Coexistence of Wannier-Stark Transitions and Miniband Franz-Keldysh Oscillations in Strongly Coupled GaAs-AlAs Superlattices

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Using differential photocurrent spectroscopy we have studied the field dependent absorption in a GaAs/AlAs superlattices, which have only one monolayer AlAs barriers, with unpreceded dynamical resolution. We are able to resolve a symmetric Wannier-Stark (WS) fan up to an index of ± 9 and for the first time Franz-Keldysh (FK) oscillations across the whole energy width of the lowest combined miniband. A modulation of the WS transitions by FK oscillations (and vice versa) is clearly visible. We also present results of theoretical calculations which describe in detail this coexistence of the linear WS fan and the nonlinear fans of the FK oscillations.

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In semiconductor bulk material the wave functions of the valence and conduction bands are extended Bloch functions. The three dimensional combined density of states determines the absorption spectra resulting in a square root line shape of the three dimensional M_0 and M_1 critical points if excitonic effects are neglected. By the application of an electric field F the plane wave envelope functions transform into Kane functions [1,2]. Near the lower and upper band edges the Kane functions resemble Airy functions. The alternating constructive and destructive interference of the valence and conduction band Airy functions results in the well known Franz-Keldysh (FK) oscillations at the M_ν critical points ($\nu=0,1,\ldots$) in the absorption spectra [3]. The oscillations shift inside the band region with increasing field according to

$$\hbar\omega_m = E_\nu + (-1)^\nu \hbar \left(\frac{e^2}{2|\mu_\parallel^\nu|\hbar} \right)^{1/3} x_m F^{2/3}, \qquad (1)$$

where x_m is the mth zero crossing of the Airy function $\mathrm{Ai}(x)$, $\mu_\parallel^\nu$ the effective mass at the critical point M_ν in field direction, E_ν the energy of the critical points M_ν, and F the applied field. Because of a lattice constant a of only several Å ($a_{\mathrm{GaAs}}=5.66$ Å) the energetic difference eFa between the Kane states or the separation of the Wannier-Stark (WS) ladder states [4,5] is small and a fine structure due to WS transitions [6] cannot be resolved at normal applied fields. The FK oscillations with an oscillation period much larger than eFa dominate the absorption spectra, reflecting the three dimensional character of the joint density of states in semiconductor bulk material.

In a superlattice (SL) consisting of many identical wells and thin barriers adjacent wells couple and the resonant subbands transform into minibands with a width Δ of a few hundred meV or less [4,7,8]. As a result of a miniband width which is about a factor of 10 (or more) smaller than in bulk material the localization length Λ of the Kane states, given by $\Lambda = \Delta/eF$, is strongly reduced at correspondingly low electric fields. Considering a superlattice period d of several nm the energetic difference eFd between the Kane states is about 10 times larger as compared to bulk material. The well known WS fan characterizing optical transitions between valence and conduction minibands becomes correspondingly widely spaced [5,9,10]:

$$\hbar\omega_n = \bar{E} \pm |n| eFd, \quad n=0,\pm 1, \pm 2, \ldots. \qquad (2)$$

Here, n is the index of the WS transitions and $\bar{E}$ is the "center of mass energy" from which the WS fan originates. The WS levels reflect the two dimensional character of the localized Kane states resulting in a steplike absorption curve.

However, if there is no field applied the superlattice joint density of states of the minibands is three dimensional with M_0 and M_1 critical points at the lower and upper miniband edges E_l and E_u, respectively. In analogy to bulk material FK oscillations should occur in the SL absorption at weak applied fields reflecting the three dimensional character of the miniband. They can be clearly distinguished from WS transitions by their nonlinear field dependence and their energetic position [cf. Eqs. (1) and (2)].

The subject of this Letter is a theoretical and experimental investigation of the gradual transition from the "miniband" or "FK" regime described by a three dimensional joint density of states to the WS regime reflecting the two dimensional character of the localized Kane states. Using differential photocurrent spectroscopy (DPCS) we are able to resolve WS transitions with indices n between -9 and $+9$ (cf. [8]). In addition we identify FK oscillations originating from the lower (cf. [8,11,12]) and for the first time from the upper miniband edge. The modulation of the WS transitions by FK oscillations (and vice versa) is in very good agreement with our calculations.

Our theoretical approach is based on a superlattice crystal momentum representation of the wave functions [7] including the lowest electron and heavy hole miniband. The wave function and the miniband energies have been obtained from a Kronig-Penney model using the design parameters of the experimentally investigated superlattice (given later). Because of the very thin AlAs barriers the energy dispersion even of the lowest conduction miniband differs strongly from a tight binding band. In particular, the effective mass for the lower miniband edge $\mu_\parallel^l$ is larger than that for the upper one $\mu_\parallel^u$ and the origin of the WS fan $\bar{E}$ is below the (arithmetic) center of the miniband. Neglecting the influence of the Coulomb interaction the SL absorption is proportional to the square of the overlap between the electron and hole wave functions. Since the heavy hole wave function can be considered to be localized already at weak fields ($\Delta_{hh}=50$ meV) the strength of an individual WS transition is determined by the squared amplitude of the electron wave function in the corresponding well (lower part of Fig. 1). In order to understand the field dependence of the SL absorption it is sufficient to investigate the shape of the electron wave function (Fig. 1) which consists of a SL periodic and an envelope part.

At low fields the transition strengths corresponding to the individual WS ladder states are modulated by the slowly varying field dependent envelope function. Close to the lower and upper miniband edges the square of the envelope function is similar to the square of an Airy function resulting in a modulation of the WS transitions by FK-like oscillations. The energetic distance eFd between the individual WS transitions is small, thus adding only a fine structure to the wide FK oscillations.

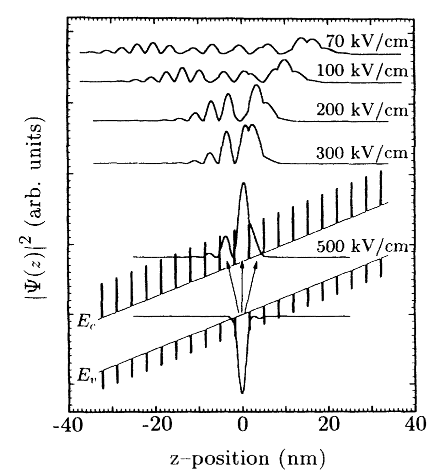

FIG. 1. Squared amplitude of the superlattice wave functions for various electric fields. In the lower part of the figure a schematic drawing of the band modulation and the square hole wave function are included. The arrows mark the Wannier-Stark transitions.

With increasing field the FK oscillations move away from the edges towards the center of the miniband $\propto F^{2/3}$. Because of a higher effective mass the oscillation period at the lower miniband edge is smaller compared to the upper one [cf. Eq. (1)]. At the same time the WS fan, originating from $\bar{E}$, widens $\propto F$, making the WS fine structure increasingly coarse. The coexistence of WS levels and FK oscillations within a wide field range produces the checkered pattern of the field-induced absorption changes displayed in Fig. 2(a) [13]. At high fields when the first FK absorption maxima corresponding to the lower and upper miniband edges would formally merge with each other the "FK picture" becomes meaningless. Obviously this is the well known extreme high field or WS limit where the absorption spectra change from being dominated by the $n=\pm 1$ WS levels to spectra which exhibit mainly the $n=0$ transition [4,5,7,9].

To prove our theoretical findings we investigated a GaAs/AlAs superlattice which consists of 80 periods of 11 monolayer (1 ML$=2.83$ Å) GaAs wells and only one monolayer AlAs barriers to get a large combined miniband width of 380 meV. The SL is embedded between two 0.6 μm wide $Al_{0.45}Ga_{0.55}As$ n- and p-doped regions, followed by 0.2 μm Si-doped GaAs on the n side and 300 Å Be-doped GaAs layers on the p side of the sample. The whole structure is grown by molecular beam epitaxy on a (100) GaAs n^+ substrate.

Since it is much more difficult to study the transition from miniband to the WS regime with conventional absorption techniques such as excitation or photocurrent spectroscopy [4,5,8] we used differential photocurrent spectroscopy (DPCS), a special wavelength modulation technique. This new technique which has been described in detail elsewhere [14] is much better suited for such investigations because the large background signal, which usually dominates the absorption spectra, is eliminated. Because of its first derivative character the interpretation of the spectra becomes very straightforward because each transition or critical point of the miniband (square root line shape) as well as of the WS regime (steplike absorption) causes only one peak in our modulated spectra when excitonic effects are neglected.

Figure 3(a) shows the photocurrent (PC) measured at 77 K and an applied voltage of 0.12 V. Only the fundamental heavy hole miniband edge and slowly varying field independent Fabry-Pérot (FP) oscillations above the band edge are observable. In the DPC spectra of Fig. 3(b) a sharp structure at the miniband edge and FP oscillations above the gap energy are observable again. But a closer look reveals a fine structure caused by WS transi-

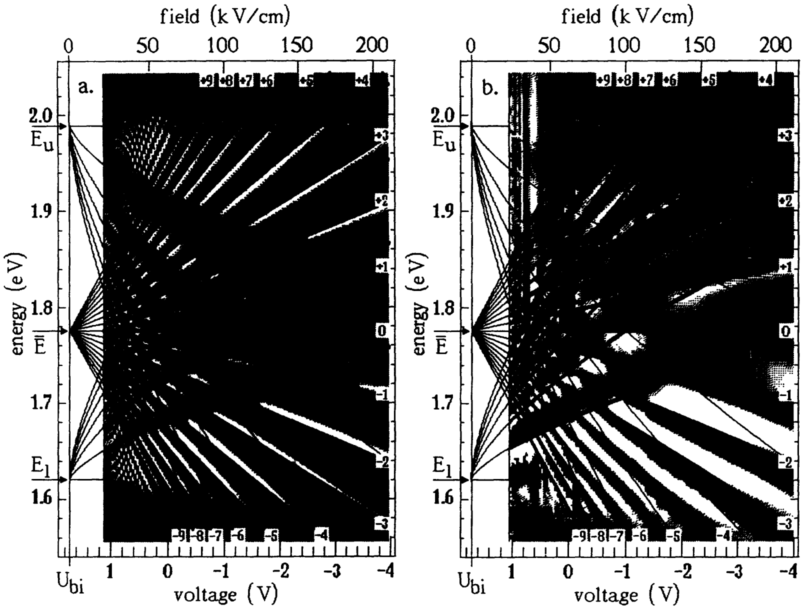

FIG. 2. Calculated (a) and measured (b) wavelength derivative of the field induced change of the photocurrent $I_{photo}(U,\lambda) - I_{photo}(U-\Delta U,\lambda)$ ($\Delta U = 0.02$ V) depicted in a grey scale graphic [small amplitude = white high amplitude = black; cf. Fig. 3(c)]. The linear WS fan is labeled by black numbers [cf. Eq. (2), $F=(U_{bi}-U)/d_i$, $\bar{E}=1.772$ eV, built in voltage $U_{bi}=1.7$ V, intrinsic region $d_i = 2748$ Å]. The FK oscillation zero crossings, indicated by white numbers, are calculated according to Eq. (1) with the values $E_l = 1.621$ eV and $\mu_{\parallel}^{l} = 0.065 m_0$ obtained from the Kronig-Penney model. The small lines at the upper miniband edge are only guidelines for the eye (here the effective mass approximation is no longer valid).

tions. In order to obtain more detailed information about the field dependent optical behavior of the sample we subtract two DPC spectra measured at slightly different applied electric fields. In these spectra [Fig. 3(c)] the whole field independent structure like Fabry-Pérot oscillations has disappeared. They reflect immediately the first wavelength derivative of the field induced change of the absorption which is proportional to $d^2\alpha/dFd\lambda$. Figure 3(c) shows clear features between 1.58 and 1.96 eV caused by heavy hole to conduction miniband WS transitions. As a result of a 3 times smaller oscillator strength and a much larger localization length of the Kane states, no light hole transitions are observable.

To investigate the field dependence of our spectra it is useful to have a synoptic of many spectra taken at different fields in a single figure [Fig. 2(b)]. WS levels with indices from −9 to +9 are observable shifting linearly towards the energy $\bar{E}$. The transitions can be traced

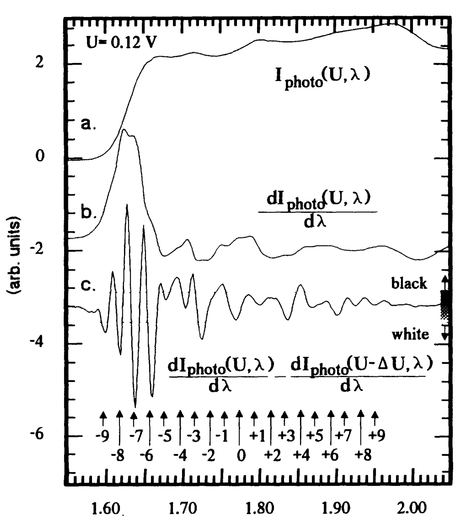

FIG. 3. Comparison between PC (a), DPC (b), and DDPC (c) spectra ($\Delta U = 0.02$ V). The calculated WS transition energies are indicated in the lower part of (c).

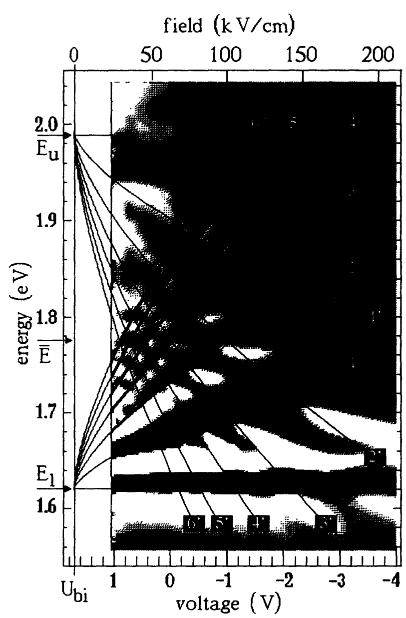

FIG. 4. Measured wavelength derivative of the field induced change of the PC $I_{photo}(U=1.1\ \text{V}, \lambda) - I_{photo}(U < 1.1\ \text{V}, \lambda)$ depicted in a grey scale graphic. The lower and upper miniband edge and the FK oscillations (labeled 1 to 6 and 1′ to 6′, respectively) are clearly visible.

down to $U=0.6$ V. The WS transitions are clearly modulated by miniband FK oscillations, which move away from the spatially direct transition towards the miniband edges with decreasing field.

In order to see more clearly the FK oscillations and the critical points at the miniband edges it is advantageous to relate DPC spectra measured at higher fields to a DPC spectrum taken in the very low field limit by investigating the difference of these two spectra (Fig. 4). In such difference spectra the low field WS transitions are not resolved and FK oscillations dominate. The lower and upper miniband edges ($E_l \simeq 1.621$ eV, $E_u \simeq 1.960$ eV) are also clearly observable because each difference spectrum contains the quasi zero field DPC spectrum with its characteristic peak at each miniband edge. At higher applied fields WS levels appear.

The calculated lower heavy hole miniband edge energy E_l and the origin $\bar{E}$ of the WS fan are in very good agreement with the experimental data (cf. Figs. 2 and 4). For higher fields the experimental spectra contain a Stark shift [10] which is not included in the theory. The experimentally observed upper miniband edge energy E_u is smaller than expected from our theory. This deviation is attributed to the conduction band nonparabolicity or deviations from the ideal rectangular shape of the superlattice potential.

In conclusion we have investigated the coexistence of WS transitions and FK oscillations in a strongly coupled $GaAs_{11}/AlAs_1$ SL from the theoretical and experimental point of view. Using DPCS, which shows the first derivative of the photocurrent with respect to the wavelength, a symmetric WS fan with indices up to ± 9 is observable. Our calculated as well as measured spectra clearly demonstrate the interplay of the linear WS fan, originating at the "center of mass" $\bar{E}$ of the miniband with the nonlinear fans of the FK effect evolving from the lower and upper miniband edges. This causes a modulation of the intensity of the WS transitions by FK oscillations and vice versa. Because of an asymmetric miniband dispersion the FK oscillation periods at the lower band edge are smaller than those observed at the upper one and the origin of the WS fan is found at an energy $\bar{E}$ below the (arithmetic) center of the miniband.

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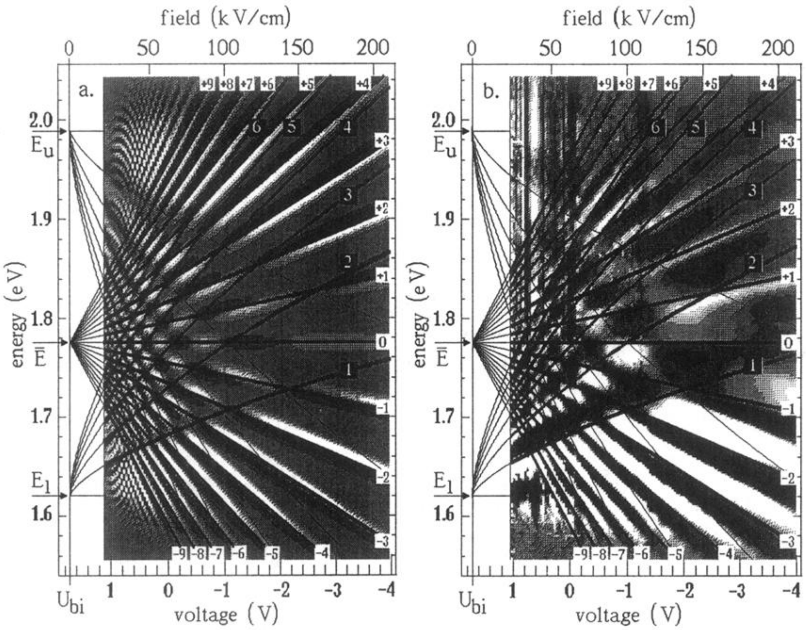

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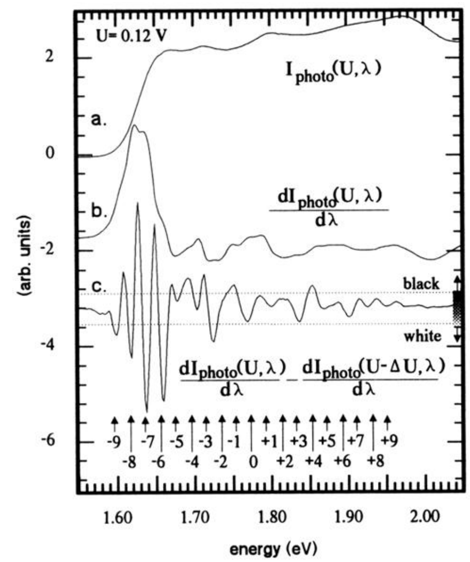

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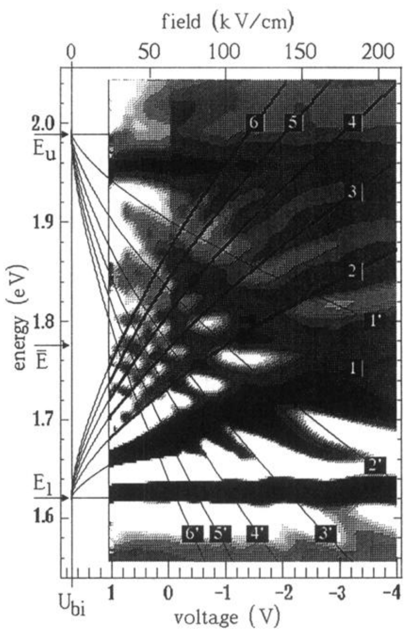

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