Coupling of Quantum Dots on GaAs

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With far-infrared spectroscopy, coupling between electron quantum dots becomes visible in the electronic excitation spectrum. We employ gated GaAs-AlGaAs quantum wells that enable field-effect tuning of the coupling between adjacent dots. For noninteracting quantum dots in a magnetic field we observe the characteristic edge- and bulk-mode spectrum. The coupling of dots is reflected by a branching of the bulk mode into a cyclotron-resonance-like and a magnetoplasmonlike mode and a splitting of the edge mode. The latter is caused by formation of new edge orbits embracing two adjacent dots.

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A laterally periodic modulation of the confining potential of electrons in a quasi-two-dimensional electron gas formed at a semiconductor interface has proven to be a powerful tool for the creation and investigation of low-dimensional electron systems. Direct insight into the energy spectrum of such systems is promoted by the application of magnetic fields such that characteristic magnetic and electric lengths are of comparable size. As predicted by Hofstadter[1] this should eventually result in an energy spectrum of intriguing richness and beauty. Several attempts to realize such systems have already been made: In the limit of weak one-dimensional modulation Weiss *et al.*[2] and Winkler, Kotthaus, and Ploog[3] observed a novel type of oscillation in the magnetoresistance of GaAs heterostructures. The other limit of a very strongly modulated potential results in separated, virtually noninteracting electron systems, i.e., quantum wires or quantum dots. Quantum-dot systems have recently been realized on different semiconductors employing various confinement schemes.[4-10] In this Letter we report on the electrostatic generation of quantum dots such that the coupling strength between dots can be tuned by the applied gate voltage. We present far-infrared investigations that show new features in the excitation spectrum in the regime of gate voltages where isolated quantum dots transform into an electron mesh of connected dots. We demonstrate that the onset of these features reflects the competition between electrostatic confinement and magnetic-field-induced delocalization. The experimental observations can be explained by both a billiard-type trajectory model and a tunneling model of coupled dots.

The samples are grown by molecular-beam epitaxy. On a semi-insulating substrate the following are deposited: a 200-nm short-period superlattice (SPS) consisting of 2.5-nm GaAs and 2.5-nm AlAs layers, a 2.5-nm layer of δ-doped GaAs, a 20-nm SPS spacer, a 50-nm GaAs quantum well, a 20-nm SPS spacer, 2.5-nm Si δ-doped GaAs, and a 50-nm SPS cap layer. A $4\times5\text{-mm}^2$ large piece of the wafer is cut and wedged to avoid interference phenomena in the far-infrared measurements. Small pads of an In-Ag alloy are evaporated at the edges of the sample and diffused for 2 min at 420 °C to serve as Ohmic contacts to the two-dimensional electron gas. 5×10^7 photoresist dots of 200 nm diam forming a cross-grating of period $a=450$ nm are defined using holographic lithography. An evaporated layer of 10-nm NiCr serves as a modulated transparent gate that is used to deplete the electrons around the dots.[3] Illuminating the sample at liquid-helium temperatures creates a bypass in the doped GaAs below the well which serves as a back contact when depleting the electrons in the well. This is essential, since without a back contact the problem arises that as the regions around the dots become depleted electrical contact to large areas of the sample is lost and the electron density can no longer be tuned.[11]

To characterize the electronic properties of such a quantum-dot array we study the far-infrared excitation spectrum with a Fourier-transform spectrometer. The sample is cooled to 2 K in the center of a superconducting solenoid with the direction of the magnetic field parallel to the surface normal. Figure 1 shows transmission spectra of the sample at various magnetic fields and a gate bias V_g at which the electron system consists of isolated dots containing about $N_0=50$ electrons each. At magnetic field $B=0$ a dimensional resonance is visible as a minimum in the normalized transmission at 33 cm^{-1}. With increasing magnetic field this resonance splits into a bulklike mode that approaches the cyclotron resonance in high magnetic fields and an edge mode decreasing in frequency with increasing field. Such a behavior is characteristic for electron systems confined in all three spatial dimensions. We can also deduce that isolated dots have formed at gate bias $V_g=-3.1$ V from

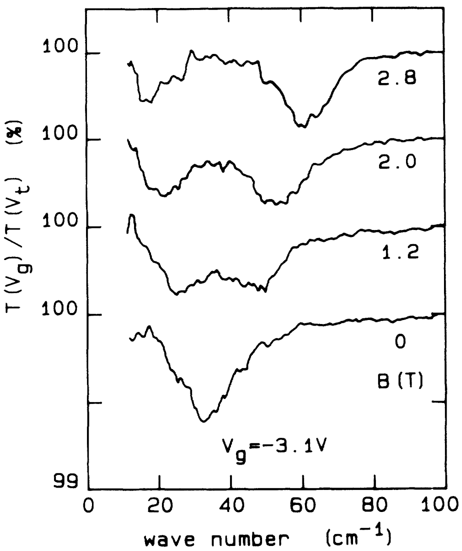

FIG. 1. Transmission spectra of isolated quantum dots normalized by the transmission at threshold voltage V_t at which the dots are fully depleted. The dimensional resonance that is visible at magnetic field $B=0$ as a minimum in transmission at 33 cm^{-1} splits into a high-frequency bulk and a low-frequency edge mode with increasing B. Here about fifty electrons per dot occupy approximately seven quantum levels at $B=0$.

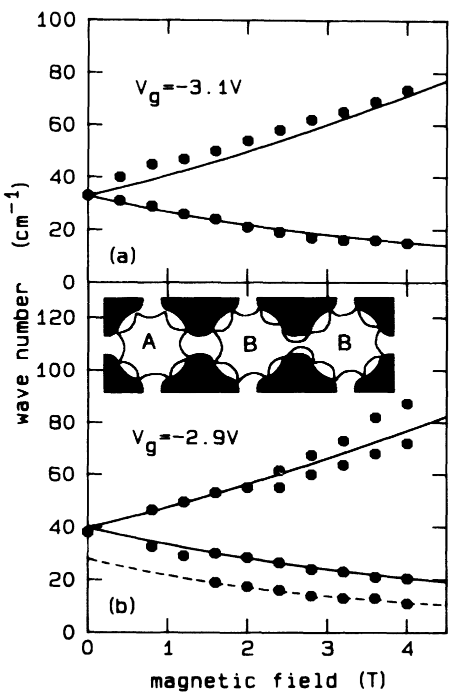

FIG. 2. Measured resonance positions as a function of the magnetic field for (a) isolated and (b) connected quantum dots. The solid lines reflect the dispersion of Eq. (1). Coupled dots show additional modes. Inset: Trajectories responsible for the upper- (A) and the lower- (B) frequency edge modes. The dashed line gives the dispersion expected for a type-B edge mode.

capacitance-voltage measurements. The average number of electrons per dot can be extracted from fits to the cyclotron resonance at high magnetic fields and magnetocapacitance studies.[4,6]

The resonance positions for traces such as in Fig. 1 are summarized in Fig. 2(a) for the same gate voltage. The solid lines are calculated with the following equation that can be derived from electrodynamics,[12] classical mechanics,[13] and quantum mechanics[14] and holds for mesoscopic electron disks[12] as well as for quantum dots:

$$\omega_\pm = (\omega_0^2 + \omega_c^2/4)^{1/2} \pm \omega_c/2 . \tag{1}$$

Here ω_c is the cyclotron frequency and ω_0 is the resonance frequency at $B=0$. The upper mode is not very well described using $\omega_0 = 33$ cm^{-1} and for $B > 1$ T rather follows Eq. (1) with $\omega_0 = 37$ cm^{-1}. Such a behavior of the bulk mode has also been observed for electron disks on liquid He (Ref. 15) and can be attributed to the fact that the confining potential of dots is not perfectly parabolic as assumed in deriving Eq. (1) and rather softens towards the edges. Measurements on silicon metal-oxide-semiconductor field effects where the shape of the confining potential can electrostatically be tuned support such a picture.[10]

The single-particle energy-level spacing $\hbar\omega_{sp}$ can be calculated for a parabolic potential from

$$\hbar\omega_{sp} = 2\hbar^2(n+1)/m^* r_F^2 , \tag{2}$$

with m^* being the effective mass, r_F the radius of the electron orbit at the Fermi energy, and n the quantum number of the highest occupied level ($n \cong 6$ for $N_0 = 50$). If we assume $r_F = 100$ nm agreeing with the geometric size of the dots, Eq. (2) results in a level spacing of 1.6 meV. This is comparable to $\hbar\omega_{sp}$ derived for quantum wires of similar confinement and electron density[16,17] and accounts for about 40% of the observed resonance energy $\hbar\omega_0$. For parabolic confinement $\hbar\omega_{sp}$ reflects the level spacing in the screened potential whereas $\hbar\omega_0$ is understood as the characteristic energy of the bare potential.[18] Alternatively, $\hbar\omega_0$ can be expressed as a combination of single-particle and collective contributions $\hbar\omega_D$ as $\omega_0^2 = \omega_{sp}^2 + \omega_D^2$. We thus conclude that single-particle and collective effects are of comparable size for the dots studied here.

The large tunability of our device enables us to study the transition from isolated to strongly coupled quantum dots by simply changing the applied gate voltage. Capacitance measurements show that at $V_g = -2.7$ V the dots are still electrically connected, although there are already voids in the two-dimensional electron gas such that an electron mesh has formed. In the following we wish to concentrate on the gate-voltage regime where the transformation takes place from an electron mesh to a system of isolated dots. Figure 3 displays spectra taken

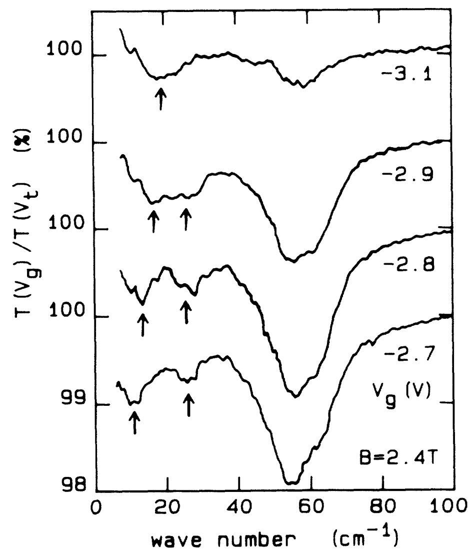

FIG. 3. Transmission spectra at $B=2.4$ T for different gate voltages. Two edge modes appear (arrows) as the bias is increased such that the dots couple to form an electron mesh. A shoulder appearing on the high-energy side of the bulk mode is identified as a magnetoplasmon.

at $B=2.4$ T for various gate voltages in this regime. At $V_g=-2.7$ V the edge mode is split into two that merge as the bias is changed to -3.1 V, i.e., as the dots become decoupled. The bulk mode ω_+ centered at about 60 cm^{-1} rapidly loses strength with decreasing bias. For the coupled dots ($V_g \geq -2.9$ V) and $B=2.4$ T an additional resonance becomes apparent as a shoulder on the high-energy side of ω_+. This resonance shifts away from the ω_+ mode as the magnetic field is increased.

Figure 2(b) summarizes the resonance positions at a gate potential $V_g=-2.9$ V where we have well defined but already strongly coupled electron dots. With increasing magnetic field we observe additional branches close to the ω_+ and ω_- branches that appear at about 2 and 1 T, respectively. From the electron number per unit area N_0/a^2 we can estimate a local electron density $N_s \cong 2N_0/a^2 \cong 1.6\times10^{11}$ cm^{-2}. At $B=2$ T this corresponds to a classical cyclotron diameter at the Fermi energy of $2R_c=2(2\pi N_s)^{1/2}(\hbar/eB)\cong 70$ nm. This is comparable to the width of the constriction that connects adjacent dots in the situation realized experimentally. As long as $2R_c$ is larger than this constriction the system is expected to behave similarly to an array of isolated dots as is observed experimentally in low fields. As $2R_c$ becomes smaller then the constriction electrons on bulklike orbits can communicate between adjacent dots. Then the periodic configuration of the electron mesh should make it possible to excite "two-dimensional" magnetoplasmons.[19,20] This is, in fact, what we observe in the experiment. To unambiguously identify the highest-lying mode ω_{++} in Fig. 2(b) the large tunability of the sample is of great advantage. Since the entire range between a two-dimensional electron gas ($V_g=0$ V) and an electron mesh ($V_g=-2.9$ V) is accessible in the experiment, it is possible to study how the cyclotron resonance and the magnetoplasmon develop with decreasing bias. We observe that in magnetic fields where the ω_{++} mode has established it develops out of the magnetoplasmon with decreasing bias whereas the ω_+ mode develops out of the cyclotron resonance. In magnetic fields >5 T where $2R_c$ is very small compared to the width of the constriction we observe that the highest mode follows a dispersion relation $\omega_{++}^2=\omega_p^2+\omega_+^2$, with ω_p the plasmon frequency similar to the two-dimensional magnetoplasmon dispersion.[19]

Figure 3 shows that the edge mode persists even for relatively high bias. This indicates that the edge charge can still move on the perimeter of the dots though the dots are already connected. In addition, we observe a second edge mode at lower frequencies. This additional mode is lower in frequency than the fundamental ω_- mode that merges with the ω_+ mode at $B=0$. Hence it should not be mistaken for higher harmonics of the ω_- mode that have been observed for electrons on liquid He (Ref. 15) and in etched GaAs quantum dots.[9] In a classical picture of edge modes in sufficiently high magnetic fields, the charge moves along boundaries and the mode frequency is determined by Eq. (1) taking $\omega_0^2 \propto 1/p$, with p the dot perimeter. We therefore identify the new edge mode as a charge moving along a boundary of about twice the length of the perimeter of an isolated dot. This is supported by the magnetic-field dependence calculated for such a mode [dashed line in Fig. 2(b)]. Thus a charge moving along a peanut-shaped orbit enclosing two dots as indicated in the inset of Fig. 2(b) explains the second observed edge mode. Such an orbit needs only two transmission events through a constriction and therefore appears the most likely involving more than one dot. The observation that the development of a second edge mode takes place at much lower magnetic fields than the splitting of the bulk mode is consistent with the picture of a charge moving along the edge on "skipping orbits." On a skipping orbit electrons can pass the constriction between adjacent dots even if $2R_c$ is larger than the width of the constriction.

The branching of the bulk mode and the appearance of an additional edge mode can be equally explained by coherent transmission through the narrow constriction connecting adjacent dots and magnetic breakdown of the barrier imposed by the constriction. Then the spectrum can be understood in a similar fashion as that of a two-dimensional electron system under the influence of a one-dimensional periodic potential.[21] In such a picture the development of the splitting with increasing bias as shown in Fig. 3 becomes clear as a lifting of the degeneracy of the electronic levels in adjacent dots as the coupling becomes stronger. Thus the far-infrared spectra directly reflect the strong coupling of adjacent dots in an electron mesh.

In conclusion, we have prepared quantum dots with variable interaction strength and investigated the far-infrared transmission spectra at low temperatures. For isolated quantum dots in a magnetic field an edge mode (ω_-) and a bulk mode (ω_+) are observed as expected. For strongly interacting dots new spectral features become apparent: An additional edge mode at frequencies lower than ω_- develops and the bulk mode branches into a cyclotron-resonance-like and a magnetoplasmonlike mode. These features display the transition from isolated dots to an electron mesh quite similar to the transition from atoms to molecules or from atoms to a solid state. The former is manifested in the appearance of an edge mode enclosing two adjacent dots; the latter in the formation of a collective excitation, the magnetoplasmon.

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