Electric field control of magnetism in oxide heterostructures

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Power consumption of ICT systems

Global Semiconductor market size ~ $5 trillion by 2030

Average US Household Computing Power Consumption: 2-3kWh / day

Year


TWh

0 2000 4000 6000 8000 10000

Do Nothing
Energy ~ 100pJ/op
~20% primary energy

New Moore scaling
In 20 yrs
Energy = 20pJ/op
IT=30-40% growth

New Moore scaling in 10 yrs
Energy = 20fJ/op
IT=hold to 8%

Projection based on consumer electronics + data centers


Courtesy R. Ramesh
Power needs in microprocessors

Intel « Sandy bridge »

- Read one 64-bit number in SRAM: 14 pJ
- Multiply two 64-bit numbers: 50 pJ
- Move one 64-bit number 10 mm away: 300 pJ
- Move one 64-bit number from external RAM: 10000 pJ

Power needs in microprocessors

Data transfer on-chip consumes most of the power!

- « Bring memory into logic »
- Embed memory elements in the logic units
- Ferroic materials can bring solutions for beyond CMOS electronics

GPUs and the future of parallel computing, W.J. Dally et al, IEEE Micro (2011)
Enter spintronics...

The electron has a charge (-e) and a spin (↑,↓).

Electronics
- Charge
- Electric field
- Current or voltage measurement

Magnetism
- Magnetization
- Magnetic field
- External element (magnetometer)

Spintronics
- Electron spin
- Magnetic field, spin-polarized current
- Current or voltage measurement

Information vector
Control
Detection
Enter spintronics...

The electron has a charge (-e) and a spin (↑, ↓).

Information vector

Electronics
Charge
Electric field
Current or voltage measurement

Magnetism
Magnetization
Magnetic field
External element (magnetometer)

Spintronics
Electron spin

Electric field?

External element (magnetometer)

Current or voltage measurement
Non-magnetic metal: DOS is the same for spin up and spin down
Ferromagnetic metal: different DOS for spin up and spin down
- spin-polarization of electrons near $E_F$
- different transport properties for spin up and spin down electrons

Spintronics exploits spin-sensitivity of electron transport
MTJ: Trilayer device: two ferromagnetic electrodes separated by thin insulator

MTJs show tunnel magnetoresistance (TMR)
- The TMR amplitude increases with the spin-polarization of the electrodes
- Typically switching between P and AP configuration is done by a magnetic field
- Useable for **non-volatile data storage**
Magnetic random access memory (MRAM)

- MRAM are commercial since 2006
- Chip capacity approaching 1 Gb
- Market ~ $ 1 billion
- So far small companies (Everspin, Freescale)
- Samsung announced mass production for 2018
Electric field control of magnetism with oxide heterostructures

Magnetic random access memory (MRAM)

- Move from current-based approaches to electric-field-based approaches
- Electric-field applied across an insulator: power consumption \( \sim 0 \)

**GOAL**

- How to achieve electric-field control of magnetism?
  - Use multiferroic materials or multiferroic architectures

E > 1000 fJ/bit

E ~ 10-100 fJ/bit

E < 0.1 fJ/bit
Introduction to ferroic orders

**Ferroic orders**

- **Ferroelectric**
  - $P$ vs $E$
  - Hysteretic dependence of order parameter: good for data storage

- **Ferromagnetic**
  - $M$ vs $H$
  - Multiple order parameters: increased storage density
  - Coupled orders: enhanced flexibility for data writing

- **Ferroelastic**
  - $\sigma$ vs $T$

- **Ferrotoroidic**
  - $S$ vs $T$

**Multiferroic / Magnetoelectric**

- $P$ vs $E$
  - "Intrinsic"

- $M$ vs $H$
  - "Artificial"

**Different approaches for E-field control of magnetism**

### Intrinsic magnetoelectric
- Use single-phase multiferroic material

### Field-effect
- Combine strong ferroelectric with carrier-mediated ferromagnet

### Strain-driven
- Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet
Controlling magnetism with electric fields

Magnetic anisotropy

Exchange bias

Magnetic moment

Magnetic order

Curie temperature

Spin polarization

Different approaches for E-field control of magnetism

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E-field control of magnetism with intrinsic multiferroics

There are very few (room-temperature) multiferroics

BiFeO$_3$: a room-temperature multiferroic

**Ferroelectric properties**
- Very high $T_C \approx 1100$ K
- Very large $P=100$ µC/cm$^2$

Béa, MB et al, APL 93, 072091 (2008)

**Magnetic properties**
- G-type antiferromagnetic + cycloidal modulation ($\lambda=62$ nm)
- Weak moment with periodic modulation
- $T_N \approx 640$ K

Influence of epitaxial strain on the magnetic properties of BiFeO$_3$

Strain (%)

- Cycloidal state is destabilized by strain-induced (magnetoelastic) anisotropy
- Weak-FM state at high tensile or compressive state
- New cycloid stabilized at low tensile strain

\[ W - W_{L=[1\overline{1}0]} \text{ (kJ/m}^3\text{)} \]

E-field induced magnetization switching with BiFeO$_3$ thin films

Sequential switching of P promotes switching of weak M

Application of out-of-plane voltage to BFO film promotes local switching of magnetization in Co film grown on top of BFO

Heron et al, Nature 370, 516 (2014)
Different approaches for E-field control of magnetism

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Field-effect control of magnetism

- Charge accumulation / depletion thanks to a dielectric or ferroelectric (non-volatile)
- If magnetism in channel material is (highly) sensitive to carrier density
  > **Change of magnetic properties by electric field**
- Effect occurs over small distance, typically **Thomas Fermi screening length** (Å for metals, nm for oxides)

Hemberger et al., PRB, 66, 094410 (2002)
Field-effect control of Curie temperature

- Combination of a **ferroelectric** and a **carrier-mediated ferromagnet**
- Switching P in ferroelectric PZT produces charge accumulation/depletion in manganite
- Change $T_C$ of manganite
- Limited to low-temperature (also with GaMnAs)

Field-effect control of Curie temperature

Increase accumulated charge density: ionic liquids

- Large field effect in 0.6 nm Co film using ionic liquid gating
- Possible with ferroelectrics (i.e. PZT/ultrathin Co)?

Electric-field control of spin polarization

Change of spin polarization of Fe depending on ferroelectric polarization direction

Probe this effect in Fe/BTO/LSMO tunnel junctions

Duan et al., PRL 97, 047201 (2006)
Fechner et al, PRB 78, 212406 (2008)
Electric-field control of spin polarization

- Change of spin polarization of Fe depending on ferroelectric polarization direction
- Probe this effect in Fe/BTO/LSMO tunnel junctions

- TMR amplitude depends on direction of P
- Ferroelectric control of spin polarization
- Combination of field-effect and hybridization changes

Different approaches for E-field control of magnetism

**Intrinsic magnetoelectric**
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**Field-effect**
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Strain-induced control of magnetic anisotropy


**Principle:**
E-field applied to PZT: change in PZT dimensions due to **converse piezoelectric effect**
→ Change in dimensions induced in Ni: strain effect
→ Due to **magnetostriction** in Ni, strain modifies the magnetic properties

Electric-field induced control of magnetization easy axis
Strain-induced control of magnetic order

\[ \text{Fe CONTENT (at.\%)} \]
\[ \begin{array} {c c c c c c}
20 & 30 & 40 & 50 & 60 & 70 & 80 \\
\hline
300 & 600 & 900 & 1200 & 1500 \\
\end{array} \]

Paramagnetic phase  Antiferromagnetic phase  Ferromagnetic phase

\( \gamma \) phase : fcc ; \( \alpha \) phase : disordered bcc  
\( \alpha' \) phase : Fe/rh ordered bcc

van Driel et al, JAP 85, 1026 (1999)

- Near Fe\(_{50}\)Rh\(_{50}\), transition from AFM to FM at about 370K
- Transition is first order
- Associated large resistivity drop
- Jump of cell volume by ~1% at \( T^* \)

Magnetic state of FeRh is sensitive to pressure

Grow on \textbf{ferroelectric/ferroelastic BaTiO}_3 substrate to achieve E-field control

Zakharov et al, Sov. Phys. JETP 19, 1348 (1964)
Strain-induced control of magnetic order

- At 0V at 20 kOe, $T^* \approx 360$ K
- Voltage shifts $T^*$ by $\sim 20$K
- Effect is reversible
- Positive or negative voltages give roughly similar effect

Max magnetization change $\sim 600$ emu/cm$^3$
- ME coupling $\alpha = 1.6 \times 10^{-5}$ s/m
- Larger than in any single phase material by 5 orders
- Larger than in any artificial multiferroic by factor $> 10$

Strain-induced control of magnetic order

Direct imaging of magnetic state using XCMD-PEEM

-20V
Ferromagnetic state

0V
Mixed ferro/antiferromagnetic state

50V
Antiferromagnetic state

T=385 K

Switch ferromagnetism **OFF and ON** by electric field, just above room temperature

Different approaches for E-field control of magnetism

**Intrinsic magnetoelectric**

- Use single-phase multiferroic material

- **✓** Simple approach, just one material
- **✓** Beautiful physics, potential for new science
- **✗** BFO only RT multiferroic
- **✗** Can be leaky, hard to switch

**Field-effect**

- Combine strong ferroelectric with carrier-mediated ferromagnet

- **✓** Broader choice of materials
- **✓** Well-suited for perpendicular transport
- **✗** Few ferromagnetic oxides with high $T_C$; need simple metals
- **✗** Effect occurs over very small thickness (few nm max)
- **✗** Needs very large fields

**Strain-driven**

- Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

- **✓** Broader choice of materials
- **✓** Effect occurs over whole FM film
- **✗** Fatigue + low endurance
- **✗** Hard to miniaturize
Different approaches for E-field control of magnetism

- New approaches / new ingredients
  - Interconvert charge and spin currents using spin-orbit coupling
  - Engineer topological spin-textures controllable by electric fields

Hermes Trismegistus « Emerald tablet »
Yoshinori Tokura « Quantum Science on Strong Correlation Report 2014 »
Fermi contours in 2DEGs

Topological insulator

Rashba interface


Direct and inverse Rashba-Edelstein effects

Direct Rashba-Edelstein effect

- Inject a charge current $J_C$
- Generation of a spin accumulation $\rightarrow$ Spin current $J_S$

V. M. Edelstein, Solid State Commun. 73, 233 (1990)

Inverse Rashba-Edelstein effect

- Inject a spin current $J_S$
- Inequivalent shift of both Fermi contours $\rightarrow$ Generation of a charge current $J_C$


- 3D spin current produces 2D charge current $\rightarrow$ figure of merit is a length

$$\lambda_{\text{IEE}} = \frac{J_C}{J_S} = \frac{\alpha_R \tau}{\hbar}$$

$\alpha_R$ : Rashba coeff.
$\tau$ : scattering time
LaAlO$_3$/SrTiO$_3$ interface system

- Well-known oxide interface system  
- 2-dimensional electron gas forms at interface despite both LAO and STO being two insulators
- High mobility (>1000 cm$^2$/Vs) and low carrier density ($\sim$10$^{13}$ cm$^{-2}$)
- Gate-tuneable **Rashba spin-orbit coupling**  
  A.D. Caviglia et al., PRL. 104, 126803 (2010)

- Combine 2 unit-cells of LAO and 2 nm of NiFe (permalloy)
- TEM and AFM analysis indicates smooth surface and interfaces
Detected voltage:
- Symmetric Lorentzian shape
- Sign reversal upon \(+H\rightarrow -H\) inversion

\[ +\sigma \rightarrow -\sigma \]
\[ +V \rightarrow -V \]
Efficient spin-to-charge current conversion via the Inverse Edelstein Effect (IEE):

\[ \lambda_{IEE} = \frac{j_c}{j_s} = \frac{\alpha_R \tau}{\hbar} \]

Strong gate dependence, reminiscent of gate dependent Rashba coefficient in WAL data


Can one quantify \( \lambda_{IEE} \)?

E. Lesne, MB et al., Nature Mater. 15, 1261 (2016)
Spin to charge current conversion

- Efficient spin-to-charge current conversion via the Inverse Edelstein Effect (IEE):
  \[ \lambda_{IEE} = \frac{j_c}{j_s} = \frac{\alpha_R \tau}{\hbar} \]

- Largest efficiency reported for any material

- Efficient larger than in Bi/Ag interface (\(\lambda_{IEE} = 0.3 \text{ nm}\)) and in topological insulator \(\alpha\)-Sn (\(\lambda_{IEE} = 4 \text{ nm}\))
  

- Values of \(\lambda_{IEE}\) compatible with reported values of \(\alpha_R \sim 0.01-0.05 \text{ eV.Å}\) and measured \(\tau \sim 10-100 \text{ ps}\)
  
  E. Lesne, MB et al., Nature Mater. 15, 1261 (2016)
Conclusions and perspectives

- Oxide materials and heterostructures offer **many possibilities for E-field control of magnetism**
  - With multiferroics (works but at room temperature limited to BiFeO$_3$)
  - Through field effect (limited efficiency, requires ultrathin films and large fields)
  - Through field-controlled strain (efficient but hard to miniaturize)
  - New possibilities for **spin/charge interconversion** at oxide interfaces with **Rashba SO coupling**
    - Could work at room temperature? Be larger in other systems than LAO/STO?

  *Topological states at the (001) surface of SrTiO$_3* M. Vivek et al, ArXiv 1702.05974

- Opportunities for devices in spintronics
  - Memory: future generation of MRAMs?
  - **Memory into logic**: new spin-based transistors combining ME coupling + spin-charge conversion

  *Spin-Orbit Logic with Magnetoelectric Nodes* S. Manipatruni et al (INTEL), ArXiv 1512.05428

- Opportunities for new physical effects
  - **Topology meets correlations**
  - In real space:
    - Topological spin textures \(\Rightarrow\) new physical effects (topological Hall effect, top. orbital moment)
    - Effects amplified by correlations?
    - Controllable through field-effect?

  *Role of Berry-phase for describing orbital magnetism* J. Hanke et al, PRB 94, 12114 (2016)
  *Giant topological Hall effect from skyrmion bubbles in correlated manganite thin films*, L. Vistoli, MB et al, submitted

  - In reciprocal space:
    - Novel types of topological materials (iridates, osmates, etc)
    - New state variables for information processing (beyond spin and charge)