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Obstacles for Collective-Spin Devices: Spin wave computing and Nanomagnet logic

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I. Introduction

We focus on the problems involved in spin wave computing and nanomagnet logic, as representative of Collective-Spin devices. Spin wave computing designs do not seem to meet the basic requirements for large scale digital logic computations. There are several different nanomagnet logic schemes that have been proposed. While these designs explicitly address all requirements for computing, there are physical limitations involved with achieving a high density of magnetic islands. We assess these technologies assuming that they will be used as a CMOS replacement for Boolean logic, which imposes the constraints of Boolean completeness, concatenability, gain, signal restoration, and input/output isolation[1]. We further describe potential difficulties in scaling the materials used for each technology.

We do not address the question of whether some technologies provide better solutions to niche special purpose analog processing tasks. We do not comment on whether new materials are likely to be discovered that will dramatically change the outlook for these designs. Both of these Collective-Spin devices could benefit from new materials and further device-level experiments. This implies that it is unlikely that any of these devices will be manufacturable in 5-10 years. What is needed is further basic research focused on systems-level questions to prove the feasibility of these schemes.

II. Spin wave computing

Spin waves are propagating hydrodynamic modes of magnetic materials. There are numerous types of spin waves. The type of spin waves normally studied for computing are known as magnetostatic modes[2], which are derived from Maxwell's equations in the magnetostatic limit. The behavior of magnetostatic modes are similar to guided electromagnetic waves. MSW modes have typical wavelengths of 0.1-1 μm at GHz frequencies, whereas a free space EM wave has a wavelength of ~1 cm at such frequencies. There is a large field devoted to discrete analog microwave components using the propagation of magnetostatic spin waves. We refer the reader to the literature for a full summary of spin wave computing[3]. Since magnetostatic waves (MSW) can be thought of as a type of electromagnetic wave, spin wave computing has many of the same disadvantages as optical computing.

a. Logic constraints. The logical unit of a spin wave computer is a majority gate. Three spin waves are launched along separate arms and made to interfere along a single, output arm. Each "arm" is a strip of magnetic material, which acts as a MSW waveguide. Binary information is encoded in the phase of the output MSW. This device is a MSW interferometer. Switching time is determined by the time of flight of a spin wave packet across the dimension of the gate. Boolean completeness is achieved by changing the length of an arm to be an odd integer multiple of the wavelength. This logic unit will be very sensitive to dimensions and tolerances, being essentially an interferometer. The need for a large number of Boolean operations rules out the possibility of tuning a logic unit in real time. Optical logic elements have the same disadvantage[4].

Spin wave logic units have no intrinsic gain. There is no way to standardize the phase of the interference of multiple spin waves through numerous logic steps. This prevents the directly concatenating of multiple spin wave majority gates. Devices based on multiferroics have been proposed to switch a magnetic domain based on a phase threshold. However, chaining numerous logic units together can not be accomplished in this way. In order to achieve gain and signal standardization, CMOS drivers could be used, but this implies further, unquantified overheads. Spin wave logic units have no intrinsic input/output isolation. Spin waves will reflect at boundaries, and so the output of a computation can in principle reflect across a logic unit and influence the phase at the input. A further consequence of this is that in the presence of disorder, wave reflections along the length of the MSW strip will result in localization; the transmission will decrease exponentially with the length of the strip, apart from dissipative considerations.

A fundamental architectural problem with spin wave computing is that the materials that support MSW propagation must normally be fabricated in straight, line-of-sight, lines. It is difficult to guide spin waves around corners due to the demagnetizing field of magnetic materials with a non-ellipsoidal shape. Fabricating computer architectures with only straight lines imposes a severe constraint.

b. Scaling constraints. The MSW majority gate will be difficult to scale down to sizes below 100 nm. MSW frequency and propagation velocity change significantly in arrays of MSW wires versus a single wire, for wires of different dimensions[5], and for MSW wires in contact with metal films[6]. This fact means that it will be difficult to maintain consistent spin wave characteristics as more and more MSW waveguides are packed to higher and higher density, possible with additional CMOS or multiferroic drivers.

A more fundamental problem is that spin wave majority gates of less than a wavelength no longer support propagating modes, which implies that there will be nodes at the edges of the device where input and output connections are made. This, in turn, implies that phase information cannot be transmitted across small structures. MSW wavelengths range down to ~0.1 μm. Smaller wavelengths are possible when using non-dipolar, exchange spin waves, but manipulation of these types of spin waves have not been demonstrated and likely involve higher energy.

III. Nanomagnetic logic

Small ferromagnetic islands have an approximately homogenous bistable magnetic state. Numerous schemes have been proposed to utilize such bistability for logic gates. There are two major classifications for logic using nanomagnets. First, nanomagnet logic (NML) expresses bits as the direction of magnetization on a particular bit. Logic gates are constructed from arrays of magnetic islands, which interact through dipolar forces alone[7]. NML can be used to implement cellular automata and conventional Boolean computation. The second classification is known as All Spin Logic (ASL). Here, the magnetization of ferromagnetic islands is through a metal or semiconductor interconnect that supports a spin polarized current to another ferromagnetic island[8]. In both these schemes, magnetic islands act as bits and are assumed to have a spatially homogeneous magnetization state.

a. *Logic.* Both schemes can be used to construct a Boolean complete set of gates. Gain is achieved through bistability because a ferromagnetic island has two minimum degenerate energy states separated by an energy barrier. Arguments for why these nanomagnet logic schemes should satisfy all logic constraints have been presented[7,8]. There is a need for more systems-level experiments to support these arguments.

b. Scaling. The use of small ferromagnetic islands introduces some fundamental problems when considering scaling constraints. First, relative to electrical interconnects, it is more difficult to confine the directionality and spatial extent of stray magnetic fields from small ferromagnetic islands. The relative permeability of silicon or air is ~1. Nanomagnetic logic experiments typically use permalloy, which has a relative permeability of $\sim10^5$. For different magnetic materials, the permeability will be lower. The electrical conductivity of air is more than 20 orders of magnitude lower than for a metal interconnect. The electrical conductivity of silicon is becoming a major problem in CMOS scaling. High resistivity silicon is $\sim10^7$-10^6 times less conductive than metals. If SOI approaches are used, higher substrate resistivity is possible. For this reason, packing a large magnetic components onto a chip will be more difficult than the equivalent problem in CMOS.

The second problem involves the manipulation of ferromagnetic islands. Simulations in this area assume that a homogeneous magnetization for a single domain island. However, that assumption will break down at small length scales, where magnetization reversal of nanoscale islands will induce spin wave excitations[9]. The consequences of this for scaling have not been explored for nanomagnet logic. We point out possible problems. The presence of spin waves can influence or trigger magnetization reversal[10]. A problem encountered in magnetic tunnel junction memories[11] that may also affect logic devices is that current induced spin wave excitations result in higher electrical noise.

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