Lecture 5

Magnetic Tunnel Junction (MTJ)
or
Tunnel Magnetoresistance (TMR)
or
Junction Magneto-Resistance (JMR)
Short history

- Spin dependent tunneling between two ferromagnets first proposed by J.C. Slonczweski in 1975
- Spin dependent tunneling first observed by M. Julliere in 1976
- First demonstration of room temperature spin dependent tunneling by Moodera et al., 1995
History of MTJ

TMR = 14 % at 4.2 K
Fe/Ge/Co
M. Julliere, Phys. Lett. 54A (1975)

TMR = 18 % at 300 K
Fe/Al₂O₃/Fe

TMR = 11.8 % at 295 K
CoFe/Al₂O₃/Co

TMR = 20.2% at 295 K
Co/Al₂O₃/ Ni₈₀ Fe₂₀
(1) Introduction

(2) Epitaxial MTJs with single-crystal MgO(001) barrier
   • TMR
   • $t_{\text{MgO}}$-dependence of TMR

(3) MTJs with poly-crystalline MgO(001) barrier
   • TMR
   • Current-induced magnetization reversal (CIMS)
Streszczenie

W 1995 roku magnetyczne, metaliczne złącza tunelowe wykazywały w temperaturze pokojowej 20 % wzrost magnetorezystancji tunelowej, w roku 2002 złącza tunelowe o strukturze zaworu spinowego wykazywały już 60% wzrost, a w roku 2004 (październik) wzrost aż 220% IBM, S.S.P. Parkin

2005 – New world record
230%! Anelva & Advanced Industrial Science and Technology (AIST), Japan
2006 – 472% AIS
2008 – 604%

Magnetoresistance ratio = 230 % (room temperature)

128 Mbit ⇒ 370 mV
TMR ratio of MTJs with an MgO barrier

MgO-barrier MTJs
Tohoku-Hitachi

500%
(1010% @ 5K)

AIST

ANELVA & AIST
IBM

Al₂O₃-barrier MTJs

@ RT

Year
**TMR effect of CoFeB/MgO/CoFeB MTJ**

![Graph showing TMR effect](image)

- **MR ratio = 300% at RT**

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**FIG. 1.** TMR ratio as a function of annealing temperature for PSV MTJs having Co$_x$Fe$_{80-x}$B$_{20}$ electrodes with $x=0\% - 60\%$ and $t_{CoFeB}=4.3$ nm. The MgO thickness of the MTJs is 1.5 nm except for the open circles (2.1 nm).

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**Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature**


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**Appl. Phys. Lett. 93, 082508 (2008)**
472% AIST(2006)

Al-O barrier

MgO(001) barrier


(a) Conventional device
Using aluminum oxide (amorphous). Electrons are scattered due to disorder atom arrangement.

(b) Novel single-crystal device
Using magnesium oxide (single-crystal). Electrons can move straight without suffering dispersion.
XAS and XMCD study revealed that the interface Fe atoms are not oxidized at all.

Structure of the MTJ

Standard structure for MRAM and read head
Highly-oriented poly-crystal MgO(001) barrier


◆ Ideal for industrial applications
  • No special substrate and seed-layer are needed.
  • Highly compatible with manufacturing process
- Micro-fabrication (photolithography, Ar-ion milling, etc.)

\[ \Rightarrow \text{Junction size: } 3 \times 3 \ \mu\text{m}, \ 3 \times 12 \ \mu\text{m} \]
TMR vs. RA summary Singulus Al-O

Ta10/PtMn15/CoFe2.4/Ru0.7/CoFeB2.8/Alx/Ox/CoFeB3.5/Ta5
Ta10/PtMn20/CoFe2.2/Ru0.8/CoFe2.2/Alx/Ox/CoFe1.5/NiFe4/Ta5
Huge TMR effect expected for Fe/MgO/Fe MTJs

Fe(001) / MgO(001) / Fe(001)

Recent results

$T_g$ for the top Fe layer: 200 °C

Bias $V = 10$ mV
- $T = 20$ K: MR = 247%
- $T = 293$ K: MR = 180%

Importance of the barrier symmetry

Fe(001)/MgO(001)/Fe(001)  MR = 250 %

Fe(001)/Al-O/FeCo  MR = 20%

Coherent tunneling  Incoherent tunneling

$S$  $S$

$\Delta_{2,5}$  $\Delta_1$

$\Delta_1$

S. Yuasa, et al. – Giant room temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions, Nature vol. 3 December (2004), 868

• The origin of giant TMR effect in single-crystal Fe(001)/MgO(001)/Fe(001) structure (prepared by MBE) is coherent spin-polarized tunnelling, where the symmetry of electron wave functions play an important role.

• The oscillations as a function of tunnel barrier thickness, indicating that coherency of the wave functions is conserved across the tunnel barrier.

• The coherent TMR effect is a key to making spintronic devices with novel quantum-mechanical functions, and to developing to giga-bit scale MRAM.
Sputter-deposited polycrystalline MTJs grown on amorphous underlayer, but with highly oriented (100) MgO tunnel barrier and CoFe electrodes, exhibit TMR values of up to ~ 220% at RT and ~ 300% at low temperature.

Superconducting tunnelling spectroscopy experiments indicate that the tunnelling current has a very high spin polarization of ~ 85%.

Abstract

A 16Mb Magnetic Random Access Memory (MRAM) is demonstrated in 0.18 µm three-Cu-level CMOS with a three-level MRAM process adder. The chip, the highest density MRAM reported to date, utilizes a 1.42 µm² 1-Transistor 1-Magnetic Tunnel Junction (1T1MTJ) cell, measures 79mm² and features a *16 asynchronous SRAM-like interface. The paper describes the cell, architecture, and circuit techniques unique to multi-Mb MRAM design, including a novel bootstrapped write driver circuit. Hardware results are presented. (5 References).

News

Infineon and IBM Present World’s First 16 Mbit MRAM - Innovative Chip Design Results in Highest Density Reported to Date

2004-06-22

The increasing number of mobile applications such as smartphones and notebooks with additional multimedia features results in the need for more advanced memory chips. MRAM is a promising candidate for universal memory in high-performance and mobile computing as it is faster and consumes less power than existing technologies.
Difference between GMR and TMR

GMR: spin dependent scattering

TMR: spin dependent tunneling
Tunneling between two ideal normal and non-magnetic metals

I-V Characteristic:

Conductance \( \frac{dI}{dV} = G \):

\( G \)
Tunneling between two real non-magnetic metals

The tunneling current has the general form: \( I \propto \alpha V + \beta V^3 \)

Note that for small bias voltage there is still a linear I-V characteristics and a constant conductance \( G \). Otherwise \( G \) has a parabolic shape.
Tunneling conductance measured as a function of bias voltage at fixed H-value.

I-V Characteristic: Conductance:

Rel. + norm. conductance:

parallel

antiparallel
Spin Polarization, Density of States

Spin Polarization

\[ P = \frac{n^\uparrow - n^\downarrow}{n^\uparrow + n^\downarrow} \]

Density of states 3d

Ferromagnetic metal (Fe)

Normal metal (Cu)

Material Polarizations

Ni 33 %
Co 42 %
Fe 45 %
Ni\textsubscript{80} Fe\textsubscript{20} 48 %
Co\textsubscript{84} Fe\textsubscript{16} 55 %
CoFeB 60 %
CoFe/MgO/ 85 %

\[ n^\uparrow (E_F) > n^\downarrow (E_F) \quad n^\uparrow (E_F) = n^\downarrow (E_F) \]
Tunneling in FM/I/FM junction

\[ P_I = \frac{n_I^{\uparrow} - n_I^{\downarrow}}{n_I^{\uparrow} + n_I^{\downarrow}} \]

\[ P_{II} = \frac{n_{II}^{\uparrow} - n_{II}^{\downarrow}}{n_{II}^{\uparrow} + n_{II}^{\downarrow}} \]

\[ I_{M^{\uparrow\uparrow}} \propto n_I^{\uparrow} n_{II}^{\uparrow} + n_I^{\downarrow} n_{II}^{\downarrow} \]

\[ I_{M^{\uparrow\downarrow}} \propto n_I^{\uparrow} n_{II}^{\downarrow} + n_I^{\downarrow} n_{II}^{\uparrow} \]

\[ TMR = \frac{I_{M^{\uparrow\uparrow}} - I_{M^{\uparrow\downarrow}}}{I_{M^{\uparrow\downarrow}}} = \frac{2P_I P_{II}}{1-P_I P_{II}} \]

\[ TMR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} \]
First observation of a TMR at RT

First observation of Magnetic tunnel junction at RT

Design of a tunneling junction with mask technique

J S Moodera et al., *PRL* 74 3273 (1995)
Spin polarization

<table>
<thead>
<tr>
<th></th>
<th>Meservey/Tedrow</th>
<th>Moodera/Mathon</th>
<th>Monsma/Parkin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>+40%</td>
<td>+44%</td>
<td>+45%</td>
</tr>
<tr>
<td>Co</td>
<td>+35%</td>
<td>+45%</td>
<td>+42%</td>
</tr>
<tr>
<td>Ni</td>
<td>+23%</td>
<td>+33%</td>
<td>+31%</td>
</tr>
<tr>
<td>Ni$<em>{80}$Fe$</em>{20}$</td>
<td>+32%</td>
<td>+48%</td>
<td>+45%</td>
</tr>
<tr>
<td>Co$<em>{50}$Fe$</em>{50}$</td>
<td>+47%</td>
<td>+51%</td>
<td>+50%</td>
</tr>
</tbody>
</table>

![Graphs showing density of states and energy levels](image_url)
Type of MTJs

Standard junction

Spin valve junction (SV- MTJ)

Double barrier junction

- FM
- I
- FM

- FM
- I
- FM
- AF
- B

- FM
- I
- FM

$M \ [T]$
$H \ [kA/m]$
Application-Oriented Properties of S-V MTJ

SV-MTJ

Materials
- I (Al-O,MgO..)
- FM (Co, CoFe, NiFe)
- AF (MnIr, PtMn, NiO)
- Buffer (Ta,Cu, NiFe)

Preparation
- Sputtering deposition
- Oxidation

Treatment
- Annealing
- Field cooling

Electric
- Tunnel Magnetoresistance -TMR
- Resistance area product -RxA

Magnetic
- Interlayer coupling field $H_S$
- Exchange bias field $H_{EXB}$
- Coercive field pinned $H_{CP}$ and free $H_{CF}$ layer
- Switching field $H_{SF}$
Magnetic and Electric Parameters

- Interlayer coupling $H_S$
- Exchange coupling $H_{EXB}$

Graphs showing:
- $M$ vs $H$ for $H_{SF}$ switching fields
- $TMR$ vs $H$ with $TMR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$
Our experiments on SV-MTJs

**A** structure prepared in laboratory of University Bielefeld

**B** structure prepared in laboratory of Tohoku University
Effect of Annealing on TMR

As deposited

TMR = 13.4%

Annealed

TMR = 48%

H = 80 kA/m

Annealing temperature (°C)

H = 80 kA/m

annealing 1 hour in vacuum 10^-6 hPa
MTJ systems for electrical measurements
AGH samples

Buffers

Substrate Si(100)

SiO

Cu 30

Ta 5

NiFe 3

AlO 1.4

CoFe x

IrMn 12

Au 25

Substrate Si(100)

Cu 25

Ta 5

SiO

Substrate Si(100)

(a1) $H_{s} = 13.8$

(b1) $H_{s} = 49.5$

(a1) $H_{E_X} = 618$

(b1) $H_{E_X} = 920$

(a1) $H_{E_X} = 618$

(b1) $H_{E_X} = 920$
TEM measurement – columnar growth of grains

- soft electrode + Ta capping
- AlOx – barrier
- reference – layer (InMn/CoFe-AAF)
- Ru 30
- Ta 5
- glue
- 15.5 nm
- 14 nm
- 31.5 nm
- 3 nm
- silicon oxide
Barrier quality

AFM
a) RMS = 0.3 nm  

b) RMS = 0.6 nm

XRD – rocking curve

XRD – pole figure

a)

b)
Pole figure measurements

CoFe thickness = 15nm

buffer:

IrMn(111)

Cu(111)

CoFe(110)
AFM measurements

Rms: 0.42 nm  
Rms: 0.30 nm

buffer:

buffer:

buffer:

buffer:
Magnetic parameters

Exchange coupling \( H_{\text{EX}} \)

\[
H_{\text{EX}} = \frac{J_{\text{EX}}}{\mu_0 M_p t_p}
\]

Interlayer coupling \( H_S \)

\[
H_S = \frac{J_S}{\mu_0 M_F t_F}
\]

For applications is important small \( H_s \) and \( H_{\text{CF}} \)
Nèel coupling

roughness amplitude \( h \) determine the coupling strength

\[
H_s = \frac{\pi^2 h^2 M_p}{\sqrt{2} \lambda t_f} \left[ 1 - \exp\left(\frac{-2\pi \sqrt{2} t_f}{\lambda}\right) \right] \times \left[ 1 - \exp\left(\frac{-2\pi \sqrt{2} t_p}{\lambda}\right) \right] \exp\left(\frac{-2\pi \sqrt{2} t_S}{\lambda}\right)
\]

no interlayer coupling \( (H_S=0) \) if interfaces are smooth \( (h=0) \)
Domain images

Free layer reversal magnetization – NiFe 3nm

Pinned layer reversal magnetization – CoFe 15nm
Domain crossing in free layer of MTJ

\[
\text{Si/Ta}_5/\text{Cu}_{30}/\text{Ta}_{20}/\text{Cu}_5/\text{MnIr}_{12}/\text{CoFe}_3/\text{AlOx}_{(1.6)}/\text{NiFe}_{8}/\text{Ta}_{10}
\]

Courtesy of G.Reiss, J.Schötter, Bielefeld University, Germany
TMR measurements

TMR for strong textured (b) MTJ monotonically decreases with increasing the thickness of pinned layer. For weak textured (a) MTJ, TMR decreases significantly for $t_{\text{CoFe}} > 9$ nm.
Sputtering system– EMRALD II
Sputtering system University of Bielefeld

6 Target, 4 Inch Automatic Sputtering System
Wafer Load-Lock and Handling System
UHV sputtering system of Takahashi Lab.
Tohoku Univ.

LL 1: wafer-in

Metal depo.

LL 2: Bridge

Plasma Oxidation

Reactive sputter: surface smooth
TIMARIS: Tool status

Tool #1 – process optimization on Ø200 mm wafers since mid of March 03

Tool #2 – The Worlds 1st Ø300 mm MRAM System is Ready for Process in August 03

Clean room

Multi (10) Target Module

Oxidation / Pre-clean Module

Transport Module
Deposition of xMR stacks

Tool Set: TIMARIS

Multi (10) Target Module
Ion - Source
Handling with insitu 4-point probe, 300 mm Load lock
Sputtering deposition

@ Anelva Corp.

Sputtering machine for mass-manufacturing

RF sputtering from MgO target

8-inch substrate (thermally oxidized Si)

More than 200 films a day
MOKE with Orthogonal Coils
Measurement tools

MOKE

R-VSM

Control system for magnetic field
Lock-in amplifier
Reference Signal system
Voltmeter
Control system for piezoelectric transducer
Generator 50 kHz
Real time image processing – hardware for Kerr microscope

PC-configuration

- Monitor 1
- Monitor 2
- Graphic card (dualhead)
- AGP 528 MB/s
- Chip Set
- PCI Interface card
- PCI 132 MB/s
- 1 GB/s
- System memory
- 1 GB/s
- Pentium III processor
- 8 bit framegrabber

16-bits digital camera

Kerr microscope

- Mirror
- Analyzer
- Objective
- Polarizer
- Magnet
- Sample
- CCIR camera

M. Zoladz et al. Real time image processing during observation of the magnetic domain structures by Kerr microscopy - phys. stat. sol. (a) vol. 189, (2002), 791
Spin Transfer Torque (STT)

\[
\frac{1}{\gamma_0} \cdot \frac{dm_2}{dt} = H_{\text{eff}} \times m_2 + \frac{\alpha}{\gamma_0} m_2 \times \frac{dm_2}{dt}
\]

\[
\frac{1}{\gamma_0} \cdot \frac{dm_2}{dt} = H_{\text{eff}} \times m_2 + \frac{\alpha}{\gamma_0} m_2 \times \frac{dm_2}{dt} + p_{\text{effective}} J \frac{(\hbar)}{e\mu_0 t_2 M_{S2}} (m_2 \times (m_2 \times m_1))
\]

\text{M}_2, m_2^- \text{ FL magnetic moment}

\text{M}_1, m_1^- \text{ RL magnetic moment}

\text{Slonczewski ‘96}

\text{I} > 0 \text{ favors P state}

\text{I} < 0 \text{ favors AP state}

\text{Spin-Transfer Torque amplifies precession motion!}

T.Devolder ‘06
STT

Moment in an applied field along z with no anisotropy

a. Applied field
b. Low current → damped motion
c. High current, → stable precession
d. High current, → switching

Thin-film sample with biaxial anisotropy, easy axis in-plane along x, hard direction along z

e. Initial Magnetization
f. Easy plane, Easy axis
    Initial Magnetization

g. Stable precession
h. Switching
STT

• According to theory:
  a) electrons with certain spin orientation (filtered by pinned layer) transfers magnetization direction to the free layer – favors parallel state
  
b) electrons with spin orientation antiparallel to the pinned layer magnetization cannot pass (bands are occupied) - they accumulate in the free layer - favors antiparallel state

Deriving the critical current

Dimension less efficiency factor

\[
\left( p_{\text{effective}} \frac{\hbar I}{2e} \right) = \alpha \times \mu_0 H_{\text{eff}} M_s S V_{\text{volume}}
\]

Dimension less energy loss rate

Available energy

\[
\text{energy} = \frac{\hbar JS_{\text{surface}}}{e}
\]

Available energy

\[
\frac{\mu_0 M_s H_K V_{\text{volume}}}{2} = \text{energy}
\]

\[\mu_0 M_s \text{ – Magnetization (T)}\]

\[H_K \text{ – Anisotropy field (A/m)}\]

\[V \text{ – Volume (m}^3\text{)}\]
Critical current

\[ J_{c0} = \alpha \gamma e M_s t (H_{\text{ext}} \pm H_k \pm H_d) / \mu_B g, \]

\[ g = P/[2(1 + P^2 \cos \theta)], \]

\[ J_{c0}^{\text{ave}} \approx \frac{\alpha \gamma e M_s t H_d (g^{(P\rightarrow AP)} + g^{(AP\rightarrow P)})}{\mu_B g^{(P\rightarrow AP)} g^{(AP\rightarrow P)}} \]

\[ J_c = J_{c0} [1 - (k_B T/E) \ln(\tau_p/\tau_0)], \]

\[ E = M_s V H_k / 2, \]

\[ J_c^{\text{ave}} = J_{c0}^{\text{ave}} [1 - (2k_B T/M_s V) \ln(\tau_p/\tau_0)/H_c] \]
Micromagnetic switching modelling (OOMMF)

Current-assisted switching

Field-assisted switching

$I = 7$ mA, $P = 0.7$

$\alpha = 0.01$

$H = 796$ kA/m
Measurements (PİMM) [Q2]

- New collaboration with PTB in Braunschweig prof. Schumacher
- Precession of

\[ V(t) = A \cdot e^{-t/\tau} \cdot \sin(2\pi f t - \phi) \]
\[ \alpha = \frac{2}{\gamma \cdot \tau \cdot M_s} \]

Serrano-Guisan et al. JPD 41 (2008)
MgO WEDGE

- Samples with following structure (nm):
  Ta(5)/CuN(50)/Ta(3)/CuN(50)/Ta(3)/PtMn(16)/CoFe(2)/Ru(0.9/
  CoFeB(2.3)/**MgO**(0.6-1)/CoFeB(2.3)/Ta(10)/CuN(30)/Ru(7)

with MgO wedge sputtered in Singulus, J.Wrona

○ RA product range: 0.4 – 10 Ω μm²
BASIC CHARACTERISTICS

Field (Oe) vs. Resistance (Ohm)

- Figure a) shows the resistance behavior for a specific field range.
- Figure b) illustrates the resistance behavior under different conditions.

Current (mA) vs. Voltage (V)

- Figure c) depicts the relationship between current and voltage with two different states: parallel and antiparallel.
JUNCTION FABRICATION

- Layer structure (nm):
  Ta(5)/CuN(30)/Ta(5)/
  PtMn(20)/CoFe(2.5)/Ru(0.8)/
  CoFeB(3)/MgO(1.1)/CoFeB(3)/
  Ta(10)/CuN(10)/Ru(7)/Au(50)
- Two lithography steps
e-beam LITOGRAPHY

- Nanopillars fabricated on standard MTJ stack wafer from Singulus A.G. company (0.25, 1 μm²) by J. Wrona
- MTJ with MgO wedge wafer (0.03 – 0.15 μm²)

K. Rott, not published
Deep-submicron MTJs for CIMS experiment


TEM image

100 nm x 180 nm – MTJs

$RA = 2.4 \, \Omega (\mu m)^2$, $MR = 138\%$ at RT
Nanofabrication INESC-MN Lisbon

- Optical lithography bottom electrode
- E-beam lithography nanopillar
- Optical lithography top electrode

Dimensions (in nm):
- 40x70
- 50x80
- 60x80
- 70x100
- 90x120
- 100x200
- 150x350
- 200x450
- 300x700
- 400x900

Size: 91x121 nm²
MEASUREMENT SETUP

- Constant voltage method – measurement of current 4 probe system
- During CIMS measurement – „high” voltage switches junction, resistance measured under low voltage
CIMS MEASUREMENTS

- TMR loop (a) and CIMS loop (b) of MTJ with 0.71 nm (1) and 0.96 nm (2) thick MgO

Pillar switches with currents 2.2 mA and -3.75 mA (7.3 \times 10^6 A/cm^2, 12.5 \times 10^6 A/cm^2) from AP to P state and from P to AP state, respectively

Pillar switches with currents 1.7 mA and -2.4 mA (5.7 \times 10^6 A/cm^2, -8 \times 10^6 A/cm^2) from AP to P state and from P to AP state, respectively.
Surface energy

Complete Spin Valve structure

\[ E = \]
\[ -t_{FL} \mu_0 M_{FL} H \cos\theta_{FL} - K_{FL} t_{FL} \cos^2 \theta_{FL} \]
\[ -J_{FL} \cos(\theta_{FL} - \theta_{RL}) \]
\[ -t_{RL} \mu_0 M_{RL} H \cos\theta_{RL} - K_{RL} t_{RL} \cos^2 \theta_{RL} \]
\[ -J_{AF} \cos(\theta_{RL} - \theta_{AP}) \]
\[ -t_{AP} \mu_0 M_{AP} H \cos\theta_{AP} - K_{AP} t_{AP} \cos^2 \theta_{AP} \]
\[ -J_{EB} \cos(\theta_{AF} - \theta_{AP}) - K_{AF} t_{AF} \cos^2 \theta_{AF} \]
MOKE measurements

MOKE major loops

MOKE minor loops

2296

Field [Oe]

Kerr signal [normalized]

-4000 -3000 -2000 -1000 0 1000 2000 3000 4000

0,0
0,2
0,4
0,6
0,8
1,0

-50 0 50 100 150 200 250

0,0
0,2
0,4
0,6
0,8
1,0

Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Applications of SV-MTJ

- M-RAM
- SENSORS
- SPIN-LOGIC
- READ HEADS
Writing technologies for MRAM

Field writing

Not scalable!

CIMS writing

Effective for high density MRAM

Switching current density $J_{SW} < 1 \times 10^6 \text{ A/cm}^2$
CIMS was demonstrated in MgO-MTJs.

\[ J_{\text{sw}} = 6 \times 10^6 \text{ A/cm}^2 \]

⇒ Reduction of \( J_{\text{sw}} \) is our next goal.
Mangetoresistive Random Access Memory (MRAM)

MTJ: Magnetic Tunnel Junction

Non-volatile, high speed, infinite write endurance

Universal Memory Device
SV-MTJ Based MRAM

SV-MTJ as MRAM component must fulfill requirements

- Thermal stability
- Magnetic stability
- Single domain like switching behaviour
- Reproducibility of RxA, TMR and Asteroids

Critical switching fields $H_x, H_y$ (S-W) asteroid

Motorola: S.Tehrani et al. PROCEEDINGS OF THE IEEE, VOL. 91, NO. 5, MAY 2003
Features of M-RAM

- Non-volatility of FLASH with fast programming, no program endurance limitation
- Density competitive with DRAM, with no refresh
- Speed competitive with SRAM
- Nondestructive read
- Resistance to ionization radiation
- Low power consumption (current pulses)

- Single 3.3 V power supply
- Commercial temperature range (0°C to 70°C)
- Symmetrical high-speed read and write with fast access time (15, 20 or 25ns)
- Flexible data bus control — 8 bit or 16 bit access
- Equal address and chip-enable access times
- All inputs and outputs are transistor-transistor logic (TTL) compatible
- Full nonvolatile operation with 10 years minimum data retention

Motorola: S.Tehrani et al. PROCEEDINGS OF THE IEEE, VOL. 91, NO. 5, MAY 2003
SV-MTJ Based Spin Logic Gates

SV- MTJ as spin logic gates must fulfill requirements

- Thermal stability
- Magnetic stability
- Centered minor loop
- Single domain like switching behaviour
- Reproducibility of R, TMR

\[ V_{\text{OUT}} = I_S(R_{\text{MTJ3}} + R_{\text{MTJ3}} - R_{\text{MTJ1}} - R_{\text{MTJ2}}) \]

Features of Spin Logic Gates

- Programmable logic functions (reconfigurable computing)
- Non-volatile logic inputs and outputs
- Fast operation (up to 5 GHz)
- Low power consumption
- Compatibility to M-RAM
SV-MTJ as a read sensor for high density (> 100Gb/in²) must fulfill requirements:

- Resistance area product (RxA) < 6 Ω-μm²
- High TMR at low RxA
Requirements for industrial applications

☑ Giant MR ratio at RT
☑ Junction resistance suitable for MRAM and read head
☑ High reproducibility and uniformity
☑ Excellent bias-voltage dependence
☑ Thermal stability up to 375 °C
☑ Compatibility with mass-manufacturing process

Major requirements have been already satisfied.

Many manufacturers have introduced our technology together with Anelva’s multi-million $ sputtering machines.
Dziękuje za uwagę!