SPECTRUM AND POLARIZATION OF RECOMBINATION RADIATION IN DEFORMED SILICON

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We have observed recombination radiation of "hot" excitons and have investigated the difference between the radiation polarization of the excitons and the condensed phase in silicon deformed in the (100) direction.

It is known that when silicon crystals are compressed in the (100) direction, the two absolute minima of the conduction band, which are located along the deformation axis, shift towards lower energies, whereas the energy positions of the four other absolute minima remain practically unchanged relative to the valence band [1]. When the deformed crystal is excited by radiation quanta with energies appreciably exceeding the width of the forbidden band, the non-equilibrium electrons become distributed over all six minima of the conduction band. If the time of relaxation of the electrons from the upper minima to the lower ones is long enough, then the electrons belonging to the upper valleys can become bound into "hot" excitons. The recombination radiation of such hot exciton was successfully observed in experiment.

The investigated samples were pure silicon containing about 3×10^{12} cm^{-3} of boron. The lifetime of the free excitons in the samples was about 1 microsecond at 4.2°K. Samples measuring 1.5×1.5×1.5 mm were cut along the [100] direction and subjected to uniform compression along this direction in a device analogous to that described in [1]. The samples were placed in the helium bath of a cryostat. The quasistationary excitation was produced with a gallium-arsenide laser with power rating up to 200 mW. The excitation density could be varied in a wide range by changing the laser focusing.

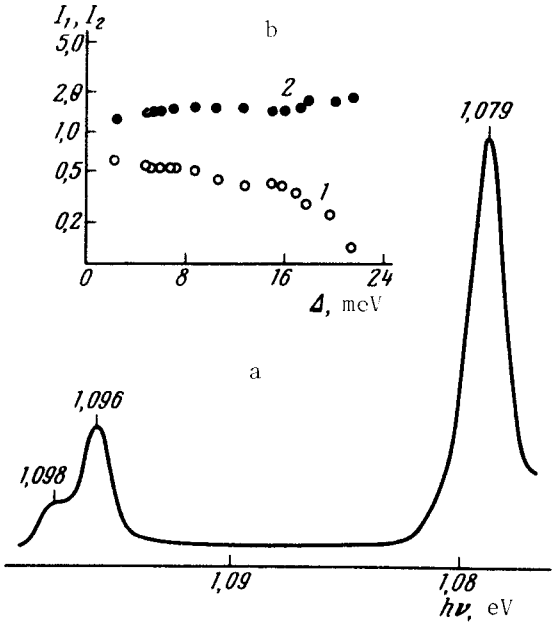

Fig. 1. a — LA and TO components of the spectrum of the recombination radiation of silicon at 2°K, at low photoexcitation density, and a pressure P = 2000 kgf/cm^2 along the [100] direction; b — dependence of the radiation intensity of the "hot" (1) and "cold" (2) excitons in silicon on the splitting Δ of the conduction band at 4.2°K and at a low excitation density.

Figure 1a shows part of the recombination radiation spectrum of the deformed silicon, corresponding to the annihilation of free excitons with emission of a longitudinal (LO) and a transverse (TO) optical phonon, registered at 2°K and at low excitation density. It is seen from the figure that besides the 1.079 eV peak corresponding to annihilation of the excitons connected with the lower values, the spectrum reveals peak with energies 1.096 and 1.098 eV. The position and structure of each peak is identical with the spectrum of free-exciton annihilation with emission of LO and TO phonons in undeformed silicon. We can therefore conclude that these peaks are due to annihilation of "hot" excitons connected with the upper valleys. The energy difference between the TO peak of the "hot" and "cold" exciton radiation agrees well with the values of the energy splitting Δ of the conduction band at different pressures, as determined in [1]. What is unexpected is the absence of an LO component in the emission spectrum of the "cold" excitons.

Figure 1b shows the emission intensities I_1 and I_2 of the "hot" and "cold" excitons as functions of the energy splitting Δ of the conduction band, corresponding to different deformations at 4.2°K. It is seen from the figure that I_2 is practically constant in the entire investigated range of splittings, whereas I_1 decreases rapidly when the splitting Δ exceeds the exciton binding energy E_{ex} = 14.7 meV [2]. At low pressures we have $I_1/I_2 \simeq 0.3$. Assuming that I_1/I_2 is determined by the density ratio of the excitons connected with the four upper and two lower valleys, and that the exciton lifetimes in the samples is 10^{-6} sec under the conditions of the experiment, we can estimate the intervalley relaxation time of the excitons at $\sim 10^{-7}$ sec. The reason for the rapid decrease of I_1 at $\Delta > E_{ex}$ may be that in this case the energy level of the "hot" excitons falls in the region of the continuous energy spectrum of the lower valleys.

With increasing sample-excitation density, the excitons are condensed and electron-hole drops with concentration 3.7×10^{18} cm^{-3} are produced [3]. When the silicon crystal is compressed along the [100] axis, the binding energy and carrier density in the condensed phase decrease somewhat, until the conduction-band splitting Δ reaches the electron Fermi energy ∿ 8 meV [4]. With further compression, the condensed-phase electrons fill only the lower

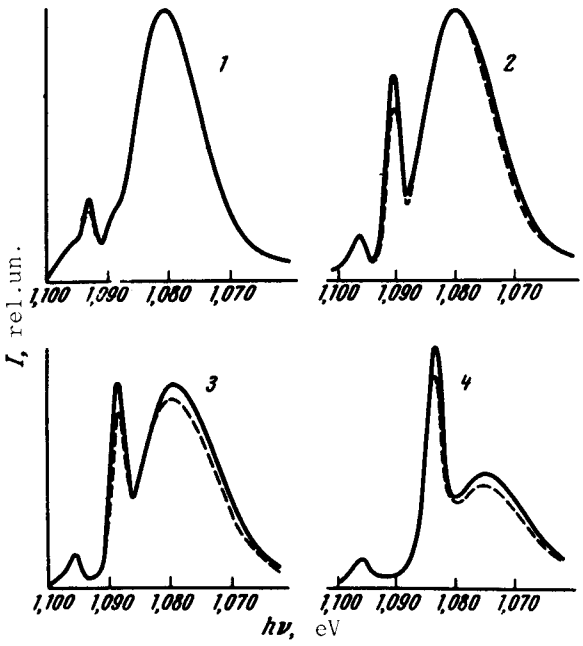

Fig. 2. LA and TO components of the emission spectrum of silicon at 2°K and at high photoexcitation density. The pressure P is applied along the [100] axis. 1) P = 250 kgf/cm^2, Δ = 3.2 meV; 2) P = 500 kgf/cm^2, Δ = 6.1 meV; 3) P = 820 kgf/cm^2, Δ = 7.9 meV; 4) P = 1500 kgf/cm^2, Δ = 13.10 meV. The dashed and solid curves represent the polarizations parallel and perpendicular to the pressure direction.

valleys of the conduction band, so that the binding energy and the concentration no longer change. As expected [1], uniaxial compression leads to the appearance of characteristic polarization of the recombination radiation of silicon. Figure 2 shows the emission spectra recorded for two polarization directions at 2°K and at different pressures along the [100] axis. It is seen from the figure that the emission of the "hot" excitons is not polarized at arbitrary pressures, and the emission of the excitons connected with the lower valleys is partially polarized in a direction perpendicular to the pressure even at minimal deformations. Polarization of the condensed-phase radiation was observed only at much higher pressures and started in the long-wave region. With increasing pressure, the polarization spread over the entire emission band of the condensed phase. At a splitting $\Delta \geq 8$ meV, this band and the emission of the "cold" excitons were polarized in approximately the same manner. This change in the polarization of the condensed-phase emission with increasing splitting of the conduction seems natural. Indeed, the long-wave region of the emission of the electron-hole drops is due primarily to the radiative recombination of low-energy electrons [3], i.e., those belonging to the lower valleys. With increasing splitting of the conduction band, the contribution of the lower valleys to the recombination radiation increases. At a splitting Δ exceeding the Fermi energy for the electrons in the condensed phase, the radiation polarization should reach saturation, for in this case all the electrons are concentrated in the lower valleys.

The arguments considered here offer only a qualitative explanation of the experimental results. For a quantitative interpretation it is necessary to develop a theory for the corresponding electronic transitions in silicon.

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