The Extinction of Transistors, an Exploration of Nanomagnets as a Viable Replacement

Afnan Enayet

Maggie L. Walker Governor's School for Government and International Studies

Author Note

Abstract

Over time, computational processors have been getting more efficient in terms of power and size. Eventually, the transistors that power processors will get so small and so close to each other that they will interfere with each other, forming a plateau in the generally steady progression of computational performance. This size dilemma in processors and other transistor based electronics could be rectified by switching from transistor based logic to nanomagnet based logic, which poses several distinct advantages, including reduced power consumption and heat loss. Part of operating these nanomagnets effectively involve changing their magnetic orientation in order to configure them and manipulate data. This paper will explore a hypothetical configuration that uses two parallel IDTs that emit surface acoustic waves and utilize wave interference on a piezoelectric substrate to apply stress to nanomagnets in the delay line to make them reverse polarities. This paper will also explore supplemental theory pertaining to nanophysics, magnetism, and waves.

Keywords: nanomagnets, physics, magnetism, dipole, computation, transistors, processors, processing, wave, interference, surface acoustic wave, logic gates, efficiency

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Computers and their associated computational abilities are the basis for the modern world: they power cars, servers, and medical devices. The proverbial brain of a computer is its processor. Processors pair up millions of logic gates to perform complex operations. These logic gates are based on transistors, tiny electronic switches that turn on and off based on a voltage cutoff. These transistors are grouped together to create logic gates, which can perform rudimentary logic operations such as AND, OR, NOR, NAND, and XOR. The problem with transistors is that they fundamentally use electricity. This change of voltage also means that transistors generate heat, and cooling is always a challenge that hardware developers have to tackle. Nanomagnets can be used as functional alternatives to transistors in processors. They also consumer less power, generate significantly less heat, and can be compacted with closer proximity than transistors can.

Nanomagnets operate quite differently from transistors. They must be oriented correctly in order to produce an effective logic gate, and must be switched through means more creative than pushing a voltage. Nanomagnets also differ in conventional magnets in terms of their magnetism. They are smaller than dipoles, so they are permanently magnetized, which is beneficial for hardware longevity. In the experiment, the software OOMMF was used to model magnets and display how magnetic axis orientation changes as the shape of the nanomagnets are altered.

The purpose of the experiment was to find a more effective way of "switching" these nanomagnets. For the purposes of computation, the north and south poles of a nanomagnet are analogous to the 1's and 0's of binary. In order to alter data, the orientation of the magnetic axes must be switch, and this can be achieved by physically stressing the nanomagnets, through

surface acoustic waves, waves that propagate themselves along an elastic surface. The experiment proposed using two interdigital transducers, devices that can propagate surface acoustic waves, in unison. If the waves are phased correctly and can properly utilize constructive interference, they will provide a greater strain on the nanomagnets. This should theoretically raise the effectiveness of surface acoustic waves in switching nanomagnets and delivering stress on a piezoelectric surface.

Nanomagnetism

The nanoscale is small. One nanometer is one billionth of a meter. At this scale, there are some properties of magnetism that do not act like they do in conventional macrophysics. The permanent magnetism of magnets are a notable example of this. These magnets are smaller than a magnetic domain, and as a result, they can never have their magnetic domains come out of alignment: there aren't enough for a misalignment. A magnetic domain is a region that has fully aligned magnetic dipole moments, so everything in that region is magnetized. In order for a magnet to be magnetized as a whole, the majority of the magnetic domains in the magnet have to be aligned. The more domains that are aligned, the more strongly that the magnet will be magnetized. Making a magnet small enough so that the entirety of it is covered by only one domain solves all of these problems, so a nanomagnet will never become demagnetized. Permanence is a property that improves the longevity of any constructed hardware.

Nanomagnetic Geometry

At the nanoscale, the geometry of a nanomagnet holds very important implications for the magnet's anisotropy. Traditionally, magnets have one North Pole and one South Pole. These rest together on a magnetic axis. The orientation of this axis can vary depending on the nanomagnet. This directional dependence is called magnetic anisotropy (Beach, 2013). The axis tends to rest

at the orientation of the lowest energy. This axis is called the "soft axis". The other orientation, of peak energy, is called the "hard axis". The magnetic axis can be forced to reside at the hard axis, but without any stimulation, it will naturally return to the soft axis, the lowest energy state.

At the nanoscale, changing the shape of these magnets can affect the axes. It can alter the orientation of the axis, and determine what the hard and soft axes will be, or it may yield more than one axis, so that instead of having one magnetic pair, there are two axes that have a functional North Pole and a functional South Pole. This can be utilized for its processing potential. Instead of just having 1's and 0's correspond to North Poles and South Poles, a nanomagnet can have four states: 1, 0, 01, and 10. This could help make more complex processors and simultaneously conserve space.

Simulating nanomagnetic geometry. There are mathematical equations that can determine how magnetic dipoles will interact and form axis, but often times, there are too many calculations to perform that manually calculating them is not efficient. There is a software program, called "OOMMF" developed by the National Institute of Standards and Technology that allows for a user to determine the magnetic orientation of the axes and the number of axes of a nanomagnet with a given shape, orientation, and magnetic field. OOMMF has been used to determine the axial properties of various geometries of nanomagnets, showing that the ellipsoid is the best shape to use for a uniaxial nanomagnet. A diamond concave nanomagnet, when simulated, provides a biaxial configuration (Fashami and D'Souza, 2014). In the early stages of the experiment, OOMMF was used to simulate the magnetic dipoles of various shapes with differently oriented magnetic fields. Figure 1 displays the results from an OOMMF simulation with a four-state nanomagnet. It shows that there are two north-south pole axes. Figure 2 displays

the results of a simulation with a two-state ellipsoid shape nanomagnet, which has one north pole and one south pole.

Surface Acoustic Waves

Surface acoustic waves are commonly referred to as SAWs. They are acoustic waves that propagate themselves along an elastic surface (Garrido, n.d., Tyagi and Mahesh, 2012). They are fairly small waves, their wavelengths generally range in the tens of nanometers. There are many devices and practical applications that utilize surface acoustic waves. These devices are called SAW devices. The most common use of SAWs are in small sensors, especially pressure sensors (Mamishev, Sundara-Rajan, Yang, Du & Zahn, 2004). Temperature sensors also frequently use SAW mechanisms (Garrido, n.d., and Token, 2010).

Surface acoustic waves are relevant to the experiment being undertaken by Dr. Atulasimha because they allow for bit switching with nanomagnets. For the purposes of computing, the north and south poles of nanomagnets represent 1s and 0s. These nanomagnets would be useless for computation if they weren't dynamic. Surface acoustic waves can apply mechanical stress to the nanomagnet and change its shape momentarily – just long enough for the magnetic axis to reverse, so that the north pole is where the south pole was, and vice versa. This allows for information to be manipulated by bit, a necessary level of hardware control for any realistic computing device, be it dynamic memory or a logic gate.

Utility of Replacing Transistors with Nanomagnets

Nanomagnets pose very distinct advantages when used as logic gates or in memory devices. Both computer processors and memory devices operate using binary, a system of 1's and 0's to communicate with the lowest levels of software, written in the programming language assembly.

Traditionally, transistors have been used to represents these 1's and 0's in hardware. Transistors operate on a voltage threshold. When a transistor is activated, it carries a voltage. Anything below that voltage, and the transistor will be switched off. This electronic switching uses power and generates heat. For most devices in today's era, power is a problem, and engineers are constantly trying to find a solution. As more devices become mobile and start to rely on batteries that are finite and not always connected to the power grid, power efficiency becomes increasingly important. Power efficiency is also important at a large scale. Nanomagnets do not consume as much power as traditional transistors, as they rely on mechanical stress or surface acoustic waves in order to manipulate data, rather than a voltage threshold.

Heat is a classic problem that plagues most processors. Heat can damage components, especially batteries, if temperatures aren't throttled sufficiency through scaling back the activity of a processor, activating fans, or water cooling. Nanomagnets inherently do not generate as much heat as transistors, an ideal property for computational hardware.

The basic idea behind improving processors is to make transistors smaller, compact them as tightly as possible, and try to get as many as possible to fit in one processor. More transistors generate more computational power. There is a limit to how close these transistors can be placed near each other, because when the transistors are too close, the electrons from both transistors will actually interfere with each other (Moore, 1998, p.84), and result in inconsistent switching, an unpredictable behavior that is unacceptable for computing.

Using nanomagnets in computing devices offers a solution to the two behemoths that plague most computing devices today. Nanomagnets can reduce heat, increase speed, and reduce power consumption offering a veritable way to subvert Moore's Law.

Experimentation

The purpose of the experiment was to see the effect of surface acoustic waves and wave interference on nanomagnets that fall at the nodes of the SAW at the delay line between IDTs. Practically, it is useful because computation inherently relies on data manipulation, and switching the axial polarity of the nanomagnets through the aforementioned setup can provide a reliable method of data manipulation at the most fundamental hardware layer. Nanomagnets must be dynamic in order to function as suitable binary devices. As it stands, most laboratory procedures for manipulating data with nanomagnets are not reliable, or have been unsuccessful. A reliable and accurate method could spur research forward and carry many practical applications.

The concept for this experiment was based on the experiment being conducted by Vimal Sampath of the Nuclear and Mechanical Engineering Department of Virginia Commonwealth University. He is currently working on a method to apply stress to nanomagnets from a surface acoustic wave launched from a transmitting interdigital transducer. This experiment extends that concept to use constructive wave interference to maximize the effect of those acoustic waves on a piezoelectric surface. Placing two waves in phase will increase the effect of the wave (Kumar et al., 2004). Using constructive wave interference will maximize the impact SAWs (surface acoustic waves) on the nanomagnets that are placed on the delay line between the two transmitting interdigital transducers.

Hypothesis

In this experiment, it was hypothesized that using a dual IDT setup that utilized constructive interference with SAWs would result in a process that is more efficacious than using

a surface acoustic wave with a transmitting IDT and a receiving IDT. Efficacy refers to the number of nanomagnets that are switched and the reliability of the process.

Procedure

In this experiment, there were three main components to the procedure: the fabrication of nanomagnets, the fabrication of IDTs (interdigital transducers), and testing the setup. Both IDTs and nanomagnets are produced with a lithography process, followed by deposition. The testing setup involved taking the masks that the IDT setups were fabricated on and connecting it to a voltage source, and recording that voltage.

Fabricating nanomagnets. The nanomagnets were fabricated through electron beam lithography. Electron beam lithography is a lithography process that allows for extremely precise fabrication, allowing for designs that require precision at the nanomagnetic level. EBL (electron beam lithography) starts with a wafer. This wafer is made of lithium niobate, and this base material is referred to as a substrate. A layer of resist, which is a chemical that will essentially act as a template or stencil is applied to the top of the wafer using a centrifuge that will spin and create an even coating of resist all over the wafer (Washington University, n.d.). This wafer is placed in an SEM (scanning electron). An SEM works by firing electrons in a focused beam and reading how they deflect (Schweitzer, n.d.). This deflection pattern allows the microscope to find the shape and terrain of the object that is to be examined by the microscope.

In EBL, the beam is used to carve away the resist in the shape of the nanomagnets. The beam carves away a pattern dictated by a CAD file. These CAD files were created in a computer attached to the SEM. For the nanomagnets, a one layer CAD file was created with matrices of nanomagnets of four different configurations: rectangular, ellipsoid, square, and four-state diamond concave. After the pattern has been burned into the resist using the SEM, cobalt was

deposited onto the wafer. Cobalt cannot stick to the resist, but it can stick to the wafer, so cobalt was only deposited into the regions that were carved out by the SEM. After the cobalt was deposited, the resist was removed, leaving a bare wafer, save for the matrices of nanomagnets.

For quality control, the wafer is brought to an AFM (atomic force microscope), which has a miniscule head that taps on the surface. A laser beam shines on the head and a sensor records the deflection pattern. If this tip taps on something with a higher elevation than normal, then it will be displaced to a different degree, and this displacement will be indicated by the laser reflection. The AFM allows for very fine qualitative measurements, allowing for a more precise view than an optically based microscope can offer.

Fabricating IDTs. Interdigital transducers are fabricated using a different method of lithography, called photolithography. The first step in this process is creating the IDT designs. This was done through a Linux program called Pyxis. Pyxis is a CAD software that allows a user to create CAD files that are compatible with the machine that transfers the pattern from the design file to the wafer. The IDT designs were created using the parameters listed in Table 1, as well as parameters shown in another paper that used two transmitter IDTs (Shi, Mao, Ahmed, Colletti, & Huang, 2008, p. 222). These parameters include the length of the delay line gap, the height of each finger in the IDT, and the space between each finger.

A layer of photoresist is applied to a lithium niobate wafer using a centrifuge to apply the layer of PMMA resist evenly. The wafer is then brought to a machine that uses the CAD file to etch out the pattern in the resist. After etching, the metal is deposited onto the wafer. Subsequently, the metal and the remaining resist are washed away, leaving only the lithium niobate substrate and the IDTs.

Quality control was conducted with an optical microscope. While an optical microscope does not have as much fidelity as an AFM, IDTs are larger than nanomagnets - large enough to show fine points of production on an optical microscope.

Testing the hypothesis. For the experiment, the two IDTs were set up parallel to each other. At first, a wave was launched, transmitted from one IDT and received with another IDT (Milsom, Redwood, & Reilly, 1977) to ensure that the IDTs themselves were working properly and that the signal generator and amplifier were working properly. Both IDTs were wired to the amplifier using alligator clips. The amplifier was wired to a signal generator which was manually adjusted to transmit a suitable frequency. The IDTs were also connected to a four channel oscilloscope as well as a NI DAQ interface which allowed the user to see the voltage readings from the signal generator, the amplifier, and the IDTs.

When these two IDTs are set up against each other, a SAW is generated. As discussed previously, the wave is reinforced through constructive interference. The lithium niobate wafer being used is a piezoelectric substance. Due to the nature of piezoelectrics, these mechanical waves will be converted into electric charge, applying stress on the substrate at a node of the interfering waves in the delay line (Wood, Evans, Cunningham, O'Rorke, Waiti & Davies, 2008).

Analysis and Results

The oscilloscope displayed inconclusive results from the IDTs. Unfortunately, these results are too subtle to be accepted as significant evidence. Though some voltage changes were observed, the changes in voltage were so small that they could be attributed to natural fluctuations, interference, and imperfections in the equipment. Upon further investigation, it was found that the amplifier was not amplifying the signal properly, rendering the evidence inconclusive rather than providing a sufficient rejection of the hypothesis.

The results do not prove or disprove the efficacy and viability of the theory presented in this paper. Further testing must be conducted in order to determine whether or not this method is effective. Theoretically, it is sound, but at such a small scale, it may not be an effective method to use because of the limits of production technology. As it stands, the results are inconclusive.

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Tables

Table 1

IDT Parameters for Fabrication

|	D (microns)		
Metallization ratio	800	3500	3000
0.7	280	1225	1050
0.75	300	1312.5	1125
0.8	320	1400	1200
W (microns)	8000	35000	30000

Note: This table contains specifications for the parameters for interdigital transducers that were used to create IDT designs in Pyxis. The speed of sound through the lithium niobate substrate is approximately 4000 meters/second. D represents the gap between fingers, and W represents the width of each finger.

Figures
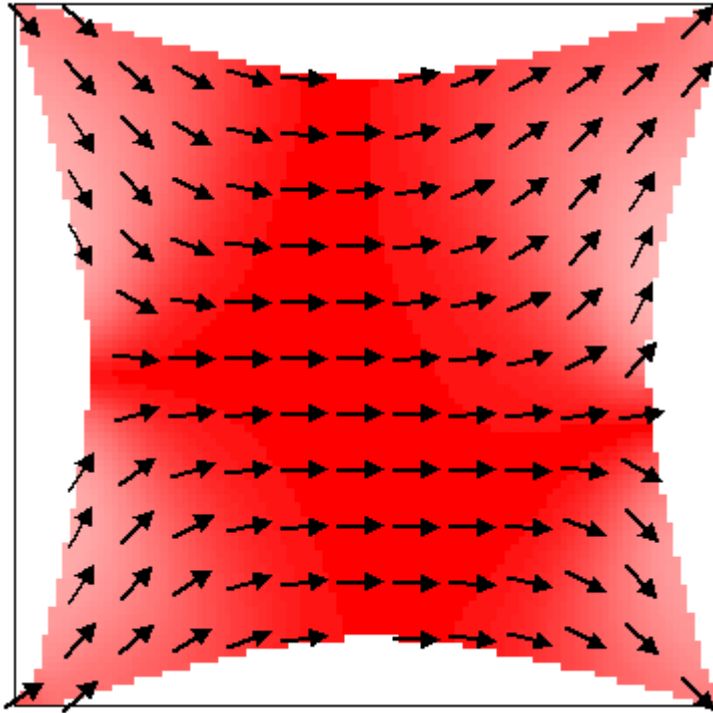
Figure 1. A simulation of magnetic dipoles in OOMMF of a four-state diamond concave

nanomagnet. The applied field has a theta value of 0^{0} and a phi value of 80^{0}. At the left corners,

there are south poles, and on the right corners, there are north poles.
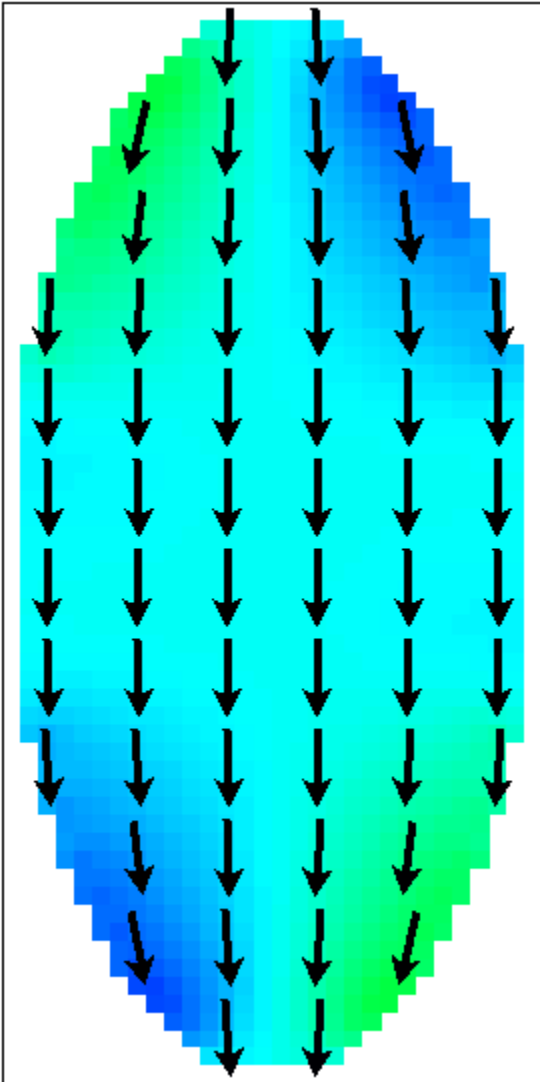
Figure 2. A simulation of the magnetic dipoles in a two-state ellipsoid configuration in the simulation software, "OOMMF". The applied field has a theta value of 0^0 and a phi value of 80^0. At the top, with the arrows flowing down, there is a south pole, and at the bottom, there is a north pole.
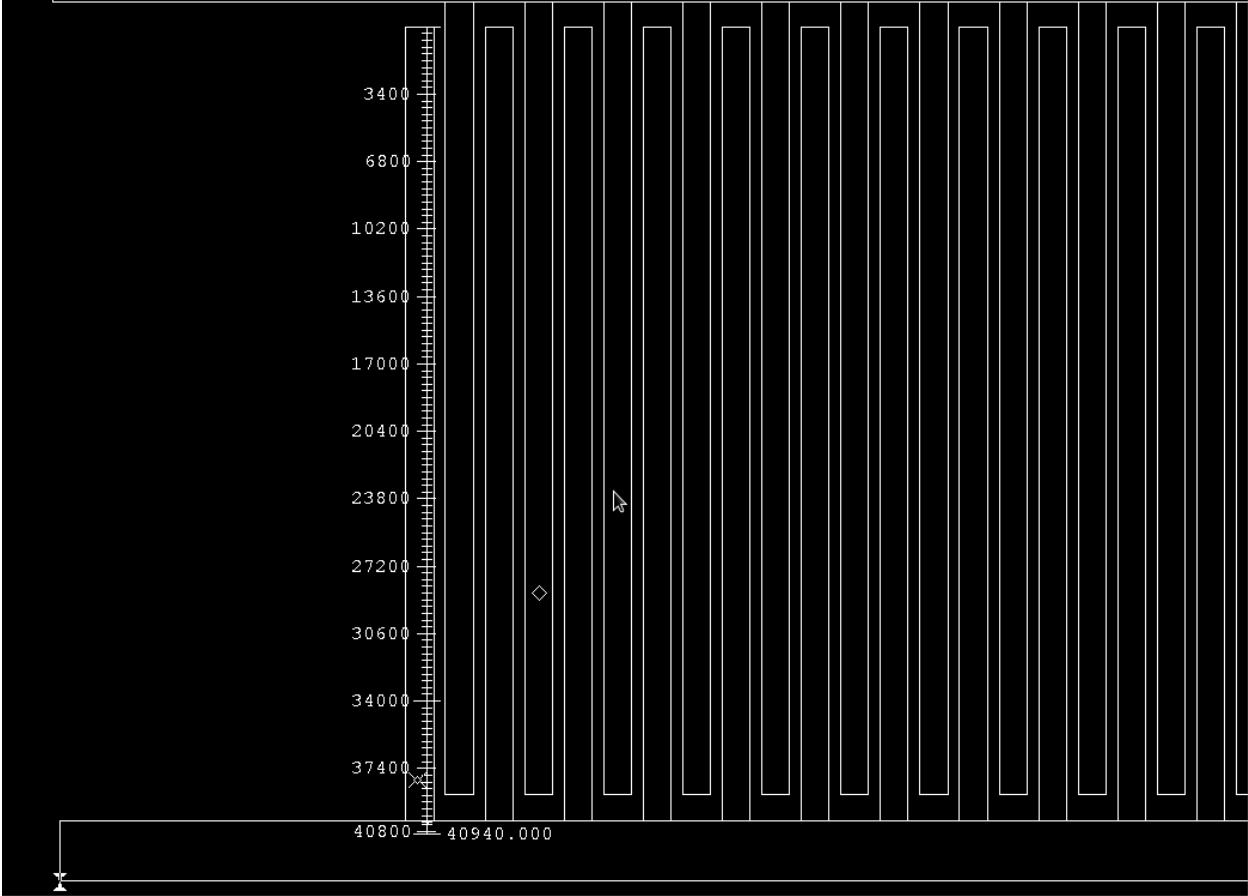
Figure 3. Part of the IDT design used in the experiment with a scale overlay. The scale is in micrometers.