Quasi-2*D* and freed excitons in quantum-well structures

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The electrons and holes which are photoexcited in quantum wells relax separately, and quasi-2*D* excitons are formed from the thermalized carriers. Above-barrier excitation gives rise to freed excitons, which effectively collect in quantum wells and give rise to an intense emission of quasi-2*D* excitons.

We have studied the luminescence of periodic GaAs-$Al_{0.3}Ga_{0.7}As$ semiconductor structures, grown by molecular-beam epitaxy, at $T = 1.6$ K. The structures consist of 100 layers of GaAs between layers of $Al_{0.3}Ga_{0.7}As$, 8 nm thick. The widths of the quantum wells studied are 7.5–12 nm. The structures are not deliberately doped; the GaAs and AlGaAs are of *p*-type conductivity.

The spectrum of electronic states in the quantum wells is determined entirely by quantum size effects; i.e., the carrier energy levels depend on the carrier mass m^* and the width (L_z) and depth of the quantum well. The stepped profile of the state density, which is characteristic of quantum-well structures and which was first discovered in the absorption spectrum,[1] can be seen clearly in the luminescence excitation spectrum of these structures (Fig. 1a). We observe three steps in the state density, corresponding to transitions between size-quantization subbands of electrons and holes with $n = 1, 2, 3$; these steps begin from exciton peaks. At the beginning of the first step, we can clearly see the lines of excitons involving a heavy hole and a light hole; the arrow shows the width of the band gap of the solid solution, i.e., the boundary of the discrete spectrum of the quantum wells.

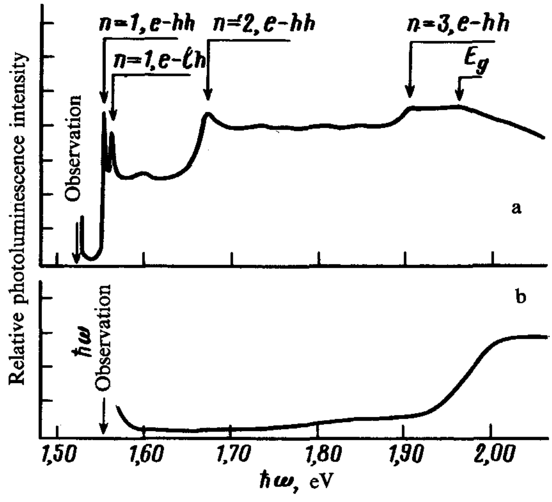

FIG. 1. Luminescence excitation spectra of a quantum-well structure with $L_z = 10.5$ nm at an excitation density of 10^{-4} W/cm^2 and at $T = 1.6$ K. a—$\hbar\omega_{obs} = 1.524$ eV; b—1.552 eV.

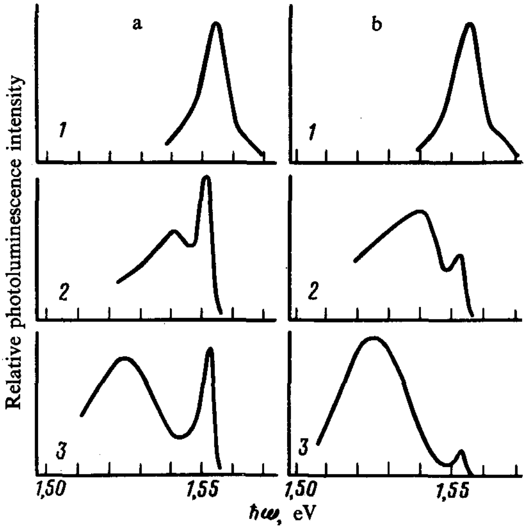

FIG. 2. Luminescence spectra of a quantum-well structure with $L_z = 10.5$ nm at several excitation densities: 1—5×10^2; 2—5×10^{-2}; 3—10^{-4} W/cm^2. a: $\hbar\omega_{\text{exc}} = 1.92$ eV. b: 2.41 eV.

The luminescence spectrum of the quantum-well structures depends on the intensity of the exciting light (Fig. 2). At extremely low excitation levels, we observe long-wave lines in addition to the line of an exciton involving a heavy hole. These long-wave lines are associated with the transition of an electron from the first subband to an acceptor at the center of a quantum well (curve 3 in Fig. 2) or at the interface (curve 2 in Fig. 2).[2] As the excitation level is raised, the impurity luminescence reaches saturation, and the spectrum becomes dominated by the emission line of an exciton with a heavy hole. On the short-wave wing of this line we see evidence of the recombination of a light-hole exciton (curve 1 in Fig. 2). The positions of these emission lines depend on the width of the quantum wells; as the wells shrink from 12 to 7.5 nm, the observed spectrum is displaced 30 meV up the energy scale, reflecting the behavior of the carrier size-quantization states.

We found that the relative intensities of the lines of the impurity and intrinsic recombination in the quantum-well structures become redistributed upon a change in the frequency of the exciting light, specifically, when we switch from intrawell to above-barrier excitation. For example, at an extremely low excitation density with $\hbar\omega_{\text{exc}} = 1.92$ eV, the exciton luminescence line is barely distinguishable against the background of the impurity band, while at $\hbar\omega_{\text{exc}} = 2.41$ eV the exciton emission exceeds the impurity emission in terms of peak intensity at any excitation level (Fig. 2). Since the integral emission intensity at a given excitation level is essentially independent of the energy of the exciting photon, and a change in the relative intensities is observed over a broad range of excitation densities, 10^{-4}–1 W/cm^2, this effect cannot be attributed to either an escape of carriers or a redistribution of carriers among quantum wells. The effect is observed both (a) during excitation and observation of the luminescence along the direction perpendicular to the plane of the layers and (b) in either of the 90% configurations, i.e., with excitation along the layers and observation perpendicular to them or vice versa. The effect is thus independent of the geometry of the excitation and observation of the luminescence. An explanation for the effect should be sought in the kinetics of the excitons and carriers in the quantum-well structures.

Figure 1b shows the excitation spectrum of the emission line of a heavy-hole exciton. This spectrum is radically different from the excitation spectrum of the luminescence due to the recombination of electrons at an acceptor in a quantum well (Fig. 1a). In the case of intrawell excitation, with $\hbar\omega_{\text{exc}} < E_g$ a quasi-$2D$ exciton does not form. The photoproduced carriers become thermalized separately, contributing to the emission in the impurity line. The lines of a quasi-$2D$ exciton begin to be seen at a low intensity of the exciting light, when the impurity transition reaches saturation (curve 1 in Fig. 2). This fact is evidence that a quasi-$2D$ exciton forms only from thermalized carriers in the case of intrawell excitation. As the frequency of the exciting light approaches the upper boundary of the quantum well, the intensity of the exciton luminescence begins to rise, and it reaches its maximum values at the transition to the continuum of the quantum-well structure.

These experimental results show that above-barrier excitation gives rise to freed excitons which, along with free carriers, effectively collect in quantum wells. By "freed excitons" we mean excitons for which at least one of the carriers is not trapped by a potential well. The binding energy of such excitons is determined primarily by the Coulomb interaction between the electron and the hole, in contrast with that of the quasi-$2D$ excitons, whose binding energy depends primarily on the degree of carrier trapping in the quantum well. In the case of a strong quantization, in which the electron motion becomes two-dimensional, the binding energy is $4R_0$, where R_0 is the binding energy of a $3D$ exciton. In our case the binding energy of the quasi-$2D$ exciton is $2.3R_0$.

The formation of freed excitons can be suggested in view of the quantum effects in the continuum of the quantum-well structure. It has been shown by the pseudopotential method[3] and also in a calculation of the transmission coefficient for particles moving perpendicular to the plane of the layers[4] that the continuum of a quantum-well structure contains electronic states with a predominant localization near the barrier. An exciton formed from an electronic state of this sort is described by a wave function which is freed with respect to the well and which penetrates strongly into the barrier region. We believe that evidence for the existence of precisely this type of exciton state has been found in spectra of resonant Raman scattering, where both types of optical phonons, belonging to GaAs and AlGaAs, have been observed.[5]

The effect discovered by us proves the existence of two types of excitons in a quantum-well structure: one which is bound by the potential of the quantum well and by the short-range part of the Coulomb interaction (a quasi-$2D$ exciton), and another determined primarily by the Coulomb interaction (a freed exciton).

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