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NANOMAGNETS CHALLENGE SEMICONDUCTOR TRANSISTORS

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ABSTRACT

That the magnetic orientation of ferromagnets can be changed using magnetic fields has been known for centuries. But the exploration of magnetization control without any additional magnetic field has only just begun. Ever since William Gilbert's sixteenth century treatise De Magnete, it has been known that magnetic fields can be used to manipulate the magnetic orientation of ferromagnets. This has been the foundation for electronic applications of magnetic materials for the past 100 years, in the form of, for example, inductors, microwave isolators and magnetic disk drives.

A nanomagnet is a submicrometric system that presents spontaneous magnetic order (magnetization) at zero applied magnetic field (remanence). Researchers at the Technische Universität München (TUM) have demonstrated a new kind of building block for digital integrated circuits which uses 3D arrangements of nano-scale magnets instead of transistors. In a 3D stack of nanomagnets, the researchers have implemented a so-called majority logic gate, which could serve as a programmable switch in a digital circuit.

A reversal of polarity represents a switch between Boolean logic states. The state of the device is determined by three input magnets, one of which sits 60nm below the other two, and is read out by a single output magnet. Magnetic circuits are non-volatile, have extremely low energy consumption and can operate at room temperature and resist radiation. They can allow very dense packing. The most basic building blocks, the individual nanomagnets, are comparable in size to individual transistors.

Furthermore, where transistors require contacts and wiring, nanomagnets operate purely with coupling fields. Also, in building CMOS and nanomagnetic devices that have the same function – for example, a so-called full-adder – it can take fewer magnets than transistors to get the job done. Finally, the potential to break out of the 2D design space with stacks of 3D devices makes nanomagnetic logic competitive.

***Keywords**: Nanomagnets, Semiconductor, Transistor etc.*

I. INTRODUCTION

Canonical examples of nanomagnets are grains [1][2] of ferromagnetic metals (iron, cobalt, and nickel) and single-molecule magnets.[3] The vast majority of nanomagnets feature transition metal (titanium, vanadium, chromium, manganese, iron, cobalt or nickel) or rare earth (Gd, Eu, Er) magnetic atoms. A nanomagnet can have enhanced electronic properties due to size effect, such as long spin relaxation time of conduction electron, which may be useful for nano-scale spintronic device.[9]

In a continuous ultrathin film with thickness smaller than the so-called exchange length all the magnetic spins are held together by the exchange forces. Typically the exchange length is around 5-10 nm in ferromagnetic transition metals. Provided the film thickness is much smaller than the lateral dimensions, the lowest stable energy state is a single domain state in which all the spins lie parallel and in the plane of the film. One possible approach to circumventing the superparamagnetic limit in conventional media is to use patterned media in which each element is a magnetic dot arranged in a periodic array and which has a thickness of a few atomic layers. Such structures will remain stable down to much lower lateral dimensions than conventional bits in continuous media. Research is now focusing on the spin configurations and dynamics of such magnetic nanostructures.

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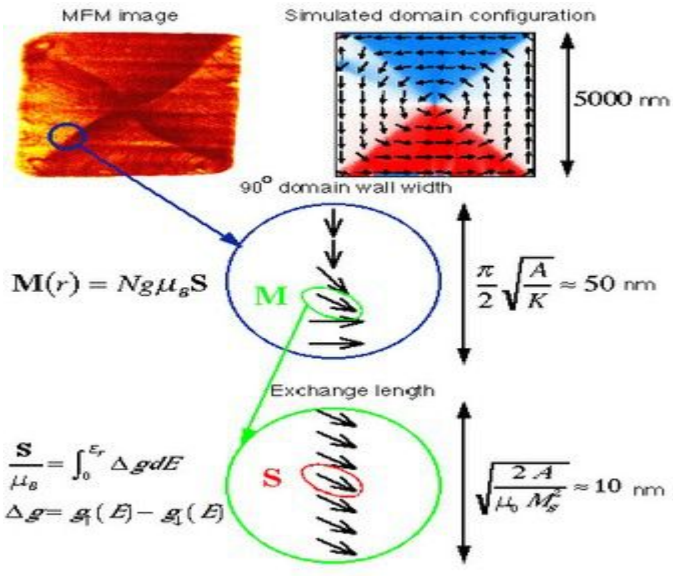
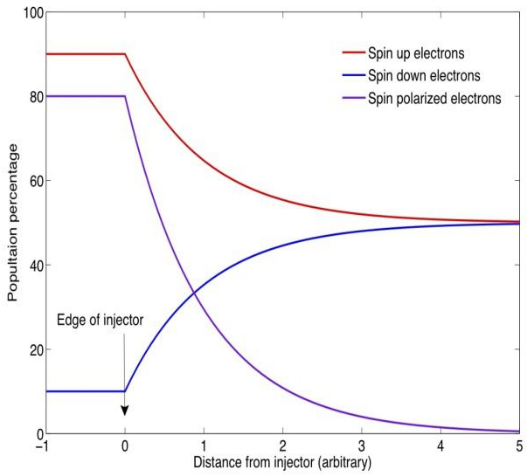


Sprintronics

Spintronics ("spin transport electronics"), also known as spinelectronics or fluxtronic, is an emerging technology exploiting both the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices.
Spintronics differs from the older magnetoelectronics, in that the spins are not only manipulated by magnetic fields, but also by electrical fields.

There are many mechanisms of decay for a spin polarized population, but they can be broadly classified as spin-flip scattering and spin dephasing. Spin-flip scattering is a process inside a solid that does not conserve spin, and can therefore send an incoming spin up state into an outgoing spin down state. Spin dephasing is the process wherein a population of electrons with a common spin state becomes less polarized over time due to different rates of electron spin precession. In confined structures, spin dephasing can be suppressed, leading to spin lifetimes of milliseconds in semiconductor quantum dots at low temperatures.
By studying new materials and decay mechanisms, researchers hope to improve the performance of practical devices as well as study more fundamental problems in condensed matter physics.



A plot showing a spin up, spin down and the resulting spin polarized population of electrons. Inside a spin injector, the polarization is constant, while outside the injector, the polarization decays exponentially to zero as the spin up and down populations go to equilibrium.

II. METAL-BASED SPINTRONIC DEVICES

The simplest method of generating a spin-polarised current in a metal is to pass the current through a ferromagnetic material. The most common applications of this effect involve giant magnetoresistance (GMR) devices. A typical GMR device consists of at least two layers of ferromagnetic materials separated by a spacer layer. When the two magnetization vectors of the ferromagnetic layers are aligned, the electrical resistance will be lower (so a higher current flows at constant voltage) than if the ferromagnetic layers are anti-aligned. This constitutes a magnetic field sensor.

What are nanomagnets?

- Nanomagnets are very small magnets - measured at the nanoscale - that have special properties when compared to standard magnets.
- Nanomagnets are small collections of magnetic particles - sometimes even a single magnetic particle - that are magnetised, but without the formation of a magnetic domain (in which all the magnetic moments of the particles being aligned in the same direction). Nanomagnets also have no applied magnetic field, and display quantum effects consistent with other nano-sized objects, for instance quantum tunnelling and quantum phase interference.
- Nanomagnets are most often made from metals, such as iron, titanium, nickel and cobalt.

Applications of nanomagnets

- There are many possible uses for nanomagnets. Medical applications are numerous, including the use of nanomagnets in the treatment of cancer: nanomagnets could be guided to the site of the tumour, and once in place could be heated via the application of an opposing magnetic field. The heat they generate would destroy the cancer cells, while doing little damage to surrounding healthy tissue.
- Another medical use for nanomagnets is blood cleansing: they are targetted at and attached to the contaminant or pathogen using target-specific ligands, with the blood then passed through an external purification chamber where magnetic fields are used to seperate the magnets and targets from the healty blood. The blood is then passed back into the host.
- Nanomagnets also have possible uses in computing, specifically in the field of data storage. Scientists have succeeded in changing the magnetic state of single molecule nanomagnets, effectively making them function as single molecule transistors. This promises great advances in the miniaturisation of computer chips, with a resulting increase in speed and processing power.
- Aside from this, nanomagnets have been mooted to have more radical uses. They have even been named as an essential component for a prototype invisibility cloak! In this protoype, nanomagnets are used to aid generation of a magnetic field used to defelect light from the wearer of the cloak.
  Single-molecule Nanomagnets
- Jonathan R. Friedman, Myriam P. Sarachik
- Single molecule magnets straddle the classical and quantum mechanical worlds, displaying many fascinating phenomena. They may have important technological applications in information storage and quantum computation. Review of physical properties of two prototypical molecular nanomagnets, Mn_12-acetate and Fe_8 shows: behaviour as a rigid, spin-10 object, and exhibit tunneling between up and down directions. As temperature is lowered, the spin reversal process evolves from thermal activation to pure quantum tunneling. At low temperatures, magnetic avalanches occur in which the magnetization of an entire sample rapidly reverses. Symmetry-breaking fields play an important role in driving tunneling and in producing Berry-phase interference. Recent experimental advances indicate that quantum coherence can be maintained on time scales sufficient to allow a meaningful number of quantum computing operations to be performed. Efforts are underway to create monolayers and to address and manipulate individual molecules.

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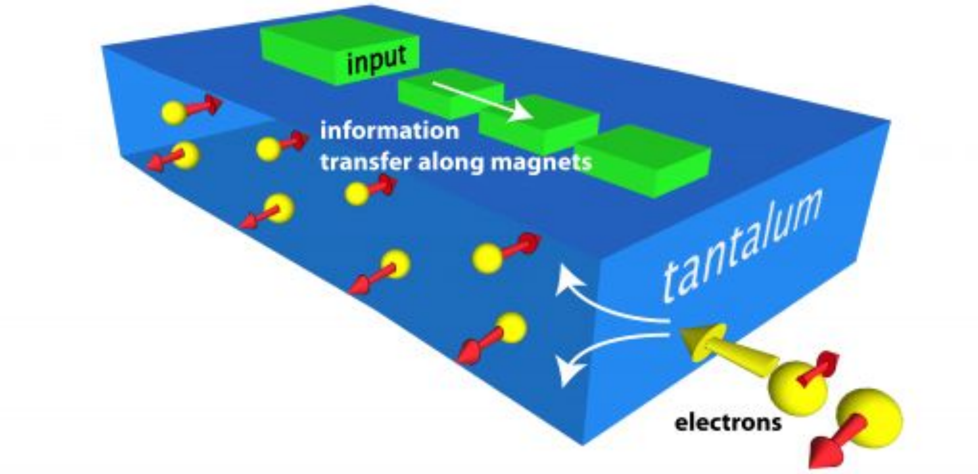
How nanomagnets work?



As the current passes through a strip of tantalum, electrons with opposite spins separate. This "clocking" helps in orienting nanomagnets (on the top of the tantalum strip) so that they can be switched easily. New work by University of California Berkeley researchers could one day make nanomagnetic switches a viable replacement for the conventional power-consuming transistors found in all computers.
Increased energy consumption of modern day computers is a major challenge that the computer industry faces. "The faster the computers are, the hotter they get". This is because of a fundamental physical limit to the switching energy of a transistor, a semiconductor-based switch, which is at the heart of a computer. Nanomagnetic logic uses magnets as an ultra low energy alternative to transistors for computing because of their much sharper switching behavior. It is projected that the innovation, when implemented in the same scale as that of modern CMOS [used in transistors], would consume 10 times lower power.

Nanomagnetic computing

UC Berkeley researchers overcame the limitation of energy savings by exploiting the special properties of the rare heavy metal tantalum. They created a "*Spin Hall effect*" by using nanomagnets placed on top of tantalum wire and then sending a current through the metal. Electrons in the current will randomly spin in either a clockwise or counterclockwise direction. When the current is sent through tantalum's atomic core, the metal's physical properties naturally sort the electrons to opposing sides based on their direction of spin. This creates the polarization researchers exploited to switch magnets in a logic circuit without the need for a magnetic field. This is a breakthrough in the push for low-powered computing. The power consumption seen is up to 10,000 times lower than state-of-the-art schemes for nanomagnetic computing. Experiments are the proof of concept that magnets could one day be a realistic replacement for transistors.

Spin-based computing schemes could enable new functionalities beyond those of charge-based approaches. Examples include nanomagnetic logic, where information can be processed using dipole coupled nanomagnets, as demonstrated by multi-bit computing gates. One fundamental benefit of using magnets is the possibility of a significant reduction in the energy per bit compared with conventional transistors. However, so far, practical implementations of nanomagnetic logic have been limited by the necessity to apply a magnetic field for clocking. Although the energy associated with magnetic switching itself could be very small, the energy necessary to generate the magnetic field renders the overall logic scheme uncompetitive when compared with complementary metal-oxide-semiconductor (CMOS) counterparts.

A nanomagnetic logic scheme has been demonstrated at room temperature where the necessity for using a magnetic field clock can be completely removed by using spin-orbit torques. A chain of three perpendicularly polarized CoFeB nanomagnets has been constructed on top of a tantalum wire and show that an unpolarized current flowing through the wire can 'clock' the perpendicular magnetization to a metastable state. An input magnet can then drive the nanomagnetic chain deterministically to one of two dipole-coupled states, '2 up 1 down' or '2 down 1 up', depending on its own polarization. Thus, information can flow along the chain, dictated by the input magnet and clocked solely by a charge current in tantalum, without any magnetic field. A three to

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four order of magnitude reduction in energy dissipation is expected for the scheme when compared with state-of-the-art nanomagnetic logic.

The International Technology Roadmap for Semiconductors (ITRS), Emerging Research Devices section indicates that "nanomagnetic logic (NML) has potential advantages relative to complementary metal–oxide semiconductor (CMOS) of being non-volatile, dense, low power, and radiation-hard. Such magnetic elements are compatible with magnetoresistive random-access memory (MRAM) technology, which can provide input-output interfaces. Compatibility with MRAM also promises a natural integration of memory and logic. Nanomagnetic logic also appears to be scalable to the ultimate limit of using individual atomic spins."

III. HOW IT WORKS

Instead of using transistors, the standard components in computers today, NML depends on arrays of nanomagnets ranging in size from a few nanometers to a few hundred nanometers to transmit data. Nanomagnetic computers use tiny bar magnets to store and process information. NML-based circuits process information by manipulating the magnetization states of single-domain nanomagnets coupled to their nearest neighbors through magnetic dipole interactions. The state variable is magnetization direction and computations can take place without passing an electric current. This makes them extremely attractive as a replacement for conventional transistor-based computing architectures for certain ultra-low power applications."
These different magnetization states can be used to represent binary ones and zeros, the fundamentals of computer-based arithmetic, and the interactions between the nanoscale magnets are then used to process information. Lithographically defined magnets can process and move information in a cellular, locally interconnected architecture. Wires, gates and inverters have been demonstrated at room temperature and it is estimated that if 10 to the tenth power magnets switch 10 to the eight times per second, the magnets themselves will dissipate only about 0.1 W of power.

A crucial challenge for this technology is a viable clocking field. "Field clocking with buried wires may be competitive with CMOS and useful for experimental studies, but the adaptation of a novel computing architecture probably requires at least an order of magnitude improvement for it to be worth the cost. An efficient clock using magnetoelectric clocking would allow nanomagnetic logic to operate closer to the fundamental limits of computing. However, magnetoelectric clocking is not yet a mature technology.

IV. ADVANTAGES OF NML

Other key NML characteristics compared to standard semiconductor technology include:

- NML consumes up to 100 times less power than current computer technologies, which results in far less heat generated.
- NML memory is "nonvolatile" in that it doesn't lose the information it is using when it shuts down, so no time is required to boot up when the system is restarted.

One application for nanomagnets is in microcontrollers, like those used for low-power, real-time control systems. Those based on NML will ultimately be very low power, be radiation hard (ideal for space missions or nuclear reactors), operate at reasonably high temperatures, and when switched off will still retain their state. These are also ideal properties for robotic systems.

V. CONCLUSION

Recent advances include the development of layers of magnetic nanoparticles (much smaller than nanomagnets) that increase the field strength near the magnets to lower the overall system power, as well as a simple, field-coupled input for logic gates based on nanowires. Continued NML research will hopefully lead to the development and commercialization of an all-magnetic information processing system. Ultimately, operating at lower power will be a very big deal since computers consume enormous amounts of power worldwide. Nanomagnets can also be scaled to very small sizes and can be stacked in a three-dimensional configuration, so Moore's Law scaling may also continue in a post-CMOS technology.

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