Competition between magnetic-field- and electric-field-induced localizations in GaAs/Ga$_{0.65}$Al$_{0.35}$As superlattices

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We have observed that an in-plane magnetic field applied perpendicular to an electric field along the growth axis of GaAs/Ga$_{0.65}$Al$_{0.35}$As superlattices causes the interband Stark transitions seen in photocurrent spectra to lose intensity and eventually to disappear. For sufficiently high magnetic fields, however, new transitions appear, which we interpret as transitions of magnetic origin. A calculation of the interband transitions that includes excitonic effects gives good agreement with the measured energies and intensities and shows that these results are due to a competition between magnetic-field- and electric-field-induced localizations.

The effects of a magnetic field on semiconductor quantum wells and superlattices have drawn considerable attention in recent years. The case of a magnetic field applied perpendicular to the growth axis z is particularly interesting, since the magnetic field tends to localize the electron motion to cyclotron orbits in the same plane as that of the quantum-well confinement potential. "Bulk-like" interband Landau transitions have been observed in superlattices for energies falling within the hole and the electron subband width,[1] which implies the formation of cyclotron orbits tunneling through the thin periodic barriers.[2] The localization effects of an in-plane magnetic field on a superlattice also have been studied by the inclusion of an enlarged quantum well:[3] Its luminescence decreased when the cyclotron energy $\hbar\omega_c = eB/m^*$ (where m^* is the effective mass) became comparable to the heavy-hole miniband width or when the cyclotron radius r for the lowest Landau level [given by $r = (\hbar/eB)^{1/2}$] became comparable to the superlattice period d in the case of negligible miniband width.

An electric field $\mathcal{E}$ applied parallel to the growth axis of a superlattice misaligns adjacent quantum wells by $e\mathcal{E}d$, and thus also localizes the wave functions. For intermediate electric fields, the electron wave functions still extend over a number of quantum wells, and several Stark transitions, labeled m, between heavy (h) or light (l) hole and electron levels are observed[4] with energies

$$E_m(\mathcal{E}) = E_0(\mathcal{E}) + me\mathcal{E}d, \quad m = 0, \pm 1, \pm 2, \ldots, \quad (1)$$

where E_0 is the intrawell ($m = 0$) transition energy and the $m \neq 0$ transitions are interwell transitions between holes and electrons with wave functions centered in different quantum wells.

The purpose of this work is to study the combined and competing localization effects of perpendicular magnetic and electric fields ($\mathbf{B} \perp z, \mathcal{E} \| z$) in superlattices. Except for some preliminary experimental results presented by us earlier,[5] there is hardly any work on this subject. There have been several recent studies of resonant tunneling into wide quantum wells under an in-plane magnetic field.[6-8] However, the applied electric field mainly serves the purpose of bringing the states in the emitter in alignment with those in the quantum well. These quantum-well states are often called hybrid magnetoelectric states[6-8] but this actually refers to the competition between the magnetic-field quantization and the quantum-well-potential quantization.[9] The effects of parallel magnetic and electric fields ($\| z$) have also been studied[5,10] but in this case the localization effects of the magnetic and electric fields are not competing.

We have used photocurrent spectroscopy to investigate the interband transitions in GaAs/Ga$_{0.65}$Al$_{0.35}$As superlattice under perpendicular magnetic and electric fields of different relative strengths. While resonant tunneling probes electron[6-8] or hole states[11] that satisfy the conservation of momentum and energy upon tunneling, interband absorption experiments probe excitonic states with appreciable electron-hole overlap. Three different regions

could be distinguished: one where the electric field dom-inates over the magnetic field, a second where the Stark transitions are seen to lose intensity and disappear as the magnetic field increases, and a third where the magnetic field dominates and the transitions observed are of mag-netic origin. A calculation of the exciton states describes well the experimental results and demonstrates that electric-field-induced localization prevails in the first re-gion whereas magnetic-field-induced localization prevails in the third.

The experiments reported here were performed on an undoped superlattice grown by molecular-beam epitaxy, consisting of 27 GaAs and 26 $Ga_{0.65}Al_{0.35}As$ alternating layers with nominal thicknesses 40 and 20 Å, respectively, terminated by 600 Å undoped $Ga_{0.65}Al_{0.35}As$ on each side. This structure constituted the intrinsic region of a p^+-i-n^+ GaAs diode. The photocurrent spectra were measured using low-power excitation from a LD700 dye laser.

When only the electric field was applied, the usual exci-tonic Stark transitions were observed in the photocurrent spectrum[4] (Fig. 1). Under perpendicular magnetic and electric fields, no Landau-like transitions appear, as in the work of Belle, Maan, and Weimann,[1] since the electric field has destroyed the superlattice minibands. Instead, the Stark transitions shift to higher energies, lose intensi-ty, and finally disappear as the magnetic field is increased. A simplistic attempt at an explanation of this behavior[5] involves the reduction of the extension of the electron wave function as the cyclotron orbit shrinks for increasing magnetic field. However, for high magnetic fields the magnetic energy ($\hbar\omega_c$) and the electric energy ($e\mathscr{E}d$) be-come comparable and a description in terms of Stark tran-sitions breaks down. For an electric field of 30 kV/cm, the electric energy becomes equal to the magnetic energy at around 10 T. Indeed, it is at about 10 T that the sharp Stark transitions disappear, leaving the photocurrent spec-
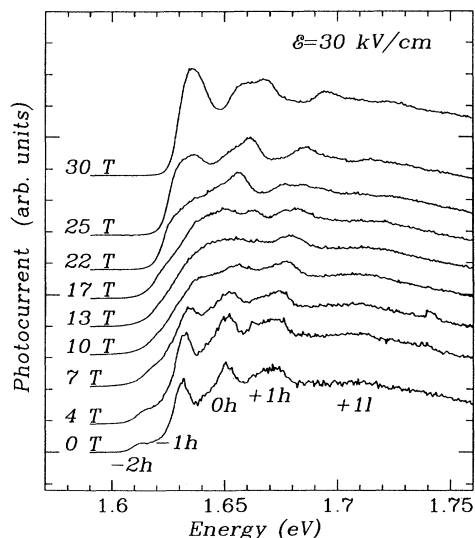
tra fairly featureless (see Fig. 1). When the magnetic field is increased further, we observe the intriguing reem-ergence of structure in the photocurrent spectra (Fig. 1). This structure increases in intensity and gives rise to well-defined, intense peaks, which we attribute to transitions of magnetic nature. (Note that the background photo-current due to absorption in the continuum is practically not affected by the magnetic field, which means that scat-tering leads to sufficient current flow along z.[6-8])

The transition energies and the corresponding intensi-ties are obtained from the peak positions and the area un-der the photocurrent peaks, respectively; they are shown in Fig. 2(a) as a function of magnetic field. For fields much lower than 10 T the electric field dominates and the transitions can be described as Stark transitions. In this region, the Stark transitions show a roughly parabolic dependence on the magnetic field. Moreover, this blue-shift is larger for the $-2h$ than for the $-1h$ transition
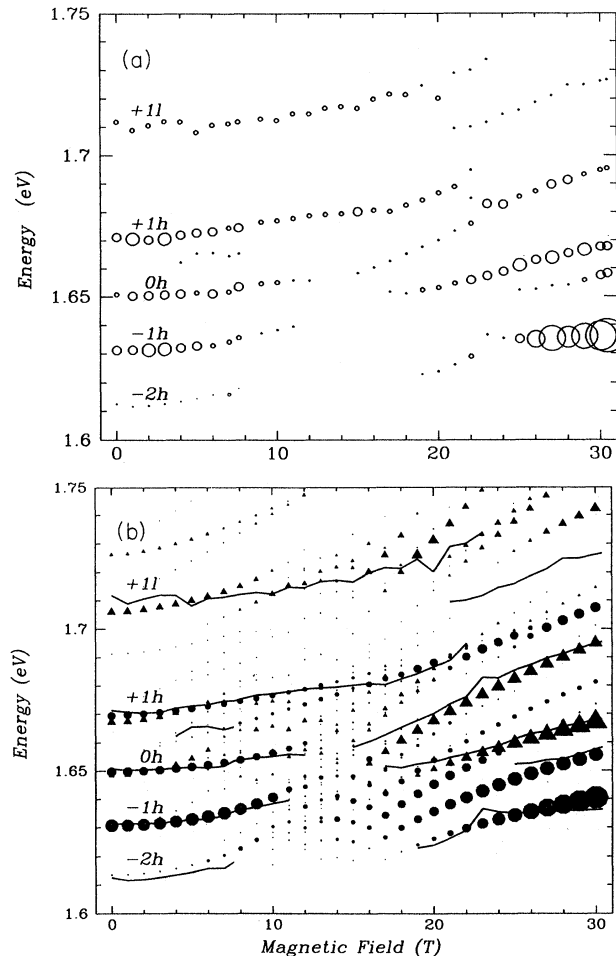

FIG. 2. (a) Experimental and (b) theoretical transition ener-gies and intensities as a function of magnetic field for an electric field of 30 kV/cm. In (b), the circles (triangles) denote heavy-(light-) hole excitons and the lines connect the experimental data of (a). The radius of the symbols in (a) and (b) is propor-tional to the photocurrent intensity and absorption strength, re-spectively.

FIG. 1. Selected photocurrent spectra for the 40-Å GaAs/20-Å $Ga_{0.65}Al_{0.35}As$ superlattice at 4.2 K at a constant electric field for increasing magnetic-field values. The spectra have been offset vertically for clarity.

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and larger for the $-1h$ than for the $0h$ transition. Above 17 T, the magnetic field dominates and the observed transitions resemble Landau transitions in that they shift to higher energies essentially linearly. (Note that even for the highest magnetic field the magnetic length is 47 Å, still larger than the well width.)

We have calculated the exciton energies and oscillator strengths using a generalization of a method successfully employed before on the exciton Stark ladder problem,[12] where the importance of including the excitonic interaction in the calculation of superlattice states was demonstrated. Here, where the exciton binding energies are large due to the magnetic localization, the excitonic modifications to the single-particle results are expected to be even larger, and so must be included. We only outline the theory here as the details of the calculation will be presented in a future publication.[13] Because the symmetries of the exciton Hamiltonian are quite different from those of the single-particle Hamiltonian, it turns out to be advantageous to use the gauge $\mathbf{A}(\mathbf{r}) = -Bx\hat{z}$ rather than the usual gauge $\mathbf{A}(\mathbf{r}) = Bz\hat{x}$.[1] This yields a Hamiltonian which is invariant under simultaneous translation of the electron (hole) z coordinate, z_e (z_h), by an integral number of superlattice periods. We are therefore able to use as our basis the "two-well" exciton states,[12] in which the hole is in one well and the electron is in a well a distance ld away, where l is an integer. The major contributions of the magnetic field to the Hamiltonian are a term proportional to B^2z^2 and one proportional to B^2x^2, where z and x denote electron-hole separation. This second term requires us to generalize our basis[12] to include states of excited in-plane motion, which correspond roughly to the $n=0,1,2$ harmonic oscillator states as a function of x.[14]

The calculated results for the heavy- and light-hole excitons are shown in Fig. 2(b). In the low magnetic-field regime, in which the electric field dominates, there is quantitative agreement with the experimental data. To lowest order in the magnetic field, the excitonic states are left unchanged and it can be shown that the energies of states of Stark index m are blueshifted roughly as $B^2m^2d^2$. This means that, as the magnetic field is increased, the Stark transitions of large $|m|$ are pushed to higher energies much faster than the lower $|m|$ ones, in agreement with the experiment. Thus, at around 9 T, transitions with large negative Stark indices start crossing the higher-energy states which have smaller indices. This is not obvious from Fig. 2(b) because these large-index states have very little oscillator strength until they mix with the low-index ones. The increasingly strong interaction and mixing between the different excitonic Stark states leads to the loss of oscillator strength and the final disappearance of the low-index Stark transitions. This behavior explains all of the experimental features of the low magnetic-field regime: Because the interaction region sets in earlier for lower-energy states, the $-2h$ Stark state disappears for lower magnetic fields than $-1h$, and the latter disappears before the $0h$ state [see Figs. 1 and 2(a) as well as Fig. 3(b) of Ref. 5]. The $+1h$ state persists because it is only crossed by the states with $m \leq -2$, and since these have very little overlap with the $m = +1$ state, it is left essentially unperturbed in character up to very

high fields (< 20 T). For lower electric fields the quenching of the Stark-like transitions sets in for lower magnetic fields [see Fig. 3(c) of Ref. 5]. Lowering the electric field decreases the energy difference $e\mathcal{E}d$ between Stark states and therefore shifts the anticrossing region to lower magnetic fields. Indeed, as mentioned above, it is the relative strength of the two fields that matters.

In the field region between 10 and 17 T, most of the states have lost their Stark-ladder character, but have not yet been strongly localized by the magnetic field. All of the states in this region have small oscillator strengths and are close together in energy [see Fig. 2(b)]. They are therefore not resolvable and this yields the broad, featureless hump seen in Fig. 1. This feature is also seen in Fig. 3, where we present the calculated absorption spectra for various magnetic fields. There is very good agreement with the experiment except at high energies, where the continuum (not included in the calculation) becomes important.

In the high-field regime, strong, distinct peaks reemerge for light and heavy holes. The lowest two observed states are found to be heavy hole and the next two light hole. The agreement between the experiment and theory for both oscillator strengths and energies (Fig. 2) is generally good with the exception of the precise energy of the ground state and the position of the fifth highest observed state. This is perhaps partially due to the omission of light- and heavy-hole mixing in the calculation.

Our calculations indicate that the observed states at high magnetic field are somewhat similar to the Landau states that one observes in the absence of an electric field. This can be seen (Fig. 4) from the conditional probability densities $P(z_e|z_h=0)$ for the excitons at 30 T with and without the electric field. In the absence of an electric
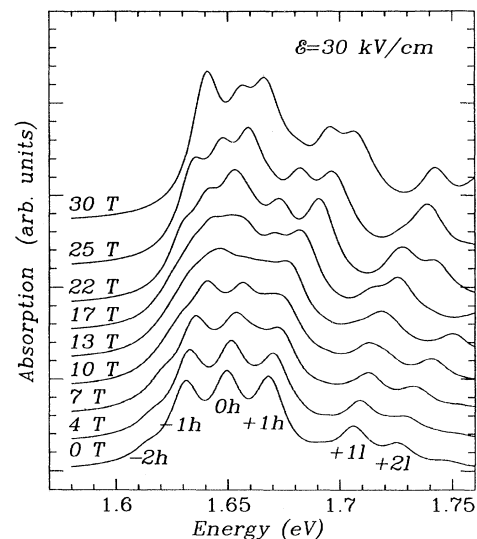

FIG. 3. Theoretical absorption spectra as a function of energy for the same magnetic fields as in Fig. 1. The ratio of the heavy-hole to light-hole bulk optical matrix elements has been taken to be 1.5, and a phenomenological lorentzian broadening of 8 meV has been added to aid in the comparison to Fig. 1.
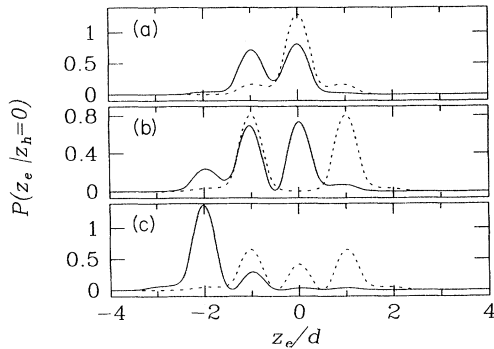
FIG. 4. Calculated conditional probability densities, $P(z_e|z_h=0)$, of finding the electron at z_e given that the hole is at $z_h=0$ for the three lowest-energy heavy-hole exciton states (in order of increasing energy) at 30 T in zero electric field (dashed lines) and in an electric field of 30 kV/cm (solid lines).

field, the Landau-level states are localized in a manner similar to what one finds in the Stark-ladder problem.[12] Here, however, it is the magnetic—rather than the electric—energy which serves to misalign the energy levels in adjacent wells and produce localization. The electron and hole in the ground state [Fig. 4(a)] are found to be primarily localized in the same well, and hence the oscillator strength is large (see Fig. 2). The electron and hole in the higher-energy states become localized further and further apart, and so have smaller and smaller oscillator strengths. This allows one to understand the observed loss of oscillator strength at energies near the band edge in a way that is complementary to the physical picture usually presented.[1]

In the presence of an electric field, the picture at high magnetic field, where the magnetic-field-induced localization is dominant, is very similar to the $\mathscr{E}=0$ case. The

ground state [Fig. 4(a)] is found to be similar to a high-field Landau ground state or an $m=0$ Stark-ladder state,[12] except that the electron is not found only in the same well as the hole but also has a high probability of being found one well upfield (electric) from the hole. This is due to the electric-field polarization of the state. The probability distribution of the first excited state [Fig. 4(b)] resembles more that of a high-field $m=-1$ Stark ladder state. The states of still higher energy are similar to the excited Landau states, except that the electrons are localized on either one side or the other of the hole, rather than on both as is found in the $\mathscr{E}=0$ case. Due to this strong localization of the electron and hole in separate wells these states have very little absorption strength.

In conclusion, we have demonstrated experimentally and theoretically the competition of magnetic-field-induced and electric-field-induced localization in superlattices under crossed electric and magnetic fields. In the regime in which the electric field dominates, Stark-ladder transitions, reflecting the electric-field-induced localization, are observed. Their oscillator strength drops drastically and finally vanishes as the magnetic field is increased until it begins to dominate over the electric field, at which point states governed by the magnetic-field-induced localization appear. The calculated probability densities of the latter states show their similarities with pure Landau and Stark states.

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[14]The physical parameters employed in the calculation are the following: 318 meV (171 meV) for the conduction- (valence-) band barrier heights; 0.0665 (0.08), 0.34 (0.45), and 0.094 (0.128) for the effective masses (in units of the free-electron mass) of the electron, heavy hole, and light hole in the z direction in the GaAs ($Ga_{0.65}Al_{0.35}As$) layers, respectively; 0.0665 (0.08), 0.18 (0.24), and 0.16 (0.2) for the masses of the same particles parallel to the planes; 1.5185 eV for the band gap of GaAs, and 12.5 for the static dielectric constant of both materials.