

## Quantum-dot cellular automata: Review and recent experiments (invited)

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An introduction to the operation of quantum-dot cellular automata is presented, along with recent experimental results. Quantum-dot cellular automata (QCA) is a transistorless computation paradigm that addresses the issues of device density and interconnection. The basic building blocks of the QCA architecture, such as AND, OR, and NOT are presented. The experimental device is a four-dot QCA cell with two electrometers. The dots are metal islands, which are coupled by capacitors and tunnel junctions. An improved design of the cell is presented in which all four dots of the cell are coupled by tunnel junctions. The operation of this basic cell is confirmed by the externally controlled polarization change of the cell. © 1999 American Institute of Physics. [S0021-8979(99)26608-X]

### I. INTRODUCTION

For more than 30 years, the microelectronics industry has enjoyed dramatic improvements in the speed and size of electronic devices. This trend has long obeyed Moore's law, which predicts that the number of devices integrated on a chip will double every 18 months. Adherence to this exponential growth curve has been a monumental task requiring rapid improvements in all aspects of integrated circuit (IC) fabrication, to permit manufacturers to both shrink the size of devices and increase chip size while maintaining acceptable yields. Since the early 1970s the device of choice for high levels of integration has been the field effect transistor (FET), and while the FET of today is a vast improvement over that of 1970, it is still used as a current switch much like the mechanical relays used by Konrad Zuse in the 1930s. At gate lengths below  $0.1 \mu\text{m}$  FETs will begin to encounter fundamental effects that make further scaling difficult. A possible way for the microelectronics industry to maintain growth in device density is to change from the FET-based paradigm to one based on nanostructures. Here, instead of fighting the effects that come with feature size reduction, these effects are used to advantage. One nanostructure paradigm, proposed by Lent *et al.*,<sup>1,2</sup> is quantum-dot cellular automata (QCA), which employs arrays of coupled quantum dots to implement Boolean logic functions.<sup>3,4</sup> The advantage of QCA lies in the extremely high packing densities possible due to the small size of the dots, the simplified interconnection, and the extremely low power-delay product. Using QCA cells with dots of 20 nm diameter, an entire full adder can be placed within  $1 \mu\text{m}^2$ .

A basic QCA cell consists of four quantum dots in a square array coupled by tunnel barriers. Electrons are able to tunnel between the dots, but cannot leave the cell. If two excess electrons are placed in the cell, Coulomb repulsion will force the electrons to dots on opposite corners. There are thus two energetically equivalent ground state polarizations, as shown in Fig. 1, which can be labeled logic "0" and "1." Coulombic interactions between the electrons cause the cell to exhibit highly bistable switching between these two polarizations. The simplest QCA array is a line of cells, shown in

Fig. 2(a). Since the cells are capacitively coupled to their neighbors, the ground state of the line is for all cells to have the same polarization. In this state, the electrons are as widely separated as possible, giving the lowest possible energy. To use the line, an input is applied at the left end of the line, breaking the degeneracy of the ground state of the first cell and forcing it to one polarization. Since the first and second cell are now of opposite polarization, with two electrons close together, the line is in a higher energy state and all subsequent cells in the line must flip their polarization to reach the new ground state. No metastable state (where only a few cells flip) is possible in a line of cells.<sup>2</sup> A tremendous advantage of QCA devices is the simplified interconnect made possible by this paradigm. Since the cells communicate only with their nearest neighbors, there is no need for long interconnect lines. The inputs are applied to the cells at the edge of the system and the computation proceeds until the output appears at cells at the edge of the QCA array.

Computing in the QCA paradigm can be viewed as computing with the ground state of the system. A computational problem is mapped onto an array of cells by the placement of the cells, where the goal is to make the ground state configuration of electrons represent the solution to the posed problem. Then computation becomes a task of applying a set of inputs that put the system into an excited state, and then letting it relax into a new ground state. For each set of inputs a unique system ground state exists that represents the solution for those inputs. The mapping of a combinational logic problem onto a QCA system can be accomplished by finding arrangements of QCA cells that implement the basic logic functions AND, OR, and NOT. An inverter, or NOT, is shown in Fig. 2(b). In this inverter, the input is first split into

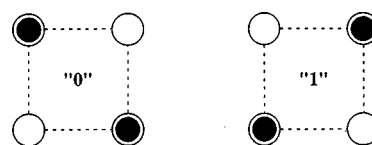


FIG. 1. Basic four-dot QCA cell showing the two possible ground-state polarizations.

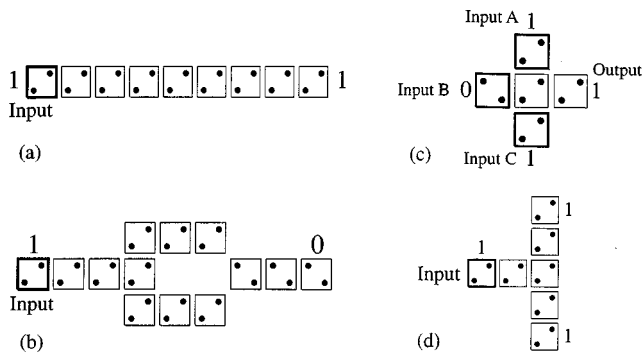


FIG. 2. (a) Line of QCA cells. (b) QCA inverter. (c) QCA majority gate. (d) Fanout.

two lines of cells then brought back together at a cell that is displaced by  $45^\circ$  from the two lines, as shown. The  $45^\circ$  placement of the cell produces a polarization that is opposite to that in the two lines, as required in an inverter. AND and OR gates are implemented using the topology shown in Fig. 2(c), called a majority gate. In this gate the three inputs “vote” on the polarization of the central cell, and the majority wins. The polarization of the central cell is then propagated as the output. One of the inputs can be used as a programming input to select the AND or OR function. If the programming input is a logic 1 then the gate is an OR, but if a 0 then the gate is an AND. Thus, with majority gates and inverters it is possible to implement all combinational logic functions. Memory can also be implemented using QCA cells,<sup>5</sup> making general purpose computing possible.

Some additional explanation is necessary for the fan-out structure shown in Fig. 2(d), which was also employed in the inverter. When the input of one of these structures is flipped, the new ground state of the system is achieved when all of the cells in both branches flip. The problem is that the energy put into the system by flipping the input cell is not sufficient to flip cells in both branches, leading to a metastable state where not all of the cells have flipped. This is not the ground state of the system, but can be a very long-lived state, leading to erroneous solutions in a calculation. Avoiding these metastable states is simply a matter of switching the cells using a quasi-adiabatic approach, which keeps the system in its instantaneous ground state during switching, thus avoiding any metastable states. Details of quasiadiabatic switching have been published previously.<sup>2,6</sup> Quasiadiabatic switching can be implemented in both semiconductor and metallic QCA systems.

## II. EXPERIMENT

The experimental work presented is based on a QCA cell using aluminum islands and aluminum-oxide tunnel junctions, fabricated on an oxidized silicon wafer. The fabrications uses standard electron beam lithography and dual shadow evaporations to form the islands and tunnel junctions.<sup>7</sup> The area of the tunnel junctions is an important quantity since this dominates island capacitance, determining the charging energy of the island and hence the operating temperature of the device. For our devices the area is ap-

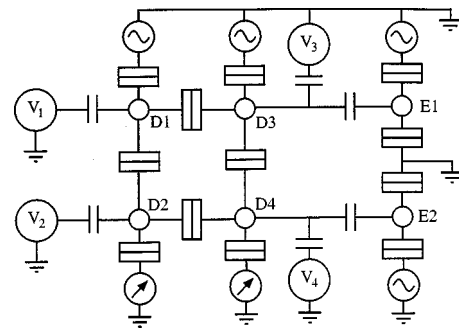


FIG. 3. Simplified schematic of the four-dot QCA cell and electrometers.

proximately 60 by 60 nm, giving a junction capacitance of 400 aF. These metal islands stretch the definition of a quantum dot, but we will refer to them as such because the electron population of the island is quantized and can be changed only by tunneling of electrons.

We recently demonstrated the first step in the development of QCA systems i.e., a functional QCA cell where we can switch the polarization of a cell. This confirms that the switching of a single electron between coupled quantum dots can control the position of a single electron in another set of dots.<sup>8,9</sup> A simplified schematic diagram of our latest QCA system is shown in Fig. 3. The four-dot QCA cell is formed by dots D1–D4, which are coupled in a ring by tunnel junctions. A tunnel junction source or drain is connected to each dot in the cell. This implementation is an improvement over earlier designs in that the tunnel junctions coupling D1–D3 and D2–D4 provide a capacitance more than twice as large as the lithographically defined capacitance used previously. A larger capacitance is expected to improve the bistability of the cell. The two individual dots E1 and E2 are used as electrometers. The device is mounted on the cold finger of a dilution refrigerator that has a base temperature of 10 mK, and characterized by measuring the conductance through various branches of the circuit using standard ac lock-in techniques. A magnetic field of 1 T was applied to suppress the superconductivity of the aluminum metal. Full details of the experimental measurements are described elsewhere.<sup>8–11</sup>

Since the operation of a QCA cell depends on the position of a single electron, it is necessary to track the position of electrons within the cell. This can be done by two different methods. One is to measure the conductance through each pair of dots within the cell. A peak in the conductance as the gate voltages are changed indicates that the Coulomb blockade has been lifted for both dots simultaneously, and a change in the dot population has occurred. The other way to detect the change of an electron position within the cell is using the electrometers E1 and E2,<sup>11</sup> which are capacitively coupled to the cell dots D3 and D4. A small potential change in the dot being measured causes a change in the conductance of the electrometer. A decrease in the conductance of the electrometer indicates a lower potential on the measured dot, meaning that an electron has entered the measured dot.

QCA operation is demonstrated by first biasing the cell, using the gate voltages, so that an excess electron is on the point of switching between dots D1 and D2, and a second

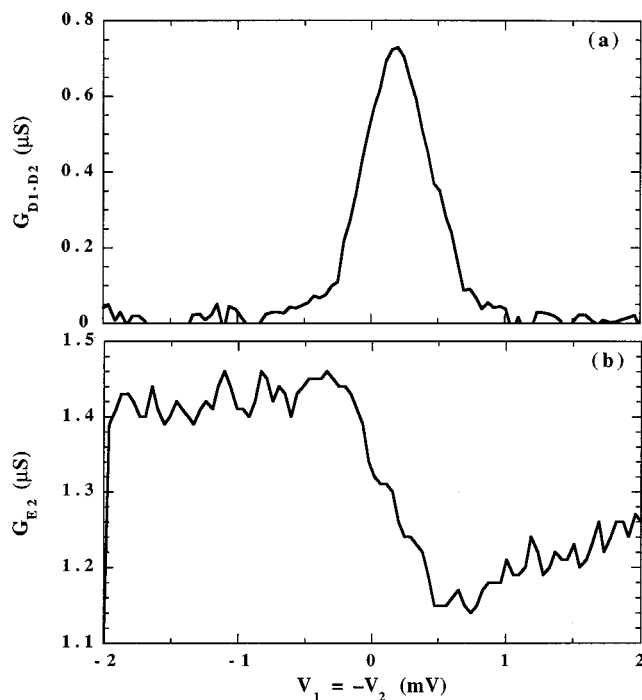


FIG. 4. (a) Conductance through dots D1 and D2. The peak occurs when the electron moves from D2 to D1. (b) and (c) Electrometer conductance. A drop in conductance occurs when an electron moves on to D4.

electron is on the point of switching between D3 and D4. A differential voltage is then applied to the input gates  $V_1$  and  $V_2$  ( $V_1 = -V_2$ ), while all other gate voltages are kept constant. As the differential input voltage is swept from negative to positive, the electron starts on D2, then moves from D2 to D1, as indicated by the peak in the conductance through D1–D2 seen in Fig. 4(a). This forces the other electron to move from D3 to D4. Figure 4(b) shows the response of electrometer E2, which is coupled to dot D4. When the electron switches from D2 to D1 there is a drop in the conductance of E2, indicating that an electron has moved from D3 to D4. This confirms the polarization change in the cell, and demonstrates QCA operation.

### III. SUMMARY

A device paradigm based on QCA cells offers the opportunity to break away from FET based logic, and to exploit the quantum effects that come with small size. In this new paradigm, the basic logic element is no longer a current switch but a small array of quantum dots, and the logic state is encoded as the position of electrons within a quantum dot cell. We have demonstrated the operation of a QCA cell fabricated in aluminum islands with aluminum oxide tunnel where the polarization of the cell can be switched by applied bias voltages. QCA cells are scalable to molecular dimensions, and since the performance improves as the size shrinks, a molecular QCA cell should operate at room temperature. While the device demonstrated here operates using single electrons, an implementation of QCA using magnetic domains should also be possible.

### ACKNOWLEDGMENTS

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