

## Evolution of Coulomb blockade spectra in parallel coupled quantum dots

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We report low-temperature conductance measurements in the Coulomb blockade regime on two nominally identical tunnel-coupled quantum dots in parallel defined electrostatically in the two-dimensional gas of a GaAs/AlGaAs heterostructure. We find that the Coulomb blockade spectra of such devices exhibit two distinct sets of peaks, each of which behaves differently with varying interdot tunnel conductance and with temperature. The results conform to recent theories regarding the role of interdot quantum charge fluctuations, and provide evidence for the possible role of inelastic cotunneling between dots at finite interdot conductances. © 1999 American Institute of Physics. [S0003-6951(99)03929-7]

In recent years there has been considerable interest in the electronic transport properties of multiple quantum dot systems in the Coulomb blockade (CB) regime. Recently, such transport properties of two or more coupled quantum dots in semiconductor electron gas systems in the CB regime have been explored both experimentally<sup>1–8</sup> and theoretically.<sup>9–13</sup> Effects due to interaction between the coupled dots are anticipated, and are observable in the resulting conductance spectra. In this letter we investigate the evolution of the CB conductance spectra of such a device as a function of both varying interdot tunnel conductance and temperature.

The device used in this study consists of two nominally identical adjacent quantum dots of lithographic size  $0.8\ \mu\text{m} \times 0.5\ \mu\text{m}$ . Figure 1 is a scanning electron micrograph of the electrostatic gates defining the parallel double dot system. The dots are defined by seven independently tunable Cr:Au Schottky gates on a GaAs/AlGaAs heterostructure containing a two-dimensional electron gas (2DEG) located  $520\ \text{\AA}$  beneath the surface. The 2DEG low-temperature sheet carrier density and mobility are  $n_s = 3.5 \times 10^{11}\ \text{cm}^{-2}$  and  $\mu = 5.2 \times 10^5\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ , respectively. The gates define five separately tunable quantum point contacts (QPCs). The outer QPCs are used to measure the conductance of each dot, while the inner QPC controls the interdot tunnel coupling between the dots. Voltages applied to the side gates are used to change the electrostatic potential of each dot. The sample device is mounted on the mixing chamber of a helium dilution refrigerator with a base temperature of 30 mK. From separate measurements,<sup>4</sup> the total capacitance for each single dot is determined to be  $C_\Sigma \cong 275\ \text{aF}$  corresponding to a charging energy  $U = e^2/C_\Sigma \cong 582\ \mu\text{eV}$ , and the single particle level separations were measured to be  $\Delta E \sim 50\ \mu\text{eV}$ .

The QPCs between dot 2 and its reservoirs (reservoirs III and IV) are biased to the nonconducting regime  $G_{EF} = G_{BC} = 0$ , where  $G_{ij}$  is defined as the conductance of the QPC defined by gates  $i$  and  $j$ . Dot 2 is thus completely isolated from its leads (leads III and IV), and can therefore only

interact with dot 1 through the QPC defined by gates  $B$  and  $E$  which define the interdot barrier conductance. Dot 1 is formed by setting  $G_{AB}$ ,  $G_{DE} \approx 0.02e^2/h$ . Additionally, the voltages on the two side gates,  $V_1$  and  $V_2$ , are varied together by electrically connecting gates 1 and 2.

In this letter we investigate the CB spectra as measured through dot 1, the conducting dot, for influences of changes in the occupancy of dot 2, the nonconducting dot, as a function of both interdot conductance and temperature. We first examine the effect of varying interdot conductance. Figures 2(a)–2(d) present a set of measurements taken at different values of the interdot barrier conductance  $G_{BE}$  listed in Fig. 2. Evident in these conductance traces are two distinct sets of peaks: a larger amplitude primary set of peaks and a smaller amplitude secondary set. As the interdot tunnel conductance is increased, these secondary peaks grow in amplitude and their positions shift until  $G_{BE}$  attains a value of  $G_{BE} \approx 2e^2/h$ , at which point the double dot system behaves as a single large composite dot. This observation conforms to recent theories, based upon consideration of quantum charge fluctuations between the dots, which show that the behavior of the double dot system becomes that of a single large dot when the interdot conductance reaches exactly  $2e^2/h$ .<sup>9–11</sup>

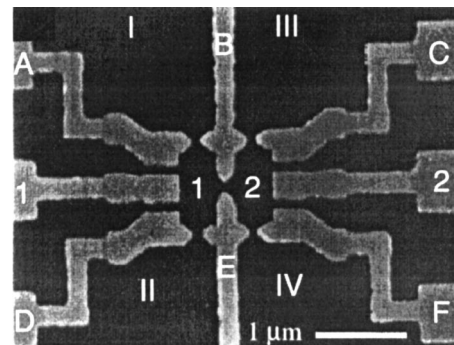


FIG. 1. Scanning electron micrograph with labeling convention used in text for the dots and gates. The left dot is designated dot 1 and the right dot is designated dot 2. Regions of the 2DEG connected to ohmic contacts are denoted I, II, III, and IV.

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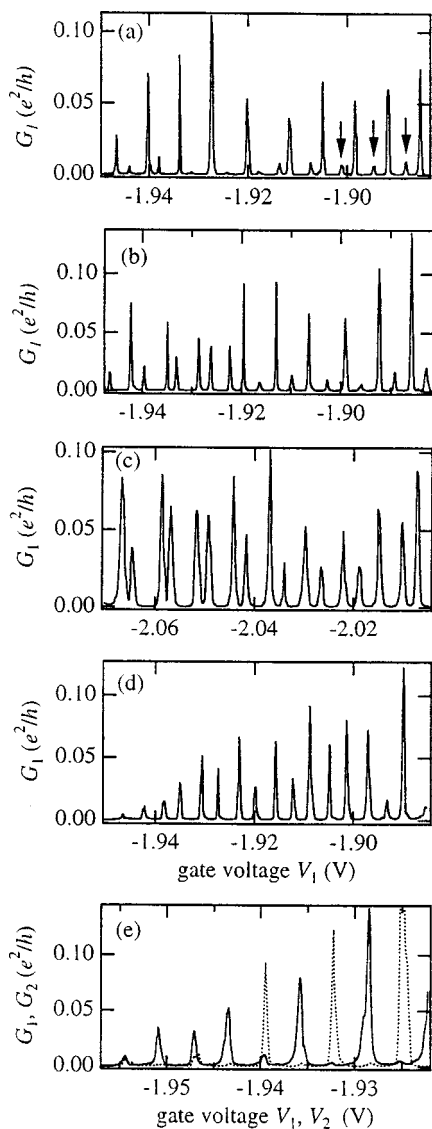


FIG. 2. Conductance  $G_1$  of dot 1 measured as a function of the two side gate voltages  $V_1 = V_2$  for  $G_{BE} \approx 0.8e^2/h$  (a),  $G_{BE} \approx 1.0e^2/h$  (b),  $G_{BE} \approx 1.6e^2/h$  (c), and  $G_{BE} \approx 1.9e^2/h$  (d). Arrows in (a) indicate secondary peaks. (e) Simultaneous measured conductances  $G_1$  (solid line) and  $G_2$  (dashed line) as a function of gate voltage  $V_1 = V_2$  for  $G_{BE} \approx 0.2e^2/h$ . The mixing chamber temperature is constant at 30 mK for all traces.

This last result was further verified by analyzing data taken on this device at larger values of the interdot conductance  $G_{BE}$ .<sup>4</sup> The fractional splitting parameter  $f_c$  defined by Golden and Halperin<sup>11</sup> was extracted from these measurements. Figure 3 compares measured values of  $f_c$  at various

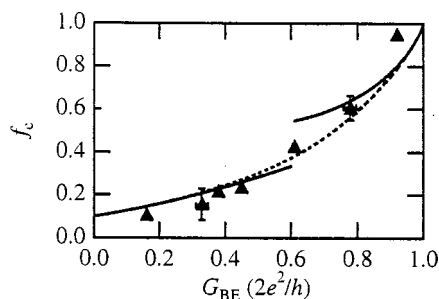


FIG. 3. Measured fractional splitting  $f_c$  (solid triangles), theoretically predicted splitting (solid lines), and theoretical interpolation (dotted line) plotted as a function of interdot conductance  $G_{BE}$ .

settings of  $G_{BE}$  to results expected from charge fluctuation theories,<sup>11</sup> showing good agreement between theory and experiment.

The finite secondary conductance maxima are not expected to be observable within a purely capacitive model of the system,<sup>6</sup> and reflect quantum mechanical tunneling of charge into and out of dot 2, the isolated nonconducting dot. To verify that the observed smaller secondary peaks, measured for  $G_{BE} < 2e^2/h$ , do indeed reflect changes in the occupancy of dot 2, a separate set of experiments was performed on the parallel dot device in which both of the dots were set to conduct and simultaneous measurements of the conductances through each dot were made. This was accomplished by adjusting the outer QPCs of all the dots to  $G_{AB}$ ,  $G_{BC}$ ,  $G_{EF}$ ,  $G_{DE} \approx 0.02e^2/h$ , and by using two independent measurement circuits to measure both dot conductances simultaneously. As previously, the two side gates are tied together so that  $V_1 = V_2$ , and the conductances are measured as a function of the common voltage applied to these side gates. A representative data trace is shown in Fig. 2(e) for  $G_{BE} \approx 1.1e^2/h$ . As in Figs. 2(a)–2(d), a secondary peak structure emerges in the conductance traces of each dot. In particular, it is seen that the larger amplitude primary Coulomb blockade peaks in the conductance of one dot coincide with the smaller secondary peaks of the neighboring dot, and vice versa. This observation provides strong evidence that the measured secondary peaks do indeed correlate with changes in the charge state of the neighboring dot at low interdot tunnel conductances.

In the limit of low interdot tunnel coupling, one possible mechanism leading to the appearance of these secondary peaks is inelastic cotunneling, a higher-order correlated tunneling process.<sup>10,14</sup> By this mechanism, gate voltage values resulting in a lifting of the Coulomb blockade on dot 2 allow an electron to tunnel from lead I onto the still-blockaded dot 1 and then to occupy dot 2. The reversal of this process, in which the electron tunnels from dot 2 to lead II, results in a finite measured current through the device.

In investigating the origin of the observed secondary conductance peaks, the temperature dependence of the measured conductance data was analyzed. A series of traces of the conductance through dot 1 at an interdot conductance of  $G_{BE} = 1.1e^2/h$  was measured, with  $G_{AB}$ ,  $G_{DE} \approx 0.02e^2/h$  and  $G_{EF} = G_{BC} = 0$ , so that dot 1 was conducting and dot 2 was isolated from all leads. Observed pairs of primary Coulomb blockade peaks and secondary peaks were fit to the sum of two thermally broadened line shapes.<sup>15</sup>

Figure 4 summarizes on a double logarithmic scale the temperature dependences of the amplitudes of one representative pair of adjacent primary and secondary Coulomb blockade peaks measured at a fixed interdot tunneling conductance of  $G_{BE} \approx 0.4e^2/h$ . The most striking feature of the data in this figure is the differing behavior of the primary and secondary peak amplitudes as a function of temperature. The temperature dependence of primary Coulomb blockade peaks are expected to follow a  $T^{-1}$  power law for tunneling into a single energy level in this temperature range where the electron temperature is less than  $\Delta E/k_B \approx 600$  mK.<sup>16</sup> The dotted line in Fig. 4 is a least squares fit to this temperature

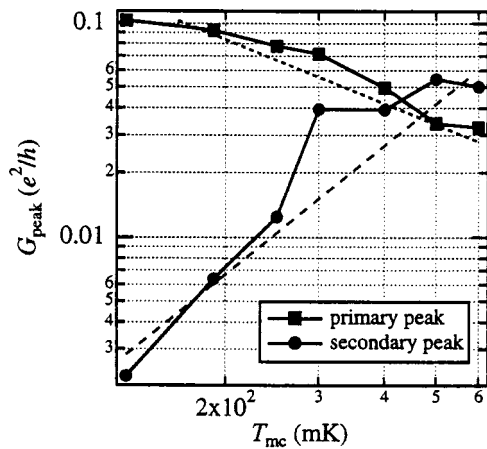


FIG. 4. Peak heights for primary and secondary Coulomb blockade peaks as a function of mixing chamber temperature  $T_{mc}$ .

dependence, revealing reasonable agreement with this predicted temperature behavior.

The behavior of the secondary peak amplitudes with temperature is seen to be more complicated. Recently, the temperature dependence of inelastic cotunneling processes governing the exchange of electrons in a coupled quantum dot system has been calculated,<sup>10</sup> and predicts a peak amplitude  $G_{\text{peak}}$  of the form  $G_{\text{peak}} \sim T^2$  for interdot tunnel conductances much less than  $e^2/h$ . The dashed line in Fig. 4 is a least squares fit of the secondary peak amplitude data to a such a temperature dependence. As is seen from Fig. 4, this quadratic temperature dependence agrees with the data for low temperatures but  $G_{\text{peak}}$  increases more slowly at higher temperatures.

In conclusion, we have presented results obtained in a double quantum dot system revealing the influence of changes in the charge state of one quantum dot on the con-

ductance through the adjacent dot. Simultaneous measurements of the conductance of both quantum dots in the device were performed to confirm this result. In addition, we have investigated the temperature dependencies of CB effects arising from both quantum dots in the conductance through one of the pair, and have identified a striking difference in the temperature behavior which is not fully explained by current theory.

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