MIT-UVa NRI-NSF MRSEC Project Kickoff (Oct 14, 2010)
Project: Reconfigurable Array of Magnetic Automata (RAMA)
Location: MIT, Cambridge, MA, Bldg 13, Room 5002

Attendees:

NRI liaison team	**Professors & Students**
Steve Kramer (Micron) An Chen (Global Foundries) Luigi Colombo (TI) Bill Gallagher (IBM) George Bourianoff (Intel)—call-in Absent (NIST)—no representative	Caroline Ross (MIT PI) Nicolas Aimon (MIT Grad student) Stuart Wolf (UVa PI) Ryan Comes (UVa Grad Student) Mehdi Kabir (UVa Grad Student) Absent Mercea Stan (UVa Prof) Jiwei Lu (Research Asst Professor)

Meeting schedule:

10:00 - 12:00AM	Research presentations by MIT and UVa teams
12:00 - 12:30	Closed session of review team
12:30 - 1:30	Lunch
1:30 – 2:30	Lab tours & wrap up

Project Objective:

To develop a new, fully reprogrammable, ultra-low power spin logic architecture based on a Reconfigurable Array of Magnetic Automata (RAMA) operated at room temperature.

Project Overview

From last year's statement of work:
The objective of this proposal is to provide the proof of principle of both the RAMA structure and the self assembly methods that will provide a pathway to a very high density, fast, inexpensive logic array for post CMOS electronics. The University of Virginia will demonstrate both the feasibility of this approach using more conventional fabrication techniques during the first two years and MIT will develop the self assembly techniques that will enable the inexpensive, large scale manufacturing of these circuits. During the second year the team will work to use the self assembly methods and will start to self assemble prototypes of the RAMA structure with a small number of gates in the third year.

Device Concept

Stu Wolf explains the function as thus:

> The proposed logic array would be similar to a Magnetic Quantum Cellular Automata (MQCA) and would work in the following fashion. The ferromagnetic pillars are designed to couple antiferromagnetically through their dipolar interactions and thus there would be two stable configurations of the array with each magnet being oppositely

magnetized for the two configurations. A bit consists of four pillars in a square with two corners magnetized up and two down.

In this novel logic architecture, each bit consists of 4 pillars such that each adjacent pair couples antiferromagnetically. With the presence of E field, the moment within the pillar is rotated from out-of-plane to in-plane thus the pillar/bit is de-activated from any operation and no current flows. Thus we can reprogram RAMA to perform operations with very small energy dissipation and no physical reconstruction.

Meeting Summary

Ferromagnetic Coupling simulations

Modeling of MQCA error rate was madewith respect spacing and volume at different temperatures. This resulted in an understanding of min and max spacing to get needed interaction while insuring acceptable levels of cross-pillar interfence, giving plots of zero-error bonds. Pillar volume modeling indicated that a larger volume had a better error-free zone, but this would be at the cost of switching energy and time.

Nanopillar multiferroic behavior modeling was done using a phenomenological, thermodynamic model, rather than a complicated magnetic one. This sacrifices some precision and ignores some material parameters; however, it provides qualitative insight into switching process and can be extended to include other multiferroic coupling effects. It was assumed that the material interaction was linearly ferroelectric rather than magnetic. Under applied voltage, results suggest a rotation of easy access to in-plane, matching experimental observation. Half-select issue appears to be surmountable by staying below a "cascading" threshold in the half-selected cell—adjacent cells have a non-linear magnetization remnance. .

Material Deposition and Patterning

The Wolf group made Cobalt Ferrite ($CoFe_2O_4$) films by pulsed electron deposition (PED) were grown on STO and MgO substrates, with the latter having better crystalline and magnetic properties. Large island type growth observed. NIST and NRL resources were used for lithography and etch, respectively, for nm scale pillars of the CFO. Films are rather rough, but reasonably good patterning was obtained, but conically shaped pillars limited FWHM size at ~75nm fromsputter etch. Magnetization followed by MFM analysis showed that underlying grain (island) structure is dominating the magnetic ordering in the pillars. More uniform surface and columnar grain grain growth are needed.

Codeposited CFO and BFO by PED was also explored. CFO phase segregated to islands ~100 nm in size in a BFO matricx. Random distribution of CFO may have the ability to be template by a patterned CFO underlayer.

Device Construction

The Ross group used pulsed laser deposition to codeposit BFO-CFO films from a single BCFO target onto STO, as well as alternating BFO and CFO targets. Codeposition yielded fairly uniform 150 nm thick films with rectangular, 20—70 nm, columnar CFO pillars with ~100 nm period. The alternating target method yielded somewhat lower CFO density (20% by area). Both methods showed similar saturation magnetizations of ~85emu/cc (20% of bulk).

Some initial block copolymer templating work was done to serve as a method to pre-pattern BFO-CFO buffer layers, to hopefully result in patterned deposition. Pattern transfer of a random line pattern into YSZ was accomplished.

Feedback from liaison team:

- The liaison group was quite excited by the work and progress. The pace of the research appeared to be appropriate for the resources afforded. This BFO-CFO system was felt to be a good material system with obvious (room temperature) benefits.
- We have expressed previously that the goals of this initial foray into RAMA are quite lofty, so if the device concept ultimately does not come to fruition, we expect much of the materials work to have possible potential for other devices within the NRI
- Material growth processes are a concern, as is not clear which path will provide a good path for success. We like the idea of a template, composite (co-) deposition approach, as well as an approach that first patterns the CFO and later adds the BFO matrix. The liaison committee has been asked for CMP advice and is available for consultation in this route.
- There is a large degree of concern over how readout will be accomplished. There has been no work to date on coupling, namely the project-specified magnetocapacitive coupling. Hopefully the mentioned approved Argonne proposal in this realm will help address this. Other methodologies such as tunnel junction and induction were also mentioned, but details are lacking as to their practicality, as well.
- Another concern is demonstration of cell switching.
- Relatively little work thus far has been dedicated to Block Copolymer Patterning. An accelerated plan for reaching patterning goals is likely needed.
- With the design and architecture team (Mircea's group) on board, the center is making good progress on the design and evaluation of this switching device concept. We would encourage more close discussions with industry assignees and the NRI architecture evaluation team, to further improve the design and evaluation methodologies. The QCA-like switching concept appears to be more feasible than simple crossbar structure previously suggested. We applaud the amount of collaborative interaction with outside entities that has been accomplished thus far like that with NIST and NRL. These and the newly approved DARPA and Argonne resources, including another graduate student, will likely go far to accelerate already good progress in the coming years. Modeling should be closely aligned and leveraged with the MIND center.
- The outside and parallel collaboration in this project was not clear, so a chart showing these collaborations in detail would aid the liaison committee and may give insight into further leverage possibilities