Few-Electron Open Dots: Single Level Transport

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We confirm the existence of a new regime for small few-electron open dots, in which the transport occurs through individual eigenstates of the corresponding closed dot. In particular, at low magnetic fields the characteristic features in the conductance are related to the underlying eigenspectrum shells. When the number of modes in the leads is reduced, a more detailed structure becomes discernible within the shells due to single eigenlevels. At higher fields Landau level condensation is evident as well as the crossing of levels collapsing to different Landau levels.

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Small quantum dots have been compared to artificial atoms [1]. Unlike real atoms, however, quantum dot elements are not uniquely defined, e.g., the influence of electron-electron interactions is dependent upon the specifics of the dot confining potential, $\hbar\omega_0$. This has led to a strong interest in, e.g., the optical spectroscopy of small few-electron quantum dots ($\hbar\omega_0 \sim 50$ meV). Spectroscopy on larger single dots ($\hbar\omega_0 \sim 3$ meV) but still in the few-electron regime is possible, however, using single electron tunneling techniques based on the Coulomb blockade effect [2]. In particular, much has been learned about these artificial atoms over the past two years from measurements on three terminal vertical quantum dots [3] and more recently on lateral dots [4]. A charging term, e^2/C, which dominates the spacing between Coulomb blockade peaks constitutes an ambiguity in the interpretation of these measurements. By contrast, in the regime of the open dot the charging term is unimportant. This is because the charge quantization in the dot no longer holds as electrons can easily leave/enter the dot. In this paper we demonstrate that for low magnetic fields transport through small open dots allows us to observe spectroscopic features such as shell structure, level crossing, and Landau level condensation without the complication of a charging term.

The study of transport through open dots has received much attention in recent years for a variety of reasons. In larger dots quantum corrections to transport, namely, conductance fluctuations and weak localization effects, are observed in which the impurity scattering of disordered conductors is replaced by elastic scattering with the dot boundaries. Since the dot boundaries are controllable, this has led to many important studies and insights into areas such as quantum chaos. Such fluctuations are modeled either by a statistical analysis for the chaotic dots [5–7] or alternatively in terms of a periodic orbit analysis of some model closed billiards (circular, triangular, square, etc.) [8]. For a circular dot, for example [9], fluctuations in the conductance were shown to be related to caustics of the eigenspectrum of the closed system. It has been further shown by explicit analysis of the scattering wave functions that transport through a dot is effectively mediated by the eigenstates of the corresponding closed structure [10–12]. Moreover, under conditions in which only a few propagating modes in the leads exist, the lifetime broadening of the level associated with the open leads may be sufficiently small (i.e., less than Δ the level spacing) that observed features in the conductance are found to be related to individual levels in the underlying dot level spectrum [12].

Thus, as mentioned above, under these conditions, one can in principle perform spectroscopic measurements of a closed dot by measuring the conductance of an open dot with the same geometry. The position of the leads is predicted to play an important role in determining not only the strength of the tunneling process but also its sign, i.e., whether the resonant level results in a reflection or transmission process [12]. However, for the quantum dot of a typical size (area $\sim 1\ \mu\text{m}^2$; $\Delta \sim 80$ mK), the features in the conductance associated with the underlying discrete spectrum can be easily hindered by temperature smearing, inelastic scattering, etc. Therefore in this paper we use a small lateral dot where $\Delta \lesssim 2$ K. This enables us for the first time to resolve single energy levels in the transport measurements on the *open* dot.

The inset of Fig. 1 is a scanning electron microscopy (SEM) micrograph of a device identical to one of the two used in these measurements. The second device (lower inset of Fig. 1) had leads at the dot corners allowing for a direct transmission. The dot is electrostatically defined by four gates above a GaAs/AlGaAs heterostructure: a top gate which in combination with left and right finger gates is used to define the dot boundaries, and a narrow plunger gate (at the bottom) which can be used as a third terminal. The lithographic width and height of the triangular dots was approximately 0.45 μm. The two dimensional electron gas (2DEG) was about 100 nm below the wafer top surface. The bulk density (mobility) of the AlGaAs/GaAs wafer used were 1.7×10^{11} cm^{-2} (2×10^6 cm^2 V^{-1} s^{-1}). The density in our small device, however, is expected to be much lower. This was confirmed by an analysis of a well understood magnetic focusing feature

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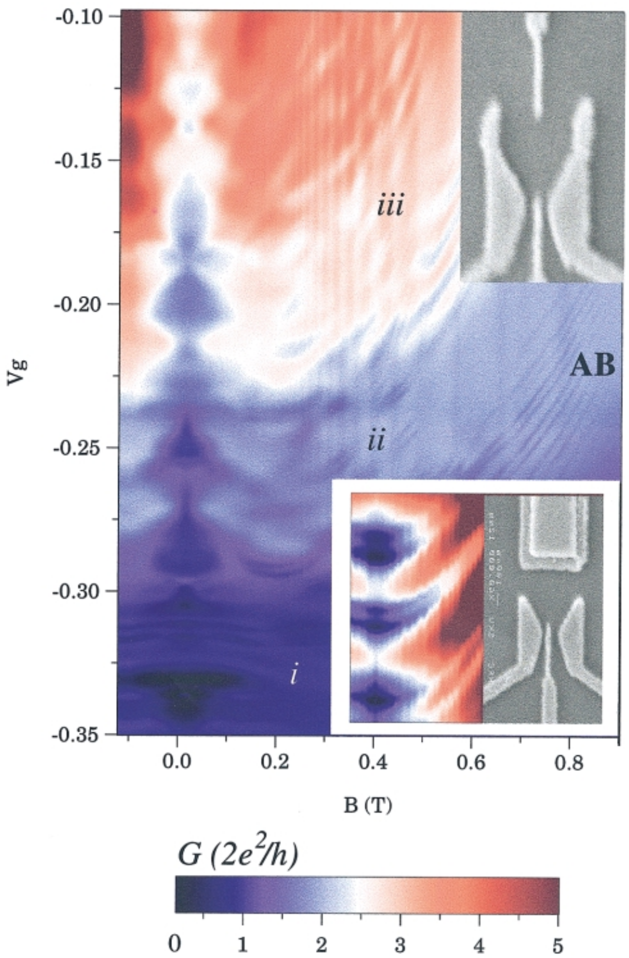

FIG. 1 (color). A color scale of the conductance G vs magnetic field B and gate voltage V_g at 50 mK. The top inset is an SEM micrograph of a device similar to the one used in these experiments. The bottom inset shows the results (-0.04 to 0.17 T) and SEM micrograph from a second device with leads placed in different locations.

observed in the magnetoconductance of a square dot (with lithographic dimensions of 0.5 μm) which was also defined electrostatically from material taken from the same molecular-beam epitaxy (MBE) wafer [13]. The 2DEG density in that dot was found to be $\sim 0.7 \times 10^{11}$ cm^{-2} and therefore one would expect the density in our dot to be even smaller. Based on the above estimations as well as on the results of the single electron tunneling measurements performed on these two triangular dots [14], we estimate the lowest number of electrons to be $N \gtrsim 20 \sim 30$. Thus, our dot is expected to contain far fewer electrons than any previously measured open dot.

Figure 1 shows the magnetoconductance of the dot shown in the inset from -0.1 to 1.0 T as a color scale. It is composed of many individual gate voltage sweeps. All the gates were swept uniformly to preserve the triangular shape of the dot. A variety of regimes are visible. First, the coarse changes in shade separate the regimes (i)–(iii), which correspond to a the number of transmitted modes in the constrictions from 1 to 3, respectively. The regions marked by "AB" refer to the edge state Aharanov-Bohm regime [15]. The small gate voltage independent effects due to the bulk Shubnikov-de Haas oscillations (i.e., from the 2DEG outside the dot) are visible as a series of faint vertical streaks. The region of interest for this paper, however, lies in the regime at lower fields. As can be seen this region breaks up into characteristic triangles centered at $B = 0$. The internal structure of these triangles becomes more highly resolved as the number of modes in the leads is reduced. Between these features and the AB regime there exists sets of lines of various width and direction. These lines often occur in pairs.

Here we concentrate on measurements made on one dot. The experimental results from the second dot were similar except in one respect. In both devices the sequence of characteristic triangular features near $B = 0$ was observed. Also for both devices sets of resonances were observed leaving each triangle. The difference resides in the relative strength of the different resonances exiting the triangles (shell remnants). In the device described in this paper most of the resonances are of relatively equal strength. In the second dot two sets of resonances corresponding in the calculated eigenspectrum to levels associated with higher Landau levels (LLs) were appreciably stronger than the rest. We suspect that this difference is related to the different locations of leads in the two dots and a corresponding discussion will be reported elsewhere. It is also worth stressing that for both devices qualitatively similar plots were obtained either by sweeping a single gate or by sweeping all of the gates.

We argue below that the many features seen in the magnetoconductance of the devices can be related to the eigenspectrum of the *isolated* dot. In particular, the characteristic low-field features represent a shell structure of the dot. To understand these features theoretically fully quantum-mechanical transport calculations are performed within the Landauer formalism which relates the zero-temperature two terminal conductance of the device, G, and the transmission coefficient, T, by the formula $G = (2e^2/h)T$ [16]. A "hybrid" recursive Green's function technique [17] is used to compute T. The eigenspectrum of an isolated, equilateral triangular dot is calculated variationally by expanding the eigenstates in the set of exact analytical solutions for $B = 0$. We use a model of the hard-wall confinement which is certainly an oversimplification of the actual dot potential. However, the main purpose of the present calculations is to underline the relationships between the calculated conductance and the eigenspectrum of the dot, rather than to achieve a detailed one-to-one correspondence between the calculated and observed magnetoconductance.

Figure 2(b) shows an eigenspectrum of the equilateral triangular dot as a function of magnetic field B. In

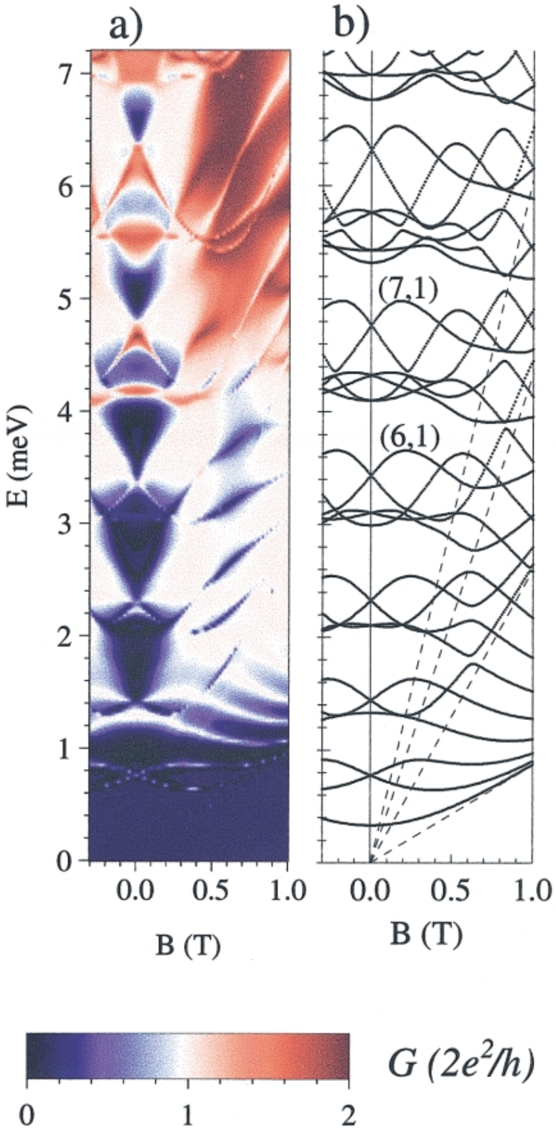

FIG. 2 (color). (a) A color scale of the calculated conductance vs magnetic field and the Fermi energy of an equilateral triangular dot with the lead geometry corresponding to the first experimental dot. The lead openings are 75 nm; the size of the dot is $L = 300$ nm; (b) Eigenspectrum of the same isolated dot. Some quantum numbers are indicated according to Eq. (1), as referred to in the text. Dashed lines indicate the Landau level fan.

the chosen energy interval the dot contains $2 \leq N \lesssim 70$ electrons (including a factor of 2 which accounts for the spin degeneracy). Although this system is not separable, it is integrable at $B = 0$ with energy levels [8]

$$E_{nm} = \frac{\hbar^2 k_{mn}^2}{2m^*}; \qquad k_{mn}L = (4\pi/3)\sqrt{n^2 + m^2 - mn}, \tag{1}$$

where m, n are positive integers with $m \geq 2n$ and m^* being the effective mass and L the side of triangle. Levels are doubly degenerate except for $m = 2n$. The eigenspectrum exhibits the characteristic "shell structure" with quantum number $m - 1$ giving the shell number. The magnetic field lifts the level degeneracy. The level splitting at low field ($\lesssim$0.15 T) depends on the symmetry of the corresponding zero-field eigenfunctions, and its strength can be understood within the framework of perturbation theory. At high magnetic fields the energy spectrum exhibits the "Landau level condensation" where the eigenlevels coalesce to the bulk LLs [18].

Figure 2(a) shows the calculated magnetoconductance of the open equilateral triangular dot whose lead geometry corresponds to the first experimental device. Most of the features in the conductance can be easily traced to those of the eigenspectrum. In particular, the characteristic triangular features centered at zero field represent the shell structure of the eigenspectrum at $B = 0$ and its evolution as the magnetic field is raised. Intermediate and high-field features of the eigenspectrum (including the level crossings and anticrossings as well as the LL condensation) are also clearly manifested in the transport calculations. However, the above correspondence is not perfect: Some energy levels are not seen in the conductance. Besides, many closely lying energy levels are apparently merged because the lifetime broadening in this case exceeds the level separation.

Let us now turn to the comparison of the theory and the experiment. The most striking similarity between these two is the triangular structures at low magnetic fields. To demonstrate that experimentally observable features can be explained within the eigenspectrum picture outlined above, one has to relate the variation of the experimental gate voltage to the energy (or k) scale. We perform this calibration on the basis of the high-field Aharonov-Bohm oscillations observed as a function of the gate voltage. We use the Aharonov-Bohm formula which determines the periodicity of the oscillations, $\Delta S = h/(eB)$, as the enclosed flux is changed, $\Delta\Phi = B\Delta S\, e/h$. Thus, from the experimentally observed periodicity $\Delta V_g = 0.013$ V at $B = 0.85$ T we can deduce the change in the side of the triangle, $\Delta L \approx 19$ nm. In the above estimation we used the expression for the area of the triangle, $S = \sqrt{3}L^2/4$, where $L = 300$ nm. We also assumed that the changing of the gate voltage affects primarily the dot size and not the electron density (this was proven to be the case for a similar open quantum dot defined in the same MBE wafer [13]). Then, the typical interval between neighboring triangles, $\Delta V_g = V_{g1} - V_{g2} \approx 0.025$ V translates into a difference in the dot size, $\Delta L_{\mathrm{exp}} \approx 36$ nm. On the other hand, we can use scaling arguments in (1) to estimate the difference in the triangle side dimension for a fixed k corresponding to the two neighboring shells. Assuming $k = 0.65 \times 10^8$ m^{-1}, the distance between, for example, sixth and fifth shells [i.e., distance between levels ($m = 7$, $n = 1$) and (6, 1) which lie at the top of the respective shells, see Fig. 2] corresponds, at the fixed k, to the changing of the dot size, $\Delta L_{\mathrm{theor}} \approx 65$ nm. Because of the uncertainty in the dot size, potential shape, the

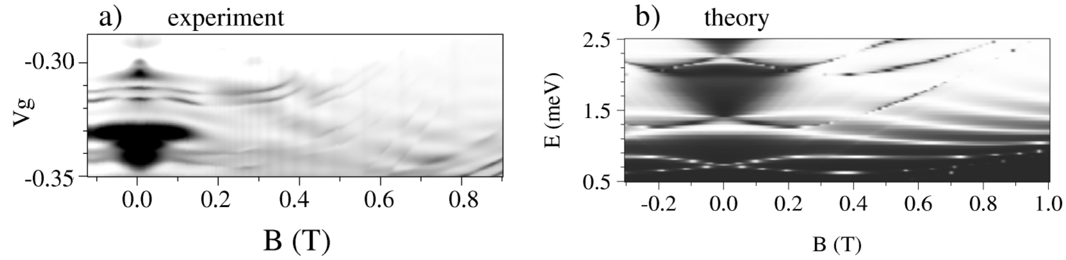

FIG. 3. A close-up of (a) the lower part of Fig. 1; (b) the lower part of Fig. 2(a). Broad resonances going down in both figures are due to levels collapsing to the lowest LL. They cross with sharper resonances raising up to the next LL. Near $B = 0$ the shell structure as well as contribution from single levels are clearly resolved in both plots.

assumption of a constant density used above, etc., one cannot expect the two estimated values $\Delta L_{\mathrm{theor}}$ and ΔL_{exp} to be identical. However, the fact that they are in a good quantitative agreement strongly supports our conclusion that the observed triangular features correspond to the shell structures of the isolated dot.

Both theory and experiment agree that as the number of modes in the leads is reduced more detailed structures within the shells becomes discernible. This is illustrated in Fig. 3(a) which expands the region (i) of Fig. 1, i.e., there exists one mode in the leads. Figure 3(b) shows the conductance calculation for the second through fourth shell. The experimental results should also be compared directly to eigenspectrum calculations of the closed dot shown in Fig. 2. Many of the theoretical features can be observed in the experimental data. The broad resonances moving down as the magnetic field is raised are the levels collapsing to the lowest LL at high fields. This is a clear manifestation of the Landau level condensation discussed above. They are broad because the wave functions are largely close to the boundaries of the dot and hence the coupling to them is strong. Second, the shell structure observed for more modes in the leads is seen to break into three lines at $B = 0$ for each of the two shells shown. These correspond to the three degeneracies of levels seen in the eigenspectrum (e.g., between 4 and 6 meV in Fig. 2). Consider the top shell in the experimental data of Fig. 3(a). The top line is largely due to a single level, while the bottom two contain several levels each. The sharp amplitude modulation along the levels seen both experimentally and theoretically is due to the interplay of these levels. At slightly higher fields the resonances sharply turn up again both experimentally and theoretically going to the next LL. They apparently cross with the levels collapsing to the lowest LL. Thus, the level crossings seen in the eigenspectrum clearly translates into the theoretical as well as experimental conductances. Amazingly, these levels can be followed all the way to magnetic fields where they become responsible for the edge state Aharanov-Bohm resonances.

In summary, we are able to conclude that the shell structure of the underlying closed dot dominates the conductance of the open few-electron dot for conditions in which several modes exist in the leads, whereas single level transport begins to dominate as the number of modes in the leads is reduced to one. This is clearly a new regime for open quantum dot transport.

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