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Indirect-to-direct crossover of laterally confined excitons in coupled quantum wells

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Lateral confinement of excitons in coupled double quantum wells can be tailored to control exciton interwell tunneling. An indirect exciton in a coupled asymmetric double quantum well under applied bias can be made a direct exciton by lateral confinement. Large changes in exciton ground-state energies and oscillator strengths occur at this crossover. This crossover provides a new signature for lateral-confinement effects on excitons in zero-dimensional nanostructures such as quantum dots and electron-hole double-layer systems in a strong magnetic field.

One-dimensional (1D) confinement of an exciton in a quantum well increases the overlap of the electron-hole pair, strengthens the electron-hole attraction, and enhances the exciton binding. These effects of 1D confinement can be weakened by coupling two wells through a thin barrier to allow electron and hole interwell tunneling. Excitons in coupled asymmetric double quantum wells with zero applied bias between the wells are spatially direct. Under strong applied bias, the exciton is spatially indirect, the electron and hole are localized in different wells, with reduced binding.[1–3]

Lateral confinement of intrawell motion can be imposed by forming quantum dots from the well or by applying a strong magnetic field perpendicular to the well. The electron-hole attraction and exciton binding are further enhanced by lateral confinement.[4] Quantum dots which are presently made lithographically[5–10] are much bigger than the confined excitons. In these dots, the electron-hole attraction is larger than lateral-quantization energies, so lateral-confinement effects are weak. Lateral confinement of excitons in large dots is difficult to observe because the small shifts of the exciton energy produced by the lateral quantization of the exciton center-of-mass motion compensate the weak enhancement of the exciton internal motion and binding.[4,11]

In this paper, I present the properties of laterally confined excitons in coupled quantum wells. In these systems, the interwell tunneling can be used to tailor exciton states for probing lateral-confinement effects, and lateral confinement can be used to tailor exciton states for probing interwell tunneling. When the lateral confinement is the same in each well, *single-particle* electron and hole interwell tunneling is unaffected by the lateral confinement. However, electron-hole binding is enhanced by lateral confinement, so interwell tunneling of an electron and hole *bound* together in an exciton is modified by lateral confinement. I show that lateral confinement of an indirect exciton in an asymmetric double quantum well under applied bias can enhance the electron-hole attraction enough to induce a crossover from indirect back to direct exciton. There are no compensating effects on interwell tunneling due to the quantization of the exciton center-of-mass motion when the quantization is the same in both wells. Large changes in exciton ground-state energies and oscillator strengths occur at this crossover and provide a signature for lateral confinement of excitons in quantum dots which should be experimentally observable.

This signature of lateral-confinement effects should also be observable in double quantum well electron-hole systems laterally quantized by a strong magnetic field. Time-resolved photoluminescence[12] can distinguish between direct and indirect excitons in double well systems and should be able to detect a magnetic-field-induced crossover. Recently, Coulomb-coupled electron-hole double-layer systems in a strong magnetic field have received renewed theoretical attention[13,14] so that a better understanding of ordered, interwell excitonic states, possibly observed by recent photoluminescence experiments on coupled well systems, could be developed.[15] Lateral confinement by the magnetic field should strongly modify interwell tunneling. The magnetic-field-induced crossover from indirect to direct exciton will determine the maximum magnetic field, for a given interwell tunneling, where indirect excitons are stable. The phase diagram of ordered excitonic states in double well structures where interwell tunneling occurs should reveal complexity resulting from the interplay of interwell tunneling and lateral confinement.

These properties of laterally confined excitons in coupled asymmetric double quantum wells are demonstrated by the use of the following simple model.[16] I assume that the two wells are sufficiently narrow that the electron and hole can only occupy the lowest-energy single-particle subbands in each well. These states are coupled by the interwell tunneling so all four configurations for the electron and hole in the two wells can contribute to the exciton ground state. Typically, the length L of the lateral confinement (dot size or cyclotron radius) is much greater than the widths w_i of the two coupled quantum wells $(i=1,2)$ and the intrawell motion of the electron-hole pair in the plane of each well is correlated. However, the correlation may be different for each configuration of the electron and hole in the two wells. For this model, I use the following wave function for the exciton ground state (based on extensions of the wave functions used by Bryant[4] for single dots and by Dignam and Sipe[1] for coupled quantum wells),

$$\Psi_{\mathrm{ex}}=C_e(x_e,y_e)C_h(x_h,y_h)S(x_e,y_e,x_h,y_h;z_e,z_h)\,, \quad (1)$$

where $C_{e\,(h)}$ is the single-particle electron (hole) ground-state wave function for lateral (x and y) confinement, and S accounts for electron-hole correlation in the lateral direction and the tunneling between wells (the z direction)

$$S(x_e,y_e,x_h,y_h;z_e,z_h)=\sum_{i,j=1,2}\phi_{ei}(z_e)\phi_{hj}(z_h)\times\chi_{ij}(x_e,y_e,x_h,y_h)\,. \quad (2)$$

$\phi_{e(h)i}$ is the electron (hole) ground state for well i and χ_{ij} is the lateral correlation when the electron is in well i and the hole in well j. Implicit in Eq. (1) is the additional assumption that the lateral confinement is the same in the two wells and in the barriers. This assumption could be relaxed, but the results would not change qualitatively.

For specific calculations, I model the lateral confinement for square quantum dots with infinite barrier confining potentials.[4] In this case ($-L/2\le x,y\le L/2$),

$$C_e(x,y)=C_h(x,y)=(2/L)\cos(kx)\cos(ky)\,, \quad (3)$$

with $k=\pi/L$. Parabolic confinement in a circular dot that models charge depletion at the sidewalls or a magnetic field could also be used. Both models for lateral confinement will give similar results. For the correlated lateral motion, I choose

$$\chi_{ij}(x_e,y_e,x_h,y_h)=\sum_n c_{ij,n}\exp\{-a_n[(x_e-x_h)^2+(y_e-y_h)^2]\}\,. \quad (4)$$

Accurate energies and wave functions are obtained by the use of 5–10 Gaussians.[4]

The 1D confinement in the two coupled asymmetric wells is modeled by a band profile with an infinite barrier, the wide first well, the middle barrier with height determined by the band discontinuity, the narrow second well, and another infinite barrier. A flat band profile is assumed for each region. For finite applied bias between the two wells, I assume that the bands remain flat with the first well's band edge fixed, the middle barrier height shifted by half the applied bias, and the second well's band edge shifted by the applied bias. These assumptions allow simple analytic wave functions for the well states to be used. The ground state $\phi_{e(h)i}$ for well i is found by assuming that the middle barrier extends across the other well. Accurate energies and wave functions for the two lowest electron and two lowest hole 1D states in the coupled wells are obtained when $\phi_{e(h)1}$ and $\phi_{e(h)2}$ are used as the basis functions which are coupled by interwell tunneling.

The effective-mass Hamiltonian is solved with the wave function defined by Eqs. (1)–(4) to determine the $c_{ij,n}$, the exciton ground-state energies, and oscillator strengths. The electron-hole interaction is the Coulomb interaction screened by the background dielectric constant. The effective masses and dielectric constant for GaAs are used for the two wells and the middle barrier. The barrier heights are 250 meV for the conduction band and 100 meV for the valence band. These heights correspond to $Al_{0.3}Ga_{0.7}As$. Results are presented here for heavy-hole excitons confined in a double well structure, with 15- and 10-nm wells and a 3-nm middle barrier (the same structure as studied in Ref. 12), at positive bias (defined so the hole states are resonant at positive bias). Similar calculations for light-hole excitons, for other asymmetric and symmetric structures, and for crossovers at electron resonances will be discussed in detail elsewhere.

At zero applied bias the electron and hole are localized in the wide well of the coupled well structure. A noninteracting hole localizes to the narrow well for positive biases V greater than the hole single-particle resonance at V_h, independent of the lateral confinement. However, a higher bias $V_{ex}(L)$, which depends on the dot size L, is required to overcome the electron-hole attraction and localize the hole to the narrow well when the hole is part of an exciton. This dependence of the direct-indirect crossover on dot size provides a signature for lateral confinement effects. The ground-state energies for laterally confined excitons in a double well are shown in Fig. 1 as a function of the applied bias and of the width of the lateral confinement (which I refer to as the dot width, but would correspond to the cyclotron radius for an applied magnetic field). For the structure considered here, $V_h=4$ meV [see Fig. 1(b)]. In my model the bias is applied from the center of the first well to the center of the second well. A 4-meV bias corresponds to a 2.5-kV/cm applied field. For

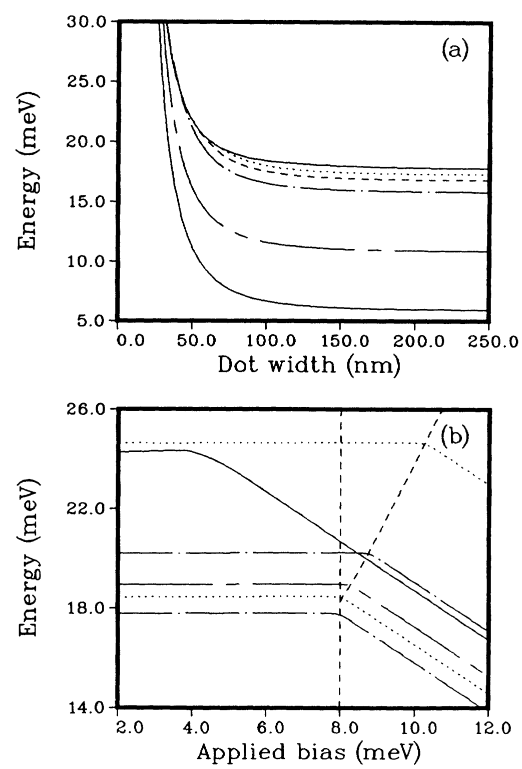

FIG. 1. Exciton ground-state energy. (a) Dependence on dot width L for applied bias: 0 meV (upper solid curve), 8.5 meV (dotted curve), 9 meV (dashed curve), 10 meV (dash-dotted curve), 15 meV (long dash–short dash curve), and 20 meV (lower solid curve). (b) Dependence on applied bias for dot width: 40 nm (upper dotted curve), 60 nm (upper dash-dotted curve), 80 nm (long dash–short dash curve), 100 nm (lower dotted curve), and 300 nm (lower dash-dotted curve). The dashed lines show the direct-indirect crossover with and without lateral confinement. The solid line is the ground-state energy in the absence of Coulomb effects.

$V < V_{ex}$ the exciton is direct and the exciton energy is independent of the bias. However, for $V_h < V < V_{ex}$, the difference between the exciton energy and the subband energy increases with increasing bias because the higher-energy hole state is being mixed into the exciton ground state to keep the exciton direct. For $V > V_{ex}$, the exciton is indirect and the energy shifts with applied bias, following the subband edge for the indirect electron-hole pair. In large dots where lateral confinement is negligible ($L \approx 300$ nm), the resonance bias is $V_{ex} = 8$ meV. For small dots, V_{ex} shifts to substantially higher bias because the lateral confinement enhances the electron-hole attraction. The shift in resonance bias due to lateral confinement, $V_{ex}(L) - V_{ex}(\infty)$, can be as large as the shift in resonance bias, $V_{ex}(\infty) - V_h$, due to excitonic effects in the absence of lateral confinement.

The electron-hole attraction provides the coupling between 1D and lateral confinement which allows one to use confinement in one direction to probe confinement effects in the other direction. For fixed lateral confinement [Fig. 1(b)], applying a bias produces a crossover from direct to indirect exciton which depends on the lateral confinement. For fixed applied bias $V < V_{ex}$ [Fig. 1(a), upper solid curve], the exciton is confined in the wide well. Lateral confinement of the exciton produces the energy shifts expected for an exciton in a single quantum dot.[4] For fixed applied bias $V > V_{ex}$, a crossover from indirect to direct exciton is induced by lateral confinement. As a consequence, the shift of the exciton ground-state energy that is induced by increasing the lateral confinement is much larger at high bias, where the indirect-direct crossover occurs, than at low bias, where the exciton is always direct.

The indirect-direct crossover induced by the lateral confinement will produce a large change in the exciton photoluminescence. The exciton ground-state oscillator strength divided by the dot area L^2 (normalized to be near unity for an unconfined two-dimensional exciton) is shown in Fig. 2. For fixed lateral confinement [Fig. 2(b)], the direct-indirect transition in the oscillator strength induced by applying a bias is sharp, with a width of 0.3 meV for this structure, and complete, with no oscillator strength when the exciton is indirect. For fixed applied bias well below $V_{ex}(\infty)$ [Fig. 2(a), upper solid curve], the oscillator strength is constant in large dots, as expected for weak lateral confinement,[4] and varies as $1/L^2$ in small dots where the exciton is a strongly confined, uncorrelated electron-hole pair.[4] For fixed applied bias $V > V_{ex}(\infty)$, the indirect-direct crossover induced by increasing the lateral confinement is clearly observable in the oscillator strength. At high applied bias the crossover is from indirect exciton to spatially direct (but uncorrelated) electron-hole pair and a large modulation of the oscillator strength is produced by changing lateral confinement.

The exciton ground state is a mixture of the indirect and the direct exciton states. Normally, increasing the lateral confinement increases the probability that the exciton ground state is direct. For large dots the exciton ground state can become more indirect, with a reduction in the oscillator strength, as lateral confinement increases for biases near $V_{ex}(L)$ [within the halfwidth for the

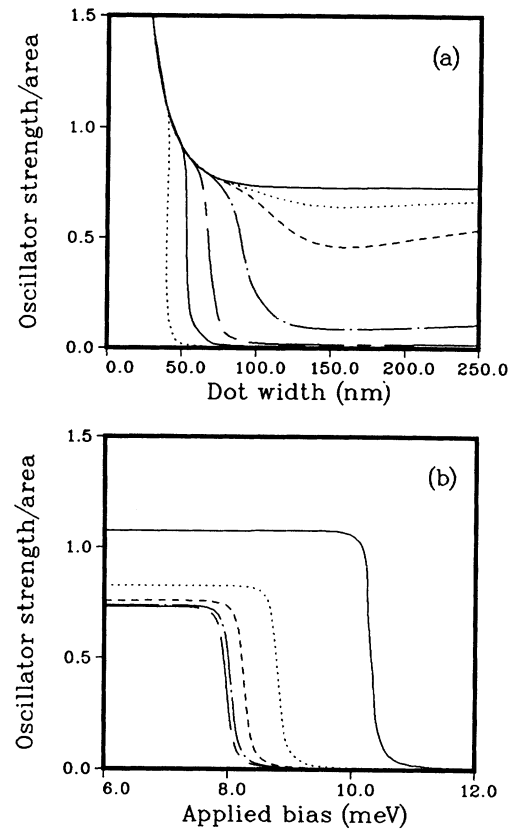

FIG. 2. Ground-state exciton oscillator strength normalized by the dot area L^2. (a) Dependence on dot width for applied bias: 0 meV (upper solid curve), 7.8 meV (upper dotted curve), 7.9 meV (dashed curve), 8.1 meV (dash-dotted curve), 8.5 meV (long dash–short dash curve), 9 meV (lower solid curve), and 10 meV (lower dotted curve). (b) Dependence on applied bias for dot width: 40 nm (solid curve), 60 nm (dotted curve), 80 nm (dashed curve), 100 nm (dash-dotted curve), and 300 nm (long dash–short dash curve).

direct-indirect transition; see Fig. 2(a), $V = 7.8$, 7.9, and 8.1 meV]. This anomalous behavior occurs for dots much wider than the *direct* exciton but more comparable in lateral size to the *indirect* exciton. In this size regime, increasing lateral confinement enhances the indirect-exciton binding without increasing the direct exciton binding, so the exciton ground state becomes more indirect and the crossover bias is reduced slightly by 0.1 meV (which is not visible in Fig. 1). For $L < 100$ nm, increasing the lateral confinement enhances the direct exciton binding, makes the exciton ground state more direct, and produces large increases in the crossover bias.

In summary, laterally confined excitons in coupled asymmetric double quantum wells can be probed by the confinement in one direction to reveal the effects of confinement in the other directions. A crossover from indirect to direct exciton occurs when the exciton in a coupled quantum well under applied bias is laterally confined. Large lateral-confinement-induced changes in the exciton energy and oscillator strength at this crossover provide a new signature for lateral confinement effects on excitons.

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