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Quantum Cellular Automata.

• Introduction

Quantum cellular automata or QCA for short are a relatively new development within the world of nanostructure engineering. Microprocessors at the present time are fabricated using field effect transistors and while great advances have been made in reducing the size of these FETs, eventually a physical quantum limit will be reached. This physical limit on size will thus also lead to a limit on the computational power available to microchip architects of the future. Therefore in order to maintain progress a different foundation for digital logic must be sought.

One such candidate is the single electron transistor (SET) and more specifically with regards to this essay, a particular type of SET, the quantum cellular automata. The fundamental difference between QCA and FET logic is that the binary information is encoded via the arrangement of individual electrons, rather than by currents, and since individual electrons (or groups of electrons) are being manipulated the scale of such QCA devices is several orders of magnitude smaller than that of a FET based circuit.

In this essay I will aim to give a wide ranging appraisal of current developments in QCA research, as well as looking at the possible applications of the technology. Finally I will endeavour to make critical comparisons with other potential future technologies that are not based on the QCA paradigm.

• QCA microchips

There are several areas of nanotechnology that could benefit from quantum cellular automata. One of these has been briefly discussed before (that of microchip design), and I will now go into further detail of how such a device might be implemented. Firstly, however it is necessary to understand the basics of QCA logic. The building block of a cellular automaton is the quantum dot. Quantum dots are made either from metal or semiconductor material and their purpose is to store a well defined (small) number of electrons. By controlling the dot’s electrostatic environment different numbers of electrons can be deposited or removed, a quantum cell is formed by a arrangement of these quantum dots. The basic quantum cell consists of four quantum dots in a square arrangement and two electrons (or two small groups of electrons). Since the electrons repel each other via the electrostatic force, they move to opposing corners of the square cell. This produces a system with two energetically equal states which are arbitrarily named “1” and “0” and are the basis of logic operations within a QCA circuit.

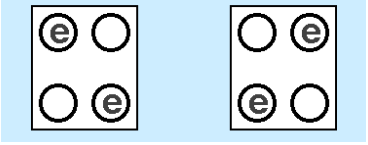

Fig. 1. The basic QCA cell showing the two logic states

When QCA cells are placed adjacent to one another the electrostatic interaction between the two pairs of electrons produces a configuration of minimum energy. This type of implementation is known as a majority logic gate, because the output from three inputs will be equivalent to the majority input.

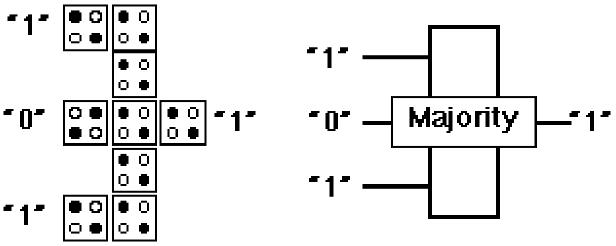

Fig. 2. A QCA majority gate

If one of the three inputs is fixed to "0" then the remaining two inputs combine to form an AND gate. However if the fixed input is set to "1" the majority gate becomes an OR gate.

Input 1	Input 2	Input 3	Output
0	0	0	0
0	0	1	0
0	1	1	1
0	1	0	0
1	1	0	1
1	1	1	1
1	0	1	1
1	0	0	0

Tab. 1. Truth table for a QCA majority gate

One way to implement a QCA gate is to use the metal tunnel junction method. In this system the quantum dots are made from four aluminium islands which are etched using electron beam lithography. Tunnel junctions connect each of the dots in a ring, and are made by oxidising the aluminium from which the cell is constructed.

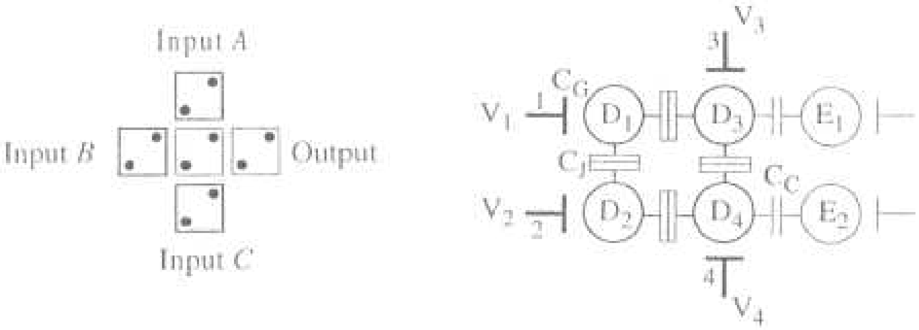

Fig. 3. QCA majority gate in theoretical form on the left, and an experimental schematic right

Above is a diagram of a real experimental QCA system. The four quantum dots are represented by D_1-D_4 , the tunnel junctions are missing from the diagram for clarity. Two electrons are introduced into the system via the tunnel junctions at the start of the experiment. The junction capacitences C_J between each dot are there to provide charge quantisation. Gate capacitences C_G provide a way of controlling the charge state on each dot, and the electrometers (E_1+E_2) capacitively coupled to D_3 and D_4 allow a method of monitoring the output of the system. The actual inputs of the system are replaced with potential shifts in the experiment, and are controlled via electrodes V_1-V_4. Figure 4 below outlines the necessary shifts required to set all inputs to high.

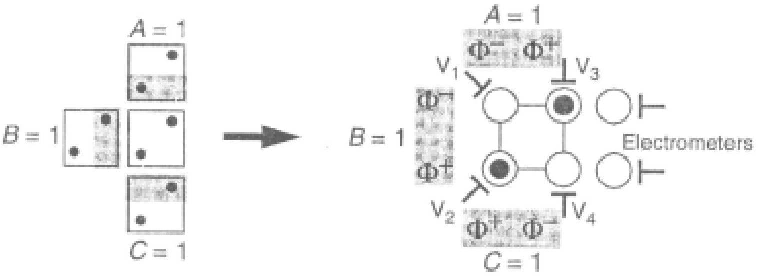

Fig. 4. Experiment requires inputs A, B and C to be replaced by potential shifts on the gates

As can be seen, the positive/negative bias (Φ^+/Φ^-) on the gates represents the absence/presence of an electron on each of the input cell's dots. Since D_1 and D_2 are coupled to just one voltage gate each (V_1 and V_2 respectively), yet depend on two inputs (from A+B, and B+C respectively) the voltage shifts are added, mimicking the effect of two input dots. In the above scenario of all inputs being set to high, the voltage shifts are as follows $V_1 = 2\Phi^-$, $V_2 = 2\Phi^+$, $V_3 = \Phi^+$ and $V_4 = \Phi^-$. The output from the system, recorded by the electrometers is the potential difference between D_4 and D_3. Figure 5 shows the actual (solid line) and predicted (broken line) output values for all possible input values.

The output low V_{OL} and output high V_{OH} define the minimum values for output states “0” and “1” respectively. A clear separation between these states is required for digital logic and this is displayed on the figure. The separation would be greater if the temperature at which the QCA operate was to be reduced, or the capacitences lowered. Since the experiment is already conducted at 70 mK the more attractive option, especially if QCA microchips are to be realised, is to reduce the capacitences. This can be done through the use of molecular cells, and the potential is there for room temperature operation with such an implementation.

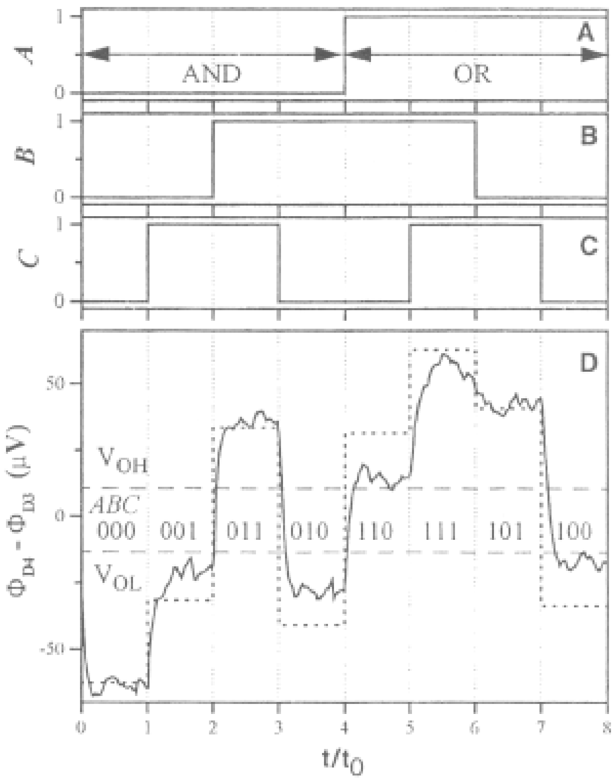

Fig. 5. Experimental and theoretical output from a majority gate QCA.[1]

A possible solution to the problem of very low operating temperatures and a lack of molecular cells could come in the form of magnetic QCA. Initially electronic QCA cells are biased using quantum tunneling (the tunnel junctions described earlier serve this purpose). After this the electrostatic interaction between cells conveys the logic information. In a magnetic QCA (MQCA) network, exchange interactions between spins within single dots go on to form a giant classical spin. The resulting magnetization vector of each dot holds the logic information, e.g. logic '0" if the vector points to the left, and vice-versa for right. Magnetostatic interactions between adjacent dots propagate the logic state, much like the electrostatic interactions involved with electronic QCA networks. The real advantage of MQCA however, is that they have been shown to operate at room temperature.

MQCA are fabricated in a similar way to their electronic counterparts with the exception that the dots must be constructed from a magnetic material. Input dots are elongated which introduces shape-anisotropy and with it, the ability to retain field orientation regardless of adjacent dots whose own orientation may differ. Because no electrons are involved in this type of network a non-electrical method is required to measure the output. One way of going about this is to use magneto-optical analysis, and the Kerr effect (the rotation of plane polarized light after reflection from a magnetic material). A focussed laser beam can record the total component of magnetization, assuming the dots lie in a chain, and can also gather information as to how many dots are switching once calibration has taken place.

Fig. 6. An MQCA chain with the elongated input dot on the left hand side.

The operation of MQCA is slightly more abstract and thus harder to understand than that of electronic QCA. To begin with the elongated input dot is set by a large magnetic pulse, positive for logic "1", negative for logic '0". A much weaker oscillating magnetic field with a negative bias is then set up, and acts as a second input to the system. During the negative phase of the oscillations (which has a larger magnitude than the positive phase due to the negative bias) a field is produced that is strong enough to create what is known as a magnetic soliton. These solitons are analogous to domain walls within bulk magnetic materials and separate dots of left and right magnetization. Since the magnetic pulse is passed from one dot to the next the solitons can be thought of as moving objects carrying the signal along the chain. The most likely point for soliton creation is the far right hand side of the chain since the last dot has only one nearest neighbour. As the soliton travels from right to left changing all the dots to logic '0" (negative field) it eventually reaches the elongated input dot. At this point one of two things can happen, if the input dot itself has previously been set to logic '0" the positive phase of the oscillating field will not have sufficient energy to create another soliton and the entire chain will remain at logic '0" indefinitely. On the other hand if the input dot has been set to logic "1", a new soliton is automatically created between the input dot and the first circular dot (whose magnetic fields are facing in opposite directions). The new soliton is then propagated from left to right switching the chain to logic “1”, and the process continues. Thus the entire chain switches in step with the oscillating field.

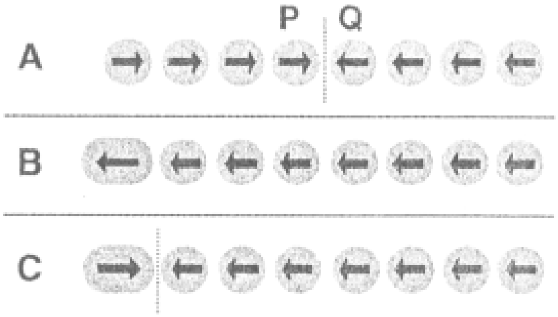

Fig. 7. ***A*** shows a soliton between dots P and Q; ***B*** shows the result of having the input dot set to logic state ‘0”; ***C*** shows the formation of a new soliton between the input dot and the first circular dot when the input dot is set to logic state “1”.

This simple chain of MQCA acts like an AND gate, with the elongated input dot as one input and the oscillating field as the other. Experimentally the logic “1” output is oscillatory with the same frequency as that of the input field.

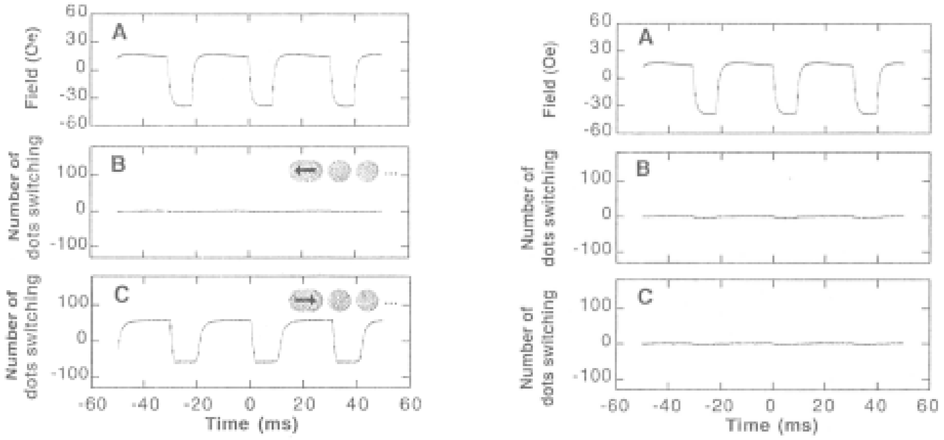

Fig. 8. The results to the left show the switching response of the chain when the input dot is set to logic ‘0” (***B***) and logic “1” (***C***). On the right the response is seen after the removal of the input dot.

In order to verify that actual switching has occurred, the input dot can be removed. Even though an initial large magnetic pulse is still sent across the chain no apparent switching response is seen, leading to the conclusion that the input dot is responsible for the signal seen in figure 8 (left ***C***).

Although this particular setup of MQCA is very simple, much more complex ones can be built in order to achieve all the logic operations necessary for computation. Oscillatory fields can be set up with components in both the x and y directions in order to create networks that can turn corners or fan out in two directions from a single point. In theory solitons propagate with no energy loss, however slight imperfections in the circularity of the dots leads to a very small dissipation of energy. Since the energy is provided by the oscillating field, power gain to overcome these losses is easily achievable. On the subject of dot imperfections a circularity accuracy of ±2% is required, tests with multiple networks show that this too is easily achievable, and in fact the requirement is an order of magnitude less stringent than that of electronic QCA fabrication.

It appears then, that MQCA networks have great potential for use in microelectronics. One of the biggest advantages over current FET based circuits is the integration density that is possible, and perhaps more importantly the potential for even higher densities in the future. If a single MQCA dot is taken to be analogous to a transistor, then the network described in this essay has an integration density of 5500 million/cm^2, current CMOS technology is around the 10 million/cm^2 mark. The interaction energy between two dots in this network is 200 kT (Boltzmann's constant; room temperature). In order to keep thermally induced data errors below approximately one per year, an interaction energy of at least 40 kT is required. Using simple scaling laws it can be shown that dots of 20nm are possible before stability becomes an issue. At this size integration density soars to around 250,000 million/cm^2 giving plenty of scope for the future.

Another advantage of MQCA cells is that since very little energy is dissipated when a dot changes state, the overall power consumption of a microchip would be very low. Estimates of typical power consumption for a MQCA chip are around 1W whereas modern CMOS chips consume about 50W or more. At the moment handheld computer devices and other portable computer applications are constrained by these huge power demands so MQCA chips would benefit this area. Research into layered computer architectures is also coming up against the problems caused by large power consumption. Keeping these chips cool is a major challenge since transistors are easily damaged by excess temperatures. Heat build up wouldn't be a problem if layered MQCA architectures could be developed, and in principle there is no reason why they couldn't be.

• Conclusion

So far in this essay I have tried to give a fact based summary of the current developments in quantum cellular automata. I will now endeavour to express my own views on how successful I think that QCA will be, and if they have a real future within the microelectronics industry.

In terms of practicality and commercialisation I think that electronic QCA have a long way to go. Using current fabrication techniques a room temperature electronic QCA is an impossibility and the only real hope is for molecular implementations. Since this type of research is very much in its infancy it could be decades before we see an electronic QCA microchip. Of course by the time we have the ability to manipulate molecular devices another superior paradigm, such as quantum computing (not to be confused with quantum cellular automata) could have supplanted the need for QCA.

Only time will tell which type of device will be successful, however I believe that MQCA are the more likely candidate, at least in the short term. They seem to bring all of the advantages of QCA with little or no drawbacks, what's more the technological challenges ahead, pre-commercialisation, look far less fearsome than those of electronic QCA. This in the end maybe the key, since the microelectronics industry will be more willing to adopt a paradigm that shares at least some of the fabrication aspects of current microprocessors (for example, lithography).

The possibility still remains that QCA technology will never make it out of the laboratory and with seemingly endless microchip improvements this maybe the most likely outcome. Spurred on by the large profits generated by the thriving technology markets, more research goes into optimising the transistor than any other possible alternatives to it. Moore's Law that transistor integration density doubles every eighteen months has continued to stay true, and is expected to do so for around another decade. Current lithographic techniques such as EUV (extreme ultraviolet) push the limits on the size of features that can be fabricated using an optical approach. Even then it may be possible to use quantum lithography which beats the diffraction limit imposed on masking, by exploiting entangled photon states. Another recent development is the vertical replacement-gate (VRG) transistor. All FET transistors have gates, which are current controlling electrodes. Accurate gate length is critical for a transistor to function correctly, as features become smaller however maintaining accuracy becomes more difficult. Chips must be designed to tolerate variations in gate size leading to inefficiency and a hit in overall performance. Instead of relying on lithography to produce the gate, VRG transistors use a material layer of accurate thickness (easy to produce via well developed semiconductor technology). The result is a transistor that sits on top of a silicon wafer, with components through which current flows vertically. Not only is it very small (~50 nm), but it contains two gates allowing current to flow down both sides of its rectangular structure. This could potentially double the speed of circuits fabricated using this transistor. Finally its unique construction means that another potential pitfall awaiting future transistors could be side-stepped. As the silicon dioxide insulating layer becomes ever thinner in modern transistors, electrons will start to tunnel through it thus causing power loss and eventual chip failure due to layer breakdown. The search for new alternatives to silicon has been hampered due to their sensitivity to the high temperatures involved in semiconductor manufacture. This fails to be an issue with VRG transistors since the insulating layer and gate are applied at the end of the manufacturing process.

The future of the microelectronics industry is clearly by no means certain. No-one can predict what new invention or discovery is just around the corner which could alter the path of developments. QCA and in particular MQCA definitely have some potential as a possible alternative to the current computing paradigm. It's hard to say whether they offer significant advantages over the current paradigm to warrant a change, but if pressed I'd be inclined to say that they do not. The amount of research and investment, together with its almost assured future for at least another decade, means the current paradigm will continue to evolve until something really big comes along and initiates a revolution.

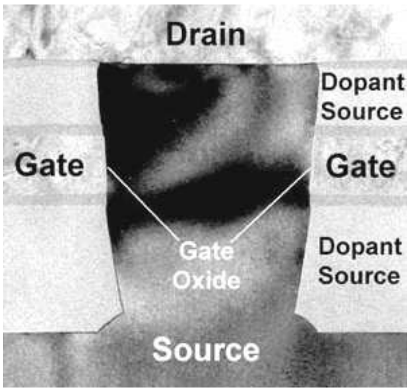

Fig. 9. A VRG transistor.

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WWW sites

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