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LETTER TO THE EDITOR

# Magneto-optics and magneto-capacitance studies of voltage-tuneable GaAs/AlGaAs quantum dots

D D Arnone†, T J B M Janssen§, N K Patel†, M Pepper†‡, J A A J Perenboom§, D A Ritchie†, J E Frost† and G A C Jones†

† Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

§ High-Magnetic-Field Laboratory, University of Nijmegen, Holland

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**Abstract.** An array of quantum dots has been defined in a GaAs/AlGaAs two-dimensional electron gas (2DEG). The array allows both far-infrared (FIR) transmission (i.e. cyclotron resonance (CR)) and magneto-capacitance (analogous to Shubnikov–de Haas SdH) measurements to be made on the same sample *in situ*. CR measurements permit the quasi-zero-dimensional resonant energy ($\omega_0$) associated with the confining potential to be mapped as a function of gate voltage ($V_g$). Magneto-capacitance investigations allow the carrier density to be obtained as the dots are formed. The amplitude of the magneto-capacitance oscillations decreases dramatically for $V_g \leqslant -0.3$ where the 2DEG transforms into an array of isolated quantum dots. Accompanying this reduction of amplitude is an absence of CR-like absorption peaks in the FIR spectrum at low magnetic fields. The possible origin of this behaviour is discussed in terms of the competition between edgelike and bulklike states.

Voltage-tuneable quantum dots [1–4], which allow the confining potential and/or the number of electrons per dot to be varied *in situ* in a controlled manner, have recently acquired increased importance because of the current interest in single-electron charging of mesoscopic systems [5,6]. Because effects such as Coulomb blockade are superimposed upon zero-dimensional (0D) energy resonances in these dots, measuring and understanding these resonances are important. The current investigation therefore seeks to demonstrate how the combination of CR and capacitive SdH-like measurements may be used to obtain a more comprehensive picture of the 0D electron energy levels in an array of voltage-tuneable quantum dots, as well as better understanding of the extent to which these levels may be associated with edgelike and bulklike states in the presence of magnetic field.

The structure used is similar to that of Patel *et al* [4] and is illustrated schematically in figure 1. Figure 1. shows a cross section of the heterostructure which consists of a high mobility 2DEG at the AlGaAs/GaAs interface, and a lower mobility Si $\delta$-doped conducting layer 400 mm below the top 2DEG. This $\delta$-doped layer serves as a back contact which remains continuous even when bias is applied to the gate. This layer can therefore be used as a ground plate relative to which the gate bias is applied,

‡ Also at Toshiba Cambridge Research Centre, 260 Cambridge Science Park, Milton Road, Cambridge CB4 4WE, UK.

 

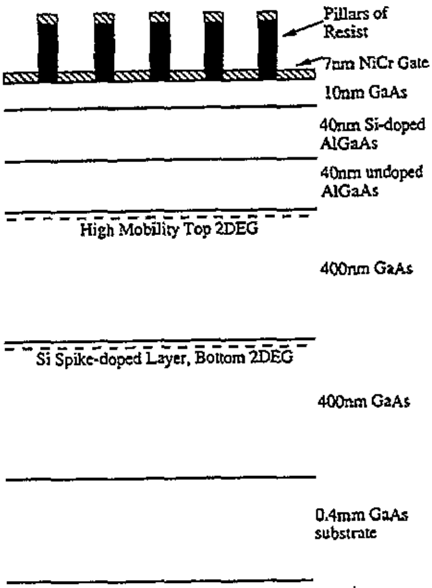


**Figure 1.** Cross section of the structure.

allowing for the electrostatic squeezing necessary to define the dots and permitting the capacitance of the structure to be measured. Because the $\delta$-doped layer is also transparent to FIR radiation, both FIR transmission and capacitance measurements are possible. Ohmic contacts were formed with NiAuGe annealed sufficiently to make contact to both 2DEGs. At 1.5 K after illumination, the carrier concentration $N_s$ and mobility $\mu$ of the top 2DEG were $1.9\times10^{11}$ cm$^{-2}$ and $1\times10^{6}$ cm$^{-2}$ V$^{-1}$ s$^{-1}$ respectively, while these values were $2\times10^{12}$ cm$^{-2}$ and $\leqslant1\times10^{4}$ cm$^{-2}$ V$^{-1}$s$^{-1}$ for the $\delta$-doped layer. The dots were 600 nm $\times$ 1200 nm, and a period of $\sim$1640 nm was used. All measurements were carried out at $\sim$450 mK and in perpendicular magnetic field when it was applied.

Cyclotron resonance measurements were carried out at two FIR laser frequencies, namely $\omega_{FIR}$ = 7.61 meV and $\omega_{\rm FIR}$ = 2.64 meV (all frequencies are quoted in energy units). Significant differences occur between the CR spectra at these frequencies. This is illustrated in figure 2 where CR spectra are presented for $\omega_{\rm FIR}$ = 7.61 meV (figure 2(*a*)) and for $\omega_{\rm FIR}$ = 2.64 meV (figure 2(*b*)) at various gate voltages. The important difference between the two spectra is the dip in transmission (denoted by $\omega_+$ in figure 2(*a*)) at $B$ = 4.49 T that appears at gate bias $V_g$ = $-$0.3 V in the $\omega_{\rm FIR}$ = 7.61 meV spectrum. Figure 2(*a*) shows that the magnetic field at which this new absorption peak appears falls with decreasing bias $V_g$. No new absorption peaks of this type appear in the $\omega_{\rm FIR}$ = 2.64 meV CR spectrum in figure 2(*b*). These observations are independent of the linear polarization of the incident FIR radiation.

Figure 3 shows the capacitance and resistance characteristics of the device as a function of gate bias $V_g$. The AC capacitance measurements were made between the NiCr gate and one of the ohmic contacts, whereas the AC resistance measurements were made between ohmics on opposite sides of the mesa. The top 2DEG is seen to completely deplete at $-$0.36 V, whereas the capacitance falls quite sharply between $-$0.3 V and $-$0.44 V. The dots thus become electrically isolated at $-$0.36 V.

As shown by Smith *et al* [7], the magneto-capacitance of the 2DEG in a GaAs/AlGaAs heterostructure is related to the density of states; oscillations in the capacitance are observed as a function of magnetic field, similar in some respects

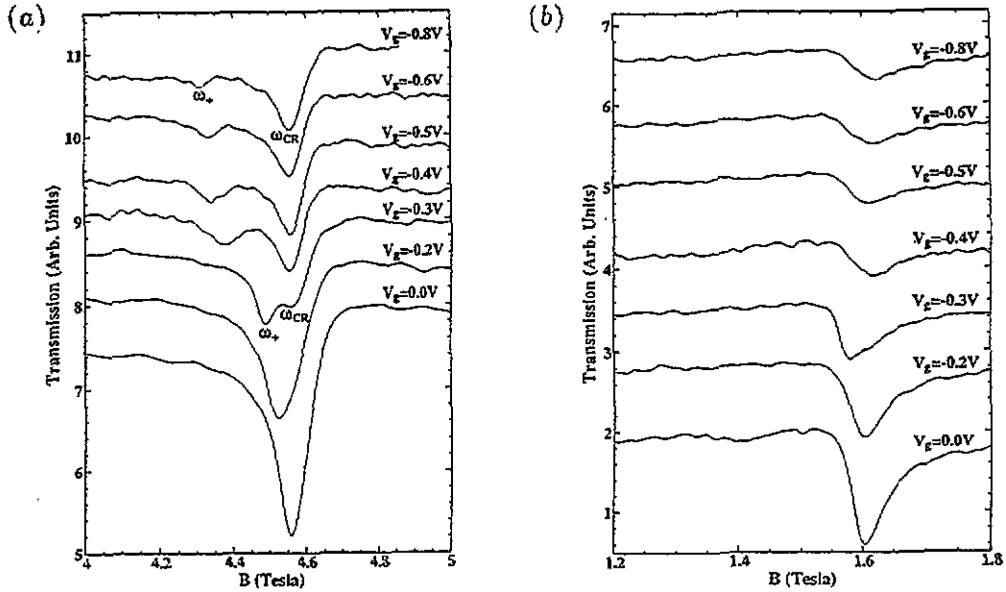


**Figure 2.** A comparison between cyclotron resonance spectra at laser frequencies (*a*) $\omega_{\mathrm{FIR}}$ = 7.61 meV and (*b*) $\omega_{\mathrm{FIR}}$ = 2.64 meV. Spectra at the various gate biases $V_g$ are offset for clarity. In (*a*) $\omega_+$ designates the high-frequency branch of equation (1) and $\omega_{\mathrm{CR}}$ denotes the absorption at the cyclotron frequency. $\omega_+$ and $\omega_{\mathrm{CR}}$ are marked at $V_g$ = −0.3 V and $V_g$ = −0.8 V to emphasize the evolution of these modes with gate bias.

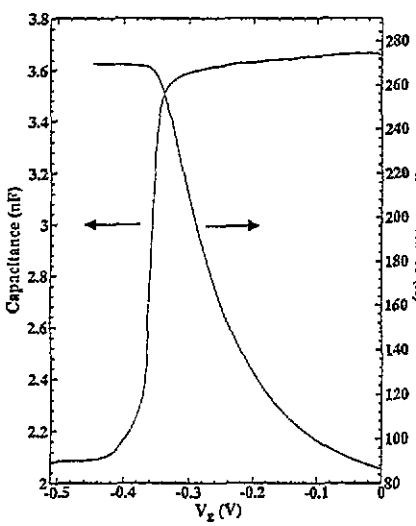


**Figure 3.** Capacitance and resistance of the sample as a function of gate bias $V_g$.

to SdH oscillations in the longitudinal conductivity $\sigma_{xx}$. Such oscillations in the capacitance have been observed in our device and are shown at various gate biases $V_g$ in figure 4. For $V_g$ = 0.0 V our oscillations resemble those observed in [7] for an unmodulated 2DEG. As $V_g$ decreases however the oscillations in capacitance shift down in field, corresponding to a decrease in carrier density as the 2DEG becomes more heavily modulated. Plotting the filling factor $\nu$ versus $1/B$ allows the carrier

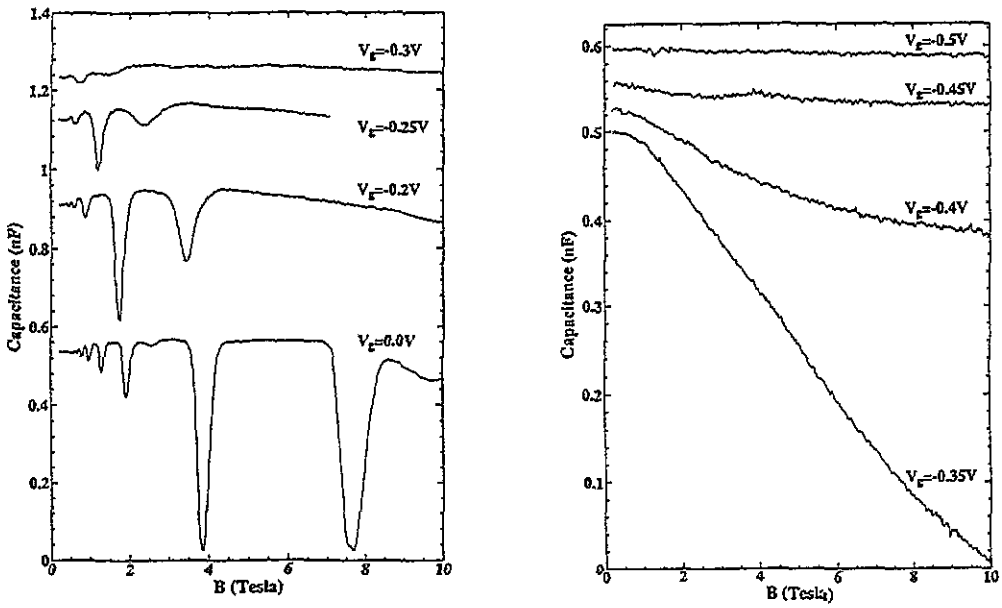


**Figure 4.** Magneto-capacitance of the sample at various gate biases $V_g$. Traces at the different biases are offset for clarity.

density at a given $V_g$ to be determined, the results being summarized in table 1. The amplitude of the oscillations in figure 4 is seen to fall with decreasing gate bias, a dramatic reduction occurring at $V_g = -0.3$ V, until at $V_g = -0.35$ V they disappear and the capacitance is seen to decrease with increasing magnetic field. $V_g = -0.35$ V is approximately the bias at which the dots become electrically isolated. At $V_g = -0.45$ V a dip in the capacitance occurs near $B = 2.4$ T which is broad and weak but nevertheless reproducible, whereas at lower $V_g$ the capacitance remains constant as a function of magnetic field up to 10 T. The oscillation at $V_g = -0.45$ V could be attributed to a Landau level in the $\delta$-doped layer, but this seems unlikely in view of the low mobility of the layer. In addition, the oscillation disappears below $V_g = -0.45$ V, indicating that it is a function of gate bias. We therefore associate the oscillation with a Landau level in the top 2DEG.

To analyse the results above, consider first the absorption peak that appears at $V_g \leqslant -0.3$ V in the $\omega_{FIR} = 7.61$ meV spectra of figure 2(*a*). Such a peak has associated with it a resonance energy $\omega_0$ at $B = 0$ which, in magnetic field, yields two modes $\omega_\pm$ [1,2]

$$\omega_\pm = \sqrt{\omega_0^2 + (\omega_{CR}/2)^2} \pm \omega_{CR}/2 \qquad (1)$$

where $\omega_{CR} = \hbar eB/m^*$ is the cyclotron energy for electron effective mass $m^*$ and $\omega_0$ is attributed to a resonance arising as a consequence of the quasi-zero-dimensional confinement. When probed using FIR spectroscopy, the measured resonance involves collective excitations of all the electrons in the dot [8], so that the absorption can be considered to be that of a plasmon localized in the dot [9]. $\omega_+$ is ascribed to a bulklike mode that approaches the cyclotron resonance in high magnetic field, and $\omega_-$ is an edge mode decreasing in frequency with increasing field [2,3]. Attempts to

**Table 1.** Carrier density, Fermi energy, and resonance energy $\omega_0$ as a function of gate voltage. $\omega_0$ are derived from cyclotron resonance spectra at the laser frequency $\omega_{\rm FIR}$ = 7.6 meV using the $\omega_+$ branch of equation (1).

| Gate bias $V_g$ (Volts) | Carrier density ($\times 10^{11}$ cm$^{-2}$) | Fermi energy $E_F$ (meV) | $\omega_0$ ($\pm$0.20 meV) |
|---|---|---|---|
| 0.0 | 1.89 | 6.52 | — |
| −0.1 | 1.40 | 4.83 | — |
| −0.15 | 1.12 | 3.86 | — |
| −0.2 | 0.89 | 3.07 | — |
| −0.25 | 0.60 | 2.07 | — |
| −0.3 | — | — | 1.00 |
| −0.4 | — | — | 1.55 |
| −0.5 | — | — | 1.70 |
| −0.6 | — | — | 1.73 |
| −0.8 | — | — | 1.82 |

identify the modes at low $B$ in figure 2(*a*) with $\omega_-$ fail when the measured values of $B$ and $\omega_{\rm FIR}$ are used in equation (1) to extract $\omega_0$; the result is a prediction of $\omega_0 \geqslant$ 10.8 meV, which is inconsistent with the Fermi energy $E_{\rm F}$ calculated for the dots from the carrier concentrations (see table 1). As the measured modes lie relatively close in magnetic field to the CR absorption peaks, their assignment as $\omega_+$ modes is more appropriate.

The resonant energies $\omega_0$ calculated for various $V_g$ on the basis of this assignment and equation (1) are shown in table 1, where they are seen to be plausible when compared to the values of $E_{\rm F}$. Our spectra at $\omega_{\rm FIR}$ = 7.61 meV and our identification of the new absorption mode as $\omega_+$ are consistent with those of Sikorski and Merkt [1] at $\omega_{\rm FIR} > \omega_0$.

The plasmon with resonant energy $\omega_0$ has been variously identified as either an edge magnetoplasmon [4, 10] or as a depolarization mode [9, 11], with $\omega_0$ given by (see [9])

$$\omega_0^2 = A\frac{\hbar^2 N_s e^2}{2m^* \epsilon_0 \epsilon_{\rm eff} R} \tag{2}$$

where $e$ is the electronic charge, $m^* = 0.0695 m_e$, $\epsilon_{\rm eff}$ is the effective dielectric constant, and $R$ is the electronic radius of quantum dot. $A$ is a prefactor which depends on the exact shape of the bare confining potential and the nature of the plasmon mode. Kern *et al* [9] used $A \sim 1$ in equation (2) for a generalized plasmon. As for $R$ in equation (2), in our gated GaAs/AlGaAs heterostructures the amount of lateral depletion away from the gate edge at dot definition is roughly equal to the separation between the gate and 2DEG [12]; this suggests an average radius of $R \sim$ 360 nm for our quantum dots. Using $A$ = 1 along with $R \sim$ 360 nm, $\epsilon_{\rm eff}$ = 15.5 [4, 13], and $N_s = 0.60\times 10^{11}$ cm$^{-2}$ (at $V_g$ = −0.25 V from table 1), equation (2) yields $\omega_0 \sim$ 1.03 meV at definition. This value agrees reasonably well with the measured value of $\omega_0$ = 1.00($\pm$0.2) meV given in table 1. Based on the values of $\omega_0$ in table 1, equation (1) predicts that at $\omega_{\rm FIR}$ = 2.64 meV the CR spectrum should have an absorption peak at $B$ = 1.34 T for $V_g$ = −0.3 V. Such a peak is not present in figure 2(*b*), and no other peaks appear at lower values of magnetic field. Possible reasons for the absence of this peak are discussed below.

Consider now the magneto-capacitance oscillations of figure 4 for $V_g \geqslant -0.25$ V. Because the carrier density initially falls with decreasing gate bias, the oscillations are shifted to lower magnetic field at lower $V_g$, which is also accompanied by a fall in amplitude. This fall in amplitude is expected because the magnetic density of states is proportional to magnetic field. However, for $V_g \leqslant -0.3$ V, the magneto-capacitance undergoes a qualitative change; the amplitude of the oscillations decreases *dramatically from its value at higher gate biases, and between* $V_g = -0.3$ V *and* $V_g = -0.45$ V the capacitance is seen to decrease with increasing $B$. The dramatic drop in the amplitude of the magneto-capacitance oscillations at $V_g = -0.3$ V coincides with the appearance of the quasi-0D plasmon ($\omega_+$ mode) in figure 2(*a*). This gate bias is also that at which the capacitance in figure 3 begins to fall rapidly, indicating the transition from a modulated 2DEG to an array of dots with increasingly smaller diameters. Additional evidence of the influence of confinement on the magnetic subbands at $V_g = -0.3$ V is provided by figure 5 where a plot of filling factor versus $1/B$ is presented for $0.0 \text{ V} \geqslant V_g \geqslant -0.3$ V. Berggren *et al* [14] found that in their 1D split-gate devices, a similar plot of Landau level index versus $1/B$ deviated from non-linearity at small $B$ for gate biases sufficiently negative such that the lateral confinement was $\leqslant$250 nm. More specifically these investigators noted that the period $\Delta(1/B)$ between Landau indices were larger at small $B$. This is precisely the behaviour exhibited by our dot array in figure 5.

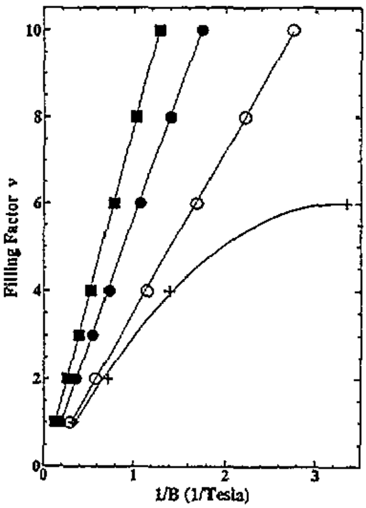


**Figure 5.** Plot of filling factor $\nu$ versus $1/B$ at various gate biases $V_g$. *For the solid squares* $V_g = 0.0$ V, *for the solid circles* $V_g = -0.1$ V, for the open circles $V_g = -0.2$ V, and for the crosses $V_g = -0.3$ V.

The above observations indicate that the magnetic energy levels of the electrons in the dot are significantly perturbed by the confining potential at magnetic fields near 1.5 T; there is an absence of the $\omega+$ mode in the CR spectrum in this range, and only a broad, weak oscillation is observed in the magneto-capacitance at $V_g = -0.45$ V. This is surprising because the magnetic length $l_B = \sqrt{\hbar/eB}$ is 21 nm at $B = 1.5$ T, whereas the dot radius is given approximately by $R \leqslant 360$ nm for $V_g \leqslant -0.3$ V. One possible explanation is that at $B = 1.5$ T the magnetic subbands have not yet fully evolved into unperturbed Landau levels characteristic of bulklike states. Instead the magnetic subbands retain characteristics associated with edgelike states. Such behaviour is predicted by the calculations of Kumar *et al* [13] for an electrostatically defined GaAs/AlGaAs quantum dot similar in many respects to the dots under discussion here. For the quantum dot investigated in [13], the slow evolution of the edgelike states into bulklike Landau levels with increasing magnetic field is attributed to a soft confining potential at the walls of the dot.

The view that a soft confining potential might also be characteristic of our 0D structures is supported by the experimental data. The absence of the $\omega_+$ CR-like mode in the CR spectrum of figure 2(*b*) suggests a lack of unperturbed Landau levels at $B \sim 1.5$ T, as does the dramatically reduced amplitude of the magneto-capacitance oscillations in this region. One important difference between the dot in [13] and those studied here is the diameter at $V_g \approx -1.0$ V; in [13] the electronic radius is calculated to be 50 nm in this bias region, whereas $R \leqslant 116$ nm (using equation (2) and table 1 with $N_s = 0.60 \times 10^{11}$ cm$^{-2}$) places an approximate upper limit on the average radius of our dots at $V_g = -0.8$ V. In [13] Kumar *et al* note that in their model dot a clear-cut distinction cannot be made between edgelike states at low magnetic field and bulklike states at $B \simeq 5$ T. By contrast we observe such as distinction in figure 2 where the $\omega_+$ mode can be readily observed near $B = 4.5$ T but not at $B \simeq 1.5$ T. The ability to better distinguish bulklike Landau levels in our dots at $B = 4.5$ T relative to that in [13] is most likely due to our larger dot diameter.

The magneto-capacitance measurements described above should be contrasted with those of three other investigations. Smith *et al* [15] also observed SdH-like capacitance oscillations in their GaAs/AlGaAs quantum dots. Distinct oscillations in the magneto-capacitance occurred only at $B \geqslant 3.5$ T, a region inaccessible in the dot array used in the present investigation because of our lower carrier concentration. For $B \leqslant 3$ T the magneto-capacitance traces in [15] closely resemble our data in this range of magnetic field for $V_g \leqslant -0.3$ V. In addition, Hansen *et al* [16] measured the differential capacitance characteristic $\mathrm{d}C/\mathrm{d}V_g$ versus $V_g$ of an array of GaAs/AlGaAs quantum dots. This array was similar in many respects to that used in the present investigation, with the important difference again being that the radii of their dots was $R \sim 100$ nm (somewhat smaller than our radii at $V_g = -0.8$ V). They observed an increase in the oscillation amplitude of the differential capacitance at high magnetic field, which was attributed to a condensation of complex magneto-electric subbands (influenced by the confining potential) into bulklike Landau levels at $B > 2$ T. These observations are consistent with our data and suggestions given above.

Lastly, our data should also be contrasted with that of Patel *et al* [4], whose dots were identical to ours except for size; at $V_g = -0.3$ V near dot definition $R = 420$ nm in [4] compared to $R \sim 360$ nm in the present investigation. At a given gate bias we therefore expect their dot radius also to be larger than our average radius, and thus for their dots to exhibit bulklike behaviour to a larger degree than ours do. This is exactly what occurs. In [4] the capacitance oscillations at $V_g < 0$ V are reduced in amplitude when compared to those at $V_g = 0$ V, but still larger than the amplitude of our oscillations at the same gate biases. In addition, by contrast to our CR spectrum in figure 2(*b*), they observed an absorption attributed to the $\omega_+$ mode at $\omega_{\mathrm{FIR}} =$ 2.64 meV, which is also indicative of relatively unperturbed Landau levels existing in their dots at $B \simeq 1.5$ T. An important point to note here is that because their device is identical to our array except for the dot radius, we expect that the soft potential suggested above for our dots also characterizes the dots in [4]. The larger degree of bulklike behaviour of the dots in [4] is then attributed to their larger radius.

In conclusion we have measured the cyclotron resonance spectra and magneto-capacitance of an array of voltage-tuneable quantum dots. Both of these measured quantities change dramatically as the gate bias $V_g$, which defines the dots, falls below $-0.3$ V. At $V_g \leqslant -0.3$ V the $\omega_+$ plasmon mode and magneto-capacitance oscillations associated with the bulklike states in the 2DEG either disappear or are greatly reduced in amplitude in the region near $B = 1.5$ T, an unexpected result since the dot diameter is larger than the magnetic length at such magnetic fields. At higher magnetic fields ($B = 4.5$ T) the $\omega_+$ CR-like mode reappears, testifying to the presence of relatively unperturbed Landau levels. One possible explanation is that due to a soft confining potential, distinguishing between edgelike states and bulklike Landau levels is difficult in the $B = 1.5$ T regime. The influence of the soft confining potential on the magneto-electric subbands is seen to decrease with increasing dot radius, as expected. The $\omega_+$ mode has been observed by other investigators (e.g. [5]) around $B \sim 1.5$ T in quantum dot arrays similar to ours. The discrepancy between their observations and ours may be due to the existence of different boundary conditions at the walls of our dots, possibly leading to a higher population of edgelike states at low magnetic fields in our structure (as suggested by the model of Kumar *et al* [13]). In order to understand better the absence of the $\omega_+$ mode and capacitance oscillations at low magnetic fields in our structure, further investigation is required.

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