Deformation splitting of *L* valleys of the conduction band and intervalley scattering in GaAs

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A lifting of the degeneracy of the L valleys of the conduction band has been observed in the hot-photoluminescence spectra of uniaxially deformed GaAs crystals. Analysis of the spectra reveals the constant of the intervalley interaction, $D_{LL} = (5 \pm 1) \times 10^8$ eV/cm, and the constant of the shear strain energy, $\Xi_u^L = 15 \pm 1.5$ eV.

The hot-photoluminescence spectra of uniaxially deformed GaAs crystals have been studied in the frequency range corresponding to the positions of the degenerate lower side valleys of the conduction band. Direct spectroscopic measurements reveal quite accurately the magnitude of the deformation splitting and, correspondingly, the strain energy, as will be shown below. This method of course also tells us the symmetry of the extrema completely unambiguously. Analysis of the intensities in the hot-

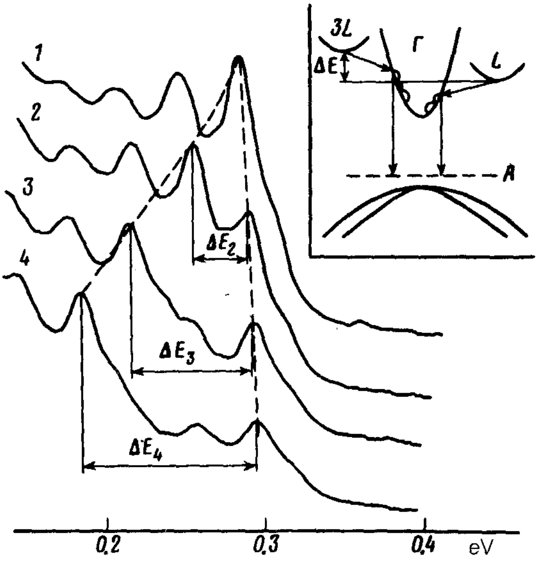

FIG. 1. Hot-photoluminescence spectra in terms of the energy of the recombining electrons. 1—$P = 0$; 2—$P = 3.7$ kbar; 3—$P = 7.5$ kbar; 4—$P = 10.7$ kbar. The dashed lines connect the first (high-frequency) peaks of the two series of peaks corresponding to the recombination of electrons from the point of arrival in the Γ valley after the $3L \to \Gamma$ and $L \to \Gamma$ transitions (the transition scheme is shown in the inset). The values of the splitting ΔE for various stresses are shown.

photoluminescence spectra has made it possible, for the first time, to experimentally determine the probability for scattering between equivalent valleys in GaAs.

Luminescence is excited in p-GaAs crystals doped with Zn (2×10^{17} cm^{-3}) by the beam from an Ar laser (2.54 eV) at $T = 2$ K. The energy of the electrons which are produced (during scattering from the heavy-hole band) is approximately 0.8 eV. Figure 1 shows hot-photoluminescence spectra for three values of the stress P, applied along the [111] axis. In the absence of the uniaxial deformation (spectrum 1 in Fig. 1), the hot-photoluminescence spectrum is formed as a result of radiative recombination to an acceptor level for electrons which have reached the Γ valley from the four equivalent L valleys through the emission of an "intervalley" phonon with[1] $q \sim \pi/a$. Uniaxial compression along the [111] axis partially lifts the degeneracy of the four-fold-degenerate L valleys. In spectra 2–4 in Fig. 1, this lifting of degeneracy is seen as two systems of peaks (the transition scheme is shown in the inset). The series of peaks corresponding to lower energies is due to transitions from the L valley which is oriented along the compression direction. The series of peaks with higher energies corresponds to transitions from the other degenerate $3L$ valleys.

From the dependence of the splitting ΔE on the stress P found from the results (Fig. 2), ΔE (meV) $= (11 \pm 1)P$ (kbar), and the relation[2] $\Delta E = 4/9\Xi_u s_{44} P$ with[3] $s_{44} = 1.63 \times 10^{-3}$ kbar^{-1}, we find the strain-energy constant to be $\Xi_u = 15 \pm 1.5$ eV. This value is slightly lower than the values found from measurements of the piezoelectric resistance: 19.6 ± 3 eV (Ref. 4) or 22 ± 7 eV (Ref. 5). In the present study, in

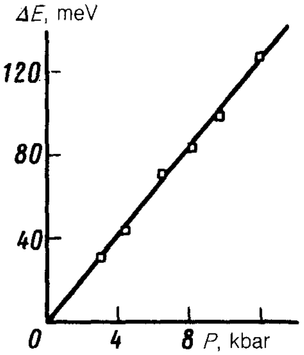

FIG. 2. Deformation splitting of the L valleys versus the stress.

contrast with Refs. 4 and 5, the value of Ξ_u is found directly from the splitting in the spectrum without the use of other band parameters. There is no splitting in the spectrum during deformation along the [100] axis, confirming the conclusion[4] that the lower side values in GaAs lie on the ⟨111⟩ axes.

In addition to the splitting in the spectrum, we observe a change in the ratio of intensities of the two series of peaks, i.e., of the populations of the L valleys, depending on the deformation. In the absence of an intervalley $L \rightarrow L$ relaxation, we would expect an intensity ratio of 3:1 on the basis of the degree of the degeneracy. This is what we do observe experimentally as long as ΔE remains below $\hbar\omega_{iv}$, which is the energy of the intervalley phonon (≈ 30 meV). As ΔE is increased, the intervalley relaxation changes this ratio in favor of the lower (nondegenerate) valley.

The presence of a sharp high-frequency threshold in the spectra in Fig. 1 is evidence that transitions in the side valleys are frequent in comparison with transitions to the Γ valley (electrons accumulate near the bottom of the valleys). The kinetics of transitions between valleys can therefore be described in terms of the populations of the valleys (without resorting to the energy distributions with the valleys) and the probabilities for intervalley transitions. Denoting by n_3 the total population of the triply degenerate valleys, by n_1 the population of the nondegenerate valley, by w_{30} and w_{10} the probabilities for transitions to the central Γ minimum, and by w_{31} the probability for $3L \rightarrow L$ intervalley transitions, we find

$$\frac{w_{31}}{w_{30}} = \frac{1}{4}\left(3\frac{n_1}{n_3}\frac{w_{10}}{w_{30}} - 1\right). \qquad (1)$$

We have used (1) to find the ratio of probabilities of two types of intervalley transitions: $w_{31}/w_{30} \equiv \tau_{L\Gamma}/\tau_{LL}$. The population ratio n_1/n_3 is determined from the experimental results on the ratio of the intensities of the two series in the spectrum. The value of w_{10}/w_{30} is approximately unity, differing from unity in proportion to the difference between the densities of final states in the Γ valley in the $L \rightarrow \Gamma$ and $3L \rightarrow \Gamma$ transitions, respectively (the calculations are carried for a Kane dispersion law). The resulting values of the ratio w_{31}/w_{30} (Fig. 3) are proportional to the final-state density for $3L \rightarrow L$ transitions $(\Delta E - \hbar\omega_{iv})^{1/2}$. (The probability w_{30} should depend only very

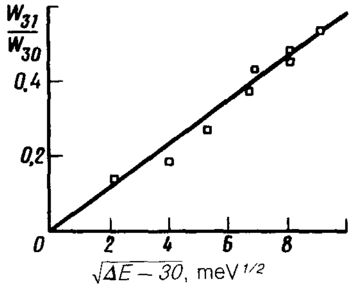

FIG. 3. The probability for $3L \rightarrow L$ transitions versus the deformation splitting.

weakly on the deformation, since the position of the bottom of the triply degenerate $3L$ valley varies only slightly with respect to the Γ point).

In particular, with $\Delta E = 75$ meV we have $\tau_{L\Gamma}/\tau_{LL} = 0.4$. Comparison of this result with previous measurements of $\tau_{\Gamma L}$, the scale time for the removal of 0.38-eV electrons from the Γ valley to the L valley ($\tau_{\Gamma L} = 0.25$ ps), reveals the ratio of intervalley-coupling constants: $D_{LL} = 0.6 D_{\Gamma L}$. Using the value[1)] found in Ref. 6, $D_{\Gamma L} = 8 \times 10^8$ eV/cm, we find the estimate $(5 \pm 1) \times 10^8$ eV/cm for D_{LL}.

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[1)] The results of recent direct femtosecond measurements[7] of the electron removal time in GaAs can be explained satisfactorily by a value which is not greatly different, $D_{\Gamma L} = 10^9$ eV/cm.

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