Magnetic cellular automata coplanar cross wire systems

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Quantum cellular automata 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. The first system was implemented via two ferromagnetic coupled coplanar crossing wires and demonstrated all possible logic combinations. The second more complex cross wire system consisted of nine junctions and one hundred and twenty single domain nanomagnets. The complex system's 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 MCA.
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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 are fabricated in such a manner as depicted in Fig. 1(a), the junction, where the two crossing wires intersect, could cause 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 expanding the nontrivial intricacies of designing the layout of a system currently containing over two billion transistors. As technology continues to scale deeper into the lower boundaries of nanospace, the delicacy of multiple layer alignment could probably lower the yield of working devices.

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°. Due to the physical nature and the need for experimental data of the system, researchers have expressed concerns over the viability of coplanar crossing wires.[1]

In magnetic celluar automata (MCA), the basic cells are single domain nanomagnets. The cells are enumerated based on the orientation of the magnetic dipole moments, as shown in Fig. 2(a). By engineering the nanomagnets 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 Figs. 3(a) and 3(b). Many advantages of MCA computing systems include room temperature operation, radiation hardness, ease of fabrication, and possible integration with technologies such as magnetic random access memory (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 Fig. 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 show no occurrences of errors in the cross wire junc-

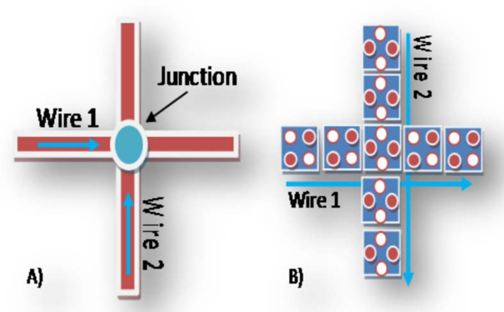

FIG. 1. (Color online) (a) An abstract representation of two coplanar crossing wires. The area where the two wires cross is called the junction. Information propagation is shown via the arrows. (b) A representation of QCA coplanar crossing wires. For traditional wires, the junction would create a source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

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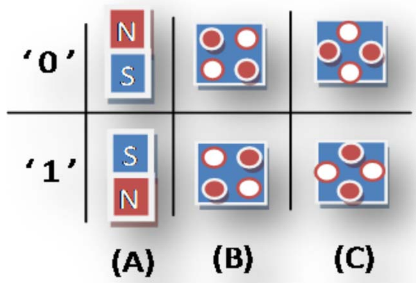

FIG. 2. (Color online) A standard abstract representation of MCA and EQCA cells. The top row can be interpreted as a logical zero and the bottom a logical one. (a) Enumerates the nanomagnetic cells based on their magnetic dipole moments. (b) Depicts the standard QCA cell. Two electrons are represented 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°. This is necessary for a cross wire layout in EQCA.

tions. 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 CA, MCA has demonstrated the most functionality. Csaba *et al.*[2] established a scheme for a digital type of computation by using shape engineered rectangular nanomagnets as the basic cell. They proposed to use antiferromagnetic 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.[3] The initial proof of concept for MCA was accomplished by Cowburn *et al.*[4] using circular nanomagnets in a ferromagnetic coupling scheme. This proved that data propagation via single domain nanomagnets was indeed possible.

Figures 3(a) and 3(b) show an abstract representation of both ferromagnetic and antiferromagnetic coupled wires. As described above, in MCA, a basic cell is a single domain nanomagnet. 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 antiferromagnetic. In ferromagnetic coupling, the magnetic moment at each cell in a wire has the same orientation as its neighbor. Antiferromagnetic coupling essentially inverts the orientation of the magnetic dipole moment at every cell.

The cross wire system is a unique architecture to CA 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 EQCA coplanar cross wire systems are discussed, followed by the implementation of the MCA coplanar crossing wires.

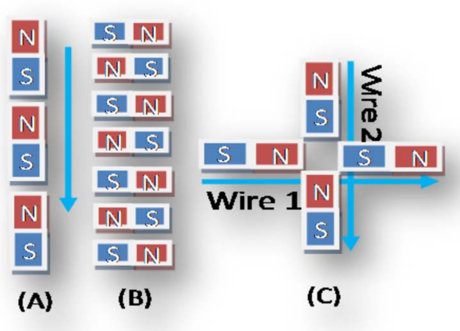

FIG. 3. (Color online) Three different MCA wire architectures. (a) An abstract representation of a ferromagnetic wire. Information is propagated through ferromagnetic coupled neighboring cells. (b) An abstract representation of a antiferromagnetic wire. (c) An abstract representation of the junction in MCA coplanar crossing wires. The junction of MCA cross wires consists of two magnets from wire 1 and two magnets of wire 2.

III. CA CROSSING WIRES

The novelty of QCA and the associated fabrication difficulties creates a great opportunity 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 70 mK.[5] Due to the energies involved, the dimensions necessary for EQCA to work at room temperature are approximately a few nanometers. This creates a challenge for current fabrication technology. This gap 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.*[6] proposed the idea of coplanar wire crossings for EQCA, and explained that by physically rotating the electron sites by 45°, as shown in Fig. 2(c), two coplanar crossing wires could propagate information successfully. 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° rotation in order to minimize any influence that it could have on wire 1. Walus *et al.*[1] explains that the 45° rotated junction cell has a null effect on neighboring cells of wire 1 regardless if it is propagating a 0 or a 1. Concerns are also expressed over coplanar crossing wires. Walus *et al.*[1] states that 45° cross wires breaks the nonrotated wire into several weakly coupled segments. This is due to the energies associated with the columbic interactions of EQCA. Bhanja *et al.*[7] further characterized various cross wire architectures (triple modular redundancy, double-triple modular redundancy and thick crossing wires) in terms of polarization loss and thermal stability by modeling the cross wire system as probabilistic Bayesian network model. The coplanar cross wire systems were probabilistically inferred under various thermal conditions and the robustness was characterized under single missing cell defects.

We have ported the architecture into MCA 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

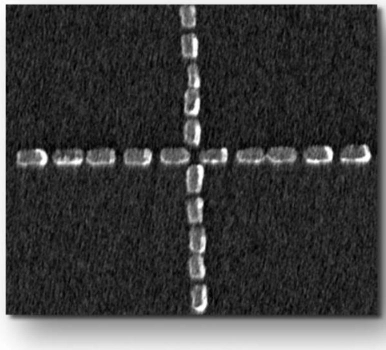

FIG. 4. A SEM image of the two coplanar cross wire system.

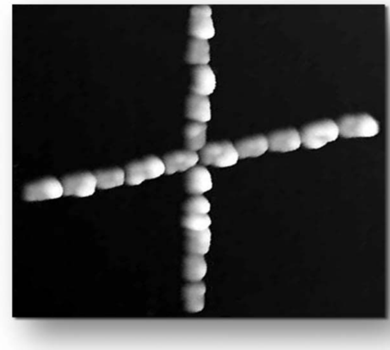

FIG. 5. An AFM image of the two coplanar cross wire system.

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 scanning electron microscope with the Nabity NPGS system was used to fabricate all devices. A Veeco DI 3100 was used to collect all magnetic force and atomic force microscopy (AFM) data. All the systems studied were provided an external field via a custom built electromagnet. Further details of fabrication and setup can be found in Ref. 8.

V. RESULTS AND DISCUSSION

A. Two coplanar cross wire system

We have fabricated a cross wire 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 ten nanomagnets. 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 more accurate 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 $100\times 50\ \text{nm}^2$ with a spacing of 20 nm 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 nanomagnetic cells are nonuniform, with several peaks covering the surfaces. Previously, we reported that surface roughness led to faulty data propagation for antiferromagnetic wires, here, our intent is to determine if surface roughness has a significant role in the coupling of ferromagnetic wires as well.[8] Bryan *et al.*[9] also notes that edge roughness increased the coercivity of rectangular nanomagnetic structures. The thicknesses of the cells are approximately 35 nm with a maximum peak height of 104 nm. We have determined, via bearing analysis, that approximately 55% of the surface is covered with peaks greater than 10 nm 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 is provided for stimulus and then removed. Afterward, the system is 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 are 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 nonideal 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 nanomagnetic cells where the two wires intersect each other, as shown in Fig. 3(c). Due to the nature of magnets, if the junction performs in a reliable manner, any subsequent nanomagnetic 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 nanomagnet attempting to minimize its internal magnetic energy. For a nanomagnet neighboring

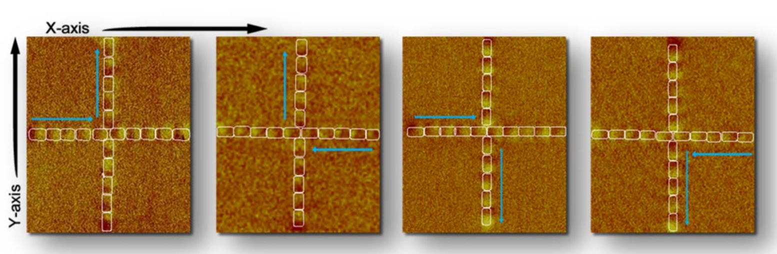

FIG. 6. (Color online) A MFM image of all possible combinations of a simple cross wire. White ellipses have been overlaid to outline each nanomagnet. The arrows represent the flow of data propagation for each wire.

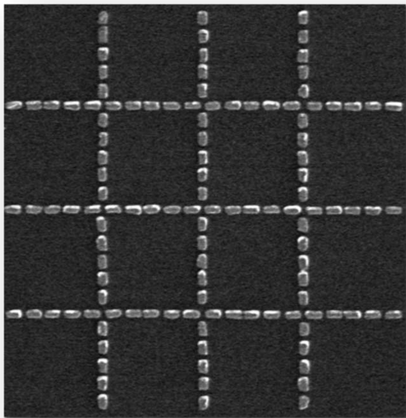

FIG. 7. A SEM image of the complex cross wire system. The system consisted of six wires with nine junctions. Each wire was 20 nanomagnets long.

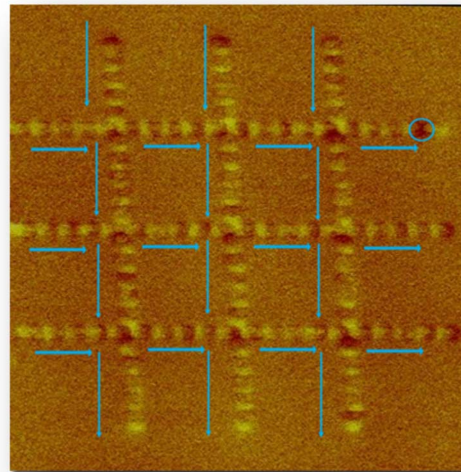

FIG. 8. (Color online) A MFM image of the complex cross wire system. The blue arrows represent the propagation of data down the wires. As can be seen all nine junctions have no frustrations.

the junction, the magnetostatic energy it experiences would be similar to neighboring a cell in a traditional wire.

B. Complex cross wire system

In an effort to determine if indeed the hypothesis of wires being self-gaining after the junction was true, 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 six wires, each 20 nanomagnets long, as shown in the SEM image Fig. 7. Each magnet is approximately $100 \times 50 \times 35$ nm and the system has a total of nine junctions. As mentioned before, an external field is provided for stimulus, removed, and the system is allowed to reach a ground state. The arrows depict the orientation of the magnetic dipole moment along the 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 Fig. 8 with a blue circle. We are familiar with this 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 nanolevel, currently, the system is left to attain an energy minimum after the external field is removed. When this occurs a multiple driver scenario is created in the wire. As can be seen in Fig. 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.[10] 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 Fig. 1(b), MCA has a free area of space which is able to compute, as shown in Fig. 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 nanomagnetic cells with nine junctions and report that the system is 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 MCA. 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.

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