スピントロニクス・デザインコース

Spintronics Design Course

基　礎　1

Fundamentals 1

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Outline

0. スピントロニクスと社会
   – *Spintronics* and the human society
1. トンネル磁気抵抗
   Tunneling magnetoresistance (TMR)
   – 高スピン偏極（ハーフメタル）材料
     High *spin-polarization* (*half-metallic*) materials
2. 界面磁気異方性
   Interface magnetic anisotropy
   – 電圧制御
     voltage control

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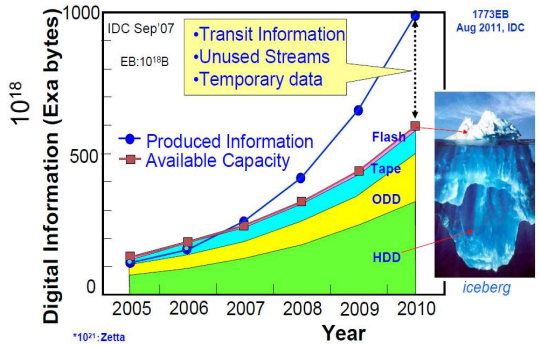
0. スピントロニクスと社会

Spintronics and the human society

3

デジタル情報の年間生産量と記録可能容量

Produced digital information / Available recording capacity

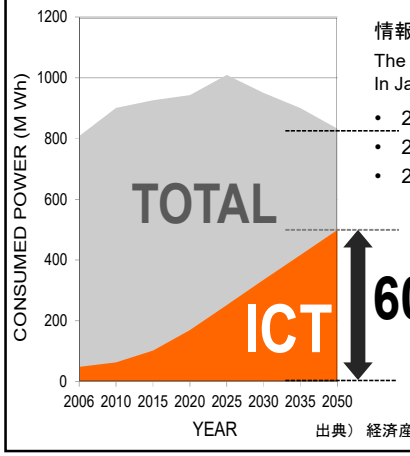


- デジタル情報生産量は5年で10倍増加
  Digital information has been expanding 10 times over 5 years.
- 記録媒体の容量は大幅に不足 Insufficient recording capacity

4

急増する情報通信機器の電力使用量

Rapid increase of power consumption of ICT equipments



情報通信(ICT)機器の電力使用量（日本）

The power consumption of ICT equipments In Japan:

- 2008年： 全電力使用量の約 6%
- 2030年： 〃 約40%
- 2050年： 〃 約60%

スピントロニクスによる省エネルギー・環境調和型デバイスの必要性

We need energy-saving / environmentally harmonic devices based on spintronics.

出典） 経済産業省 METI / Estimation of Green IT (2008)

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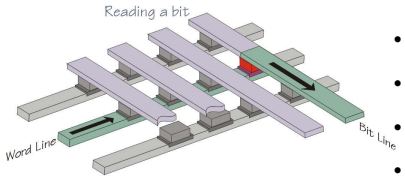
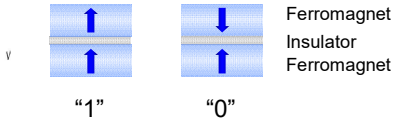
MRAM (Magnetoresistive Random Access Memory)



- 不揮発 *Non-volatile*
- 高速入出力 *Fast read/write*
- 高集積化 *Scalability*
- 高耐久性 *High endurance*

Magnetic tunnel junctions (MTJ)



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Conventional Technology in Electronics

© Intel

Processing *Semiconductor* devices

Storage *Ferromagnetic* devices

Electronic Degrees of Freedom

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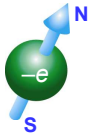
Charge *Spin*



Spintronics

- High-performance devices in the next generation
  High speed, Large scale, Low power consumption
- New paradigm in information technology

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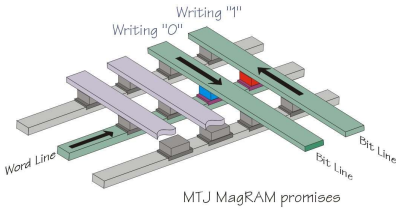
Requirements for Magnetic Tunnel Junction (MTJ)

- *Non-volatility*: $\Delta = E_B / k_B T > 60$ (for 10-year data retention)
- *High output*: TMR ratio > 100%
- *Low switching current*: $I_{c0} < F$ μA (for cell size F nm)
- *Fast read and write*



MTJ MagRAM promises
- density of DRAM
- speed of SRAM
- non-volatility

- *CMOS compatibility*
- *Low resistance*
- *Low error rate*
- *Low cost*

© S. S. P. Parkin (IBM)

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1. トンネル磁気抵抗

Tunneling Magneto-Resistance (TMR)

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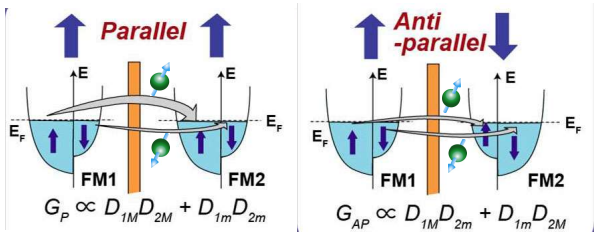
トンネル磁気抵抗効果の起源

The origin of TMR effect



低抵抗
Low resistance

高抵抗
High resistance

Jullier's model

スピン偏極率 spin polarization

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_{\mathrm{FM1}}P_{\mathrm{FM2}}}{1 - P_{\mathrm{FM1}}P_{\mathrm{FM2}}} \qquad P = \frac{D_{\mathrm{Maj}} - D_{\mathrm{min}}}{D_{\mathrm{Maj}} + D_{\mathrm{min}}}$$

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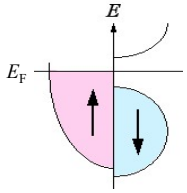
Half-metallic ferromagnets

Unique electronic structure:

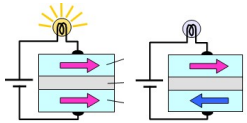
- *Metallic* for spin-up
  Semiconducting for spin-down
- Complete *spin polarization* at E_F



$$P = \frac{D_\uparrow - D_\downarrow}{D_\uparrow + D_\downarrow} = 1$$

D_σ: Density of states at E_F

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_{\mathrm{FM1}}P_{\mathrm{FM2}}}{1 - P_{\mathrm{FM1}}P_{\mathrm{FM2}}} \to \infty$$



Potential materials for electrodes of MTJ

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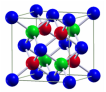
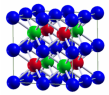
Half-metallic ferromagnets (theoretical prediction)

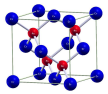
- Half Heusler alloys: NiMnSb, PtMnSb
  R.A. de Groot, *et al.*, Phys. Rev. Lett. **50**, 2024 (1983).



- Full Heusler alloys: Co_2MnGe, Co_2MnSi
  S. Ishida, *et al.*, J. Phys. Soc. Japan **64**, 2152 (1995).



- Fe_3O_4 A. Yanase, *et al.*, J. Phys. Soc. Jpn. **53**, 312 (1984).
- CrO_2 K. Schwarz, J. Phys. F: Met. Phys. **16**, L211 (1986).
- (La,Sr)MnO_3, Sr_2FeMoO_6
- zinc-blende CrAs, CrSb
  H. Akinaga, *et al.*, Jpn. J. Appl. Phys. **39**, L1118 (2000).
  M. Shirai, Physica E **10**, 143 (2001).
  J. Appl. Phys. **93**, 6844 (2003).



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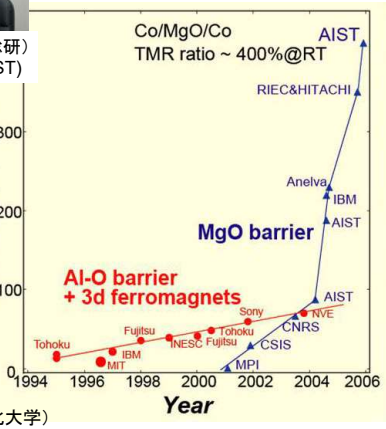
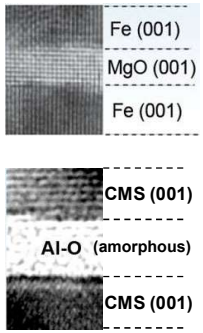
湯浅新治（産総研）
S. Yuasa (AIST)

宮崎照宣（東北大学）
T. Miyazaki (Tohoku Univ.)





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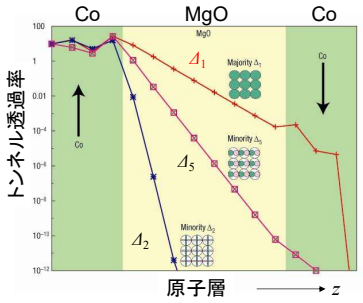
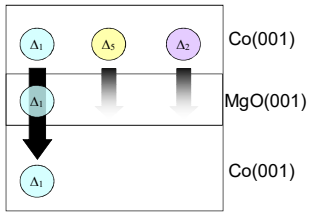
コヒーレント・トンネル効果
Coherent tunneling effect

反平行磁化配置



Δ_1: s, p_z, d_{z2} Δ_2: d_{xy}, d_{x2-y2}
Δ_5: p_x, p_y, d_{yz}, d_{zx}

Δ_1対称性をもつ電子
Δ_1–symmetry electrons
減衰が緩やか
slow decay
↓
優先的に透過
predominant transmission



W.H. Butler *et al.*, Nature Mater. **3**, 845 (2004).

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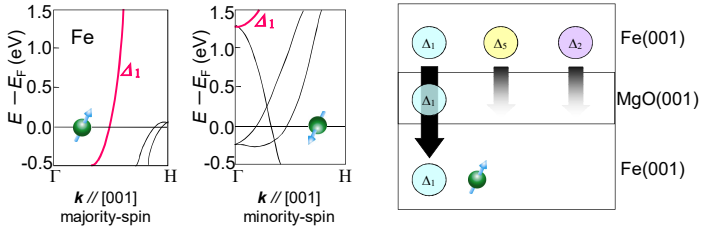
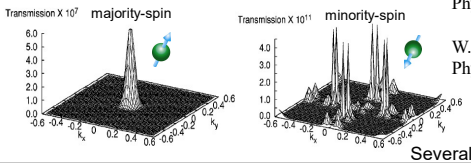
コヒーレント・トンネル効果
Coherent tunneling effect

High spin polarization for Δ_1 band. Selective transmission via Δ_1 channel.



$k_{//}$ dependence of transmittance



J. Mathon and A. Umerski, Phys. Rev. B **63**, 220403R (2001).

W.H. Butler *et al.*, Phys. Rev. B **63**, 054416 (2001).

Several orders of magnitude smaller

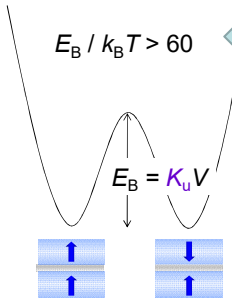
15

Large magnetic anisotropy for *high thermal stability*

Small magnetic anisotropy for *low switching current*

$E_B / k_B T > 60$ ⇔ trade-off ⇔ $I_{c0} < F$ μA (for cell size F nm)

$I_{c0} \propto \alpha E / g(P)$



α : magnetic damping constant
g : spin-transfer efficiency
P : spin polarization

K_u : magnetic anisotropy energy
V : volume of ferromagnetic layer

High magnetic anisotropy (K_u), *High* spin polarization (P), and *Low* magnetic damping (α) are required for electrode materials.

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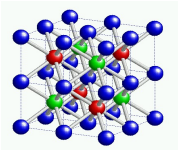
Half-metallic Heusler alloys: Co_2YZ

- *High Curie temperatures*
  - advantage for room-temperature device applications.
- *High spin polarization* at the Fermi level
  - even in *disordered B2 structure.*

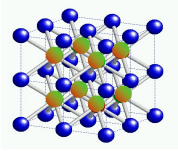
Y. Miura, K. Nagao, M. Shirai,
Phys. Rev. B **69**, 144413 (2004).
J. Appl. Phys. **95**, 7225 (2004).

- *Low magnetic damping*
  - even in *disordered B2 structure.*

S. Mizukami, *et al.*,
J. Appl. Phys. **105**, 07D306 (2009).



Ordered $L2_1$ structure



Disordered B2 structure

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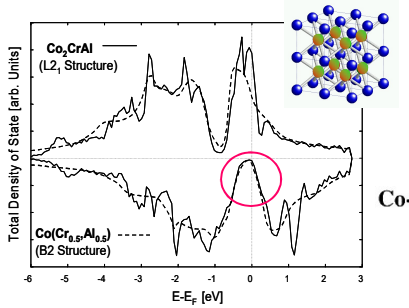
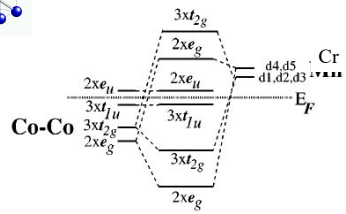
Effects of B2 disorder (Cr-Al substitution)



Molecular orbitals (minority-spin)



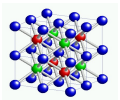
Galanakis, *et al.*,
Phys. Rev. B **66**, 174429 (2002).

Near-edge states of the minority-spin band gap:
Non-bonding Co *3d* orbitals

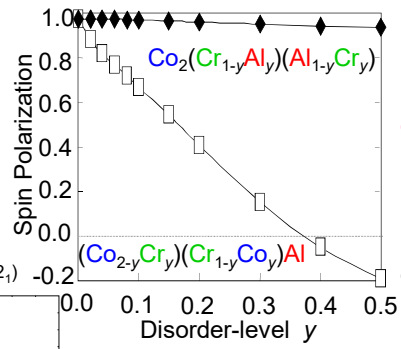
Y. Miura, K. Nagao, M. Shirai, Phys. Rev. B **69**, 144413 (2004).

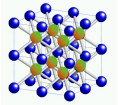
19

Effects of Atomic disorder on Spin polarization

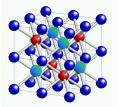


ordered $L2_1$



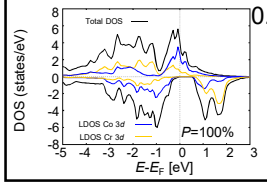


disordered B2



disordered $D0_3$

Co_2CrAl ($L2_1$)



KKR-CPA

Y. Miura, K. Nagao, M. Shirai,
Phys. Rev. B **69**, 144413 (2004).

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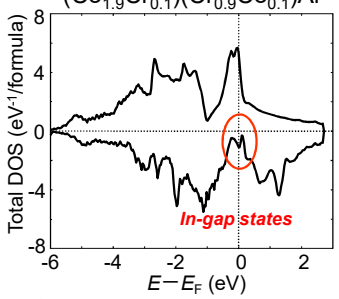
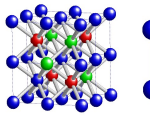
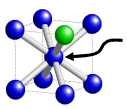
Effects of $D0_3$ disorder (Co-Cr substitution)

$(Co_{1.9}Cr_{0.1})(Cr_{0.9}Co_{0.1})Al$

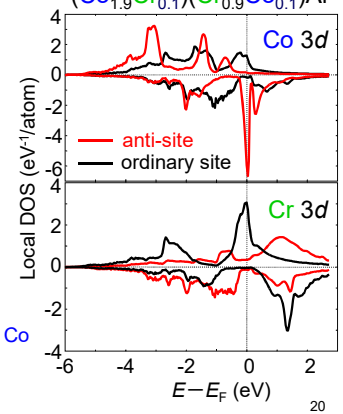






anti-site Co

$(Co_{1.9}Cr_{0.1})(Cr_{0.9}Co_{0.1})Al$



Y. Miura, K. Nagao, M. Shirai, Phys. Rev. B **69**, 144413 (2004).

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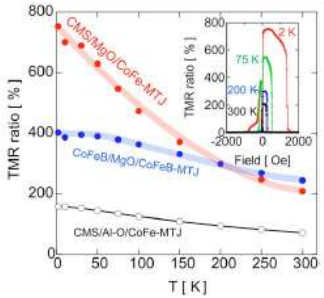
Co_2MnSi / MgO / FM (001) magnetic tunnel junctions



Remarkable temperature dependence

Co_2MnSi / MgO / CoFe MTJ
TMR = 753% at 4.2K
= 217% at RT

S. Tsunegi, *et al.*,
Appl. Phys. Lett. **93**, 112506 (2008).

Remaining problems

- Elucidating the origin of remarkable reduction of TMR ratio with increasing temperature.
- How to improve TMR ratio at room temperature.

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2. 界面磁気異方性

Interface magnetic anisotropy

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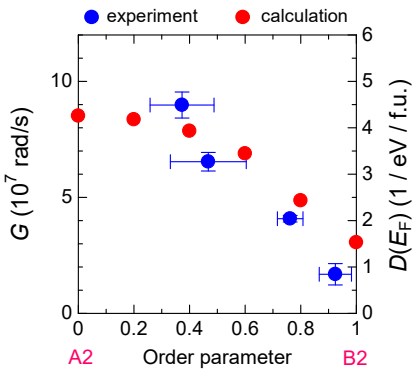
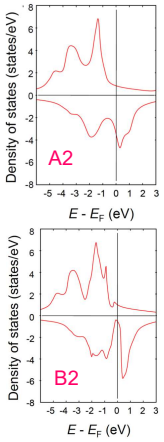
Gilbert damping constants of Co_2FeAl
Ferromagnetic resonance (FMR)



$G \propto \xi_{SO}^2 (D_\uparrow + D_\downarrow)$ (Kambersky)



S. Mizukami, *et al.*, J. Appl. Phys. **105**, 07D306 (2009).

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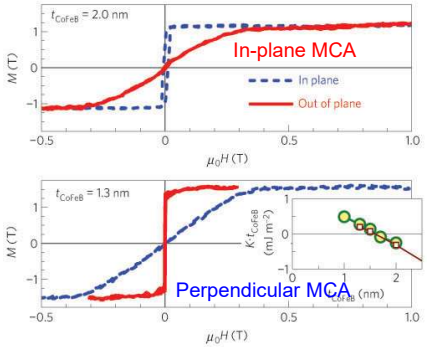
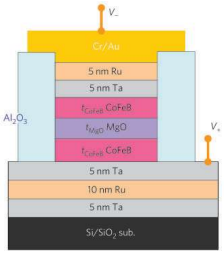
Perpendicular magneto-crystalline anisotropy (MCA) observed at CoFeB / MgO interfaces.





Interfacial MAE density:
$K_i = 1.30$ erg/cm^2

$E / k_B T = 43$
TMR ratio: 124%
$I_{co} = 49$ μA ($\phi = 40$ nm)

S. Ikeda, *et al.*, Nature Mater. **9**, 721 (2010).

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Large magnetic anisotropy for *high thermal stability*

Small magnetic anisotropy for *low switching current*

$E / k_B T > 60$ trade-off $I_{c0} < F$ μA (for cell size F nm)

$I_{c0} \propto \alpha E / g(P)$

$E = K_u V$

α : magnetic damping constant
g : spin-transfer efficiency
P : spin polarization

K_u : magnetic anisotropy energy density
V : volume of ferromagnetic free layer

$$I_{c0} V_{sw} t_{sw} \approx 50\ \mu\text{A} \times 0.5\ \text{V} \times 1\ \text{ns} \approx 2.5 \times 10^{-14}\ \text{J}$$

$$60\, k_B T \approx 60 \times 1.38 \times 10^{-23}\ \text{J/K} \times 300\ \text{K} \approx 2.5 \times 10^{-19}\ \text{J}$$

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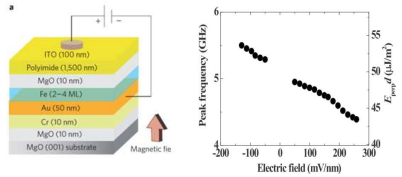
Electric-field modulation of interfacial magnetic anisotropy

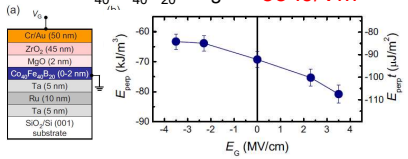
Experiment

- Au / $Fe_{80}Co_{20}$ (0.5nm) / MgO -37.2 fJ/Vm



T. Nozaki, *et al.*, Appl. Phys. Lett. **96**, 022506 (2010).

- Ta / $Co_{40}Fe_{40}B_{20}$ / MgO -33 fJ/Vm



M. Endo *et. al.*, Appl. Phys. Lett. **96**, 212503 (2010).

Theory

- MgO / Fe (9ML) / Cu(001) 32 fJ/Vm

M. K. Niranjan *et. al.*, Phys. Rev. Lett. **96**, 222504 (2010).

- Au (3ML) / Fe (3ML) / MgO 8.1 fJ/Vm

K. Nakamura, *et. al.*, Phys. Rev. B. **81**, 220409(R) (2010).

- MgO / Fe (2ML) / Au(001) 11.6 fJ/Vm

M. Tsujikawa, *et al.*, J. Appl. Phys. **109**, 07C107 (2011).

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Large magnetic anisotropy for *high thermal stability*

Small magnetic anisotropy for *low switching current*

$E / k_B T > 60$ trade-off $I_{c0} < F$ μA (for cell size F nm)

$V_g = 0$ $E = K_u V$ $E = K_u V$ $V_g \neq 0$

Outlook: Another solution to overcome the trade-off relation is

Electric-field control of magnetic anisotropy.

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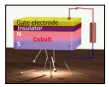
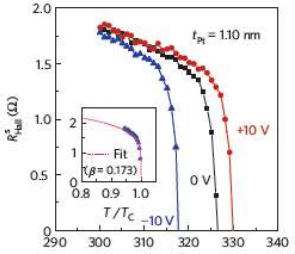
Electric-field effect on Curie temperature

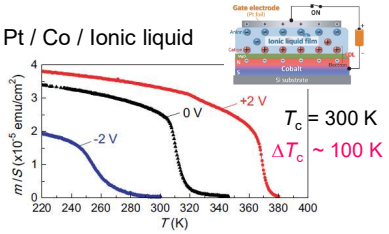
Pt / Co / MgO





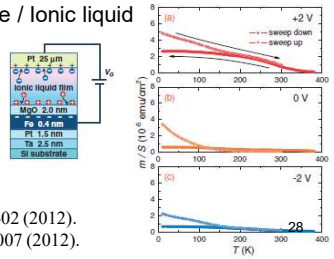
T_c = 326 K ΔT_c ~ 10 K

Pt / Co / Ionic liquid



T_c = 300 K
ΔT_c ~ 100 K

Pt / Fe / Ionic liquid



D. Chiba, *et al.*, Nature Mater. **10**, 853 (2011).
K. Shimamura, *et al.*, Appl. Phys. Lett. **100**, 122402 (2012).
M. Kawaguchi, *etal.*, Appl. Phys. Express **5**, 063007 (2012).

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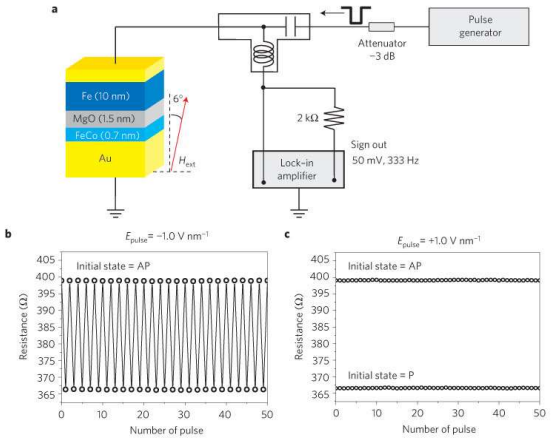
Magnetization switching by voltage pulses



Y. Shiota, *et al.*, Nature Mater. **11**, 39 (2012).

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Summary

Required *magnetic materials* for *spintronics*:

- *High spin polarization* (for high magetoresistance)
- *High magnetic anisotropy* (for high thermal stability)
- *Low magnetic damping* (for low switching current)
- *Small magnetization* (for low switching current and stray field)

Required *innovative functionality* for *spintronics*:

- *Voltage control* of magnetic properties
  e.g. magnetic anisotropy, damping, Curie temperature
  (for magnetization switching with low power consumption)

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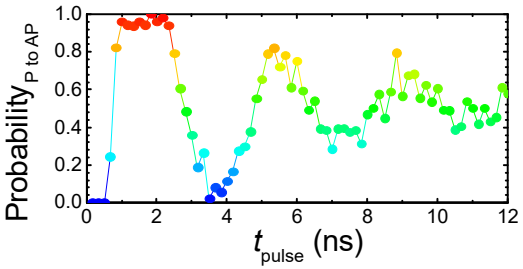
Magnetization switching by voltage pulses

Perpendicular magnetization
CoFeB/MgO/CoFeB MTJ (ϕ = 70 nm)



Switching probability vs. Voltage-pulse duration t_{pulse}

S. Kanai, *et al.*, Appl. Phys. Lett. **101**, 122403 (2012).

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