Exciton localization in quantum-well structures

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Study of the luminescence of structures with quantum wells, whose width is less than the Bohr radius of the exciton, reveals that the excitons localize at fluctuations of the well width. These fluctuations are insular increases of one lattice constant in the thickness of the layer of the narrow-gap material. The luminescence is dominated by islands with a dimension on the order of the exciton diameter.

Exciton photoluminescence is predominant in high-quality GaAs–AlGaAs structures with quantum wells.[1] The inhomogeneous width of the exciton photoluminescence line and its energy position at low temperatures are attributed to a localization of excitons at roughnesses of the heterojunction boundaries in the quantum-well structures.[2]

In this letter we report a study at $T = 1.6$ K of the photoluminescence of several quantum-well structures grown by molecular-beam epitaxy in the GaAs–$Al_{0.4}Ga_{0.6}As$ system with quantum-well widths $L_z = 7$–13 nm. In the photoluminescence spectrum of a structure with $L_z = 12$ nm, we observe two lines of an exciton formed by size-quantized electrons (e) and heavy (hh) and light (lh) holes with $n = 1$ (curve 1 in Fig. 1b). These peaks are clearly observed in the luminescence excitation spectrum (Fig. 1a). At excitation intensities below 10 W/cm^2 we see a long-wave 2.5-meV Stokes shift of the photoluminescence line (curve 2 in Fig. 1b). The half-width of the photoluminescence line under these excitation conditions is 3 meV.

Study of the photoluminescence kinetics shows that for 1 ns after the exciting pulse the peak of the photoluminescence line coincides with the peak in the luminescence excitation spectrum (curve 1 in Fig. 1c); this situation corresponds to the case of a high pump intensity (above 100 W/cm^2). After 20 ns, the photoluminescence peak is shifted 2.5 meV in the long-wave direction (curve 2 in Fig. 1c). Consequently, the photoluminescence shifted in the long-wave direction, with a significantly longer afterglow time, comes from low-energy thermalized states. These states are usually linked[2] with the local increase in L_z, which causes a lowering of the levels of the size quantization of the electrons and holes. The peak in the luminescence excitation spectrum corresponds to the peak in the exciton state density, and its position is determined by the average width of the quantum well. The photoluminescence line observed during excitation by light with a photon energy smaller than the width of the energy gap of the solid solution essentially coincides with this peak along the energy scale (Fig. 1d). In this case the thermalization to low-energy states is hindered by the competition with the intense impurity pathway for photoluminescence.[3]

Evidence for localization of an exciton at inhomogeneities of the width of a quantum well comes from the curves of the energy position of the photoluminescence line versus the temperature and the excitation intensity (Fig. 2). Over the temperature

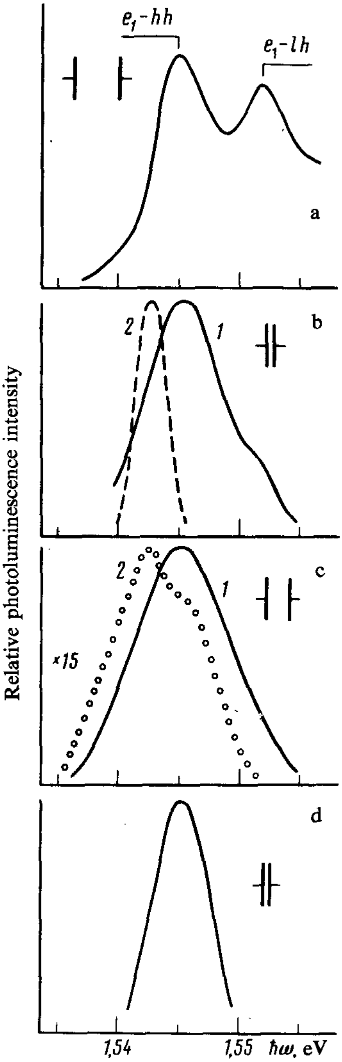

FIG. 1. Photoluminescence and luminescence excitation spectra for quantum-well structures with $L_z = 12$ nm at $T = 1.6$ K. a: Luminescence excitation spectrum. b: Photoluminescence at $\hbar\omega_{\text{excit}} = 2.41$ eV. 1—Excitation intensity of 500 W/cm^2; 2—1 W/cm^2. c: Photoluminescence at $\hbar\omega_{\text{excit}} = 3.68$ eV. 1—Delay time of 1 ns; 2—20 ns. d: Photoluminescence at $\hbar\omega_{\text{excit}} = 1.92$ eV.

interval 15–20 K, we observe a high-energy shift ~2.5 meV of the line; this shift corresponds to a thermal delocalization of the excitons. With a further increase in the temperature, this peak follows the thermal contraction of the energy gap of the GaAs in the quantum-well structure. As the intensity of the exciting light is increased, we also observe the disappearance of the Stokes shift (Fig. 2b) due to the filling of localized states. Our measurements of the behavior of the increase in the Stokes shift and the half-width of the photoluminescence line as the width (L_z) of the quantum well is reduced from 13 to 9 nm leads to the conclusion that the localization of the excitons in our quantum-well structures occurs at fluctuations of L_z on the order of two monolayers.

To determine the mechanism for the localization of an exciton at fluctuations of

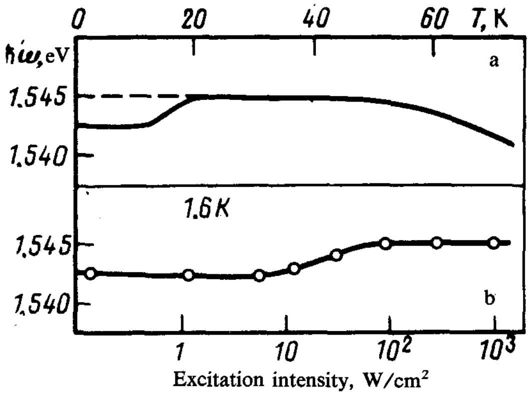

FIG. 2. Position of the exciton photoluminescence line ($L_z = 12$ nm). a—As a function of the temperature; b—as a function of the excitation intensity.

the width of a quantum well, we studied the effect of a magnetic field on the exciton photoluminescence line. The magnetic field **B** was applied in the direction perpendicular to the layers, and it reduced the dimension of an exciton along a layer. In weak fields we observe a linear dependence of the line shift. At $B \geqslant 4$ T, there is a significant contribution from the diamagnetic shift, which also determines the behavior of the curve in strong fields (curve 2 in Fig. 3). As the field is increased, the intensity at the line peak doubles ($B = 7.5$ T), while the integral intensity of the peak remains constant (curve 1 in Fig. 3). The increase in the peak intensity results from a narrowing of the line, primarily at the expense of its long-wave edge. These facts can be explained in a model which assumes the localization of the exciton as a whole at an insular increase of one lattice constant a_0 in the thickness of the GaAs layer.

An island creates a potential well for an electron (or hole) of depth

$$V_{e,h} = (\hbar^2\pi^2 / m_{e,(h)} L_z^2)(\delta L_z / L_z),$$

where $\delta L_z = a_0$. A necessary condition for the localization of an electron (or hole) in such a way is that its dimension (the island radius R) must be quite large; i.e., $V_{e,(h)}$ must be greater than the kinetic energy of an electron (or hole) in this well, $\sim\hbar^2/2m_{e,(h)}R^2$. It follows that the electron and the hole localize at islands of the same size,

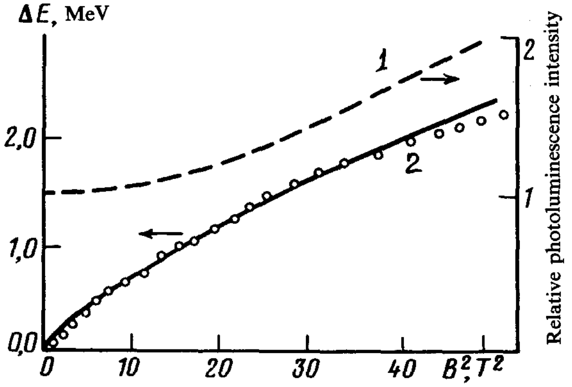

FIG. 3. Energy shift and intensity of the peak of the localized-exciton line versus the square of the magnetic field **B** ‖ z. 1—Energy shift; 2—intensity at the peak of the line of the localized exciton ($L_z = 12$ nm). The parameter values used in calculating curve 2 are $M = 0.19m_0$ and $r_{\text{exc}} = 120$ Å.

with $R > L_z (L_z/a_0)^{1/2}$. An exciton as a whole may localize at considerably smaller islands, with $R_l \geqslant L_z (L_z/a_0)^{1/2} \times (m_e/m_h)^{1/2} \simeq 100$ Å $(m_e/m_{hh}{}^{1/2} \simeq 0.2$ for GaAs). The reason is that a strong fluctuational potential $\sim V_e$ is acting on an exciton, and the translational mass of the exciton satisfies $M = m_e + m_h \gg m_e$. The possible localization of an exciton as a whole at islands with dimensions too small for the trapping of an electron and a hole separately makes it possible to distinguish this localization mechanism.

We can estimate the scale dimension of the islands that localize an exciton from the magnitude of the Stokes shift (ΔE) of the photoluminescence line and the luminescence excitation spectrum. The difference between $V_e(L_z)$ and ΔE is the kinetic energy of an exciton at this island. This value of E_k turns out to be on the order of 0.5 meV for $L_z = 90$–130 Å. Treating the island as an infinitely deep two-dimensional potential well of radius ρ, we find the estimate

$$E_k \simeq \frac{\hbar^2 (2{,}4)^2}{2M\rho^2} . \tag{1}$$

Knowing M, we can then determine the scale dimension of the localizing islands: $\rho = 300$ Å. An exciton, treated as a point, might be localized at islands of size $R_l \simeq 100$ Å, but this size is smaller than the scale dimension of an exciton (r_{exc}), and an exciton could not fit into such a fluctuation. Localization occurs at islands whose size ρ is several times greater than r_{exc}. In our quantum-well structures we find $\rho/r_{\text{exc}} \simeq 2.5$. Consequently, as r_{exc} is reduced by a magnetic field, an exciton can localize at smaller islands. To estimate the radius of an exciton in a magnetic field, we use the approximation $\sim \exp[-(\rho/r_{\text{exc}}) - (\rho/2\lambda)^2]$ of the wave function, where $\lambda = 265.5/B^{1/2}$ is the magnetic length. The condition for localization of an exciton then holds for an island whose dimension ρ_B satisfies

$$\frac{\rho_B}{r_{\text{exc}}} + \frac{\rho_B^2}{4\lambda^2} = 2{,}5. \tag{2}$$

Determining ρ_B from (2), and substituting it into (1), we find the energy shift of the peak of the exciton length as a function of the magnetic field which is represented, with allowance for the diamagnetic shift, by curve 2 in Fig. 3, along with experimental points.

We have thus shown that an exciton localizes as a whole at fluctuations in the width of a quantum well on the order of two monolayers, which are in the form of islands with a scale size 2.5 times the radius of the exciton. This effect is observed in quantum-well structures with $L_z \geqslant 80$ Å. In narrower wells, the intrinsic localization of carriers becomes more effective, since the scale energy for the localization of a carrier is greater than the exciton binding energy. This circumstance can be seen in the essential disappearance of the Stokes shift of the lines in the photoluminescence and the luminescence excitation spectrum; it can also be seen in the change in the behavior of the photoluminescence line in a magnetic field.

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