Photoluminescence of gallium arsenide produced by pumping via the *L* valley. Spectrum and phonon oscillations

D. N. Mirlin, I. Ya. Karlik, L. P. Nikitin, I. I. Reshina, and V. F. Sapega
A. F. Ioffe Physico-Technical Institute, USSR Academy of Sciences

(Submitted 13 May 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 1, 34–37 (5 July 1980)

A recombination radiation of hot electrons entering the Γ valley from the L valley was observed for the first time. Phonon oscillations, whose location is associated with the energy of the L minimum and is independent of the excitation wavelength, were observed in the hot photoluminescence spectrum.

PACS numbers: 78.55. – m, 63.20.Kv

As a result of raising the electrons high into the conduction band by light, we observed hot photoluminescence (PL) with a high-frequency threshold in the spectrum at energies of about 1.82 eV. The photoluminescence spectrum was independent of the energy of the exciting light quanta (ϵ_{ex}) (see Fig. 1). We obtained identical spectra with excitation lines of 5145Å (2.41 eV), 4880 Å (2.54 eV), and 4416 Å (2.81 eV). Estimates of the energy of photoexcited electrons at the moment of creation (ϵ_0) give values of 0.75, 0.85, and 1.07 eV, respectively, for the indicated ϵ_{ex} values.[1)] Oscillation with a

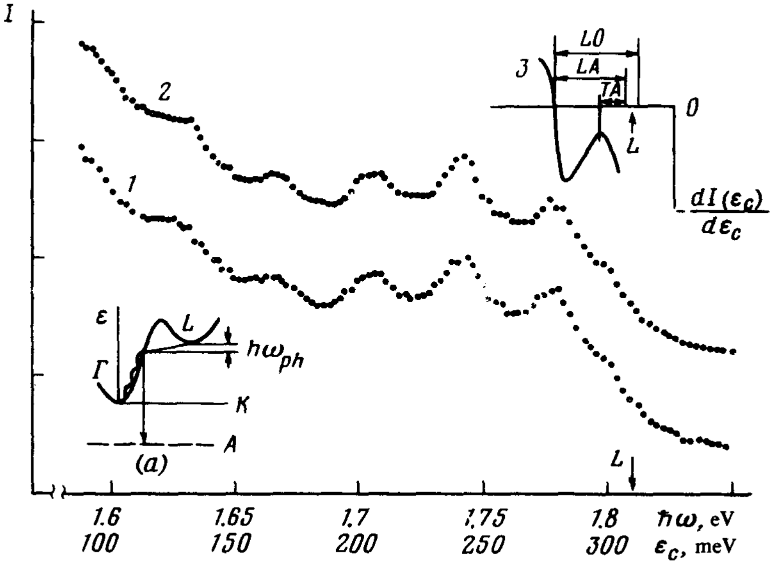

FIG. 1. Photoluminscence spectrum I of the p-GaAs(Zn) sample, $N_A - N_D = 0.9 \times 10^{17}$ cm^{-3}, $T = 1.6$ K. The spectrum is plotted as a function of the energy ϵ_c of the recombining electrons and the energy $\hbar\omega$ of the emitted photons: 1, $\epsilon_{ex} = 2.54$ eV; 2, $\epsilon_{ex} = 2.41$ eV; 3, $dI(\epsilon_c)/d\epsilon_c$; lower left (a) a diagram of the $L \to \Gamma \to A$ (acceptor) transitions.

period of ~ 37 meV were observed in the spectrum. The photoluminescence intensity is independent of the wavelength of the excitation line within an accuracy of the order of 10%, and is determined only by its intensity.

The results can be interpreted in the following manner. As the result of a series of successive intervalley transitions, the photoexcited electrons slide down to the bottom of the lowest side (L) valley, and from there enter the Γ valley with the emission of an "intervalley" phonon $\hbar\omega_{\rm ph}$ (see Fig. 1a). The L valley becomes a secondary source of monoenergetic electrons. The observed photoluminescence spectrum $I(\hbar\omega)$ was produced under the experimental conditions (at helium temperatures) due to electron transitions from the Γ valley of the conduction band to the acceptor levels. The oscillations in the spectrum are caused by the successive emission of LO ($q \approx 0$) phonons during the energy relaxation of the electrons in the Γ valley. The first high-frequency maximum in the spectrum at an electron energy $\epsilon_c \approx 285$ meV, with allowance for the assumptions made above, is attributable to the intervalley $L \to \Gamma$ transition with the emission of LO ($\hbar\omega_{\rm ph} = 29$ meV) or LA ($\hbar\omega_{\rm ph} = 26$ meV) phonons with $q = \pi/a$ (111).[2)] Transitions of this type are allowed by the selection rules in GaAs crystals.[2] Because the energy of LO phonons is close to that of LA phonons, the corresponding peaks in the spectrum are not resolved. However, a shoulder, which is clearly visible in the differential spectrum (curve 3 in Fig. 1), can be obtained on the high-frequency slope of the spectrum at $\epsilon_c \approx 300$ meV. We attribute this to the $L \to \Gamma$ transition that occurs with the emission of a TA phonon ($\hbar\omega_{\rm ph} = 8$ meV). This transition can be partially resolved because the wave vector **k** of the electrons in the Γ valley is large after an intervalley transition ($\mathbf{k} \approx 10^7$ cm^{-1}). The location of the bottom of the L valley with respect to the bottom of the Γ valley, which can be determined from the location of the peaks on curve 3 (Fig. 1), is 304–307 meV. This result is in good agreement with the results obtained by using other methods (330 ± 40 meV,[3] 310 meV,[4] 297 ± 10 meV[7]). The high-frequency "tail" in the spectrum can be attributed to

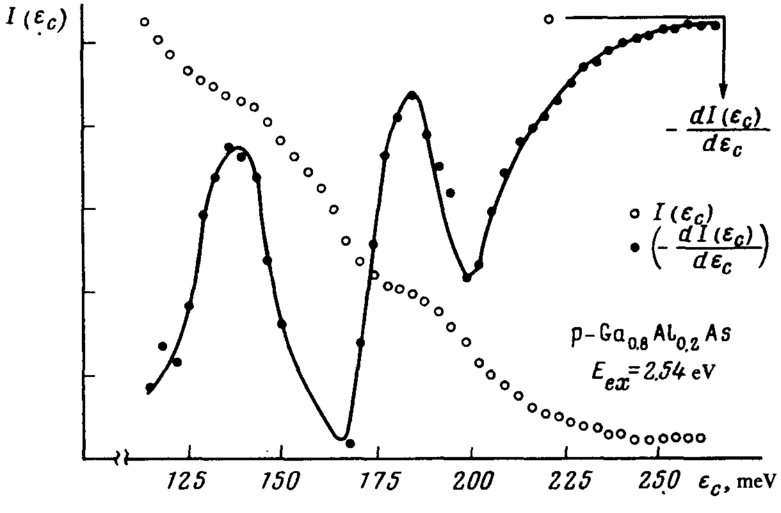

FIG. 2. Photoluminescence spectrum and its derivative for the p-Ga$_{0.8}$Al$_{0.2}$As sample.

a certain nonmonoenergetic state of the electrons that undergo a transition from the L valley, which is caused by the accumulation of electrons with a lower energy than that of the optical phonon near the bottom of the L valley.

The described effect provides a method for direct measurement of the energy gap between the bottom of the conduction band and the bottom of the lowest side valley in a straight-band semiconductor. Figure 2 shows a part of the hot photoluminescence spectrum of a crystal of the solid solution $Ga_{0.8}Al_{0.2}As$. The oscillations of the hot photoluminescence in this case are superimposed on the "tail" of the edge photoluminescence. The location of the bottom of the side valley, which is determined from the location of the high-frequency maximum in the differential spectrum, is 210 ± 10 meV above the bottom of the conduction band.

The distribution function $f(\epsilon_c)$ of hot electrons can generally be reconstructed from the photoluminescence spectrum. Since the dependence on ϵ_c of the probability $W_{CK,A}$ of a conduction band-to-acceptor transition is not known with much certainty, we used the hydrogen-like approximation for the calculations, setting $W_{CK,A} \sim 1/(1+x)^4$, where $x = m_c\epsilon_c/m_A\epsilon_A$, m_c and ϵ_c are the mass and energy of electrons in the Γ valley, ϵ_A is the ionization energy of the acceptors, and m_A is the hole mass.[5] The reconstruction of the function $n(\epsilon_c) = f(\epsilon_c)g(\epsilon_c)$ from a photoluminescence spectrum [where $g(\epsilon_c)$ is the density of states] for one of the samples is shown in Fig. 3. In the calculations of GaAs(Zn) we set $m_c = 0.07\ m_0$, $\epsilon_A = 25$ meV, and $m_A = 0.6\ m_0$. The average value $\bar{n}(\epsilon_c)$ in Fig. 3 is almost independent of ϵ_c for the $W_{CK,A}$ and the value of m_A used by us. This is plausible, since the scattering by optical phonons dominates in this sample and $\bar{n}(\epsilon_c) = G\tau_{p0}(\epsilon_c)$,[6] where G is the pumping intensity and $\tau_{p0}(\epsilon_c)$ is the optical phonon emission time, which is almost independent of energy in the investigated range.

As a result of exciting the electrons with a lower initial energy ($\epsilon_0 < 0.4$ eV), we

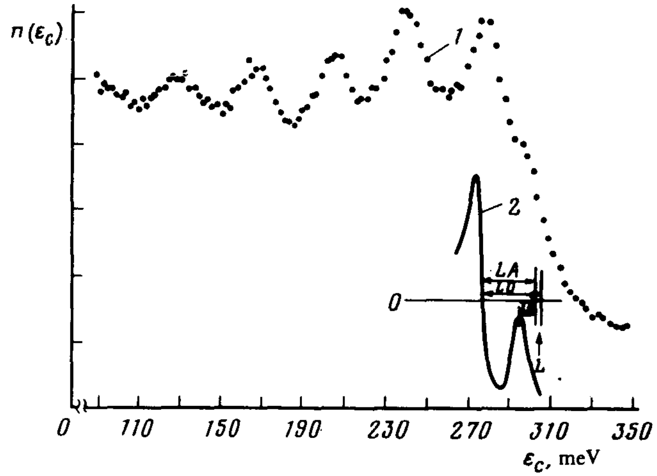

FIG. 3. Distribution function of electrons in the Γ valley for the same sample as in Fig. 1 (curve 1) and its derivative (curve 2), $\epsilon_{ex} = 2.54$ eV.

observed phonon oscillations in the hot photoluminescence spectrum that were "correlated" to the excitation line. A discussion of them, however, falls outside the scope of this paper. We shall mention that the phonon oscillations in the spectrum of recombiation radiation of free hot electrons were observed for the first time in this investigation.

The authors thank B. P. Zakharchena and V. I. Perel' for their interest in this work and for useful discussion.

[1] The average values of ϵ_0 for electrons excited from the heavy-hole band to the Γ valley of the conduction band are given with allowance for corrugation.
[2] The phonon energies at the L point were taken from the neutron spectrometry data.[1]

---

[1] J. L. Waugh and G. Dolling, Phys. Rev. **132**, 2410 (1965).
[2] J. L. Birman, M. Lax, and R. London, Phys. Rev. **145**, 620 (1966).
[3] D. E. Aspnes and M. Cardona, Phys. Rev. B **17**, 741 (1978).
[4] R. D. Dupuis, P. D. Dapkus, R. M. Kolbas, and N. Holonyak, Jr., Solid State Commun. **27**, 531 (1978).
[5] H. Barry Bebb and E. W. Williams, In: Semiconductors and Semimetals, Vol. 8, Academic, New York-London, 1972, p. 261.
[6] I. B. Levinson and B. N. Levinskiĭ, Zh. Eksp. Teor. Fiz. **71**, 300 (1976) [Sov. Phys. JETP **44**, 156 (1976)].
[7] V. P. Al'perovich, A. F. Kravchenko, N. A. Pakhanov, and A. S. Terekhov, Pis'ma Zh. Eksp. Teor. **28**, 551 (1978) [JETP Lett. **28**, 509 (1978)].