Geminate radiative recombination in GaAs/AlGaAs quantum-well structures in magnetic field

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An appearance of a secondary emission band near the laser excitation line has been observed in GaAs/AlGaAs quantum-well structures in a magnetic field applied in the direction perpendicular to the plane of the layers. This emission is a consequence of a geminate recombination of electron-hole pairs.

In the present study we used GaAs/$Al_{0.28}Ga_{0.72}As$ structures with isolated quantum wells of widths $L_z = 50$, 70, and 100 Å. The width of the barriers was 100 Å, and the number of periods was 60–100. The structures were fabricated by molecular beam epitaxy on GaAs substrates in the ⟨100⟩ orientation. The structures were not deliberately doped; the concentration of residual acceptors (carbon) was 10^{15}–10^{16} cm^{-3}. The structures were excited by lines from a krypton laser with $\hbar\omega_{exc} = 1.65$, 1.83, and 1.92 eV.

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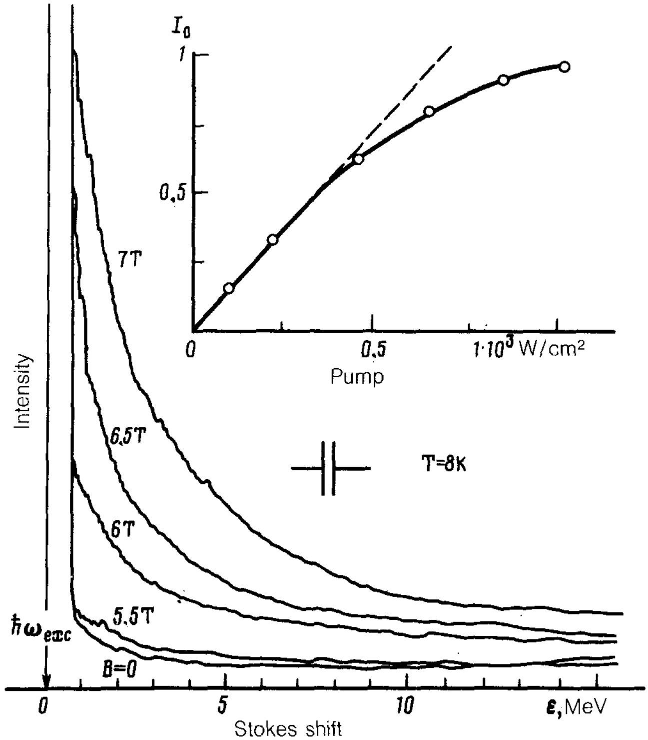

FIG. 1. Spectra of the secondary luminescence band for a $GaAs/Al_{0.28}Ga_{0.72}As$ structure with quantum wells of width $L_z = 70$ Å for various values of the magnetic field (the curve labels). The initial energy of the electrons is $E_0 = 215$ meV ($E_0 > \hbar\omega_{LO}$), and the excitation energy is $\hbar\omega_{exc} = 1.83$ eV. The inset shows the pump dependence of the intensity of the secondary emission.

A secondary emission band appears (Fig. 1) at liquid-helium temperatures in a magnetic field $B > 4$, applied perpendicular to the plane of the quantum wells, along the direction of the exciting laser beam. The intensity of this new band increases rapidly with B. The intensity spectrum of the secondary emission in the Stokes region is described approximately by the exponential law $I(\epsilon) = I_0 \exp(-\epsilon/\epsilon_0)$, where ϵ is the Stokes shift, ϵ_0 is a quantity on the order of 2 meV, and I_0 is a linear function of the pump intensity up to 5×10^2 W/cm^2 (Fig. 1). The secondary emission which arises in the magnetic field is linearly polarized if the exciting light is. The degree of linear polarization reaches ~ 0.6 in a field of 7 T. In addition, the polarization plane is rotated. The intensity of this secondary emission decreases with increasing temperature. The band disappears at 80 K.

We wish to suggest that this secondary emission is a consequence of a geminate recombination, specifically, a recombination of an electron and a hole which were produced in the same photon absorption event. The magnetic field limits the spatial motion of the 2D carriers in the plane of the quantum well, increasing the overlap of the wave functions of the electron and the hole. The probability for their radiative recombination thus increases. This recombination mechanism might play an important role in magnetic fields in which the product of the cyclotron frequency and the scattering time becomes greater than unity: $\omega_c\tau > 1$. In this model, one can find an explanation for the basic features of the secondary emission , e.g., the linear dependence of its intensity on the pump and the linear polarization which increases with the magnetic field. This linear polarization is a consequence of a correlation between the spins of an electron and a hole produced in the same absorption event.[1] In the reccombination of hot electrons and holes which have lost their coherence, one would expect a quadratic dependence of the luminescence intensity on the pump.[2]

If the kinetic energy of the electron at the time of excitation, E_0, is greater than the energy of an optical phonon, $\hbar\omega_{LO}$, then τ is determined by the polar optical scattering time: $\tau \approx \tau_{po} = 160$ fs (Ref. 3). The condition $\omega_c\tau > 1$ holds in this case at $B > 4$T. It is in this range of magnetic fields that the geminate recombination arises, and its intensity and polarization begin to increase monotonically with increasing B. In the spectrum we find second and third phonon repetitions of the geminate recombination band (at intervals of 36.6 meV) in the region of Raman scattering of light by optical phonons (Fig. 2). The width of this band and of its LO-phonon repetitions is determined by the scattering of the geminate electron-hole pair by acoustic phonons.

The behavior of the lines due to scattering by LO optical phonons of GaAs and by

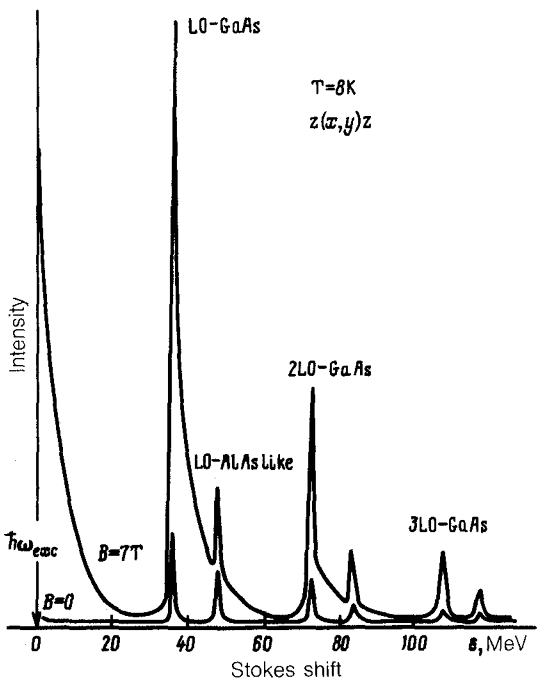

FIG. 2. Spectra of Raman scattering by LO phonons, of the secondary emission band, and of its LO-phonon repetitions for two values of the magnetic field: $B = 7$ T and $B = 0$. The excitation energy is $\hbar\omega_{exc} = 1.83$ eV. The structure is the same as that in Fig. 1.

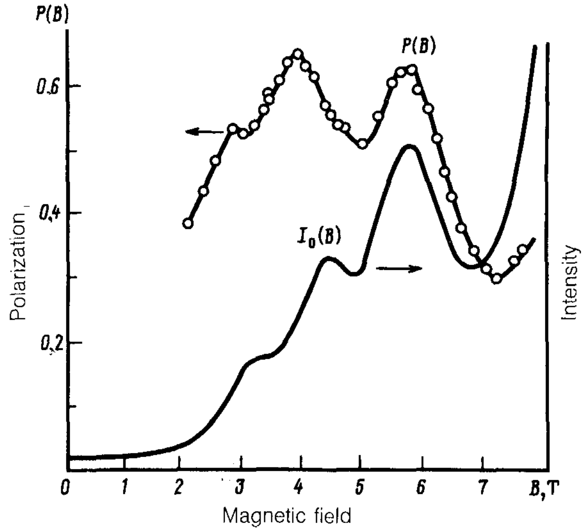

FIG. 3. Intensity and polarization of the secondary emission band versus the magnetic field for a structure with quantum wells of widths $L_z = 50$ Å. The initial energy of the electrons is $E_0 = 32$ meV ($E_0 < \hbar\omega_{LO}$). The excitation energy is $\hbar\omega_{exc} = 1.65$ eV.

interface modes in the magnetic field (including the behavior found as the temperature is raised) is similar to the behavior of the geminate recombination band. One observes a pronounced increase (by a factor up to 15) in the intensity of the *LO*-GaAs phonon line in a field of 7 T. A similar magnetic-field dependence has been observed for the intensity of scattering by optical phonons in quantum-well structures in Refs. 4 and 5. For the case of excitation far from exciton resonances, this effect can be explained on the basis of the model which we are proposing here, provided that we assume that the geminate electron-hole pair is an intermediate state during the scattering by *LO* phonons.

During the excitation of electrons with a kinetic energy below the energy of an optical phonon, $E_0 < \hbar\omega_{LO}$, the scattering time is determined by the emission of acoustic phonons. In this case, the condition $\omega_c\tau \gg 1$ holds in fields $B > 3$ T. In this magnetic-field interval we observe oscillations in the intensity and polarization of the geminate recombination band (Fig. 3). These oscillations apparently arise because of a resonance of the exciting photon with the distance between Landau levels of the size-quantized electron and hole subbands.

In the case of above-barrier excitation ($\hbar\omega_{exc} > E_g$ of the barrier), all of the effects caused by the magnetic field which were listed above disappear completely. It can apparently be assumed that geminate recombination in a magnetic field is characteristic of 2D systems.

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