Fano Resonances in Semiconductor Superlattices

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We report the first observation of Fano resonances in biased semiconductor superlattices: The excitonic Wannier-Stark ladder transitions show asymmetric absorption due to the coupling to the continua of lower transitions. In contrast to other known examples of Fano resonances, the Fano coupling can be continuously tuned in this system by changing the static field across the superlattice. The line shapes and their coupling dependence are in excellent agreement with theory. We also investigate the dephasing dynamics of the resonances and observe an increase in dephasing with increasing Fano coupling. [S0031-9007(98)06702-7]

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In 1961, Fano theoretically investigated a quantum mechanical coupling of a discrete energy state with a degenerate continuum [1], a so-called Fano resonance (FR). It can be understood semiclassically by considering the states involved as a set of coupled oscillators. The discrete state acts as a driving force for the continuum oscillators, so the eigenstates consist of mixed excitations of the discrete state and the adjacent continuum. The continuum oscillators on either side of the discrete state move with opposite phase, according to whether the driving frequency is above or below their resonant frequency. Hence on one side they interfere constructively with the discrete state, on the other, destructively. This leads to the characteristic asymmetric FR line shape in the linear optical response, with the absorption on one side pulled below the continuum value. The extent of the asymmetry depends on two parameters: the oscillator strength of the continuum, and the homogeneous broadening, Γ, of the discrete state due to the coupling.

The first success of the Fano model has been the explanation of features in the optical spectra of rare gases. In a bulk semiconductor, FR of electronic states are generally not expected since the mixing of discrete and continua states is not present. For semiconductors with reduced dimensionality (either by heterostructure or magnetic field confinement), however, several cases of resonances are known (for an overview, see Ref. [2]). The first unambiguous experimental observations of FR in semiconductor systems with reduced dimensionality have been reported for GaAs/AlGaAs quantum wells by Oberli *et al.* [3] and later by Glutsch *et al.* for bulk GaAs in a magnetic field [4].

Another system where strong FR effects have been predicted [5] are biased semiconductor superlattices (SL) [6]. Theoretical calculations predict that the exciton transitions in biased SL show pronounced FR due to the coupling to the continuum of lower-lying Wannier-Stark states [5]. The electronic spectrum of a biased superlattice at a bias field F is characterized by the so-called Wannier-Stark ladder (WSL) of states with spacing $\Delta E = eFd$, with d as the SL period. In the optical spectra, one observes a so-called fan chart if the field is swept. In a single particle picture, the transition energies are given by

$$E_n = E_V + neFd; \qquad n = 0, \pm 1, \pm 2, \ldots, \tag{1}$$

with E_V as the energy of the vertical transition between electron and hole in the same well [7,8].

Usually, the optical spectra under a bias field are dominated by excitonic transitions [9]. For every Wannier-Stark state, the Coulomb interaction of the electron-hole pair discretizes the relative motion up to a certain energy which is followed by an ionization continuum above this energy. These quantized states associated with a Wannier-Stark subband with index n are *degenerate with the exciton continua of lower subbands*. Coupling between the discrete and continuous excitonic states of the relative motion, mediated by Coulomb interaction, leads to the Fano effect.

A unique feature of SL is that, unlike any other system investigated so far, the Fano coupling parameter Γ can be *continuously tuned by changing the electric field:* For increasing bias field, the WSL spacing and thus the momentum mismatch between the discrete exciton with $k = 0$ and the continuum at higher k increase; leading to a decrease of the coupling matrix. The Fano coupling Γ strongly depends on the matrix element and is thus decreasing concomitantly. Additionally, the coupling is reduced with increasing field to the axial localization of the wave function which reduces the coupling of the excitons to continuum states of the same well at high fields. The FR strength for a given WSL transition is thus generally decreasing with increasing bias field.

Another topic of great importance is the dynamical response of Fano resonances: The interference between the polarization of the continuum and the discrete line can lead to a fast decay of the optical polarization, as first suggested for the case of semiconductors by Schultheis *et al.* [10]. The first study of the polarization decay for FR in semiconductors was carried out by Siegner *et al.* [11,12] on bulk GaAs in a magnetic field. They found an immediate decay of the time-integrated four-wave-mixing signal, in contradiction to the time-resolved signal. Meier *et al.* [13] studied theoretically the four-wave-mixing signal of a Fano resonance. Cohen *et al.* have studied effects of FR in weakly coupled SL in a magnetic field [14].

In this Letter, we report the first experimental observation of Fano resonances in semiconductor superlattices: The Wannier-Stark transitions show the characteristic asymmetric absorption with a dip above the line, with line shapes in excellent agreement with theory. We experimentally prove that SL offer the *unique possibility to continuously tune the Fano coupling.* We derive the Fano resonance parameters as a function of the electric field corresponding to a variation of the coupling. Using transient four-wave mixing, we perform a study of the polarization decay of the Fano resonances. For the first time, we show that the *interference causes a fast polarization decay with a decay time which is controlled by the Fano coupling.*

For our study, we use a $GaAs/Al_{0.3}Ga_{0.7}As$ superlattice with 35 quantum wells of 67 Å thickness separated by 17 Å thick barriers [15]. Transmission experiments are carried out at a temperature of 10 K in a standard setup using a halogen lamp with correction of the spectrum. Figure 1 shows the experimental absorption spectra (solid lines) as a function of the applied voltage. The spectra show the evolution of the miniband-related excitons into the WSL, as previously observed [7,8]. The heavy-hole transitions are labeled as hh_n, with n as defined in Eq. (1). The individual peaks of the WSL clearly show the typical FR behavior: The asymmetric extension to lower energies and the dip below the continuum absorption above the transition. The Fano coupling conditions are fulfilled for all ladder excitons since they energetically overlap with the subbands of states with lower indices. However, tunneling of states through the barriers with index much different from zero is strongly suppressed with increasing field and the amplitude of their excitonic wave functions increasingly vanishes.

We compare the experimental spectra with results from a theoretical model [5]. In this model, the excitonic wave function is restricted to a single pair of minibands. The wave function can then be expressed in terms of localized Wannier functions. The exciton Hamiltonian in this basis consists of contributions from the kinetic energy

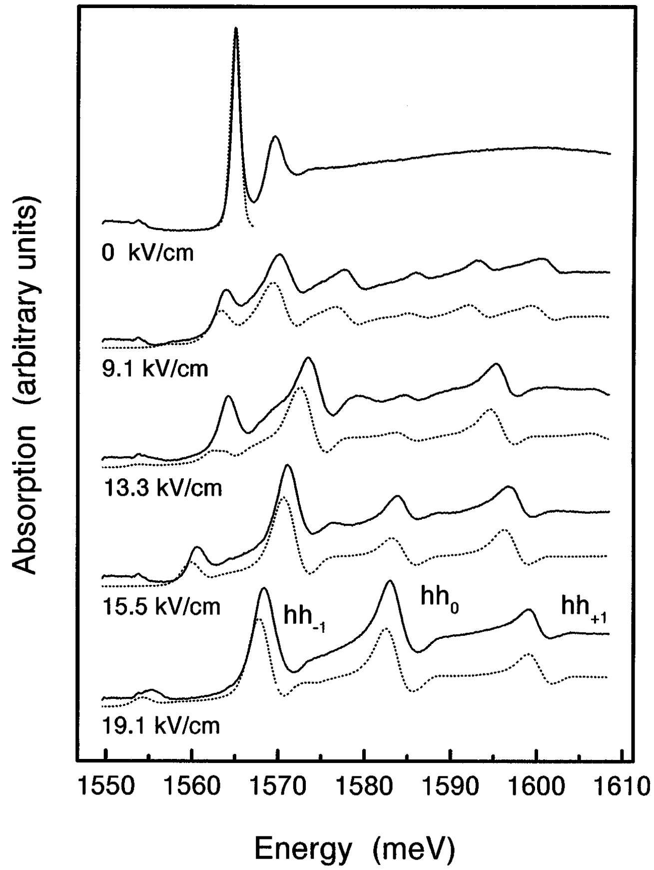

FIG. 1. Solid lines: Experimental absorption spectra of a 67/17 angstrom superlattice for various fields. Dashed lines: Theoretically calculated spectra.

in the confined and nonconfined directions, the Coulomb interaction between the electrons and holes, and the external electric field. Optical spectra are calculated by constructing numerically the real space Green's function for this Hamiltonian, using the method described in Ref. [16]. The calculation is free of parameters, except for the absolute scaling of the absorption and a broadening of the theoretical spectra which is needed to match the experimental data. We ascribe this broadening to interface roughness and field inhomogeneities. One broadening value can be used to describe all transitions, independent of the large variations in Γ and q. We thus believe that the broadening has no significant effect on our results.

The theoretical spectra are displayed in Fig.1 as dashed lines. They show an excellent agreement with the experimental results and reproduce basically all features and line shapes. A small deviation in the WSL splitting could be removed if the nominal values of the field inserted into the theoretical calculation would be slightly increased. The adjustment necessary is well within the error bar of the experimental determination. The theoretical model does not include light-hole (lh) transitions. In the experimental spectra, a lh transition is clearly visible for the $F = 0$ case (the peak at 1570 meV). For finite field, the lh transitions are visible as some weak transitions not predicted by theory (for instance, the peak at about 1579 meV in the 13.3 kV/cm spectrum corresponds to the lh_{-2} transition). In doing the data analysis, we have taken care to avoid fields where lh transitions are of influence. Note that the lh transitions are also subject to FR, as visible for the $F = 0$ transition.

Finally, one can fit the Fano line shape to the spectra in order to extract the Fano parameters. In this way it is possible to trace the Fano coupling with varying field and index. The changes of the optical spectra due to Fano coupling can be expressed by the ratio $A(\omega)$ of the absorption with coupling $\alpha(\omega)$ to the absorption of the continuum without coupling $\alpha_{\mathrm{cont}}(\omega)$:

$$A(\omega) = \frac{\alpha(\omega)}{\alpha_{\mathrm{cont}}(\omega)} = \frac{(q + \epsilon)^2}{1 + \epsilon^2}, \qquad (2)$$

with ϵ as a normalized energy and q as line shape parameter [1]. For large values of this line shape parameter q, the discrete state dominates the absorption, and the uncoupled line recovers. The sign of q determines whether the fast rise of the line shape is on the low or high-energy side of the resonance since $A(\omega, q) = A(-\omega, -q)$. Here, q is negative, since the absorption dip is above the resonances. The Fano coupling parameter Γ describes the homogeneous broadening of the discrete state due to the coupling and is linked to the density of continuum states and the coupling matrix element.

Figure 2 depicts the extracted values for Γ [part (a)] and the inverse of q [part (b)] for several heavy hole transitions. Generally, there is a decrease of Γ with increasing field, which is expected by two reasons: (i) an increased mismatch of the out-of-plane momenta of the coupled states and (ii) an increased axial localization at higher fields. The experimental data thus clearly prove the theoretical expectation that the *Fano coupling strength can be tuned in this system*. However, at low fields, there are pronounced deviations from this behavior: The Fano coupling parameter for the hh_0 line increases with field at low fields, despite the increasing mismatch in momentum space. This peculiar behavior can be well explained by the fact that at a field around 10 kV/cm, the amplitude of the electronic contribution to the exciton wave function is strongly reduced in its center well but achieves high values in the neighbored wells. Thus, the amplitude of the whole exciton wave function is small and the Fano coupling matrix element is greatly reduced. There seems to be also an influence of the transition index on the Fano coupling at fixed field. The coupling is strongest for the hh_0 transition, with some deviations at low fields as discussed above. The values for the hh_{+1} and hh_{-1} lines coincide over a wide field range and lie between the values for the hh_0 and hh_{-2} transitions. This behavior is expected since the amplitude of the excitonic two-particle wave function generally decreases if the separation between the electrons and holes increases (i.e., $|n|$ grows) and thus, the Fano coupling matrix element is reduced. The dependence of the coupling parameter is in our case not caused by collisional broadening of the involved states [17]: It has been shown that the interband dephasing time is decreasing with applied field [15]. Thus, such broadening would cause the opposite effect as observed here. The inverse of the line shape parameter q which is displayed as part (b) in Fig. 2 is also decreasing with increasing field: Because of the increase of the oscillator strength of the WSL excitons with increasing field localization, the Fano effect is being suppressed.

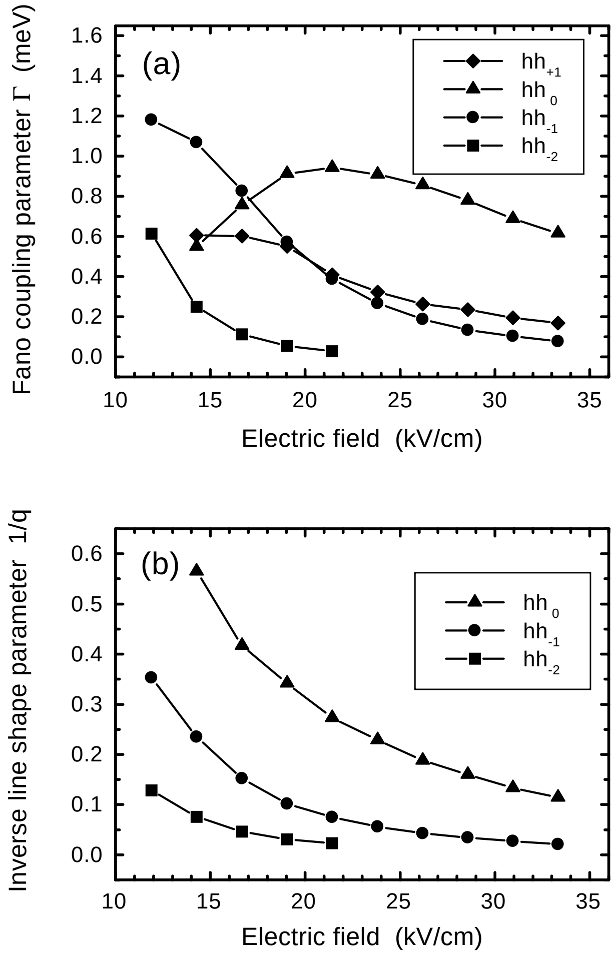

FIG. 2. (a) Fano coupling parameter Γ vs field for various WSL indices n. (b) Inverse of the Fano line shape parameter q as a function of field.

We have also performed transient four-wave mixing (FWM) experiments [18] to investigate the dynamical response. For excitation, pulses with 7 meV full width at half maximum, corresponding to a pulse duration of about 300 fs are used. Thus, only one Wannier-Stark state is excited even when the ladder separation is small at low fields. The excitation densities are about 3×10^9 cm^{-2} per well. The center of the laser is set approximately 2 meV below the absorption peak as shown in Fig. 3(a).

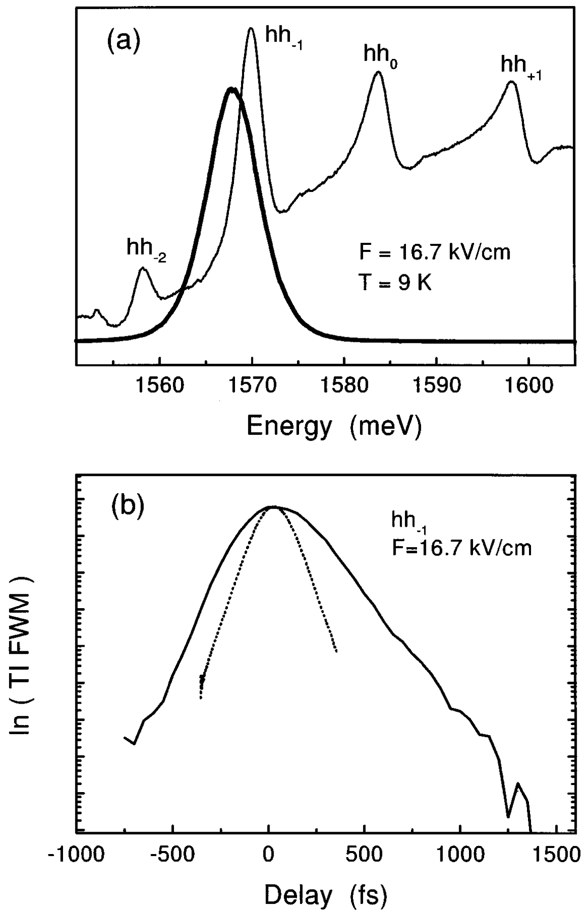

FIG. 3. (a) Example of the excitation conditions for the time-resolved experiments: The laser maximum is shifted approximately 2 meV below the absorption peak (fat line: laser spectrum). (b) Resulting FWM signal in comparison to the autocorrelation of the laser pulse (dashed line).

A typical experimental FWM trace is shown in Fig. 3(b). In contrast to previous investigations [11], both rise and decay can be well resolved from the pulse shape (dashed line: autocorrelation). The dephasing times (taken as 2 times the decay times [18]) of the hh_{-1} transition displayed in Fig. 4 show generally a decrease with increasing Fano coupling (i.e., decreasing field). The rise time is approximately half of the decay time (as expected, if the rise signal is ascribed to diffraction of polarization [19]). The observed decay times of the FWM signal agree well with the times expected from the FWM line width. The measurements on the hh_0 transition (not displayed) show a much less clear picture. This is partly attributed to the fact that the bias field is determined unreliably in the measurements as the transition is only weakly dependent on field. Furthermore, the hh_0 transition undergoes anticrossings with higher transitions in the range of discussion which makes the system hardly predictable.

Our results disagree with the only up to now reported time-resolved measurements on Fano-coupled systems,

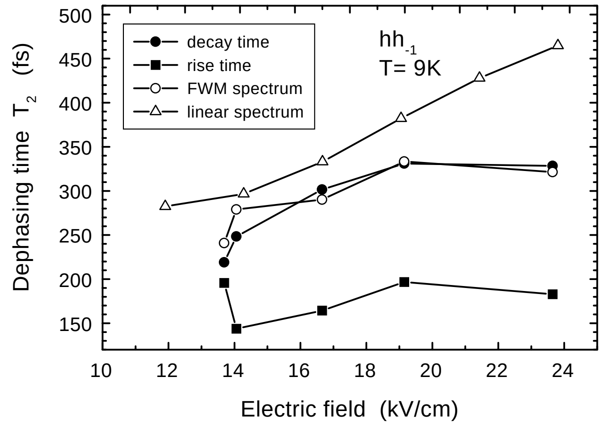

FIG. 4. Dependence of the dephasing time T_2 on the Fano coupling for the hh_{-1} transitions. The full symbol data are derived from the transient FWM data: the open symbol data are derived from the line widths of the FWM and linear spectra.

which were performed in bulk GaAs in a magnetic field (Refs. [11,12]). In these experiments, the decay time could not be resolved and a correlation between Fano coupling and decay time was not observed. A possible explanation is the underlying collisional broadening of the coupled states [17].

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[1] U. Fano, Phys. Rev. **124**, 1866 (1961).
[2] S. Glutsch, *Festkörperprobleme/Advances in Solid State Physics,* edited by R. Helbig (Vieweg, Braunschweig/Wiesbaden, 1998), Vol. 37, p. 151.
[3] D. Y. Oberli *et al.*, Phys. Rev. B **49**, 5757 (1994).
[4] S. Glutsch *et al.*, Phys. Rev. B **50**, 17 009 (1994).
[5] D. M. Whittaker, Europhys. Lett. **31**, 55 (1995).
[6] L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1970).
[7] E. E. Mendez, F. Agullo-Rueda, and J. M. Hong, Phys. Rev. Lett. **60**, 2426 (1988).
[8] P. Voisin *et al.*, Phys. Rev. Lett. **61**, 1639 (1988).
[9] M. M. Dignam and J. E. Sipe, Phys. Rev. Lett. **64**, 1797 (1990).
[10] L. Schultheis *et al.*, Phys. Rev. B **34**, 9027 (1986).
[11] U. Siegner *et al.*, Phys. Rev. Lett. **74**, 470 (1995).
[12] U. Siegner *et al.*, Phys. Rev. B **51**, 4953 (1995).
[13] T. Meier *et al.*, Phys. Rev. B **51**, 13 977 (1995).
[14] G. Cohen, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. B **52**, R11 642 (1995).
[15] P. Leisching *et al.*, Phys. Rev. B **50**, 14 389 (1994).
[16] D. M. Whittaker, Phys. Rev. B **41**, 3238 (1990).
[17] M. V. Marquezini *et al.*, Phys. Rev. B **57**, 3745 (1998).
[18] T. Yajima and Y. Taira, J. Phys. Soc. Jpn. **47**, 1620 (1979).
[19] K. Leo *et al.*, Phys. Rev. Lett. **65**, 1340 (1990).