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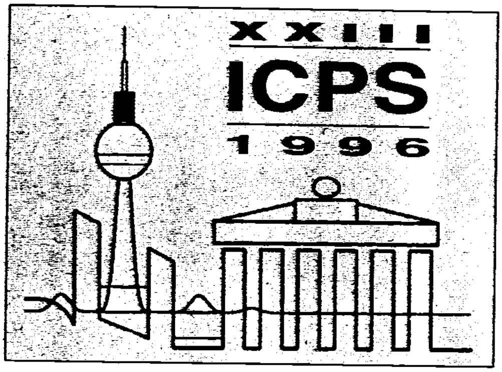

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QUENCHING OF FANO RESONANCES IN GaAs DUE TO ELECTRON-PHONON POLARONIC INTERACTION

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ABSTRACT

We have observed distinct Fano resonances in the pseudo-absorption spectra of GaAs in an external magnetic field. The polaronic interaction quenches the resonances whenever the energies of the electrons (holes) of a magneto-exciton are tuned, by the magnetic field, to one longitudinal-optical phonon above the fundamental Landau level in the conduction-(valence-) band. A line shape analysis of the resonances yields a singular behavior of the parameters characterizing the Fano profiles.

Absorption[1,2] and photoluminescence-excitation (PLE) spectroscopy[3] measurements in bulk GaAs have revealed that the inter-band transitions have asymmetric line shapes in the presence of an external magnetic field. The asymmetry of these structures arises from Fano interferences[4] between discrete transitions (magneto-excitons) and the energetically degenerate continuum of states which remains along the field direction. The Fano line shapes should be sensitive to the additional coupling of the electronic states with longitudinal-optical (LO) phonons by Fröhlich interaction. This interaction, known as polaronic coupling, leads to a modification of the Landau levels (LL's).[5] In particular, the resonant polaron coupling (RPC) gives rise to a pinning and a splitting of the LL's .

We have investigated a high quality GaAs film grown by molecular beam epitaxy on a GaAs substrate. A 200-nm GaAs buffer was followed by 500-nm of $Al_{0.4}Ga_{0.6}As$, a 500-nm GaAs layer and 300-nm of $Al_{0.4}Ga_{0.6}As$. The sample was capped by 10 nm of GaAs. The PLE spectra were recorded at 2 K, using circularly polarized light, with the magnetic field, up to 13.5 T, applied in Faraday configuration.

In the presence of a magnetic field, the conduction band of a cubic semiconductor has two series of LL's, $|\alpha_n>$ and $|\beta_n>$, for electrons with spin up and down, respectively, with n the Landau number. In the valence band, there are four series of non-equally spaced levels, $|a_n^+>$, $|a_n^->$, $|b_n^+>$ and $|b_n^->$, whose wave-functions are linear combinations of Bloch and harmonic oscillator wave-functions.[6] The allowed optical transition are: $|a_n^\pm> \Leftrightarrow |\alpha_n>$, $|b_n^\pm> \Leftrightarrow |\beta_n>$ for σ^+ excitation, and $|a_{n+2}^\pm> \Leftrightarrow |\alpha_n>$, $|b_{n+2}^\pm> \Leftrightarrow |\beta_n>$ for σ^- excitation. The energy of a LL with respect to the bottom (top) of the conduction (valence) band is $E_n^{e(h)} = (n+1/2)\hbar\omega_c^{e(h)}$, being $\omega_c^{e(h)} = eB/m^*_{e(h)}$ the cyclotron frequency and $m^*_{e(h)}$ the effective mass of the electron (hole). Whenever the energy of an electron (hole) involved in a Landau level ,LL_n, is one LO-phonon energy, $\hbar\omega_{LO}$, above a lower lying level LL_m, the polaronic coupling becomes resonant: LL_n anticrosses the virtual energy level formed by LL$_m$ plus one $\hbar\omega_{LO}$, and an energy splitting appears in the spectra. The two transitions form the upper and lower magneto-polaron branches.[5] The resonant polaron threshold for electrons (holes), neglecting excitonic effects, has an energy given by:

$$\hbar\omega_t^{e(h)} = E_g + \left(\frac{\hbar\omega_c^{e(h)}}{2} + \hbar\omega_{LO}\right)\left(1 + \frac{m^*_{e(h)}}{m^*_{h(e)}}\right) \tag{1}$$

with E_g the energy gap of the semiconductor.

Figure 1 reports the PLE spectra of the GaAs film at a field of 8 T. The upper (lower) trace corresponds to excitation with σ^- (σ^+) polarized light. The transitions are labeled according to the nomenclature introduced by Vrehen.[6] For energies below E_g, indicated by a vertical line in the figure, the peaks have a Lorentzian profile. However, those structures above E_g show clearly an asymmetric line shape. Many mechanisms could be responsible for the interferences between the discrete states and the continua which give rise to the Fano profiles. So far, theoretical calculations have assumed Coulomb interaction[1] and elastic scattering by residual impurities or defects[7] to describe satisfactorily the experimentally observed Fano profiles.

The profile of a Fano resonance can be written as[3,4]

$$I \propto \left(q+\varepsilon\right)^2 / \left(1+\varepsilon^2\right), \tag{2}$$

where q is a dimensionaless parameter, and ε is a reduced energy given by $\varepsilon = 2\left(E - E_f\right)/\Gamma$. E_f and Γ are the energy of the discrete transition and its broadening modified by the coupling with the continuum states, respectively.[1,3]

In the rest of the work, we will concentrate on σ^+ excitation. A detailed view of the $|b_2^+> \Leftrightarrow |\beta_2>$ transition (squares), at a magnetic field of 9 T, is given in Fig. 2 together with its best-fit (dashed line) using Eq. (2).

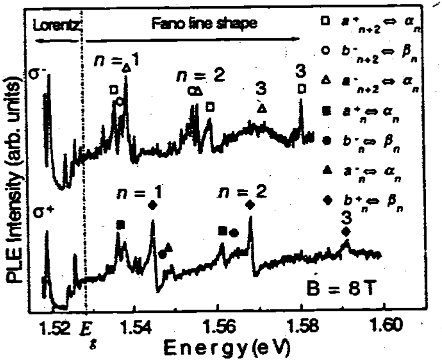

Figure 1: Low temperature (T = 2 K) PLE spectra of GaAs in a magnetic field of 8 T.

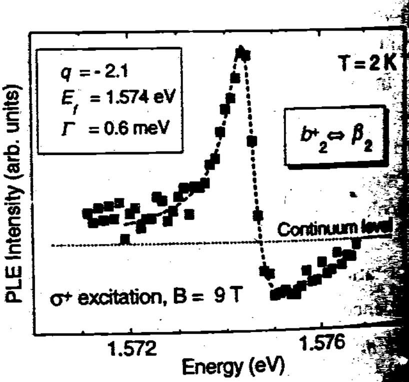

Figure 2: PLE spectrum (squares) and
(dashed line) of the $|b_2^+> \Leftrightarrow |\beta_2>$ transition.

The fitting parameters, q and Γ, of the $|b_n^+> \Leftrightarrow |\beta_n>$ Fano resonances are almost independent of the Landau index and of the magnetic field strength (see peeks 1◆ and 2◆ in Fig. 1), except when the transitions lie ~ $2\hbar\omega_{LO}$ above the excitonic ground state (see peek 3◆ in Fig. 1). Since the electron and hole effective masses are similar, this excess energy corresponds, according to Eq. (1), to the threshold of the RPC.

The evolution of the $|b_3^+> \Leftrightarrow |\beta_3>$ transition with magnetic field is shown in Fig. 3. The line shape, asymmetric at 6 T, progressively looses it asymmetry. Furthermore, the structure broadens and quenches at ~ 8.5 T. Meanwhile, a second structure appears at a slightly higher energy, which grows and obtains a Fano line shape with increasing field. A new and stronger quenching takes place close to 11.5 T. Both extinctions are due to the RPC between the LO phonon and the electron and the hole of the magneto-exciton, respectively. The inset of Fig. 3 illustrates the resonant polaron coupling in the conduction band for the $|b_2^+> \Leftrightarrow |\beta_2>$ Fano resonance.

The magnetic field dependence of the $|b_3^+> \Leftrightarrow |\beta_3>$ energy is compiled in Fig. 4. The splitting due to RPC of the lower and upper branches of the resonant magneto-polaron, which amounts to ~ 3.5 meV, is observed between 7 and 8 T, ~ 64 meV above the excitonic ground state.

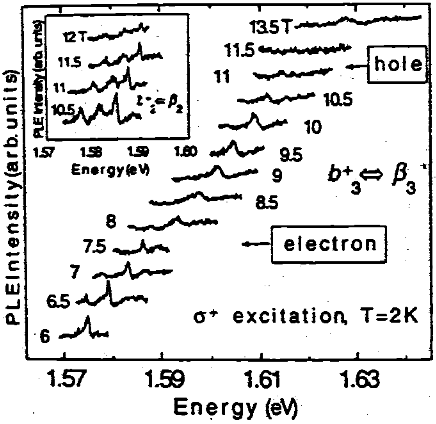

Figure 3: Evolution of the $|b_3^+> \Leftrightarrow |\beta_3>$ transition (in the inset the $|b_2^+> \Leftrightarrow |\beta_2>$ transition) with magnetic field.

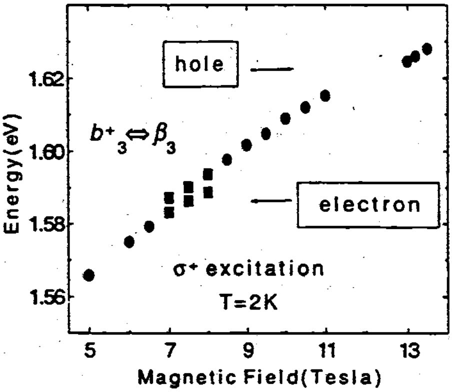

Figure 4: Energy of the $|b_3^+> \Leftrightarrow |\beta_3>$ transition as a function of magnetic field. The squares correspond to the two branches of the magneto polaron.

From Eq. (1), taking $\hbar\omega_{LO} = 36.3$ meV and $m^*_e = 0.065\ m_0$ we calculate $m^*_h = (0.085 \pm 0.002)\ m_0$. The ratio of the magnetic field strengths, $B^{(3)}_h / B^{(3)}_e = 1.34 \pm 0.08$, at which the quenchings of the $|b_3^+> \Leftrightarrow |\beta_3>$ Fano resonance occur, is close to the ratio of the effective masses of the carriers involved in the RPC, $m^*_h / m^*_e = 1.31$. This agreement confirms that RPC is the origin of the extinctions. An additional confirmation is obtained from the ratio between the threshold fields, $B^{(3)}_e / B^{(2)}_e = 0.67 \sim 2/3$, which is inversely proportional to that of the corresponding Landau numbers.

Figure 5 reports the best fit parameters q and Γ of $|b_3^+> \Leftrightarrow |\beta_3>$ versus field. Note the large increase of $|q|$ and of the broadening at fields where the RPC takes place. The coupling reduces the lifetime of the transition (Γ increases) and destroys the interference paths responsible of the Fano asymmetry ($q \to \pm \infty$ gives a Lorentzian line shape).

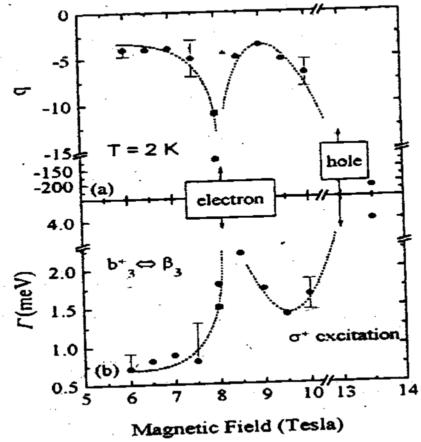

Figure 5: Fano line shape parameter q (a) and broadening Γ (b) of the $|b_3^+> \Leftrightarrow |b_3>$ transition as a function of the magnetic field.

The effect of the RPC on the $|b_3^+> \Leftrightarrow |\beta_3>$ transition is stronger in valence- than in conduction-band. This can be due to the additional contribution of the deformation potential scattering mechanism and to the presence of the heavy-hole ladders in the valence band, which gives extra scattering paths for the holes.

In conclusion, we have studied the Fano line shapes of the magneto-excitons in GaAs and have observed their quenching due to resonant polaron coupling. The Fano line shape parameters, q and Γ, show a singular behavior. The quenching of the resonances is stronger in the valence- than in the conduction- band. From our measurements we extract an effective mass for the light-hole of $(0.085 \pm 0.002)\ m_0$.

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