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MAGNETIC FIELD EFFECTS IN HIGHLY RESOLVED TWO-DIMENSIONAL EXCITONS

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We have studied the pseudo-absorption of GaAs–GaAlAs quantum wells by means of photoluminenscence excitation spectroscopy in the presence of an external magnetic field perpendicular to the layers. The unprecedented quality of the sample is obvious in the enormous complexity of the spectra, which is resolved for the first time. All the structures correspond to ground and excited states of confined excitons, and are identified by comparison with calculations that take into account the complexity of the valence band structure and exciton mixing in the presence of electric and magnetic fields.

1. Introduction

The absorption spectra of undoped quantum wells (QW's) are dominated by the strong Coulomb interaction between electrons and holes. Sharp excitonic peaks, rising on a step-like background characteristic of two-dimensional systems, correspond to bound states of electrons and holes of the different confined subbands [1]. In high quality samples, the first excited state (2s) of the heavy-hole and the light-hole excitons can be observed routinely [2–4]. Higher excited states can be revealed by the application of external electric and magnetic fields [5].

Important information regarding ground state binding energies and band structure parameters, in bulk and quasi-two-dimensional semiconductors, has been obtained from theoretical [6–10] and experimental [11–15] studies of the effects of a magnetic field on the optical absorption. However, in GaAs/GaAlAs QW's, the fine structure discussed in this paper was not noticed before due to the relatively large line widths of the excitons. In high quality samples, the exciton oscillator strengths are enhanced by the magnetic field and broad continuum resonances are split into discrete lines, corresponding to exciton excited states [9].

We present completely resolved exciton term spectra in a high-quality GaAs–GaAlAs QW from low (0.5 T) up to high magnetic fields (17 T). The spectra can be understood only by comparison with elaborate calculations, which take into account the effects of external fields, the complexity of the valence band structure, and which realistically treat confinement effects. We are able to identify the lines in the spectra and to account quantitatively for the magnetic-field dependence of the energies and oscillator strengths of the excitons.

2. Results and discussion

Photoluminescence excitation (PLE) spectra were obtained in a polyhelix resistive magnet with fields applied in the Faraday configuration. The spectra were recorded with circularly polarized light from an LD700 dye-laser, pumped by a Kr^+-ion laser, at a temperature of 2 K. The sample was a p^+–i–n^+ GaAs–$Ga_{0.65}Al_{0.35}As$ heterostructure with five isolated 160 Å QW's in the intrinsic region, and it has been described previously [4].

Fig. 1 shows PLE spectra, at different magnetic fields, recorded with σ^- polarized light. The spectra

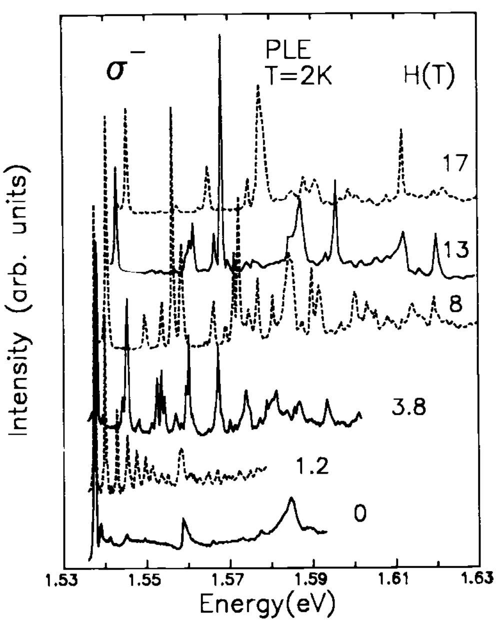


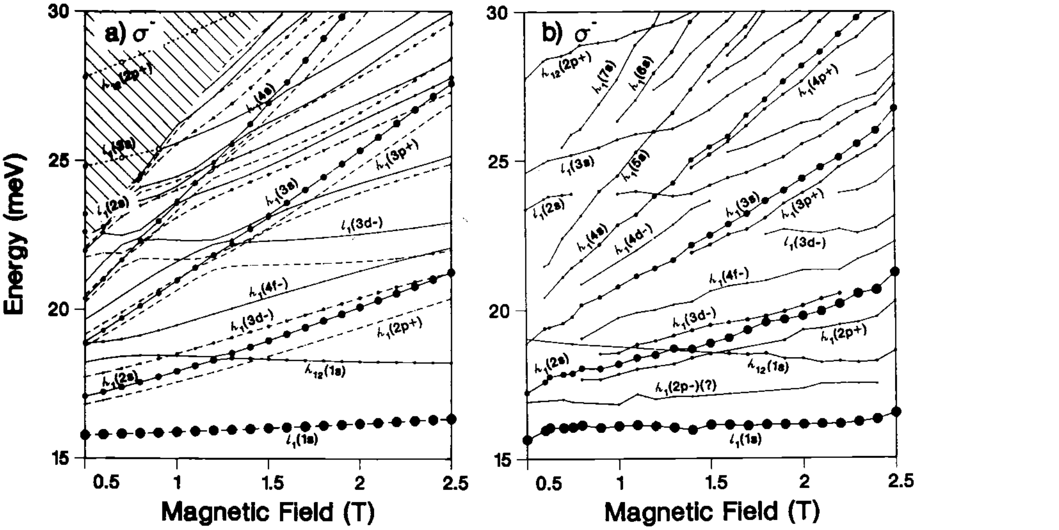
Fig. 1. Low-temperature photoluminescence excitation spectra of a 160 Å quantum well at several magnetic fields normal to the well. The excitation was performed with σ^- polarization. An electric field of ~5 kV/cm is present in the n–i–p heterostructure.

are drawn alternately with solid and dashed lines for clarity. The zero-field pseudo-absorption consists of "allowed" and "forbidden" excitonic transitions, superimposed on a step-like background. The main structures in this spectrum correspond to the ground-state of the light-hole exciton (l_1(1s), 1.538 eV), the first excited states of the heavy-hole exciton (h_1(2s), 1.539 eV) and the light-hole exciton (l_1(2s), 1.545 eV), the h_{13}(1s) exciton (1.558 eV) and the h_2(1s) exciton (1.584 eV). The heavy-hole exciton h_1(1s) (not shown) was measured directly by photoluminescence.

When the magnetic field is applied new peaks appear in the region of the continuous absorption, and the density of states between the peaks vanishes. The reduction of the exciton radius and the increase in the binding energy favors the observation of the excited states. The strongest features correspond to the *n*s levels of the h_1 and l_1 excitons (where $n=1,2,3...$), except in some cases when they interact with other excitonic states and share with them their oscillator strength. A complementary set of spectra is obtained when the sample is excited with σ^+ polarized light.

Fig. 2 shows the calculated (a) and measured (b) shifts of the excitons as a function of magnetic field for σ^- polarization between 0.5 and 2.5 T. In this field range most of the excited excitonic states develop. The energies are measured relative to the band gap of GaAs, with the experimental points rigidly shifted by 2.7 meV towards lower energies. The area of the points is proportional to the calculated and observed intensities (normalized to the intensity of l_1(1s), which increases only weakly with field). In the calculated pictures, the shaded areas correspond to regions where many states develop and only the main resonances l_1(3s) and h_{12}(2p+) are shown. An electric field of ~5 kV/cm present in the sample, which makes some forbidden transitions allowed, is also taken into account in the calculations. The overall agreement between theory and experiment is very good: high-angular-momentum states as h_1(3p+), h_1(3d−) and h_1(4f−) are identified in the experiments; the negative diamagnetic shift of h_{12}(1s) is also predicted by theory. A good agreement is also obtained for the oscillator strengths.

Except at anticrossings, it is possible to label the peaks according to the predominant character of the exciton envelope function. However, this does not



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always hold: the dashed lines in the upper quadrant of fig. 2a represent a strong mixture of $l_1(s)$, $h_1(d-)$ and $l_1(p-)$ states, which cannot unambiguously be disentangled. Symmetry arguments predict that $h_1(2p-)$ should be observed only in σ^+, however, it is also observed in σ^- with similar intensity. The breaking of this selection rule is presently not understood.

Fig. 3 compiles the calculated (a) and measured (b) excitons in the whole field range. The lowest line in fig. 3a corresponds to the ground state of the heavy-hole exciton, which is not plotted in the experimental counterpart. At high magnetic fields the spectra become simpler, resembling the spectra of Landau interband transitions [16]. The qualitative agreement with theory somewhat deteriorates mainly due to basis set limitations [10].

In figs. 2a and 3a the solid (dashed) lines corre-

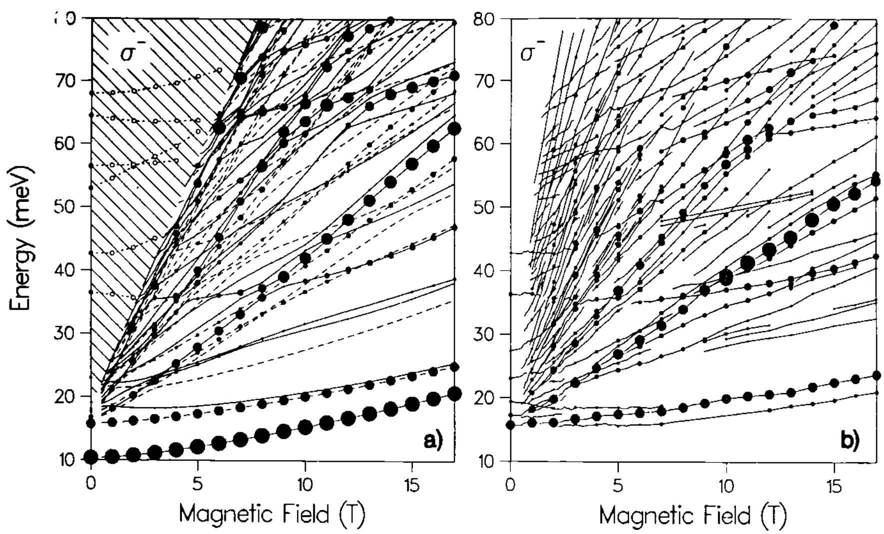

Fig. 3. Same as fig. 2 in the whole range of magnetic fields of the experiments. The area of the points is proportional to the oscillator strenghts.

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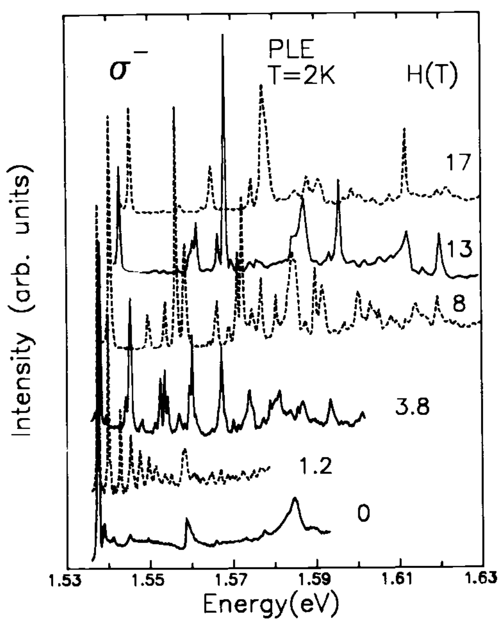

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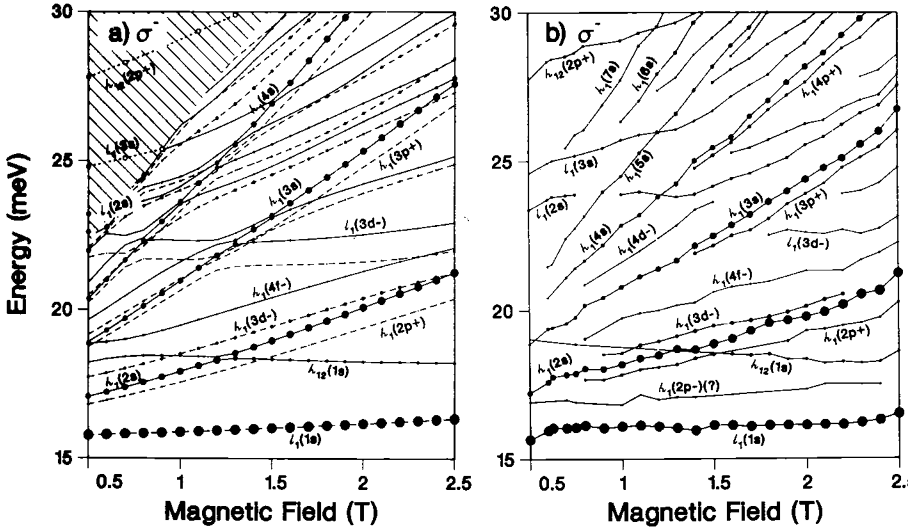

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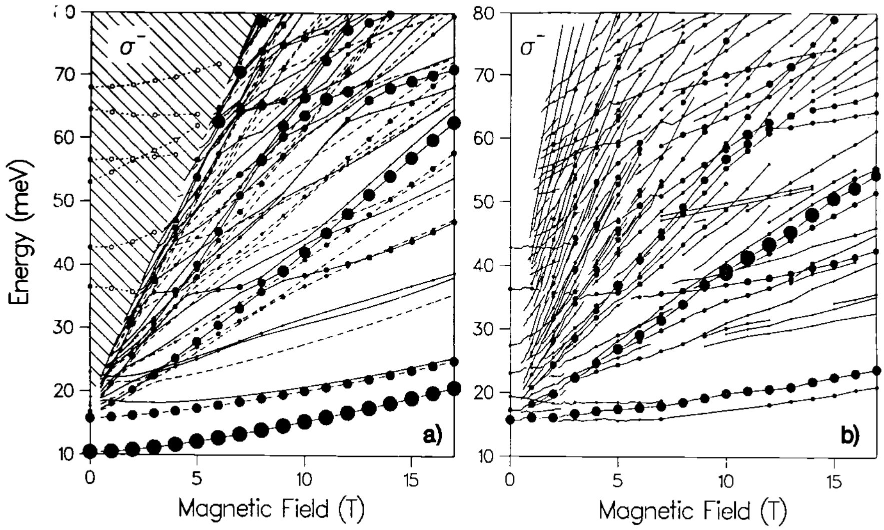

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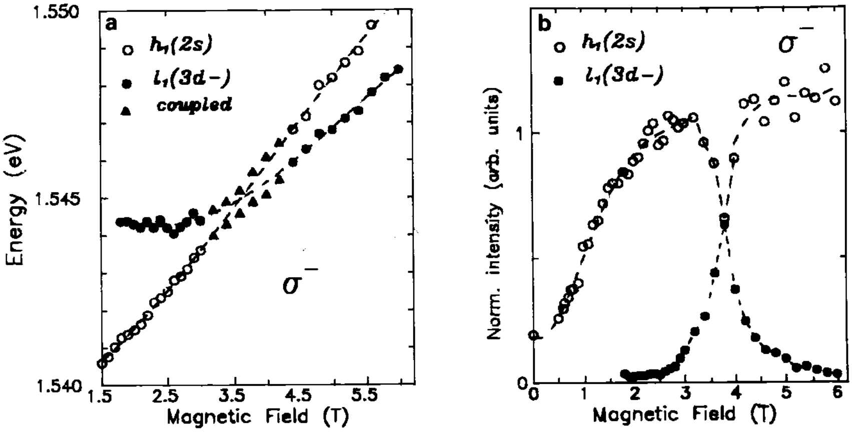

Fig. 4. Energy shifts (a) and oscillator strenghts (b) of $h_1(2s)$ and $l_1(3d-)$ as a function of magnetic field in σ^- polarization. The states are depicted by triangles in (a) in the region of strong interaction. The oscillator strengths are normalized to those of $l_1(1s)$.

spond to excitons with $\Gamma_7(\Gamma_6)$ symmetry in the convention of ref. [10]. States belonging to the same irreducible representation can couple and many interactions are expected in the spectra. Fig. 4 depicts the detail of one anticrossing observed in the experiments. As the field is increased, $h_1(2s)$ approaches $l_1(3d-)$ and looses intensity. In fig. 4a the points are shown as triangles in the region of strong interaction, where they repel each other and share oscillator strength as demonstrated in fig. 4b. Both states belong to Γ_7 symmetry and can interact. Only the group Γ_7 remains a good label and it is not possible to associate a higher symmetry to the excitons because they are of mixed character.

In conclusion, by high-resolution experiments we were able to demonstrate that at non-zero magnetic field the absorption spectrum of quantum wells is composed of well-defined excitonic lines, which reveal the term structure of hydrogenic pair states in semiconductors. The comparison with theory enables the labeling of the levels and the establishment of the symmetry of the wave functions.

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