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Fabrication and Demonstration of Quantum-Dot Cellular Automata Systems

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1. Introduction

The quantum dot (QD), or "0-dimensional" structure, represents the ultimate in scaling – hence the allure in investigating its properties and seeking applications for it. To our knowledge, the first computation scheme to exploit the QD was that of quantum-dot cellular automata (QCA). Conceived at the University of Notre Dame in 1993 [1], QCA is widely investigated as a possible contender to ultimately augment, and perhaps even replace, conventional CMOS.

Basically, QCA is an array of elements (at first conceived to be QDs, but now expanded to include other elements) that interact through local field effects to change their electronic or magnetic polarizations, the configuration of which represents the computational state of the machine. These elements have variously been realized so far in semiconductors [2], metal tunnel junctions, arrays of nanomagnets, and hopefully soon, molecules.

2. Semiconductor and Metal Tunnel Junction QCA

When QCA was introduced, it was envisioned that semiconductor quantum dots confined by leaky barriers would lead to QCA architectures. These include quantum dots formed in either heterostructure or Si/SiO_2 two-dimensional electron gases. Confinement barriers are created by potentials applied to surface gates, which squeeze the electrons into QD formations. This scheme was found to be cumbersome and prone to charge fluctuations caused by impurities and defects.

Metal tunnel junctions (MTJ) of the Fulton-Dolan type [3] for charge confinement were found to be easier to fabricate, more reliable, and easier to analyze and model. A set of experiments resulted from the continued refinement of the MTJ system. However, this serves only as a prototype system, and is subject to several problems of stray charge in the substrate, as well as the inevitable limit to the number of control lines needed to bias the cells. Nevertheless, successful demonstrations of MTJ QCA systems at temperatures of around 70 mK include basic QCA cell operation [4], logic gates[5], clocked QCA cells (in which a third dot is added between end dots for control of electron switching) [6], electron latching, shift registers, and power gain (deriving from the clock inputs) [7]. Together these papers form a convincing case that the basic notion of QCA can be made to work, albeit in a system that is likely impractical for large-scale systems. This impracticality is due to the required mK temperatures (which might be overcome by size scaling), the presence of background charges (which might yield to continued research), and the need for biasing lines (which may be obviated by eliminating background charge).

3. Magnetic QCA

The systems architectures discussed above have charge coupling in common. Field-coupled nanomagnet arrays, however, offer the possibility of QCA systems exhibiting robust room temperature operation [8].

Fig. 1 shows the atomic force microscope (AFM) and magnetic force microscope (MFM) images of a line of 64 rectangular magnets exhibiting perfect antiferromagnetic behavior down the entire line. Such strong coupling is totally outside the realm of random chance, and suggests that using nanomagnets for QCA coupling is indeed feasible. Fig. 2 shows one possible embodiment of in-plane, trapezoidal nanomagnets configured as a majority gate, as simulated by OOMMF. The three horizontal trapezoids to the left are the inputs that can be held at their logical values by current carrying wires during the clock phase. As the horizontal clocking field increases, the vertical magnets are magnetized horizontally, and when the clocking field decreases, they are allowed to relax to the ground state. In the figure, the input magnets are all magnetized to the right, which in this case signifies a "1," for the top two magnets (because of their relative configurations with the vertical direction of the coupling magnets) and a logic "0" for the bottom dot. As expected, the central dot is influenced by the majority vote and is magnetized up, starting the signal propagating down the wire.

4. Molecular QCA

The ultimate size limit of computing must necessarily be a single molecule. At these size scales, QCA operation at room temperature would be possible with unheard of circuit density, speed, and low power dissipation. Such a notion is within the realm of the possible, as many variations of molecules have been designed that incorporate redox active corners connected by tunnel junctions, as well as chemical moities to serve as surface attachment

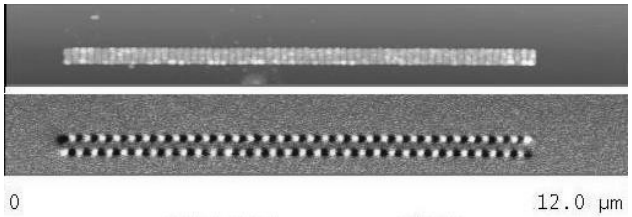

Fig. 1. Perfect antiferromagnetic ordering along a 64 magnet-long chain. Top- AFM and bottom – MFM images.

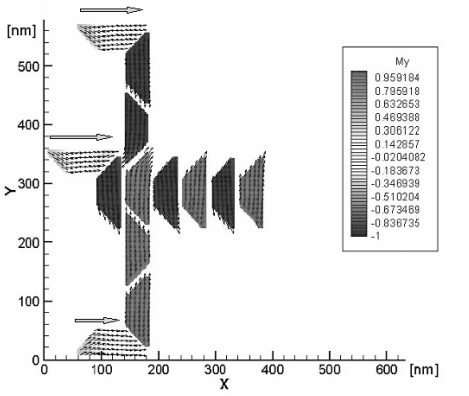

Fig. 2. OOMMF simulated result of planar majority gate.

sites. In these cases, we envision single molecules functioning as whole QCA cells. There are numerous examples of the analogous two-dot cell, for example silicon phthalocyanine dimers [9]. The HS-group (thiol) is an example of feet that attach the molecules preferentially to a surface, in this case gold. We have demonstrated that a liftoff process of molecules, similar to that commonly used for metals, is possible [10]. A requirement for such a process is that the molecules stick to the surface and not to the resist. Also, the molecules must not be soluble in a suitable resist remover. Fig. 3 shows nominally 20 nm lines formed by EBL of polymethylmethacrylate (PMMA) on SiO_2, development, submersion in a solution containing specialized Creutz-Taube molecules (called "CT5"), and removal of the PMMA in methylene chloride for improved surface cleanliness [11]. A practical molecular QCA system would consist of lithography at the few nm scale, molecules that attach in the channels, and self assembly in lines to form circuits with sufficiently few errors. We have demonstrated EBL of 4-5 nm lines, which should allow single or double lines of QCA molecules to be formed.

5. Conclusions

We have reviewed the paradigm of QCA and discussed several experiments in metal tunnel junction and magnetic QCA. Some limitations to the adoption of the technology were discussed. It is likely that the ultimate utility of QCA, in any form, will be in combination with currently existing, advanced technologies, such as CMOS, for the case of molecular QCA, or some totally magnetic technology incorporating logic by QCA and memory by magnetic random access memory, for example.

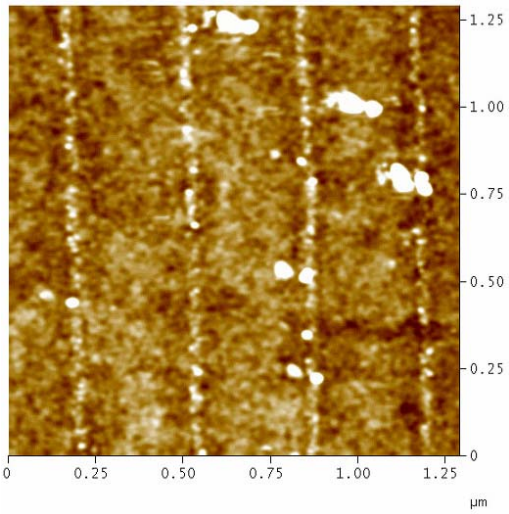

Fig. 3. Atomic force microscope image of lines of CT5 molecules formed by liftoff. The apparent linewidth is about 20 nm. The radius of the AFM tip is estimated to be 10 nm, so the actual linewidth is somewhat smaller.

Acknowledgements

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References

[1] C.S. Lent, P.D. Tougaw, W. Porod, and G.H. Bernstein, "Quantum cellular automata," *Nanotechnology* vol. 4 (1993) 49.

[2] G. Bazán, A.O. Orlov, G.L. Snider, and G.H. Bernstein, "Charge detector realization for AlGaAs/GaAs quantum-dot cellular automata," *J. Vac. Sci. Technol. B*, vol. 14, no. 6 (1996) 4046.

[3] T.A. Fulton and G.J. Dolan, "Observation of single-electron charging effects in small tunnel junctions," *Phys. Rev. Lett.*, vol. 59, no. 1 (1987) 109.

[4] G.H. Bernstein, I. Amlani, A.O. Orlov, C.S. Lent, and G.L. Snider, "Observation of Switching in a Quantum-dot Cellular Automata Cell." *Nanotechnology*, 10 (1999) 166.

[5] I. Amlani, A.O. Orlov, G. Toth, G.H. Bernstein, C.S. Lent, and G.L. Snider, "Digital logic gate using quantum-dot cellular automata," *Science*, vol. 284 (1999) 289.

[6] A.O. Orlov, R.K. Kummamuru, R. Ramasubramaniam, C.S. Lent, G.H. Bernstein, and G.L. Snider, "Clocked Quantum-dot Cellular Automata Devices: Experimental Studies," IEEE-Nano 2001, Maui, Hawaii, October, 2001.

[7] R.K. Kummamuru, J. Timler, G.Toth, C.S. Lent, R. Ramasubramaniam, A.O. Orlov, G.H. Bernstein, and G.L. Snider, "Power gain in a quantum-dot cellular automata latch," Appl. Phys. Lett., vol. 1 no. 7 (2002) 1332.

[8] G. Csaba, A. Imre, G. H. Bernstein, W. Porod, and V. Metlushko, "Nanocomputing by field-coupled nanomagnets," *IEEE Trans. Nanotechnol.*, vol. 1, no. 4 (2002) 209.

[9] Z. Li, M. Lieberman, and W. Hill "XPS and SERS study of silicon phthalocyanine monolayers: umbrella vs octopus design strategies for formation of oriented SAMs," *Langmuir*, vol. 17 (2001) 4887.

[10] Q. Hang, Y. Wang, M. Lieberman, and G. H. Bernstein, "Molecular patterning through high-resolution polymethylmethacrylate masks, "*Appl. Phys. Lett.*, vol 80, no. 22 (2002) 4220.

[11] Q. Hang, D. A. Hill, and G. H. Bernstein, "Efficient removers for polymethylmethacrylate," *J. Vac. Sci. Technol. B*, vol. 21 (2003) 91.