PHYSICAL REVIEW B **66**, 161312 (2002)

Bouncing states in quantum dots

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(Received 15 April 2002; revised manuscript received 9 July 2002; published 24 October 2002)

We observe sequences of asymmetric Coulomb blockade resonances in the conductance of a closed quantum dot. Around a symmetric peak at the center of such a sequence, several asymmetric resonances with a steep flank facing the central peak are found. This effect occurs for an average coupling of the quantum dot states to the leads which is of the order of both their average energy level spacing as well as of the thermal energy. These observations are interpreted in terms of a single state ("bouncing state") that couples particularly well to the leads. Such a state can influence the line shapes of several neighboring Coulomb blockade resonances.

DOI: 10.1103/PhysRevB.66.161312 PACS number(s): 73.63.−b, 73.21.−b

I. INTRODUCTION

Quantum dots in the Coulomb blockade (CB) regime are model systems for the investigation of quantum effects.[1,2] The position of CB resonances as a function of a gate voltage contains information on the energetic structure of the electron gas confined in the quantum dot. For a single current-carrying discrete state in the dot and within the constant-interaction model, the line shape of the resonances is given by the convolution of a Lorentzian with the derivative of the thermally smeared Fermi function.[3] The linewidth Γ of the Lorentzian is determined by the coupling of the resonant state to the leads. Within this model, the resonances are thus symmetric. However, various types of asymmetric CB resonances have been observed as well. At quantum dots with $\Gamma \ll \Delta$ (Δ is the average energy level spacing in the quantum dot), characteristic steplike resonances are observed for source-drain bias voltages comparable to Δ.[4] Adjacent peaks with strongly temperature dependent broad wings facing each other are often a signature of the Kondo correlation.[5] Furthermore, Fano-type resonances[6] as well as parametric[7] and dynamic[8] background charge rearrangements have been identified as possible sources of CB resonance asymmetries. Moreover, the origin of asymmetries observed in several experiments has remained unexplained.[9]

Here we report on sequences of asymmetric peaks, in direct neighborhood to an approximately symmetric resonance at the center of the sequence. The steep flanks of these peaks face the symmetric resonance, and are governed by thermal smearing. The gently sloped flanks pointing away from the center peak, on the other hand, are reasonably well approximated by a Lorentzian. This pattern is observed only in the regime where $\Delta \approx \Gamma \approx kT$ (kT denotes the thermal energy).

We interpret these findings in terms of sparse dot states that couple particularly strongly to the leads.[10] The wave functions of such states correspond to semiclassical electron trajectories that bounce back and forth between the entrance and the exit of the quantum dot. The picture developed can be generalized to explain qualitatively the occasional occurrence of asymmetric CB resonances in other experiments.

II. EXPERIMENTAL SETUP AND RESULTS

The quantum dot is defined by applying negative voltages to gate electrodes [Fig. 1(a)], on top of a parabolic Ga[Al]As quantum well containing an electron gas in the two-dimensional limit, i.e., only the lowest two-dimensional subband in growth direction is occupied. The details of the sample fabrication and the basic properties of the as-grown heterostructure are described in Refs. 11 and 12. The dot studied in this paper has a geometric area of $400 \times 600\ \text{nm}^2$, and contains about 200 electrons. The experiments have been carried out in a dilution refrigerator with a base temperature of 60 mK. DC source-drain bias voltages of $V_{sd} = 10\ \mu\text{V}$ have been applied, and the conductance of the quantum dot is measured as a function of two plunger gate voltages. In all experiments reported here, the dot was in the CB regime. From measurements of CB diamonds, we estimate $\Delta \approx 25\ \mu\text{eV}$, in agreement with the level spacing expected from the geometric dot area, reduced by the lateral depletion length of ≈ 80 nm. By fitting symmetric CB peaks[13] not related to a sequence of asymmetric resonances, we find a peak width of 40–50 μeV. With the same procedure applied to the Coulomb resonances in a family of states close to a bouncing state the peak width is 70–100 μeV We are therefore in a regime where $\Gamma \approx \Delta \approx kT$.

Figure 1(b) shows a series of CB resonances as a function of the right plunger gate voltage. The numbering of the CB peaks introduced here is kept throughout the paper. The central and highest peak is No. 6. The other peaks are smaller and display asymmetric line shapes, with an amplitude and an asymmetry that decreases as the separation to peak No. 6 increases. This can be seen immediately by comparing the measurement to a fit assuming purely thermal broadening [thin line in Fig. 1(b)]. As such fits are only appropriate for $\Gamma \ll kT$, deviations occur in the tails of the symmetric peak as well. We nevertheless use the derivative of the Fermi function as the fit function, since in the following we are going to quantify the peak asymmetries from these fits. This requires

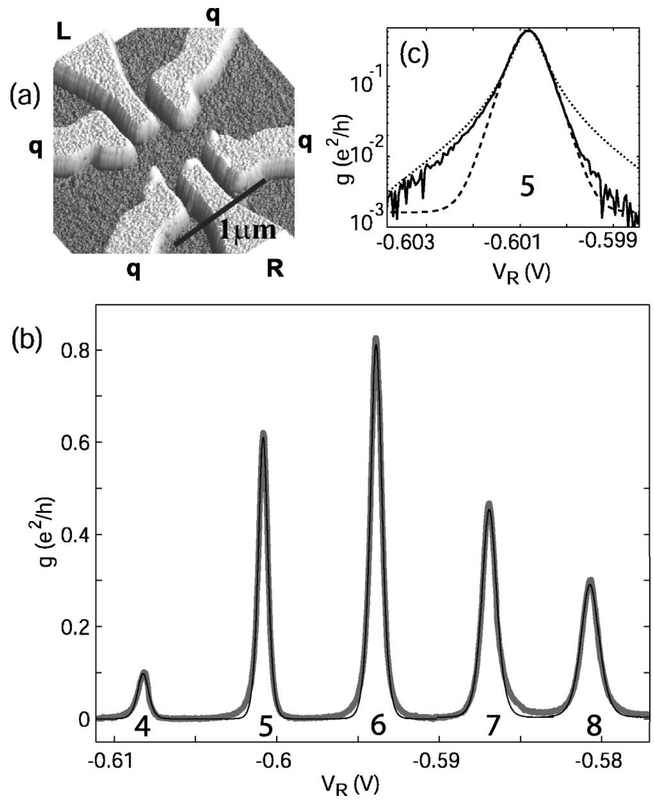

FIG. 1. (a) The gate arrangement fabricated by electron beam lithography. The split gates labeled q allow for an adjustment of the tunnel barriers that couple the island to source and drain. The plunger gates L and R are used to tune the electrostatic potential of the dot. (b) Conductance through the quantum dot as a function of plunger gate voltage. The peak numbering as presented in this figure is kept throughout the text. The thin line is a fit of a thermally broadened lineshape to the measured CB resonances (semitransparent gray line). (c) Peak No. 5 on a logarithmic scale with a Lorentzian fit (dotted line) and a fit to a thermally broadened line shape (dashed line).

a nominally identical fit parameter for all resonances, which in this case is the temperature. The homogeneous part of the line shape, on the other hand, depends on the particular resonance.

The character of the peak asymmetry is investigated more closely in Figure 1(c). It shows peak No. 5 on a logarithmic conductance scale. While the broad tail pointing away from the central peak (No. 6) is well described by a Lorentzian fit (dotted line), a thermally broadened line (dashed line) fits significantly better to the steep tail facing the central peak. This indicates that the asymmetric peaks have a gentle Lorentzian wing and a steep wing governed by thermal broadening.

It is noteworthy that the presence of a sequence as shown in Fig. 1(b) depends delicately on the experimental conditions, and could only be established within narrow parameter ranges. The best yield was obtained by starting out from a weakly coupled dot ($\Gamma \ll kT$) and searching for suitably looking sequences of CB resonances, i.e., a peak of high amplitude, symmetrically haloed by several weaker CB resonances. Next, the coupling of the dot to its leads is increased by reducing the height of the two tunnel barriers. This is achieved by changing the voltages applied to the gates labeled q in Fig. 1(a) accordingly.

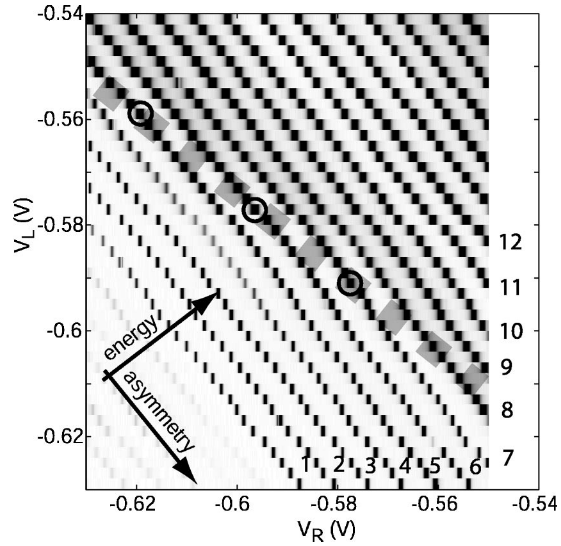

FIG. 2. Coulomb peak positions as a function of both plunger gate voltages. The symbols running from the upper left to the lower right resemble Coulomb maxima for a fixed electron number. The arrows along the diagonals indicate the directions in which we predominantly tune the energy of the dot, and its asymmetry, respectively. The symmetric resonance is indicated by circles.

The symmetry of the dot potential plays a crucial role. In the most symmetric situation (i.e., for identical voltages applied to both plunger gates, as well as similar voltages applied to the q gates), we found the highest amplitude for the symmetric center peak and pronounced asymmetries in the halo peaks. In order to investigate the stability of the peak asymmetries with respect to the asymmetry of the dot potential, we studied the evolution of the sequence shown in Fig. 1 as a function of the two plunger gate voltages (Fig. 2).[14,15]

In the plane spanned by the two plunger gate voltages, the CB peak positions basically follow straight lines with a slope of 1, which means that the two gate voltages, which deform the dot differently, modify the energy spectrum almost identically. Therefore, we can attribute the direction perpendicular to the resonance shifts as an energy axis, while the direction parallel to the resonance position corresponds to the asymmetry of the dot. The symmetric line shape, however, cannot be attributed to a single resonance line in Fig. 2. Rather, it moves from peak No. 5 to peak No. 8 as the right plunger gate voltage is increased. This is an indication of gate-voltage induced energy level crossings in the dot.

In Fig. 3, we show how the asymmetries of several peaks in Fig. 2 evolve along the dot asymmetry axis. In order to quantify the asymmetry of the resonances, we have calculated the area enclosed by a measured resonance, minus the area enclosed by the fit based on thermal broadening, for both wings of the resonance. The normalized ratio of these two numbers is taken as a measure of the peak asymmetry, which is plotted in Fig. 3 for resonance Nos. 4–8. While the sign of the asymmetry is arbitrary within our definition, a sign change occurs as one moves across the symmetric center peak, as can be seen already in the raw data of Fig. 1. Interestingly, the asymmetric halo of peaks follows the sym-

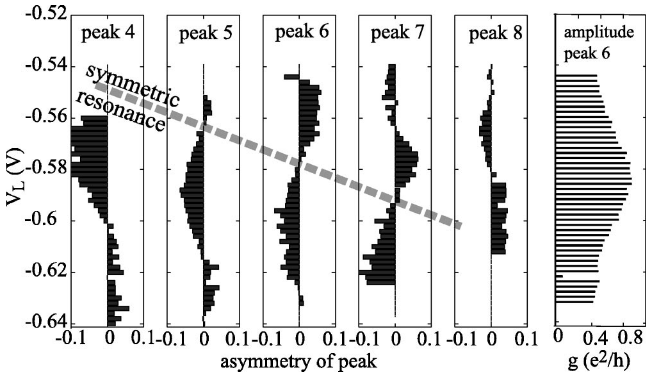

FIG. 3. Normalized asymmetry vs left plunger gate voltage for five consecutive Coulomb maxima. The dashed line marks zero asymmetry and shows how the symmetric line shape is transferred between the resonances. At the same time, the right plunger gate voltage has been changed accordingly so as to follow a particular peak at constant electron number in the dot.

metric central peak. Since we know that the dot deformation generates energy level crossings (see above), it can thus be concluded that the asymmetry *correlates with the energy of the symmetric resonance*, and is *not* an intrinsic property of the particular energy level in resonance with the chemical potential of the leads.

In the rightmost part of Fig. 3, the amplitude of resonance No. 6 is shown as a function of the dot asymmetry. The amplitude assumes a maximum for the most symmetric situation. Such a behavior is also observed for the other resonances discussed in Fig. 4. Hence *the state that imposes the asymmetry on its neighbors couples particularly well to the leads*.

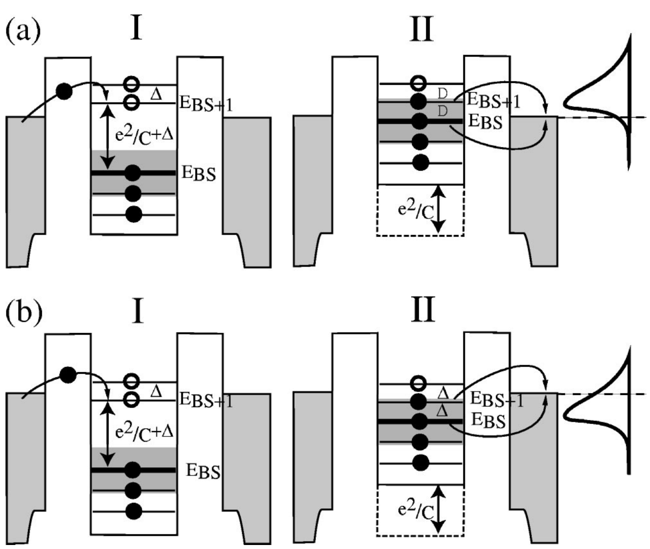

FIG. 4. Origin of the asymmetry of conductance resonances close to a bouncing state (BS). In resonance, the dot oscillates between two configurations I and II. (a) For $E_{\mathrm{BS}+1}>E_F$, and $E_{\mathrm{BS}+1}-E_F\leq k_BT$, the average coupling of the dot to the leads is small, and a small conductance results. (b) If $E_{\mathrm{BS}+1}<E_F$ and $E_F-E_{\mathrm{BS}+1}\leq k_BT$, the average conductance is increased. The corresponding position and shape of the resonance is sketched in between states I and II for both scenarios. Full circles denote occupied states, while transparent circles represent empty states.

As already pointed out above, the peak asymmetries vanish as the coupling of the dot to the leads is reduced. Upon further increasing the coupling, or the temperature, respectively, the CB peaks start to overlap, such that an analysis of asymmetries is no longer appropriate. We have furthermore applied in-plane magnetic fields up to 1 T to the quantum dot, and have not observed any significant changes of the observed asymmetries. Since an in-plane magnetic field predominantely influences the spin degrees of freedom while leaving orbital effects basically unchanged,[12] this suggests that the asymmetries are evoked by an orbital effect.

Similar to the plunger gate voltages, a perpendicular magnetic field could be used to study the parametric evolution of the resonance asymmetries. This magnetic field direction, however, was not available during the cooldown in which the data reported here have been taken. In different cooldowns with the sample rotated, we have been unable to establish an equally well pronounced sequence of asymmetric peaks. We attribute this experimental difficulty to the narrow parameter range in which these effects are observable, an issue that will be revisited in the discussion.

III. INTERPRETATION IN TERMS OF BOUNCING STATES

The interpretation of these observations is based on the idea that the dot supports quantum states that are exceptionally well coupled to the leads, as suggested in Ref. 10. In accordance with the expression used there, we refer to such states as *bouncing states*. These states are related to classical trajectories on which electrons bounce back and forth between the source and drain; the associated wave functions therefore have a strong overlap with the leads. Consequently, the bouncing states will be much broader than the neighboring states which couple much less to the leads. Hence bouncing states are somewhat reminiscent of states in open ballistic dots with a large wave function amplitude at the entrance and the exit, which are known to cause transmission maxima.[16] Whenever a bouncing state is close to the Fermi energy, it will dominate the current through the dot within a certain energy interval. The current through sharp levels in this interval is negligible, but the thermal occupation of these levels is important as it determines the electrostatic energy of the dot. When a bouncing state is in resonance with the Fermi energy of source and drain the familiar regime of resonant tunneling is entered which gives rise to a symmetric conductance peak (peak No. 6 in Fig. 1).

In order to obtain a qualitative understanding of the origin of the asymmetry, consider the level diagram in Fig. 4. The strongly coupling level, i.e., the bouncing state, is labeled BS and the neighboring level with higher energy is denoted BS+1. In Fig. 2(a) the electrochemical potential of level BS+1 lies within k_BT *above* the Fermi level E_F in the leads. In such a situation, the Coulomb blockade is lifted and a current can flow. The dot oscillates between two configurations I and II, with level BS+1 either empty (I) or occupied (II). Since $E_{\mathrm{BS}+1}$ is above E_F, the tunneling-in process indicated in I has a smaller rate than the tunneling-out processes indicated in configuration II. The thermal activation necessary for an electron to tunnel into the dot will therefore dominate the tunneling current. For the line shape of the conductance resonance, this results in the sharp thermally activated slope on the inner side of the peak for which the intrinsic level broadening of the BS is plays no role. Figure 4(b) shows the scenario, where level BS+1 lies within k_BT *below* E_F and is thus occupied most of the time. In this case the tunneling-in process has a rate which is not governed by exponential activation. Consequently, there will be a competition for tunneling out between the BS level and the BS+1 level indicated in configuration II which is dominated by the strongly lifetime broadened BS. In the current-gate-voltage diagram this contribution is seen in the broad flank of the Coulomb peaks pointing *away* from the symmetric center peak. This flank is therefore determined by Γ and not by thermal smearing. Consequently, in scenario (b), the overall conductance is larger than in scenario (a), for *identical* absolute values of $E_F - E_{\mathrm{BS}+1}$. A similar argument can be made for energy levels below E_{BS}. According to this line of arguing, peak asymmetries can only be observed if the level broadening of the bouncing state is of the order or larger than kT and if kT is comparable to the average level spacing Δ.

Furthermore, as theoretical considerations have shown, the asymmetries can only be observed if the parameter $a_{\mathrm{eff}} k_{F,\mathrm{dot}} > 1$.[10] Here a_{eff} means the effective electronic width of the tunnel barrier perpendicular to the transport direction and in the plane of the electron gas, while $k_{F,\mathrm{dot}}$ denotes the electron wave number at the Fermi level inside the dot. In other words, this means that the transverse confining strength in the tunnel barrier must be small, and the electron density in the dot must be high. This condition essentially ensures that the electrons are predominantly injected in the dot within a small angle in forward direction and couple well to a bouncing state, if present. For our sample we estimate $a_{\mathrm{eff}} k_{F,\mathrm{dot}} \approx 3.5$, which is comparable to the value assumed in Ref. 10.

So far, we have neglected the spin degeneracy in our discussion. In case the shape of the orbital wave function is the characteristic feature of a bouncing state, one might expect that bouncing states occur in pairs, which we do not observe experimentally. In order to explain this, we speculate that one peculiar feature of bouncing states is a comparatively large spin splitting. Regular states in similar dots have a spin-splitting energy of the order of Δ.[15,17] The bouncing state wave function, however, is strongly concentrated along a straight line connecting the two tunnel barriers and thus extends only over a small fraction of the dot area. Therefore, one would expect that the corresponding zero-field spin splitting is rather large because of the exchange interaction,[17] leading to a single bouncing state in a comparatively large energy range.

IV. DISCUSSION AND CONCLUSIONS

We have detected a type of asymmetry in Coulomb blockade resonances as a function of the gate voltage. In its purest form, a symmetric CB resonance that couples particularly well to the reservoirs is haloed by a sequence of asymmetric peak amplitudes. The steep flanks of these peaks face the central peak and are governed by thermal smearing, while the gently sloped flanks point away from the central peak and have a Lorentzian shape. Both the amplitudes and asymmetries of the halo peaks decrease as their distance from the central peak increases. We have argued that in highly symmetric dots, a bouncing state can exist which couples especially well to the leads, and therefore dominates the conductance in several neighboring resonances. Both the experiment and the model demonstrate that the observation of this effect depends crucially on several parameters, in particular on the symmetry of the dot potential, the shape of the tunnel barriers that couple the dot to source and drain, and the Fermi energy inside the dot. Therefore, small changes in the impurity potential typical for thermal cycling of the sample may already be sufficient to hamper the reproducibility. In addition, the coupling of the energy levels to the leads must be comparable to both the thermal energy and the energy level separation in the dot. Due to the narrow parameter range in which a whole sequence of asymmetric peaks can be observed, in combination with gate-voltage induced energy level crossings, it can be easily imagined that the mechanism discussed here generates single, or few, asymmetric CB resonances as observed occasionally in this type of experiments.

ACKNOWLEDGMENTS

It is a pleasure to thank A. Fuhrer for valuable discussions. Financial support by the Schweizerischer Nationalfonds is gratefully appreciated.

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