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Interplay between Landau and Stark quantizations in GaAs/$Ga_{0.65}Al_{0.35}As$ superlattices

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We report the observation of Landau ladders attached to each Stark transition in GaAs/$Ga_{0.65}Al_{0.35}As$ superlattices under magnetic and electric fields parallel to the growth axis, z. For certain ratios of magnetic and electric fields, anticrossings occur between Landau ladders associated with different Stark levels. The coupling between the Landau ladders is ascribed to the excitonic interaction and the valence-band mixing. For an increasing magnetic field perpendicular to the electric field ($B \perp z$), the excitonic Stark transitions broaden and their intensities decrease until they eventually vanish. This behavior can be explained in terms of a competition between magnetic-field- and electric-field-induced localizations.

Resonant coupling between the quantum-well states in a superlattice leads to the formation of three-dimensional (3D) minibands. Application of an electric field $\mathcal{E}$ parallel to the growth axis of the superlattice misaligns adjacent quantum wells by $e\mathcal{E}d$, where d is the superlattice period and e the electron charge, reduces the coupling between them, and tends to localize the electronic wave functions. At intermediate electric fields the electron wave functions still extend over several quantum wells giving rise not only to intrawell but also to interwell Stark transitions, labeled m, between heavy (hh) or light (lh) hole and electron levels whose wave functions are centered in different quantum wells, with energies:[1,2]

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

where E_0 is the intrawell ($m=0$) transition energy. At the high-electric-field limit, $\mathcal{E} \gg \Delta/ed$ (Δ is the miniband width), the wave functions are completely localized in individual wells, resulting in quasi-2D bands.[1,2] It is intriguing to study the effects of a magnetic field on a structure that can be continuously varied from the 3D to the quasi-2D limit. In addition, for certain ratios of parallel magnetic and electric fields, Landau transitions associated with different Stark transitions were predicted to coincide in energy and drastically change the shape of the absorption spectrum.[3]

Magnetic fields applied parallel to the electric field in $Ga_{0.47}In_{0.53}As/Ga_{0.24}Al_{0.24}In_{0.52}As$ superlattices have led to the observation of further reduction in the dimensionality due to the quantization of the in-plane motion.[4,5] However, Landau transitions could be discerned only in association with the $m=0$ Stark transition;[4] hence the predictions of Ref. 3 could not be tested. In this work, using photocurrent spectroscopy, we have observed, in addition to dimensionality effects, the formation of Landau ladders associated with each Stark transition in GaAs/$Ga_{0.65}Al_{0.35}As$ superlattices. In contrast to the predictions in Ref. 3, no crossings of transitions were observed: The different Landau ladders are found to anticross, i.e., to be coupled, presumably because of the excitonic interaction and the valence-band mixing. We also report on the effects of magnetic-fields perpendicular to the electric field: Both the interwell and the intrawell excitonic transitions drastically diminish in intensity and eventually disappear. The magnetic field necessary for this effect to set in depends on the electric field and on the Stark index.

The experiment was done on an undoped superlattice grown by molecular-beam epitaxy, consisting of 27 40-Å GaAs and 26 20-Å $Ga_{0.65}Al_{0.35}As$ layers, clad on each end by 600-Å undoped $Ga_{0.65}Al_{0.35}As$ caps. This structure formed the intrinsic region of a p^+-i-n^+ GaAs diode. The electric field was obtained from the applied voltage V by using the relation $\mathcal{E} = (V - V_b)/W$, where V_b is the built-in voltage (estimated to be $\simeq 1.55$ eV) and W the total width of the undoped region (2800 Å). The photocurrent spectra were measured using low-power excitation from a LD700 dye laser pumped by a Kr^+ laser.

Neglecting the excitonic interaction and assuming parabolic bands, the Hamiltonian for a magnetic field, B, parallel to the growth axis (z) of the superlattice decouples into two independent terms: One describing the z motion due to the superlattice potential and the electric field and one describing the in-plane (xy) motion in the presence of the magnetic field.[6] (Here we ignore the z dependence of the effective mass.) Then each of the Stark transitions gives rise to a series of Landau transitions [see Fig. 1(a)] and Eq. (1) transforms into

$$E_{n,m}(B,\mathcal{E}) = E_0(B,\mathcal{E}) + (n + \tfrac{1}{2})\hbar\omega_c + me\mathcal{E}d, \qquad (2)$$

where $n = 0,1,2,3,\ldots$ is the Landau-level index, $\omega_c = \omega_c^e + \omega_c^h$, and $\omega_c^{e(h)} = eB/m^*_{e(h)}$ with $m^*_{e(h)}$ being the electron (hole) in-plane effective mass. Under these conditions, the Landau ladders associated with different Stark transitions are decoupled and whenever two Landau transitions coincide in energy (i.e., whenever $\hbar\omega_c/e\mathcal{E}d = p/q$ with p,q integers) an enhancement in the absorption was predicted to occur.[3] However, if the Coulomb interaction between electrons and holes and the mixing of light- and heavy-hole states in the valence band[7] is taken into account, the Hamiltonian is no longer separable. Disorder effects may also cause a coupling of the xy and z motions. In this case, the Landau ladders associated with different Stark levels interact and the repulsion between them leads to anticrossings instead of crossings.

Indeed, this is the situation encountered in the experiment, as can be seen from the selected photocurrent spectra of Fig. 1(c), where two of the anticrossings have been highlighted with dashed lines. When the magnetic field is increased, the energy difference between the $n=1$ and 0 electron Landau levels approaches the electric energy $e\mathcal{E}d$ and tends to align the $n=1$ level with the $n=0$ level of the first neighboring well. The two levels repel each other and form a doublet, as depicted in Fig. 1(b). This anticrossing of electron levels is observed in the photocurrent spectra as an anticrossing of the (1, −1 hh) and the (0,0 hh) transitions around 1.65 eV and 6 T. (Note that (1,−1 hh) involves the $n=1$ hole Landau level, while (0,0 hh) involves the $n=0$ level [see Fig. 1(a)].) As the two levels approach, the initially unequal peak intensities of (1, −1 hh) and (0,0 hh) become comparable and are then inverted. With further increase of the magnetic field, the energy difference between $n=1$ and 0 becomes equal to twice the Stark-ladder spacing and the repulsion between the $n=1$ level and the $n=0$ level in the second neighboring well shows up in the photocurrent spectra as an anticrossing between the (1, −1 hh) and the (0,+1 hh) transitions around 1.68 eV and 16 T.

More regions of anticrossing [e.g., between (1,0 hh) and (0,+1 hh) around 1.675 eV and 7 T] are evident in Fig. 2(a), where the transition energies are plotted as a

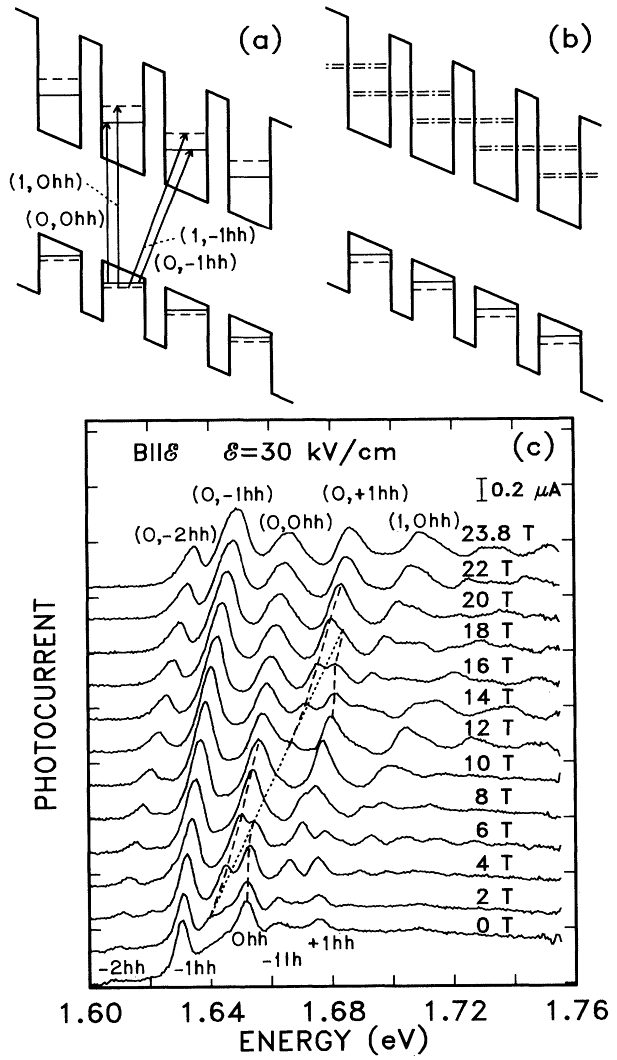

FIG. 1. (a) Schematic diagram of the potential profile and energy levels of a superlattice under electric and magnetic fields parallel to the growth axis. For clarity, only the $n=0$ and 1 Landau levels are shown, as solid and dashed lines, respectively. The arrows indicate allowed optical-interband transitions ($\Delta n=0$) and are labeled (n,m), where $n(m)$ is the Landau (Stark) index. (b) Same as in (a) but for a higher magnetic-field such that the $n=1$ electron level coincides with the $n=0$ level in the adjacent well. The two levels repel each other and form a doublet shown with dot-dashed lines. (c) Selected photocurrent spectra at 4.2 K at a constant electric field for different magnetic-field values. The dashed lines in the regions of anticrossing between the (1,−1 hh) and the (0,0 hh) transitions around 6 T and between (1,−1 hh) and (0,+1 hh) around 16 T are a guide to the eye, while the dotted-straight line shows the approximate energy position of (1,−1 hh) as it would be without interaction. The spectra have been offset vertically for clarity.

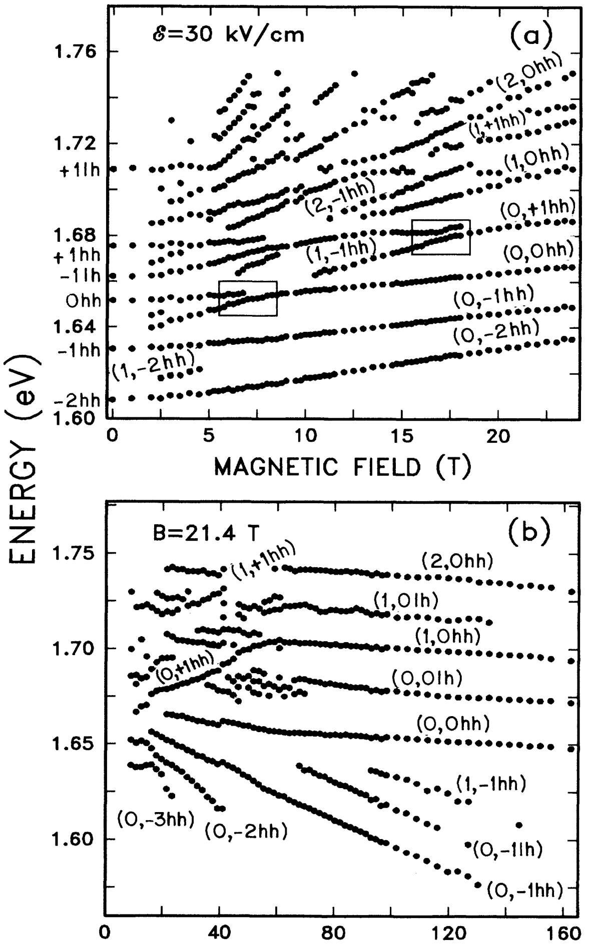

FIG. 2. Transition energies for the 40-Å GaAs/20-Å $Ga_{0.65}Al_{0.35}As$ superlattice (a) for a constant electric field as a function of magnetic field and (b) for a constant magnetic field as a function of electric field, obtained from photocurrent measurements at 4.2 K. The electric and magnetic fields are parallel to the superlattice growth axis. The anticrossings discussed in the text are highlighted with rectangles.

function of magnetic field. The smallest energy splitting between (1,−1 hh) and (0,0 hh) and between (1,−1 hh) and (0,+1 hh) is about 4 meV. However, the interaction energy between the different levels cannot be readily extracted from the transition energies since the latter include different hole Landau levels and exciton binding energies. When the $n \neq 0$ Landau transitions are visible at low magnetic fields and are not distorted by anticrossings, the binding energy of the Stark transitions can be obtained from the different extrapolations to zero magnetic field of the $n = 0$ and $n \neq 0$ transitions.[8,9] In the case of −1 hh, the energy of the $n = 1$ Landau transition extrapolates to 5 ± 1 meV above the $n = 0$ one. This is the difference in binding energy between the 1s and 2s exciton states and yields a binding energy of 6.7 ± 1 meV for the 1s state at 30 kV/cm. This result is in agreement with the value of 6.2 meV calculated in Ref. 10 for a similar superlattice.

Figure 2(b) shows the transition energies as a function of electric field for a constant magnetic field. Anticrossings [e.g., between (0,+1 hh) and (1,0 hh)] are observed here as well. The $n \neq 0$ Landau transitions associated with the different Stark transitions are identified as peaks shifting parallel to the $n = 0$ parent Stark peaks. The 0 hh Landau ladder is not equidistant due to excitonic and hole-mixing effects[7] and the differences in the splitting between $n = 0$ and 1 for the various Stark transitions are related to the differences in the initial exciton binding energy.

As the magnetic field is increased, the intensities of the Stark transitions are enhanced [Fig. 1(c)]. This enhancement is stronger the higher the order of the transition. Conversely, the intensity of the $m = 0$ Landau transitions is enhanced when the electric field is increased. These two effects are related to the dimensionality reduction and corresponding "sharpening" of the joint density of states and also have been observed and studied in more detail in Refs. 3 and 4. The broadening of the absorption peaks in Fig. 1(c) is probably due to the unresolved spin splitting which is about 3 meV at 24 T.[11]

We now turn to the results for crossed magnetic and electric fields. A superlattice in a magnetic field parallel to the layers shows interband Landau-level transitions for energies falling within the electron and hole subband width, whereas for a narrow quantum well no Landau-level transitions are observed.[12] The photocurrent spectra of a 40-Å GaAs/20-Å $Ga_{0.65}Al_{0.35}As$ superlattice subjected to an electric field parallel to the growth axis and a magnetic field parallel to the layers [Fig. 3(a)] show no extra structure due to Landau-level transitions. This can be viewed as additional evidence for the breaking up of the superlattice minibands induced by the electric field.

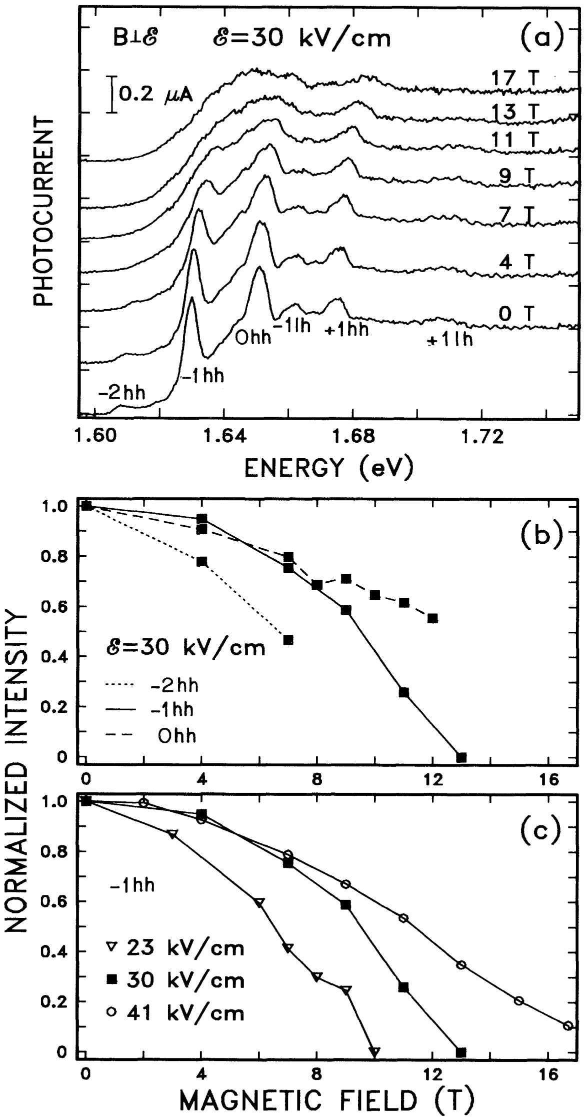

FIG. 3. (a) Selected photocurrent spectra at 1.8 K at a constant electric field for different magnetic-field values. The electric field is parallel to the growth axis and the magnetic field is perpendicular to it. The spectra have been offset vertically for clarity. (b) Intensity of the −2 hh, −1 hh, and 0 hh Stark interband transitions as a function of magnetic field for an electric field of 30 kV/cm. (c) Intensity of −1 hh as a function of magnetic field for different electric-field values. Both in (b) and (c) the area under the peaks in the photocurrent spectra at 1.8 K was taken as a measure of the intensity. Each intensity vs magnetic-field curve was normalized to the $B = 0$ value. The lines are a guide to the eye.

Several interesting features should be noted in Fig. 3(a): The peaks associated with the different excitonic Stark transitions broaden and lose intensity, as the magnetic field is increased, and eventually disappear. However, the smooth absorption background hardly exhibits any intensity losses even for the highest magnetic fields. The higher the order $|m|$ of the Stark transition, the smaller is the magnetic field necessary to quench it [see Fig. 3(b)]. Furthermore, Fig. 3(c) shows that the magnetic field necessary for the quenching of the −1 hh transition depends on the electric field. The same is valid for the other transitions. In addition, the Stark transitions exhibit a blueshift as the magnetic field increases [Fig. 3(a)].

In an unbiased quantum well under an in-plane magnetic field the energy levels are blueshifted by an amount proportional to B^2 and to the spread of the wave function $\langle z^2 \rangle$.[8] Moreover, the energy levels show a dispersion as a function of position in the quantum well which increases with the magnetic field and causes the corresponding transitions to broaden.[8] The blueshift observed in our experiments exhibits, indeed, a parabolic dependence on magnetic field and is larger the higher the Stark index of the transitions, which is consistent with the larger spread of the associated wave functions.

In order to understand the Stark-index and the electric-field dependence of the disappearance of the Stark transitions, we resort to the following simple picture: A Stark transition will be quenched (this is defined to happen at the magnetic field for which its intensity is reduced to one-half of its initial value at zero magnetic field) when the semiclassical cyclotron radius r of the $n=0$ electron orbit becomes comparable to or smaller than the mean electron-hole distance for this transition. (The extension of the heavy-hole wave function is smaller than that of the electron.) Using the relation $r=(\hbar/eB)^{1/2}$ we obtain from Fig. 3(b) for the mean electron-hole distances of the −2 hh, −1 hh, and 0 hh transitions $\rho_{-2\,\mathrm{hh}}=100$ Å, $\rho_{-1\,\mathrm{hh}}=83$ Å, and $\rho_{0\,\mathrm{hh}}=71$ Å, respectively. These values are reasonable considering the 60-Å period of the superlattice. As was pointed out in Ref. 10, a Stark index m does not necessarily imply $\rho_m=md$. In fact, at low electric fields ($\mathcal{E}<\Delta/med$), ρ_m is, on the average, larger than md and converges to md for high electric-field values,[10] which explains the electric-field dependence shown in Fig. 3(c).

However, the behavior of the +1 hh transition does not fit in the above picture. The +1 hh peak broadens but still persists at magnetic fields at which even the 0 hh one has disappeared [Fig. 3(a)]. Absorption strength asymmetries between +1 hh and −1 hh have been reported both in experiments[13] and in calculations.[10] Nevertheless, this inequality cannot account for the strikingly different behavior encountered here and, if anything, is of the opposite sign for this field range.[10] Theoretical calculations are needed for a more complete understanding of these effects.

In conclusion, we have studied the effects of a magnetic field on the Stark-ladder transitions in GaAs/$\mathrm{Ga_{0.65}Al_{0.35}}$-As superlattices with the help of photocurrent spectroscopy. For parallel magnetic and electric fields we have observed the formation of Landau ladders associated with each Stark transition, thus allowing the determination of their binding energy. The interplay between Landau and Stark quantizations is made evident as anticrossings between the different Landau ladders when the magnetic and electric energies are equal. The interaction is thought to originate from the electron-hole Coulomb interaction and the valence-band mixing. For crossed magnetic and electric fields, the disappearance of the excitonic Stark transitions can be interpreted as the domination of the magnetic-field-induced localization over the electric-field-induced one.

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