Spintronics:
a review and outlook

2016. 5. 11

민 병 철

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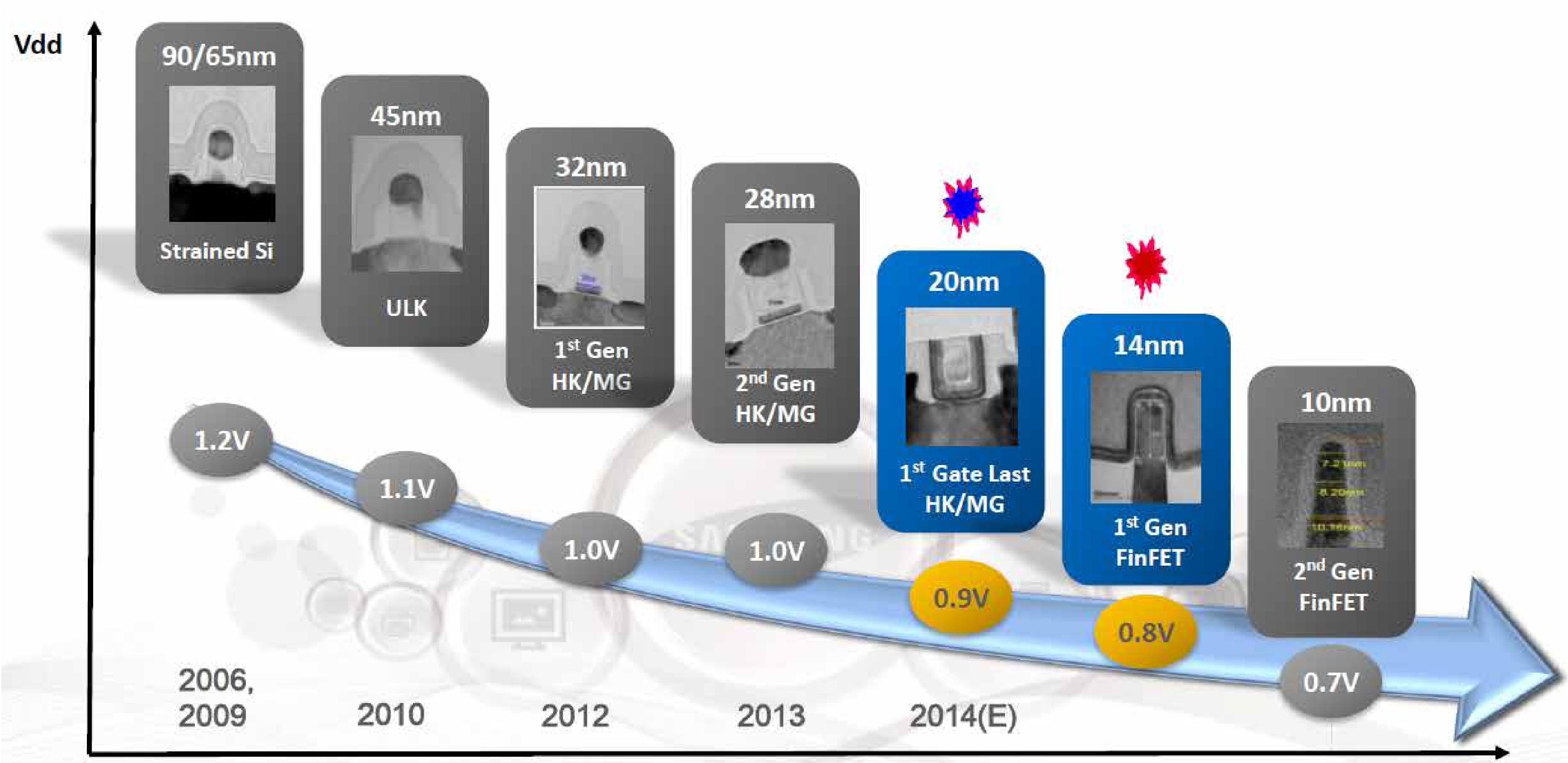
KIST
Korea Institute of Science and Technology

Outline

- ***Spin –Transfer-Torque Magnetoresistive Random Access Memory (STT –MRAM)***
- ***E-field Control of Magnetism***
- ***Spin-Orbit-Torque MRAM***
- ***Thermal Spin-Transfer Torque***
- ***Spin Torque Nano-Oscillator***

반도체 트랜지스터의 개발 동향



* Source : Samsung Electronics Co., Ltd.

*Vdd : Supplying voltage of drain

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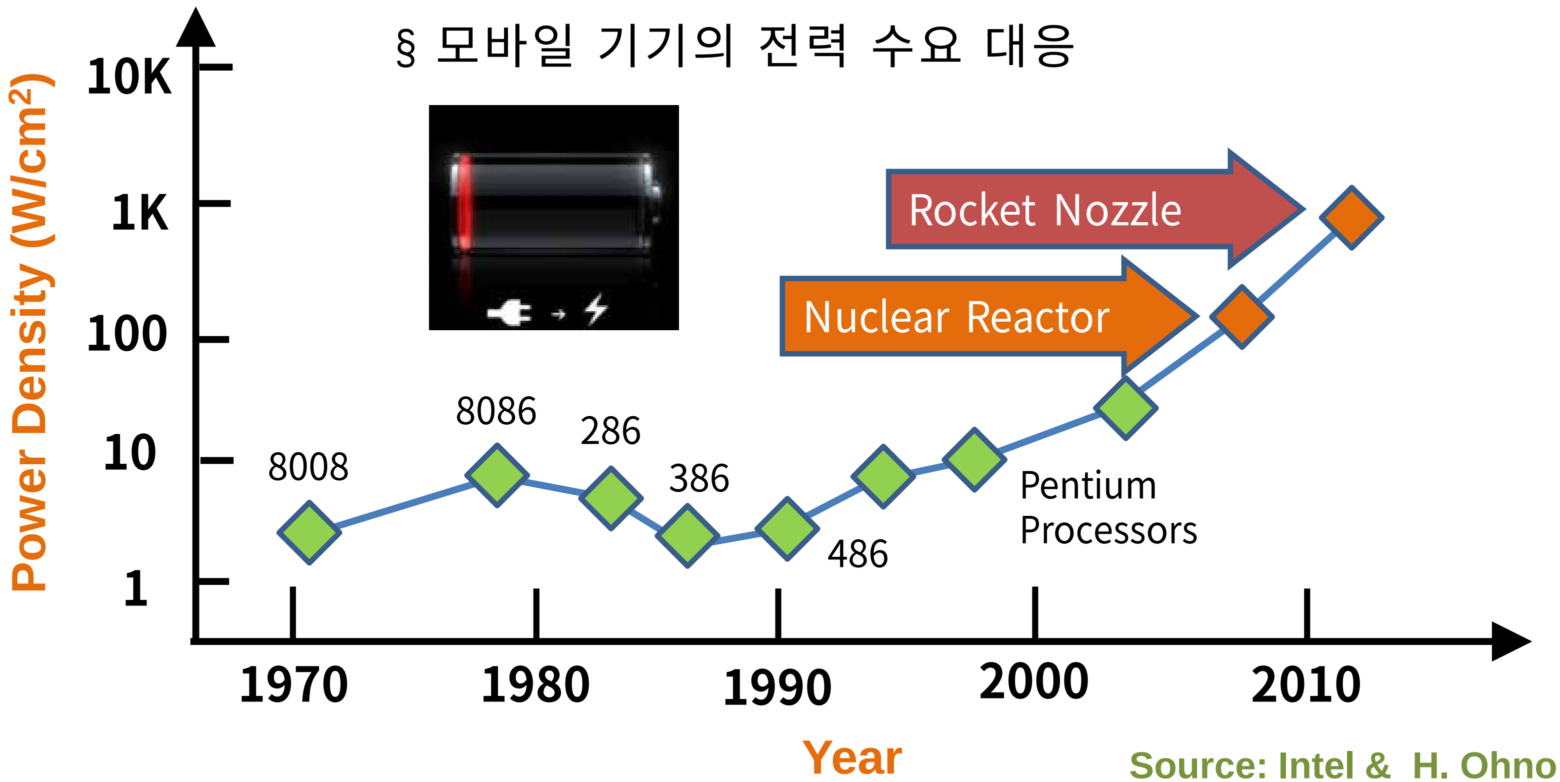
Explosive increase of power consumption

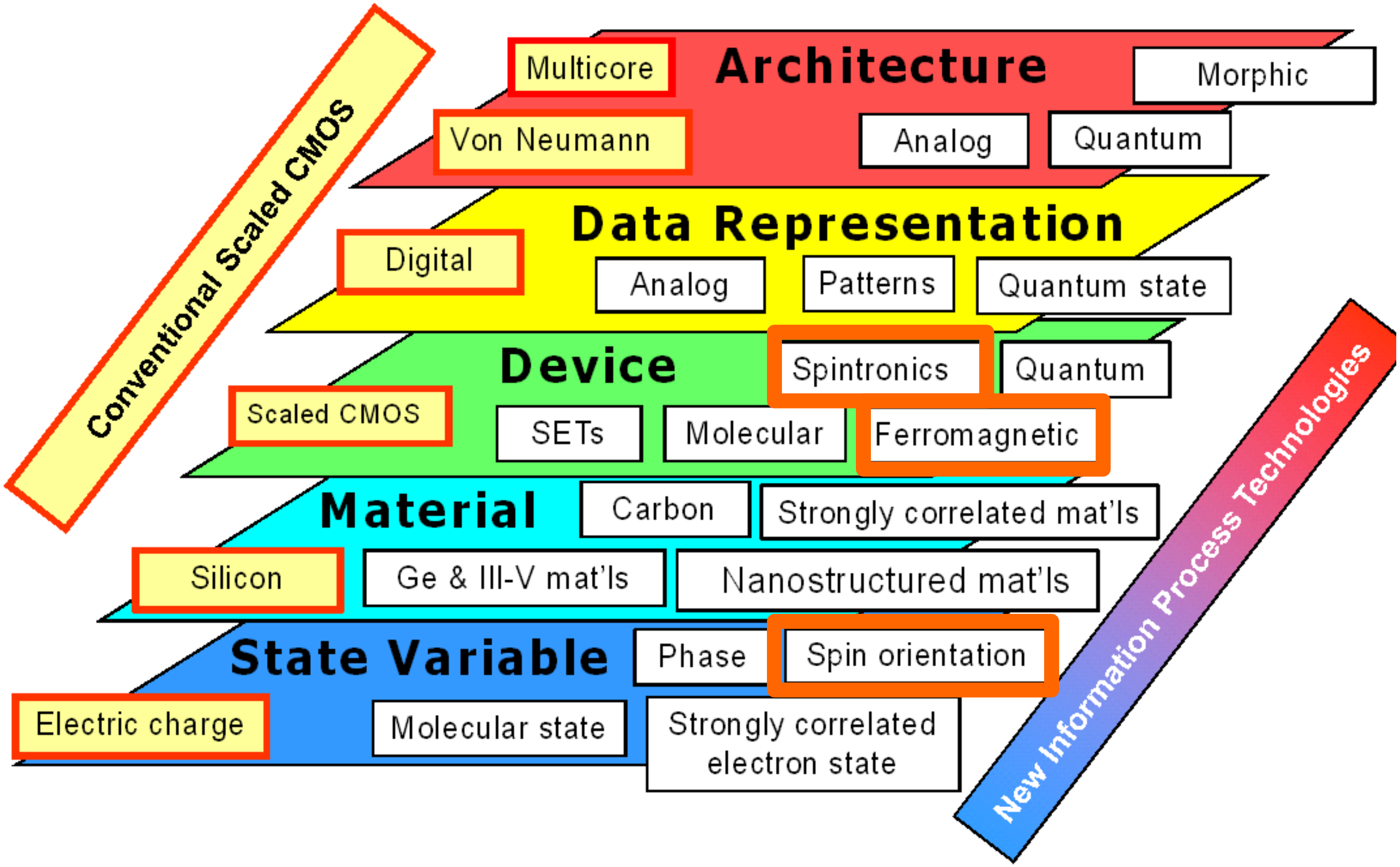


Subsea data centers

“Natick” project
Microsoft

나노 정보 처리 소자의 발전 방향

A Taxonomy for Nano Information Processing Technologies



ITRS 2013 roadmap

스핀트로닉스

반도체 트랜지스터

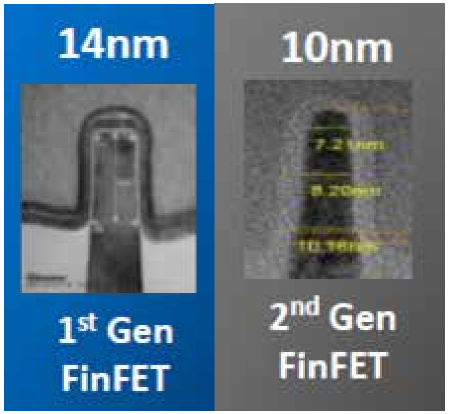
Transport, manipulation,
storage of Charge

First
transistor

micrometer

nanometer

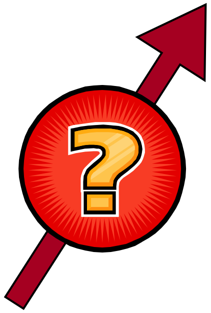
2015

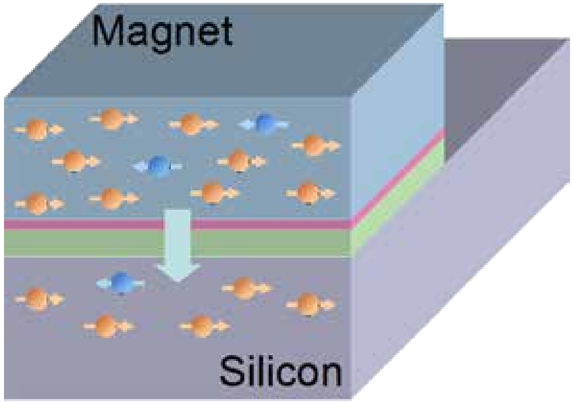


삼성전자

스핀트로닉스

Transport, manipulation,
storage of Spin





Spin-polarized electron transport: History

- ***The discovery of electrons***
  J.J. Thomson (1897)
- ***The discovery of electron spin***
  George E. Uhlenbeck (1925)
- ***Spin-dependent electron scattering***
  Nevill Mott (1936)
- ***Transistor***
  Bell Laboratory (1948)
- ***Giant magnetoresistance (GMR)***
  Baibich et al (1988)

Thomson showed that cathode rays were particles with a negative electric charge and much smaller than an atom. He also thought all atoms contained them. These particles were later named electrons.

Lorentz (or ordinary) MR

Ø **Ordinary MR obeys the Kohler rule.**

$$\frac{\Delta\rho}{\rho} = F\left(B/\rho_0\right)$$

$$\rho_0 = \rho(B=0)$$

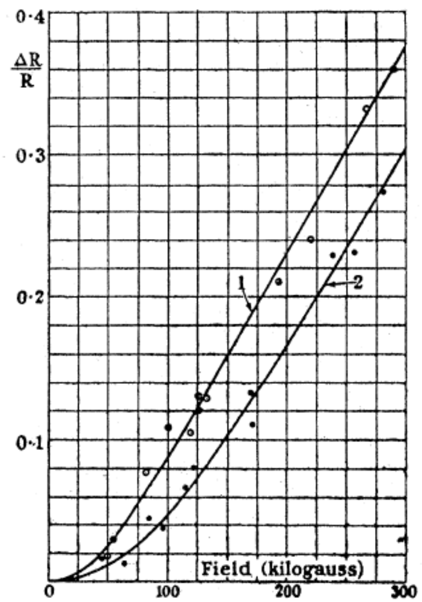


Fig. 6.—Silver H ⊥ I.
Curve I—Ag annealed. Temperature of Liquid Nitrogen.
Curve 2—Ag hard. Temperature of Liquid Air.

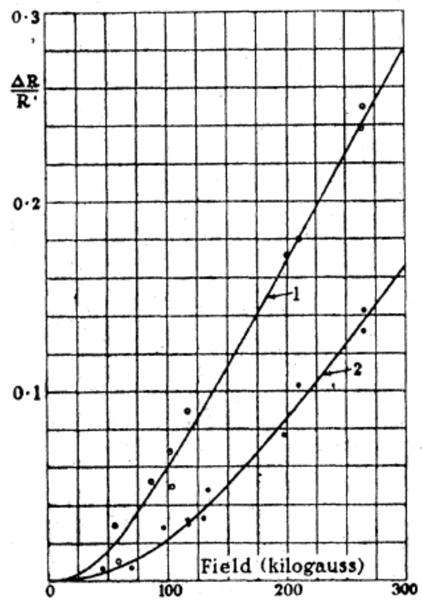
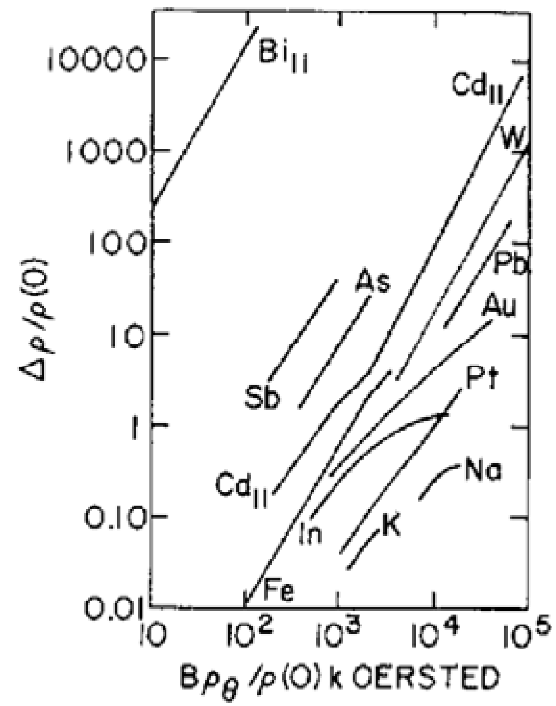


Fig. 7.—Gold H ⊥ I.
Curve 1—Au_I soft. Temperature of Liquid Nitrogen.
Curve 2—Au_{II} hard. Temperature of Liquid Air.

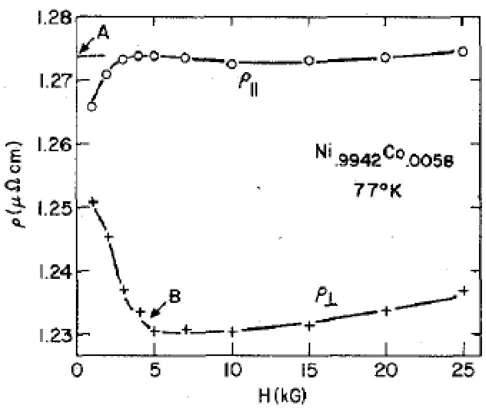


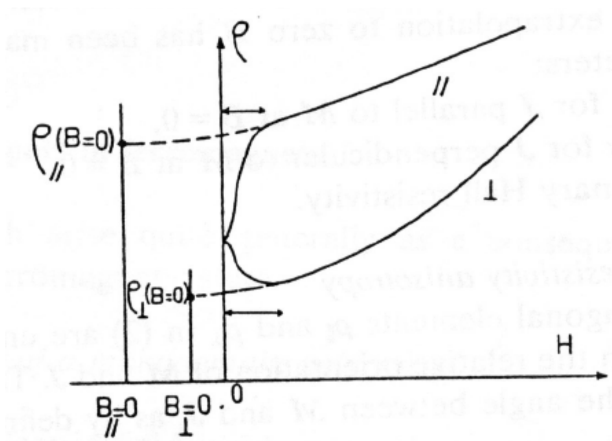
Kapitza, *Proc. Roy. Soc. A123*, 292 (1929).

Anisotropic MR (AMR)

- The electrical resistivity of ferromagnetic metals changes depending on the direction of the sensing current and the magnetisation (William Thomson, Lord Kelvin, In 1857)

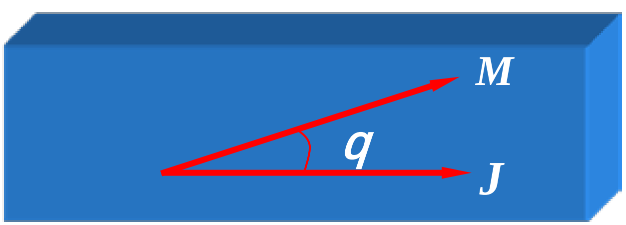
$$\vec{E} = [\rho_{\parallel}(B) - \rho_{\perp}(B)][\vec{m} \cdot \vec{J}]\,\vec{m}$$





$$\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho_0}$$

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{(1/3)\rho_{\parallel} + (2/3)\rho_{\perp}}$$



$$\rho = \rho_{\perp} + \Delta\rho \cos^2\theta$$

ρ : the wire resistivity

$\Delta\rho = \rho_{//} - \rho_{\perp}\ (> 0)$

Spin-polarized electron transport: History

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  Samuel A. Goudsmit (1925)

- **Spin-dependent electron scattering**
  Nevill Mott (1936)

- **Transistor**
  Bell Laboratory (1948)

- **Giant magnetoresistance (GMR)**
  A. Fert Group & P. Grünberg (1988)

... it occurred to me that , since (I had learned) each quantum number corresponds to a degree of freedom of the electron, Pauli's fourth quantum number must mean that the electron had an additional degree of freedom -- in other words the electron must be rotating.

Spin-polarized electron transport: History

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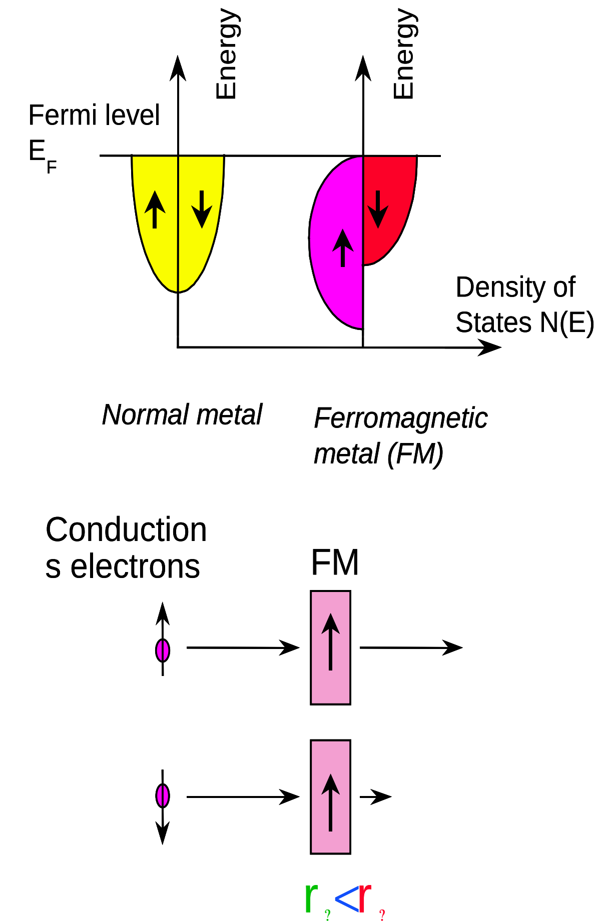

Different d-band N(E) for spin up and spin down electrons at E_F in ferromagnetic metals
The s-d scattering rate is different for spin up and spin down electrons in ferromagnetic metals.

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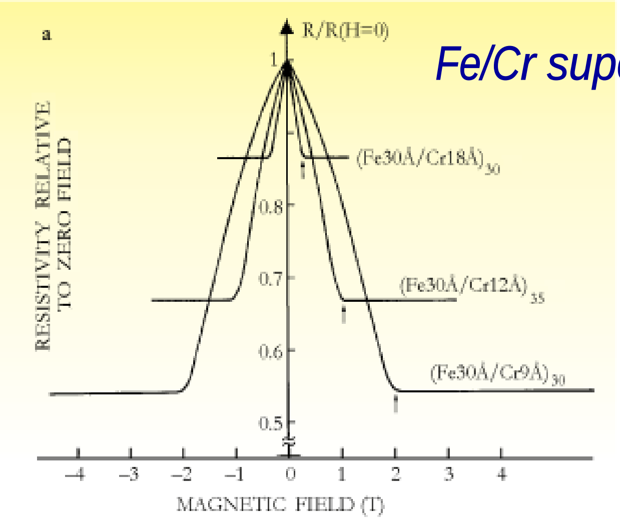
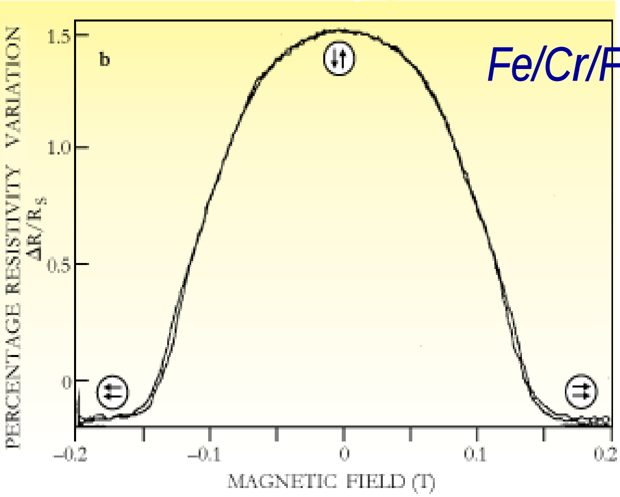


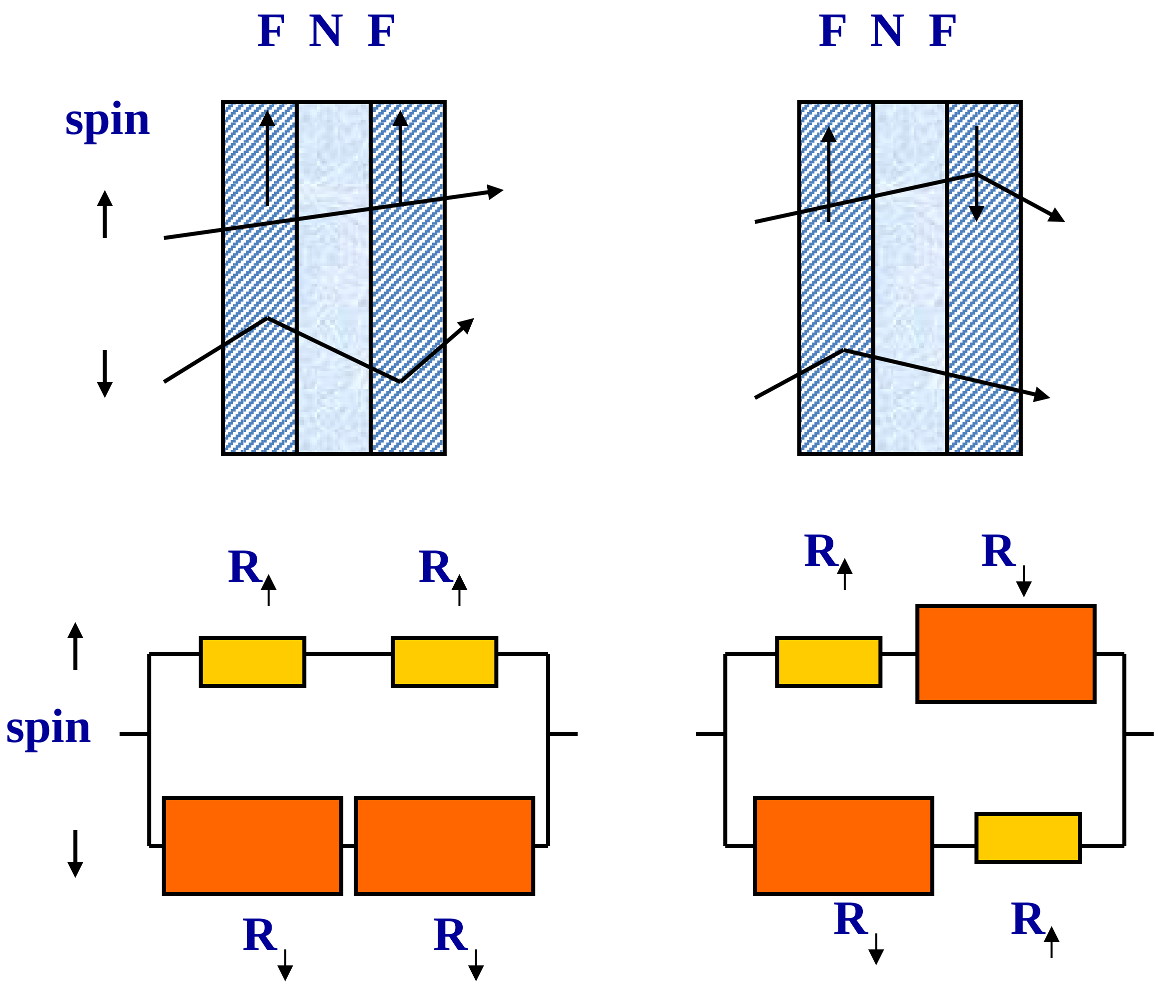
Fe/Cr superlattices



Fe/Cr/Fe trilayers

Phys. Rev. Lett. 61, 2472 (1988)
Phys. Rev. B 39, 4828 (1989)

GMR in tri-layer



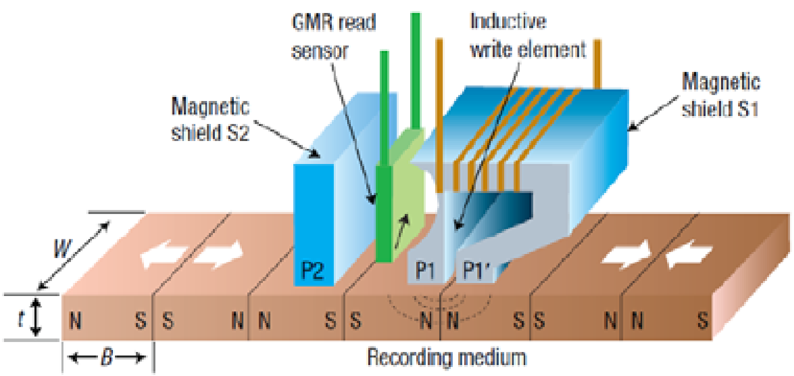
$$R^{P} = 2R_{\uparrow}R_{\downarrow}/(R_{\uparrow} + R_{\downarrow})$$

$$R^{AP} = (R_{\uparrow} + R_{\downarrow})/2$$

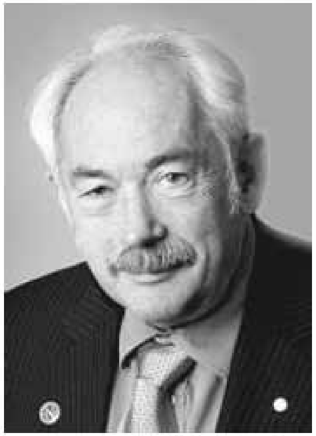
The Nobel Prize in Physics 2007

The Nobel Prize in Physics 2007 was awarded jointly to
Albert Fert and Peter Grünberg
"for the discovery of Giant Magnetoresistance"

1000x capacity of hard drives



A. Fert

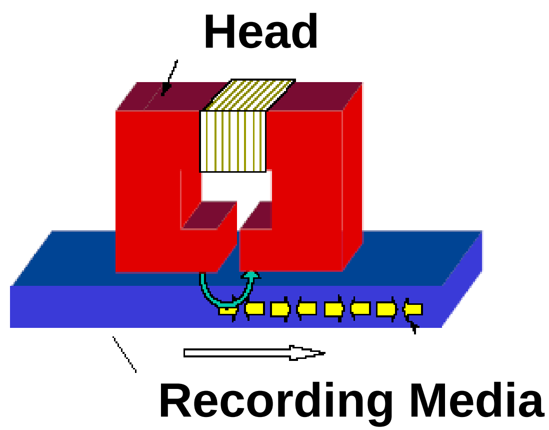


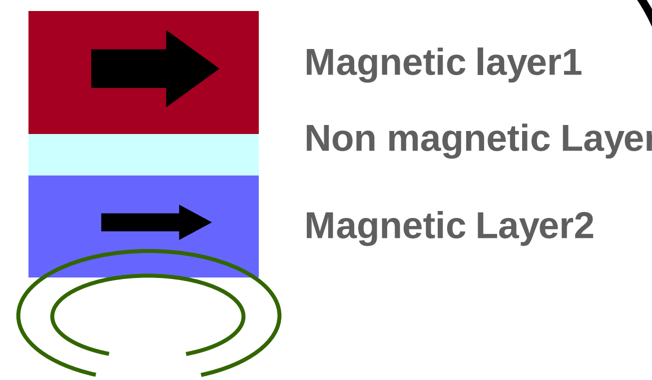
P. Grunberg

Spintronics & Applications of Magnetism

Magnetic Data Storage

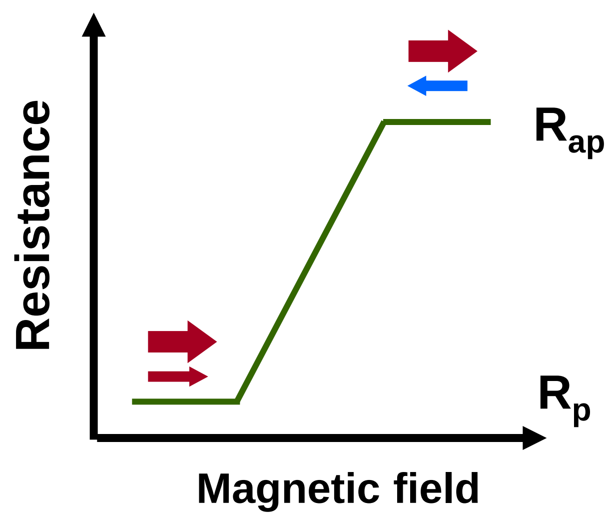
Hard disk drive





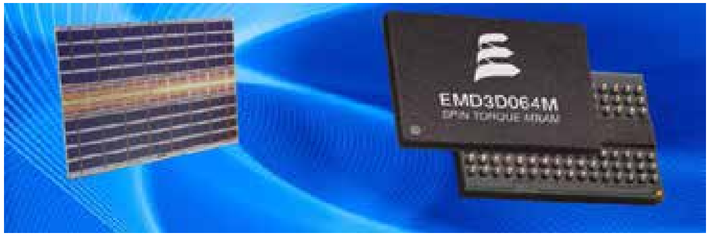
- Giant Magnetoresistance (GMR)
- Tunnel Magnetoresistance (TMR)

$$\frac{DR}{R} = \frac{R_{ap} - R_p}{R_p} = 1 \sim 400\%$$

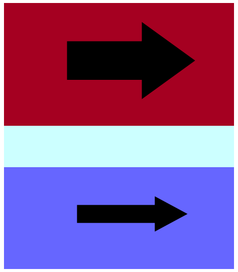


Spintronics & Applications of Magnetism

Memory



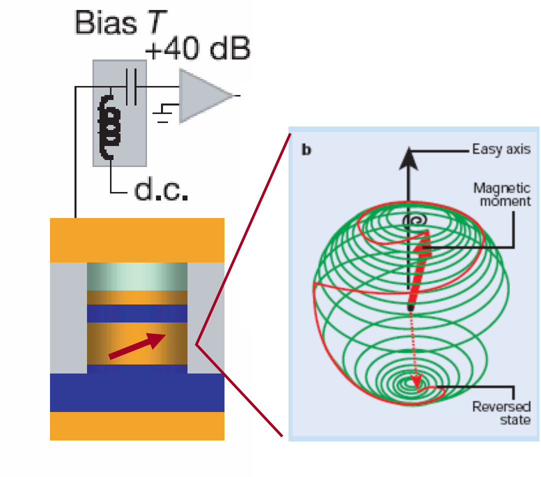
64 Mbits STT-MRAM (MRAM), Everspin



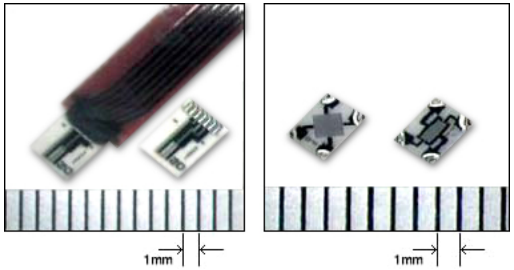
Magnetic layer1
Tunnel barrier
Magnetic layer2

Magnetic tunnel junction

Electrical Components



Microwave oscillators



Magnetic sensors

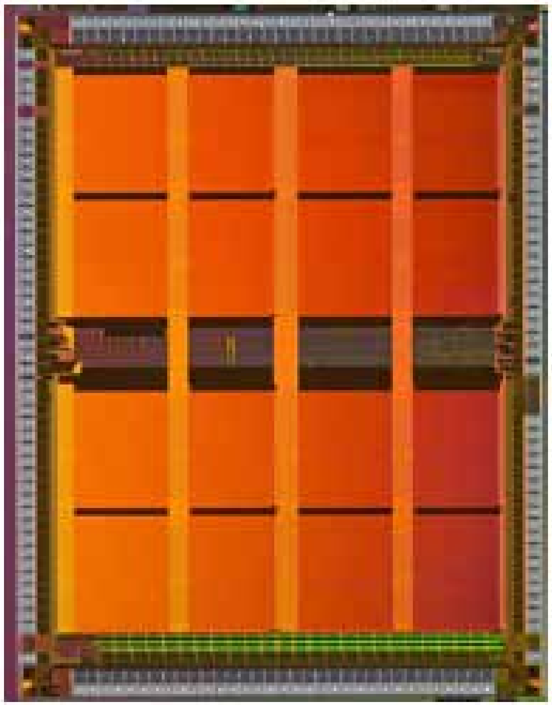
Outline

- ***Spin –Transfer-Torque Magnetoresistive Random Access Memory (STT –MRAM)***
- ***E-field Control of Magnetism***
- ***Spin-Orbit-Torque MRAM***
- ***Thermal Spin-Transfer Torque***
- ***Spin Torque Nano-Oscillator***

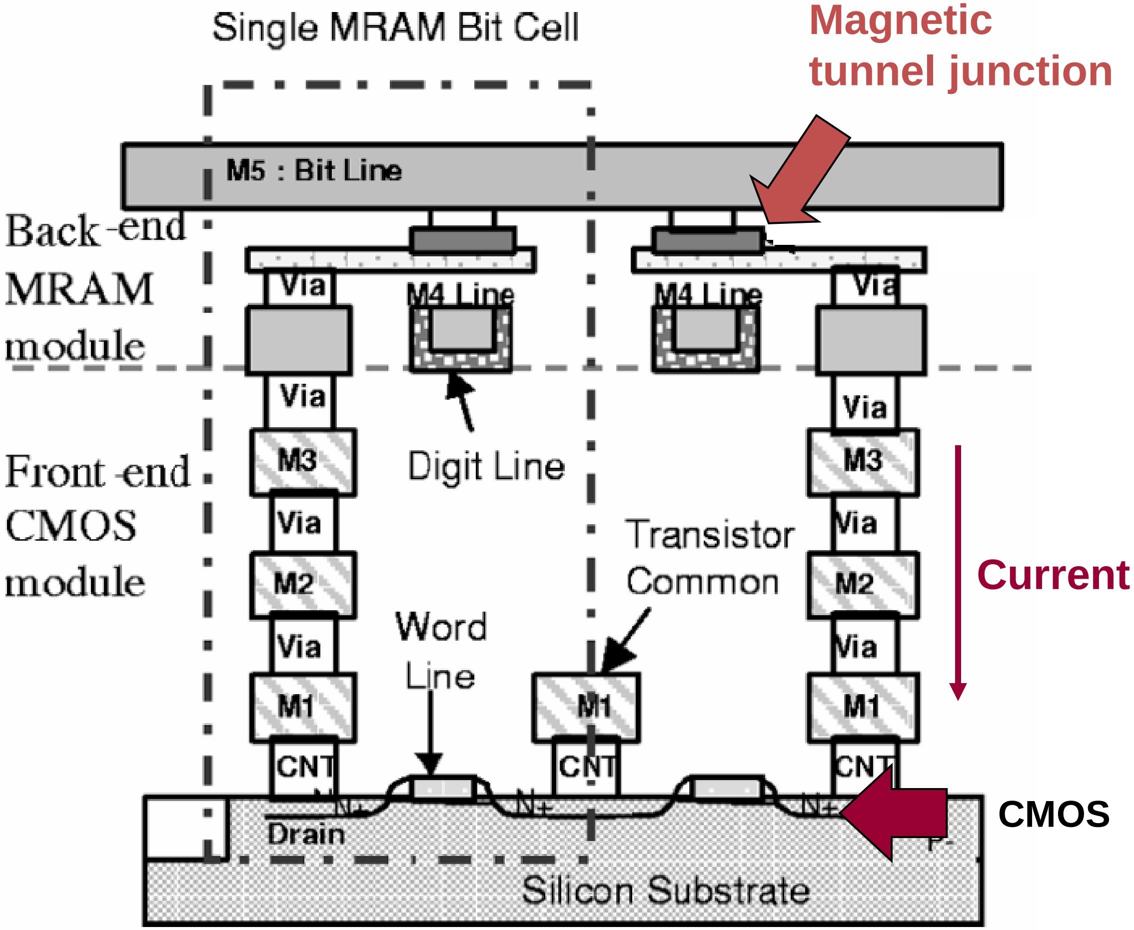
MRAM

Magnetoresistive Random Access Memory

Conventional Magnetoresistive RAM (MRAM)



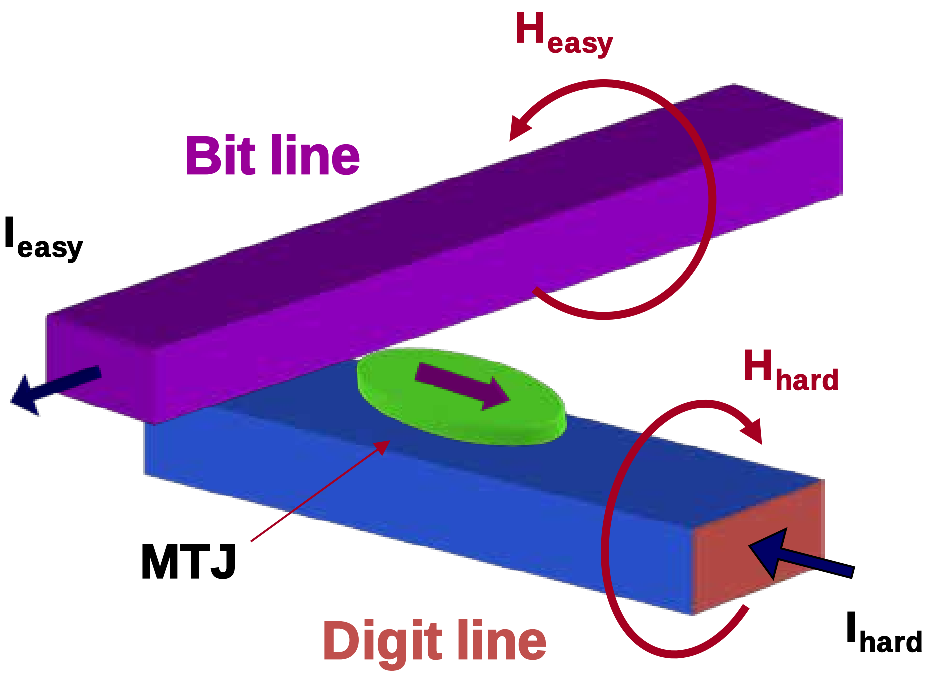
4 Mbits Magnetoresistive RAM (MRAM), Everspin Inc.



S. Tehrani (2003) Proc. of IEEE 91 p704

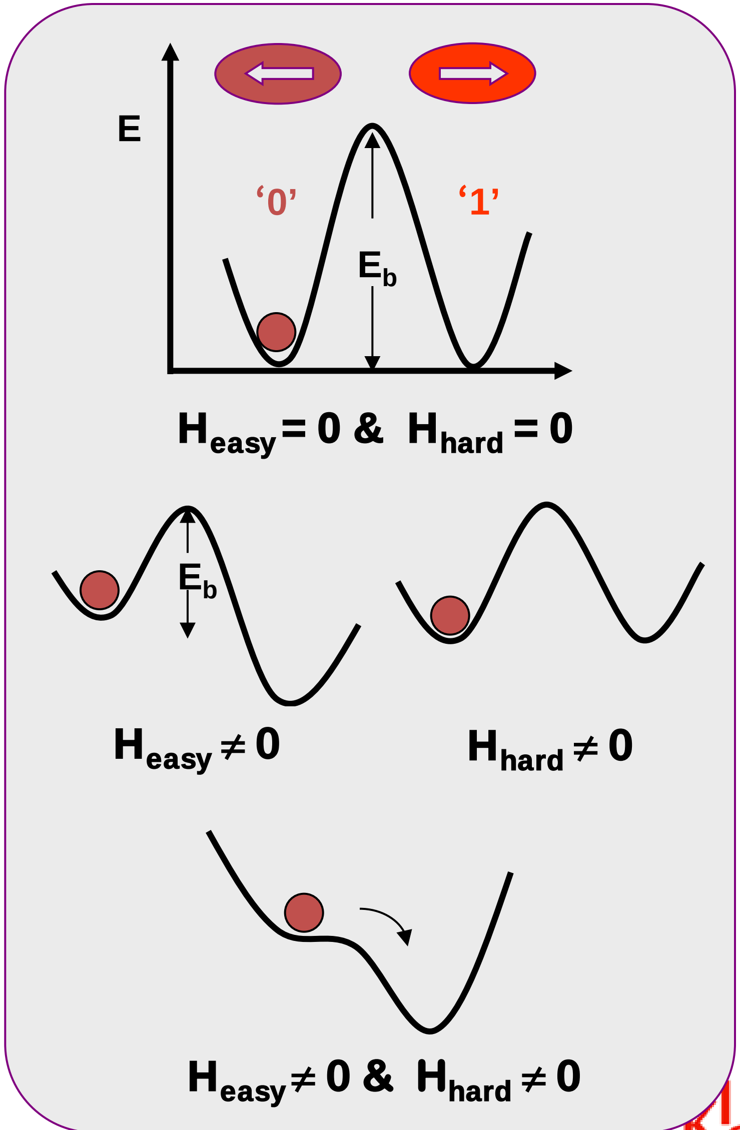
Basic MRAM operation

Writing operation



Cross-point architecture

S. Tehrani (2003) Proc. of IEEE 91 p704



MRAM into market

MRAM used as write journal for RAID Storage
Power fail recovery increasing system reliability & uptime

Recognized Everspin for Perfect MRAM Quality
250k+ systems with no reported failures to-date

Critical Storage for Industrial Computing Boards
Robust & reliable non-volatile memory solution

MRAM products for A350 Flight Control Computer
Critical program and data storage in extreme environment

Non-volatile memory for Superbike Engine Control
Reliable power fail safe memory for automotive temperature

Source: Everspin Inc.

STT-MRAM

(Spin-Transfer-Torque Magnetoresistive Random Access Memory)

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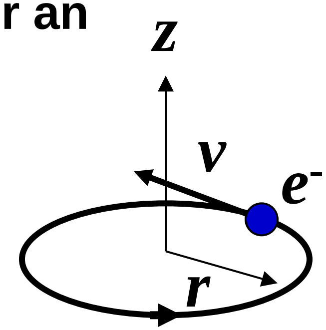
Magnetic moment vs angular momentum

Classical model for an atom:



Magnetic moment for atomic orbit:

$$\vec{\mu}_L = I\vec{A}$$

$$= -\left(\frac{ev}{2\pi r}\right)\left(\pi r^2\right)\hat{z}$$

$$= -\frac{evr}{2}\hat{z}$$

Angular momentum for atomic orbit:

$$\vec{L} = \vec{r} \times \vec{p}$$

$$= rmv\hat{z}$$

$$\vec{\mu}_L = \gamma\vec{L} \qquad \gamma = -\frac{evr/2}{rm_e v}$$

“The gyromagnetic ratio”

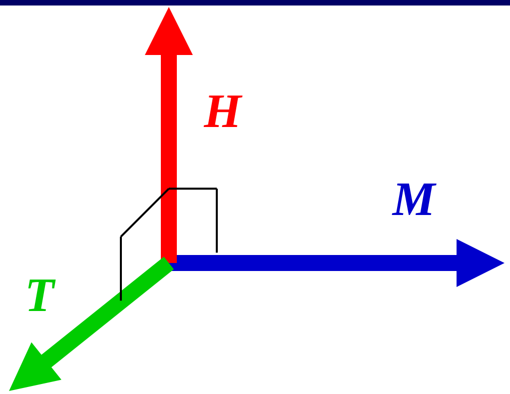
$$\boxed{g_L = -\frac{e}{2m_e} = -\frac{\mu_B}{\hbar}} \longrightarrow g_s = -\frac{2\mu_B}{\hbar}$$

For spin angular momentum, extra factor of 2 required.

Pufall *et al.* (NIST)

KIST Korea Institute of Science and Technology

Larmor Equation



$$\vec{T} = \mu_0 \vec{M} \times \vec{H}$$

Magnetic field exerts torque on magnetization.

(definition of torque) $\dfrac{d\vec{L}}{dt} = \vec{T}$ $\gamma \equiv \dfrac{\mu}{L}$ **(gyromagnetic ratio)**

$$\frac{d\vec{M}}{dt} = \gamma \vec{T}$$
$$= \gamma \mu_0 \left(\vec{M} \times \vec{H} \right)$$

Pufall *et al.* (NIST)

Spin transfer torque

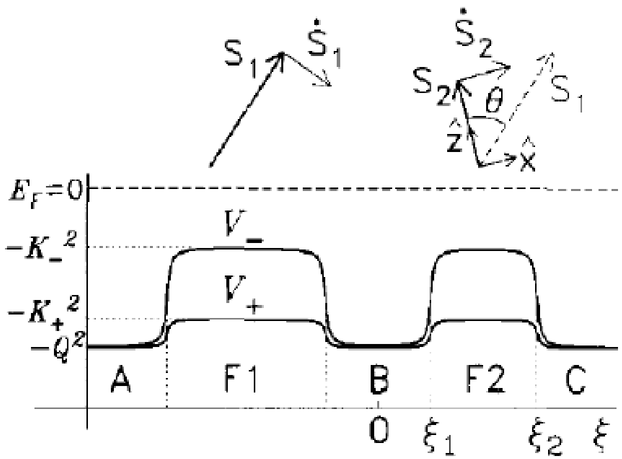
In 1996, Slonczewski and Berger independently calculated the spin torque in metallic multilayers.

Current-driven excitation of magnetic multilayers

J.C. Slonczewski *

IBM Research Division, Thomas J. Watson Research Center, Box 216, Yorktown Heights, NY 10596, USA

Received 27 October 1995; revised 19 December 1995



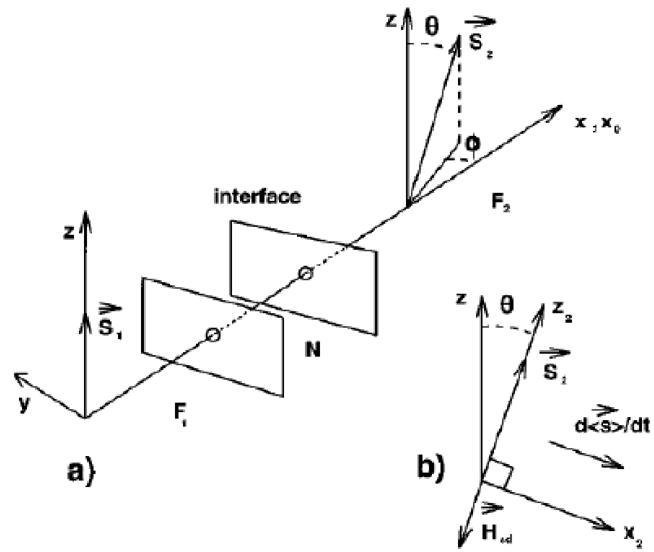
$$\dot{\mathbf{S}}_{1,2} = (I_e g/e)\hat{\mathbf{s}}_{1,2} \times (\hat{\mathbf{s}}_1 \times \hat{\mathbf{s}}_2)$$

Emission of spin waves by a magnetic multilayer traversed by a current

L. Berger

Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213-3890

(Received 31 January 1996)



Stiles *et al.* (NIST)

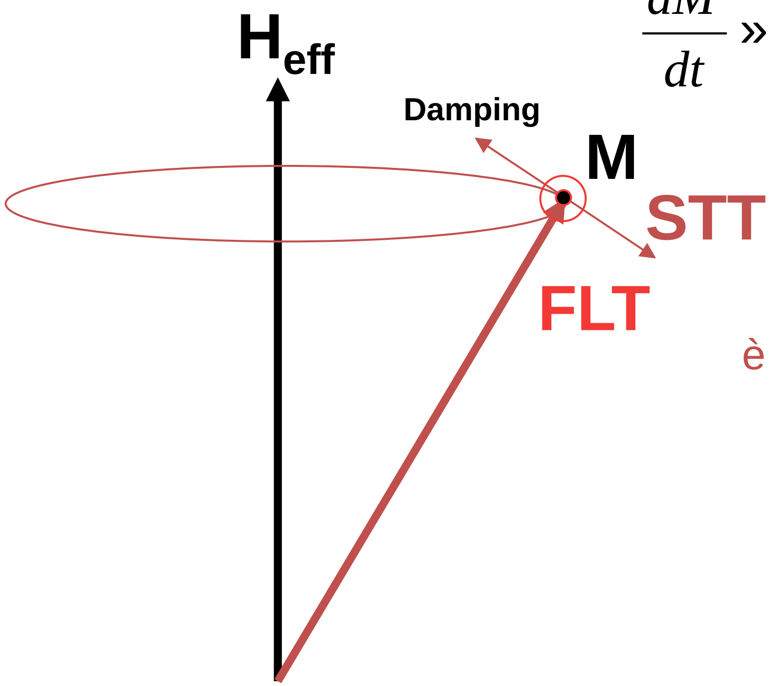
Equation of motion

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M}\times\vec{H} + \frac{\alpha}{Ms}\vec{M}\times\frac{d\vec{M}}{dt} + \frac{\gamma a_J}{M_S^2}\vec{M}\times(\vec{M}\times\vec{M}_2) + \frac{\gamma b_J}{M_S}(\vec{M}\times\vec{M}_2)$$

In-plane STT

Perpendicular STT

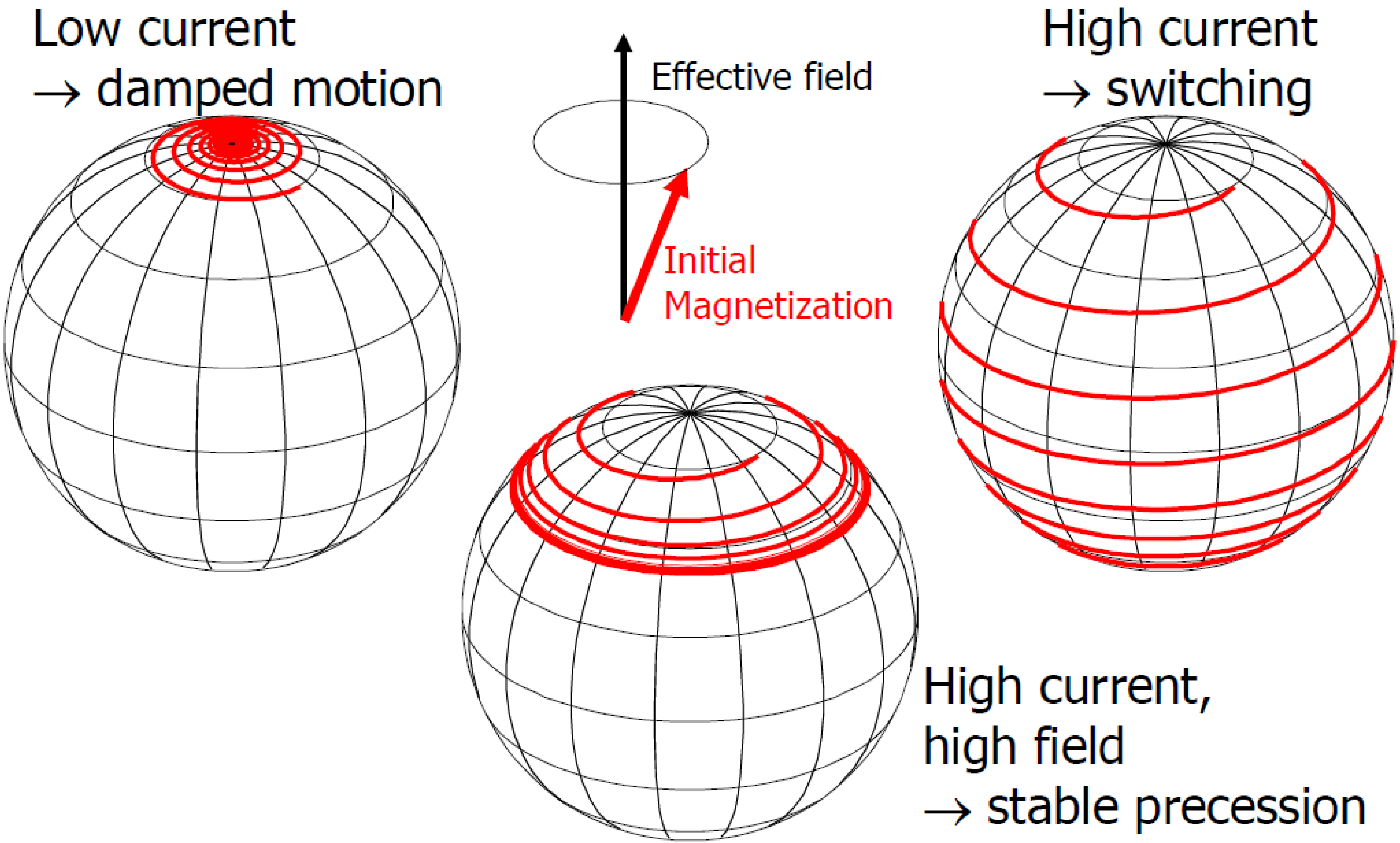
$$\frac{d\vec{M}}{dt} \approx -\gamma \vec{M}\times(\vec{H} + b_J\vec{M}_2) - \frac{\gamma}{Ms}\vec{M}\times[\vec{M}\times(\alpha\vec{H} + a_J\vec{M}_2)]$$



⇒ **In-plane torque (a_J) competes with the damping (α) whereas perpendicular torque (b_J) acts like an effective magnetic field.**

By courtesy of prof. K. J. Lee (Korea Univ.)

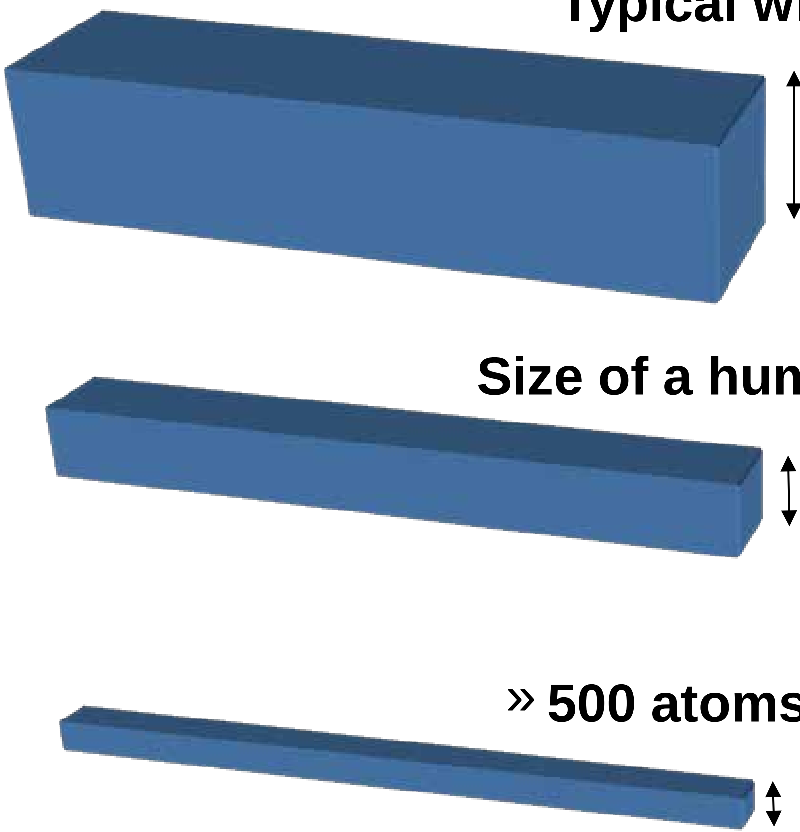
Current-induced Switching dynamics



Stiles *et al.* (NIST)

How much current to induce spin dynamics?

Torque μ to current density: must have high current *densities* to produce large torques



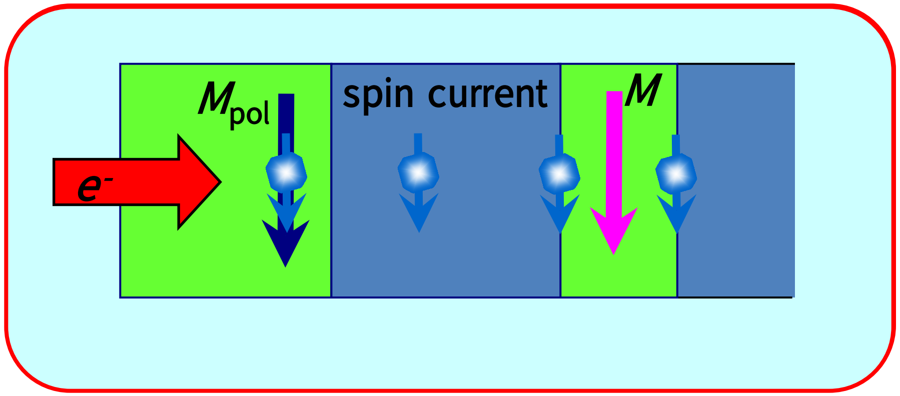
		Required I_{dc}	Possible
Typical wire	1 mm	I » 0.1 MA	X
Size of a human hair	10 mm	I » 10 A	X
» 500 atoms across	100 nm	I » 1 mA	✓

We will use *nanopillar* and *nanocontact* structures

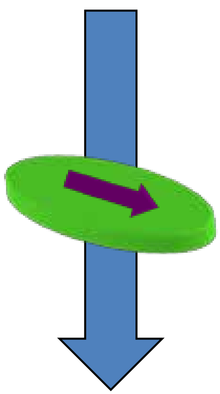
Pufall *et al.* (NIST)

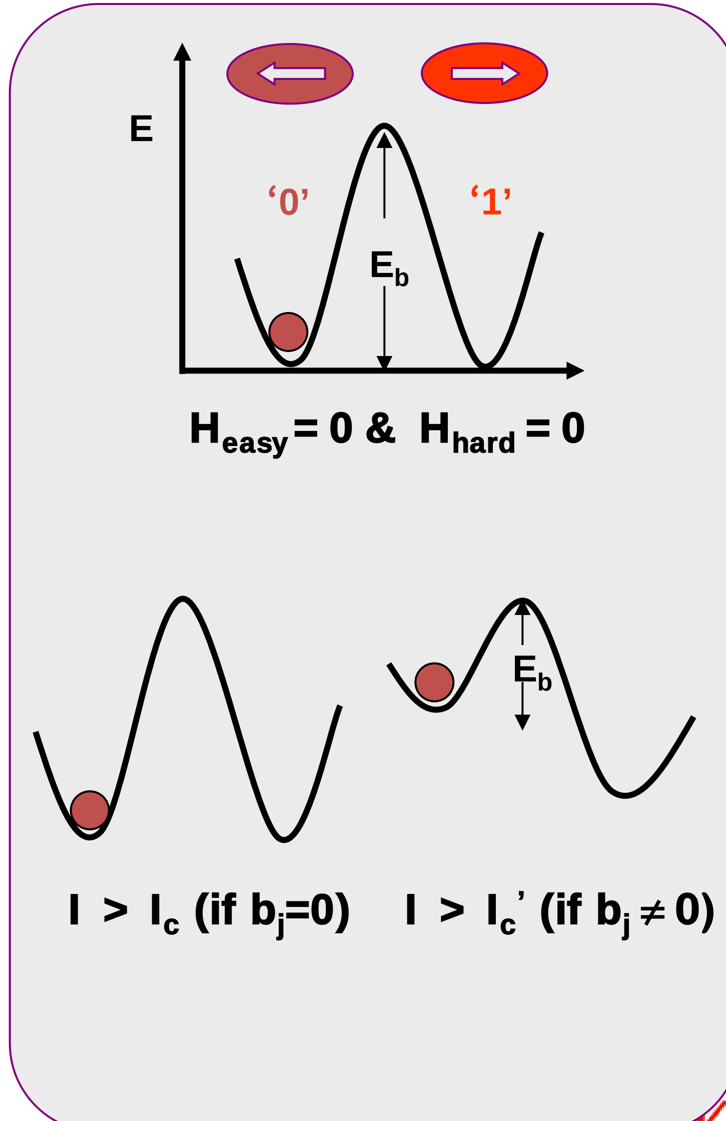
Basic MRAM operation

Writing operation

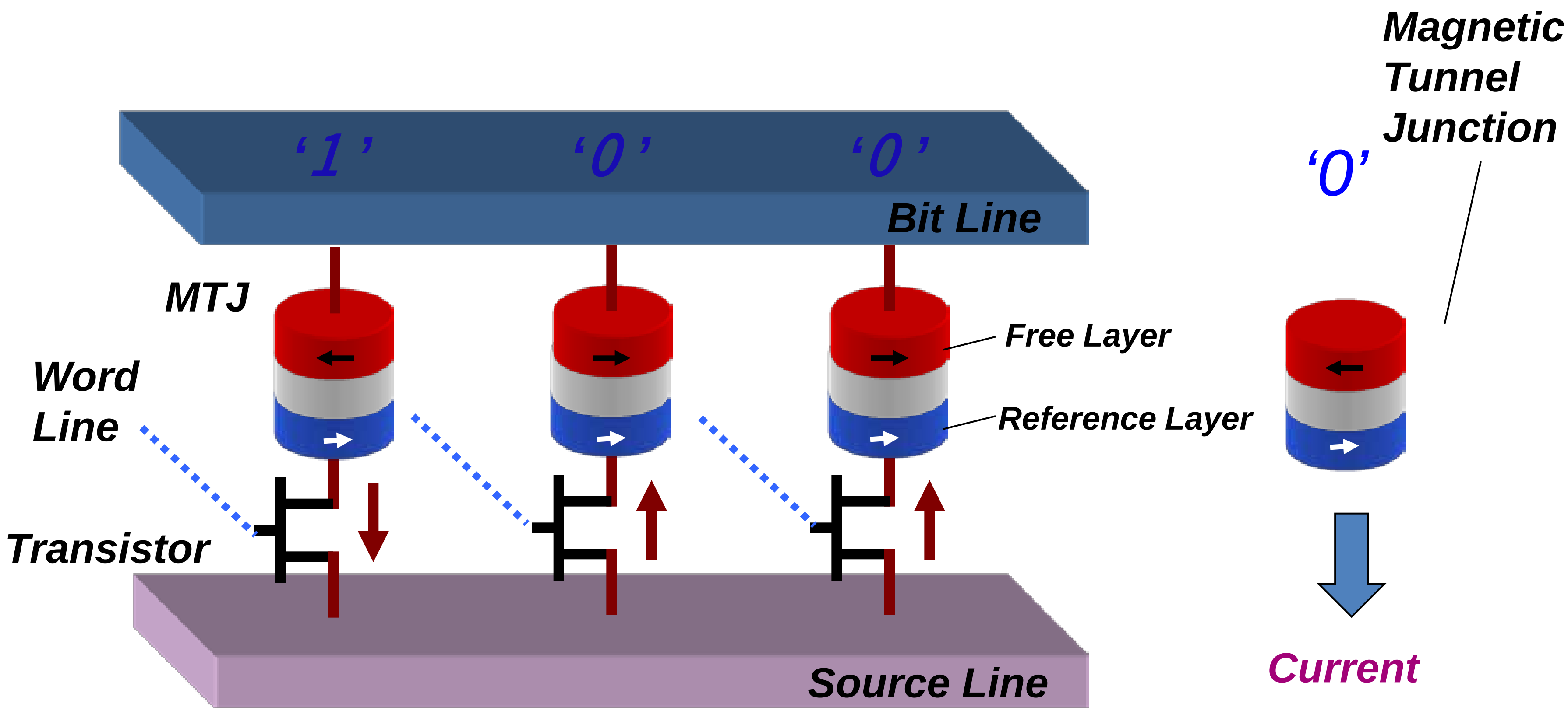


$$\frac{d\vec{M}}{dt} \approx -\gamma \vec{M} \times (\vec{H} + b_J \vec{M}_2) - \frac{\gamma}{Ms} \vec{M} \times [\vec{M} \times (\alpha \vec{H} + a_J \vec{M}_2)]$$





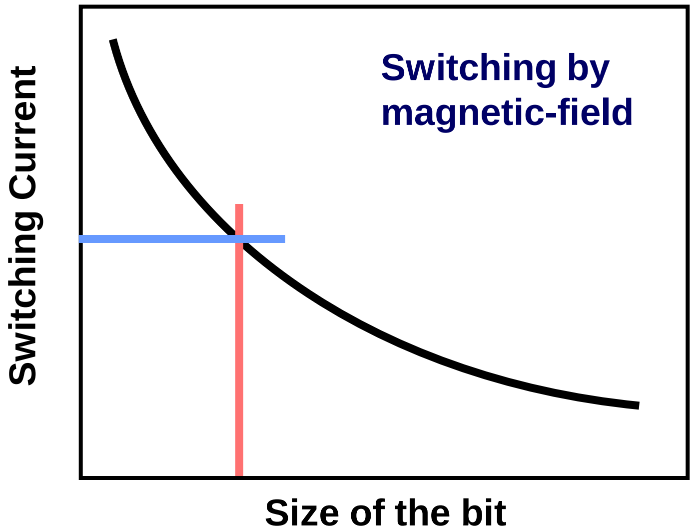
STT-MRAM architecture



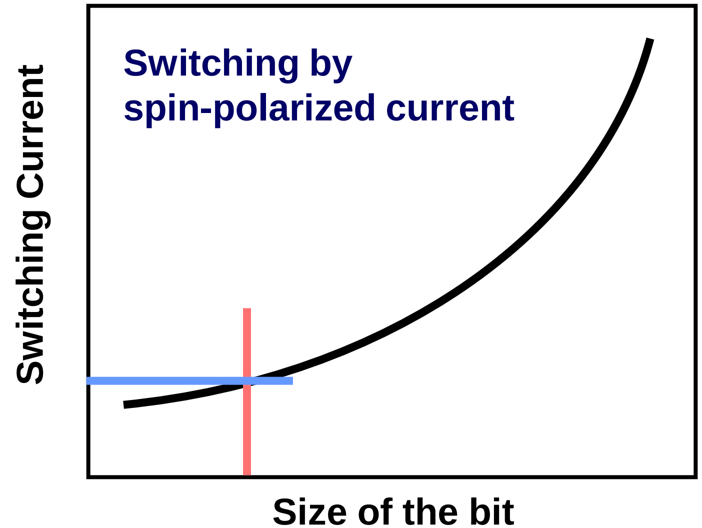
Architecture of
the spin-transfer-torque (STT) memory

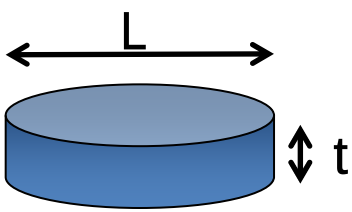
MRAM vs. STT-MRAM

Standard MRAM



STT- MRAM





- Current (MRAM) ~ t / L
  è Shape anisotropy dependence

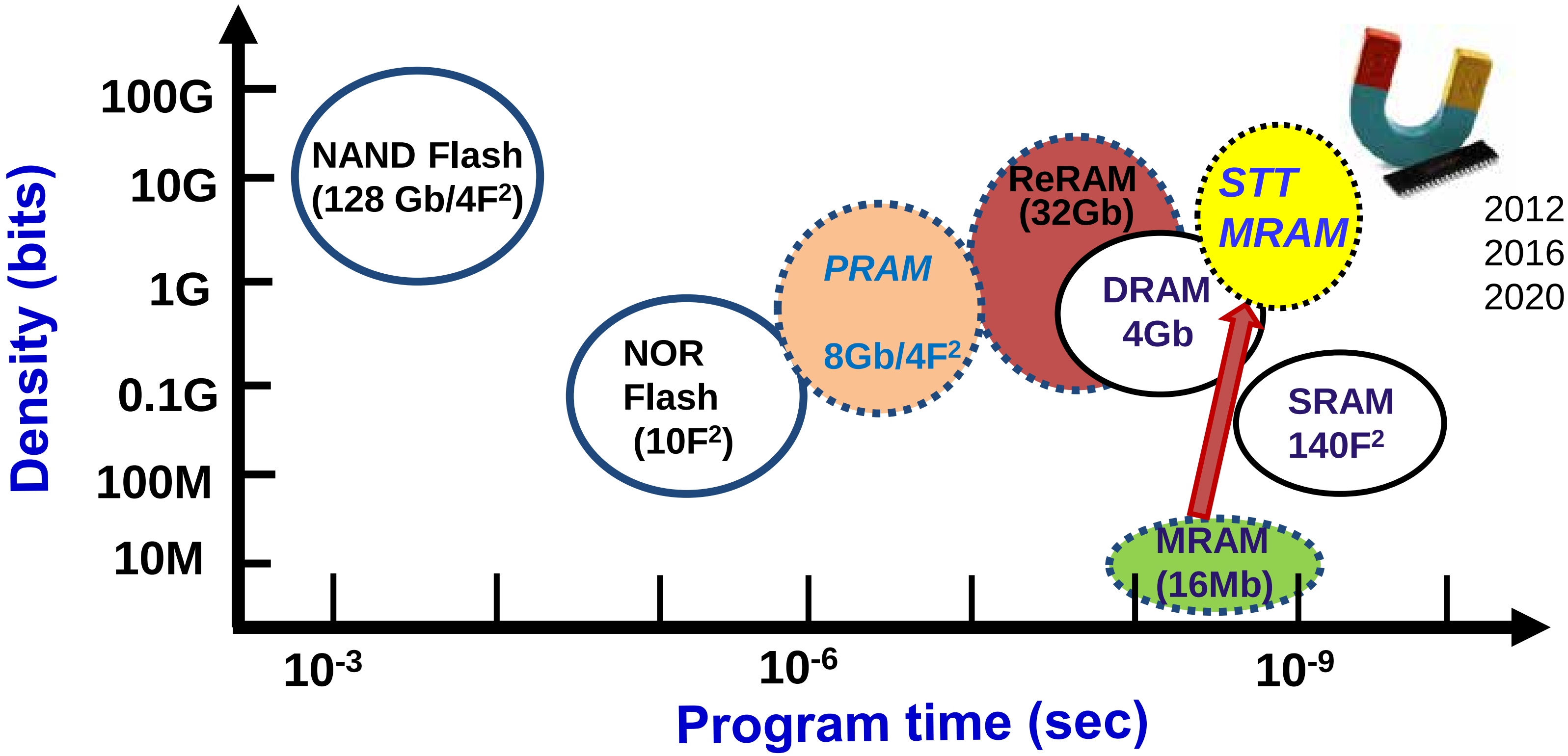
- Current (ST-RAM) ~ t x L^2
  è Constant current density

	Standard MRAM	*DRAM/SRAM*	*FLASH*	*STT-MRAM*
Program Energy (90 nm process)	**120 pJ**	**5 pJ**	**30-120 nJ**	**0.4 pJ**

S. A. Wolf, *IBM J. RES. & DEV.* 50, 101 (2006)

MRAM into market

§ DRAM 및 Flash 메모리 기술의 scaling 한계 극복 필요



2012년 64Mb급
2016년 1Gb급
2020년 16Gb급

STT-MRAM into market

Everspin Introduces
The 64Mb DDR3 ST-MRAM

EVERSPIN®
TECHNOLOGIES
The MRAM Company™

KIST
Korea Institute of Science and Technology

STT-MRAM in Korea

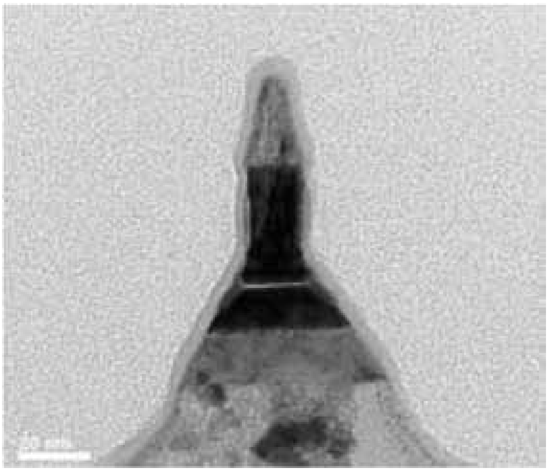
Hynix & Grandis sign
License Agreement
2008. 4. 3

Samsung acquires Grandis
2011. 8. 2

Hynix & Toshiba
co-develop and produce
MRAM products
2011. 7. 13

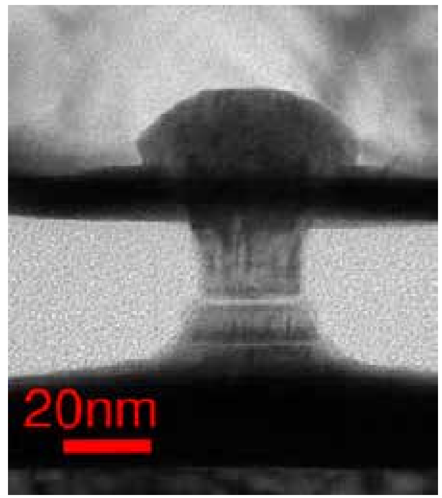
Perpendicular MTJs

17 nm



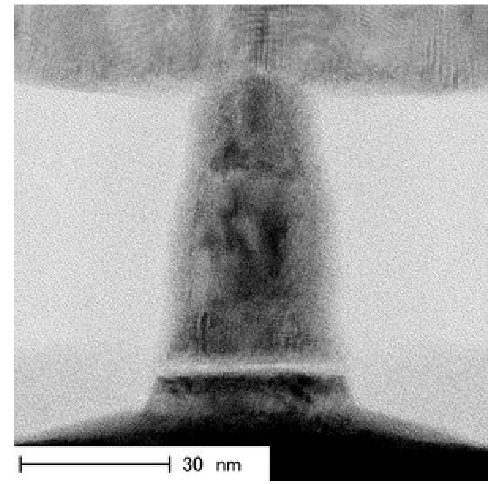
Samsung (2011)

20 nm



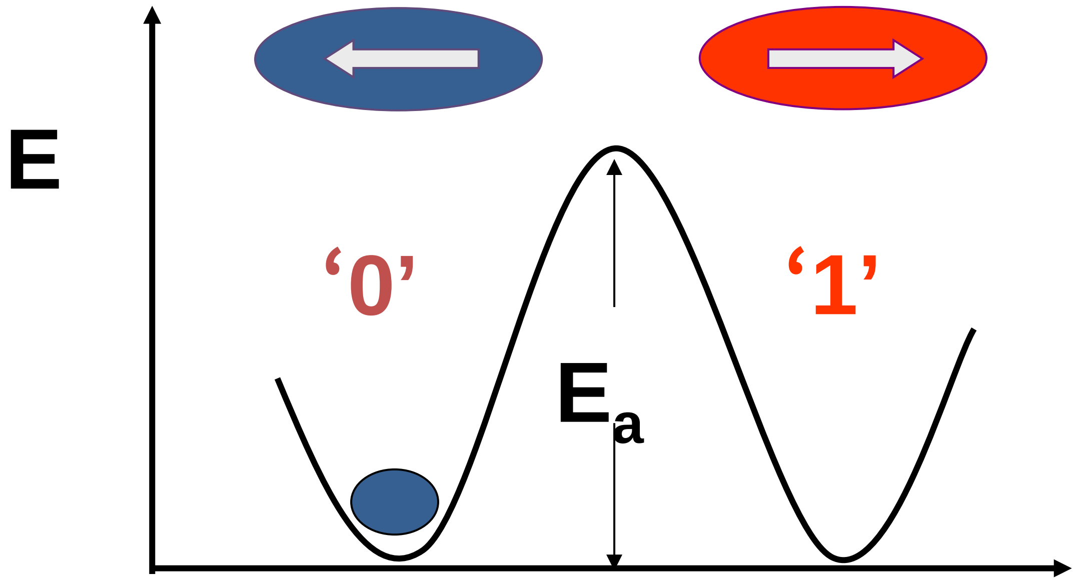
IBM & MagIC (2012)

30 nm



Toshiba & AIST (2012)

Thermally-stable ferromagnets

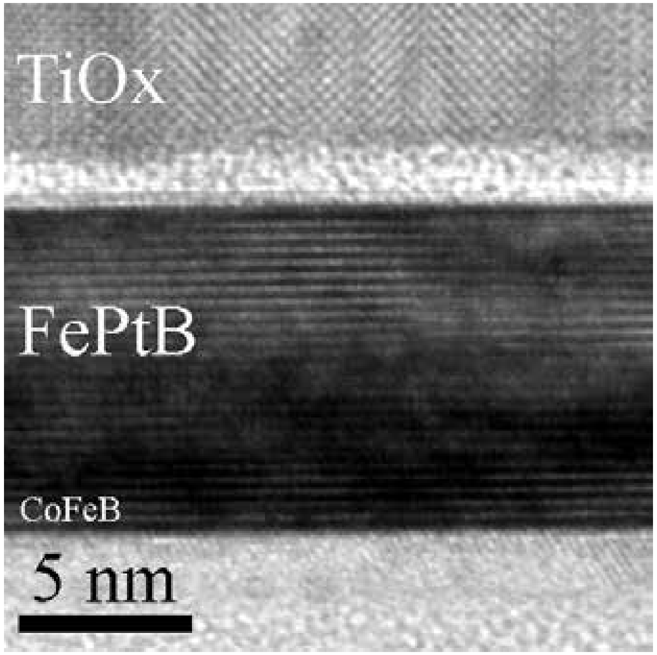


$$E_b = 60 \sim 80 k_B T$$

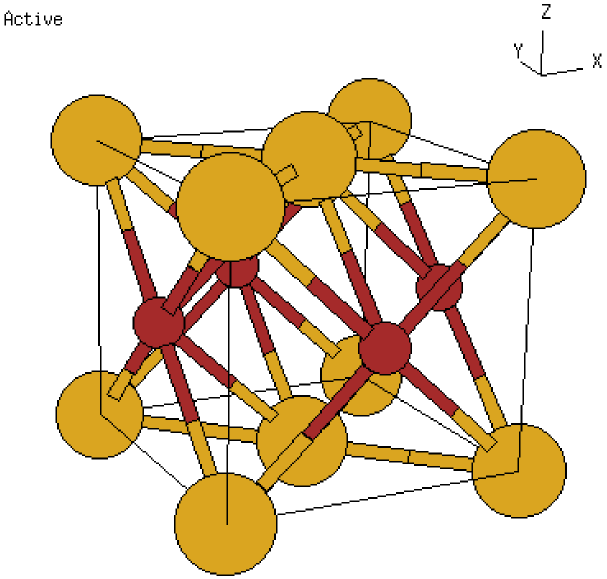
$$D \quad o \quad \frac{E_a}{k_B T} \quad o \quad \frac{KV}{k_B T}$$

Thermally-stable ferromagnets

- **$L1_0$ structure** of FePtB layer
  on the CoFeB/MgO layer



Appl. Phys. A 111, 389 (2013) KIST

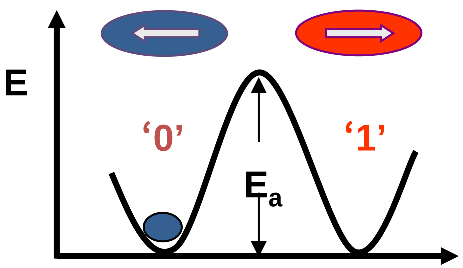


K_U > 1.0 x 10^7 erg/cc

Outline

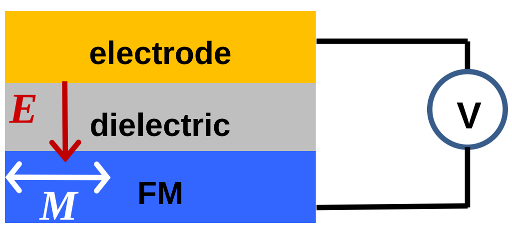
- Spin –Transfer-Torque Magnetoresistive Random Access Memory (STT –MRAM)
- E-field Control of Magnetism
- Spin-Orbit-Torque MRAM
- Thermal Spin-Transfer Torque
- Spin Torque Nano-Oscillator

STT-MRAM의 한계/대안



$E_b = 60 \sim 80 k_B T$

$\Delta \propto \frac{E_a}{k_B T} \propto \frac{KV}{k_B T}$



- **High power consumption (Joule heating) in magnetization switching**

$$\left.\begin{aligned} I &= 10\,\mu A \\ V &= 0.5V \\ t &= 5\,n\sec \end{aligned}\right\} E = 25\,fJ = 6.25 \times 10^{6} k_B T$$

$E_b = 60 \sim 80 k_B T$

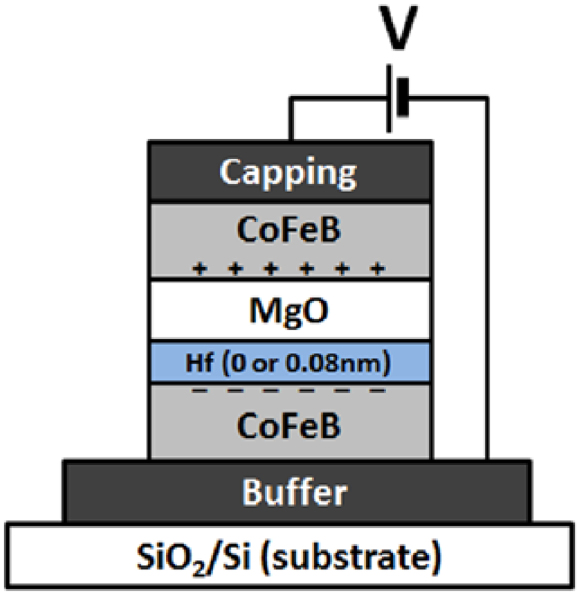
- **Electric Field Control of Magnetization**

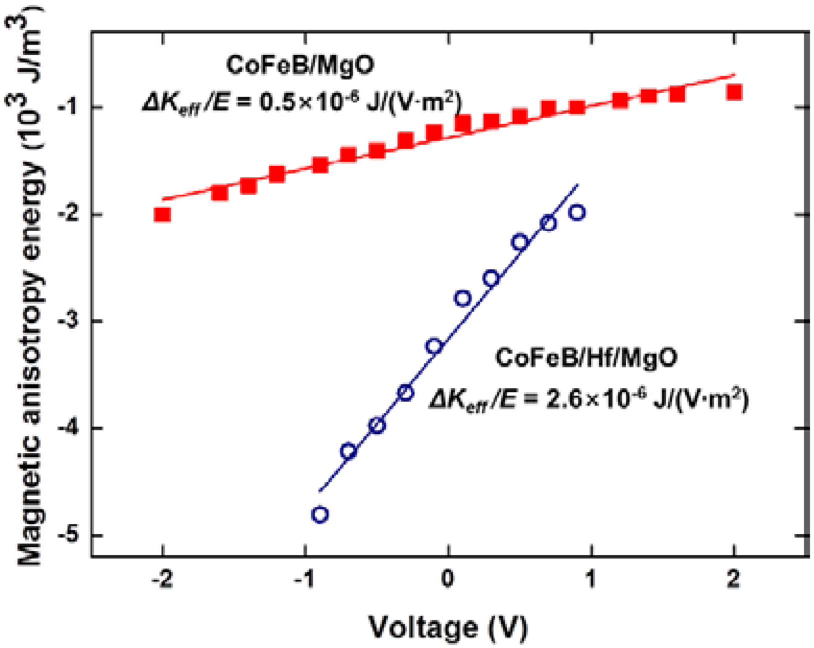
  - Reduced power consumption

  - Compatibility of electric field effect devices with semiconductor integrated circuits

Enhanced E-field control of magnetism

- **Enhanced electric-field control of magnetism by interface engineering**





J. Phys. D 48, 225002 (2015)

Outline

- ***Spin –Transfer-Torque Magnetoresistive Random Access Memory (STT –MRAM)***
- ***E-field Control of Magnetism***
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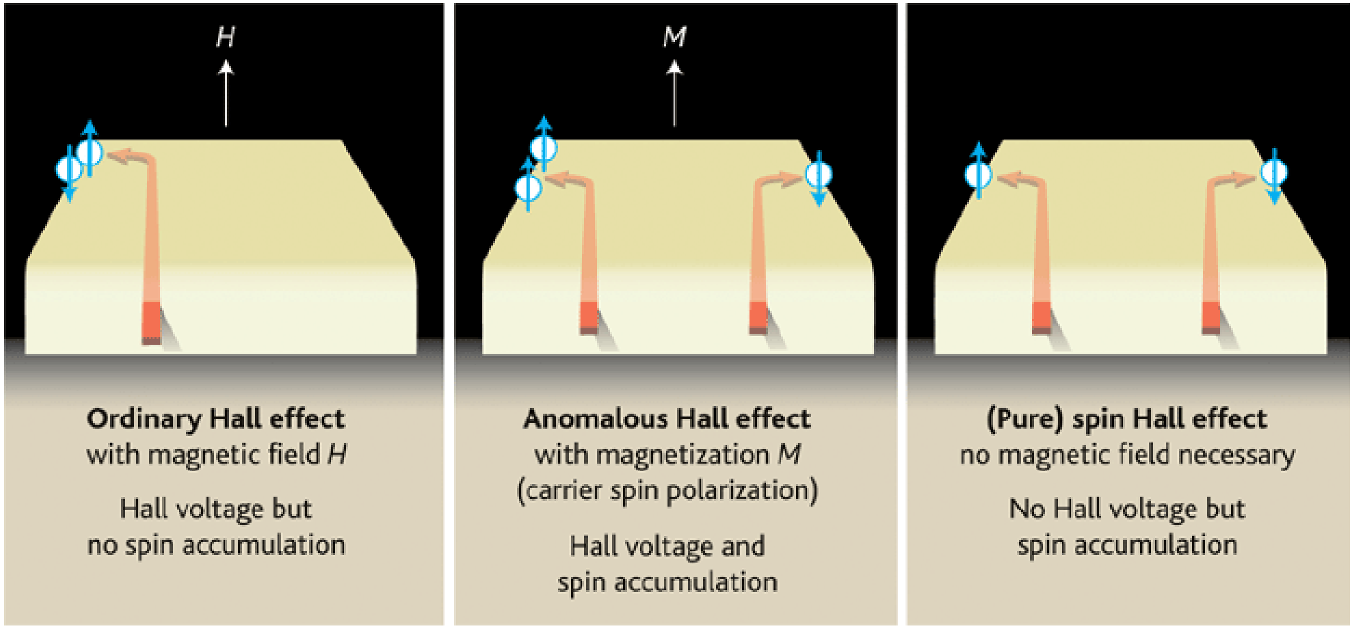
- ***Thermal Spin-Transfer Torque***
- ***Spin Torque Nano-Oscillator***

Anomalous and Spin Hall effect (AHE)

Ø Magnetoresistance (MR) and Hall effects



$$V_{\mathrm{NHE}} = \frac{R_0 I}{d} H_z \qquad V_{\mathrm{AHE}} = \frac{R_s I}{d} M_z$$

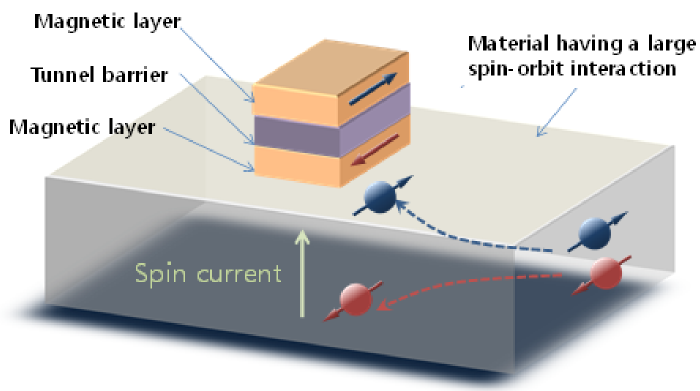
KIST Korea Institute of Science and Technology

스핀궤도 토크 (SOT)-MRAM

- 고밀도, 저전력, 초고속의 조건을 만족하는 emerging 메모리 기술
- 스핀-궤도 결합을 이용한 새로운 스핀 메모리

Mott device (Magnetoresistance)

à Dirac device (S-O coupling)

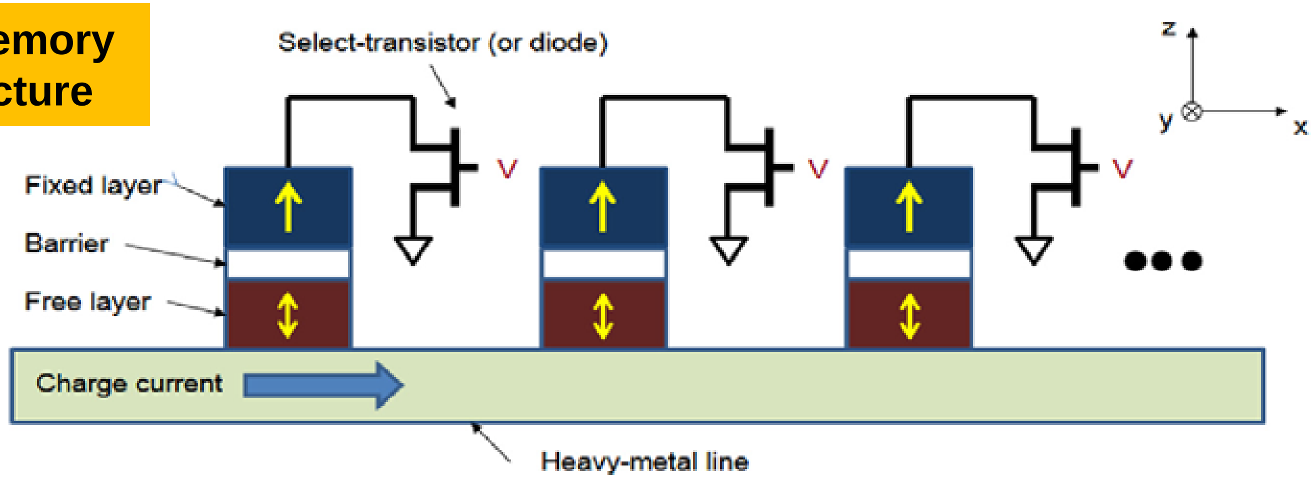


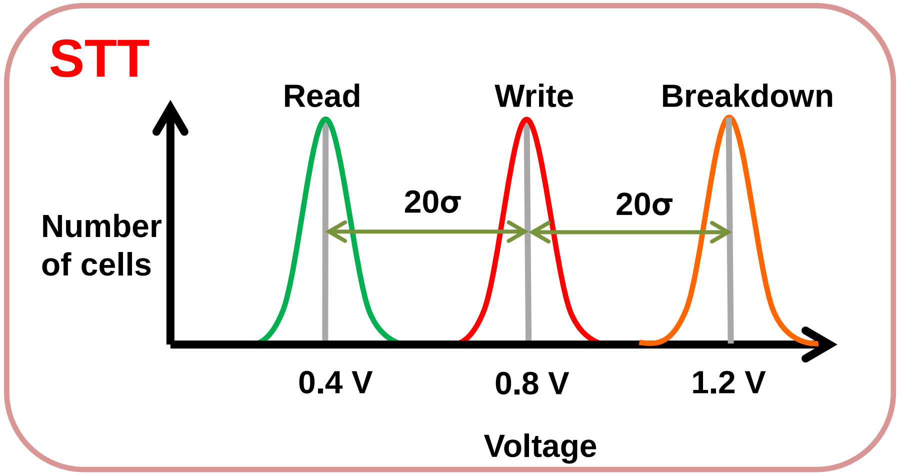
	STT-MRAM	SOT-MRAM
TMR	™	J
RA	™	J
Write current (I_{sw})	™	™
Speed	△	J
Stability (D)	™	™
Decoupling I_{sw} & D	Ð	™
Endurance	™	J

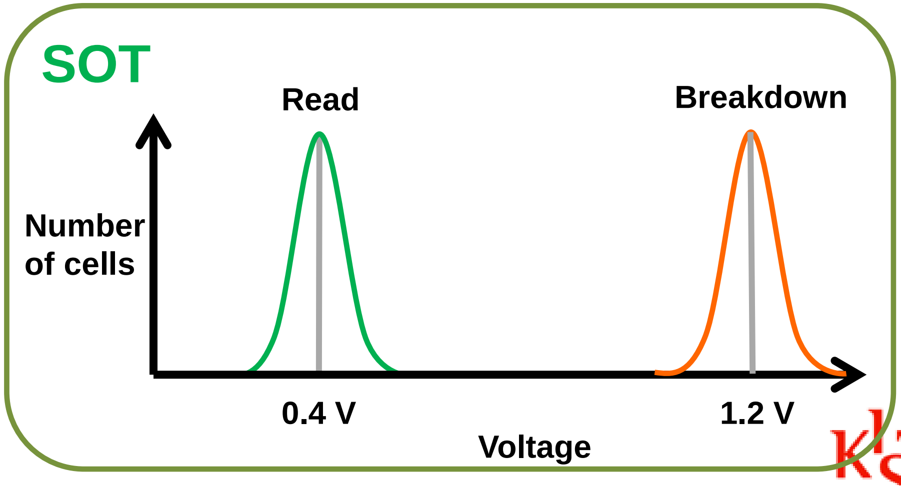
스핀궤도 토크 (SOT)-MRAM

1. E-field control of magnetic anisotropy
2. Switching of nano-magnet by spin-Hall effect/ spin-orbit torque

New memory architecture







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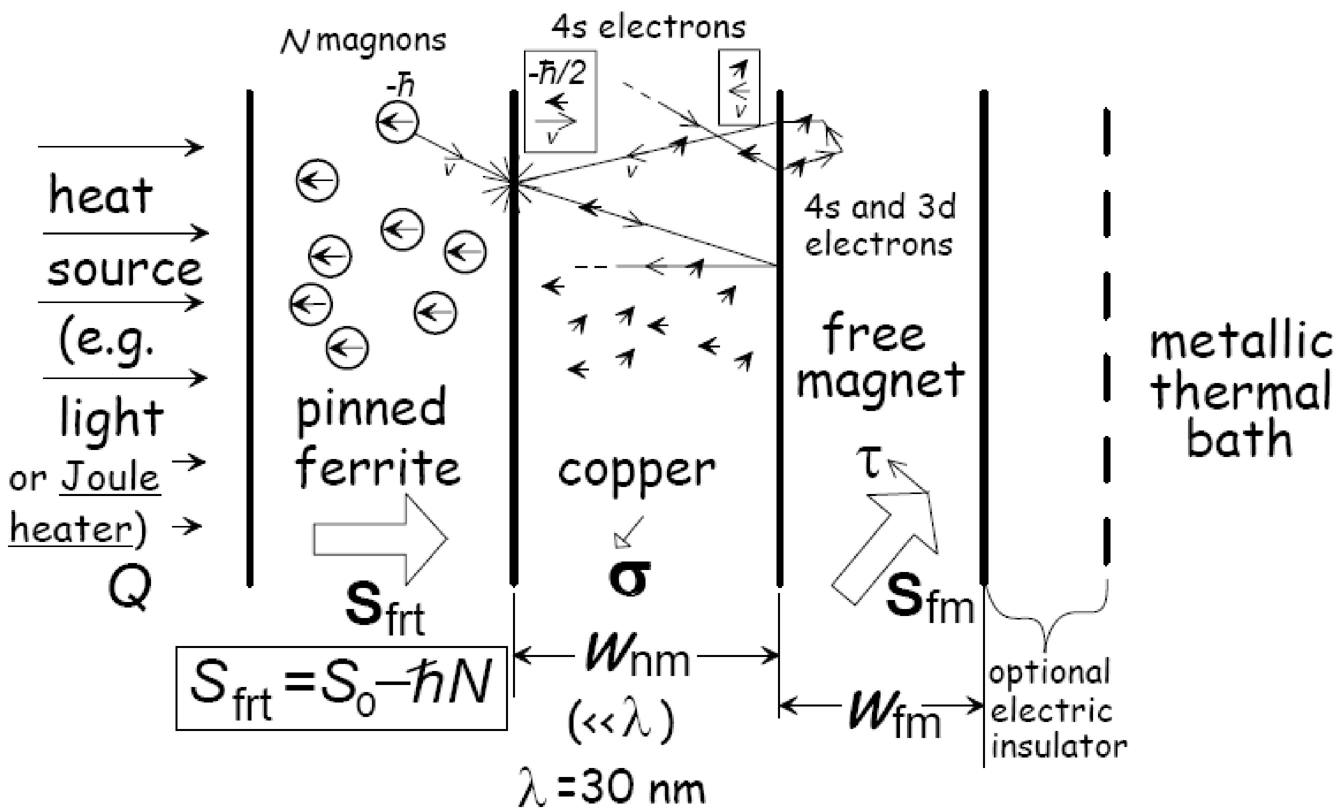
Spin transfer torque driven by heat flow

Physics of thermagnonic spin transfer

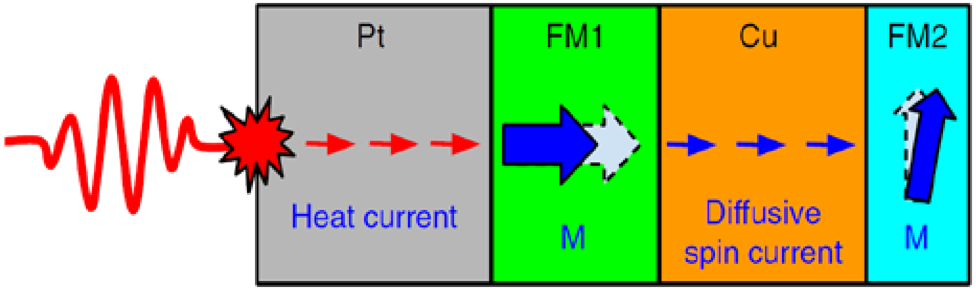
Phys. Rev. B **82**, 054403 (2010)

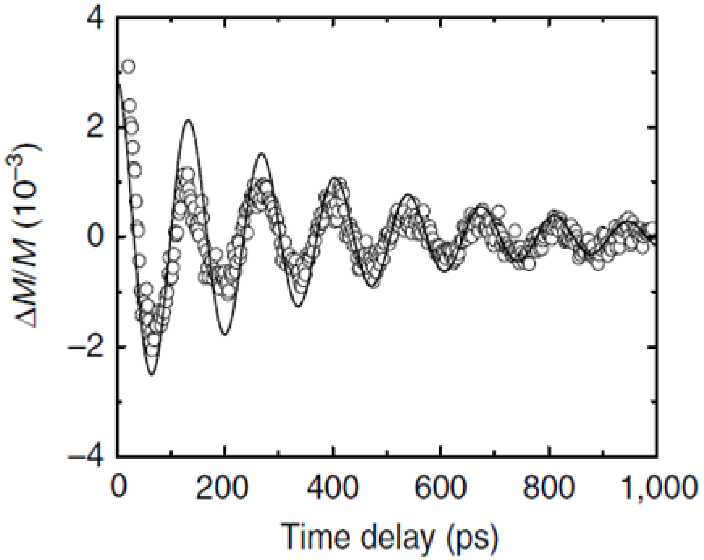


Slonczewski (Kantonah)

Spin current driven by ultrafast demagnetization

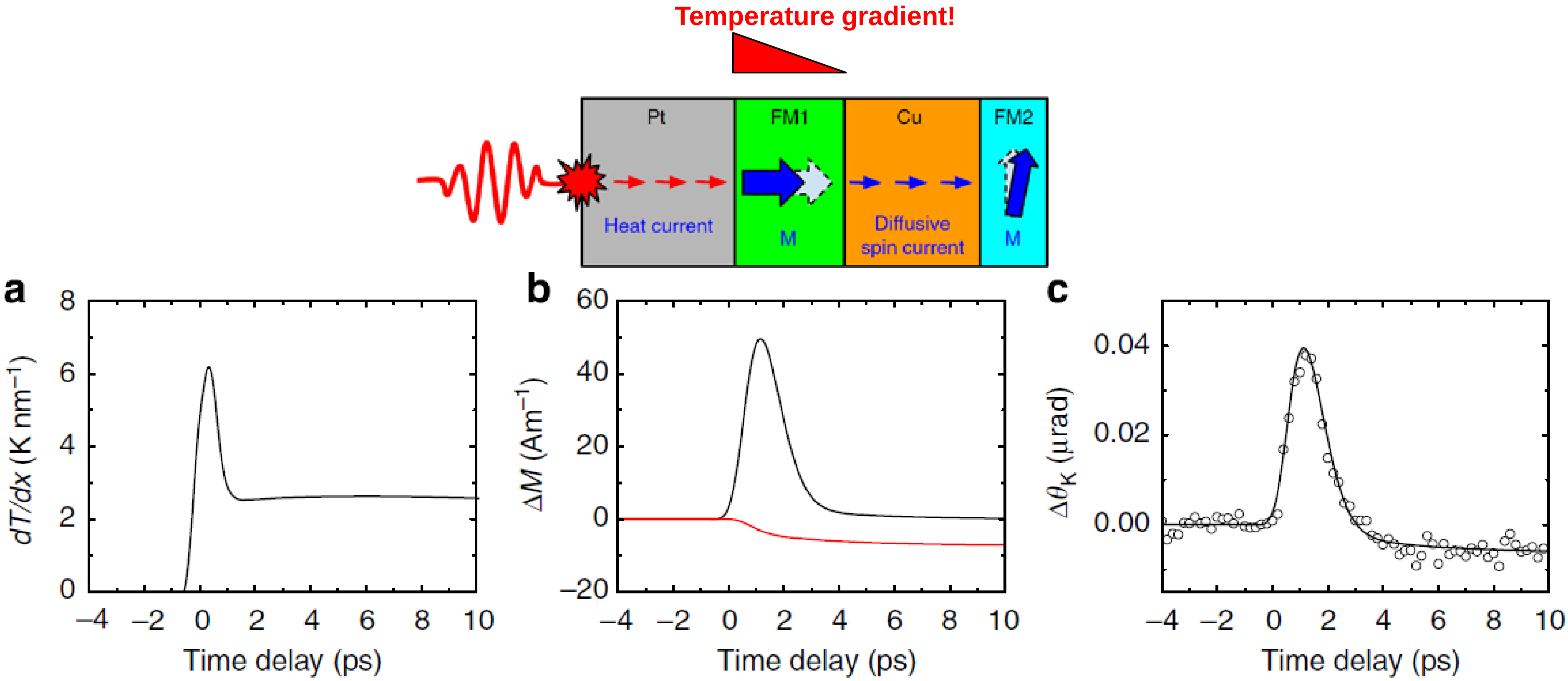
- Generation of spin current in picoseconds
  - Thermally-driven ultrafast demagnetization
  - Spin accumulation in a normal metal
  - Spin transfer torque in an in-plane ferromagnet





Nature communications 5:4334 (2014)

Spin current by spatial temperature gradient



a. **Estimated electronic temperature gradient of Co/Pt layer**

b. **Estimated spin accumulation at the end of Cu layer (200 nm)**

Black: ultrafast demagnetization **Red: Spin dependent Seebeck**

c. **Comparison b/w experimental data and calculation**

Spin-dependent Seebeck effect

$$\begin{pmatrix} J_{\uparrow} \\ J_{\downarrow} \\ Q_{\uparrow} \\ Q_{\downarrow} \end{pmatrix} = -\begin{pmatrix} \sigma_{\uparrow} & 0 & -\sigma_{\uparrow} S_{\uparrow} & 0 \\ 0 & \sigma_{\downarrow} & 0 & -\sigma_{\downarrow} S_{\downarrow} \\ -\sigma_{\uparrow} \Pi_{\uparrow} & 0 & \kappa_{\uparrow} & 0 \\ 0 & -\sigma_{\downarrow} \Pi_{\downarrow} & 0 & \kappa_{\downarrow} \end{pmatrix} \begin{pmatrix} \nabla V_{\uparrow} \\ \nabla V_{\downarrow} \\ \nabla T_{\uparrow} \\ \nabla T_{\downarrow} \end{pmatrix}$$

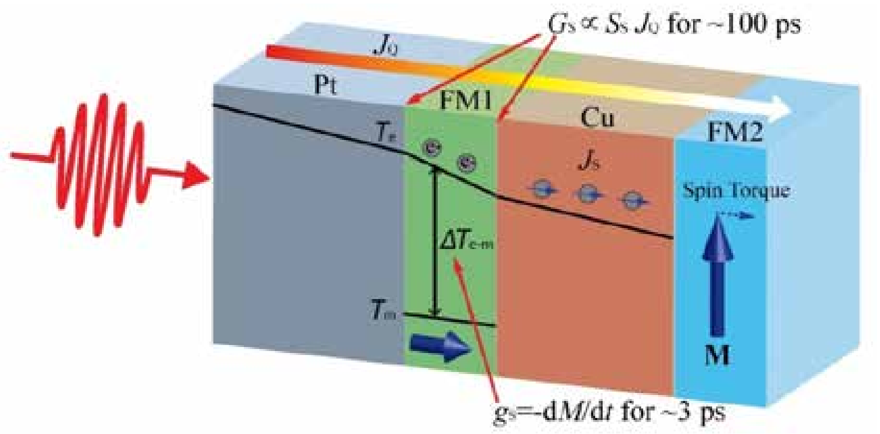
$$J_S = J_{\uparrow} - J_{\downarrow} = -\left(\sigma_{\uparrow} S_{\uparrow} - \sigma_{\downarrow} S_{\downarrow}\right) \nabla T$$

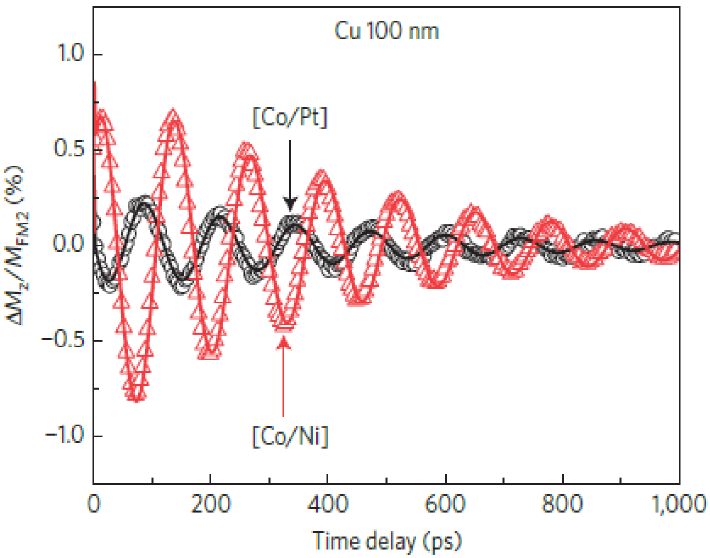
Thermal spin-transfer torque

- **Spin-dependent Seebeck effect** in metallic spin valves
- **Thermal spin transfer torque and magnetization precession**

Pt (20)/ [Co/Pt] (3.2)/ Cu (*h*)/ CoFeB (2) S_s = 6 μV/K

Pt (20)/ [Co/Ni] (3.2)/ Cu (*h*)/ CoFeB (2) S_s = -12 μV/K





Nature physics 11, 576 (2015)

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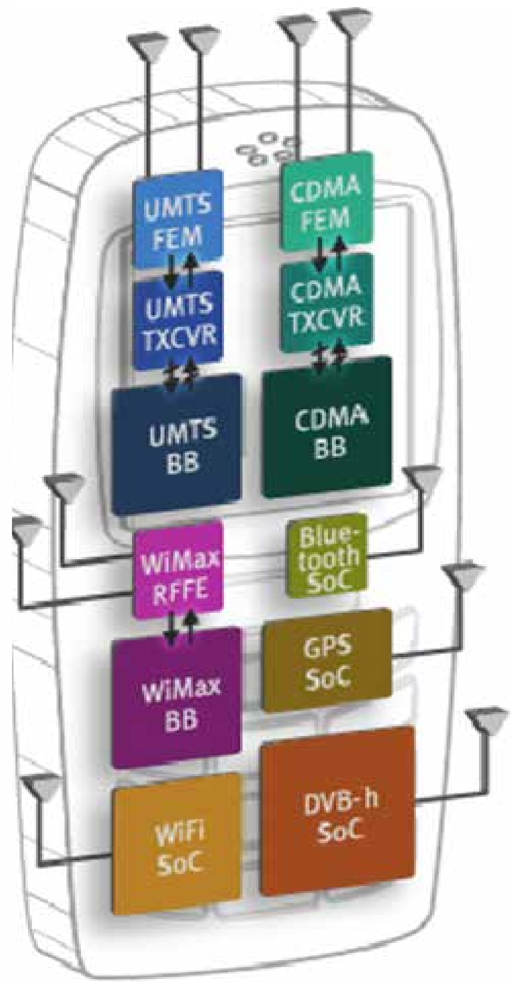
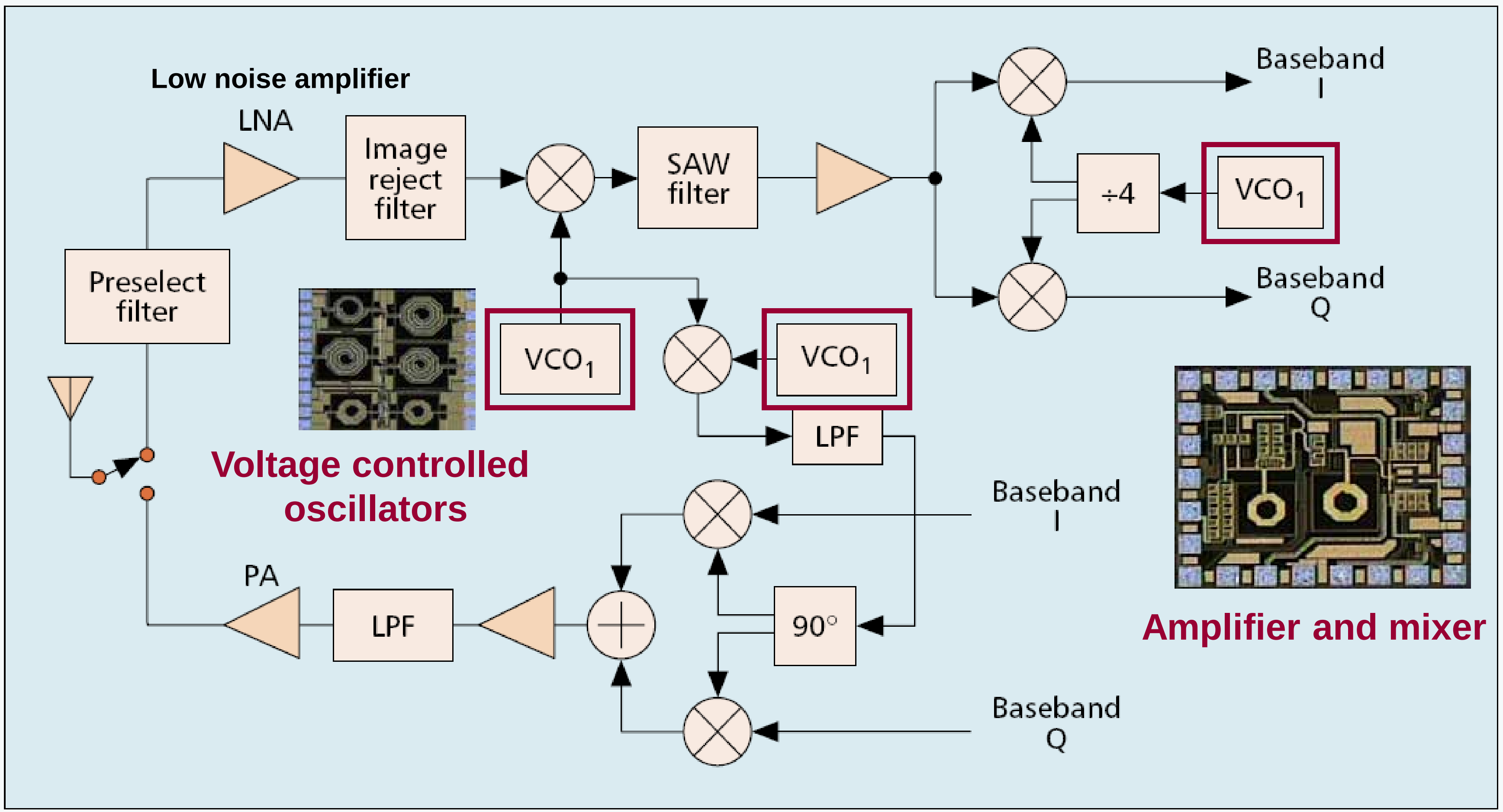
Wireless communication



Microwave oscillator

Heterodyne transceiver



B. Razavi, IEEE Comm. Magazine (2003)

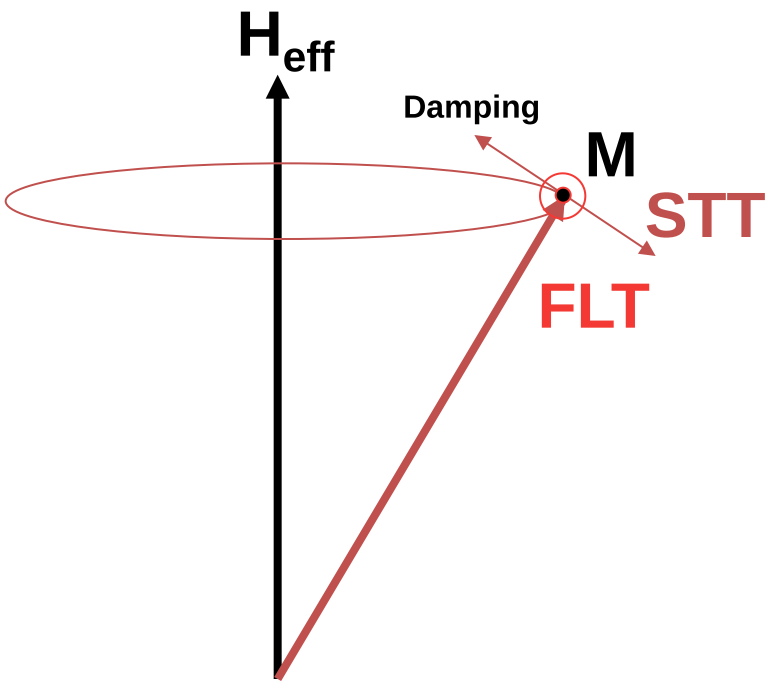
Spin torque nano oscillator

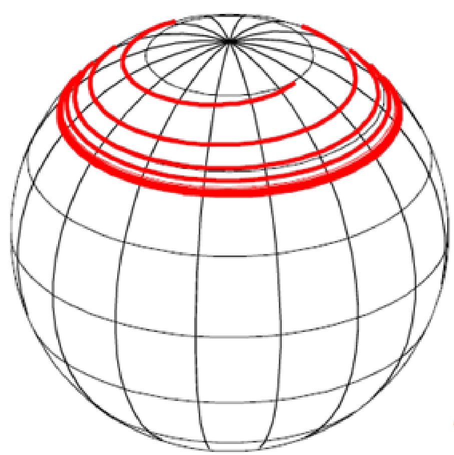
- Precession of magnetization vector by spin transfer torque
- Microwave oscillation in 0.1 – 100 GHz range

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H} + \frac{\alpha}{Ms} \vec{M} \times \frac{d\vec{M}}{dt} + \frac{\gamma a_J}{M_S^2} \vec{M} \times (\vec{M} \times \vec{M}_2) + \frac{\gamma b_J}{M_S} (\vec{M} \times \vec{M}_2)$$

In-plane STT

Perpendicular STT





High current,
high field
→ stable precession

Advantages & disadvantages of STNOs

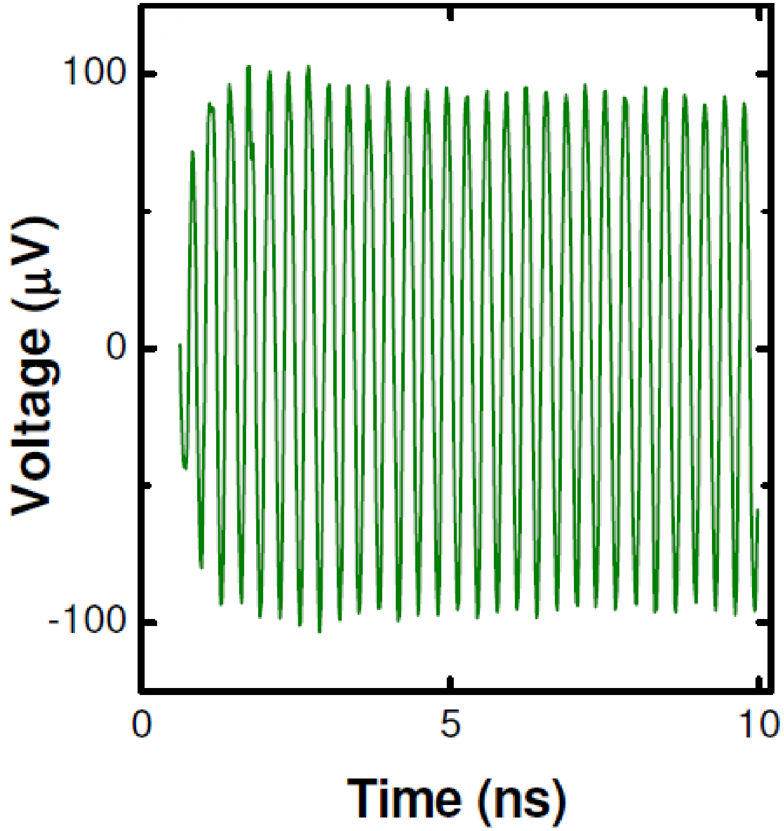
	LC-VCO	STNO
Size	1 mm^2	1 μm^2
Output power	0 dBm	< -30 dBm
Phase noise	-115 dBc @ 400kHz	< -3 dBc @ 400kHz
Power consumption	0.4 mA @0.82V	1~5 mA @0.5V
Tunable range	10%	10-100%
Agility	μs	ns

Chappert (CNRS, Paris Sud)

Korea Institute of Science and Technology

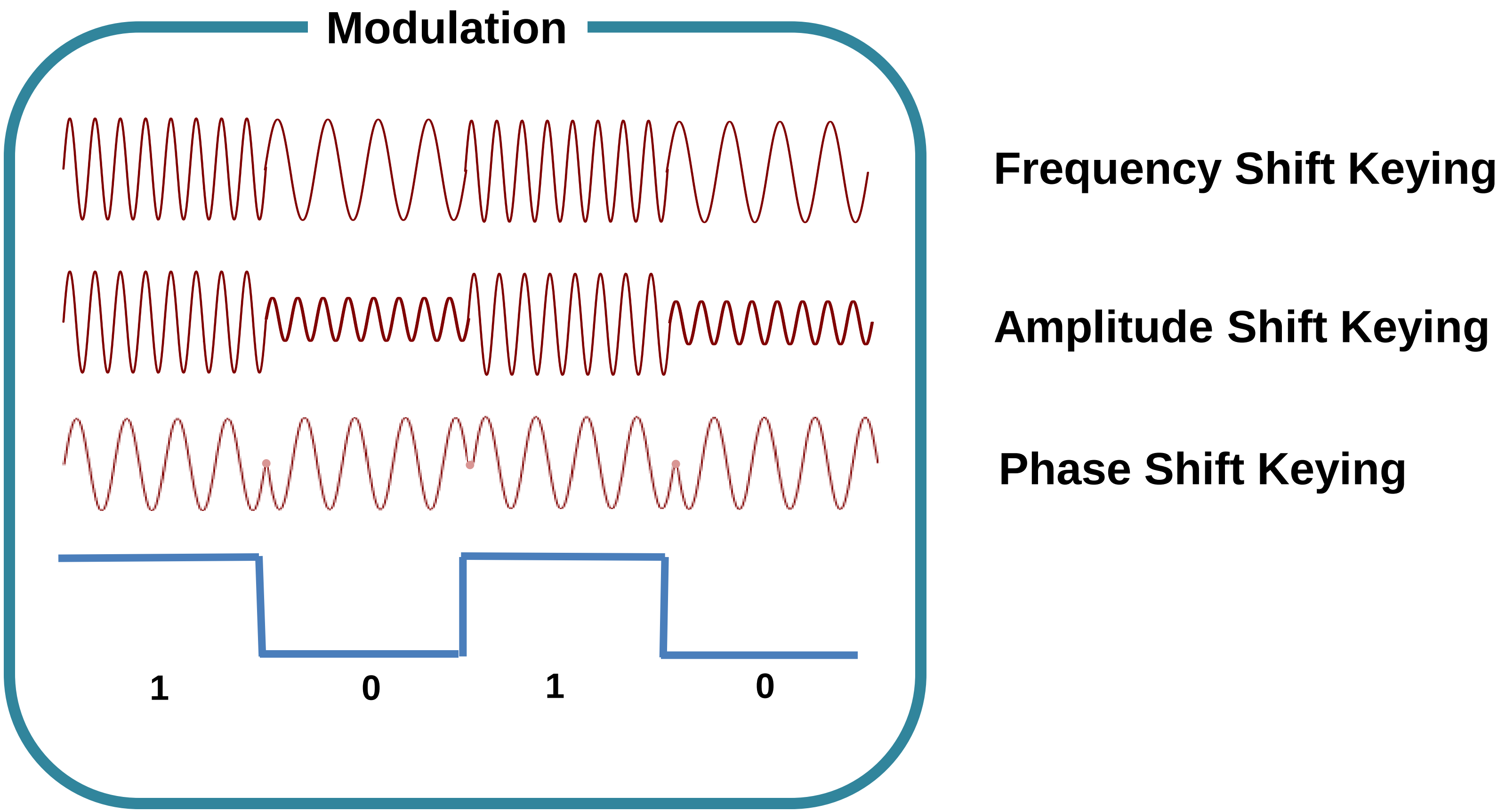
Agility of STNO

- **STNO can be turned on in a few nanoseconds.**

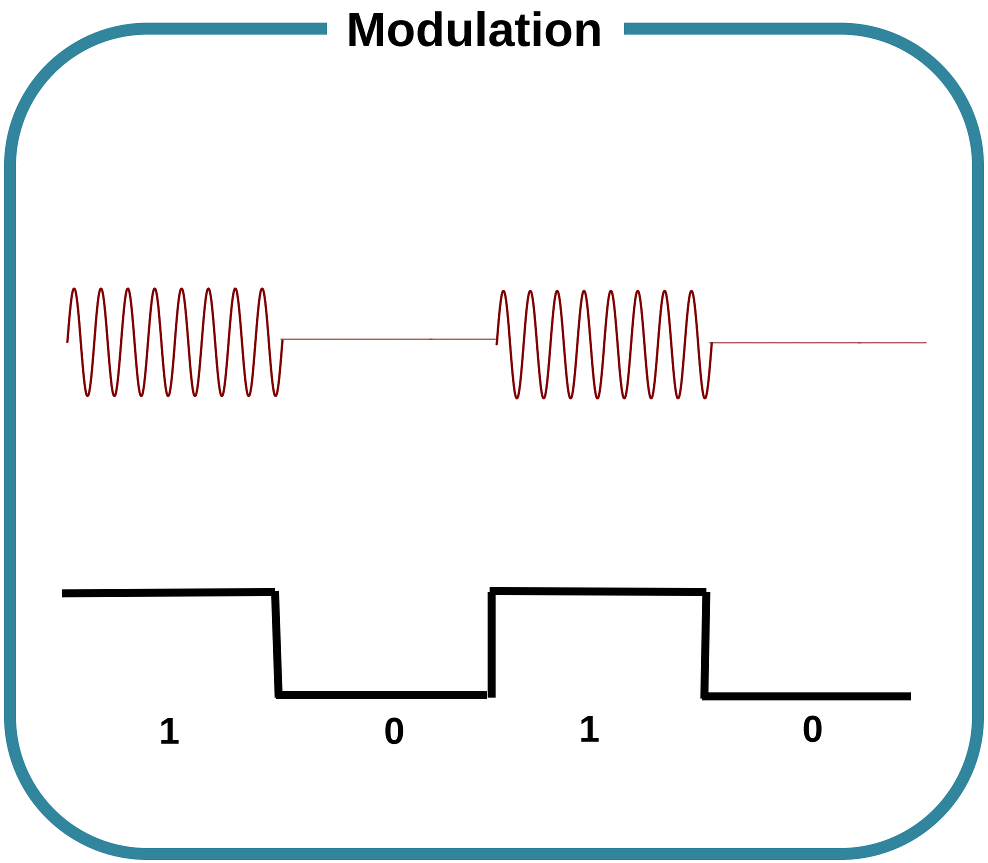


Krivorotov, Science 307, 228 (2005)

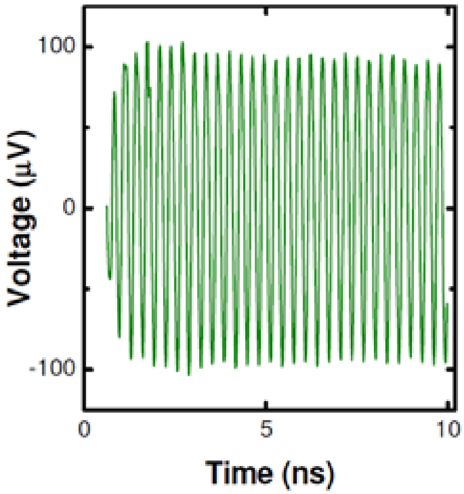
Modulation for Wireless Communication



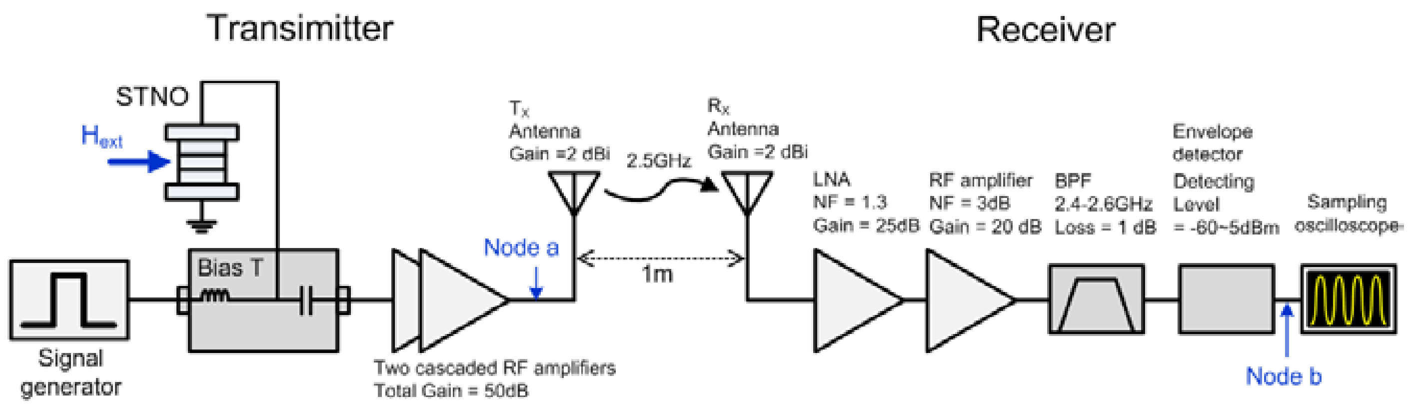
Frequency modulation



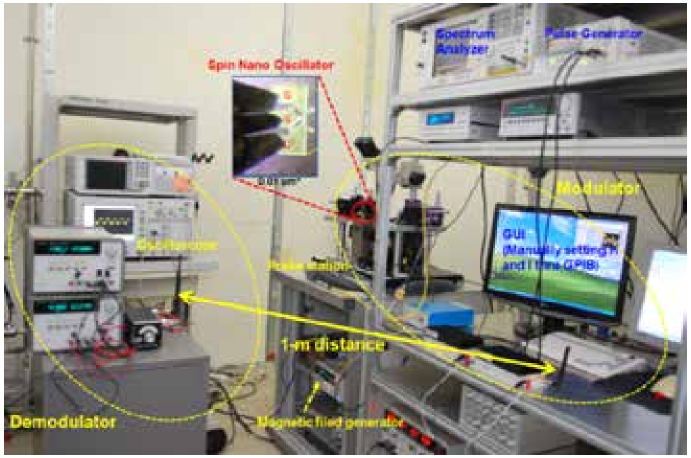
On-OFF Shift Keying



STNO-based Wireless Communication



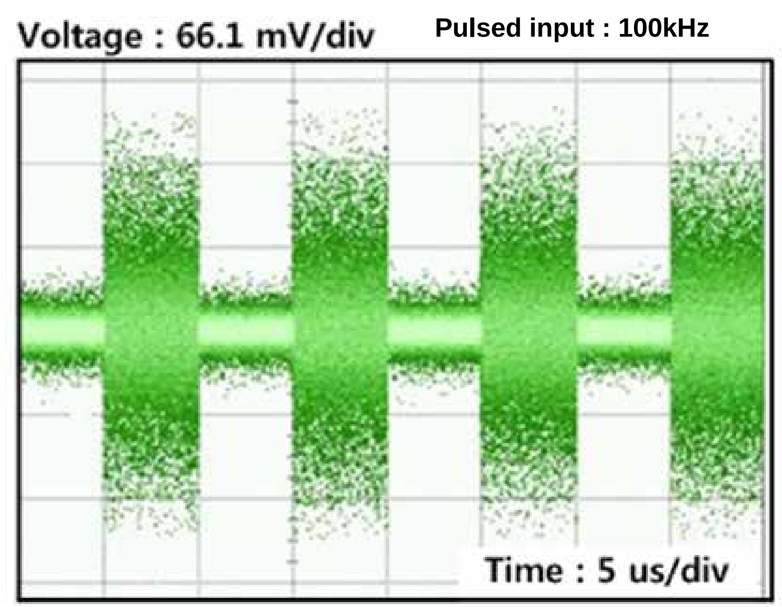
- On-OFF shift keying modulation and non-coherent demodulation
- STNO-based wireless communication with 200-kbps data rate at a distance of 1 m between transmitter and receiver



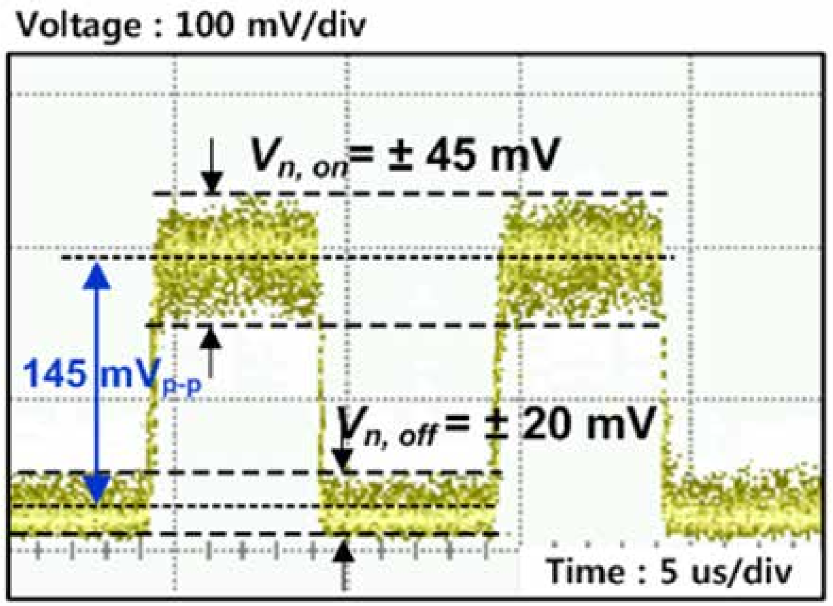
Sci. Rep. 4, 5486; DOI:10.1038/srep05486 (2014)

STNO-based Wireless Communication

Modulated signal



Demodulated signal



- **Data Rate=Bandwidth x $\log_2$ (SNR + 1)**
- **SNR=11.2dB (Noise of STNO=-96.9 dBm, Signal Power=-85.7 dBm)**
- **Bandwidth = 152 MHz (minimum pulse duration=3.3 nsec)**
- **Maximum data rate R=1.16Gbps**

Sci. Rep. 4, 5486; DOI:10.1038/srep05486 (2014)