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Invited

Spectroscopy of Quantum Dots and Antidots

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We review the preparation of semiconductor microstructures, quantum dots and antidots, and their investigation by far infrared spectroscopy. This gives us important inside into the potentials and energy spectrum of the devices. The recent achievement is that one can realize quantum dots with very small well defined numbers of electrons, N = 1,2,3.. which are reproducible controlled by a gate voltage. The reason for this one-by-one control of the electrons is the high Coulomb charging energy which is inherent to these small devices.

1. INTRODUCTION

Novel and unique properties of layered two-dimensional semiconductor structures with quantum confined energy states have challenged scientists to prepare and study systems with further reduced dimensionality. In these systems the original free dispersions of the electrons in the lateral directions are also quantized due to an additional lateral confinement. One ultimate limit is a quantum dot, where, induced by a confining potential in both the x- and y-directions, artifical 'atoms' with a totally discrete energy spectrum, are formed.[1-6] (The growth direction is labeled z in the following.) A reversed structure with respect to dots are 'antidots' where 'holes' are 'punched' into a two dimensional electron system (2DES).[7-10] Typical confinement energies are in the few-meV regime. Thus the most direct information on the quantum confined energy levels in these low-dimensional systems should be obtained by investigation of optical transitions with far-infrared (FIR) spectroscopy. In this extended abstract I can only give a very brief overview. For more information and references I refer to the original papers and recent extended review articles, for example in Ref.[11].

2. PREPARATION OF QUANTUM DOTS

Two examples of quantum dot structures, which were prepared starting from modulation-doped $AlGaAs - GaAs$ heterostructures, are sketched in Fig. 1. For the 'deep-mesa-etched' quantum dots in Fig. 1a an array of photoresist dots (with a period of $a = 1000nm$ both in the x- and y-direction) was prepared by a holographic double exposure.[2] Using an anisotropic plasma etching process, rectangular $200nm$ deep grooves were etched all the way through the $GaAs$ cap layer, the Si-doped $AlGaAs$ layer, and the undoped $AlGaAs$ spacer layer into the active $GaAs$, leaving quadratic dots with rounded corners and geometrical dimensions of about $600 \times 600nm^2$.

Field effect confined quantum-dot samples are sketched in Fig. 1b. They have been prepared starting from $Al_{0.32}Ga_{0.68}As-GaAs$ heterostructures grown by molecular beam epitaxy. A Si δ-doped layer in the $GaAs$, deposited at a distance of 330 nm from the $AlGaAs$-$GaAs$ interface, acts as a back contact to charge the dots. On top of the heterostructure we prepared a periodic photoresist dot array by holographic lithography. The periods ranged from $a = 500nm$ down to 200 nm and the lateral photoresist dot sizes were about half the period with a height of about 100 nm. An semitransparent $NiCr$ gate of 4 mm diameter was evaporated onto the photoresist structure. With a negative gate voltage we could confine the electrons under the photoresist dots and vary the number of electrons.

SPECTROSCOPY OF QUANTUM DOTS

We address in particular experiments[5,6] on periodic arrays of quantum dots where electrons are confined by the field effect of a laterally structured gate electrode. FIR transmission spectroscopy was carried out with a Fourier transform spectrometer and with FIR lasers in perpendicular magnetic fields B. We recorded the normalized transmission of unpolarized radiation, $T(V_g)/T(V_t)$, where V_t is the threshold voltage at which the dots are totally depleted. Experimental FIR transmission spectra for a sample with period $a = 200nm$ are displayed in Fig. 2a. At the laser frequency of $10.5meV$ (84 cm^{-1}) we observe a resonance at about $B = 6T$. The interesting observation in Fig. 2a is that the absorption amplitude does not increase in proportion

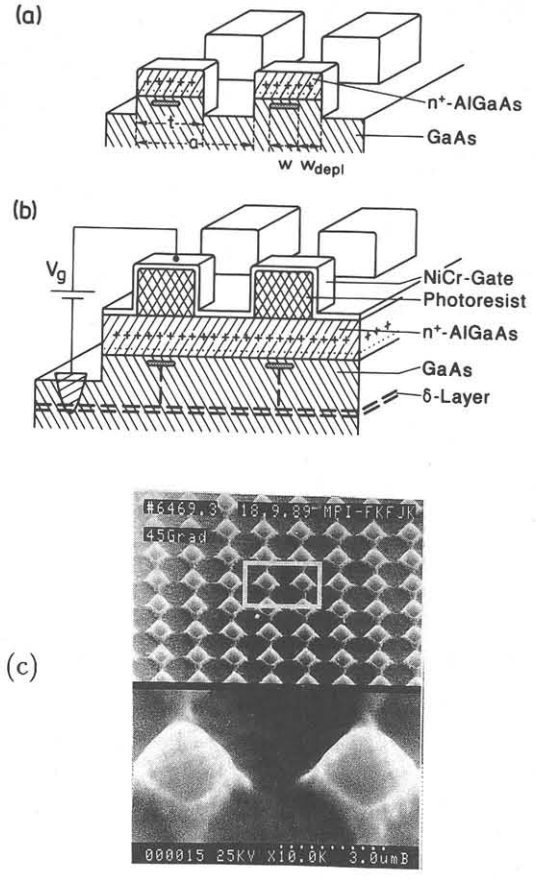

Fig. 1. Sketch of deep-mesa-etched (a) and field-effect confined (b) quantum dot arrays. In (a) a periodic pattern is etched all the way through the *AlGaAs* layer into the active *GaAs* layer. The electrons are confined in the middle of the dots by the positively charged donors in the *AlGaAs* and negatively charged surface states at the sidewalls. (b) is a so-called split-gate configuration where via a gate voltage and a varying distance between the *NiCr*-gate and the channel carriers are depleted leaving isolated quantum dots. The gate-distance modulation is achieved via a modulated photoresist layer. A low impedance δ-doped layer serves as a back contact to charge the isolated dots. (c) Electron micrograph of an array of quantum dots with geometrical dimensions of $600nm \cdot 600nm$.

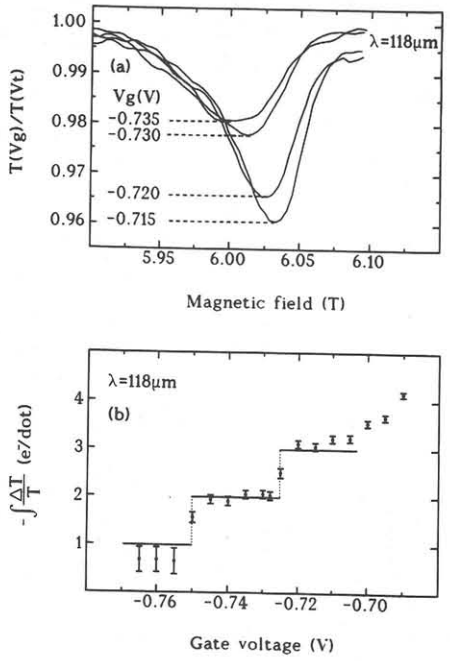

Fig. 2. (a) FIR transmission measured at a fixed laser frequency of 10.5meV at various gate voltages V_g for a quantum-dot array with period $a = 200nm$. Spectra for 3 electrons per dot ($V_g = -0.715V$ and $-0.720V$) and for 2 electrons per dot ($V_g = -0.730V$ and $-0.735V$) are shown. (b) Integrated absorption strength vs. gate voltage V_g for a series of spectra (including (a)). The step-wise increase of the absorption strength indicates the incremental occupation of the dots with N = 1, 2 and 3 e^-/dot with increasing V_g. (Error bars mark the accuracy of the fits.) The temperature is $T = 1.2K$. (From[5])

to $V_g - V_t$, rather it increases stepwise. This directly reflects that the quantum dots are occupied with a well defined small number of electrons in different V_g intervals, N =1,2,3, ... Actually we measure the transmission absolutely and since we know the matrix elements of the quantum dot transitions we can determine the number of electron directly from the signal strength.

It is surprising that for our large number of about 10^8 dots we can charge all the dots simultaneously with the same number of electrons (within the error bars given in Fig. 2b). The reason for this well defined charging behavior is the high Coulomb charging energy of the dot which we can estimate from the gate voltage intervals in Fig. 2b to be about 15 meV. This value is significantly larger than kT and ensures that Coulomb effects are not smeared out either by temperature or by potential fluctuations from impurities and related local variations of the threshold voltage in the sample. This links our experiments to another interesting topic, i.e., single-electron charging effects, which have been studied extensively in both small metallic and semiconductor systems. Another surprising observation is, on a first sight, that the spectra even for dots with several electrons are very simple, exhibiting only one resonance at $B = 0$. The reason for this is that the confining potential, which even in etched dots arises from electrostatics, has a nearly parabolic shape. Under these condition FIR dipole excitation couples only to the rigid center-of-mass motion of all electrons which one resonance frequency at $B = 0$.[12–15] However, with sophisticated technology it is also possible to produce potentials with controlled shape and distinct deviations from the parabolic potential. This allows one to couple to internal degrees of freedom in the atom and to observe various type of fine structures.[11]

3. ANTIDOT ARRAYS

A reversed structure with respect to dots are 'antidots' where 'holes' are 'punched' into a 2D electron system (2DES).[7–10] Antidot samples have been prepared by deep-mesa-etching starting from

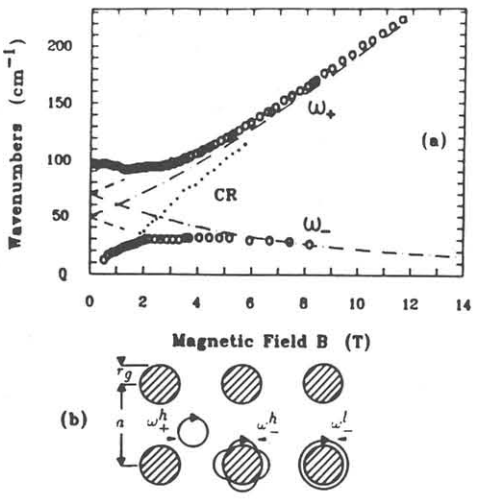

Fig. 3: (a) The experimental dispersions for an $GaInAs - AlInAs$ antidot sample with hole diameters $2r_g = 200nm$. The period is $a = 300nm$. (b) shows schematically the motions of individual electrons within the collective excitation for the high-frequency mode (ω_+^h) at high magnetic fields, and for the low-frequency mode at low (ω_-^l) and at high magnetic field (ω_-^h). The hatched areas are the geometrical holes in the original 2DES. From Ref.[10]

2DES in modulation-doped $GaInAs - AlInAs$ single quantum wells which have been grown lattice matched on semi-isolating InP substrates by molecular beam epitaxy.[10] A photoresist grid mask was prepared by a holographic double exposure and arrays of holes with typical diameters $2r_g = 100$ to $300nm$ were etched $100nm$ deep, i.e., through the active layer into the buffer. The period in both lateral directions was $a = 300nm$.

In a perpendicular magnetic field B several resonances are observed in the experimental transmission spectra. The dispersions of these resonances are shown in Fig. 3a for an antidot sample with a period $a = 300nm$, a hole diameter $2r_g = 200nm$ and carrier density $N_s = 8 \cdot 10^{11} cm^{-2}$. The excitation spectrum consists mainly of two modes, a high and a low frequency branch labeled by ω_+ and ω_-, respectively. We interprete these modes in the following way. At high B the dispersion of both branches resembles the excitation spectrum of quantum dots which we have discussed above. For dots the lower branch decreases with B in frequency and represents an edge magnetoplasmon mode at high B, the center-of-mass mode. The individual electrons of this collective mode perform skipping orbits along the inner boundary of the dot. For antidots the individual electrons within the collective excitation perform skipping orbits *around* the hole. We have sketched these orbits for high B, ω_-^h, in Fig. 3b. With decreasing B, the resonances of the low frequency branch, ω_-, first increase in frequency, but then, in contrast to dots, these resonances decrease in frequency at a certain magnetic field and approach ω_c. This arises since with decreasing B the electron orbits of the ω_--mode become larger and eventually the electrons can perform classical cyclotron orbits $r_c = \sqrt{2\pi N_s}\hbar/eB$ around a hole. Then the collective edge magnetoplasmon excitation, the skipping orbit mode, gradually changes into a classical cyclotron excitation.

4. SUMMARY

We have reviewed antidots and field-effect confined quantum-dot atoms in which a small discrete number of electrons is stabilized by a high Coulomb charging energy of 15 meV which is directly reflected in a step-like increase of the FIR absorption strength with V_g. This allows us to perform atomic spectroscopy in systems with tunable potential and gives us inside into center-of-motion and fine structures arising from relative interactions.

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