Présent et futur de la spintronique (LAAS, 17/12/08)

Spin transfer:
- writing by electrical transport of magnetic information,
- microwave generation

Spintronics with semiconductors,
molecular spintronics,
Single-electron spintronics, etc

Influence of spin on conduction
- Spin up electron
- Spin down electron

Magnetic nanostructures

Memory (M-RAM)

GMR, TMR, etc...

Spintronics

Read heads, sensors, etc.
Introduction:

Spin dependent conduction in ferromagnetic conductors,

Giant Magnetoresistance (GMR),

Tunnel Magnetoresistance (TMR)
Spin dependent conduction in ferromagnetic metals
(two current model)

Fert et al, PRL 21, 1190, 1968
Loegel-Gautier, JPCS 32, 1971
Dorlejin et al, ibid F7, 23, 1977

\[ \alpha = \frac{\rho_{\downarrow}}{\rho_{\uparrow}} \quad \text{or} \quad \beta = \frac{\rho_{\downarrow} - \rho_{\uparrow}}{\rho_{\downarrow} + \rho_{\uparrow}} = \frac{\alpha - 1}{\alpha + 1} \]
Mixing impurities A and B with opposite or similar spin asymmetries: the pre-concept of GMR

**Example: Ni + impurities A and B** (Fert-Campbell, 1968, 1971)

1st case

\[ \alpha_A > 1, \quad \alpha_B < 1 \]

2nd case

\[ \alpha = \frac{\rho_\uparrow}{\rho_\downarrow} \]

\[ \alpha_A \text{ and } \alpha_B > 1 \]

High mobility channel \( \rightarrow \) low \( \rho \)

\[ \rho_{AB} >> \rho_A + \rho_B \]

\[ \rho_{AB} \approx \rho_A + \rho_B \]

J. de Physique 32, 1971
- Magnetic multilayers
Magnetic multilayers

Magnetizations of Fe layers at zero field in Fe/Cr multilayers

P. Grünberg, 1986 → antiferromagnetic interlayer coupling
Magnetic multilayers

Magnetizations of Fe layers in an applied field in Fe/Cr multilayers

P. Grünberg, 1986 → antiferromagnetic interlayer coupling
• Giant Magnetoresistance (GMR)  
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

Orsay

Resistance ratio
\[ \frac{R}{R(H=0)} \]

~ + 80%

Magnetic field (kGauss)

(Fe 3nm/Cr 1.8 nm)
(Fe 3nm/Cr 1.2 nm)
(Fe 3nm/Cr 0.9 nm)

A\text{P} (AntiParallel) P (Parallel)

Jülich

MR=1.5%

\[ V=RI \]
- Giant Magnetoresistance (GMR)
  (Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

**Resistance ratio**

\[
\frac{R}{R(H=0)} \approx +80\%
\]

- **Magnetic field (kGauss)**
- **Current**
- **AP** (AntiParallel) **P** (Parallel)

**Condition for GMR:** layer thickness \( \approx \) nm

**Anti-parallel magnetizations**
- (zero field, high resistance)

**Parallel magnetizations**
- (appl. field, low resist.)

\[\text{Fe} \quad \text{Cr} \quad \text{Fe}\]

\[\text{Fe} \quad \text{Cr} \quad \text{Fe}\]

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Recent review: « The emergence of spintronics in data storage » Chappert, AF et al Nat. Mat. (Nov. 07)

Magnetic fields generated by the media

1997 (before GMR): 1 Gbit/in², 2007: GMR heads ~ 600 Gbit/in²
• Magnetic Tunnel Junctions, Tunneling Magnetoresistance (TMR)

ferromagnetic electrodes

≈ 0.1 μm

tunneling barrier (insulator)

Low resistance state

High resistance state

Jullière, 1975, low T, hardly reproducible

Moodera et al, 1995, Miyasaki et al, 1995, CoFe/Al₂O₃/Co, MR ≈ 30-40%

CoFeB/MgO/CoFeB, ΔR/R ≈ 500% at RT in 2006-2007

Applications: - read heads of Hard Disc Drive

- M-RAM (Magnetic Random Access Memory) and STT-RAM

"bit" lines

aims: density/speed of DRAM/SRAM + nonvolatility + low energy consumption

"word" lines

"1"

"0"

MRAM (2006, Freescale)

STT-RAM (in demonstration) with MgO tunnel junctions + writing by spin transfer
Epitaxial magnetic tunnel junctions (MgO, etc)

First examples on Fe/MgO/Fe(001):
CNRS/Thales (Bowen, AF et al, APL2001)
Nancy (Faure-Vincent et al, APL 2003)
Tsukuba (Yuasa et al, Nature Mat. 2005)
IBM (Parkin et al, Nature Mat. 2005)
…..etc

Yuasa et al, Fe/MgO/Fe
Nature Mat. 2005
\( \Delta R/R = (R_{AP} - R_P)/R_P \approx 200\% \) at RT

2006-2007
CoFeB/MgO/CoFeB,
\( \Delta R/R \approx 500\% \) at RT in several laboratories in 2006-2007

Clearer picture of the physics of TMR: what is inside the word « spin polarization »?
Mathon and Umerski, PR B 1999
Zhang and Butler, PR B 2004 [bcc Co/MgO/bcc Co(001)]

With reversed M in the right electrode, spin ↑ corresponds to a minority spin band state without Δ₁ character at E_F in which the tunneling Δ₁ el. cannot be accommodated.
Spin Transfer
(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules

Common physics:
spin accumulation

spins injected to long distances
by diffusion
Co/Cu: Current $\perp$ to Plane (CPP) -GMR of multilayered nanowires  
(L.Piraux, AF et al, APL 1994, JMMM 1999)

CPP-GMR subsists at almost 1 $\mu$m

CIP-GMR  
scaling length = mean free path

CPP-GMR  
scaling length = spin diffusion length >> mean free path  
spin accumulation theory  
(Valet-Fert, PR B 1993)

Other results: MSU group, PRL 1991, JMMM 1999
Spin injection/extraction at a NM/FM interface (beyond ballistic range)

\[ \Delta \mu = E_{F^\uparrow} - E_{F^\downarrow} \]

\[ J^\uparrow - J^\downarrow = J^\uparrow + J^\downarrow \]

(illustration in the simplest case = flat band, low current, no interface resistance, single polarity)

\[ I_{s_f}^{FM} = \text{spin diffusion length in FM} \]

\[ I_{s_f}^{NM} = \text{spin diffusion length in NM} \]

(example: 0.5 \( \mu \text{m} \) in Cu, >10\( \mu \text{m} \) in carbon nanotube)
Spin injection/extraction at a NM/FM interface (beyond ballistic range)

 NM zone of spin accumulation

FM

(illustration in the simplest case = flat band, low current, no interface resistance, single polarity)

\[ I_{\text{NM}}^{s_{f}} = \text{spin diffusion length in NM} \]

\[ I_{\text{FM}}^{s_{f}} = \text{spin diffusion length in FM} \]

\[ \Delta \mu = E_{F_{\uparrow}} - E_{F_{\downarrow}} \]

Spin current

\[ J_{\uparrow} - J_{\downarrow} \]

Description*: Boltzmann-type formalism with the distribution function associated to a spin and position dependent chemical potential \( E_{F_{\sigma}}(z) \), which leads to macroscopic equations** relating the charge and spin currents to a spin dependent electro-chemical potential

\[ \mu_{\sigma}(z) = eV(z) + E_{F_{\sigma}}(z) \]

**CPP-GMR: multi-interface with interface resistances.

Semiconductors: new problems with band bending, large currents, “conductivity mism.”

Spin torque: non-collinear situation

**Similar equ. in Silsbee-Johnson and van Son et al.
Spin injection/extraction at a Semiconductor/FM interface

$\Delta \mu = E_{F\uparrow} - E_{F\downarrow}$

$\mathbf{J}_{\uparrow} - \mathbf{J}_{\downarrow}$

1) situation without interface resistance (« conductivity mismatch »)

(Schmidt et al, PR B 2000)

If similar spin splitting on both sides but much larger density of states in F metal

much larger spin accumulation density and much more spin flips on magnetic metal side

almost complete depolarization of the current before it enters the SC
Spin accumulation \( \Delta \mu = E_{F\uparrow} - E_{F\downarrow} \)

Current Spin Polarization \( \frac{(J_{\uparrow}-J_{\downarrow})}{(J_{\uparrow}+J_{\downarrow})} \)

Spin dependent drop of the electro-chemical potential
Discontinuity increases the spin accumulation in NM
re-balanced spin relaxations in F and NM
extension of the spin-polarized current into the semiconductor

Rasbah, PR B 2000
A.F-Jaffrès, PR B 2001
Deviations from 

\[ \frac{J_{\uparrow}-J_{\downarrow}}{J_{\uparrow}+J_{\downarrow}} = \frac{\beta r_F + \gamma r_b^*}{r_F + r_N + r_b^*} \]

at large current density (drift effect) 

\[ J_{\uparrow} \Rightarrow J_{\downarrow} \]

\[ \bullet = \text{low current limit} \]

\[ \Rightarrow \text{deviations from the low current limit} \]

(nondegenerate semiconductor)

from Jaffrès and A.F. 
(see also Yu and Flatté)
Spin transfer

(tranport of magnetization by an electrical current)

- fundamentals

- switching of magnetization by spin transfer and applications (STT-RAM, reprogrammable devices)

- microwave oscillations by spin transfer and applications to telecommunications.
Spin transfer


Ex: Cobalt/Copper/ Cobalt

The transverse component of the spin current is absorbed and transferred to the total spin of the layer

\[
\frac{\text{torque}}{\hbar} = \left( \frac{d \vec{S}}{dt} \right) \propto j M \times (M \times M_0)
\]

\[\equiv \text{Torque on } S \]

\[\approx M \times (M \times M_0)\]
Trilayered pillar or tunnel junction

Free magn. layer
Cu
Polarizer

Metallic pillar ≈ 50x150 nm²

Tunnel junction ≈ 50x170 nm²

Au
CoFeB
MgO
CoFeB

70 nm
Trilayered pillar or tunnel junction

Two regimes of spin transfer

1) Magnetization switching by spin transfer

2) Sustained precession of the magnetization of the free layer and generation of radio-frequency oscillations

Applications: writing a memory, etc

Applications: spin transfer nano-oscillators (NSTOs) for communications (telephone, radio, radar)
Regime of irreversible magnetic switching

First experiments on pillars:
Cornell (Katine et al, PRL 2000)
CNRS/Thales (Grollier et al, APL 2001)
IBM (Sun et al, APL 2002)

Py/Cu/Py 50nmX150nm (Boule, AF et al)

H=7 Oe

RT

Py = permalloy

I (mA)

10^{-7} A/cm^2

switching time can be as short as 0.1 ns (Chappert et al)
Regime of steady precession (microwave frequency range)

Polarizer magnetization

Increasing current

Microwave power spectrum of the oscillations of a permalloy-based pillar
Regime of steady precession for tunnel junctions

Spin Transfer mixes very different (and interacting) problems:

- transport (in metallic pillars, tunnel junctions, point contacts)
- problems of non-linear dynamics
- micromagnetism (non-uniform excitations, vortex motion..)

CoFeB/MgO/CoFeB junction (J.Grollier, AF et al 2008, collaboration S. Yuasa et al, AIST)
Co/Cu/Py (« wavy » angular variation calculated by Barnas, AF et al, PR B 2005)

- Py (8nm, free)
- Cu (8nm)
- Co (8nm, fixed)
- IrMn (15nm)
- or CoO or Cu

100x170nm²

Free Py: fast spin relaxation
Fixed Co: slower spin relaxation

Boule, AF et al, Nature Phys. 2007 oscillations at H=0
Applications of magnetic switching by spin transfer

**Switching of reprogrammable devices (example: STT-RAM)**

To replace M-RAM (switching by external magnetic field: *nonlocal*, risk of «cross-talk» limiting integration, too large currents)

**STT-RAM**: «Electronic» reversal by spin transfer from an electrical current

*Source: SpinRAM SONY, IEEE 2005*
Applications of magnetic switching by spin transfer

Switching of reprogrammable devices (example: STT-RAM)

To replace M-RAM (switching by external magnetic field: nonlocal, risk of «cross-talk» limiting integration, too large currents)

STT-RAM: «Electronic» reversal by spin transfer from an electrical current

Current pulse

Non volatile FPGA Logic Circuits

Flash and SRAM would be replaced by a non volatile memory (<10F²) embedded directly inside the look up table (Sony, IEEE Proc. 07)
Spin Transfer Oscillators (STOs)
(telecommunications, radar, chip to chip communication...)

Advantages:
- direct oscillation in the microwave range (0.5-40 GHz)
- agility: control of frequency by dc current amplitude
- high quality factor
- small size ($\approx 0.1\,\mu m$) (on-chip integration, chip to chip com., microwave assisted writing in HDD)

Needed improvements
-- Increase of power by synchronization of a large number $N$ of STOs ($\times N^2$)
- Optimization of the emission linewidth

$$\frac{f}{f\Delta f} \approx 18000$$
Spintronics with semiconductors and molecules
Spintronics with semiconductors

Magnetic metal/semiconductor hybrid structures

Example: spin injection from Fe into LED (Mostnyi et al, PR. B 68, 2003)

Ferromagnetic semiconductors (FS)

GaMnAs ($T_c \rightarrow 170K$) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

Logic devices, spin transistor?

Semiconductor lateral channel between spin-polarized source and drain transforming spin information into large(?) and tunable (by gate voltage) electrical signal
**Nonmagnetic lateral channel between spin-polarized source and drain**

**Semiconductor channel:**

« Measured effects of the order of 0.1-1% have been reported for the change in voltage or resistance (between P and AP)…. », from the review article « Electrical Spin Injection and Transport in Semiconductors » by BT Jonker and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 2006)


**Carbon nanotubes:**

\[ \Delta R/R \approx 60-70\%, \ V_{AP}-V_{P} \approx 20-60 \text{ mV} \]

LSMO = La\(_{2/3}\)Sr\(_{1/3}\)O\(_3\)
Nonmagnetic lateral channel between spin-polarized source and drain

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Two interface spin transport problem (diffusive regime)

Condition for spin injection

\[ \text{window} \propto \left( \frac{l_{sf}}{L} \right)^2 - 1 \]

\[ l_{sf}^N = 2 \mu m \]

\[ L = 20 \text{nm} \]

\[ L = 2 \mu m \]

\[ \Delta R / R_P \]

Condition

dwell time \( \tau_n < \) spin lifetime \( \tau_{sf} \)

dwell time

\[ \tau_n = \frac{2 L}{t_r v} \propto \frac{L r_b^*}{v} \]

\[ \frac{\Delta R}{R_P} = \frac{\gamma^2 / (1 - \gamma^2)}{1 + \tau_n / \tau_{sf}} \]

\[ \frac{\Delta R}{R_P} \]

drops to zero as \( 1 / r_b^* \)

for \( \tau_n \propto r_b^* >> \tau_{sf} \)

Interface resistance \( r_b^* \)

in most experiments

\[ \tau_n >> \tau_{sf} \]

\[ r_b^* = \text{unit area interface resist.} \propto 1 / \text{trans.coeff} t_r^* \]

\[ \gamma = \text{spin asymmetry of the interface resistance (calc. with } \gamma = 0.8) \]

\[ r_N = \rho_N l_{sf}^N \]

Window only for \( l_{sf}(N) > L \)
### Two interface spin transport problem (diffusive regime)

**Condition for spin injection**

Window \( \propto \left( \frac{l_{sf}}{L} \right)^2 - 1 \)

- \( l_{sf} = 2\mu m \)
- \( L = 200\text{nm} \)
- \( L = 20\text{nm} \)

**Condition**

Dwell time \( \tau_n < \) spin lifetime \( \tau_{sf} \)

\( \Delta R / R^p = \frac{\gamma^2}{(1 - \gamma^2)} \left( 1 + \frac{\tau_n}{\tau_{sf}} \right) \)

For \( \tau_n \propto r_b^* \gg \tau_{sf} \)

- \( \Delta R / R^p \) drops to zero as \( 1 / r_b^* \)

**AF and Jaffrèe**

*PR B 2001*

+cond-mat

0612495, +

IEEE Tr.EI.Dev*,

54,5,921,2007

*calculation. for Co and GaAs at RT

**Min, Motihashi, Lodder and Jansen**

_Nature Mat. 5_, 817, 2006

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\[ \text{window} \propto \left( \frac{l_{sf}}{L} \right)^2 - 1 \]

Condition

dwell time \( \tau_n < \text{spin lifetime} \tau_{sf} \)

dwell time

\[ \tau_n = \frac{2 L}{r^*_b} \propto L \frac{r^*_b}{r^*_N} \]

\[ \frac{\Delta R}{R^P} = \frac{\gamma^2}{(1 - \gamma^2)} \left( 1 + \frac{\tau_n}{\tau_{sf}} \right) \]

drops to zero as \( 1/r_b^* \)

(Mattana, AF et al)

Window only for \( l_{sf}(N) > L \)

AF and Jaffrès
PR B 2001*
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F1

F2

Semiconductor channel

GaMnAs/AlAs/GaAs/AlAs/GaMnAs
vertical structure

Window only for \( l_{sf}(N) > L \)
Carbon nanotubes between spin-polarized sources and drains

La$_{2/3}$Sr$_{1/3}$MnO$_3$ (LSMO)

La$_{2/3}$Sr$_{1/3}$MnO$_3$ (LSMO)

MR = 72%

MR = 60%

L ≈ 1-2 μm

MR = 54%

MR = 45%

Artist: Takis Kontos
Usual conditions: experiments at small bias voltage

Usual conditions:

- Experiments at small bias voltage
- Oscillatory variation of the conductance, different signs of the MR depending on the bias voltage and from sample to sample
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\[ U_c = \frac{e^2}{2C} \]

\[ \delta E + U_c \]

\[ e\Delta V \approx \text{meV} \]

\[ \Delta V = 25-500 \text{ meV} \]

\[ \gg \text{Coulomb energy and level spacing} \]

\[ 4 \text{ K} < T < 120 \text{ K} \]

LSMO/CNT/LSMO:

- Experiments at higher voltage, thanks to relatively large interface resistances and small \( V^2/R \) heating at large \( V \)

\[ e\Delta V = 25-500 \text{ meV} \]

Quasi-continuous DOS, same conditions as for semiconducting or metallic channel (also diffusive transport regime)
Usual conditions:
Experiments at small bias voltage

\[ U_c = \frac{e^2}{2C} \]

\[ \delta E + U_c \approx 1 \text{ meV} \]

\[ \epsilon \Delta V \approx \text{meV} \]

LSMO/CNT/LSMO:
Experiments at higher voltage, thanks to relatively large interface resistances and small \( V^2/R \) heating at large \( V \)

\[ e \Delta V = 25-500 \text{ meV} \gg \text{Coulomb energy and level spacing, } 4 \text{ K} < T < 120 \text{ K} \]

Quasi-continuous DOS, same conditions as for semiconducting or metallic channel (also diffusive transport regime)

Sahoo et al., Nat. Phys. 2005
Carbon nanotubes between spin-polarized sources and drains

Bias and temperature dependence of MR

MR=72%
MR=60%
MR=54%
MR=45%

5 K 25 mV
Transport between SP source and drain: $\tau_n =$ dwell time, $\tau_{sf} =$ spin lifetime, $\gamma =$ injection SP: 

the contrast between P(on) and AP(off), \( \frac{\Delta R}{R^P} = \frac{\gamma^2}{1 + \tau_n / \tau_{sf}} \), is large if $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules): 

small spin–orbit → spin lifetime $\tau_{sf}$ is long ($\approx 5–50$ ns) 

high velocity $v$ → $\tau_n = \frac{2L}{v \tau_r}$ can be relatively short (60 ns)*

Semiconductors:

$\tau_{sf}$ can be as long as in CNT (for $n \approx 10^{16–17}$ el / cm$^3$) 

but $v$ is smaller → long $\tau_n = \frac{2L}{v \tau_r} \gg \tau_{sf}$

* CNT: $\tau_n = 60$ ns from L, $v$ of CNT and $\tau_r$ derived from interface resistance $r_b$

with $\tau_n \approx 60$ ns* 
(from interface resist.) 
fit with $\tau_{sf} \approx 30$ ns 
($l_{sf} = 48 \mu$m) and $\gamma = 0.8$

$\rightarrow \tau_n \approx \tau_{sf}$
(Hueso, AF et al, Nat. 07)

1.5 μm (MWCNT) 

$r_b^* \approx 70$ MΩ 

LSMO

$\tilde{\tau}_r = 0.9 \times 10^{-4}$ 

LSMO
Transport between SP source and drain: \( \tau_n = \) dwell time, \( \tau_{sf} = \) spin lifetime, \( \gamma = \) injection SP

: the contrast between P(on) and AP(off),

\[
\frac{\Delta R}{R_P} = \frac{\gamma^2}{1 + \tau_n / \tau_{sf}}
\]

, is large if \( \tau_n < \tau_{sf} \)

**Nanotubes (also graphene, other molecules):**

*small spin–orbit \( \rightarrow \) spin lifetime \( \tau_{sf} \) is long (\( \approx 5 - 50 \text{ ns} \))

*high velocity \( v \rightarrow \tau_n = \frac{2L}{v t_r} \) can be relatively short (60 ns)*

**Semiconductors:**

\( \tau_{sf} \) can be as long as in CNT (for \( n \approx 10^{16 - 17} \text{ el / cm}^3 \))

but \( v \) is smaller \( \rightarrow \) long \( \tau_n = \frac{2L}{v t_r} \) \( >> \tau_{sf} \)

**Solution for semiconductors:**

shorter L ?, larger transmission \( t_r \) ?

**Improvement for nanotubes:**

- \( \tau_n \approx 60 \text{ ns} \), \( \tau_{sf} > 4 \text{ ns if } \gamma < 0.95 \)
  or \( \tau_{sf} \approx 30 \text{ ns} \)
  (\( l_{sf} = 48 \mu \text{m} \)) for \( \gamma = 0.8 \)

\( \rightarrow \tau_n \approx \tau_{sf} \)

(Hueso, AF et al, Nat.07)
Next challenge for nanotubes (or graphene...):

spin control by a gate potential

Promising potential of molecular spintronics
New materials for spintronics (carbon nanotubes, graphene, molecules, ...)
MR of LSMO/Alq3/Co structures (preliminary results)

Collaboration CNRS/Thales [C. Barraud, P. Seneor et al) and CNR Bologna (Dediu et al)]

Alq3 = \pi - conjugated 8-hydroxy-quinoline aluminium
The Japan Applied Physics Society Academic Roadmap on Spintronics

Quantum Information

Spin Photonics

Storage

Spin Memory & Logic

Material & New Physics

Physics
Physics of spin 1 qubit system
Achieving long coherence time

Progress in qubit media
Superconducting qubits, photon qubits

Integration of
High speed electronics
Spintronics
Photonics

Density (bits/in²)

TMR → TMR/CPP-GMR → CPP-GMR (new materials, half-metals) → new sensors (new principles (molecular/atomic))
perpendicular, granular → patterned media (litho) → patterned media (litho+self-assembly) → multibit patterned media

MRAM technology F
180 nm 45 nm 25 F²
MRAM write energy

SRAM for Mobiles/Car electronics → Replace SRAMs in PC → Nonvolatile Logic → Soft brain-like info. processing
→ Replace part of DRAM → Nonvolatile reconfigurable logic

Materials Research
Multiferroic, transparent, half-metal
RT ferromagnetic semiconductors,
Environment friendly,
Computational design of new materials

New Physics
Current-driven physics
Spin-current, nanomagnetism
Crystalline growth with atomic manipulation
Application of strongly correlated materials

2005 2010 2015 2020 2025 2030 2035

Quantum communication network
All the backbone networks are protected by quantum cryptography

Quantum computation
Simulations from molecules through proteins to earth-scale ones that could not be done by classical computers are now being done by quantum computers

High frequency spintronics
Spin photonics

"Fujitsu" Jan. 2007

By H. Akinaga, J. Okabayashi, G. Yusa, and H. Oshima

http://www.jsap.or.jp/jsap75/academic_roadmap.html (in Japanese)
Summary

- Already important applications of GMR/TMR (HDD, MRAM..) and now promising new fields
  - Spin transfer for magnetic switching and microwave generation
  - Spintronics with semiconductors, molecules or nanoparticles
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