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Magneto optics of an electron system with variable dimensionality

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Magneto-luminescence spectroscopy is used to study the single particle subband spectrum of a parabolically confined electron system. Realized in parabolic quantum wells, this system offers the unique advantage to switch the systems dimensionality between a quasi two-dimensional and a quasi one-dimensional magneto-electric band structure depending on the angle between the direction of the electrical confinement and an external magnetic field. Strong spatial confinement of the photoexcited holes as well as the large wave function overlap with the conduction electrons makes the system a perfect candidate study the magnetic dispersion and depopulation of subbands.

In the recent past, there has been growing interest in the interband-optical properties of low-dimensional electron systems especially in high magnetic fields[1]. For example, such studies offer the advantage to investigate both the integer as well as the fractional quantum Hall effect in a contactless and alternative way[2]. Usually, radiative recombination of quantum confined carriers is investigated in quantum wells of different width, or more recently also on a new type of heterojunction[3] where bound holes are created via a δ-layer of acceptors close to the quasi-two dimensional electron system (Q2DES). Starting from this material there has been a growing interest also in the optical properties of quasi one-dimensional electron systems or quantum wires. Optical investigations on these lateral nanostructures have been intensively used to probe the lateral confining potential[4] as well as the electronic states[5] of the confined carriers. A complementary and very attractive semiconductor structure for optical investigations are so-called parabolic quantum wells (PQW's) as realized in graded $Al_xGa_{1-x}As$ heterojunctions[6]. Here, both the conduction as well as the valence band of the alloy have a parabolic shape which results in one of the simplest confining potentials for electrons in semiconductor structures. Remote doping leads to the creation a wide electron layer with usually more than one electrical subband occupied. In addition, caused by the special band structure, there is strong overlap between the electron and hole wavefunctions such that radiative recombinations are easily observed in photoluminescence (PL) experiments[7]. The spatial confinement of photoexcited carriers leads to so-called Fermi edge singularities which also allow for a determination of the energetical position of the chemical potential as a function of, e.g., the carrier density in the well or an external magnetic field. Besides this, a very attractive feature of PQW's is the striking similarity of many of their electronic properties to the ones of quantum wires as many experimental results obtained for these challenging nanostructures can be rather perfectly described in parabolic approximation.

Here, we focus on the optical spectrum of a doped PQW subjected to a strong quantizing magnetic field as obtained from photoluminescence measurements. Our sample is a 130nm wide parabolic quantum well where the aluminum mole fraction x in the $Al_xGa_{1-x}As$ alloy is graded from x=0 in the centre up to x=0.3 at the edges of the well. This parabolically graded quantum well mimics the potential of a uniform positive background of density n^+ which is solely determined by the curvature of the parabola. For the sample presented here, the curvature corresponds to a quasi-charge of $n^+=7.4\cdot10^{16}$ cm^{-3}, leading to a sheet carrier density of approximately $n_S=5\cdot 10^{11}$ cm^{-2}. In this case three electrical subbands are occupied having a typical separation of a few meV. For the detailed growth and doping procedure as well as for details on the electronic subband structure we refer the reader to earlier references[6,8].

Fig. 1 depicts a sketch of the expected band structure of a doped PQW. In the modulation doped well, the filled region of the conduction band is essentially flat and the curvature of the valence band throughout this region exhibits an increased curvature leading to a strong confinement of photoexcited holes. The arrows schematically indicate some transitions from electronic levels towards the lowest lying hole state. However, the selection rules and symmetry of the confining potential make not all of them observable in photoluminescence experiments.

Subjected to a magnetic field perpendicularly to the plane of the PQW, the free conduction subband-dispersion along the plane of the well condenses in a series of Landau-levels for each subband:

$$E_{n,l} = E_n + (l + 1/2)\hbar\omega_c + sg\mu_B B \qquad (1)$$

Here, E_n denotes the electrical subband edges that for a wide doped PQW in first order vary as $E_0 \cdot n^2$ since the resulting self consistent Hartree potential resembles a wide square well. E_0 in our case is of the order of 1 meV depending on the number of carriers in the well and the width of the electron slab, respectively. Here, $\hbar\omega_c = \hbar eB / m^*$ represents the cyclotron energy, and $sg\mu_B B$ the Zeeman energy of spin quantum number $s = \pm 1/2$ in a magnetic field B, μ_B is Bohr's magneton, and g the effective Landé g-factor. In the following we neglect this spin splitting of the Landau levels since for our structures it is a small quantity as compared to $\hbar\omega_c$. The degeneracy of the Landau levels increases with increasing magnetic field leading to a magnetic depopulation of higher levels and thus also of electrical subbands. Caused by the multi-subband occupancy the Landau levels originating from different electrical subbands cross each other at specific magnetic fields which leads to a very special signature of the magneto-transport parameters in a PQW. For example, the quantum Hall effect can be suppressed[9] for specific filling factors, whenever there is a degeneracy of two Landau levels from different subbands.

In a tilted magnetic field this degeneracy can be lifted and results in a anticrossing of the respective levels caused by a resonant interaction between the electrical subbands and the Landau levels. In parabolic approximation this level anti-crossing and the position of the Fermi level as a function of the magnetic field can be analytically calculated and directly compared to the result of a magnetotransport experiment in tilted fields[10]. This way one can gain experimental access to the single particle subband spectrum of a PQW in a very unique way.

If the magnetic field is directing along the plane of the PQW, the resulting bandstructure represents a hybrid of electrical and magnetic quantization[11]. In parabolic approximation and again neglecting spin effects, the magneto-electric hybrid subband dispersion is then given by :

$$E = \hbar\Omega(n + 1/2) + \frac{\hbar^2 k_x^2}{2m^*}\frac{\omega_0^2}{\Omega^2} + \frac{\hbar^2 k_y^2}{2m^*} \qquad (2)$$

Here, $\Omega = (\omega_0^2 + \omega_c^2)^{1/2}$ denotes an effective magneto-electric hybrid frequency, where ω_0 represents the natural frequency of the confining potential. The free dispersion along the plane of the well as represented by the quasi-momenta k_x and k_y exhibits a strong anisotropy with respect to the magnetic field direction which can be probed by, e.g., the plasmon dispersion at finite wave vector[12]. Even though the selfconsistent Hartree potential in a doped PQW is no longer parabolic, the above dispersion is a good approximation for the resulting magnetic field dispersion if ω_0 is replaced by $E_n / \hbar$ where the E_n are the subband edges for the selfconsistent Hartree potential[13].

Our experiments are performed in a low temperature optical cryostat where the sample is located in the center of a superconducting split-coil solenoid providing magnetic fields up to 8T. The sample is excited using an Argon ion laser at an excitation wavelength of λ= 514 nm. The outcoming luminescence light is analyzed using a triple grating spectrometer.

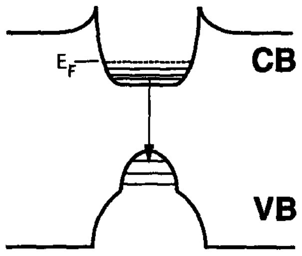

Fig. 1 : Schematic of the conduction- and valence band of a n-type doped parabolic quantum well. Over the filled region the conduction band is essentially flat wheras the valence band exhibits a larger curvature.

The PL spectrum of a PQW in a magnetic field consists of a series of lines which can be attributed to radiative transitions from the Landau levels of the conduction band to the lowest lying states in the valence band[8]. For a wide PQW this is the lowest Landau level of the lowest heavy hole subband in the valence band. Symmetry arguments only allow a certain set of transitions to occur such that not the whole fan chart is accessible in our experiments.

A typical experimental result for the PL spectrum of a PQW subjected to a perpendicular magnetic field is given in Fig. 2. The resulting band structure in this case is the one of a multi subband system as described by eq. (1). We plot the extracted PL energies (circles) together with the expected Landau fan chart and the position of the Fermi level versus the magnetic field. Both the subband edges E_n as well as the position of the Fermi level at B=0 have been adjusted to the experiment. They are in good agreement with the respective quantities as obtained from a fully self consistent calculation[14] and from transport experiments. For a similar experiment, we refer to ref.8 where especially the occurrence of Fermi-edge singularities in the PL spectra of PQW has been addressed. We here show this experimental result for comparison and to demonstrate the quasi 2D character of the electron system in this experimental geometry.

Tilting the magnetic field with respect to the sample surface leads to a different magnetic bandstructure as mentioned above. The degeneracy between Landau levels originating from different electrical subband is lifted and

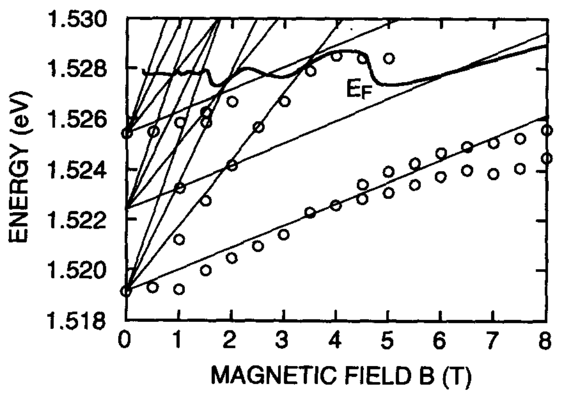

Fig. 2 : Calculated Landau-level fan chart (thin solid lines) and Fermi-level (thick solid line) of a parabolic quantum well versus the perpendicular magnetic field. In this geometry the system behaves quasi two-dimensional with three electrical subbands occupied. The symbols represent the experimentally obtained positions of the magneto luminescence in this geometry.

the respective levels repel each other. Similar to corresponding magneto-transport experiments this signature is also observed in the PL spectra, especially for the level crossing of $E_{0,1}$ and $E_{1,0}$ at around B=2T. This result of the resonant subband Landau level interaction clearly shows up in the spectra, and also the selection rules for radiative transitions change due to the strong level mixing in this case. The analysis of such an experiment, however, is for the same reasons not straightforward. Further experiments on this very interesting subject are presently carried out and will be discussed elsewhere.

Most interesting, however, is the case where the magnetic field is directing along the plane of the parabolic well. Here, the resulting magneto-electric subband structure is very similar to the one of a quantum wire in a perpendicular magnetic field and is given by eq. (2). The only difference between both is the behavior of the density of states (DOS) of the hybrid levels : For a PQW at B=0 the DOS consists of a staircase of several 2D-like and energy-independent step functions of height $m^*/\pi\hbar^2$. With increasing magnetic field there is a smooth crossover from this 2D-like DOS towards the well known 1D-like DOS of a 3D electron system in a strong quantizing magnetic field[11]. This DOS is formally identical with the one of a 1D quantum wire at zero magnetic field. Here, however, an increasing magnetic field leads to a smooth change of the 1D-like DOS of the quantum wire towards the 0D-like DOS of a Landau level in two dimensions. Simply tilting the magnetic field with respect to the sample thus changes the resulting bandstructure or dimensionality of the electron system in a PQW from quasi two- towards quasi one-dimensional behavior.

There has been strong interest in the magnetic depopulation of such 1D subbands in the past[15]. Recently, also direct observation of these levels has been reported using an optical method[5]. As we have pointed out, the magnetic field dispersion of the magneto-electric hybrid subbands of a PQW in parallel magnetic fields is in perfect agreement with the one of a quantum wire in perpendicular magnetic field. Our system, however, offers the advantage to directly probe the dispersion and also the position of the Fermi level as a function of the in-plane magnetic field. Parabolic quantum wells subjected to an in-plane magnetic field thus may be regarded as a model system for the understanding of the properties also of quantum wires.

Typical PL spectra as obtained in this quasi one-dimensional geometry are shown in Fig.3 for different magnetic fields. As can be clearly seen from the figure, there is a strong dependence on both strength as well as position of the observed lines as a function of the in-plane field. At low energies, there is a quite strong line increasing in intensity with increasing magnetic field and shifting to higher energies. At low magnetic fields a second line is observed at higher energies which first looses strength with increasing magnetic field and then appears againat around B=3 T. For magnetic fields higher than B=3.5 T this line is no longer observable, instead the typical signature of a Fermi-edge is seen for all higher in-plane fields.

The corresponding line positions as well as the position of the Fermi-level as function of the magnetic field are shown in Fig. 4. Here, the dominant line at high magnetic fields is identified as the 1h-transition, i.e., the transition between the lowest Landau level in the lowest electronic subband to the lowest Landau-level of the lowest heavy hole subband. The position of the Fermi-level is at low magnetic fields (B<3.5T) taken as the position of the second, clearly discernible peak in Fig. 3. which arises from the third hybrid subband at low fields and from the second subband at somewhat higher fields. As soon as only the lowest subband remains occupied, i.e. for B>3.5T, we derive the position of the Fermi-level E_F from the position of the Fermi-edge as explained above.

In this quasi one-dimensional geometry, the PL spectra are well explained by the magnetic field induced depopulation of magneto-electrical subbands in the PQW. At B=0 T, there are three subbands occupied, which become subsequently depopulated at specific in-plane fields. This depopulation is indicated by the characteristic kinks in the E_F vs. B plot of Fig. 4. Because of parity reasons only the 1h and 3h transition can be resolved in the PL spectra, hence we are not able to directly derive its magnetic field dispersion. The extracted depopulation fields of B_{3-2} = 1T and B_{2-1} = 3.5T, however, are in good agreement with the results of a magneto-transport experiment on the same sample. Here, the depopulation of subbands leads to a structure in the longitudinal magneto-resistance similar to Shubnikov - de Haas oscillations[14]. However, the determination of the exact depopulation field is still being disputed since it not yet fully understood which mechanism leads to a structure in the magneto-resistance. Here, our experiments may serve useful for a better understanding of the depopulation process of one-dimensional magneto-electric subbands.

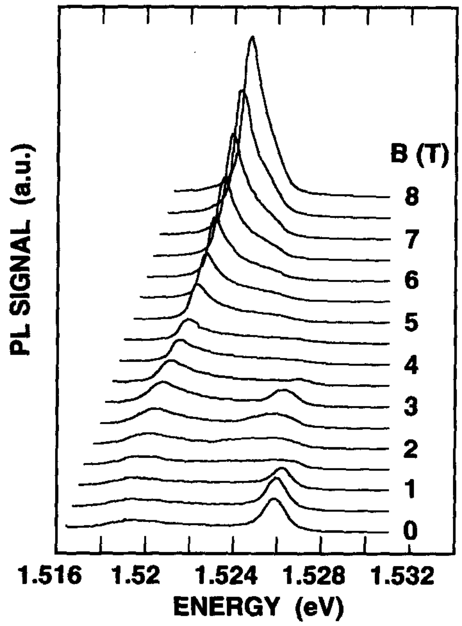

Fig. 3 : Typical set of spectra taken at different in-plane magnetic fields. Here, the electron system in a PQW exhibits a quasi one-dimensional magneto-electric band structure similar to the one of a quantum wire in perpendicular magnetic fields.

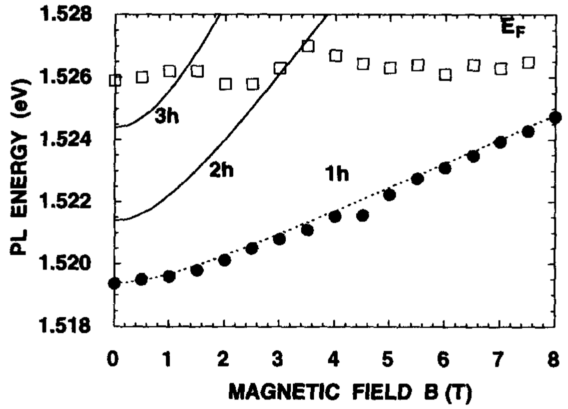

Fig. 4 : Position of the prominent radiative transition (dots) and the Fermi-level (open squares) as a function of the in-plane magnetic field as taken from Fig. 3. The lines are the result of a simple calculation taking into account the hybridization of both electrical and magnetic quantum levels in this geometry. The position of the Fermi-level has been obtained as described in the text.

In summary, we observe magneto-photoluminescence in parabolic quantum wells at low temperatures. Subjected to a perpendicular magnetic field, the resulting band structure of a PQW is identical to the one of a multi-subband quasi two-dimensional electron system. The PL spectra in this case represent the Landau-level fan chart as described by eq. (1). Tilting the magnetic field away from the sample normal leads to a gradual change of the resulting magneto-electric bandstructure. For in-plane fields it is very similar to the one of a quasi one-dimensional quantum wire in perpendicular magnetic field. Then, the magneto-electric hybrid bandstructure is given by eq. (2). The dimensionallity of the electron system thus can be switched between 2D-like and 1D-like depending on the angle between the electron system and the magnetic field direction. Our system offers the unique possibility to directly compare the PL spectra resulting from different dimensionality of the same sample and thus offers new insight into the magnetic field induced subband depopulation process of low dimensional electron systems.

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