Inter-Dot Interaction in an Array of Elliptical Quantum Dots

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Abstract

We have investigated arrays of quantum dots with elliptical confinement potential on modulation-doped GaAs heterostructures. A laterally structured gate electrode allowed us to tune the system from small isolated dots to large overlapping dots. In far-infrared transmission experiments we find that the frequency gap between the two resonances with orthogonal linear polarization, which exist in elliptical dots, first decreases and then, very surprisingly, increases again.

71.45.Gm,78.55.Cr,78.66.-w

The dynamic far-infrared (FIR) response of circular and elliptical quantum dots, with parabolic external potential, consists in a magnetic field B of two modes, ω_+ and ω_- . In elliptical quantum dots the rotational symmetry is broken and the degeneracy of the ω_+ and ω_- modes at $B = 0$ T is lifted. Here two modes, $\omega_+(B = 0) = \omega_x$ and $\omega_-(B = 0) = \omega_y$, are observed with orthogonal linear polarization. The resonance frequencies of these modes can be described in the model of Eliasson et al. for confined plasmons[1]. In this model $\omega^2_{x(y)}$ is given by

$$\omega^2_{x(y)} = \frac{N_S e^2}{2m^*\epsilon^*\epsilon_0} \cdot \frac{\pi}{w_{x(y)}} \tag{1}$$

where $w_{x(y)}$ is the electronic width of the confinement in the x (y) direction, N_S the electron density, and respectively, m^* and ϵ^* the effective mass and dielectric constant of the medium. The modes ω_x and ω_y are plasma oscillations in respectively, x and y direction, where the q vector is quantized by the width of the electronic confinement to $q_{x(y)} = \pi/w_{x(y)}$. An important consequence of the orthogonality of the plasma oscillations is that the two resonance modes can be distinguished by linearly polarized measurements, which will be demonstrated later.

For noninteracting elliptical quantum dots with parabolic confinement potential in an external magnetic field the dispersion of the resonances in is given by[2,3]:

$$\omega^2_\pm = \frac{1}{2}\left(\omega_x^2 + \omega_y^2 + \omega_c^2 \pm \sqrt{\omega_c^4 + 2\omega_c^2(\omega_x^2 + \omega_y^2) + (\omega_x^2 - \omega_y^2)^2}\,\right). \tag{2}$$

$\omega_c = eB/m^*$ is the cyclotron frequency.

In an array of quantum dots, effects due interaction between dots (inter-dot interaction) can be expected if the distance to adjacent dots is small. An interesting point is that in an array of, particularly, elliptical quantum dots, a theory beyond the model of Ref.[1] predicts that inter-dot interaction leads to a frequency shift of these modes[4]. Such inter-dot interaction has so far only been observed for adjacent large, 20-micron-size, 2D-electron disks in microwave experiments[5].

Quantum-dot arrays were prepared from modulation-doped $Al_{0.33}Ga_{0.67}As$-GaAs heterostructures with a heterostructure interface-to-surface distance of 60 nm. A Si-δ doped layer was grown 300 nm underneath the AlGaAs-GaAs interface and served as a backgate to charge the quantum dots. The electron density and mobility at 1.8 K were $N_S = 3.4 \cdot 10^{11}$ cm^{-2} and $\mu = 270\,000$ cm^2/Vs, respectively. An array of elliptical photoresist dots was prepared by holographic lithography onto the sample surface. The elliptical shape of the resist dots was achieved by performing a double exposure with an in between 90° rotation of the sample and different exposure times in x and y direction. The result is a quadratic array of elliptical dots. The ratio of the geometrical widths was $w_{y,g}/w_{x,g} \approx 1.2$ and the period of the array was $a = 810$ nm. A 7 nm semitransparent Ti gate with 3 mm diameter was evaporated onto the photoresist dot array. The gate voltage was applied between the top-gate and the δ-doped backgate. The experiments were performed using a Fourier transform spectrometer. We show in the following the normalized transmission $T(V_G)/T(V_T)$, where V_T is the threshold value at which the electron system is totally depleted. The spectral resolution was set to 1 cm^{-1} and the temperature was 1.8 K.

Experimental spectra for a strong negative gate voltage ($V_G = -0.6$ V) at low magnetic fields are shown in Fig. 1. Clearly a double peak structure is observed at $B = 0$ T. With increasing B the energetically higher resonance increases in frequency whereas the lower decreases. The magnetic-field dispersions of the resonance peaks are plotted in Fig. 2 (a). The data is well described by a calculation for elliptical dots with parabolic confinement according to eq. 2, represented by the solid lines, with ω_x and ω_y as fit parameters. Here we find the relation $\omega_x^2/\omega_y^2 \approx w_{y,g}/w_{x,g} \approx 1.2$, where $w_{x,g}$ and $w_{y,g}$ are the geometrical widths of the elliptical gate structure extracted from SEM images. For a less negative gate voltage, $V_g = -0.4$ V, the dispersion is shown in Fig. 2 (b). Surprisingly, here in unpolarized measurements, only one peak at $B = 0$ T is observed. Moreover, an anticrossing of the ω_+ mode around $B = 1$ T with a another weak resonance, which decreases in energy with increasing B, occurs. Such a behavior has been reported by Demel et al.[6] in arrays of deep-mesa etched quantum dots and theory showed that this anticrossing originates from the quadratic shape[7,8] . Most interestingly, for an even weaker confinement potential at a gate voltage $V_g = -0.34$ V (see Fig. 2 (c)) the frequency gap between the two modes at $B = 0$

T increased again and the magnetic-field dispersion can well be fitted with a calculation for elliptical dots.

In Fig. 3 the gate voltage dependence of the resonances at $B = 0$ T is displayed. In the regime from -0.6 V $\leq V_G \leq -0.34$ V the frequency gap between the two resonances first decreases to nearly zero (at $V_G \approx -0.45$ V) and then increases again. How can this peculiar behavior be understood? Linearly polarized measurements show that for all gate voltages the energetically higher excitation is polarized in x direction (see the SEM image in the inset) and the energetically lower in y direction. This shows that no rotation of the ellipse out of some electrostatic reason takes place. Thus the actual geometrical shape of the dots must be deformed by some interaction with their neighbors in dependence of the gate voltage.

To confirm this explanation we have performed calculations of the electron density distribution in the ground state for a quadratic array of elliptical quantum dots. Calculations for an array of noninteracting dots show that the ratio w_x/w_y is not affected significantly with increasing number of electrons per dot. The results including interaction in the local spin-density approximation are shown in Fig. 4. Here we see that for very small numbers of electrons per dot the elliptical shape of the dot is first enhanced but then with further increasing electron number the dot size increases more strongly to the sides and the shape becomes more square-symmetric. The latter behavior corresponds qualitatively very well to the experimental observations in the gate voltage regime displayed in Fig. 2 (a) and (b). Therefore we conclude that the decrease of the gap between the ω_+ and ω_- modes at $B = 0$ T results from Coulomb interaction between the dots in the array (inter-dot interaction).

The increase of the gap towards weaker confinement (in the regime -0.45 V $\leq V_G \leq -0.34$ V) could be explained by the dynamic inter-dot interaction calculated by Taut[4] for arrays of quantum dots with effective parabolic potential. This theory predicts a blueshift of the ω_+ and a redshift of the ω_- mode due interaction between dots, qualitatively in agreement with our findings. A quantitative comparison yields that this interaction effect should not be observable in an array with $a = 800$ nm and N in the range of 80-200.

However, in the gate voltage regime around $V_G = -0.34$ V it is reasonable to assume that the confinement potential far away from the center of the dots to be much weaker than parabolic. Together with a high enough electron density this leads to a very small distance between adjacent dots for which also strong interaction effects can be expected.

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FIGURES

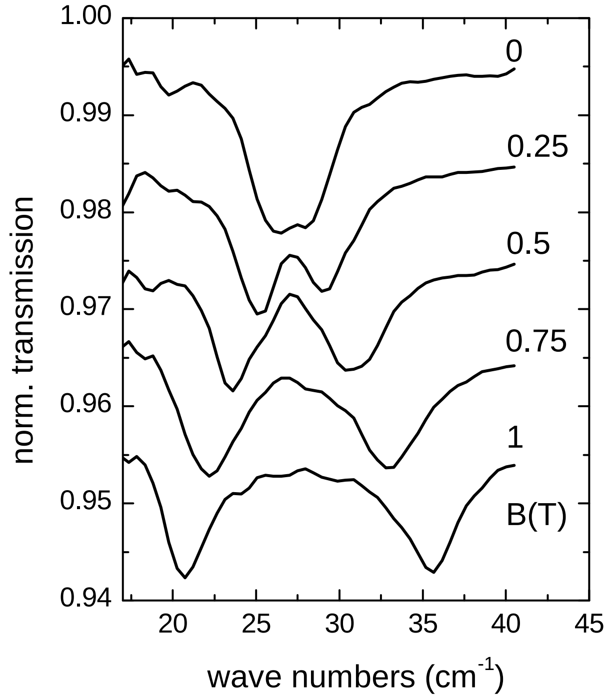

FIG. 1. Experimental transmission spectra of an array of quantum dots with elliptical confinement potential at $V_G = -0.6$ V for different B. The spectra are shifted vertically for clarity. At $B = 0$ T for unpolarized radiation clearly a double peak structure is observed.

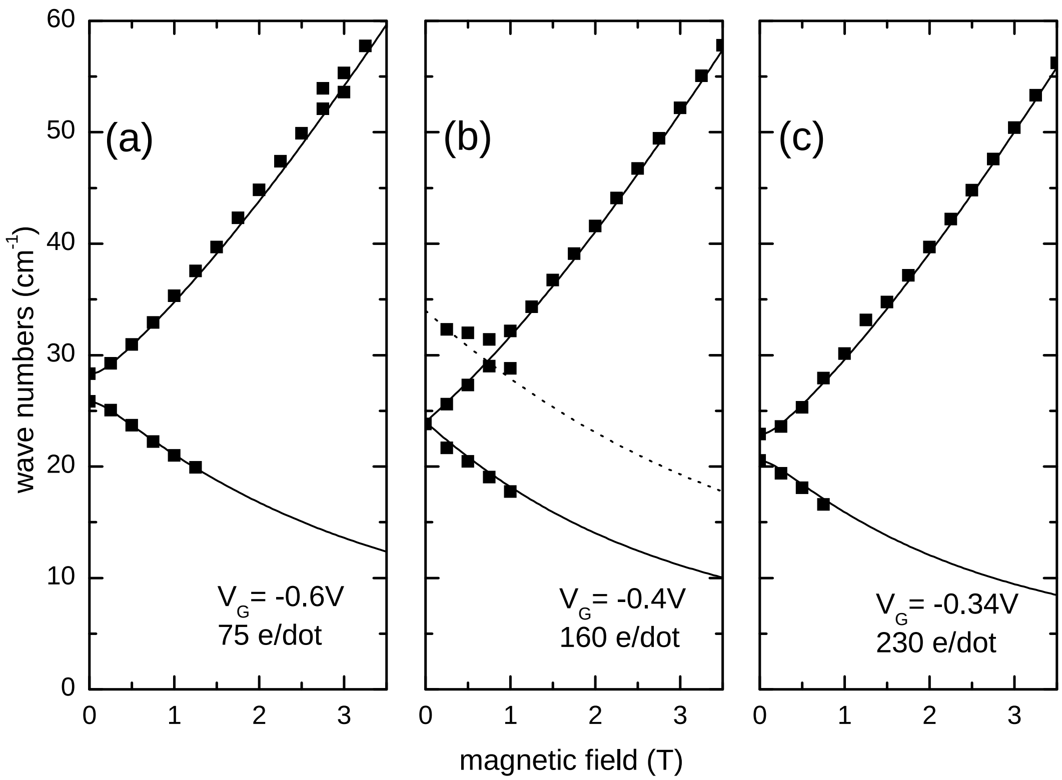

FIG. 2. Resonance frequency versus B for three different V_G (full symbols). The solid lines show a calculation according to eq. 2 with $\omega_{x(y)}$ as fit parameters. (a) $V_G = -0.6$ V: strong confinement. (b) $V_G = -0.4$ V: weaker confinement. (c) $V_G = -0.34$ V: at weak confinement the energy gap between the resonances at $B = 0$ T reoccurs.

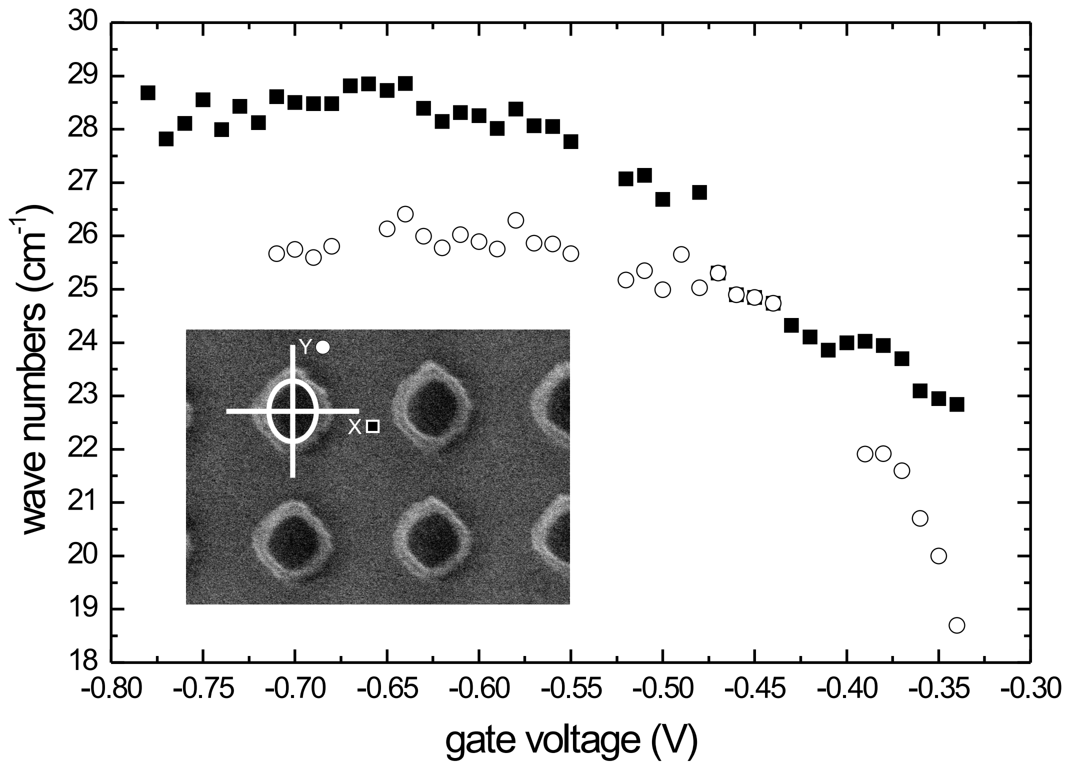

FIG. 3. Resonance frequency versus gate voltage at $B = 0$ T. The inset shows a SEM picture of the structured gate electrode. Full (open) symbols polarization along the short (long) axis.

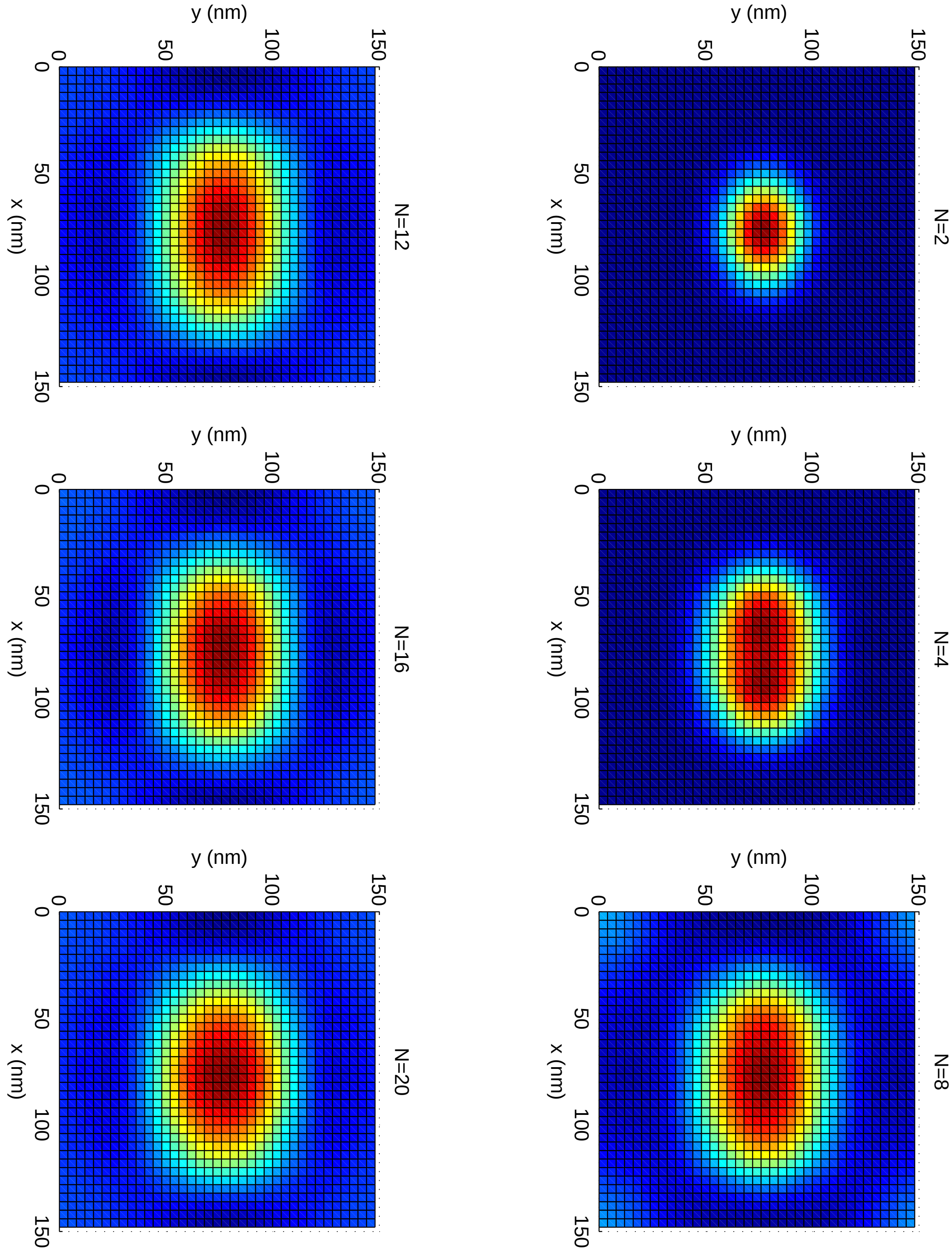

FIG. 4. Calculated electron density distribution for the ground state of interacting elliptical dots in a quadratic array at $B = 1.47$ T.

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