Magnetic Cellular Automata Coplanar Cross Wire Systems

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Quantum Cellular Automata (QCA) has proposed an exclusive architecture, where two coplanar perpendicular wires have the ability to intersect one another without signal degradation. The physical realization of cross wire architectures has yet to be implemented and researchers share concerns over the reliability of such a system. Here we have designed a coplanar cross wire layout for Magnetic Cellular Automata (MCA) and have fabricated two different systems. We have implemented a system containing two ferromagnetic coupled coplanar crossing wires and demonstrate all possible combinations. We have also fabricated a cross wire system consisting of nine junctions and one hundred and twenty single domain nano-magnets. The complex systems ability to reach an energy minimum combined with the demonstration of all combinations of the smaller system leads us to conclude that a cross wire system is physically feasible and reliable in Magnetic Cellular Automata.

I. INTRODUCTION

A theoretically unique characteristic of Quantum Cellular Automata (QCA) is the ability to not only propagate information along two independent nonintersecting coplanar wires, but also to transmit information via two independent coplanar perpendicular crossing wires. Figure 1 provides a visual representation of two different technologies implementing crossing wires. If two conventional metal interconnects were fabricated in such a manner as depicted in Figure 1 A), the junction, where the two crossing wires intersect, might lead to an electrical short (a logical 1 and 0 given simultaneously on the wires). Consequently, multiple layers are needed to overcome layout scenarios where wires cross over one another. This increases the complexity of fabrication, by creating multiple layer alignment steps, as well as expands the non-trivial intricacies of designing the layout of a system currently containing over two billon transistors (Boyd, 2009). As technology continues to scale deeper into the lower boundaries of nano space, the delicacy of multiple layer alignment could quite probably lower the yield of working devices.

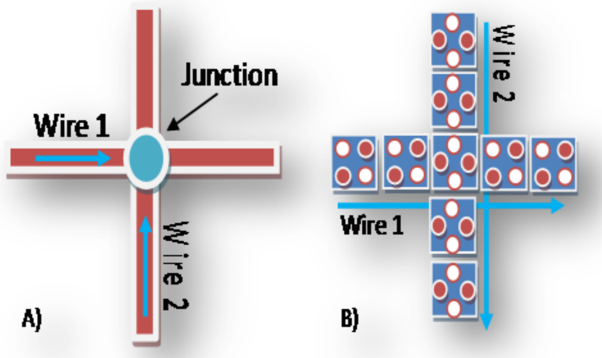

FIG. 1 A) An abstract representation of two coplanar crossing wires. The area where the two wires cross is called the junction. Information propagation is shown via the arrows. B) A representation of QCA coplanar crossing wires. For traditional wires, the junction would create a source of error and this type of structure would not be viable.

Electronic QCA (EQCA) has theoretically proposed a coplanar cross wire system. In EQCA, devices are coupled via columbic field interactions rather than physical connections. Figure 1 B) demonstrates two orthogonal sets of EQCA wires. In order to limit coupling interference between the two wires, Wire 1 is comprised of cells that are oriented in a normal fashion, while in Wire 2, the cells are rotated by 45 degrees. Due to the physical nature and the need for experimental data of the system, researchers have expressed concerns over the viablity of coplanar crossing wires (Walus *et al.*, 2004).

In Magnetic Cellular Automata (MCA), the basic cells are single domain nano-magnets. The cells are enumerated based on the orientation of the magnetic dipole moments as shown in Figure 2 A). By engineering the nano-magnets shape, an easy axis of magnetization is created via shape anisotropy energy. The logical states of the cells lie along the easy axis and are magnetic energy minimums. By establishing this as the ground state for individual cells, MCA as a system attempts to reduce its overall energy by settling into desired logical states. MCA processes information through magnetic dipolar interaction between neighboring cells as shown in Figure 3 (A-B). Many advantages of MCA computing systems include room temperature operation, radiation hardness, ease of fabrication, and possible integration with tech-

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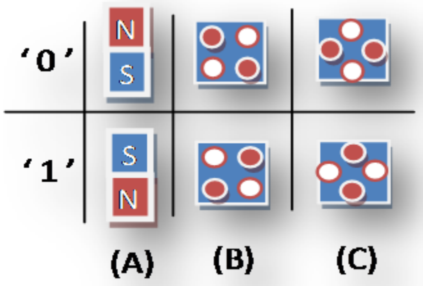

FIG. 2 Standard abstract representation of MCA and EQCA cells. The top row can be interpreted as a logical zero and the bottom a logical one. (A) enumerates the nano magnetic cells based on their magnetic dipole moments. (B) Depicts the standard QCA cell. Two electrons are represented as red dots. The white dots are the alternate electron sites which the electrons tunnel to in order to reduce the cells overall energy in accordance with its neighbors. (C) Consist of the same elements only the sites are rotated by 45 degrees. This is necessary for a cross wire layout in EQCA.

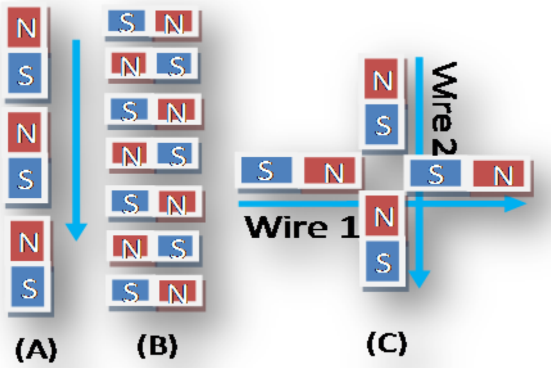

FIG. 3 Three different MCA wire architectures. A) An abstractly representation of a ferromagnetic wire. Information is propagated through ferromagnetic coupled neighboring cells. (B) An abstract representation of a anti-ferromagnetic wire. (C) An abstract representation of the junction in MCA coplanar crossing wires. The junction of MCA cross wires consists of two magnets from Wire 1 and two magnets of Wire 2.

nologies such as MRAM and magnetic sensor.

The focus of this paper however is the design and implementation of ferromagnetic coplanar cross wire systems. Essentially, two ferromagnetic coupled wires orthogonally intersect one another at a junction point as shown in Figure 3 (C). Since the wires are orthogonal to each other, the coupling interference is mitigated by the designed shape anisotropy of the cells. Thus, the wires are able to cross in the same plane with virtually no interference. Our experimental studies showed no occurrences of errors in the cross wire junctions. This suggests a stable and relatively easy to fabricate cross wire system that may be utilized by future MCA designers.

II. MCA ARCHITECTURES

Out of all the current emerging types of Cellular Automata, Magnetic Cellular Automata has demonstrated the most functionality. Csaba et al established a scheme for a digital type of computation by using shape engineered rectangular nano magnets as the basic cell (Csaba *et al.*, 2002). They proposed to use anti-ferromagnetic coupling as the main exchange interaction. Since then there have been many advances in MCA, namely all the necessary logic to implement any Boolean equation (Imre *et al.*, 2006). The initial proof of concept for MCA was accomplished by Cowburn et al, using circular nano magnets in a ferromagnetic coupling scheme (Cowburn and Welland, 2000). This proved that data propagation via single domain nano magnets was indeed possible.

Figure 3 (A) and (B) shows an abstract representation of both ferromagnetic and anti-ferromagnetic coupled wires. As described above, in MCA a basic cell is a single domain nano magnet. The magnet dipole moments are used to enumerate the states of the cell. Neighboring magnets couple with one another via magnet fields produced by each cell. The two types of coupling in MCA are ferromagnetic and anti-ferromagnetic. Anti-ferromagnetic coupling essentially inverts the orientation of the magnetic dipole moment at every cell. In ferromagnetic coupling, the magnetic moment at each cell in a wire has the same orientation as their neighbor.

and has yet to be physically implemented. This has led to debate whether the system can actually be physically realized without a loss of functionality. Here we have designed a cross wire system for MCA and present a functioning physical implementation of our design.

In the next section, a brief review of E-QCA coplanar cross-wire systems are discussed followed by the implementation of the magnetic cellular automata crosswires.

III. CELLULAR AUTOMATA CROSSING WIRES

The novelty of QCA and the associated fabrication difficulties create a great opportunity exist for experimental research to be conducted. An EQCA proof of concept cell was demonstrated to work, but the experiment was conducted at a temperature of 70mK (Amlani *et al.*, 2000). Due to the energies involved, the dimensions necessary for EQCA to work at room temperature are on the order of a few nanometers which creates a challenge for current fabrication technology. This space allows for designs such as crossing wires to be theoretically proposed and critiqued but requires a physical actualization to make such architectures viable.

Tougaw *et al.* proposed the idea of coplanar wire crossings for Electronic QCA, and explained that by physically rotating the electron sites by 45 degrees, as shown in Figure 2 C), two coplanar crossing wires could propagate information successfully (Tougaw and Lent, 1994). Figure 1 B) shows the crossing wire system propagating information. Wire 1 is propagating a logical 1 while Wire 2 is propagating a logical 0. The cells in Wire 2 have a 45 degree rotation in order to minimize any influence that it could have on Wire 1. Walus explains that the 45 degree rotated junction cell has a null effect on neighboring cells of Wire 1 regardless if it is propagating a 0 or a 1 (Walus *et al.*, 2004). Concerns are also expressed over coplanar crossing wires. Walus states that 45 degree cross wires breaks the non-rotated wire into several weakly coupled segments. This is due to the energies associated with the columbic interactions of EQCA. Bhanja *et al.* further characterized various cross-wire architectures (TMR, Double-TMR and Thick crosswires) in terms of polarization loss and thermal stability by modeling the crosswire system as probabilistic Bayesian network model (Bhanja *et al.*, 2007). The coplanar cross wire systems were probabilistically infered under various thermal conditions anrobustness was characterized under single missing cell defects.

We have ported the architecture into Magnetic Cellular Automata by designing a ferromagnetic coplanar cross wire system. Figure 3 (C) shows an abstract representation of the ferromagnetic cross wire system we have designed. It is composed of two perpendicularly intersecting ferromagnetic coupled wires. As depicted by the blue arrows, information is propagated along the two wires without a loss of information. We have studied the MCA cross wire systems under various magnetic fields and present our results in the following.

IV. EXPERIMENTAL SETUP

A JEOL 840 SEM with the Nabity NPGS system was used to fabricated all devices. A Veeco DI 3100 was used to collect all Magnetic Force and Atomic Force Microscopy data. Samples were provided external fields via a custom built electromagnet. Further details of fabrication and setup can be found here (Pulecio and Bhanja, 2007).

V. RESULTS AND DISCUSSION

A. Two Coplanar Cross Wire System

We have fabricated a crosswire similar to the one shown in Fig 3 (C). Figure 4 shows a topological SEM image of the cross wire system where Wire 1 and Wire 2 are each composed of 10 nano-magnets. Figure 5 is a 3D representation of an AFM image taken of the same cross wire structure. By combining these types of metrology we are able to attain a comprehensible representation of the cross wire structure. As can be seen in the SEM image there are a few lateral spatial irregularities as well as some irregularly shaped cells. On average most cells were approximately 100nm x 50nm with a spacing of 20nm between each cell. The AFM data allows us to determine the roughness and thickness of the nanomagnets. As can be seen in the 3D AFM image, the surface of the nano magnetic cells are non-uniform, with several peaks covering the surfaces. Previously we reported that surface roughness led to faulty data propagation for anti-ferromagnetic wires, here our intent was to determine if surface roughness has a significant role in the coupling of ferromagnetic wires as well (Pulecio and Bhanja, 2007). Bryan *et al.* also noted that edge roughness increased the coercivity of rectangular nano

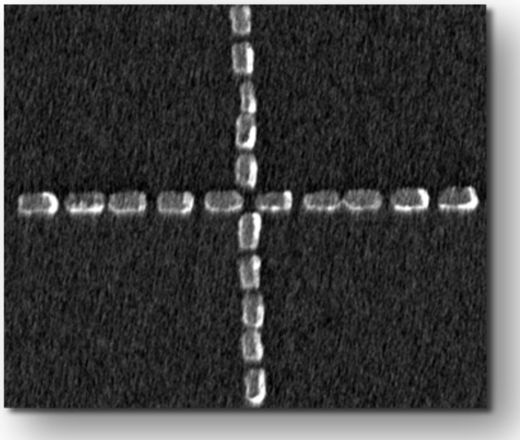

FIG. 4 A SEM image of the two coplanar cross wire system.

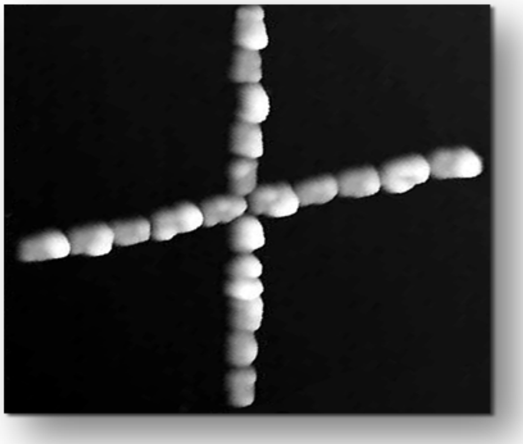

FIG. 5 An AFM image of the two coplanar cross wire system.

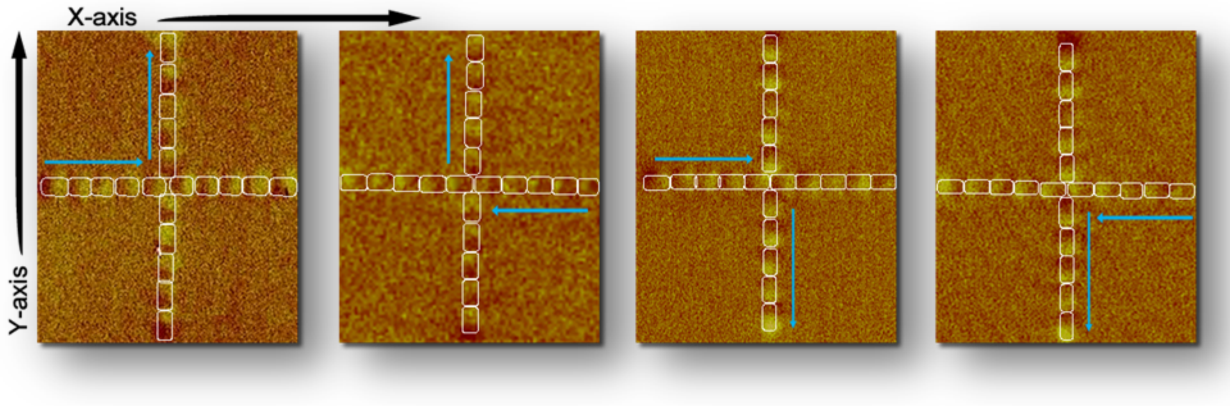

FIG. 6 An MFM image of all possible combinations of a simple crosswire. White ellipses have been overlaid to outline each nano-magnet. The arrows represents the flow of data propagation for each wire.

magnetic structures (Bryan *et al.*, 2004). The thicknesses of the cells were approximately 35nm with a maximum peak height of 104nm. We have determined, via bearing analysis, approximately 55% of the surface was covered with peaks greater than 10nm above the thickness. This presents a less than ideal case for the physical implementation of a ferromagnetic cross wire system, but if successful could demonstrate the robustness to fabrication defects of the system.

Figure 6 shows all four possible combinations for data propagation in a two coplanar cross wire system. An external magnetic field was provided for stimulus and then removed. Afterwards the system was allowed to settle in an energy minimum. The blue arrows represent the orientation of the magnetic dipole moments along the wires. As can be seen, there were no frustrations present in any four of the combinations and the system reacted as expected. We also note that the particular system we chose to present here is a non-ideal sample, due to the irregularities mentioned above.

We also note that in all of our experiments with coplanar cross wires we have never seen any frustrations at the most critical area of the system, namely, at the junction. The junction area can be considered as the four nano-magnetic cells where the two wires intersect each other, as shown in Figure 3 (C). Due to the nature of magnets, if the junction performs in a reliable manner, any subsequent nano-magnetic cell in the wire will not experience signal loss. Meaning, for MCA coplanar cross wire systems the wire is not segmented into smaller slices. The magnetization of the cell participating in the junction, once settled, will provide a self gaining effect. This is due to the nano-magnet attempting to minimize its internal magnetic energy. To a nano-magnet neighboring the junction, the magneto static energy it experiences would be similar to neighboring a cell in a traditional wire.

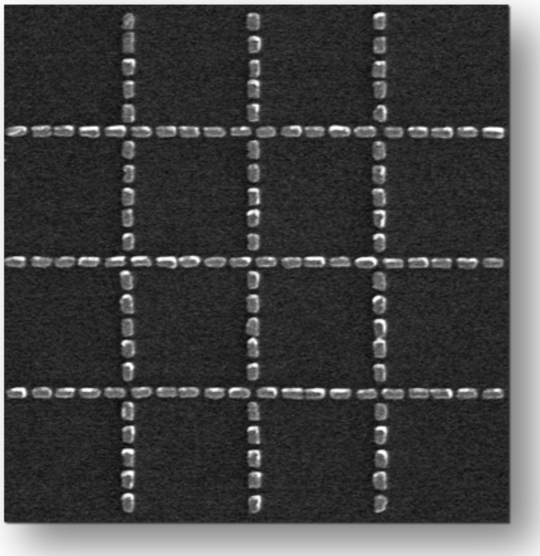

FIG. 7 A SEM image of the complex cross wire system. The system consisted of 6 wires with 9 junctions. Each wire was 20 nano-magnets long.

B. Complex Cross-wire system

In an effort to determine if indeed the hypothesis of wires being self gaining after the junction, in other words wires not becoming segmented into smaller sections at each junction, we fabricated a more complex cross wire system. The MCA system consisted of 6 wires, each 20 nano magnets long, as shown in the SEM image Figure 7. Each magnet was approximately 100x50x35nm and the system had a total of 9 junctions. As before, an external field was provided for stimulus, removed, and the system was allowed to reach a ground state. The arrows depict the orientation of the magnetic dipole moment along the

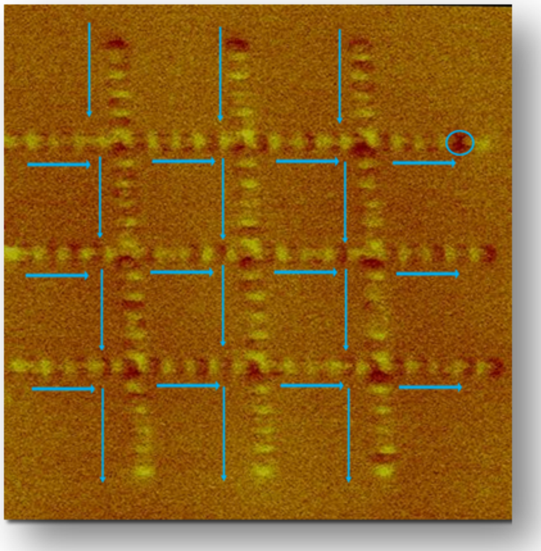

FIG. 8 A MFM image of the complex cross wire system. The blue arrows represent the propagation of data down the wires. As can be seen all nine junctions have no frustrations.

wires. As can be seen there are no frustrations at any of the junctions. In fact, there are no frustrations in the entire system except in one location. This is highlighted in Figure 8 with a blue circle. We are familiar with scenario and were pleasantly surprised that it only occurred once in such a complex system. Due to the complex nature of providing inputs and clocking fields at the nano level, currently the system is left to attain an energy minimum after the external field is removed. When this occurs you create a scenario for multiple drivers to be created in the wire. As can be seen in Figure 8, this occurs most frequently near the terminal locations of the wire. We find this result to bolster the viability of MCA as a technology. If a complex system such as this is able to attain an energy minimum on its own without the help of a driving input, it would seem that the system is very capable of minimizing its total energy.

VI. CONCLUSION

Unlike EQCA, where there is a rotated cell in the center of the junction, as shown in Figure 1(B), MCA has a free area of space which is able to compute, as shown in Figure 3(C). We experimentally demonstrated all four possible combinations of a two coplanar cross wire system, even though, physically the system was less than ideal. This demonstrates the robustness of ferromagnetic coupled cross wires systems. Furthermore, we fabricated a complex cross wire system consisting of 120 nano-magnetic cells with 9 junctions and report the system was able to reach an agreeable minimum energy. The concerns of segmentation of wires due to junctions, as in EQCA, do not seem to manifest themselves in our experimental investigations.

Our results lead us to believe that MCA is inherently able to reach energy minimums and that ferromagnetic cross wire architectures are likely to be realized in Magnetic Cellular Automata. This could possibly enable the technology to increase the density of switches, develop new layout algorithms to optimize space in the design automation process, as well as simplify the fabrication process by removing several multilayer alignment steps, thus increase yield.

Acknowledgments

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