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Quantum-Dot Cellular Automata: Line and Majority Logic Gate

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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 devices presented are QCA cells where the dots are metal islands, coupled by capacitors and tunnel junctions. A line of three two-dot cells is presented, which demonstrates that there are no metastable states in a QCA line. The final experiment presented is a QCA majority gate, a programmable AND/OR logic gate.

KEYWORDS: Quantum dot, single electron devices, quantum-dot cellular automata, Coulomb blockade, logic gate

1. Introduction

Advances in the microelectronic industry depend upon the ever-shrinking size of transistors. For more than 30 years, this trend has followed 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). 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.[3,4] 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 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". If two cells are brought close together, Coulombic interactions between the electrons cause the cells to take on the same polarization. If the polarization of one of the cells is gradually changed from one state to the other, the second cell exhibits a highly bistable switching of its polarization. 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 change the polarization of the line, an input is applied at the left end of the line, forcing it to one polarization. Since the first and second cells 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.[2]

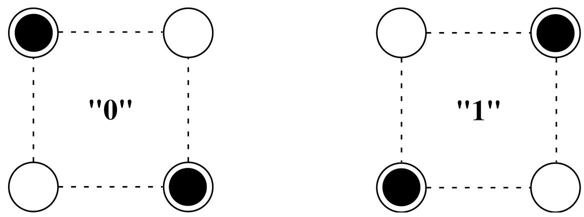

Fig. 1. Basic four-dot QCA cell showing the two possible ground-state polarizations.

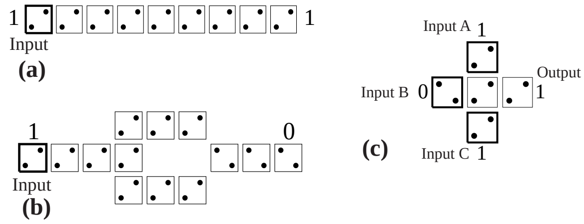

Fig. 2. (a) Line of QCA cells. (b) QCA inverter. (c) QCA majority gate.

The switching of a QCA array just described is referred to as abrupt switching, and while metastable states are not possible in a line of cells, they can appear in more complex systems. Avoiding these metastable states is possible using adiabatic switching,[2] where the barriers between the dots are modulated during the switching process to keep the array in its ground state throughout the process.

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 the posed problem. Then computation becomes a task of applying a set of inputs, 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 two lines of cells then brought back together at a cell that is displaced by 45° from the two lines, as shown. The 45° 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,[5] making general purpose computing possible.

2. Experiment

The experimental work presented is based on 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.[6] A completed device is shown in the SEM micrograph of Fig. 3. 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. 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 quantum mechanical tunneling of electrons. The QCA 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.[7–10]

We recently demonstrated the first step in the development of QCA systems, a functional QCA cell where we can switch the polarization of a cell. This confirms the basic premise of the QCA paradigm: that the switching of a single electron between coupled dots can control the position of a single electron in another set of dots.[7,8] 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 is done by two methods. The first is to measure the conductance through each half-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 second method is to employ additional dots, external to the cell, as electrometers.[10,11] These electrometers, capacitively coupled to the cell, operate by detecting small potential changes due to electron movement in the dot being measured.

The operation of a line of cells is demonstrated using the device shown in Fig. 3, where a simplified schematic is given in Fig. 4(a). Here we will define a QCA cell to consist of two dots. While a four-dot cell is desirable for some architectural functions, such as a corner or a majority gate, a two-dot cell shows the same bistable switching characteristic as a four-dot cell and is therefore a valid QCA cell. Objections have been raised that metastable states will occur even in a line of QCA cells.[12] The argument is as follows: If the first

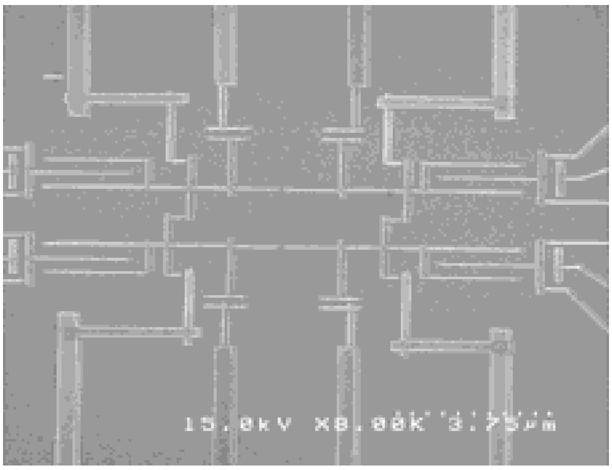

Fig. 3. SEM micrograph of QCA system and electrometers.

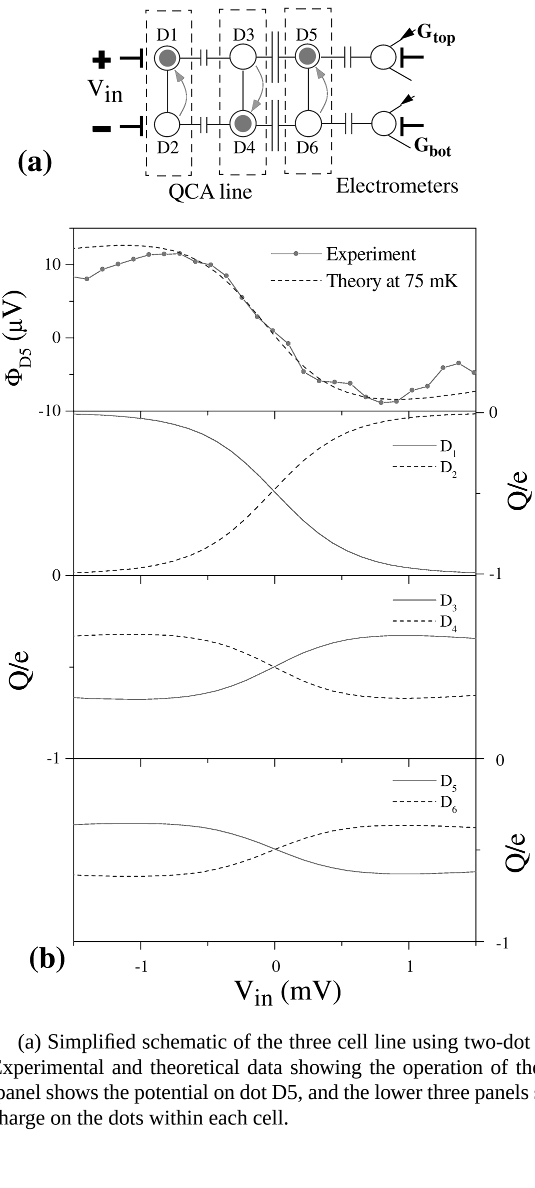

Fig. 4. (a) Simplified schematic of the three cell line using two-dot QCA. (b) Experimental and theoretical data showing the operation of the line. Top panel shows the potential on dot D5, and the lower three panels shows the charge on the dots within each cell.

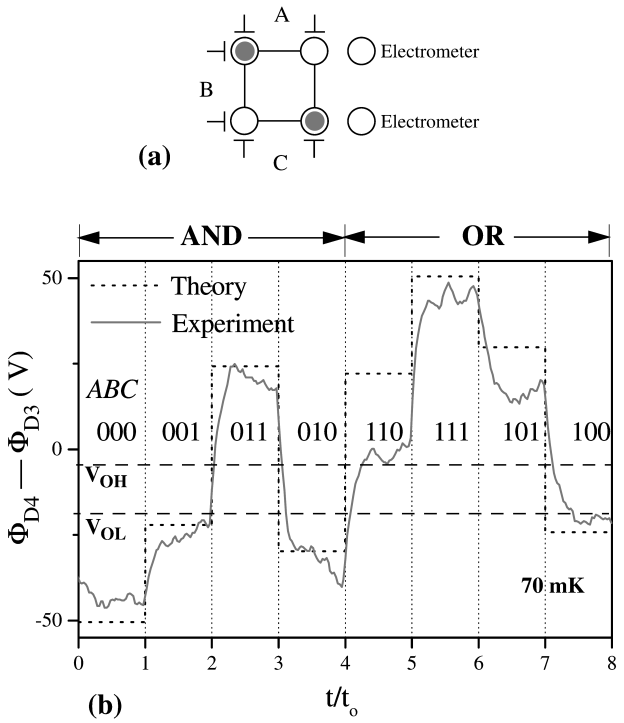

Fig. 5. (a) Simplified schematic showing the QCA majority gate with electrode inputs. (b) Experimental and theoretical data showing the operation of the logic gate. The time step $t_o = 20$ s.

cell of a line is switched the whole line will not switch because a cell in the middle of the line will see a cell on its input side telling it to switch, and a cell to the other side telling it not to switch. Since the cells on either side are identical, the middle cell's polarization is indeterminate, and it will likely not switch. Our experiment shows that this argument is incorrect: metastable states in a line do not exist. This experiment using a line of three cells is a severe test of our assertion, since the coupling between the cells is not equal along the line. The coupling between the first and second cell is only 30% of that between the second and third cell. This invites a metastable state to occur since when the first cell is flipped the second cell sees a weakly coupled cell with the new polarization to its left, and a strongly coupled cell with the old polarization to its right. This favors a metastable state since the weak first cell would have trouble flipping and holding the polarization of the second cell. The fact that a metastable state does not exist is shown by the data of Fig. 4(b).[13] The top panel shows the potential of dot D5, the top dot of the third cell, as a function of the input differential voltage, along with theory at a temperature of 75 mK (the temperature where the best fit is obtained). The bottom three panels show the charge on each dot in the line, showing that a polarization switch occurs in each cell of the line. A degradation of the polarization is seen along the line, but this is due only to thermal smearing. If all capacitances in the device were reduced by a factor of five, a very small polarization degradation would be seen. Despite the polarization degradation, all the cells of the line do switch, confirming that there is no metastable state.

The circuit of Fig. 3 can also demonstrate a QCA majority gate, using the simplified schematic of Fig. 5(a). As described earlier a majority gate consists of a four-dot cell where three input cells vote on the polarization of the central cell. In our experiment a four-dot cell is used as the logic gate cell, and electrodes are used as the input cells. The voltages on the electrodes are carefully chosen to mimic the potentials of real dots in an input cell. The input voltages are stepped in sequence to map out the truth table of the gate, with the measured output and theory shown in Fig. 5(b).[14] It should be mentioned that in this plot there are no fitting parameters used in the theory. The temperature is measured independently as 70 mK,[15] and the output of the electrometers is considered "zero" when no input is applied to the gate. The time step t_o is approximately 20 s, as determined by the limited bandwidth of the measurement system, not by the inherent speed of the logic gate, which is expected to be in the range of 200 MHz as determined by the RC time constant of the dots and tunnel barriers. There is excellent agreement between theory and experiment. The input A is used as the programming input. In the first four steps the majority gate performs the function B AND C, and in the second four steps B OR C. Dotted lines on the plot show the limits of the valid outputs high and low, V_{OH} and V_{OL}. There is a clear separation between V_{OH} and V_{OL} as required for digital logic. The output levels do not saturate "to the rails" due to temperature smearing effects. If all the capacitances in the circuit were reduced by a factor of 5, the outputs would saturate and V_{OH} and V_{OL} would be widely separated.

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 line and majority gate. 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.

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