STARK AND ZEEMAN EFFECTS IN EXCITONS IN GAAS/GAALAS QUANTUM WELLS

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We have studied the effects of electric and magnetic fields in the excitonic spectrum of GaAs/GaAlAs quantum wells by means of low-temperature photoluminescence excitation spectroscopy. The electric field, perpendicular to the layers, couples different excited states of the heavy-hole exciton with the ground state of the light-hole exciton. As a result of this coupling, fine structure becomes visible in the spectra. A small magnetic field (~0.5 Tesla) is applied to remove degeneracies of the excitons and to enhance the oscillator strength of excited exciton-states. These states are resolved with the use of circularly polarized light, which enables us to separate the Zeeman components of the excitons. We are able to assign all the peaks appearing in the complicated excitonic fine structure by comparison with calculations, which take into account valence-band mixing and electric and magnetic field effects.

1.-INTRODUCTION

Considerable effort has been devoted in the past to the understanding of the free-exciton energy spectrum of zinc-blende-type semiconductors.[1,2] Quantum size effects in quantum wells provide excitons with different characteristics as those of excitons in bulk materials: the heavy- and light-hole degeneracy is removed, the binding energy is increased, and the excitons obtain a quasi two-dimensional character. The study of the free-exciton spectrum in high-quality samples yield important information about the differences between three and quasi two-dimensional excitons, and also about the effects of the underlying band structure. The first excited states of the heavy-hole exciton, $h_1^{(2s)}$, can be observed by photoluminescence and photoluminescence excitation (PLE).[3] This observation provides a reliable measurement of the exciton binding energy.[4] By coupling the excited states with higher angular momentum with an s-type exciton, their oscillator strength can be greatly enhanced and they become resolvable in the spectra.[5,6]

Here we present the observation of several excited states of the heavy-hole exciton with angular momentum $m \geq 1$. These states will be labeled as $h_1^{(x)}$, where x can be 2p, 3p, and 3d. Their resolution in PLE spectra was achieved with the combination of an electric field, a small magnetic field, and the excitation with circularly polarized light. The electric field tunes the energy of the excitons, allowing the observation of heavy states with $m \neq 0$ through mixing with the ground state of the light-hole exciton ($l_1^{(1s)}$). The magnetic field, 0.5T, removes the Kramers degeneracy, and confines the excitons in the plane of the wells, therefore enhancing their oscillator strengths. The former effect, combined with the use of circularly polarized light, enables the resolution of closely-lying states (~0.2meV).

2.-EXPERIMENTAL

The heterostructure used in these experiments was grown by molecular beam epitaxy on an (100)-oriented n^+-GaAs substrate. It consists of five periods of GaAs (160A) and $Ga_{0.66}Al_{0.35}As$ (250A)

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layers, finished with a p^+-GaAs layer. The electric and magnetic fields were applied perpendicularly to the layers. Excitation was provided by an Kr^+ ion laser-pumped tunable dye laser (LD700). PLE spectra were recorded with circularly polarized light at a temperature of 2K. Power densities were kept below 20mW/cm^2 to avoid excessive carrier generation.

2.-RESULTS AND DISCUSSION

We will concentrate here on the results for σ^+ polarization, a more comprehensive discussion will be presented elsewhere.[7] Figure 1 shows PLE spectra in the $l_1^{(1s)}$- $h_1^{(x)}$ spectral region for several electric fields. Each spectrum spans an energy range of the order of only 4meV. For the detection, the spectrometer was set at the energy of the heavy-hole exciton (not shown in the figure), which shifts to lower energies with increasing field.[5] At zero field, two peaks, labeled (o) and (+), are resolved in the spectrum; they correspond to $l_1^{(1s)}$ and $h_1^{(2s)}$, respectively. With increasing electric field, the separation between $h_1^{(x)}$ and l_1 decreases, therefore enhancing the interaction between them. The $h_1^{(x)}$ states borrow their oscillator strength from l_1, as they approach it, and become observable in the spectra. At 10.4kV/cm, $h_1^{(2p-)}$ (e) is clearly resolved as a peak between l_1 and $h_1^{(2s)}$. At even larger electric fields (19.8kV/cm), a new structure (x) appears in the spectrum, and $h_1^{(2s)}$ is hidden below the prominent peak (e).

The energy shifts of the excitonic states are depicted in Fig.2 as a function of electric field. These states are labeled, following the convention of Ref.8, according to the irreducible representations of the direct product of the hole Bloch and exciton envelope functions, with an additional superscript indicating their ordering in energy. The heavy-hole s-states do not interact with the rest of the states and retain their character in the whole range of electric fields. The triangles represent the ground state of the heavy-hole exciton ($h_1^{(1s)}$, $\Gamma_7^{(1)}$), and the crosses the $h_1^{(2s)}$ excited state ($\Gamma_7^{(2)}$). The rest of the states may be labeled in the low- and high-field limits, whereas they are strongly mixed in the intermediate-field regime. In the low field limit, the ground state of the light-hole exciton, open circles ($l_1^{(1s)}$, $\Gamma_6^{(3)}$), is the lowest of the structures above 15meV, and it is followed by the excited states of h_1, $h_1^{(2p)}$ (black dots, $\Gamma_6^{(2)}$) and $h_1^{(2s)}$. In the high field limit the situation is reversed, the excited states of h_1 are below $l_1^{(1s)}$ (x, $\Gamma_6^{(4)}$), and their labeling is as follows: $\Gamma_6^{(1)}$ (o, $h_1^{(2p)}$), $\Gamma_7^{(2)}$ (+, $h_1^{(2s)}$), $\Gamma_6^{(2)}$ or

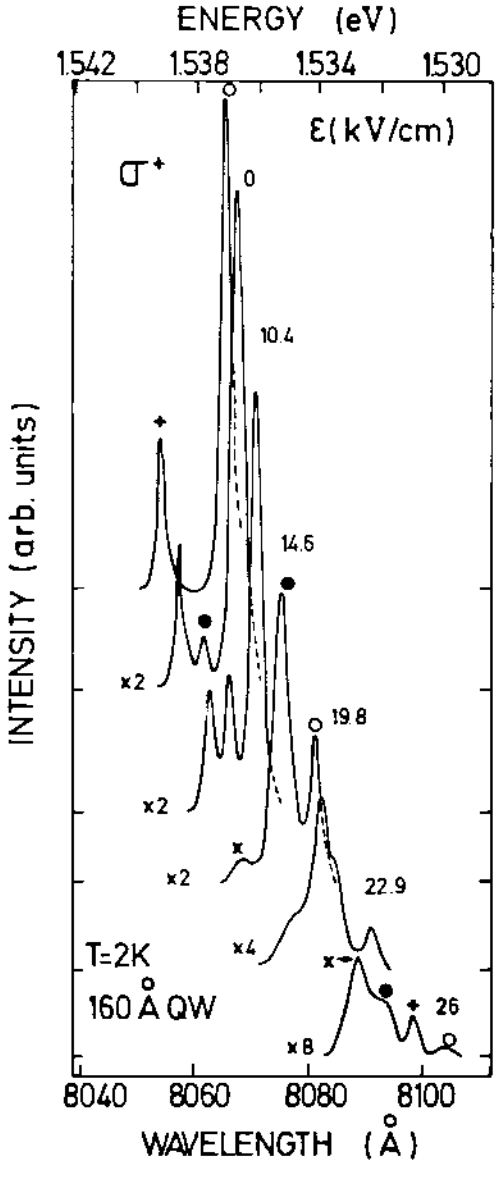

FIG. 1.- Low-temperature photoluminescence excitation spectra of a 160-Å quantum well at several electric fields normal to the well, in the presence of a magnetic field of 0.5 Tesla parallel to the electric field. Scaling factors are indicated on the left-hand side of the spectra.

$\Gamma_6^{(3)}$ (e, $h_1^{(3p)}$ or $h_1^{(3d)}$, respectively). The ambiguity in the identification of the latter structure is also present at intermediate fields: we cannot make a definite identification between $h_1^{(3p)}$ and $h_1^{(3d)}$($\Gamma_6^{(3)}$ and $\Gamma_6^{(4)}$, respectively) for the peak labeled with x. This indetermination arises from

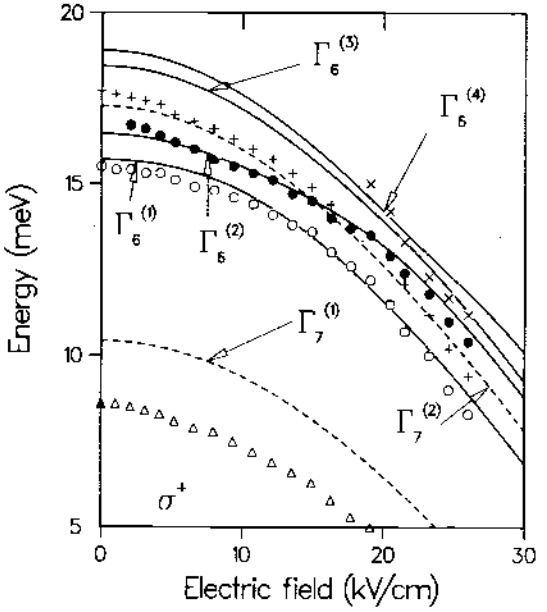

FIG. 2.- Energy shifts of the excitons as a function of electric field for σ^+ polarization. The triangles were obtained directly from photoluminescence spectra, while the rest of the points correspond to the structures in the PLE spectra. The lines represent the results of the calculations.

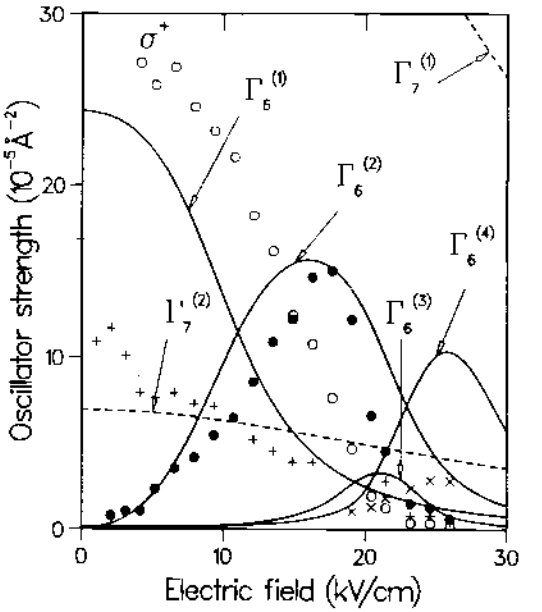

FIG. 3.- Oscillator strengths of the excitons shown in Fig.2. The lines represent the results of the calculations.

the electric-field induced broadening of the states, and the resulting difficulty to resolve these two closely-lying states.

The lines in Fig.2 represent the result of the calculations with the same set of parameters as those used in Ref.8. The agreement between theory and experiment is exceptionally good, especially taking into account the small range of energies involved in the experiments. The oscillator strengths of the excitonic states are plotted in Fig.3 as a function of electric field. The symbols have the same meaning as in Fig.2, and the lines show the results of the calculations. As the electric field is increased, $h_1^{(2p)}(\Gamma_6^{(2)})$ mixes strongly with $l_1^{(1s)}(\Gamma_6^{(1)})$ and they share their oscillator strengths. At larger fields the oscillator strength of $\Gamma_6^{(2)}$ decreases again as it separates from $\Gamma_6^{(1)}$ and a new structure (x) becomes resolvable in the spectra. Its behavior is similar to that of $\Gamma_6^{(2)}$. A comparison with the theory favors the assignment of this structure to $h_1^{(3d)}(\Gamma_6^{(4)})$, because of its larger oscillator strength. However, due to the strong dependence of the oscillator strengths on the choice of the band structure parameters, this identification is not definitive.

The mechanisms of the coupling between $h_1^{(x)}$ and $l_1^{(1s)}$ can be visualized in a four-level model:[7] two heavy states and two light states. The coupling between $h_1^{(2p)}$ and $l_1^{(1s)}$ takes place through $h_2^{(2p)}$ as an intermediate state. The electric field couples both heavy-subbands, $h_2^{(2p)}$ with $h_1^{(2p)}$, and the latter state mixes with $l_1^{(1s)}$ through non-diagonal terms in the Hamiltonian. For d-states, however, the situation is different as these states may already couple in the absence of an electric field,[6] since they belong to the same irreducible representation (Γ_{6g}) of D_{4h}. In this case, the electric field mainly enhances the coupling through the tuning of the states.

In summary, we have demonstrated that a deep understanding of excitons -the solid-state analogue of hydrogenic atoms- is possible, in quasi two-dimensional systems, with the use of optical techniques, combined with external electric and magnetic fields. We have identified the excited states of the heavy-hole exciton by comparison with calculations that take into account valence-band mixing and the effects of electric and magnetic fields.

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