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Evidence for transfer of polarization in a quantum dot cellular automata cell consisting of semiconductor quantum dots

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We present evidence for quantum dot cellular automata action in a cell consisting of four dots defined by submicron metal gates on the top surface of a molecular-beam-epitaxy-grown GaAs/AlGaAs heterostructure in which a two-dimensional electron gas layer was formed approximately 70 nm below the surface. The four-dot cell is separated by a strong barrier in two double-dot sets. We show that by polarizing one of the double-dot sets we can polarize the other set in the cell. The polarization is detected using noninvasive voltage probe without drawing electric currents from the cell.

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The necessity for even higher device density and computational power in the microelectronics industry has led to devices with feature sizes approaching quantum limits. Further scaling will require alternative concepts for computing other than the field-effect transistor based paradigm. An alternative paradigm for computation of the so-called quantum dot cellular automata (QCA) was proposed by Lent and co-workers.[1–4] Girlanda *et al.* have also recently investigated theoretically the operation of such systems.[5] In this paradigm the encoding of the binary information is achieved by using the arrangements of individual electrons in a cell, whereas the transferring of this information involves the propagation of a polarization state from one cell to its next. The cell consists of four quantum dots located at the vertices of a square. These dots are coupled by tunnel barriers. If two electrons are added to the cell, their mutual electrostatic repulsion forces them to occupy diagonal sites. This creates two possible polarizations that are energetically equivalent and are used to represent logic 0 and logic 1. By placing such cells in a line and polarizing the first cell with an external electric field, one can propagate the polarization along the line; thereby transferring information without using currents. By arranging lines of cells one can build logical gates.[6] Recently, a QCA cell consisting of four small Al islands connected in a ring by AlO_x tunnel junctions has been demonstrated. The cell polarization was measured by two dots used as noninvasive electrometers.[7–9]

In this study we present evidence for QCA action in a cell consisting of four semiconductor quantum dots. These dots were separated into two pairs. Each pair was electrically isolated from the other by a strong barrier. Tunneling was allowed only between dots belonging to the same pair. We explored the very complex interactions between the four dots in order to understand if we can operate such a structure as a QCA cell. First we set up a pair of dots as a double dot and we used one of the gates defining the other pair of dots to set up a one-dimensional (1D) ballistic channel as a noninvasive detector. This detector senses the movements of a single electron into or out of the dots.[10] We calibrated this detector so that we could measure the charging energy of the dots. Moreover, we were able to measure the movement of an electron from one dot to the next using this detector. We measured the energy required to polarize the double dot and compared this with the energy shift that such a polarization caused in a third quantum dot belonging to the other pair of dots, placed near the double-dot structure. We show that the energy shift is larger than the energy required to polarize the double dot. By arguments of symmetry this implies that when the double dot is polarized, a second double dot next to it would also be polarized. We can then think of the four dots as a single cell that will switch its output polarization when the input polarization is switched, or you can think of the one double dot as the output end of a four-dot cell and the other double dot as the input of a neighboring cell. In the latter case, we can demonstrate that polarization should propagate from cell to cell.

The four quantum dot system was defined using submicron metal gates on the top surface of a molecular-beam-epitaxy-grown GaAs/AlGaAs heterostructure 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. Figure 1 shows the device consisting of the dots *A*, *B*, *C*, and *D*. Gates $G1$, $G5$, $G7$, and $G11$ defined 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. Gates $G3$ and $G9$ were used as tunneling barriers between the dots of each pair. Gates $G2$, $G4$, $G8$, and $G10$ were used as plungers to move electrons from one dot to its neighbor or into and out of each dot. Plunger $G4$ was also used to define the 1D ballistic channel detector mentioned previously in this paper. Finally, gate $G6$ was used to electrically isolate the two pairs. All measurements were done in a dilution refrigerator with a base temperature of 100 mK. Modulated bias voltages of 10 and 100 μV were applied to the source and drain regions of the reservoirs at either side of the quantum dots and the detector (C_1, C_2, and C_3, C_4), respectively. The output current passed to the lock-in amplifiers. The dot and detector circuits were kept electrically isolated. The requirement of the extreme sensitivity of the detector meant that the gates were controlled from a battery source.

Initially, we set up the two bottom dots *C* and *D* as our first double-dot system. Figure 1 shows the conductance

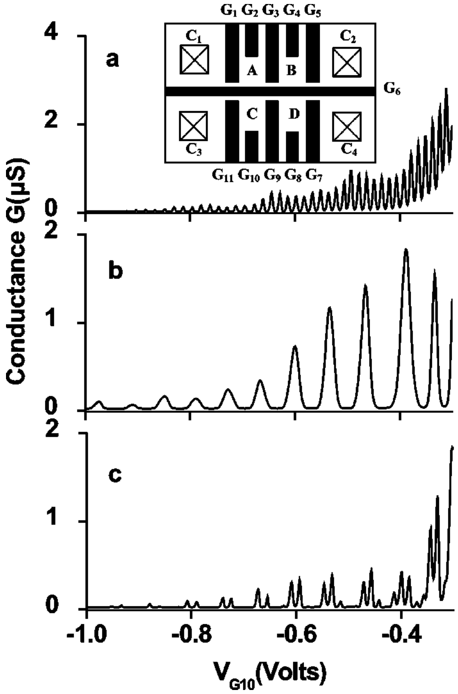

FIG. 1. Coulomb blockade oscillations of (a) dot *C*, (b) of dot *D*, and (c) of the coupled dot pair of *C* and *D*. In all cases the plunger of dot *C*, $G10$, was swept. Inset: Schematics of the QCA cell.

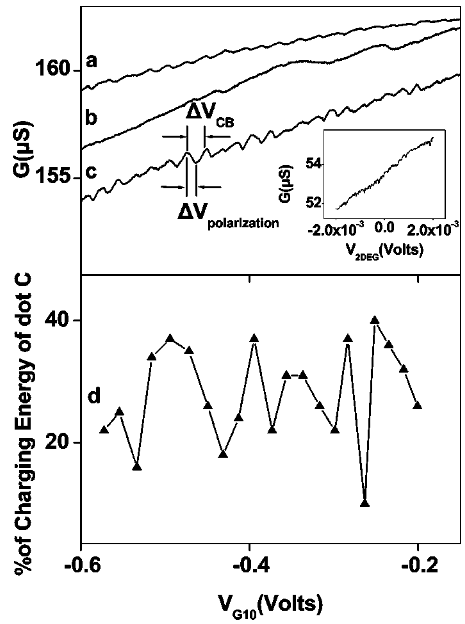

FIG. 2. Detector signal obtained (a) from dot *C*, (b) from dot *D*, (c) from the coupled dot pair of *C* and *D*. (d) The energy required to move one electron from dot *C* into dot *D* expressed as a percentage of the charging energy of dot *C*. The 1D ballistic channel between gates $G4$ and $G6$ was used as detector. In all cases, gate $G10$ was swept. Inset: Calibration of conductance into a voltage figure.

through dot *C*, through dot *D*, and finally through dots *C* and *D* when both are defined. In all the curves the plunger $G10$ of dot *C* was swept. The conductance through dots *C* and *D* was measured from contact C_3 to C_4. This enabled Coulomb blockade to be observed in the transport through the double-dot system. The capacitance coupling from all the gates to the two dots was then deduced by the measured Coulomb blockade period $\Delta V = e/C_g$. The combined dot shows the small period modulated by the large period. This corresponds to transport through the double dot when electron tunneling is allowed through both quantum dots.

In Fig. 2 we set up a 1D channel formed between gates $G4$ and $G6$. The conductance between contacts C_1 and C_2 through this channel was used to observe the charging behavior of dots *C* and *D* and also to detect electron movement in the double-dot system. From now on, we name the 1D channel as the detector and the conductance through it as the detector signal. Figure 2(a) shows the detector signal when the plunger of dot *C* is swept and only dot *C* is defined. A step in this curve corresponds to the change in the conductance of the detector due to the Coulomb charging voltage of an electron moving into or out of the dot. This has a period of 20 mV. To calculate the charging energy of dot *C*, we calibrated the detector by defining gates $G6$, $G10$, and $G11$, removing the bias from gate $G9$, 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 experienced by dot *C*. We use this curve to directly calibrate the change in conductance into a voltage figure (see inset of Fig. 2). By converting the step size in the detector signal obtained from dot *C* (which corresponds to the movement of a single electron out of the dot) into a voltage figure, we estimated the charging energy of dot *C* to be 350 μeV. As all the dots in the cell are of the same size and are surrounded by gates of the same size, we can assume that the charging energy for each dot is very similar.

Figure 2(b) shows the signal when dot *D* is defined on its own, revealing a period of 100 mV and an amplitude that is larger than that of the detector signal corresponding to dot *C*. That is because dot *D* is closer to the detector. Finally, Fig. 2(c) shows the detector signal when both dots are defined. It shows oscillations with the period of the Coulomb blockade observed in dot *C* (i.e., 20 mV), but with the amplitude being modulated at the period of dot *D* and reaching a maximum amplitude similar to that observed for the Coulomb blockade in dot *D*. This implies that when the plunger of dot *C* is swept, it is moving an electron into dot *D* and thus polarizing the dot. The saw-tooth signal shown in Fig. 2(c) can be used to estimate the voltage change required to move an electron from one dot to the next, i.e., $\Delta V_{polarization}$ in Fig. 2(c). The period observed in the detector tells us what the Coulomb charging voltage is, i.e., ΔV_{CB} in Fig. 2(c). From these two values we can estimate the energy required to polarize the double dot as a percentage of the Coulomb charging energy. This is shown in Fig. 2(d) as a function of the voltage applied to the plunger of dot *C*, $G10$. On average, we get a value of 30%, but for some jumps this can be as small as 20% or even 10%.

We could reduce considerably this percentage by isolating strongly the double-dot system from the reservoirs of electrons (2DEG) on either side of the system.[11] In this case the two barriers (gates $G7$ and $G11$) between the dots and the reservoirs were strongly depleted so that the probability of a

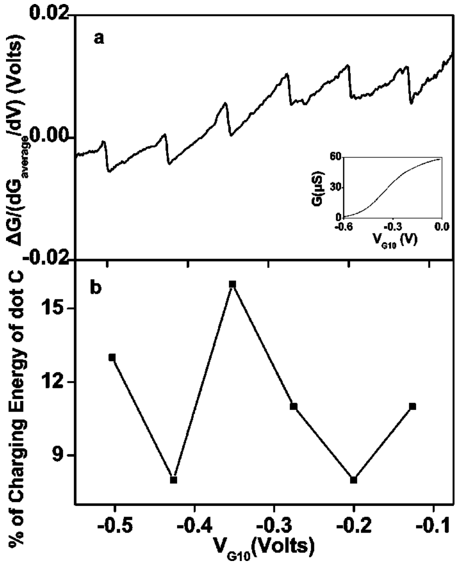

FIG. 3. (a) Detector signal obtained from the double-dot system of dots C and D when isolated from the reservoirs. (b) The energy required to move one electron from dot C into dot D expressed as a percentage of the charging energy of dot C.

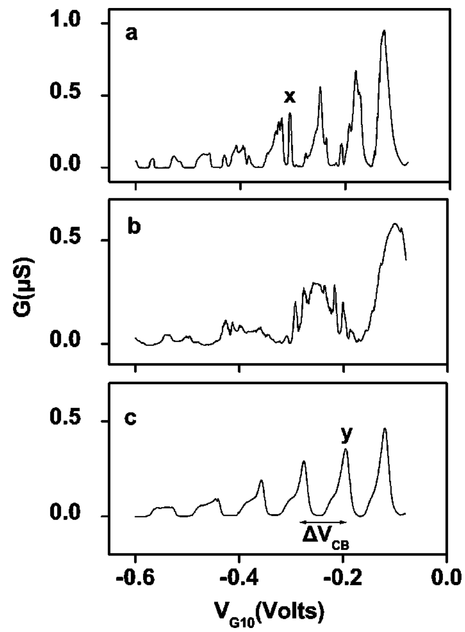

FIG. 4. Detector signal obtained from the coupled pair of dots C and D when (a) dot B was defined as detector, (b) the coupled pair of dots A and B was defined as detector. (c) Coulomb blockade oscillations of dot B when none of the dots C and D are defined. In all cases gate $G10$ was swept.

single electron tunneling out of this system was very low. Figure 3(a) shows the resulting detector signal when electrons move from dot C into dot D as the voltage applied to the plunger of dot C (gate $G10$) is swept to more negative values. In this figure 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 of Fig. 3), ΔG, over the differential of the same smooth function, $dG_{average}/dV$. This procedure corrects for the sensitivity of the detector. The structure in this figure corresponds to a polarization of the double-dot system as an electron leaving dot C tunnels into dot D. This is energetically favorable when the energy of dot C with $N-1$ electrons is equal to the energy of dot D with $N+1$ electrons. The energy of dot C reduces by e^2/C_A when an electron leaves; on the other hand, the energy of dot D 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 C and D to ground, respectively. If $C_A = C_B$, since dots C and D are of similar size, then the period ΔV of the detector signal of the isolated double-dot system corresponds to $2e^2/C$ (i.e., twice the charging energy of the dots). Figure 3(b) shows the energy required to polarize the double dot as a percentage of the Coulomb charging energy of the dots, calculated in the same way as in Fig. 2(d). Note that in this case the period of the steps, ΔV, in the figure corresponds to $2e^2/C = 750\ \mu$eV. In this case of the isolated double-dot system, the average energy required to polarize the double-dot system is reduced to 11% of the charging energy of the dots.

Then we defined the second double-dot system (dots A and B) by observing Coulomb blockade in their conductance. The combined double-dot system showed evidence of both frequencies of oscillation corresponding to dots A and B, if measured separately, as would be expected for a double-dot system. Next we measured the energy change that an electron moving from dot C to D would cause in the double-dot system consisting of dots A and B. Figure 4(a) shows the variation of the conductance of dot B when the plunger of dot C is swept and both dots C and D are defined. Figure 4(b) shows the same data when both dots A and B are defined as a detector. In all the data the 20 mV period resulting from the electron rearrangement from dot C to D can be seen. More specifically, the saw-tooth structure of the detector signal we observed when the detector was defined as the 1D ballistic channel between gates $G4$ and $G6$ causes peaks on one side of the large period Coulomb blockade peaks of the combined double-dot system of dots A and B (now set up as a detector) and troughs on the other side. The symmetric nature of the detector action on each side of a peak is shown nicely on the peak that peaks at -0.25 V in Fig. 4(b).

We tried to calibrate the shift in the Coulomb blockade peaks of dot B when it is set up as a detector, detecting the charge movement in the double-dot system of dots C and D. For this reason we compared the detector signal obtained from the coupled pair of dots C and D when dot B is defined as the detector, shown in Fig. 4(a), with the same signal when dots C and D are not defined, shown in Fig. 4(c). The first thing to notice is the loss of the fine structure resulting from the detection of charge movement in the dots C and D. We use peak y of Fig. 4(c) and peak x of Fig. 4(a) to calibrate the shift in energy caused by an electron moving from dot C to D. The large signal at x in Fig. 4(a) corresponds to a shift in the Coulomb blockade energy of dot B of 20% of the Coulomb blockade period of dot B, ΔV_{CB}. This shift, $\Delta V_{polarization}$, is shown clearly in Fig. 5.

From what we have shown so far, it can be concluded that when dots C and D of the double-dot system are defined, we

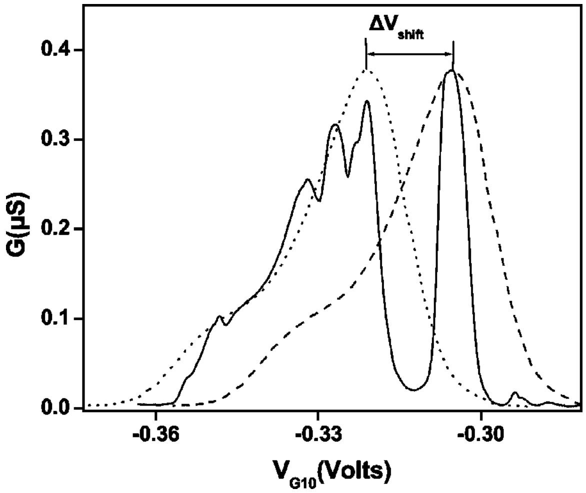

FIG. 5. The energy shift of dot *B* when defined to detect movements of single electrons from dot *C* into dot *D*.

can cause an electron to move from dot *C* to dot *D* with a shift in dot energy of dot *C* of less than 20%. This in turn causes a shift in energy of dot *B* by 20% of its charging energy (more than the average 11% energy shift required to cause an electron to move from dot *B* to dot *A* when dot *A* is defined). The situation using a double dot as a detector becomes more complicated to interpret, because an electron moving from dot *C* to *D* causes the conductance of dot *B* to decrease, but that of dot *A* to increase. This means that the signal may be smaller, but the polarization effect should be large.

We have shown that by tuning double-dot systems to be close to a polarization transition, it should be possible to make a QCA from GaAs-GaAlAs material, which will work at low temperatures. A four-dot cell with many electrons per cell can be made so that when an electron switches in one double dot, it forces an electron to switch positions in a second double dot next to the first. In this way information can be transmitted via the cell polarization. However, it may not be possible to scale this up to high temperatures and to large numbers of devices.[12] This does not mean that such a structure is without value, as they may have applications in quantum computing where it is not unreasonable to operate a few thousand devices at low temperatures.

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