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Effect of the lifting of Kramer's degeneracy on excitonic linewidths in quantum well optical modulators

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In symmetric quantum well structures, the hole subband states maintain the spin degeneracy (Kramer's degeneracy), but in asymmetric quantum wells and in optical modulators in the presence of electric field, the degeneracy is lifted. This results in splitting of excitonic transitions due to splitting in the exciton binding energy. For small splitting this will result in exciton broadening. Comparisons are presented for this broadening in symmetric and asymmetric quantum well structures as a function of electric field. The light hole exciton is found to broaden at an order of magnitude higher rate than the heavy hole exciton. Field-dependent experimental results for symmetric GaAs/Al_{0.3}Ga_{0.7}As multiquantum well structures are carried out and support the theoretical results.

The study of exciton absorption peaks and their control through transverse electric field (quantum-confined Stark effect) has recently become an important area of research.¹⁻⁵ New phenomena and device concepts point to a bright future for exciton-based devices for optical processing. Modulator and photocurrent-controlled all-optical switches with significant contrast ratios have been demonstrated using III-V heterostructure technology.⁶⁻⁸

A key ingredient in the device performance of excitonic-based optical devices is exciton linewidth. Optical modulator contrast ratio as well as operation of the self-electro-optic effect device (SEED)⁷ depends strongly on this linewidth. Extrinsic effects such as interface roughness and well-to-well size fluctuation clearly contribute to the inhomogeneous line broadening⁹ while the phonons¹⁰ contribute to the homogeneous linewidth. However, another intrinsic source of line broadening in optical modulators arises from the lifting of spin degeneracy of the hole states in quantum wells (Kramer's degeneracy).¹¹⁻¹³ This occurs whenever the well is asymmetric and shows in the Kohn-Luttinger formalism¹²⁻¹⁴ due to heavy hole-light hole mixing term. The well asymmetry may be caused either by fabrication or by electric field.

To study the significance of this effect on exciton linewidths, we have solved the exciton problem in symmetric and asymmetric quantum wells in the presence of a transverse electric field. Since it was necessary to include the heavy hole (HH)-light hole (LH) coupling to study this phenomenon, we used the Kohn-Luttinger formalism^{13,14} and applied it to the GaAs/AlGaAs system. Experimental studies were also carried out to study the exciton absorption in the presence of an electric field at low temperatures. The experimental and theoretical results are in reasonable agreement.

The subband positions for the electron and hole states are determined by solving the one-dimensional Schrödinger equation:

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(k,z) + V(z)\Psi(k,z) = E\Psi(k,z), \quad (1)$$

where $V(z)$ represents the potential barrier seen by the electrons.

To calculate the exciton binding energy and absorption constant, it is important to include the interaction between the light hole and heavy hole states, especially for the system we are considering here, since its states are very close. This is done via the Kohn-Luttinger Hamiltonian.¹⁴

Once the subband levels are known, the exciton problem is solved variationally and the absorption constant is determined by¹⁵

$$\alpha_{nm} = \frac{4\pi^2 e^2 \hbar}{\eta m_0 c W} \frac{1}{\hbar\omega} \left| \sum_{k_{\parallel}} G_{nm}(k_{\parallel}) \hat{\epsilon} \cdot p_{nm}(k_{\parallel}) \right|^2 \times \delta(\hbar\omega - E_{nm}), \quad (2)$$

where η is the refractive index of the semiconductor, ω is the photon frequency, $\hat{\epsilon}$ is the polarization vector of the radiation, and m, n are the hole and electron subband indices. The $p_{nm}(k_{\parallel})$ are optical matrix elements and the $G_{nm}(k_{\parallel})$ are the Fourier components of the exciton envelope function and are determined by the solution of the exciton problem. The Dirac δ function is replaced by the broadening function to simulate the exciton linewidth.

GaAs/Al_{0.3}Ga_{0.7}As multiquantum well samples were grown in a Varian's Gen II MBE system. The well width was 100 Å for the data reported here. p - i (MQW)- n diodes were fabricated from these samples and the field-dependent absorption measurements were made after removing the substrate. The intrinsic region of the device was 2 μm thick so that 1 V bias corresponded to a field of approximately 5 kV/cm.

Figure 1 shows the hole dispersion relation for a symmetric 100 Å GaAs/Al_{0.3}Ga_{0.7}As quantum well structure at fields of 0 and 70 kV/cm. Note that for the symmetric structure, the hole subband states are doubly degenerate at

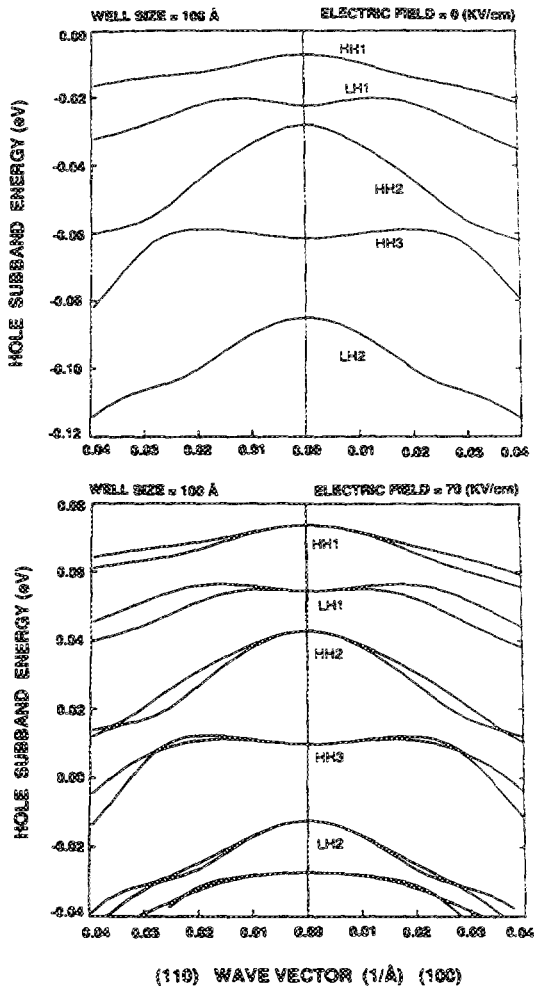


FIG. 1. Hole dispersion relations for a symmetric 100 Å GaAs/Al_{0.3}Ga_{0.7}As quantum well structure at 0 and 70 kV/cm.

zero field. In the presence of the electric field, the well is asymmetric and a splitting can be seen in the otherwise doubly degenerate HH and LH subband states. This splitting causes the exciton binding energy to be different for the two excitonic states. In the case of an asymmetric well, the structure is asymmetric even at zero bias and therefore exhibits splitting. In the presence of an electric field, the hole envelope functions may become either more asymmetric or less asymmetric depending upon the field direction. Figure 2 shows the calculated splitting for the symmetric 100 Å quantum well as a function of field. We note that the broadening of the LH1 exciton is much greater than the HH1 exciton because of the peculiar LH1 dispersion relation (as can be seen in Fig. 1). The LH1 states have negative mass due to the strong hole mixing effects and the LH1 exciton mass is consequently very large. Thus a small change in the light hole mass causes a large change in the exciton effective mass and consequently in the LH binding energy.

From the experimentally observed field-dependent absorption inset of Fig. 2, we have extracted the HH1 and LH1 exciton linewidth at 77 K where we expect that at zero bias the linewidth will be dominated by inhomogeneous broadening due to interface roughness and well-to-well size fluctuations. To determine the effect of Kramer's degeneracy lift-

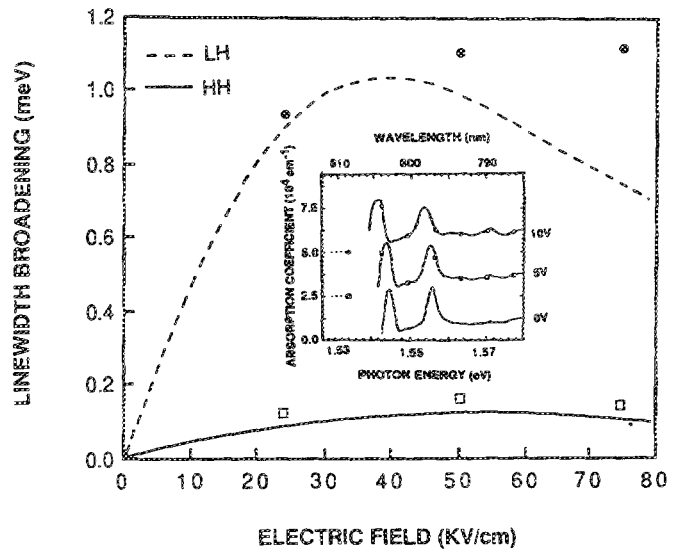


FIG. 2. Linewidth (= splitting in exciton energies) calculated for 100 Å GaAs/Al_{0.3}Ga_{0.7}As quantum well as a function of electric field. Also shown are experimentally observed absorption spectra and linewidths extracted from the data using Eqs. (3)–(5).

ing on the exciton broadening, we removed the effects of inhomogeneous broadening from the total linewidth. For this we have calculated:

$$\Delta_{\text{int}}^{\text{HH}}(E) = \Delta^{\text{HH}}(E) - \beta^{\text{HH}}(E)\Delta^{\text{HH}}(0), \quad (3)$$

and

$$\Delta_{\text{int}}^{\text{LH}}(E) = \Delta^{\text{LH}}(E) - \beta^{\text{LH}}(E)\Delta^{\text{LH}}(0), \quad (4)$$

where $\Delta^{\text{HH}}(E)$ and $\Delta^{\text{LH}}(E)$ are the field-dependent linewidths for the HH1 and LH1 transitions, and $\beta^{\text{HH}}(E)$ and $\beta^{\text{LH}}(E)$ represent the effect of electric field on inhomogeneous broadening. Note that $\beta^{\text{HH}}(E)$ and $\beta^{\text{LH}}(E)$ both increase with the field⁹ and that $\beta^{\text{LH}}(E)$ is less than $\beta^{\text{HH}}(E)$. In general,

$$\beta \approx \frac{\partial E_{\text{ex}}(E)}{\partial w} \Big|_{w=w_0} / \frac{\partial E_{\text{ex}}(E=0)}{\partial w} \Big|_{w=w_0}, \quad (5)$$

where E_{ex} is the exciton energy and w_0 is the well size.

Thus the quantities in Eqs. (3) and (4) represent the intrinsic field dependent broadening. Since electron and hole tunneling rates are quite low at these fields, these values essentially represent the broadening due to Kramer's degeneracy. We have plotted these points in Fig. 2 for the HH1 and LH1 excitons. We note that in agreement with theoretical predictions, the broadening is much stronger than for the LH1 excitonic state than for the HH1 state. We also note that it is difficult to extract linewidth from absorption data, and so we expect our values to have $\sim \pm 15\%$ error. However, since the relative broadening of LH1 and HH1 states is expected to remain fairly accurate, we find a fair agreement with our theoretical predictions.

Finally, in Fig. 3 we have plotted the linewidth due to the lifting of Kramer's degeneracy for an asymmetric well which has the composition Al_{0.2}Ga_{0.8}As/GaAs(100 Å)/Al_{0.4}Ga_{0.6}As. In this case, the well is asymmetric at zero bias and, as shown in Fig. 3, has a finite splitting at zero bias. The splitting is also found to be dependent on the direction of

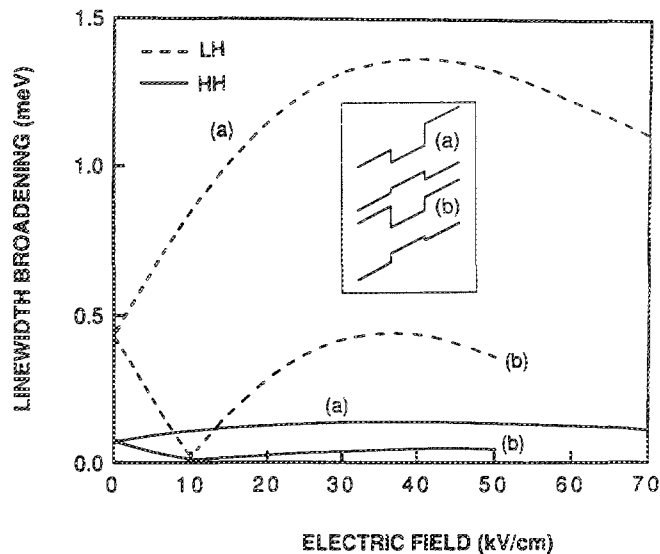


FIG. 3. Linewidth calculated for asymmetric quantum well (shown in inset) for two different directions of the transverse electric field.

the electric field as expected. When the electric field is in the direction which initially makes the hole wave function more symmetric with bias, the splitting goes through a minimum as shown. In this case we show results for fields only up to 50 kV/cm since the exciton is dissociated at higher fields.

In summary, we have discussed theoretical and experimental consequences of Kramer's degeneracy in optical modulators. Due to strong hole mixing, the effect on the LH1 state is much more dominant than on the HH1 state. Asym-

metric wells can be designed so that this broadening is minimum at a specific electric field.

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