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Quantum-Dot Cellular Automata

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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.

1. Introduction

For more than 30 years the microelectronics industry has enjoyed dramatic improvements in the speed and size of electronic devices. 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 µm 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.[1, 2], is Quantum-Dot Cellular Automata (QCA), which employs arrays of coupled quantum dots to implement Boolean logic functions [3]. 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. A QCA capable of operating at room temperature is expected to have a power-delay product of approximately 10 zJ, and a switching frequency of approximately 7 THz.

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. 1a, 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. 1b. Since the cells are capacitively coupled to their neighbors, the ground state of the line is for all cells to have the same polarization.

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 layout of the cells, where the goal is to make the ground state configuration of electrons represent the solution to

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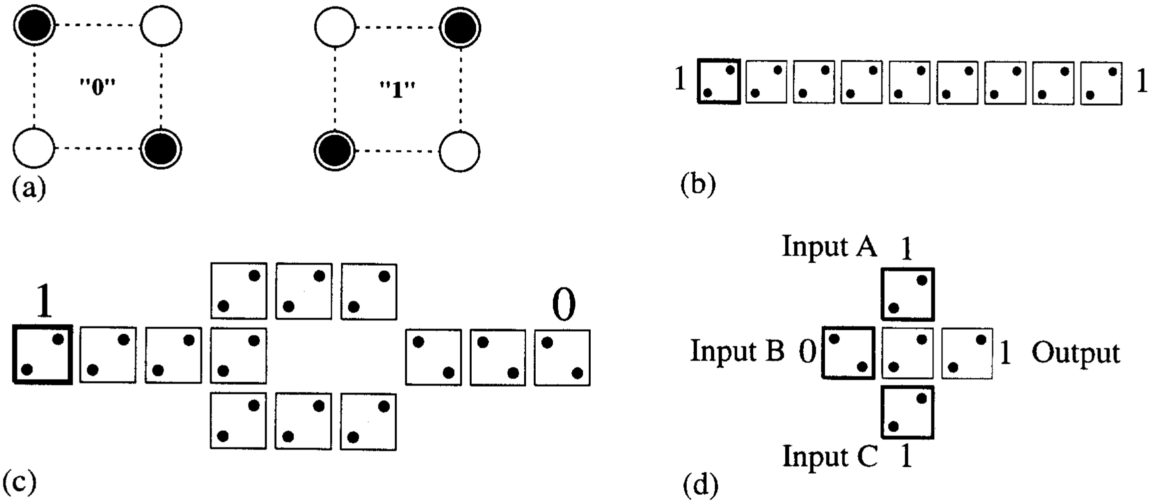

Figure 1. (a) QCA cells showing the two possible polarizations. (b) QCA line. (c) Inverter. (d) Majority gate

the posed problem. 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. 1c. In this inverter the input is first split into two lines of cells then brought back together at a cell that is displaced by 45°, which produces a polarization that is opposite to that at the input. AND and OR gates are implemented using the topology shown in Fig. 1d, called a majority gate. In this gate the three inputs "vote" on the polarization of the central cell, and the majority wins. 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, making general purpose computing possible.

2. 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 fabrication uses standard electron beam lithography and dual shadow evaporations to form the islands and tunnel junctions. 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 approximately 60 by 60 nm, giving a junction capacitance of 400 aF.

The four-dot QCA cell is formed by dots D1-D4, which are coupled in a ring by tunnel junctions, Fig. 2a. A tunnel junction source or drain is connected to each dot in 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. Full details of the experimental measurements are described elsewhere [4, 5].

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 electron is

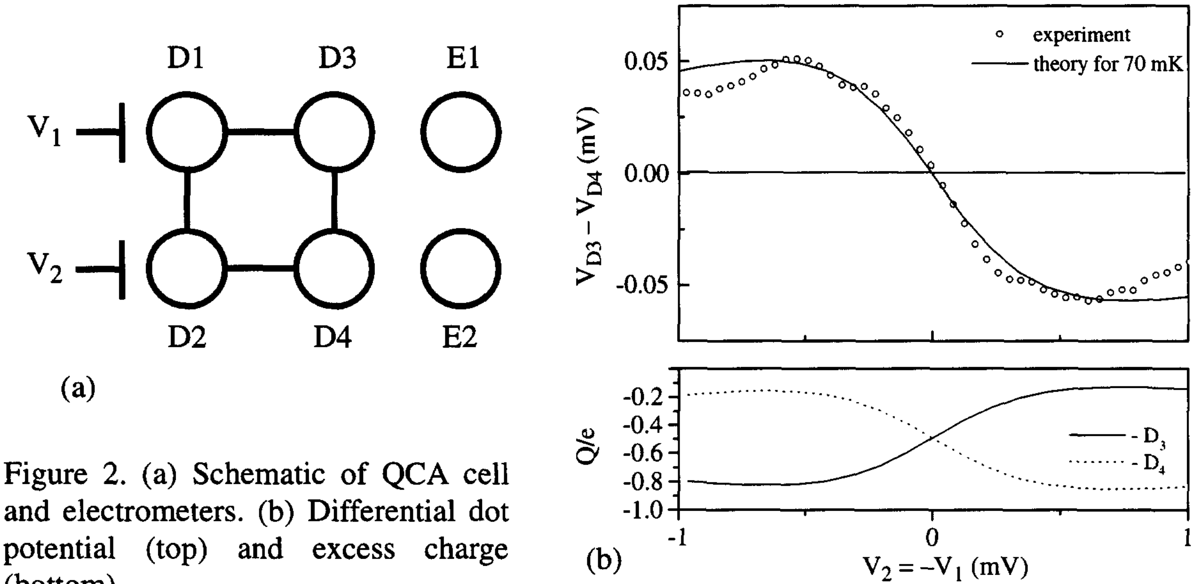

Figure 2. (a) Schematic of QCA cell and electrometers. (b) Differential dot potential (top) and excess charge (bottom).

on the point of switching between D3 and D4. A differential voltage is then applied to the input gates V1 and V2 (V1 = –V2), 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. This forces the other electron to move from D3 to D4. Figure 2b shows the differential dot potential V_{D3}–V_{D4} calculated using the electrometers, along with theory, and the charge on dots D3 and D4. This shows that an electron switches from D3 to D4 confirming a polarization change in the cell, which demonstrates QCA operation.

3. 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 junctions. QCA cells are scalable to molecular dimensions, and a molecular QCA cell should operate at room temperature.

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References

1. C.S.Lent, P.D. Tougaw, W. Porod, and G.H. Bernstein, *Nanotechnology*, **4**, (1993) 49.
2. C.S. Lent, and P.D. Tougaw, *Proceedings of the IEEE*, **85**, (1997) 541.
3. P.D. Tougaw, and C.S. Lent, *J. Apply. Phys.*, **75**, (1994) 1818.
4. A.O. Orlov, I. Amlani, G.H. Bernstein, C.S. Lent, and G.L. Snider, *Science*, **277**, (1997) 928.
5. G.L. Snider, A.O. Orlov, I. Amlani, G.H. Bernstein, C.S. Lent, J.L. Merz, and W. Porod, *Semiconductor Science and Technology*, **13**, (1998) A130.