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EVOLUTION OF FANO RESONANCES IN TWO- AND THREE- DIMENSIONAL SEMICONDUCTORS WITH A MAGNETIC FIELD

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We have studied the evolution of Fano resonances with an external magnetic field, applied in the Faraday configuration, in two- and three-dimensional semiconductors, by low-temperature photoluminescence excitation spectroscopy. The behavior of the spectra with increasing magnetic field strength depends strongly on the dimensionality of the system: Fano resonances emerge in 3D systems, while those lines which are asymmetric at zero field in 2D systems become more Lorentzian-like due to the suppression of interference paths.

Keywords: A. nanostructures, semiconductors, D. electron-electron interactions, optical properties, E. luminescence

I. INTRODUCTION

The phenomenon of the interaction of a discrete state with a continuum of energetically degenerate states was originally studied theoretically by Fano[1] and experimentally observed, in atomic physics experiments, as asymmetric line shapes in the x-ray absorption spectra of rare gases.[2,3] The line shape deriving from this interaction is known as Fano resonance. These resonances have been observed commonly in other atomic physics studies, such as the collision dynamics of open shell atoms,[4] the predissociation of molecules,[5] and Rydberg states of gases.[6] The theory of Fano has been recently reviewed using the recursion method.[7]

Fano resonances are non exclusive of atomic physics. In semiconductor physics, these resonances have been reported, mainly in doped materials, as asymmetric lines in the absorption[8] and Raman-scattering[9] spectra of impurities. Only in a few cases Fano line shapes have been observed in intrinsic bulk GaAs[10,11] and in undoped GaAs-$Al_xGa_{1-x}As$ superlattices.[12]

In semiconductor physics, the Fano resonant states of impurity levels in crystals have been calculated by Bassani and co-workers.[13,14] For the case of excitonic states, the coupling with continuum states belonging to other excitonic states has been treated by a three band model,[15] numerical integration of the Schrödinger equation[16] and by variational methods.[17] Recently, Fano resonances have been predicted in the Stark ladder spectra in semiconductor superlattices.[18]

In this work we have studied the evolution of the line shapes in the photoluminescence excitation (PLE) spectra of two- and three-dimensional GaAs in an external magnetic field. In bulk GaAs, our results are identical to those obtained by optical absorption.[11] This fact reveals the universality of the Fano interaction, and its independency on the specific technique employed for its observation.

II. EXPERIMENT

The samples were grown by molecular beam epi-

taxy (MBE) on semi-insulating GaAs substrates. The quasi-bulk sample, A, 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 quasi-two-dimensional sample, B, a 200-nm GaAs buffer layer is followed by 20 periods of GaAs-AlAs layers (both 5-nm thick), a 150-nm GaAs layer, a 15-nm $Al_{0.3}Ga_{0.7}As$ layer and 10 GaAs quantum wells (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 exciting light was supplied by a Ti-sapphire laser pumped by an Ar^+-ion laser. Before exciting the sample, the light was circularly polarized in its σ^+ and σ^- components by an achromatic $\lambda/4$ plate (the light polarization is designed in the laboratory frame). For each run, the laser power was measured simultaneously with the PLE intensity in order to normalize the spectra.

III. FANO THEORY

We recall briefly the results of the Fano theory[1] which will be used in the analysis of the experiments. Consider a system with a discrete state φ and a set of continuum states ψ_E, with the energy level of the discrete state lying within the energy range of the continuum. In the presence of a coupling, V, between the discrete state and the continuum, the resulting spectrum is continuous and the resulting eigenstates, Ψ_E, can be expressed as

$$\Psi_E = a(E)\varphi + \int dE' b_{E'}(E)\psi_{E'} , \tag{1}$$

where the coefficients a and $b_{E'}$ depend on the energy E of the state Ψ_E. The projection of the new eigenstate on the discrete state is given by

$$| a(E) |^2 = \frac{[\Gamma(E)/2\pi]^2}{[E - E_\varphi - F(E)]^2 + [\Gamma(E)/2]^2} . \tag{2}$$

The quantities F and Γ, which represent the correction to the energy of the resonance and its broadening, due to the coupling with the continuum states, respectively, are themselves energy dependent and can be written as

$$F(E) = P \int dE' \frac{| \langle \psi_{E'} | V | \varphi \rangle |^2}{E - E'} , \tag{3}$$

where P indicates the principal part of the integral, and

$$\Gamma(E) = 2\pi | \langle \psi_E | V | \varphi \rangle |^2 . \tag{4}$$

When the parameter F and Γ depend slowly on the energy, $| a(E) |^2$ is well represented by a Lorentzian function with F and Γ evaluated at its peak position.[17]

Although it is not indispensable for the discussion of the line shape analysis that we perform in the next section, it is worthwhile to mention that recent calculations[11] have demonstrated that the non-diagonal Coulomb interaction between the magnetoexcitons and the continua provides the coupling, V, for the interferences, which results in Fano profiles.

Independently of the nature of the carrier excitation mechanism, we can study the variation of the probability of excitation of the stationary state Ψ_E due to the coupling. This probability may be represented as the matrix element of a suitable transition operator T between an initial state $| i \rangle$ and the state Ψ_E. The ratio of the transition probability $| \langle \Psi_E | T | i \rangle |^2$ to the probability $| \langle \psi_E | T | i \rangle |^2$ of a transition to the unperturbed continuum can be represented by a single family of curves:[1]

$$\frac{| \langle \Psi_E | T | i \rangle |^2}{| \langle \psi_E | T | i \rangle |^2} = \frac{(q + \epsilon)^2}{1 + \epsilon^2} , \tag{5}$$

where ϵ is a reduced energy given by

$$\epsilon = \frac{2(E - E_\varphi - F)}{\Gamma} , \tag{6}$$

and q is the dimensionaless line shape parameter.

$$q = \frac{\langle \Phi | T | i \rangle}{\pi \langle \varphi | V | \psi_E \rangle \langle \psi_E | T | i \rangle} , \tag{7}$$

where

$$\Phi = \varphi + P \int dE' \frac{\langle \psi_{E'} | V | \varphi \rangle \psi_{E'}}{E - E'} , \tag{8}$$

indicates the state φ modified by an admixture of states of the continuum. Notice that

$$\frac{\pi q^2}{2} = \frac{| \langle \Phi | T | i \rangle |^2}{| \langle \psi_E | T | i \rangle |^2 \Gamma} , \tag{9}$$

is the ratio of the transition probabilities from the initial state $| i \rangle$ to the discrete state Φ, modified by the continuum, and to a band width Γ of unperturbed continuum states ψ_E.

When the probability of a transition to the state Ψ_E is considered, interference effects occur between the transition matrix elements, and in general the function expressed by Eq. (5) has an asymmetric line shape. The sign of q can be positive or negative, depending on the signs of the matrix element in Eq. (7). $q > 0$ corresponds to an asymmetrical line shape with a minimum lying at smaller energies than the maximum, while $q < 0$ originates the specular situation. With increasing abso-

lute value of q the line shapes become more symmetric; in the limit of $q \to \pm\infty$ the line shape is a Lorentzian. This can be understood inspecting Eq. (7), which shows that q is inversely proportional to the coupling between the discrete state and the continuum. Therefore, the smaller the coupling, the greater is the absolute value of q.

IV. RESULTS AND DISCUSSION

Figure 1 depicts the PLE spectra of sample A for different magnetic fields exciting with σ^+- polarized light. The two lowest lying peaks in the spectra, at all magnetic fields, are the heavy-hole and light-hole ground state excitonic transitions. We attribute the removal of the degeneracy between heavy and light valence bands at $\mathbf{k} = 0$ to the presence of a residual strain in the sample.[19,20] The splitting amounts to ~ 1 meV. At zero field, the $n = 2$ and $n = 3$ excited states of the heavy-hole exciton, close to 1.52 eV, are clearly resolved in the spectrum. The resolution of these excited transitions and also the narrowness of the heavy-hole and light-hole ground exciton peaks (FWHM ~ 0.5 meV) denote the high quality of the sample. At 0 T, the decrease of the PLE intensity with increasing energy can be related to an increase of scattering events which lead to non-radiative recombination paths, therefore quenching the radiative emission. This quenching of the PLE intensity, with increasing exciting energy, is the main difference, at 0 T, with the results obtained by absorption measurements in a similar sample.[11] Applying a magnetic field asymmetric structures appear in the PLE spectra, which become stronger and move towards higher energy with increasing field. Moreover, the fall in the continuum of the PLE intensity gradually diminishes with increasing field, and the PLE spectra resemble more closely the absorption of the sample. This effect can be linked to the effective reduction of the dimensionality of the system by the field (to one dimensional in the limit of very high field), which hinders the efficiency of non-radiative recombination processes.

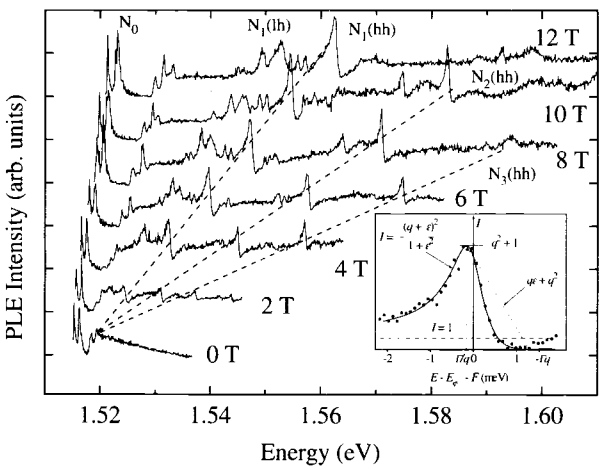

FIG. 1. PLE spectra of a 500-nm thick GaAs layer for different external magnetic fields, applied in the Faraday configuration, at T = 2 K and for σ^+ circularly polarized exciting light. The dashed lines are guides to the eye to show the energy shift of the heavy-hole magnetoexcitons with the field. The inset shows the experimental Fano line shape (dots) and the fit (line) to Eq. (10) of the N_{11}(hh) Fano structure at 10 T. The fit parameter are: $E_\varphi + F(E_\varphi) = 1.5546$ eV, $q = -2.9$, $\Gamma = 0.45$ meV. The maximum intensity has been normalized to $q^2 + 1$. The energy of the resonance, $E_\varphi + F$, has been subtracted from the experimental energies.

The asymmetric line shapes of the peaks in the spectra can be interpreted as Fano resonances,[1] deriving from the interaction of the magnetoexcitons with the continuum of states which remain along the field direction in the bulk sample. Many theoretical[21] and experimental[22] papers can be found in the literature dealing with the behavior of excitons, in bulk semiconductors, in the presence of a magnetic field. For each pair of conduction- and valence-band Landau levels, with the same Landau quantum number N_n, there is associated an exciton series. The most important peaks in the magnetoabsorption spectra correspond to these exciton levels, while the interband Landau absorption is only seen as insignificant shoulders. In Figure 1 two series of Fano resonances are recognizable: one series, with intenser structures, arising from heavy-hole magnetoexcitons, labeled N_n(hh), and a second one, with fainter structures, which is related to light-hole excitons, labeled N_n(lh). The two energetically lowest magnetoexcitonic transition, N_0(hh) and N_0(lh), and their excited states keep their Lorentzian line shape for all fields. They do not evolve in asymmetric Fano structures since they always lie at energies below any continuum of states. On the contrary, the higher order magnetoexcitonic transition, e.g. N_1, which gain oscillator strength with increasing field and are energetically degenerate with the one dimensional continuum, obtain asymmetric Fano line shapes.

We fitted the experimental Fano line shapes in the framework of Eq. (5). We assumed q, F and Γ to be constant in a range of width Γ around the resonance. This assumption is reasonable because in our system the continuum states, ψ_E, can be regarded as energy independent in an interval of width Γ around the resonance.

For a PLE experiment, assuming that the shape of the spectra is primarily determined by the absorption, the transition operator, T, is the electric dipole opera-

tor. If we assume a constant absorption probability of the continuum of states around a Fano resonance, Eq. (5) leads to the absorption (and PLE) profile of a Fano resonance which has the form

$$I \propto \frac{(q+\epsilon)^2}{1+\epsilon^2} . \qquad (10)$$

The inset of Figure 1 shows an experimental Fano profile resonance (dots) corresponding to the N_1(hh) magnetoexciton, for sample A at 10 T, and its fit (continuous line) to Eq. (10). We obtain $E_\varphi + F = 1.5546$ eV, $q = -2.9$ and $\Gamma = 0.45$ meV. The most important characteristics of the line shape according to the analysis of Piao et al.,[8] are indicated in the figure. Note that the maximum of the line shape is displaced with respect to zero (which is the position of the resonance) and occurs at Γ/q. The straight line joining the maximum (at Γ/q) and minimum (at $-\Gamma/q$) of the resonance satisfies the equation $q\epsilon + q^2$ and intercepts the Fano profile $I(\epsilon, q)$ at $\epsilon = 0$. From these fits we obtain the same value of q, within experimental error, at all magnetic fields and for all the N_n(hh) magnetoexcitonic transitions. The fact that q remains constant with field is closely linked to the invariance of the continuum intensity in the spectra of Fig. 1, and suggests that the matrix elements $\langle \Phi \mid T \mid i \rangle$ and $\langle \varphi \mid V \mid \psi_E \rangle$, which determine q, have a similar field dependence. The third matrix element $\langle \psi_E \mid T \mid i \rangle$, involved in Eq. (7), is practically field independent, since it comprises states unperturbed by the magnetic field. The goodness of the fits and the evolution of the line shapes with the field confirm the correct interpretation of the structures as Fano resonances.

Equation (9) yields the value

$$\frac{\pi q^2}{2} = 13.2, \qquad (11)$$

this result provides an estimate of the transition probability to the "modified" discrete state Φ in terms of the probability of transition to the unperturbed continuum.

The assignment of the Fano resonances as magnetoexcitons is confirmed by the dependence of their energy on the magnetic field, which is reported in Fig. 2. Each point is obtained by fitting the line shape with Eq. (10). For fields larger than 2 T the energy of the N_n(hh) resonances varies linearly with field, in agreement with the expected dependence of the ground state of the magnetoexcitons associated to the different Landau transitions (at lower fields the dependence is quadratic).[21] However, the energies of the magnetoexcitonic transitions do not follow exactly the dependence of the Landau levels, $(n + 1/2)\hbar\omega_c$, because their binding energies are field dependent and decrease with increasing n.

Figure 3 reports the PLE spectra for the 200-Å GaAs QW, sample B, at different magnetic fields for σ^+ polarized excitation. In contrast with the results of the bulk sample, at zero field the two dimensional confinement of the carriers in the QW leads to a PLE spec-

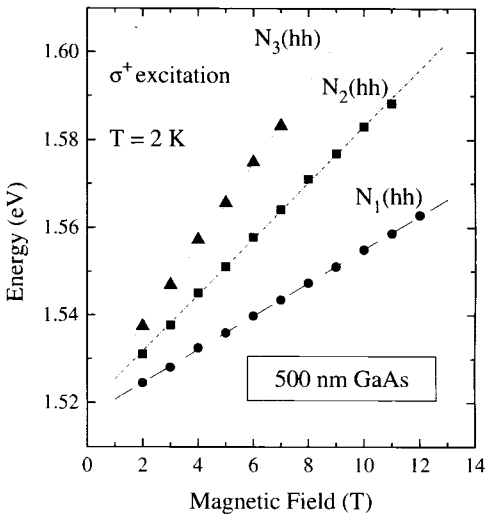

FIG. 2. Energies of three heavy-hole Fano resonances (corresponding to the Landau levels N_n(hh), n = 1, 2, 3) as a function of the magnetic field under σ^+ circularly polarized excitation for the 500-nm GaAs sample. The lines are best fits to a linear dependence, which is valid at high fields (see text).

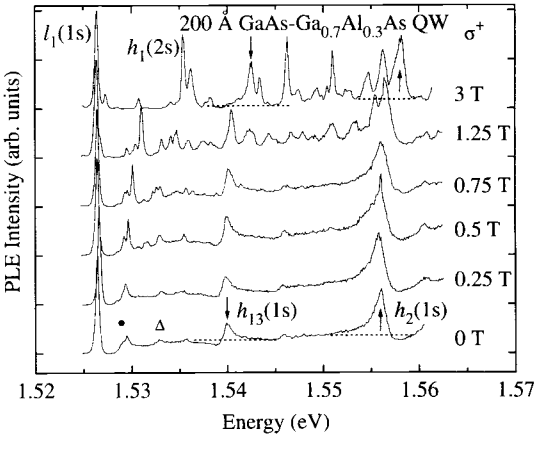

FIG. 3. PLE spectra of the 20-nm thick GaAs-$Al_{0.3}Ga_{0.7}As$ quantum well for different external magnetic fields, applied in the Faraday configuration, at T = 2 K and for σ^+ circularly polarized exciting light. The excitonic transitions h_1(2s) and l_1(2s) are marked by • and Δ, respectively. ↓ and ↑ point to the h_{13}(1s) and h_2(1s) excitons, respectively.

trum which resembles the optical absorption spectrum. At low fields the spectra show excitonic structures superimposed on a flat continuum, which decreases with increasing field. The application of the magnetic field in the growth direction of the heterostructure, z, reduces the effective dimensionality of the QW (to zero-dimensional limit for very high fields), leading to a joint density of states which is zero at all energies, except at those of the magnetoexcitonic transitions. These is observable in the experimental spectra as a reduction of the continuum level.

The lowest peak in the spectra of Fig. 3 is the $l_1(1s)$ light-hole exciton.[23] The absence of any Stoke shift between the $h_1(1s)$ excitonic peaks in emission and absorption prevents the observation of this state in the PLE spectra. This fact together with the narrowness of the $l_1(1s)$ peak (FWHM $\sim$ 0.5 meV) reveals the very high quality of the sample. This is also manifested by the presence at zero field of the $h_1(2s)$ and $l_1(2s)$ excited states in the spectra, marked by • and Δ, respectively. The two structures assigned to the $h_{13}(1s)$ and $h_2(1s)$ excitonic transitions[24] are asymmetric at zero field, due to the interaction with the continua of lower lying excitons, which give rise to Fano line shapes. The application of a magnetic field splits the two dimensional continua into discrete levels, thus lifting the energy degeneracy with $h_{13}(1s)$ and $h_2(1s)$ and leading to a reduction of the Fano interference. This is demonstrated in Fig. 3 where is clearly seen that, increasing the magnetic field, the line shapes of the transitions $h_{13}(1s)$ and $h_2(1s)$, marked with $\downarrow$ and $\uparrow$, respectively, evolve gradually from Fano-like to Lorentzian-like. Moreover, as previously observed in literature, new magnetoexcitonic structures, corresponding to excitonic excited states, appear in the spectra.[24]

Figure 4 reports two experimental Fano profiles for the QW together with their fits to Eq. (10) (lines). Note that two Fano resonances, with specular asymmetry with respect to their maximum, coexist in the same spectrum. The resonances correspond to the $h_{13}(1s)$ and $h_2(1s)$ excitonic transitions at zero magnetic field. The fits yield $q = 2.1$ and $q = -3.2$, for $h_{13}(1s)$ and $h_2(1s)$, respectively. The corresponding values of $\pi q^2/2$ are 6.9 and 16.1. The smaller the value of this quantity indicates a larger amount of interference in the Fano profile. At 3 T, q becomes 14.7 and -10.5 for $h_{13}(1s)$ and $h_2(1s)$, respectively. The larger values of $\mid q \mid$ denote more Lorentzian-like line shapes and demonstrates the disappearance of the interference paths leading to Fano shapes at high magnetic fields. The enlargement of $\mid q \mid$ from 0 T to 3 T is approximately twice smaller for the $h_2(1s)$ exciton than for the $h_{13}(1s)$, indicating a less efficient reduction of the interference paths with increasing energy. This fact is also corroborated by the increase of the continuum background, on which the magnetoexcitons lie (dotted lines in Fig. 3), with increasing energy.

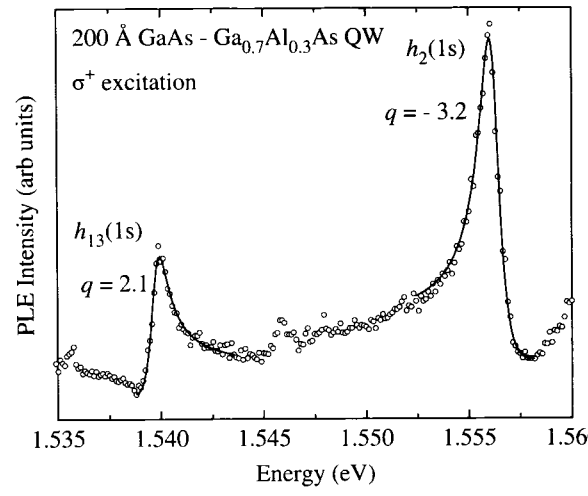

FIG. 4. PLE spectrum for the 20-nm GaAs QW at zero magnetic field under σ^+ circularly polarized excitation (dots) in the spectral region of the $h_{13}(1s)$ and $h_2(1s)$ magnetoexcitons. The best fits using Eq. (10), which yield q = 2.1 and -3.2, respectively, are shown by lines.

V. CONCLUSIONS

We have studied the dimensionality dependence of the behavior of Fano resonances in the PLE spectra of GaAs-$Al_xGa_{1-x}As$ heterostructures in a magnetic field. The evolution of the resonances with the field is markedly different in two dimensions, a 20-nm GaAs-$Al_{0.4}Ga_{0.6}As$ QW, and in three dimensions, a 500-nm thick GaAs layer. The identification of the asymmetric structures in the PLE spectra as magnetoexcitons interacting with a continuum of states, yielding Fano profiles, is supported by the goodness of the fits with the formula of Fano and by their evolution with the magnetic field.

In the 3D semiconductor, Fano resonances are absent at 0 T but appear and become stronger with increasing magnetic field. This is due to the progressive appearance of magnetoexcitons associated to different Landau series, which interact with the continua of energetically lower-lying interband Landau transitions. Two series of Fano resonances are identified in the spectra, which correspond to the heavy or light character of the discrete magnetoexcitons.

In 2D semiconductors, in the absence of an external magnetic field, there are already discrete excitonic states which are superimposed on the continua of lower lying

excitons, giving rise to Fano resonances. The application of a magnetic field splits the two-dimensional continuum into discrete levels and leads to the disappearance of the asymmetric Fano profiles, which evolve into Lorentzian line shapes.

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23. 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 parenthesis corresponds to the labeling of hydrogenic-like states.
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