Dephasing in an isolated double-quantum-dot system deduced from single-electron polarization measurements

S. Gardelis,[1,*] C. G. Smith,[1] J. Cooper,[1] D. A. Ritchie,[1] E. H. Linfield,[1] Y. Jin,[2] and M. Pepper[1]
[1]*Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, United Kindgom*
[2]*Laboratoire des Nanostructures et Photoniques, CNRS, Avenue Henri Ravera, 92222 Bagneux, France*
(Received 2 December 2002; published 12 February 2003)

We report measurements of single-electron polarization in a coupled double-quantum-dot device isolated from current probes and demonstrate that the energetics observed for this process differs from that observed in double dots coupled to reservoirs. The movement of the electrons is detected by a quantum point contact. By analyzing the energy broadening corresponding to the tunneling of a single electron from one dot to the other we estimate a minimum for the intradot scattering time to be 0.2 ns. This energy broadening follows the predicted shot-noise variation in the detector with gate voltage, but is three orders-of-magnitude higher. We speculate that two-level systems could account for the discrepancy.

DOI: 10.1103/PhysRevB.67.073302 PACS number(s): 73.63.Kv, 73.23.Ad, 73.23.Hk

Over the last few years there has been a growing interest in the use of entangled quantum states for computation.[1–4] Among the various ideas which have been considered for implementation of quantum computers are proposals using semiconductor quantum dots.[5–8] In these proposals either the spin state or the charge of an electron in a pair of quantum dots between which electron tunneling is allowed is measured. One of the basic requirements to achieve a useful quantum computation is that the decoherence of the qubits should be up to 10^4 longer than the clock time, i.e., the time it takes to switch the state of one quibit.[9] In this paper we demonstrate that it is possible to set up a coupled double dot system with no current or voltage probes and measure the single-electron polarization of the resulting double dot system using a noninvasive voltage probe. We can deduce the coupling between the dots so that it leads to broadening of 100 mK using an electrostatically coupled probe. We study the tunneling rate and deduce an upper bound on the inelastic scattering rate for electrons in this system. We show how the physical process of charge transfer between the two dots is generally altered for dots isolated from reservoirs compared with those that are coupled. The movement of electrons between the dots was deduced by studying the effect they had on the conductance of a one-dimensional (1D) ballistic channel, situated near the double dot system. The conductance of the detector changed in a steplike manner by Coulomb repulsion when an electron either moved closer or further from it.[10] Using this noninvasive detector to sense the movements of a single electron between the dots instead of letting a current pass through the dots as conventionally occurs[11,12] we decrease considerably the decoherence rate resulting from electron-electron scattering. It also enabled us to isolate the dots from the electron reservoirs which prevents cotunneling through the dots.[10]

The double-quantum-dot system was defined using submicron metal gates on the top surface of an molecular-beam-epitaxy-grown GaAs/AlGaAs heterostrusture in which a two-dimensional electron-gas (2DEG) layer was formed approximately 70-nm below the surface. The gates were fabricated using electron-beam lithography. The inset I of Fig. 1 shows the device consisting of the dots A and B. Gates (G1), (G5), and (G6) define barriers for the dots. By changing the bias voltage applied to these gates the coupling of the dots with the electron reservoirs provided by the two-dimensional electron gas could be adjusted. Gate (G3) was used as a tunneling barrier between the dots, which adjusted the tunneling rate between them. Gates (G2) and (G4) were used as plungers to move electrons from one dot to its neighbor or into and out of each dot. Finally gate (G7) was used to define a 1D ballistic channel detector next to the double dot system in order to detect noninvasively movements of electrons between the dots. All measurements were made in a dilution refrigerator with a base temperature of 100 mK. Modulated bias voltages of 100 μV were applied to the detector and the output current passed to a lock-in amplifier. The dot and detector circuits were kept electrically isolated. The extreme sensitivity required of the detector meant that the gates were

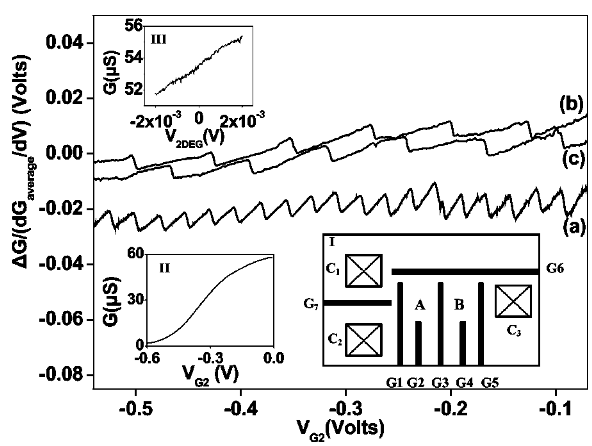

FIG. 1. (a) Detector signal of dot A, when the barriers are set up to allow tunneling to the reservoirs. (b) Detector signal of the isolated double dot system. (c) The same signal after a single electron has left the double dot system. All signals are corrected for the sensitivity of the detector. Insets: (I) Schematic of the double dot-detector system; (II) smooth function of the conductance signal without the steps used to correct the detector signals for the sensitivity of the detector; (III) calibration of conductance into a voltage figure.

controlled from a battery source. When setting up the double dot system the conductance was measured from contact C_3 to C_1. This enabled Coulomb blockade to be observed in the transport through the isolated double dot system. The capacitance coupling from all the gates to the two dots was then deduced by the measured Coulomb blockade period $\Delta V = e/C_g$. Gate (G1) was then pinched off to gate (G6), and the conductance between C_1 and C_2 through the 1D channel formed between gates (G1) and (G7) was used as a detector of electron movement in the double dot system.

First by applying suitable bias voltages to the gates the dot closer to the detector was defined (dot A). Figure 1(a) shows the detector conductance as a function of the voltage applied to the plunger (G2) of this dot, when the barriers are set up to allow tunneling to the reservoirs. The detector signal is shown as the ratio of the difference between the conductance signal of the detector and a smooth function that fits the conductance signal of the detector without the steps (inset II of Fig. 1), ΔG, over the differential of the same smooth function, dG_{aver}/dV. This procedure corrects for the variation in the sensitivity of the detector. A step in this curve corresponds to the change in the conductance of the 1D channel due to the Coulomb charging voltage of an electron moving into or out of the dot. This results in a voltage swing e/C_{total} (where C_{total} is the capacitance of the dot to the ground and is calculated to be the sum of the capacitances between each gate and the dot). This sawtooth structure has a period in gate voltage of e/C_{G2}, where C_{G2} is the capacitance between the gate being swept and the electrons in the dot. To calculate the charging energy of the dot we calibrated the detector by defining gates (G1), (G2), and (G6); removing the bias from gate (G3), i.e., opening up the far side of the dot; and by applying a voltage directly to the 2DEG (reservoir). This ensures that the capacitive coupling to the detector is similar to that seen by dot A. We use this curve to directly calibrate the change in conductance into a voltage figure [see Fig. 2(a)]. In this way the charging energy of dot A was measured to be 350 μeV.

Then using suitable voltages applied to the gates a double dot system was defined. The two barriers [gates (G1) and (G5)] between the dots and the reservoirs were strongly depleted so that the probability of a single electron tunneling out of this system is very low. Recently, we measured the decay time of single electrons from isolated dots, showing that electrons can be retained in an isolated dot for thousands of seconds.[13] It also takes thousands of seconds for a single electron to leave this isolated double dot system. The tunneling barrier between the dots can be adjusted by applying a suitable voltage to gate (G3) so that when the electrostatic energy of dot A is altered to line up the energy levels in the two dots an electron tunnels out into dot B. Figure 1(b) shows the resulting detector signal when electrons move from dot A into dot B as the voltage applied to the plunger of dot A [gate (G3)] is swept to more negative values. Figure 1(c) shows the detector signal when the voltage of the plunger of dot A is swept to more positive values letting electrons move from dot B back to dot A . These signals are corrected for the variation in the sensitivity of the detector as described earlier in the paper. It is obvious that the detector

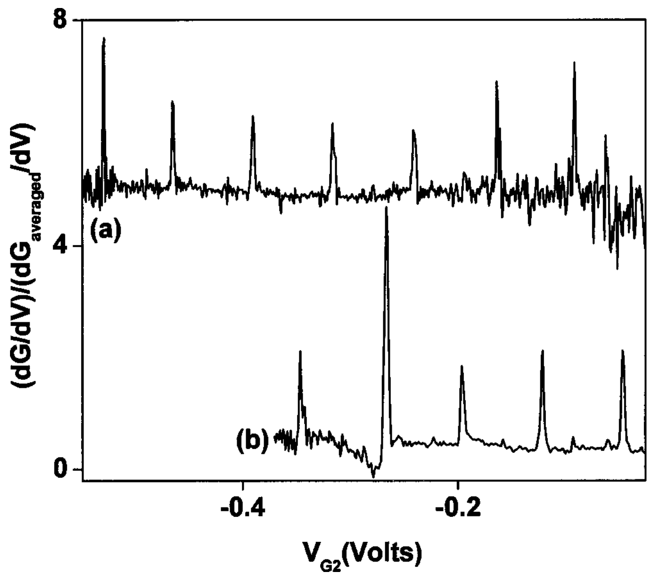

FIG. 2. (a) Differential of the detector signal of the isolated double dot system divided by the differential of a smooth function that fits the detector signal without the steps. The peaks correspond to a movement of an electron from one dot to the next. (b) The same signal when the tunneling barrier between the dots is more open and the coupling is stronger.

signal of the isolated double dot system shows a periodic steplike structure with a period nearly three times that observed for removing electrons from dot A to the reservoirs [Fig. 1(a)].

The structure in the figure corresponds to a polarization of the double dot system as an electron leaving dot A tunnels into dot B. This is energetically favorable when the energy of dot A with $(N-1)$ electrons is equal to the energy of dot B with (N+1) electrons. The energy of dot A reduces by e^2/C_A when an electron leaves, on the other hand the energy of dot B increases by e^2/C_B when this electron is accommodated in dot B. C_A and C_B are the total capacitances of dots A and B to the ground, respectively. Therefore, the energy difference of the energy levels between the two dots after the tunneling of one electron is given by

$$E_A - E_B = e^2/C_A + e^2/C_B. \quad (1)$$

If the bare quantum confined levels in each dot are small compared to the charging energy then each of the energies E_A and E_B can be written as

$$E_A = (e^2/C_A)(\Delta V/\Delta V_A), \quad E_B = (e^2/C_B)(\Delta V/\Delta V_B), \quad (2)$$

where ΔV is the period of the resulting detector signal when plunger of dot A is swept to move electrons from dot A to dot B. ΔV_A and ΔV_B are the periods of the detector signal when only dot A or only dot B is defined, respectively, and the plunger of dot A is swept. If $C_A = C_B$ then ΔV can be derived from the following expression:

$$\Delta V = \frac{2\Delta V_A \Delta V_B}{\Delta V_B - \Delta V_A}. \quad (3)$$

ΔV_A is 24 mV as can be deduced from the detector signal of dot A as shown Fig. 1(a) and ΔV_B is 76 mV as can be deduced from measurements of the conductance through dot B when the plunger of dot A is swept. By substituting these values in the equation for ΔV we derive a value of 70 mV which compares well with the measured period of 75 mV. This result suggests that we have defined a strongly isolated double dot system where electron tunneling can occur only between the dots. Another strong piece of evidence that the dot is heavily isolated from the reservoirs is that occasionally an electron leaves the double dot system. This can be detected as a jump in the amplitude of the detector signal. When this happens the gate voltage at which an electron moves from one dot to the other shifts by half the period in gate voltage required to move an electron between the dots. This is because the energy required to move an electron between the dots is $2e^2/C$, so that when one electron leaves one of the dots and enters the reservoir its energy is then shifted by e^2/C relative to the other dot. Figures 1(b) and 1(c) show how the positions of the jumps in the amplitude of the detector signal change when one electron leaves the double dot. The energy scale on the y axis shows that the amplitude of the detector signal of one trace is shifted by the typical step measured for an electron moving from one dot to the next. In the case where no electron moves out of the double dot system the two traces overlay each other.

In Figs. 1(a) and 1(b) looking closely at the steps corresponding to electrons moving from dots A to B, we see that there is not a perfectly sharp step. On the contrary there is a broadening i.e., a range of gate voltages corresponding to each step. This broadening is related to the width of the tunneling conductance peak that would be measured if we were logging the current flowing between the dots. That width has three contributions. The first originates from the height of the tunneling barrier between the dots, which sets the wave-function overlap between the dots (i.e., the symmetric-antisymmetric gap, Δ_{SAS}, which is zero when the tunneling barrier is closed). The second contribution comes from inelastic scattering from phonons or electrons outside the system which allows electrons to tunnel when the energy levels in each dot are not exactly aligned. The third contribution will come from thermal smearing. Thus the total broadening Δ_{total} is given by

$$\Delta_{total}=\sqrt{(\Delta_{SAS})^2+(k_BT)^2+(h/\tau)^2}. \tag{4}$$

Figure 2(a) shows the differential of a detector conductance signal similar to that shown in trace (b) of Fig. 1. The peak widths can be used to estimate the energy broadening. Opening the barrier between the dots leads to a larger Δ_{SAS}. This effect is shown in Fig. 2(b) which shows the differential of a detector conductance signal when the dots are more strongly coupled and the measured broadening is greater [see Fig. 3(c)]. To calibrate the peak widths [shown in Fig. 2(a)] in gate voltage in terms of energy, we use the fact that the peak separation (75 mV) corresponds to the increase in energy of one dot by $2e^2/C$ (700 μeV) over the other. Taking the energy broadening as the full width at half maximum for each peak, a distribution of values was measured which follows the sensitivity of the detector expressed as the differential of a smooth function that fits the detector conductance signal without the steps (shown in Fig. 3). The sharpest transition we could measure was 16 μeV and the broadest one was of the order of 39 μeV which corresponds to the highest sensitivity of the detector. The energy broadening of the sharpest transition corresponds to a thermal energy of 180 mK which is close to the measured temperature. Scattering between the dots would cause energy smearing of h/τ. This implies that τ must be >0.2 ns. We have to note here that although the bias voltage is large on the detector (100 μV) it does not cause any local heating because a 1D channel does not dissipate heat. The majority of the heat is dissipated in the 2D reservoirs.[14] From the expression for the quantum shot-noise maximum in a quantum point contact (QPC) given by Reznikov *et al.* in Ref. 15 (also see Ref. 16) and the argument that the time t_d required to detect an electron added in one of the dots is such that the change in the number of electrons crossing the QPC exceeds the typical shot noise,[17,18] we calculate the minimum detection time t_d from the following expression:

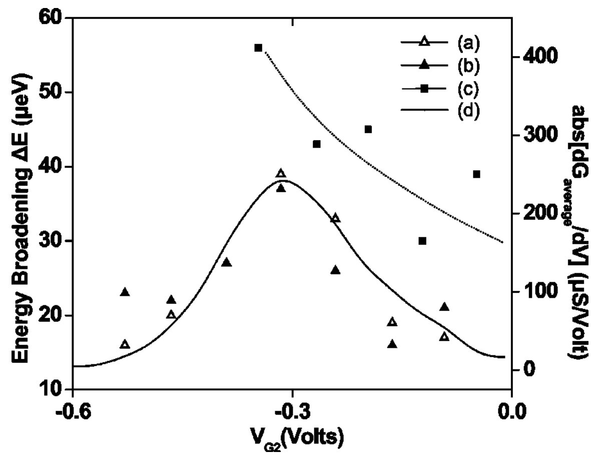

FIG. 3. (a) Energy broadening of the transition peaks. (b) Average energy broadening over several scans of the voltage applied to plunger G2. (c) Broadening for more strongly coupled dots; the dotted line is a guide to the eye. (d) Variation of the absolute value of the function dG_{aver}/dV expressing the sensitivity of the detector.

$$t_d=\frac{h}{4V_{DS}(\Delta T)^2e}, \tag{5}$$

where V_{DS} is the bias voltage applied to the QPC and ΔT is the change of the transmission coefficient T of the QPC when an electron is added to the dot (in our isolated double dot system the electron is moving from one dot to the next). By putting in the expession above $V_{DS}=100$ μV and $\Delta T=0.004$ as measured at $T=0.5$, where the shot noise is maximum, we get $t_d=0.7$ μsec. The time t_d corresponds to a dephasing rate which reflects the efficiency with which the QPC measures the charge state of one of the dots (the one which is nearer to the detector) (Ref. 17) and is due to electron-electron scattering. The time t_d is much longer than that estimated from the broadening of the peaks in the detector signal (0.2 ns). That suggests that the observed broadening is not due to electron-electron scattering alone. However the estimated time of 0.2 ns is close to experimental and theoretical estimates for electron-acoustic-phonon scattering in dots of these dimensions.[19] More specifically the tunneling between the two dots is facilitated by the emission or absorption of acoustic phonons thus causing the energy broadening of these transitions.

The distribution of the measured linewidths, shown in Figs. 3(a) and 3(b), implies that there is some mechanism that is amplifying the shot noise in the detector causing an extra energy broadening in the double dot system which follows the differential of the detector signal [Fig. 3(d)]. One possible mechanism could be charged to two-level systems that have been observed to generate telegraph noise in GaAs heterostructure material.[20] Recent scanning probe measurements close to a 1D ballistic channel defined in similar heterostructure material revealed several puddles of charge up to a micron away from the channel which affect the conductance of the 1D channel when electrons are removed from them.[21] The voltage spike in the detector caused by a shot-noise event could trigger an electron jump from one trap to its neighbor. This shift in charge then causes a change in the energy levels in the double dot system which is much larger than that caused by the shot noise alone. Although the shot-noise process may be rapid the polarization of charge in the double impurity site may be slow so that some time later the charge moves back to its original position. Because our measurements are over the time scale of seconds this causes an apparent broadening of the transitions in the dot. When the differential of the detector signal against gate voltage is a maximum the shot noise is greatest and therefore there is a greater probability of polarizing such an impurity site.

These measurements show that it is possible to detect single-electron tunneling from one dot to another in a completely isolated submicron double dot system. They also show that we can reduce the coupling between the dots and this reduces Δ_{SAS} until a minimum broadening mechanism is observed. This is larger than k_BT and indicates the existence of a dephasing mechanism acting over a time scale of 0.2 ns. This technique could be applied to the study of any isolated polarizable system such as molecules or coupled self-assembled quantum dots—structures for which it is very hard or impossible to make electrical contact to at present. In conclusion this work opens up many possibilities for the study of isolated systems in nanotechnology and mesoscopic physics.

This work was jointly supported by EPSRC and EU funding (QUADRANT Grant No. 23362). We also acknowledge support from Toshiba Research Europe Limited and the Newton Trust.

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*Electronic address: garspiro@iesl.forth.gr

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[14] The temperature rise in the reservoir due to the hot electron dT, is given by $(c_v A dT)/\tau_{e-p} = Q_{in}$, where $\tau_{e\text{-}p}$ is the electron-phonon scattering time, c_v is the electronic specific heat, and A is the area where the heat is dumped and will be comparable to the square of the electron-phonon scattering diffusion length. Q_{in} is the energy dumped into the reservoir. Simplifying leads to $dT = Q_{in}/[(\pi^2/3)(k_B^2 T n \mu/e)]$, where μ stands for the mobility. Putting in the measured value of mobility and carrier concentration, n, results in a heating of 10 mK. This value is very much less than the background temperature of 100 mK and so should not cause a problem.

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