Lead-Orientation-Dependent Wave Function Scarring in Open Quantum Dots

J. P. Bird,[1] R. Akis,[1] D. K. Ferry,[1] D. Vasileska,[1] J. Cooper,[2] Y. Aoyagi,[2] and T. Sugano[2]
[1]*Center for Solid State Electronics Research & Department of Electrical Engineering, Arizona State University, Tempe, Arizona 85287-5706*
[2]*Nanoelectronic Materials Laboratory, Frontier Research Program, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-01, Japan*
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Experimental studies of the conductance of *open* quantum dots show a series of highly regular oscillations at low temperatures as the voltage applied to their defining gates is varied. Simulations of quantum transport through these dots reveal the oscillations to be correlated to the recurrence of specific groups of wave function scars. We furthermore find that nominally identical dots, differing only in the *orientation* of their input and output contacts, may be used to excite different families of scars, giving rise in turn to measurable transport results. [S0031-9007(99)09319-9]

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Semiconductor quantum dots, consisting of a submicron sized cavity and quantum point contact leads, are ideally suited for studying the influence of environmental coupling on the discrete level spectrum of quantum systems. Of particular interest here is the nature of electron transport in *open* dots, whose leads are configured to support a *small* number of propagating modes. While it is often argued that the level spectrum is continuous in such dots, recent studies have instead emphasized the role that the leads play in selectively exciting discrete dot states during transport [1–5]. In this Letter, we consider the *sensitivity* of this selection process to the nature of the coupling that is provided between the dot and its external environment. Split-gate dots with different lead *orientations* are fabricated and their transport properties are measured at low temperatures. When the voltage applied to their defining gates is varied, a series of regular oscillations is observed in the conductance, providing a unique signature of the coupling-induced modifications that arise in the level spectra of the dots. The details of the oscillations are found to be related to the recurrence with gate voltage of strongly scarred wave function states, whose features are sensitive to the lead configuration in the dots. We discuss these results in terms of the influence of the lead openings on electron transport in open dots.

Here we summarize the results of studies of more than ten different split-gate dots, whose fabrication has been described elsewhere [6]. We focus, in particular, on the behavior exhibited by two dots with different lead configurations (see Fig. 1). The transport properties of these GaAs/AlGaAs dots were measured in a dilution refrigerator, at a fridge temperature of 10 mK and using small constant currents with lockin detection [6]. From measurements at this temperature, the wafer mobility and carrier density were determined and were found to be 4×10^{15} m^{-2} and 70 m^2/V s, respectively. The effective size of the dots was estimated from the period of Aharonov-Bohm oscillations in the edge state regime [6] and varied from 0.2–0.3 μm, depending on the value of the applied gate voltage. An upper-bound estimate of the number of electrons in the dots is therefore of the order of 100–400, for the same range of gate voltage. Another parameter inferred from magnetotransport studies was the electron phase breaking time (τ_ϕ), which was of the order of 100 ps at the low temperatures of interest here [6].

The main panel of Fig. 2 shows the measured variation of conductance with gate voltage for the dot with staggered leads. Of interest here are the fine oscillations, which ride on top of a monotonic background and which disappear on warming to a few degrees kelvin [7] (Fig. 2, lower inset). The oscillations are observed over the entire range of gate voltage for which the dot is defined and persist to conductance values as high as $15e^2/h$. After subtracting the background from the total conductance variation, the series of regular oscillations shown in the upper inset of Fig. 2 is obtained. Note how the average amplitude of the oscillations does not vary significantly with gate voltage, *even when the leads are opened so that the dot conductance exceeds* $10e^2/h$. This characteristic was confirmed in studies of the other dots, which showed similar oscillations to those discussed here. In the inset of Fig. 3, for example, we show similar behavior in the dot with aligned leads [we have already subtracted a background here, which varied from $(1–8)e^2/h$ over the voltage range shown]. A Fourier analysis of the oscillations in Figs. 2 and 3 confirms their periodic nature and reveals the presence of a small number

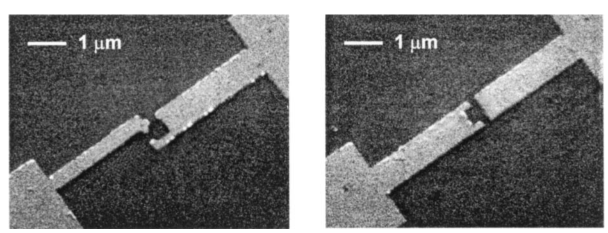

FIG. 1. SEM micrographs of the split-gate quantum dots studied here. Left: staggered-lead geometry. Right: aligned-lead geometry.

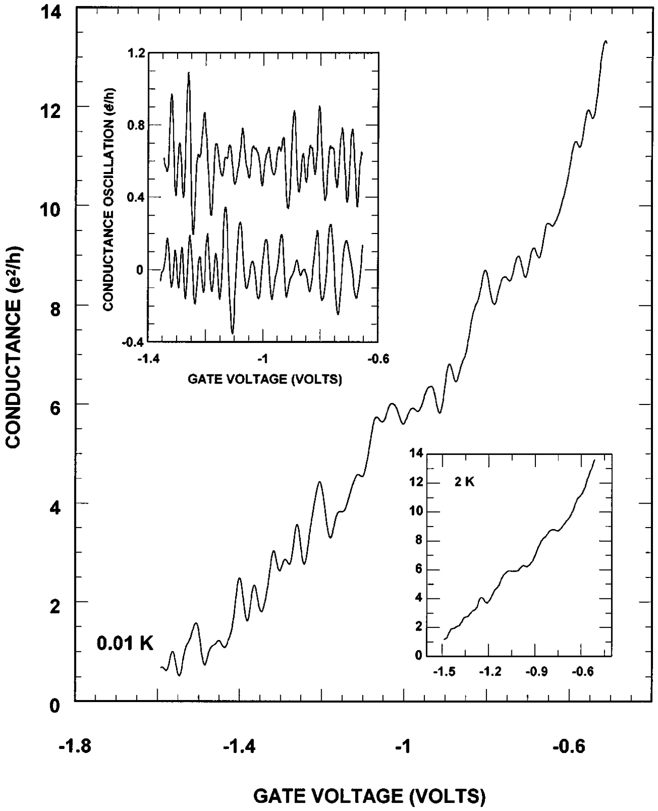

FIG. 2. Main panel: conductance-gate voltage characteristic of the staggered dot. Lower inset: same plot, measured at 2 K. Upper inset: experimental and computed conductance oscillations for the dot. The upper curve is experiment and is offset by $+0.6e^2/h$.

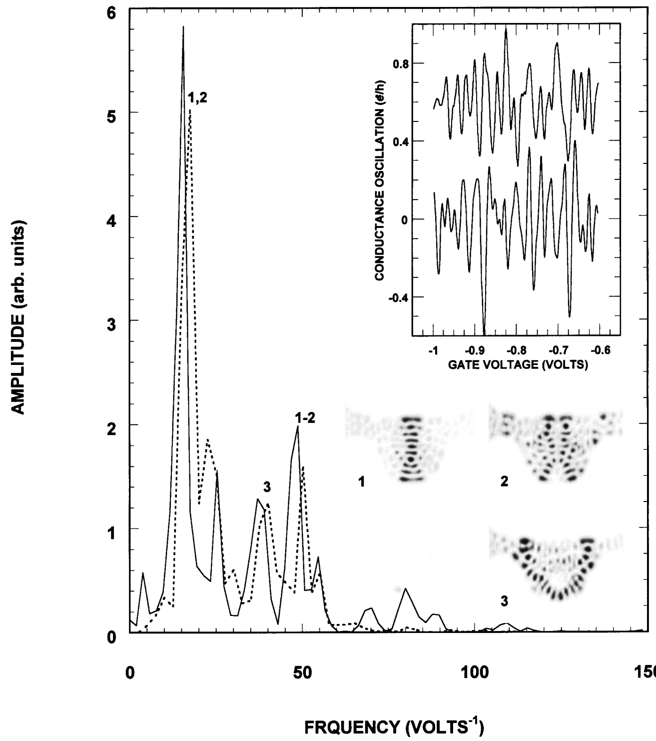

FIG. 3. Main panel: Fourier spectra of measured and computed oscillations in the aligned dot. Dashed line is theory. Upper inset: experimental and computed conductance oscillations for the dot. The upper curve is experiment and is offset by $+0.6e^2/h$. Lower inset: recurring scars of this dot. The numbers here show the association between specific scars and Fourier peaks and dark regions correspond to high probability.

of dominant peaks at isolated frequencies (Figs. 3 and 4). Crucially, these peaks occur at different *frequencies* in the two dot geometries, an issue we return to in detail below.

To account for the behavior seen in the experiment, simulations of electron transport in the open dots have been performed. These begin by computing the self-consistent profile of the dots, at more than 300 gate voltages that uniformly span the ranges considered in experiment. A three-dimensional Poisson solver is used here, whose details have been described elsewhere [8]. The solver uses only experimental parameters as inputs and reproduces very closely the pinch-off characteristics of the dots. The conductance is then computed at each gate voltage using a lattice discretization of the *single-particle* Schrödinger equation [1]. In this approach, the dot is broken into a series of lattice slices that we translate across using a numerically stable, iterative transfer-matrix technique [1]. In this way, we obtain the transmission coefficients of the dot and thus its conductance from the Landauer formula. The calculations are performed for a fixed Fermi energy that is chosen by matching the carrier density in the reservoirs to the bulk value inferred from experiment. The influence of the contacts is directly included in the simulations [1], which use the computed profile of the *open* dots in the lattice discretization. This approach also allows the wave functions within the dots to be reconstructed [1]. Dephasing may be included in the simulations by adding to the Hamiltonian an imaginary potential ($V_{\mathrm{im}} = i\hbar/2\tau_\phi$) [2] that is chosen to match the dephasing times inferred from experiment. Finite temperature is accounted for by averaging conductance traces over an energy range of order $k_B T$. Previous experiment suggests that the lowest effective temperature to which the electrons cool in the dots is of the order of 100 mK [9].

Computed conductance oscillations are compared to experiment in the insets of Figs. 2 and 3. The simulations account well for the frequency content found in experiment, a conclusion that is confirmed by comparing the Fourier spectra of the measured and computed oscillations (Figs. 3 and 4). In particular, the *number* of Fourier peaks seen in experiment is matched precisely in the simulations, which also closely reproduce the frequencies at which the peaks occur. *These peaks in fact correspond to the frequencies at which specific sets of wave function scars recur in the dots.* In the dot with aligned leads, for example, three different scars are found to recur (Fig. 3, lower inset). The bouncing-ball scars (labeled "1" and "2") recur at a frequency of 15 V^{-1}, in good agreement with the

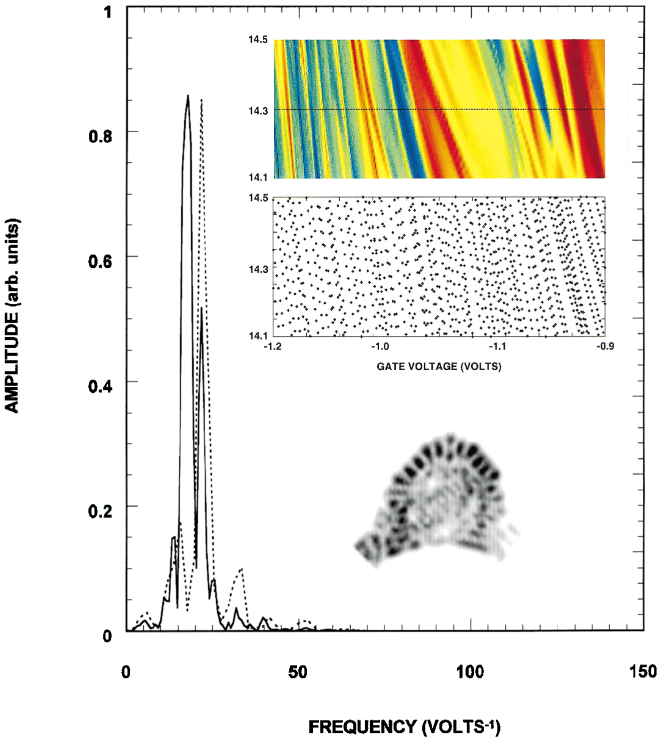

FIG. 4. Main panel: Fourier spectra of measured and computed oscillations in the staggered dot. Dashed line is theory. Lower inset: recurring scar found in this geometry. Upper inset (color): variation of the staggered-lead dot conductance with gate voltage and energy (upper plot). Color scale varies from $(0-2)e^2/h$ and the dashed line shows the Fermi energy. Also shown (lower plot) is the evolution of the *closed* dot eigenstates with gate voltage. *See text for further details.*

position of the fundamental peak in Fig. 3. The scars do not occur at the same gate voltages, however, but are phase shifted from each other by a fixed increment of 20 mV, so that the peak at 50 V^{-1} in Fig. 3 appears to result from a mixing of these. The third scar found in this dot ("3") shows a whispering-gallery form and recurs at a frequency of 40 V^{-1}, corresponding to the final major peak in Fig. 3. As for the dot with staggered leads, the conductance oscillations in this are dominated by a single-frequency component (Fig. 4). Similarly, the simulations show that *only one* scar recurs significantly in this dot (Fig. 4, lower inset) and that the frequency of recurrence of this whispering-gallery scar matches that of the dominant peak observed in the Fourier spectrum of the computed oscillations (Fig. 4).

The results above show that *quantum dots with different lead alignments may be used to excite different wave function scars, giving rise to measurable transport results.* The possibility of such manipulation was in fact predicted recently [3,5] and derives from the properties of the point contact leads [1]. Because of the quantization of transverse motion within these, electrons may only enter the dot by matching their transverse momentum component to one of the quantized values within the input lead. Electrons are therefore injected into the dot in a collimated beam [1–3] that is only able to couple to those states whose momentum components it closely matches [4,5]. That is, opening the dot by means of quantum point contacts does not obscure its discrete level spectrum, but rather results in a small set of dot states being excited in transport [5]. The coherent interference of these states is in turn thought to give rise to the wave function scarring at low temperatures [1–5]. If the orientation of the lead openings is altered, the main effect is to modify the details of the electron collimation [1] so that *different dot states will be favored in transport, giving rise to different scarring characteristics* [3].

The self-consistent calculations show that increasing the negative gate bias reduces the effective size of the dots, but leaves their overall shape relatively unaffected (not shown here). The conductance oscillations are therefore thought to arise as this size variation forces successive dot states to sweep past the Fermi surface, thus modulating the coupling between these states and the point contact leads. The connection between the eigenstates of the closed dot and the conductance of its open counterpart can be seen in the inset to Fig. 4, where we plot the energy spectrum of an *isolated* dot. These levels were computed using the self-consistent profiles for the dot with staggered leads, after closing the leads at their narrowest points. A two-dimensional finite-difference Schrödinger equation with Dirichlet boundary conditions was then solved to obtain the discrete state energies themselves. Note how these levels shift almost linearly over large ranges of gate voltage, which presumably accounts for the periodicity of the conductance oscillations. For comparison, the computed conductance variation for the *open* staggered dot is also shown in Fig. 4. While the linear striations that run through this gray scale plot follow the motion of certain closed-dot states, it is clear that *not all states of the isolated dot give rise to a marked modulation of conductance in the open dot.* Instead, this conductance provides a *filtered* probe of the density of states of the closed dot. This conclusion is confirmed by calculations performed for the dot with aligned leads (not shown here), although in this dot the previously mentioned collimation effect causes *different* groups of dot states to be excited in transport. Conductance oscillations with different periodicities, and different families of recurring scars, are thus obtained in this dot.

Coulomb blockade may also give rise to conductance oscillations when the gate voltage is varied [10–13]. Previously, it was argued that this effect is obscured in small dots if their leads are configured to support one or more propagating modes [10]. Recently, however, Coulomb blockade has been found to persist in semiopen dots, in which one lead is configured as a tunnel barrier while the other transmits a *single* mode [13,14]. In yet another study, evidence for the persistence of Coulomb blockade to dot conductances as high as $4e^2/h$ has even been presented [12]. This latter observation seems to be unique to the very special dot geometry considered in Ref. [12], however, which we emphasize is very different to the geometry studied here. Instead, it is fairly well established from experiment that in dots with lead realizations similar to those studied here, the Coulomb blockade is dramatically suppressed when *both* leads are opened to support one mode [10,11]. Nonetheless, *in the experiment here the oscillations are found to persist to dot conductances as high as 15e^2/h with little noticeable variation in amplitude* (Fig. 2). The details of these oscillations are also well accounted for by what is essentially our single electron picture of transport. We therefore believe that the oscillations *do not* result from some remnant of the Coulomb blockade effect. Indeed, a recent study suggests that charging effects should be only important in open dots at higher temperatures, *in excess* of the average level spacing [15]. For the dots of interest here, typical values for this parameter ($\Delta = 2\pi\hbar^2/m^*A$, where A is the dot area) are of the order of 1.3 K and experiment shows that the oscillations we study *grow* in amplitude as the temperature is *lowered* below this value.

In conclusion, we have demonstrated the sensitivity of wave function scarring in open dots to the orientation of the point contact leads that provide their environmental coupling.

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