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Many-body effect in an artificial atom

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Abstract

Atomic-like properties of vertical quantum dots are studied by measuring Coulomb oscillations. The Coulomb oscillations in the linear transport regime become irregular in period, reflecting a shell structure and the obedience to Hund's rule, as the number of electrons in the dot approaches *zero*. Under a high magnetic field, many-body effects become important, and we observe kink structures in the few-electron regime in the Coulomb oscillation peak positions versus the magnetic field. The kink structures are well assigned to transition in spin and angular momentum states, which we predict by the exact diagonalization approach. © 1998 Elsevier Science B.V. All rights reserved.

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Highly correlated, few-body quantum phenomena in quantum-dot systems have attracted recent experimental and theoretical interest since the importance of the *many-body* interaction effect was revealed by the complex ground or excited state behavior. The many-body effect, to a greater extent than the classical charging effect [1], emerges most strikingly when single particle levels are degenerate. In artificially structured atoms in semiconductors, or in *quantum dots*, level degeneracy is found at zero magnetic field for a highly symmetric dot, or at level crossings induced by diamagnetic shifts of the levels, or for level bunching into the Landau levels as in two-dimensional systems at very high magnetic fields. Furthermore, we can bring about level degeneracy by placing similar dots in an array [2].

In this paper we employ the Coulomb blockage and charging effects in the transport properties of gated semiconductor quantum dots to study their many-body ground states and excited states. We use a double-barrier heterostructure (DBH) to fabricate a vertical quantum dot whose geometrical diameter is 0.54 μm as shown in Fig. 1 [3,4]. The DBH consists of an undoped 12.0 nm thickness $In_{0.05}Ga_{0.95}As$ well and undoped $Al_{0.22}Ga_{0.78}As$ barriers. The source and drain contacts are made from n-GaAs and graded doping is employed near the barriers. The DBH is processed to form a pillar-shape mesa by using combined dry and wet etch to a point just below the DBH region. A Schottky gate is placed on the side of the mesa close to the DBH. The current flowing vertically through the

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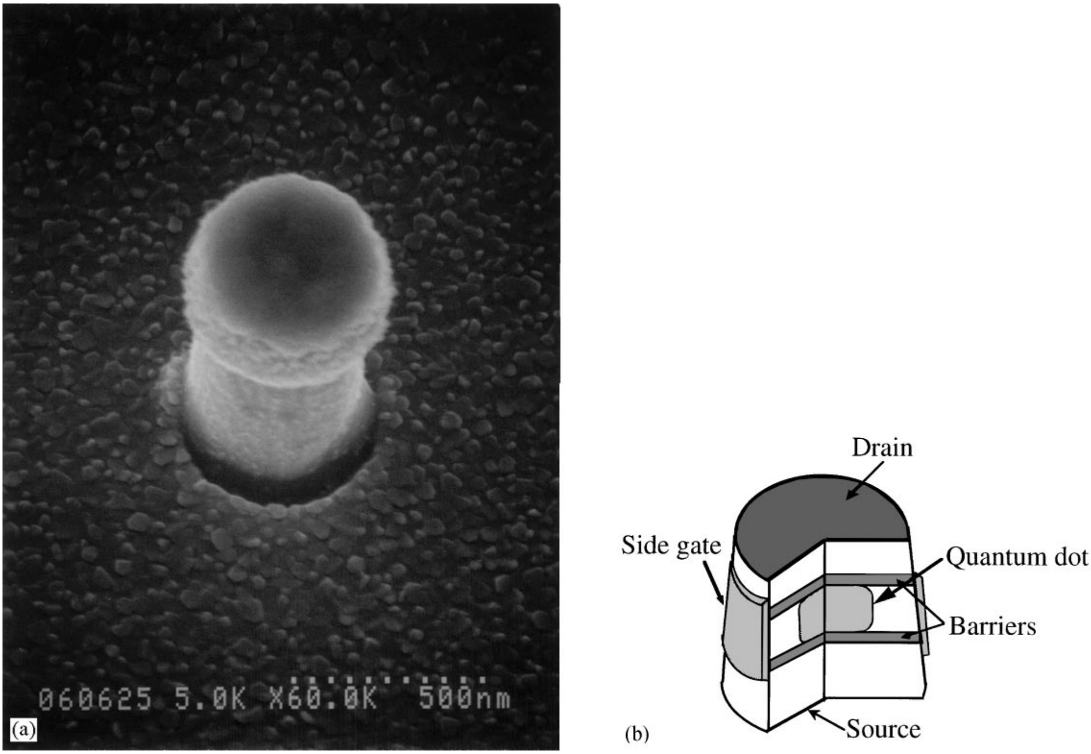

Fig. 1. (a) SEM photograph of a vertical quantum dot structure showing the top contact (drain) and a surrounding Schottky gate. (b) A schematic diagram of the device structure, where the quantum dot is formed in an $In_{0.05}Ga_{0.95}As$ well layer sandwiched by barriers made of $Al_{0.22}Ga_{0.78}As$.

dot is measured at about 90 mK in response to a small DC voltage V applied between the contacts.

The Coulomb oscillation near the linear transport regime ($V \sim 100\,\mu V$) at zero magnetic field is irregular in period, as shown in Fig. 2 reflecting a *shell structure* and the obedience to Hund's rule, as the number of electrons, N, in the dot approaches *zero*. The *shell structure* originates from the single particle spectrum confined in a cylindrically symmetric parabolic potential. The energy level in the two-dimensional parabolic potential with its strength ω_p under magnetic field B is given by

$$E_{n,m} = (2n + |m| + 1)\hbar\Omega + \frac{m}{2}\hbar\omega_c, \quad (1)$$

where ω_c is the cyclotron frequency and $\Omega = \sqrt{\omega_p^2 + \frac{1}{4}\omega_c^2}$, $n = 1,2,\ldots$ and $m = 0, \pm 1, \pm 2, \ldots$ are the radial and angular quantum numbers, respectively. In the presence of a weak magnetic field applied along the current direction, the oscillation peaks shift in pairs with the magnetic field, which is well described by a diamagnetic shift of spin-degenerate single particle states. When the magnetic field is sufficiently small, however, the pairing is modified to favor the filling of parallel spins for the degenerate single particle states, as predicted by Hund's rule [5].

Under a high magnetic field, on the other hand, correlation effects become important, and we observe, in the Coulomb oscillation peak positions versus the magnetic field, kink structures in the few-electron regime. These kink structures have been predicted as arising from the correlation effects [6–9] and have been observed in transport measurements of a sub-μm resonant tunneling diode [10,11] and also by single-electron capacitance

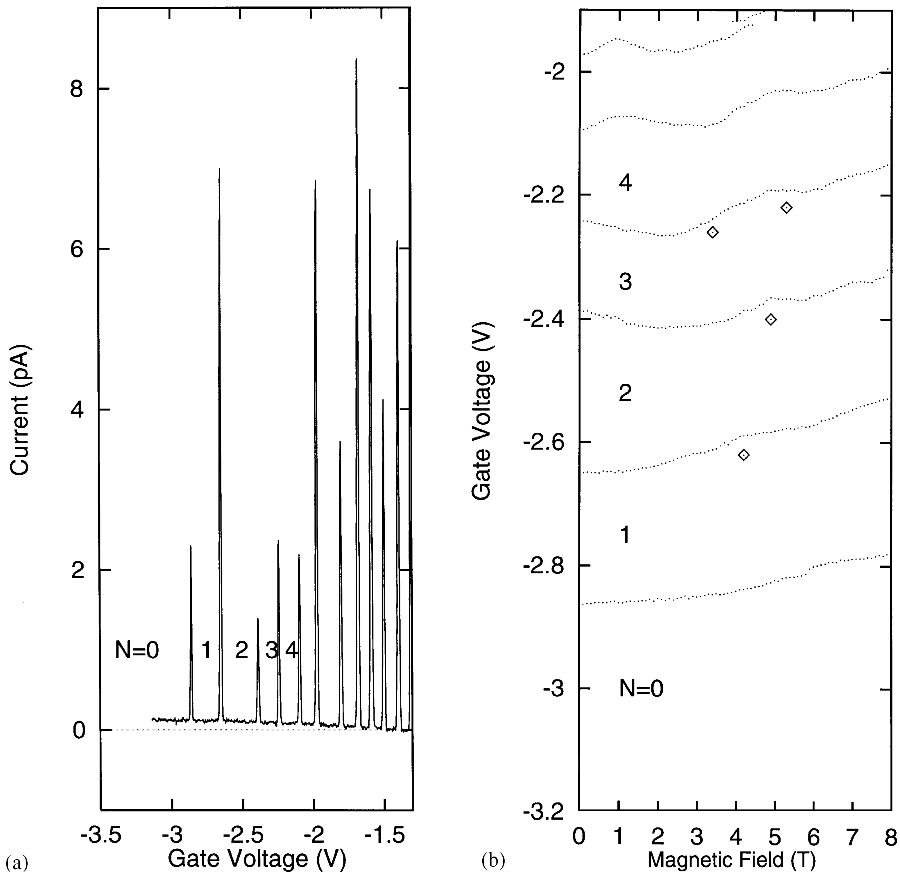

Fig. 2. (a) Coulomb oscillation in the current versus gate voltage at $B=0\,\mathrm{T}$. (b) Plot of the gate voltage position of the current oscillation peaks versus magnetic field. The kink structures originating from Hund's rule in the third and fourth peak curve at a low magnetic field are not clearly seen in this plot. The second, third and fourth peak curves show small kinks labelled by diamonds.

spectroscopy [12]. We calculated the few-electron energy spectrum with the exact diagonalization method to compare it with the experiments. Fig. 3 is a typical result for the chemical potential $\mu(N,B)$ defined by

$$\mu(N,B)=E_0(N,B)-E_0(N-1,B), \tag{2}$$

where $E_0(N,B)$ is the N-electron ground state energy under magnetic field B. We use $\omega_{\mathrm{p}}=6\,\mathrm{meV}$, GaAs effective mass value 0.067 and dielectric constant $\varepsilon^*=12.5$. We also use the following three-dimensional interaction potential to take the effect of the finite confinement width into account,

$$V(r,r')=\frac{e^2}{4\pi\ \varepsilon^*\ \varepsilon_0}\frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}}. \tag{3}$$

Compared to the result with zero thickness approximation [8], the kink positions are shifted to a higher magnetic field reflecting the weakening of the Coulomb effects. Zeeman energy is included with the effective g-factor 0.44. The diamagnetic shift and kink positions fit quite well with the experiments for the first to third peaks. However,

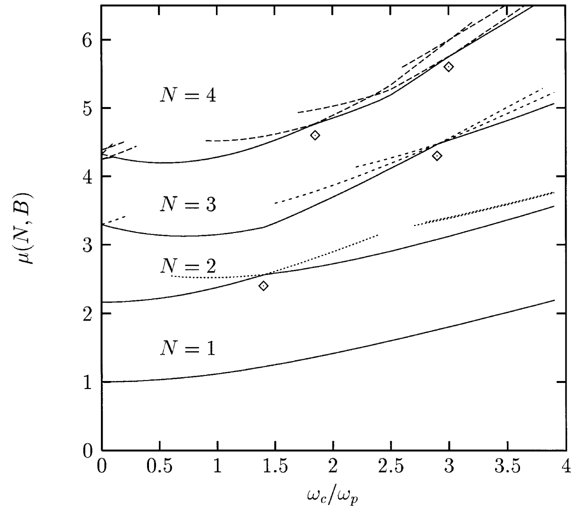

Fig. 3. Magnetic field dependence of the chemical potentials (solid lines, in units of ω_p) calculated by the exact diagonalization method ($\omega_p = 6\,\text{meV}$ was used). Excitation spectra are also shown with a $0.6\omega_p$ window above the ground states (dash lines). $\omega_c/\omega_p = 1$ corresponds to a magnetic field of 3.47 T. At the points marked with a diamond, the ground state changes.

the kinks of the fourth peak is located at a smaller magnetic field in the experiment. This, we speculate, has originated from the effectively weaker confinement potential ω_p, which is caused by the screening of the leads and the gate electrode [13]. Several lowest excited states are also shown in the figure within an energy screen of $0.6\omega_p$ from the ground state energy. We also observed Coulomb oscillations originating from the many-body excited states by applying a larger bias V (a few mV). These are clearly characterized by their magnetic field dependence on comparison with the exact diagonalization results [14].

The peak amplitudes are modified in the vicinity of the kink structures. The peak amplitudes of the third and fourth peaks are shown in Fig. 4. The transport characteristics of a quantum dot have been evaluated as a sequence of tunneling processes [15–17]. The tunneling probability is proportional to the spectral weight,

$$\sum_{\eta,\, n,\, m} |\langle \Psi_\eta(N) | c^\dagger_{n,\, m} | \Psi_0(N-1) \rangle|^2 \times \delta[E_0(N-1) - E_\eta(N)], \qquad (4)$$

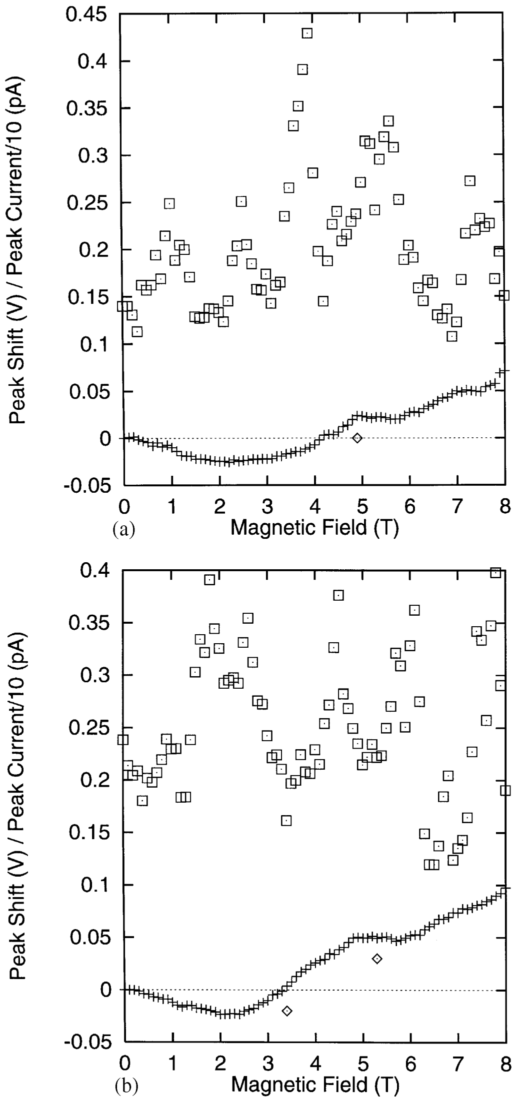

Fig. 4. Coulomb oscillation peak height as a function of the magnetic field for the third and fourth peaks (squares). The relative change of the peak position from its value at $B = 0$ is also shown (plus symbols) multiplied by a factor 10.

where η shows the states of a N electron dot and $\Psi_0(N-1)$ is the $N-1$ electron ground state wave function in the linear transport regime [15]. It has been predicted that the peak amplitude is suppressed at the kink structures because of the small overlap between $N-1$ and N electrons states. The peak amplitude is actually reduced just around the kink structures, although, there are maxima near the kinks. One possible explanation for this enhancement is an enlargement of the tunneling channel near the degeneracy of the many-body levels, however, further study is necessary to clarify this point. We also found that the peak currents are suppressed at the high magnetic field regime (~ 10 T).

In short, we have studied the atomic-like properties of vertical quantum dots by measuring the Coulomb oscillations. Under a high magnetic field, many-body effects become important, and we observe kink structures in the few-electron regime in the Coulomb oscillation peak positions versus the magnetic field, which we compare with the result of exact diagonalization.

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