Bits of the Future: Emergent Physics for Advanced Magnetic Information Technologies

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- A bit of history and introduction
- All-optical control / storage
- Current control / memory
- Conclusions and outlook
First magnetic recording 1898

Magnetic Recording
Invented

Valdemar Poulsen

Valdemar Poulsen's wire recorder from 1898
(Danish technical museum www.tekniskmuseum.dk)
Magnetic recording

writing

reading
Killer applications

The invention is of great importance for telephonic purposes.

Phone communications can be received by the apparatus when the subscriber is absent, whereas upon his return he can cause the communications to be repeated by the apparatus.

If, for example, the message, “The subscriber is not at home at present, but will return at four o’clock, at which time please ring again,” is fixed to the steel wire.
Digital magnetic storage/memory

RAMAC 1956

5 Mbyte

MIT Whirlwind 1951

1 kbyte
**Digital magnetic storage/memory**

- **RAMAC 1956**
  - 5 Mbyte
  - 2 kbits/in²
  - 70 kbits/s
  - 50x 24 in dia disks
  - $10,000,000/Gbyte

- **MIT Whirlwind 1951**
  - 1 kbyte
  - Cell Size: 1 mm²
  - Access time: 10 microseconds
  - Destructive read
  - Cost: $1/bit
Current storage/memory

500 Gbyte mobile drive

1 x 2.5” glass disk

630 Gbits/in² (3x10⁸)
1.4 Gbits/s (2x10⁴)
Non-volatile
$0.15/Gbyte

Samsung 2011

2GB DDR3 SDRAM

48nm Process

Cell Size: 0.0092 μm² (~10⁸)
20 nanoseconds (~10³)
Volatile
Cost: $0.25/gigabit
Total hard-drive capacity

Exabyte = 1 million terabytes or 1 billion gigabytes or

In 2012, humankind created 2,700 exabytes of data.

That's 86 terabytes every second of every day.

Source: Seagate Market & Competitive Intelligence
Hard-drives vs. solid state drives

~same total cost

Source: Seagate Market & Competitive Intelligence
Disk drive basics

- Disk Drive
- Suspended MR Head
- Rotating Thin Film Disk
- Track width
- Slider/ MR Head

“1”

“0”

Track width

Slider/ MR Head
Magnetic recording

Noisy Read-Back Signals
Media and the superparmagnetic effect

The edges of each recorded bit follow the grain boundaries → transition noise

500 Gb/in²: bit size ~ 15 nm x 65 nm

Independent grains SNR ~ $\sqrt{N}$

want small V

Energy/grain $K_U V > 50k_B T$

→ Scale media microstructure together with rest of recording system
Media and the superparamagnetic effect

\[ \tau \sim \tau_0 \exp\left(\frac{E_B}{k_B T}\right) \]

- \( K_U V = 100 \, k_B T \) \quad \tau > \text{age of the universe}
- \( K_U V = 45 \, k_B T \) \quad \tau \sim 10 \text{ years}
- \( K_U V = 25 \, k_B T \) \quad \tau \sim 7 \text{ seconds}
Media and the superparamagnetic effect

The edges of each recorded bit follow the grain boundaries → transition noise

500 Gb/in²: bit size ~ 15 nm x 65 nm

→ Scale media microstructure together with rest of recording system

\[ M_S, K_U, V \]
\[ \text{Energy} = K_U V \]

Independent grains \( \text{SNR} \sim \sqrt{N} \)
want small \( V \)

Energy/grain \( K_U V > 50k_B T \)
\( H_C = K_U / M_S < H_{\text{write-head}} \)

Competition for reading, writing and storing data: superparamagnetic effect
Heat-assisted recording

- <50-nm heat spot, ~300 °C rise/cool in 1 ns integrated into a head

- A magnetic media w/ high $K_U$, small grains and high $dH_K/dT$

- A head-disk interface (i.e. lubricant) that can handle repeated heating
Heat-assisted recording


HGST San Jose
Plasmonics

Surface plasmons

Lycurgus Cup - 4th Century Roman
**Plasmonics**

Surface plasmons

Metallic plate

20 nm

20 nm

bow-tie antenna

20 nm

Gain

5 nm

Peak=3500x

Gain

Gain

5 nm

Peak=3500x

Gain

t=30 nm

Plane wave (λ= 780 nm)

Polarization

Metal

heat spot

GMR laser

write coils

bow-
tie antenna

Gold

r=25 nm

5 nm

40º

t=30 nm

d=2 nm
Advanced optical guides

- Channel plasmon polariton (CPP) waveguide with V-groove

Excitation

Silicon Waveguide

V-groove Plasmonic Waveguide with Tapered End

FWHM: 31nm x 32nm
Efficiency with silver: 20%

V. Lomakin
All-optical recording?

Directly control magnetism with light?
All-optical recording?

C. D. Stanciu et al., PRL (2007)

20 nm thick Gd$_{22}$Fe$_{74.6}$Co$_{3.4}$

40 fs pulses, 1 kHz repetition

$H_{ext} = 0$
All-optical switching (AOS)

What are the origins?
• Is GdFeCo unique?
• Is heat required?
• Is it an ultra-fast process?
• Is angular momentum of the light important?

For applications
• Higher anisotropy
• Ferromagnetic recording media
Materials study of AOS

Broaden the materials space: >1000 samples

- RE-TM alloys and multilayers
- Heterostructures
- Nanostructures
UCSD experimental facility

White light

λ/4 plate

LASER 50-200fs
1 nJ -1 mJ
800nm, 1kHz

Polarizer

Magnetic pole

Analyzer & microscope

CCD

Imaging
Light induced magnetization dynamics

TbCo film
Materials study of AOS

Lanthanide series

<table>
<thead>
<tr>
<th>Lanthanum</th>
<th>Cerium</th>
<th>Praseodymium</th>
<th>Neodymium</th>
<th>Promethium</th>
<th>Samarium</th>
<th>Europium</th>
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</thead>
<tbody>
<tr>
<td>La (138.91)</td>
<td>Ce (140.12)</td>
<td>Pr (140.91)</td>
<td>Nd (144.24)</td>
<td>Pm (145)</td>
<td>Sm (150.36)</td>
<td>Eu (151.96)</td>
</tr>
</tbody>
</table>

Lu (168.93) | Yb (173.04)

$Tb_{26}Co_{74}$ alloy

$[Tb(3\text{Å})/Co(3\text{Å})]_{\times41}$

$[Tb(25\text{Å})/Co(25\text{Å})]_{\times5}$
All-optical switching

Rather general property of ferrimagnets


Can it also work with ferromagnets?

Can it work with magnetic recording media?
Ferromagnets

15-nm FePt-C and FePtAg-C granular films

Ferromagnets

15-nm FePt-C granular films

423
490
601
724
1012
1256
1395 nW
Ferromagnetic AOS

**Heating** by the laser near $T_C$

+ Magnetic field/Angular momentum from a laser beam

Inverse Faraday effect

$$\vec{H}_{\text{eff}} = \frac{\varepsilon_0}{\mu_0} \alpha \left[ \vec{E}(\omega) \times \vec{E}^*(\omega) \right]$$

*circircular polarization*

+ Suppression of domain formation during cooling
thin film, high anisotropy and/or low M
Landau–Lifshitz–Bloch simulations

Marco Menarini and Vitaliy Lomakin, UC San Diego

Landau-Lifshitz-Bloch simulations
Pulse Length 1ps with a pulse field intensity 2T
Maximum Temperature $T=700$ K and $T_C=660$ K
Future of all-optical switching?

Nano-scaled islands

Near field elements

Nano-Crescent-Moon

200 nm

Ag/Si

Anisotropic Nano-material

Sub-50nm
Leveraging the hard drive for memory

Return of magnetism in memory and processing?

Advantages of magnetism

• Non-volatile ($E_B > 50 \ k_B T$)
• Low energy $50 \ k_B T = 0.2 \ aJ$

Performance and power issues in IT

• Memory is a bottleneck (data-centric vs. compute centric)
• Hand-held devices are increasingly power limited
• Computing and data centers dissipate Megawatts of power

• Opportunities for new non-volatile memories
Magnetic RAM

P State “0”
Low Resistance

AP State “1”
High Resistance

Free layer Ferromagnet
Insulating tunnel barrier
Fixed layer Ferromagnet

Nobel Prize in physics in 2007
Einstein de Hass effect


*Proof of the existence of the Ampere molecular field*

“How treacherous nature is, when you have to deal with it experimentally”
Spin transfer torques

Angular momentum conservation
\( \Rightarrow \) spin transfer torques


Katine et al., PRL 84, 3149 (2000)

articles on spin torque edited by Stiles and Ralph
Perpendicular anisotropy devices

- Higher thermal stability
  - $E_B > 50 \ k_B T$
- More efficient reversal
  - $I_C$ scales with $E_B$

Perpendicular devices

- Use of negative HSQ resist as a high fidelity mask
- ~1000 devices/5 inch wafer: circles and hexagons from 45nm to 1500nm
Current reversal in 50x100 nm$^2$ devices

Energy and time scales?

$H_C = 2.65$ kOe

$I_{C}^{AP-P} = -2.6 \times 10^7$ A/cm$^2$

$I_{C}^{P-AP} = 7 \times 10^7$ A/cm$^2$
Time dependence and energy

\[ \frac{1}{\tau} = A(I - I_{C0}) \]

\( \tau \) = reversal time
\( I \) = current
\( I_{C0} \) = critical current to counter damping
\( A \) = dynamics parameter

---

Minimum energy

\[ E = I^2 R \tau \]

\[ \frac{1}{\tau} = A(I - I_{C0}) \]

Switching energy versus pulse duration

- **Minimum Energy** switching at:
  - \( \tau = 800 \) ps
  - \( E = 100 \) pJ

6 × 10^6 electrons
5 × 10^5 spins in the free layer
~14 electrons/spin

Energy in pulse is 5 × 10^5 times \( E_B \)
Perpendicular MRAM cells

- High anisotropy: $E_B > 50 \, k_B \, T$ (30 nm)
- High TMR
- Low $I_c$ and $V_c$
- Symmetric $I_c$
- Low read current
- $T_{\text{ann}} = 400 \, ^\circ C$

**State-of-the-art BEOL**

- Top Electrode
- Free
- Pinned

- Bottom Electrode
- 3 extra masking layers
- Bottom cont/MTJ/Plate

**Substrate/Seed Layers/BE**

- CoFeB
- MgO
- CoFeB
- Ta-Fe Spacer
- Co/Pd
- Ru
- Co/Pd

**Figures**

- Graphs showing resistance vs. field and current vs. field.
- $I_{\text{sw}} = 30 \mu A$
- $J_c \sim 1.4 \, MA/cm^2$

**References**

- APL Mater. 1, 022102 (2013)
- Appl. Phys. Lett. 102, 052405 (2013)
Magnetic Information technologies

Storage – Hard Disk Drive

Memory – MRAM

Processing

H. Dery, P. Dalal, L. Cywinski, L. J. Sham
Magnetic reversal

- Field
- Light
- Current
  - $e^-$
- Heat
- Strain
- Electric Field
  - $E$
Claude Chappert’s roadmap

Moore’s law

Magnetic Storage
HDD, MRAM controlled by Magnetic field

STT MRAM, DW spin-polarized charge current

control by Electric field
manipulate magnetization, transport, with gate voltage

Beyond CMOS

High Integration ML Circuits

pure Spin-currents
spin transfer and logic with pure spin currents

increase in anisotropy "effective" field to maintain non volatility
⇒ increase in precession frequency ⇒ speed will increase !!!!
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