Coherent Electron Transport in a Si Quantum Dot Dimer

L. P. Rokhinson, L. J. Guo,* S. Y. Chou, and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

E. Eisenberg,[1,2] R. Berkovits,[1,2,3] and B. L. Altshuler[1,2]
[1]*Department of Physics, Princeton University, Princeton, New Jersey 08544*
[2]*NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540*
[3]*Minerva Center and Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel*
(Received 14 August 2001; published 18 April 2002)

We show that the coherence of charge transfer through a weakly coupled double-dot dimer can be determined by analyzing the statistics of the conductance pattern, and does not require a large phase coherence length in the host material. We present an experimental study of the charge transport through a small Si nanostructure, which contains two quantum dots. The transport through the dimer is shown to be coherent. At the same time, one of the dots is strongly coupled to the leads, and the overall transport is dominated by inelastic cotunneling processes.

DOI: 10.1103/PhysRevLett.88.186801 PACS numbers: 73.23.Hk, 71.70.Ej, 85.30.–z

The ability to preserve quantum coherence over large distances and during an extended period of time plays a key role in the quest for alternative schemes for conventional electronics and nonclassical electronic behavior. For this purpose, low-dimensional structures, in particular, quantum dots, have an obvious advantage, because the k space for inelastic scattering events is reduced due to the reduced dimensionality. Conventionally, coherence is probed by quantum interference effects, such as weak localization. In closed quantum dots, coherence has been investigated by embedding the dot in one arm of an Aharonov-Bohm interferometer [1]. This method requires a host material with large phase coherence length l_ϕ, larger than the total length of both arms of the interferometer.

Is it possible to measure coherence in a mesoscopic device embedded in a material with small l_ϕ? We encountered this problem during our studies of Si nanostructures, where in the host two-dimensional electron gas $l_\phi < 1000$ Å and interferometric methods cannot be used. Coherence in Si nanostructures is of particular interest because Si has intrinsically long spin relaxation time, which is of great importance for future spintronic devices. In this Letter we present a new method to discriminate between coherent and incoherent transport through a double dot system. The method is based on statistical analysis of the conductance pattern, and does not rely on large l_ϕ in the surrounding contact regions.

Statistical properties of single quantum dots have been extensively investigated over the past ten years [2]. In a weakly coupled double-dot dimer the statistical properties of each dot, such as the peak heights distribution, are almost uncorrelated. However, the way the individual conductances are combined into the total conductance of the dimer depends on whether the transport is coherent or sequential. Thus, a proper deconvolution of the total conductance can identify the type of the transport through the whole structure. This method directly probes the coherence during the charge transfer through several nanostructures, which is of a paramount importance for any practical applications.

In the following, we analyze charge transport through a Si double-dot device. We show that electrons are transferred coherently through the dimer, even though the transport is dominated by inelastic cotunneling processes. This result was not anticipated *a priori,* since conventional wisdom associates inelastic processes with decoherence.

The sample is a Si quantum dot fabricated from a silicon-on-insulator wafer. A narrow bridge with a lithographically defined dot is formed from the top Si layer; the bridge is connected to wide source and drain regions via two constrictions. Subsequently, a 50 nm thick layer of SiO_2 is thermally grown around the dot, followed by a poly-Si gate. For a detailed description of sample preparation see Ref. [3]. In most cases, more than one dot is naturally formed in such Si nanostructures, and the origin of these additional dots is a subject of ongoing research [4–6]. For this particular study we have chosen a device that exhibits two distinct periods of conductance oscillations at low temperatures. As will be shown below, the device consists of two dots, both participating in the charge transport.

The conductance G through the sample is plotted in Fig. 1a as a function of gate voltage $0 < V_g < 9$ V. The temperature dependence is shown in the inset. At high temperatures, 15 K $< T <$ 60 K, the data are consistent with the conventional theory of Coulomb blockade (CB) in a single dot [7]. This dot will be called dot 1 throughout the paper. At $T <$ 15 K the behavior of the conductance changes qualitatively—oscillations with a much smaller period are superimposed on the main dot CB oscillations. A remarkably large number of these fast oscillations—more than 500—can be resolved in a single scan. This coexistence of two periods suggests that two dots are involved in the transport. In fact, we can rule out

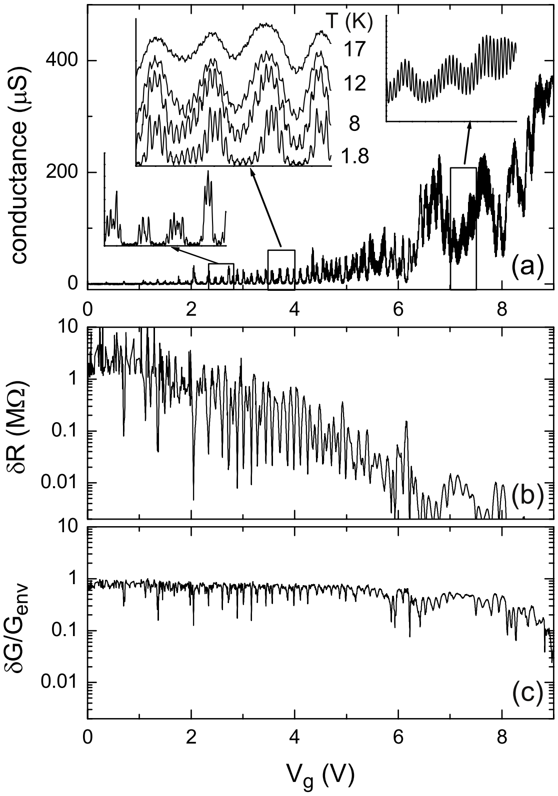

FIG. 1. (a) Conductance as a function of gate voltage measured at $T = 1.8$ K. Some regions are enlarged in the insets. In (b) and (c) the amplitude of the fast oscillations is extracted from the curve in (a) in units of resistance δR and in units of conductance, normalized by the envelope of the total conductance, $\delta G/G_{\mathrm{env}}$.

interference effects as an origin of the fast oscillations by showing that there is an electrostatic coupling between the dots.

It is well known that quantum dots can be used as sensitive electrometers, and, in our case, each of the dots can be potentially used to measure the charge on the other dot. In Fig. 2a normalized peak position of fast oscillations, $V_p'(N) = [V_g^p(N)/\langle \Delta V_{g2}\rangle - N]$, is plotted as a function of V_g, where $V_g^p(N)$ is the position of the Nth peak and $\langle \Delta V_{g2}\rangle = 14$ mV is the average peak spacing. For periodic oscillations V_p' should be a constant, independent of N (and V_g). Vertical lines mark positions of the CB peaks in dot 1. Slips of V_p' appear every time an electron is added into dot 1. These slips should be expected for capacitively coupled dots: each electron, added into dot 1, increases the electrostatic potential of dot 2 by $\Delta\phi = \frac{eC_c}{C_{\Sigma 1}C_{\Sigma 2}}$, resulting in a $\Delta\phi \frac{C_{\Sigma 2}}{C_{g2}}$ shift of the CB peaks. Here C_c, C_{g2}, $C_{\Sigma 1}$, and $C_{\Sigma 2}$ are the cross capacitance between the dots, the gate capacitance of dot 2, and the total capacitance of dots 1 and 2. The slips are extended over a few periods of the fast oscillations due to the finite broadening of the CB peaks in dot 1. We also observed two large slips extended over $\sim$20 periods (see inset). These probably reflect charging of some other traps, which do not participate in the transport. In principle, slips in peak positions can occur for

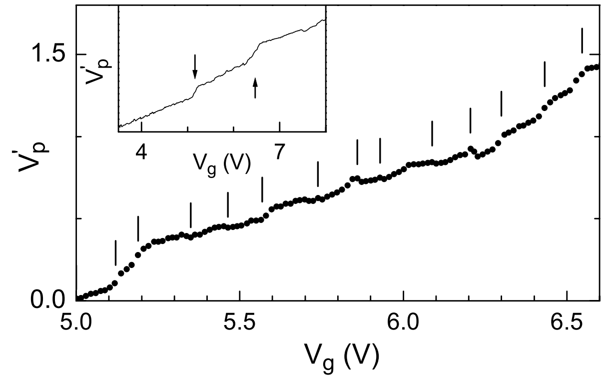

FIG. 2. Normalized peak position of fast oscillations, $V_p' = [V_g^p(N)/\langle \Delta V_{g2}\rangle - N]$, where $V_g^p(N)$ is the position of the Nth peak and $\langle \Delta V_{g2}\rangle = 14$ mV is plotted as a function of $V_g^p(N)$. N is chosen to set $V_p' = 0$ at $V_g = 5$ V. Vertical lines mark CB peaks positions in dot 1. In the inset the phase is plotted for a wider range of V_g, and two large slips, attributed to the charging of traps, are marked with arrows.

an interferometer geometry as well, as a result of the π phase shift accumulated each time an electron enters the dot. This effect would cause a slip of half a period per an added electron, which is much larger than experimentally observed. Therefore, the existence of the slips, correlated with CB peaks from dot 1, is an unambiguous experimental evidence for the presence of the second dot.

How are the dots coupled? If the dots are strongly coupled electrostatically, $C_c \gg C_{\Sigma 1}, C_{\Sigma 2}$, the dimer will behave as a single dot and the conductance should demonstrate single period oscillations. This is clearly not the case in our sample. In the opposite regime, $C_c \ll C_{\Sigma 1}, C_{\Sigma 2}$, one can distinguish between the two possibilities: (i) the dots are connected in parallel, and (ii) the dots are connected in series. At low gate voltages $V_g < 3$ V the fast oscillations are suppressed in the valleys of the CB in dot 1 (see left inset of Fig. 1a), implying that the dots are connected in series [8].

In the regime of sequential tunneling through two weakly coupled dots connected in series, the total conductance $G_{\mathrm{seq}}^{-1} \sim G_1^{-1} + G_2^{-1}$, where $G_{1,2}$ are the conductances of each dot [9]. Sequential tunneling is in qualitative disagreement with the data. In such a regime the amplitude of the fast oscillations δR of the total resistance $R_{\mathrm{seq}} = G_{\mathrm{seq}}^{-1}$ should originate from the CB in the extra dot, $\delta R \approx G_2^{-1}$. As shown in Fig. 1b, δR is strongly correlated with R_1 and changes by 2 orders of magnitude within a few periods of the fast oscillations (there are $\sim$8 periods of the fast oscillations per slow period). Such strong modulations of the peak height with such a small ($\sim$8 periods) correlation length are not expected for either weakly [10] or strongly coupled [11] dots.

As Fig. 1a shows, the amplitude of the fast oscillations δG is correlated with the envelope of the total conductance G_{env}: the amplitude is larger at the peaks and smaller at the valleys. Indeed, the ratio $\delta G/G_{\mathrm{env}}$, plotted in Fig. 1c, is practically V_g-independent up to 6 V and gradually decreases with further increase of V_g. Moreover, this ratio, rather than δG or δR, is almost the same near the minima and the maxima of the CB oscillations in dot 1. This observation hints that the total conductance should be treated quantum mechanically as a transmission problem. In this case, the total conductance is proportional to the *product* of the transmission through each dot, $G_{QM} \propto \Gamma_{\text{total}} = \Gamma_1 \Gamma_2$, and the transport through the whole dimer is *coherent*.

In the second part of the paper we use our knowledge of the transport through the dimer to analyze some intriguing features in the temperature dependence of the total conductance, and to show that the transport is dominated by inelastic cotunneling. Parameters of dot 1 can easily be extracted in the usual way [7]. The obtained gate capacitance ~1–2 aF is consistent with the geometrical estimates for the lithographically defined dot. The charging energy E_{c1} and the mean level spacing Δ_1 are extracted from the statistics of the peak spacings; see left panel of Fig. 3. The spacings form a broad distribution, consistent with $\Delta_1 \sim E_{c1} \approx 4$ meV. The mean level broadening is $\hbar\Gamma_1 \approx 0.8$ meV, less than Δ_1. The peak widths strongly fluctuate at low temperatures $k_B T < \hbar\Gamma_1$, where the width is determined by the coupling to the leads. As expected from the random matrix theory, both distributions are asymmetric.

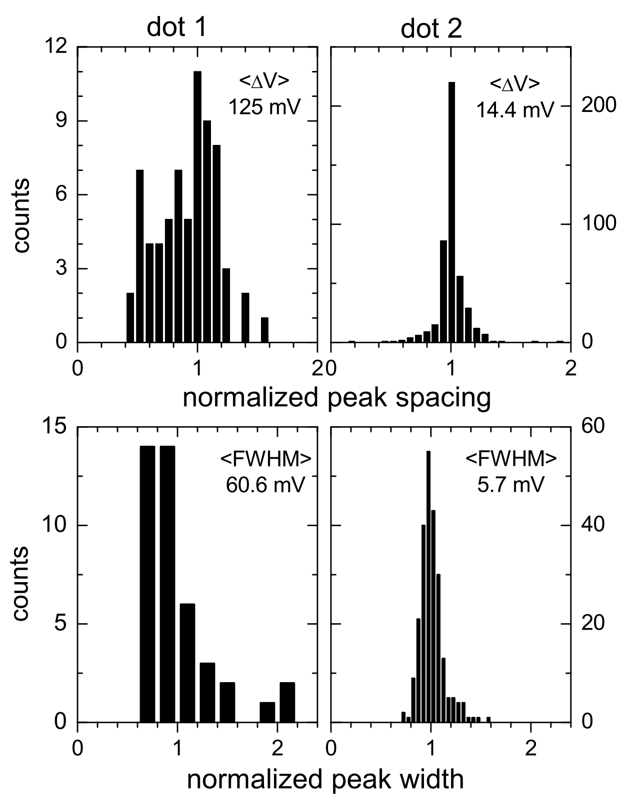

FIG. 3. Histograms of peak spacing (top) and width (bottom) are plotted for dot 1 (left) and dot 2 (right).

In Fig. 4 and the right panel of Fig. 3 we present the results of the T scaling of peak width and the distributions of peak spacing and width for dot 2, performed similarly to the analysis of the main dot. The standard CB analysis does not work for this dot: (i) the peak widths do not scale linearly with temperature; (ii) the peak shapes are not Lorentzian, although their width, Γ_2, saturates at low temperatures at 4 mV, which translates to ≈ 2 meV $\gg k_B T$; and (iii) there is no appreciable fluctuations of the peak width even at low temperatures, where the T-dependence of each peak has already saturated. Nevertheless, one can analyze the distribution of the peak spacing. The sharpness of the distribution requires the mean level spacing to be much smaller than the charging energy, $\Delta_2 \ll E_{c2}$ (E_{c2} does not fluctuate). Thus, the following set of inequalities is satisfied $\Delta_2, k_B T \ll \hbar\Gamma_2 < E_{c2}$. This means that dot 2 is in the strong coupling regime, where the standard CB theory is not applicable. The above features of the second dot can be understood within the framework of the cotunneling theory in the strong coupling regime [12].

There are two contributions to the conductance of a strongly coupled asymmetric dot. One is from elastic

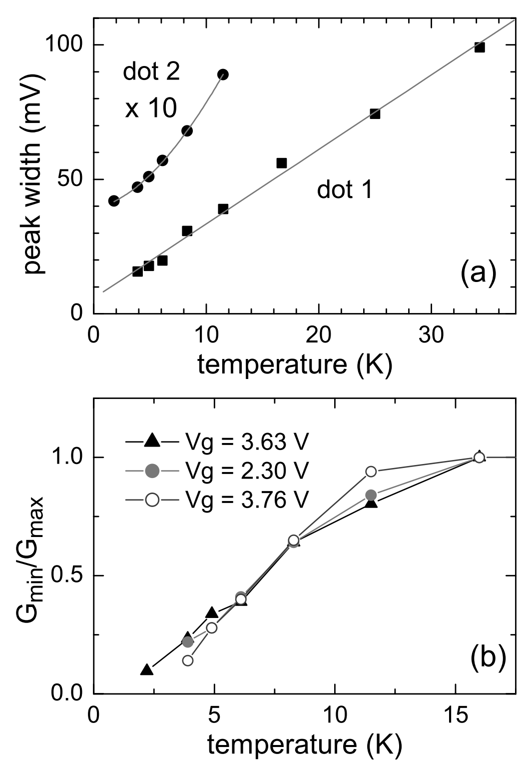

FIG. 4. (a) Scaling of the peak full width at half maximum (FWHM) with temperature is plotted for both dots. The lines are the linear and parabolic fits for dot 1 and dot 2, respectively. Peak width for dot 2 is multiplied by a factor of 10 for visibility. The peaks are close to $V_g = 3$ V. (b) Temperature dependence of the peak-to-valley ratio for the fast oscillations. Solid (open) symbols are for the ratios taken near the peaks (valleys) of the slow oscillations.

cotunneling (the dot always remains in its ground state) and the other involves inelastic processes, which create particle-hole excitations in the dot. Elastic cotunneling dominates at low temperatures, resulting in a strongly fluctuating G and, correspondingly, peak width [13]. At higher temperatures the leading mechanism of electron transport is inelastic cotunneling, and the conductance shows regular nonfluctuating periodic modulations as a function of V_g and gradually evolves with temperature from CB peaks into smooth oscillations [14]. The relevant energy scale is $E_c r^2 \cos^2(\pi \mathcal{N})$, where r is the smallest of the reflection coefficients at the barriers, and $\mathcal{N} = V_g / e C_{g2}$ measures the charge that minimizes the dot electrostatic energy, regardless of charge quantization. The conductance at the maxima and minima of the oscillations are estimated to be $G_{\max} \sim (e^2/\pi\hbar) k_B T r^2/(E_c r^2)$ and $G_{\min} \sim (e^2/\pi\hbar)(k_B T)^2 r^2/(E_c r^2)^2$, respectively. The ratio between the maxima and minima is expected to have a linear T-dependence

$$G_{\min}/G_{\max} \approx k_B T/(E_c r^2).$$

Indeed, as shown in Fig. 4b, the ratio $G_{\min}/G_{\max}$ for the fast oscillations has linear T-dependence regardless of whether it is measured near the peaks (solid symbols) or the valleys (open symbols) of dot 1 CB oscillations. The fast oscillations are observed up to $k_B T = E_c r^2$; thus strong coupling effectively renormalizes the charging energy. Note that the T-dependence of CB peaks in the strong coupling regime is very different from the thermal broadening in the weak coupling regime, and peak width does not scale linearly with T; see Fig. 4a.

The anomalous temperature dependence of the conductance, observed in the sample, can be naturally understood for the coherent transport through the dimer. Experimentally, the conductance near the peaks of dot 1 increases with temperature (see inset of Fig. 1a), contrary to the prediction of the CB theory that the peak height should be temperature independent for $k_B T < \hbar\Gamma_1$ and $\propto 1/T$ for $\hbar\Gamma_1 < k_B T < \Delta_1 < E_{C1}$ [15]. Because transport is coherent, the total conductance is $G \approx G_1 G_2/(e^2/\pi\hbar)$, and the anomalous temperature dependence is a result of the T-dependence of G_2. As we have shown above, G_2 increases with T due to the inelastic cotunneling processes. Thus, the observed anomalous temperature dependence is an additional argument in favor of both coherent transport through the dimer and inelastic cotunneling in dot 2.

In conclusion, we proposed a new method to identify coherent transport using two quantum dots, which does not require large phase coherence length in the host material. We studied the electron transport through a Si double-dot structure, and established that the electrons are transferred coherently through the whole dimer. Because of the strong coupling to the leads of one of the dots, the transport is dominated by the inelastic cotunneling processes, altering the conventional temperature dependence of the CB oscillations. In the future, this method can be used to measure l_ϕ in the interconnect region by varying the distance between the dots.

This work was supported by the ARO-MURI DAA655-98-1-0270 and by the MARCO Focused Research Center on Materials, Structures, and Devices which is funded at MIT, in part by MARCO under Contract No. 2001-MT-887 and DARPA under Grant No. MDA972-01-1-0035.

*Present address: Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109.

[1] A. Yacoby, M. Heiblum, D. Mahalu, and H. Shtrikman, Phys. Rev. Lett. **74**, 4047 (1995).
[2] For a recent review, see Y. Alhassid, Rev. Mod. Phys. **72**, 895 (2000).
[3] E. Leobandung, L. J. Guo, Y. Wang, and S. Y. Chou, J. Vac. Sci. Technol. **13**, 2865 (1995).
[4] L. P. Rokhinson, L. J. Guo, S. Y. Chou, and D. C. Tsui, Appl. Phys. Lett. **76**, 1591 (2000).
[5] L. P. Rokhinson, L. J. Guo, S. Y. Chou, and D. C. Tsui, Superlattices and Microstruct. **28**, 413 (2000).
[6] S. Horiguchi *et al.,* Jpn. J. Appl. Phys. Part 2, **40**, L29 (2001).
[7] For a review on quantum dots, see *Mesoscopic Electron Transport,* NATO ASI Series, Vol. 345, edited by L. P. Kouwenhoven, L. L. Sohn, and G. Schön (Kluwer, London, 1997).
[8] More exotic configurations are, in principle, possible, and have been experimentally investigated in our previous work [5]. The conductance pattern of this sample is consistent with the two dots being connected in series.
[9] I. M. Ruzin, V. Chandrasekhar, E. I. Levin, and L. I. Glazman, Phys. Rev. B **45**, 13 469 (1992).
[10] A. M. Chang *et al.,* Phys. Rev. Lett. **76**, 1695 (1996).
[11] S. R. Patel *et al.,* Phys. Rev. Lett. **81**, 5900 (1998).
[12] For a recent review see I. L. Aleiner, P. W. Brouwer, and L. I. Glazman, cond-mat/0103008.
[13] I. L. Aleiner and L. I. Glazman, Phys. Rev. Lett. **77**, 2057 (1996).
[14] A. Furusaki and K. A. Matveev, Phys. Rev. B **52**, 16 676 (1995).
[15] C. W. J. Beenakker, Phys. Rev. B **44**, 1646 (1991).