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THEORY OF QUANTUM WELL EXCITONS IN ELECTRIC AND MAGNETIC FIELDS

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Abstract: The effects of external electric and magnetic fields on excitons in GaAs/AlGaAs quantum wells have been calculated in the effective mass approximation. Recent experiments by Viña et al. which identify exciton couplings induced by an electric field are satisfactorily explained by the effects of valence band mixing. The properties of magneto-excitons in quantum wells are also found to be characteristically affected by electric fields.

The properties of excitons in quantum wells have attracted much interest in the last years (see [1] and references therein). The effect of electric fields on excitons in quantum wells is different from that in the bulk due to the confinement of electron and holes by the quantum well potential [2]. In a recent experiment [3] electric field induced exciton couplings have been identified which cannot be explained by a two band model, i.e. band mixing effects must be taken into account.

We have investigated [4] the properties of quantum well excitons in the effective mass approximation, neglecting the exchange interaction between electrons and holes. Hole band hybridization is described by the Luttinger Hamiltonian [5] which at zero magnetic field is invariant under the transformations of the cubic symmetry group \(O_h\). A quantum well (at zero electric field) is represented by a Kronig-Penney potential which reduces the symmetry of the effective mass Hamiltonian to \(D_{4h}\). The excitons may thus be classified by the irreducible representations of the double group of \(D_{4h}\), i.e. \(\Gamma_6\), \(\Gamma_4\), \(\Gamma_2\) and \(\Gamma_7\). An electric field normal to the well reduces the symmetry further to \(C_{4v}\). By the breaking of the inversion symmetry gerade and ungerade states are coupled and excitons are labeled by the two remaining "good quantum numbers" \(\Gamma_6\) and \(\Gamma_7\). Note that an electric field does not lead to a spin splitting, as mistakenly stated in [6]. The lifting of the Kramers degeneracy is accomplished by a magnetic field which breaks the time reversal symmetry.

For simplicity, we neglect the differences in effective masses and dielectric constants in well and barrier materials and use the 85/15 rule for the band offsets. The relevant subband energies are then comparable in magnitude to those which are calculated with a 65/35 band offset rule and taking the effective mass mismatch and non-parabolicities into account. Exciton energies and wave functions are obtained with a basis consisting of the square well eigenfunctions normal to the well and two-dimensional hydrogenic wave functions in the plane of the well with angular momentum components up to \(m = 3\) and non-orthogonal radial components of different spatial extension. For the well parameters considered here reasonably converged results are obtained by considering 4 subband wave functions for electron, and 6 for heavy hole and light hole, respectively, and 5 radial wave functions for each of the in-plane 1s, 2s, 2p and 3d angular momentum components. The effects of the cubic anisotropy in the plane of the well and the 4f components have been studied and found to be small. The parameters used in the present study...
are in the conventional notations: $m_e = 0.0665m_0$, $\gamma_1 = 6.85$, $\gamma_2 = 2.1$, $\gamma_3 = 2.9$, $\kappa = 1.2$, $q = 0.04$, $\varepsilon_0 = 12.5$, $\Delta E_p = (1155x + 370x^2)$ meV.

Figure 1: Energies of excitons in a quantum well of 160Å and an aluminum concentration of $x = 0.32$ in the barrier as a function of an electric field normal to the well. Dashed and full lines indicate the different irreducible representations to which the exciton states belong. The character of the exciton wave functions at zero field and at 30kV/cm is also indicated. Triangles indicate the experimental results from [3] after subtracting an energy gap of (1519 + 2.3)meV.

We have calculated exciton energies and wave functions for a quantum well of 160Å and an aluminum concentration of $x = 0.32$. In Figs.1 and 2 the energy positions and oscillator strengths of the exciton states close to the heavy hole band edge are displayed, respectively. In a symmetric quantum well the heavy hole $2p$ and light hole $1s$ excitons (denoted by $h(2p)$ and $\ell'(1s)$) associated with the lowest subbands belong to the different representations $\Gamma_\ell$ and $\Gamma_\mu$. They are coupled by the electric field, however, which leads to the anticrossing behaviour observed in Fig.1. Note also that for the lowest subbands there is no coupling between $h(ns)$ ($\Gamma_6$) and $\ell'(ns)$ or $h(np)$ ($\Gamma_7$) excitons. The interaction between $\ell'(1s)$ and $h(3d)$ may be observable already at zero field (both $\Gamma_{6d}$) and somewhat narrower wells [4]. At a field of about 24 kV/cm $\ell'(1s)$ merges with the heavy hole exciton continuum. Since our basis is discrete, we are not able to calculate the expected (Fano) broadening. It is possible, however, to trace the resonance energy as indicated by the dashed-dotted line in Fig.1. As seen in Fig.2 the initially heavy hole derived excitons borrow oscillator strength from $\ell'(1s)$ with increasing field, which is an obvious consequence of the exciton mixings discussed above. On the other hand, the integrated oscillator strength of the group of $\Gamma_7$ excitons only slightly decreases, which reflects the increased spatial separation of electron and hole with increasing electric field. In [3] additional fine structure in the spectra is reported at fields of about 2-8 kV/cm and interpreted as the simultaneous appearance of $h(2s)$ and $h(2p)$ excitons, which is confirmed by the present results. These states should cross in the present theory at a field of about 13 kV/cm. Symmetry breaking terms beyond the effective mass approximation and the effects due to the exchange interaction are estimated to be very small. The experimental evidence for an interaction between these $\Gamma_6$ and $\Gamma_7$ exciton states is at present not conclusive, however.

The effect of combined electric and magnetic fields on the $h(1s)$ exciton is illustrated in Fig.3. A small spin splitting is found which changes sign at intermediate fields [4], a behaviour which has been also observed in recent magneto-luminescence spectra (W. Ossau, private communi-
Figure 2: Oscillator strengths of the excitons described in Fig.1. The integrated curve also contains contributions from the quasi-continuum not displayed explicitly. The $\Gamma_7$-states are labeled with increasing energy. At zero field we have (cf. Fig.1): $\Gamma_{x}^{(1)} = \ell(1s)$, $\Gamma_{y}^{(1)} = h(2p)$, $\Gamma_{y}^{(3)} = h(3d)$.

Figure 3: Energy shifts of spin-up and spin-down heavy hole excitons as a function of magnetic field of a quantum well with $L_z = 160\text{Å}$. The dispersion at zero electric field (lower two full lines) is significantly smaller than at a field of 50 keV normal to the well (upper two full lines). The dashed lines correspond to the neglect of any mixing between heavy and light holes.
Subband separations and the exciton radii increase with increasing electric field, which leads to a larger diamagnetic shift of the exciton energies.

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