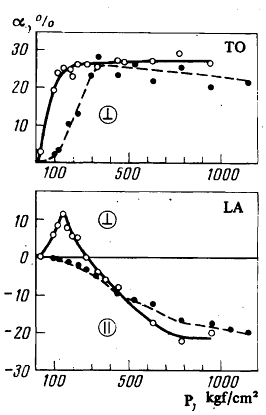

FIG. 2. Plot of the degree of polarization α(P) of the integrated radiation for the TO and LA components: ○—excitons (4.2°K), ●—electron-hole drops (2°K).

TO or LA emission bands with **E** ⊥ **P** and **E** ∥ **P**, and **E** is the vector of the electric field of the radiation. The integration in the calculation of α was carried out by the method of weighting the spectra. No spectra were recorded for the exciton radiation, only the integral intensity of the radiation at two polarization directions. The spectrometer was tuned to the maximum of the TO or LA band of the exciton radiation, and the signals were recorded, with periodic rotation of the polarizer and with cancellation of the apparatus polarization, at 2.5-meV spectral slit width, which exceeded the width of the exciton band.

It is seen from Fig. 2 that the degree of polarization of the TO exciton-emission component increases rapidly and reaches saturation at P = 120—150 kgf/cm², whereas saturation for the TO component of the EHD radiation occurs only at 300—350 kgf/cm². An even greater difference between the polarizations is observed for the LA components of the EHD and exiton radiation. It is seen from Fig. 2 that at low pressures the exciton radiation has a polarization **E** ⊥ **P**, which reverses sign at **P** = 275 kgf/cm² and then increases and reaches saturation at P ≈ 700 kgf/cm². On the other hand, the EHD radiation is polarized predominantly parallel to the pressure direction at arbitrary P, and a tendency to saturation is observed only at the maximal pressures.

4. DISCUSSION OF RESULTS

Uniaxial compression of germanium in the [111] direction causes a splitting of the conduction band and the valence band. One valley of the conduction band, which lies on the pressure axis, shifts towards lower energies, whereas the energy positions of the three remaining valleys depend little on the pressure. The splitting of the valence band was considered in[9]. The magnitudes of the splitting can be described by the empirical relations[7] $\Delta_e \approx 7.4 \times 10^{-6}$P [eV] for the conduction band and $\Delta_h \approx 3 \times 10^{-6}$P [eV] for the valence band (P is the pressure in kgf/cm²). The polarization of the intrinsic recombination radiation of deformed germanium is the result (see[3,10]) of the strong effective-mass anisotropy. The magnitude and direction of the polarization depend here on the Brillouin-zone point through which the radiative phonon transitions go. According to[3], transitions with participation of TO phonons proceed mainly through the L point and the polarization is determined by the splitting Δ_e of the conduction band. The radiation due to the transition from the lower valley of the conduction band should then have a predominant polarization **E** ⊥ **P**.

For free excitons having a Boltzmann energy distribution, the population of the upper valleys of the conduction band should be negligibly small already at a splitting $\Delta_e \approx (2-3)kT$, which corresponds at T = 4.2°K to P ≈ 100—150 kgf/cm². Indeed, it is seen from Fig. 2 that the polarization of the TO component of the exciton radiation reaches saturation at such pressures. The dependence of the polarization of the emission of the electron-hole drops on the pressure can be entirely different, since the EHD consist of a degenerate plasma of nonequilibrium carriers. At a sufficiently strong compression in the [111] direction, all the plasma electrons are concentrated in a single lower valley of the germanium conduction band, and the electron Fermi energy is then $F_e \approx 3.2$ meV.[6,11] At $\Delta_e < F_e$, only a fraction of the electrons with the minimal energies is concentrated in the lower valley. Therefore the recombination radiation of a degenerate plasma is only partially polarized at low pressures (**E** ⊥ **P**), predominantly on the low-energy side of the TO emission band. This polarization at low pressures is clearly seen in Fig. 1. At $\Delta_e \approx F_e$, which corresponds to P ≈ 350 kgf/cm², the polarization extends over the entire TO band (Fig. 1) and does not change when the pressure is increased further (Fig. 2).

Radiative transitions with participation of LA phonons, according to[3,10], go through the Γ point of the Brillouin zone, and the polarization is determined by the splitting of the valence band. The polarization of the exciton radiation depends here essentially on the sign and magnitude of the crystal splitting Δ_c of the exciton level. If $\Delta_c < 0$, then at low pressures P ($|\Delta_c| < \Delta_h$) the polarization direction corresponds to **E** ⊥ **P**. At $|\Delta_c| = \Delta_h$ the sign of the polarization should change, so that with further increase of P the direction of the polarization corresponds to **E** ∥ **P**. It is seen from Fig. 2 that the dependence of the degree of polarization of the exciton radiation on the pressure agrees with the theoretical estimate[10] for the case $\Delta_c < 0$. The reversal of the sign of the polarization is observed at P = 275 kgf/cm², which corresponds according to[7] to $\Delta_h \approx 0.8$ meV. This is somewhat larger than the value

$\Delta_c \approx 0.4-0.75$ meV cited in the literature (see[12]), possibly because of the inaccuracy in the determination of the function $\Delta_h(P)$ in[7].

The crystal splitting is peculiar to the energy spectrum of exciton and is negligible for free carriers.[3,10] Therefore the polarization direction of the LA component of a degenerate plasma should correspond to $\mathbf{E} \parallel \mathbf{P}$ at all pressures. At low pressures, polarization can be due only to holes with energies less than Δ_h, and saturation of the polarization should be expected at $\Delta_h \geq F_h$. It is seen from Fig. 1 that a polarization $\mathbf{E} \parallel \mathbf{P}$ is indeed produced on the long-wave edge of the LA band of the EHD emission, and covers the entire band as P is increased. A tendency towards saturation was observed only at the maximal pressures $P > 1000$ kgf/cm^2 (Fig. 2), corresponding to $F_h \approx \Delta_h \approx 3$ meV. This is somewhat larger than the Fermi energy of the holes in deformed germanium, which is equal, according to[6,11], to ≈ 2 meV. This discrepancy can also be due to the inaccurate determination of $\Delta_h(P)$ in[7].

It is interesting to note that the maximum degree of polarization is practically the same for the EHD and exciton emission, although it is reached at significantly different pressures and is different for the LA and TO bands (Fig. 2). This result is natural, since at sufficiently large deformation the radiative transitions are possible only between the lower branch of the conduction band and the upper branch of the valence band, the anisotropy of which determines completely the degree of polarization of any intrinsic recombination radiation.

It is useful to compare our present results with the experimental data published in[1-4]. It must be borne in mind here, however, that the absolute value of the degree of polarization can depend on the experimental conditions, primarily on the state of the sample surface,[4] and therefore the most essential are the qualitative features of the dependence of the degree of polarization α on the applied pressure P.

Figure 3 shows plots of $\alpha(P)$ for the emission of collective states, plotted in accordance with[1-4] and with the results of the present paper. It is seen from the figure that for the LA component there is a qualitative agreement between the results of[4] and our data. Some discrepancy may be due to the fact that the apparatus polarization at $P = 0$ was not completely canceled in[4]. On the other hand, our results differ strongly from the data of[1-3]. It must be noted, however, that for the LA component the results of these studies ([1,2] and[3]) are also in disagreement with one another, although the experimental data were obtained by the same group of workers.

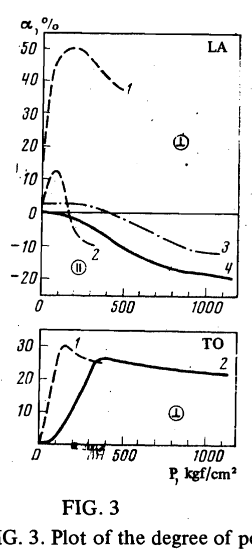

FIG. 3

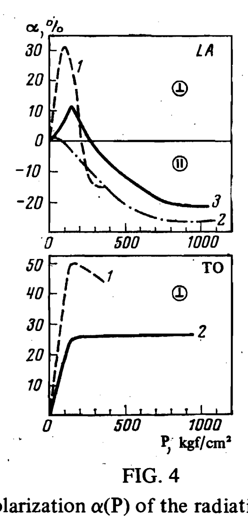

FIG. 4

FIG. 3. Plot of the degree of polarization $\alpha(P)$ of the radiation of collective state, based on the data for the LA components: 1—from [1] (polarization direction changed in accordance with [2]), 2—from [3], 3—from [4], 4—present work; for the TO components: 1—from [3], 2—present work.

FIG. 4. Degree of polarization $\alpha(P)$ of exciton radiation, plotted on the basis of the data for the LA components: 1—from [3], 2—from [4], 3—present work; for the TO components: 1—from [3], 2—present work.

Figure 4 shows a summary of the results of the investigation of the exciton-radiation polarization. It is seen from the figure that the $\alpha(P)$ dependence obtained by us is qualitatively similar to the data of[3] (reversal of the sign of the polarization for the LA component, saturation of the polarization at $P \approx 150$ kgf/cm^2 for the TO component) and with the data of[4] (the form of the $\alpha(P)$ plot for the LA component at high pressures). Unfortunately, we are unable to examine in detail the probable causes of the discrepancy between the experimental data summarized in Figs. 3 and 4, since the procedure used to investigate the polarization of the radiation of deformed germanium are not described in[1-4] with sufficient detail.

Our experimental results show that the polarization of the radiation of collective states due to uniaxial compression of the germanium conforms to the model of electron-hole drops made up of a degenerate plasma of nonequilibrium carriers.[13] A similar conclusion was drawn earlier following the investigation of the polarization of EHD radiation in deformed silicon.[14]

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