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MODULATION OF FANO RESONANCES BY AN EXTERNAL MAGNETIC FIELD IN SEMICONDUCTOR QUANTUM WELLS

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Abstract—We have studied the dimensionality dependence of the behavior of Fano resonances in the photoluminescence excitation spectra of GaAs-$Al_xGa_{1-x}As$ heterostructures in a magnetic field applied in the Faraday configuration. A striking difference is observed between quasi-two and quasi-three-dimensional systems: while the Fano profiles evolve into Lorentzian lineshapes in two-dimensional systems, Fano resonances emerge from the continuum in three-dimensional-systems with increasing magnetic field.

A Fano resonance in optical spectra is characterized by the asymmetric lineshape resulting from the interference of a discrete state and an energetically degenerate continuum of states[1]. Fano resonances are generally observed in atomic physics, for instance in the absorption spectra of rare-gases due to interactions between autoionization thresholds. In semiconductor physics this phenomenon has been reported mostly in the Raman-scattering spectra of doped semiconductors[2]. Although the existence of Fano resonances in the interband optical absorption of quantum wells (QW's) was predicted in the past [3,4], there is, to the best of our knowledge, only one experimental report in the literature[5]. More recently, a clear observation of Fano resonances in the absorption spectra of high-quality bulk GaAs was made by Glutsch *et al.*[6]. In their work they demonstrate that the coupling between the discrete states and the continuum is due to the Coulomb interaction. Previously, Becker *et al.*[7] reported on magneto-absorption spectra of GaAs, which displayed sharp, asymmetric lineshapes; however, they did not assign these structures to Fano resonances.

In this work we study the evolution of Fano resonances in "quasi-bulk" GaAs and GaAs-$Al_xGa_{1-x}As$ QW's in the presence of an external magnetic field by means of low-temperature photoluminescence excitation (PLE) spectroscopy. The samples were grown by molecular beam epitaxy on semi-insulating GaAs substrates. The "quasi-bulk" sample consists of a 200-nm GaAs buffer followed by 500-nm of $Al_{0.4}Ga_{0.6}As$, a 500-nm GaAs layer and 300-nm $Al_{0.4}Ga_{0.6}As$. The structure is capped by a 10-nm thick GaAs top layer. In the QW sample a 200-nm GaAs buffer layer is followed by 20 periods of GaAs-AlAs QW's (5-nm well and barrier width), a 150-nm GaAs layer, a 15-nm $Al_{0.3}Ga_{0.7}As$ layer and 10 GaAs QW's (20-nm wide) separated by 97.5-nm $Al_{0.3}Ga_{0.7}As$ barriers. This sample is capped by a 3-nm GaAs layer.

PLE spectra were recorded at 2 K with the magnetic field, up to 13 T, applied in the growth direction z (Faraday configuration). The photoluminescence was excited with light from a Ti-sapphire laser pumped by an Ar^+-ion laser. Right handed, σ^+, and left handed, σ^-, circular polarization of the exciting beam was achieved with an achromatic $\lambda/4$ plate.‡

Figure 1 compiles the PLE spectra of the 500-nm quasi-bulk GaAs for different magnetic fields and σ^+-polarization of the exciting light. The two lowest-lying peaks in the spectra correspond to the heavy-hole and light-hole ground state excitonic transitions. The degeneration at the top of the valence band of GaAs is lifted by a small strain present in the sample [8], which yields a splitting of ~1 meV. The very high quality of the sample is revealed by the observation of the $n = 2$ and $n = 3$ excited states of the heavy-hole exciton, which are clearly seen close to 1.52 eV in the zero field spectrum. In this spectrum we also observe that the PLE-intensity decreases with increasing energy. This dependence of the PLE-intensity contrasts with the one obtained in the absorption spectra, which reproduces the joint density of states[6]. In fact, PLE measures a pseudo-absorption, which is affected by radiative and non-radiative recombination processes. In contrast to quasi-two-dimensional semiconductors, where the PLE mimics the shape of the absorption spectra, the luminescence intensity in bulk crystals decreases with increasing excitation energies, due to a higher probability of scattering events leading to non-radiative recombination. In the presence

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‡In all the following we design the light polarization in the system of reference of the laboratory.

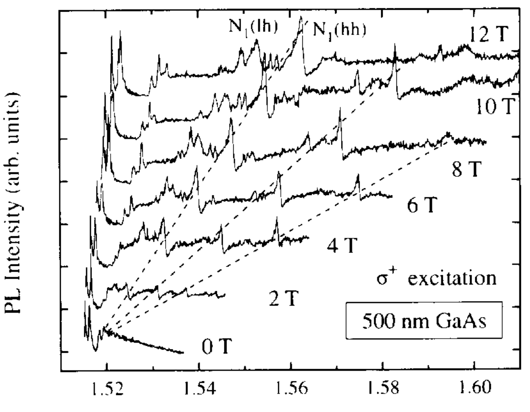

Fig. 1. Low-temperature (2 K) PLE spectra of quasi-bulk GaAs for different magnetic fields under σ^+ circularly polarized excitation. The dashed lines are guides to the eye and show the energy shift of the heavy-hole magnetoexcitonic transitions with the field.

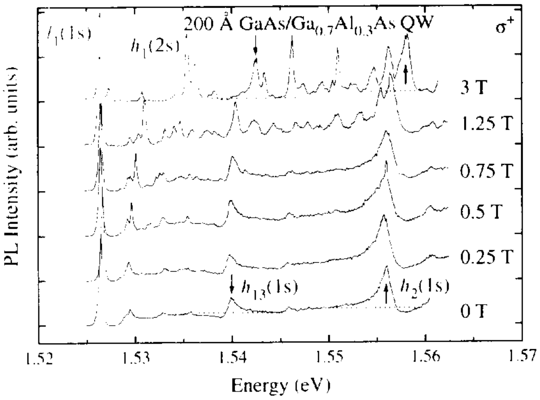

Fig. 2. Low-temperature PLE spectra of a 200-Å GaAs-$Al_{0.3}Ga_{0.7}As$ QW for different magnetic fields under σ^+ circularly polarized excitation. Down and up arrows point to the h_{13}(1 s) and h_2(1 s) excitonic transitions, respectively. The dotted lines help to observe the evolution from Fano profiles at zero field to Lorentzian-like lineshapes at higher fields.

of a magnetic field the PLE spectra changes dramatically: asymmetric resonance features appear, and become stronger and blue-shifted with increasing field. Moreover, the decrease in the continuum pseudo-absorption, which was observed at zero field, gradually disappears with increasing field and the PLE spectra becomes similar to absorption spectra (see below).

The lineshape of these resonances can be interpreted as Fano resonances[1] arising from the interference of magnetoexcitons and the continua of lower lying Landau levels. The theory of excitonic states of semiconductors in magnetic field was treated extensively by Altarelli and Lipari[9]. For each pair of conduction- and valence-band Landau levels, with the same Landau quantum number N_n, there are associated magnetoexcitonic transitions which give rise to the most prominent features of the absorption spectra. The presence of a magnetic field does not affect the wave vectors along the direction of the field, and therefore for each Landau level a one-dimensional continuum prevails. Two different series of Fano resonances are readily identified in the spectra of Fig. 1. Those with lower oscillator strength, as for example the one labeled N_1(lh), correspond to resonances arising from light-hole magnetoexcitons, while the resonances with larger oscillator strength, e.g. N_1(hh), are due to heavy-hole magnetoexcitons. The two energetically lowest light- and heavy-hole magnetoexcitons (N_0) and their excited states lie below the continuum and consequently do not show interferences. Their lineshapes are Lorentzian for all magnetic fields. The energy degeneration of the higher order magnetoexcitonic transitions, e.g. N_1, with the one-dimensional continua of lower lying Landau levels results in asymmetric lineshapes associated with Fano resonances.

The behavior of the magnetoexcitons in a quasi-two dimensional structure is markedly different to that observed in the quasi-three-dimensional sample. Figure 2 shows PLE spectra of the 200-Å QW for different magnetic fields and σ^+ exciting light. For a QW, the confinement of the carriers gives rise to a closer resemblance between the PLE and the optical absorption. At all fields, the spectra presents excitonic structures lying on a continuum which flattens and decreases with increasing field. The first peak in the spectra corresponds to the ground state of the light-hole exciton l_1(1 s)† and has a FWHM of ~0.5 meV. The narrowness of the peaks and the absence of Stokes shift between h_1(1 s) in emission and PLE spectra, which prevents the observation of the heavy-hole exciton in PLE, reveals the very high quality of our sample. This is also manifested by the observation at zero field of the first excited states of the h_1 and l_1 excitons. In the zero field spectrum two asymmetric structures, which are assigned to the h_{13}(1 s) and h_2(1 s) transitions[10], are clearly observed. These discrete excitonic states interfere with the continua of lower lying energy levels, giving rise to Fano resonance lineshapes. Increasing the field, new structures which correspond to excited states of magnetoexcitons appear. Moreover, the Fano resonances progressively lose their asymmetric shape and become more Lorentzian-like, resembling closer a pure excitonic transition, like the first excited state of the hh-exciton, labeled h_1(2 s) in the spectra at 3 T. This is due to the splitting of the two-dimensional continuum, with increasing field, into discrete levels, which leads to a suppression of the interference paths and causes the disappearance of the Fano profiles. Concurrently, the background of the spectra diminishes, because

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†We will use the following notation to label the transitions: h(l) means heavy (light) hole; a subindex indicates the same confined subband for electrons and holes; in the case of two subindices the former corresponds to electrons and the latter to holes. The notation in the parentheses corresponds to the labeling of hydrogenic-like states.

the application of the magnetic field in the Faraday configuration effectively reduces the dimensionality of the system to zero. In a zero-dimensional semiconductor the joint density of states is zero at all energies, except at those corresponding to magneto-excitonic transitions. In a similar way, the application of a magnetic field to a bulk semiconductor decreases the dimensionality of the system to one, therefore reducing the efficiency of non-radiative recombination processes. This explains why in the quasi-three dimensional sample the PLE and the absorption spectra become similar at high fields.

We fitted the experimental Fano resonance lineshapes with the expression[11]

$$I \propto \frac{(q+\epsilon)^2}{1+\epsilon^2}, \tag{1}$$

with ϵ a reduced energy given by

$$\epsilon = \frac{2(E-E_f)}{\hbar\Gamma}, \tag{2}$$

where E_f is the energy of the discrete transition and Γ is the transition rate between the ground state and the continuum

$$\Gamma = \frac{2\pi}{\hbar} V^2 \tag{3}$$

V is the coupling matrix element. The parameter q characterizes the ratio between the coupling of the ground state to the discrete state and of the former to the continuum. In particular, its squared magnitude is proportional to the relative oscillator strength of the magnetoexciton compared to that of the continuum states. Its sign depends on the relative signs of the matrix elements of the transition amplitudes to the discrete state, to the continuum and of the coupling matrix element between the discrete state and the continuum. This sign determines whether the maximum or minimum of the lineshape occurs on the low-energy side of the line. $q > 0$ corresponds to a lineshape where the minimum of the Fano profile lies at smaller energies than the maximum, while $q < 0$ corresponds to the opposite situation.

Figure 3 presents two experimental Fano profiles for the QW (open circles, upper scale) and the quasi-three dimensional sample (black squares, lower scale), together with the fits to eqn (1) (lines). For the QW the Fano resonance corresponds to the h_{13}(1 s) magnetoexciton at 0.5 T, and the fit gives $q = 2.1$. A fit of the Fano resonance lying at 1.556 eV (h_2(1 s) in Fig. 2) obtains a q of -3.1. At 3 T, the fits of the lineshapes yield values of q of 14.7 and -10.5 for h_{13}(1 s) and h_2(1 s), respectively. This demonstrates the disappearance of the Fano resonances at higher magnetic fields, because the higher absolute values of q indicate more Lorentzian-like lineshapes ($q \rightarrow \pm\infty$ for an ideal Lorentzian). The opposite sign of q for the two magnetoexcitons means that there is a change in one or more of the signs of the matrix elements on which q depends. Indeed, the larger absolute value of q for the h_2(1 s) transition, as compared with that of the h_{13}(1 s), denotes that the presence of the continuum of states affects more efficiently the latter exciton than the former one, and that the Fano asymmetry is more pronounced. For the 500-nm GaAs sample the value of q is negative for all Fano structures. As an example, we show the Fano resonance corresponding to N_1(hh) for a field of 10 T in Fig. 3 together with its fit to eqn (1), which obtains a value of q of -2.9. The accuracy of the fits and the evolution of the lineshapes with magnetic field confirm the correct interpretation of the structures as Fano resonances. Many different mechanisms could be responsible for the coupling between the discrete state and the continuum, giving rise to Fano resonances. Due to the coulombic nature of the magnetoexcitons, and based on recent calculations[6], which demonstrate that the non-diagonal Coulomb interaction between the magnetoexcitons and the continua can provide the coupling for the interferences, we believe that the Coulomb interaction is the most plausible candidate to produce the appearance of Fano profiles in the PLE spectra of semiconductor heterostructures.

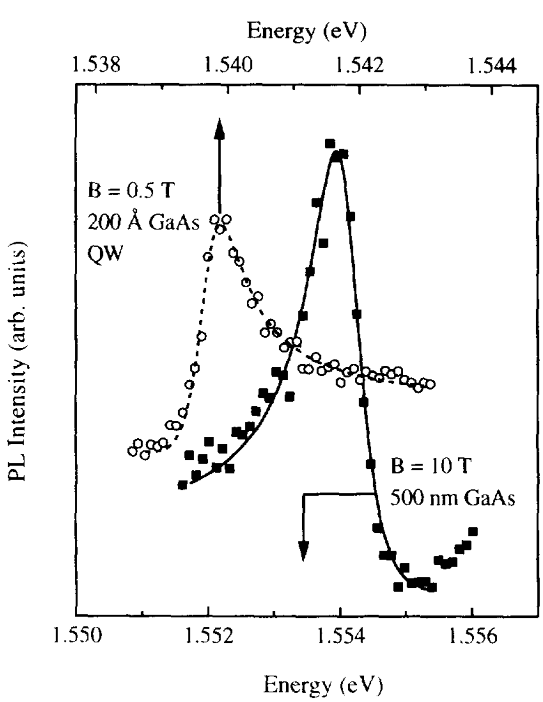

Fig. 3. Experimental Fano profiles and their corresponding fits to eqn (1). Open circles (upper scale) show the experimental Fano resonance associated with the h_{13}(1 s) transition at 0.5 T for the QW sample (dashed line, fit). Full squares (lower scale) present the experimental N_1(hh) Fano structure at 10 T in the quasi-bulk sample (continuous line, fit).

The assignment of the asymmetric peaks observed in Fig. 1 to Fano resonances is also established by the dependence of their energies on the magnetic field, which is compiled in Fig. 4. The experimental points are obtained from a complete lineshape analysis

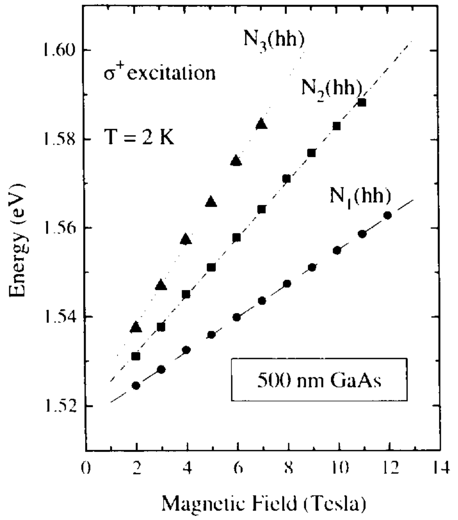

Fig. 4. Energies of three heavy-hole Fano resonances corresponding to the Landau levels $N = 1, 2, 3$ as a function of the magnetic field under σ^+ circularly polarized excitation for the 500-nm GaAs sample. The lines are best fits to a linear dependence, which is valid at high fields (see text).

of the resonances according to eqn (1). At higher fields ($B > 2$ T), the energies of the three structures (N_1(hh), N_2(hh), and N_3(hh)) vary linearly with field, in agreement with the expected dependence of the ground states of the magnetoexcitons associated to the different Landau transitions (at lower fields the dependence is quadratic). From an analysis of the fan-charts it is also possible to confirm the light- or heavy-hole character of the resonances[6]. The energies at which magnetoexcitonic transitions occur do not follow exactly the dependence for Landau levels, $(n + 1/2)\hbar\omega_c$, because of their excitonic character and the fact that the binding energy decreases for increasing N_n.

In summary, we have presented the distinct behavior of Fano resonances in the PLE spectra of quasi-three- and quasi-two dimensional GaAs-Al$_x$Ga$_{1-x}$As heterostructures in the presence of a magnetic field. The evolution of the resonances with the field is markedly different in the two cases. In three-dimensional semiconductors, Fano resonances appear and become stronger with increasing field, whereas in two-dimensional semiconductors they are clearly resolved at zero field, and progressively evolve into Lorentzian peaks for higher magnetic fields. A complete lineshape analysis of the resonances allows us to obtain the parameters of the Fano profiles and their evolution with the magnetic field.

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