Nanomagnetism

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Magnetism!

"The nation that controls magnetism will control the universe!"

Magneto
Master of Magnetism
Magnetism

*From Lodestones to Nanomagnets and Spin Torque*
Thales of Miletus is credited with discovering that amber rubbed with wool or fur attracts light bodies such as pieces of dry leaves or bits of straw, and observing that lodestone attracts iron and other lodestones. 

Magnetite A black, isometric, strongly magnetic, opaque mineral of the spinel group, (Fe₃O₄). It constitutes an important ore of iron. Magnetite is a very common and widely distributed accessory mineral in rocks of all kinds.

How is magnetite magnetized in nature?

One proposal is that this occurs during lightning strikes when strong fields are generated by the current passing through the mineral.
The First Magnetic Technology

This is one of the earliest magnetic compasses: A floating fish-shaped iron leaf, mentioned in the Wu Ching Tsung Yao which was written around 1040. The book describes how iron can be heated and quenched to produce thermoremanent magnetisation.
William Gilbert wrote *De Magnete*, arguably the first modern scientific research text, with experimental results and interpretation, in 1600. The book starts with a resolve to strip away all myth from the subject and reason from observation:

"In follies and fables do philosophers of the vulgar sort take delight; and with such like do they cram readers a-hungered for things obtruse, and every ignorant gaper for nonsense. **But when the nature of the lodestone shall have been by our labours and experiments tested,** then will the hidden and recondite but real causes of this great effect be brought forward, proven, demonstrated...and **the foundations of a grand magnetic science being laid will appear anew,** so that high intellect may no more be deluded by vain opinions"
Uniting Electricity and Magnetism

1820 - Oersted discovers that electrical currents create magnetic fields

1831 – Faraday discovers that changing magnetic fields create electric fields – Faraday induction

Two results:
The development of a fundamental understanding of electromagnetism.
Strong technological need for better magnetic materials and stronger magnets.
Ferromagnetic Domains

The magnetic energy of a ferromagnet is reduced via the formation of domains

Ideal – single crystal behavior of a magnetically “soft” material

More typically, in polycrystalline ferromagnets, domains are irregular in form and not perfectly matched

Domain size set by energy cost of forming domain walls balanced by the energy reduction by formation of domains. Domain wall thickness $\sim 10 - 1000+ \text{ nm.}$
Ferromagnets – Hard and Soft

\[ <M> = 0 \]

\[ <M> = M_{sat} \]

\( H > H_c, \) coercive field

If after \( H > H_c \)

\[ <M> = M_{sat} \]

hard ferromagnet

If after \( H > H_c \)

\[ <M> << M_{sat} \]

soft ferromagnet

Desirable for permanent magnets and magnetic recording and memory devices.

The area of the hysteresis loop is related to the amount of energy dissipation upon reversal of the field.

Desirable for transformer and motor cores to minimize the energy dissipation with the alternating fields associated with AC electrical applications.

Hard

Soft
How to obtain a hard ferromagnet?

Use **magnetic anisotropy** and optimal grain (micro-crystallite) size.

Grain size should be small enough that only one domain fits readily into a grain, but not too small, i.e. **between 10 and 100 nm**.

**magnetic anisotropy – crystalline anisotropy**

[Diagram showing magnetic anisotropy and crystal structure of Co]
Development of Hard Ferromagnets

A lodestone magnet from the 1750's and typical ferrite and rare earth used in modern appliances. Each of these contain about 1J of magnetic energy.

The number of magnets in the family car has increased from one in the 1950's to over thirty today.

Over 30g of magnets are produced annually for each person on Earth.

Permanent Magnets

- Why permanent magnets
  - No resistive losses
- What’s it worth
  - US $11.5 Billion in 2000
Production of NdFeB Magnets
General Motors – 1980’s

Currently the highest energy density (M_{sat}H_c) magnetic material known
The crystal structure and components combine to yield high M_{sat}
The grain size has to be just right to get the highest possible H_c

Melt Spinning

Radial velocity 10 – 40 m/s
Electron microscope image of NdFeBaNb ferromagnet with different grain sizes made by spin quenching.

Which material is the hard ferromagnet?

Which one is the soft ferromagnet?
Shape Anisotropy and Magnetic Memory

Shape anisotropy for ferromagnetic thin films, often restricts domains to lie in-plane.

Image of in-plane domain structure of a 3 nm thick NiFe (permalloy) film.

In patterned films domains lie in elongated direction.

Single domain switching behavior of patterned NiFe thin film nanomagnet.
Nanomagnets and the Super-Paramagnetic Limit

How small is too small?

If a magnetic domain, either a patterned ferromagnetic structure or single ferromagnet grain is too small, it becomes super-paramagnetic despite its anisotropy. Then, due to random thermal energy, Brownian energy, the domain will fluctuate randomly between its possible, preferential, directions.

Magnetic energy required to flip domain

\[ E_{mag} = \frac{1}{2} M_{sat} H_c Vol \]

Average rate of flipping

\[ \Gamma = \tau_0^{-1} e^{-E_{mag} / k_B T} \]

\( \tau = \Gamma^{-1} = \text{mean lifetime or time spent in one of the possible magnetic states.} \)

\( \tau_0^{-1} = \text{rate the magnet attempts to flip } \sim 10^9 / \text{sec} \)

For data storage we require \( \tau > 10 \text{ years.} \)

As \( Vol \) becomes smaller, \( H_c \) must become larger.

Challenge for nanoscale magnetic memory
A New Approach for Magnetic Memory

Current approach to MRAM:
MTJs switched with magnetic field. As nanomagnets get smaller, need more current - bigger wires. Also have “half-select” problem
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Possible future MRAM:
nanomagnets switched with spin polarized current

New discovery: Predicted in 1996 by IBM scientist, John Slonczewski
Actually observed in 1992 at Cornell but not understood until later
Giant Magnetoresistance as a Spin Filtering Effect

Magnetic Layer

Down spins have been filtered out. Eventually the transmitted up-spin electrons relax to equal numbers of up and down. Takes about 100 nm.

Parallel layers: low resistance

Antiparallel layers: high resistance
Spin Transfer – Something Even Newer in Nanomagnetism

Spin filtering of polarized electrons that are not parallel to a magnet can be viewed as the ferromagnet exerting a torque on the spin of the electron. A quantum physics effect.

By Newton’s third law there must also be a reaction torque on the ferromagnet.
The Spin Transfer Effect

- spin of electron
- local moment of ferromagnet

FM
The Spin Transfer Effect

If the amplitude of the spin-polarized current is high enough the result is the excitation of the nanomagnet:
- reversal of the nanomagnet moment in low field,
- steady state precession of the moment in high field.

- spin of electron
- local moment of ferromagnet
Spin-Torque Driven Nanomagnet Dynamics

Gyroscopic motion of magnet
Spin-Torque Driven Nanomagnet Dynamics

Gyroscopic motion of magnet

No applied magnetic field

Strong applied magnetic field

Microwave oscillations

1 – 80 GHz
Reversible Spin Transfer Switching of Nanomagnets

How it works

Left-going electrons are partially reflected back by fixed layer. Reflected electrons exert opposite torque on free layer, leading to anti-parallel alignment.

Right-going electrons exert torque on free layer favoring parallel alignment.

Fixed layer is larger or otherwise pinned so that spin transfer from the current does not excite it.
Spin Torque Driven Magnetic Reversal

Requires nanoscale magnets

Flipping the thin (free) layer with a magnet

Flipping the thin (free) layer with current
Future Applications of Spin Torque Effects in Nanomagnets

**Scalable** nanoscale memory
Universal replacement for Si memory in computers

*Fast (1 ns), low-power and non-volatile – instant on computers*

Nanoscale microwave sources

*Communications and signal processing applications*

At the nanoscale, new spin phenomena become accessible and some physics challenges, such as thermal fluctuations, become far more important.

Our objective is:
To understand and hence better control nanoscale spin and magnetic phenomena,
To overcome the physics and materials challenges to make them useful in technology and beneficial for society.