Advanced magnetic tunnel junctions based on CoFeB/MgO interfacial perpendicular anisotropy

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Spintronics devices
(Expectation as low power consumption devices)

- Magnetoresistive RAMs (MRAMs)
- Spin transfer torque RAMs (SPRAMs)

- Nonvolatility
- High speed operation
- Virtually unlimited write endurance

- Logic-in-memory architecture
  - Reduction of leak current (static power)
  - Reduction of interconnection delay

Sekikawa et al., IEDM 2008, Suzuki et al., VLSI Technology 2009
Ohno et al., IEDM 2010
Matsunaga et al. VLSI Circuit 2011
MRAM development


Capacity (bits/chip)

Year

MRAM (demo)
MRAM (product)
SPRAM (i-MTJ)
SPRAM (p-MTJ)
IBM
Freescale (Motorola)
SAMSUNG
Toshiba-NEC
Cypress
Everspin
Toshiba NEC
NTHU-ITRI
Hynix-Grandis

32Mb SPRAM
VLSI Circuit 2009

2Mb SPRAM
ISSCC 2007

Nonvolatile circuits for logic-in-memory

MTJ-Based Nonvolatile Full Adder


MTJ-Based Nonvolatile Lookup-Table Circuit Chip

Suzuki, ... Hanyu, et al., VLSI Circuit Symposium 2009.

MTJ-Based Nonvolatile Ternary Content-Addressable Memory (TCAM) cell


2kb-nonvolatile TCAM chip

Matsunaga, ... Hanyu, et al., VLSI Circuit Symposium 2011.
Technology issues toward realization of nonvolatile VLISs

To realize nonvolatile VLISs (MRAM and logic-in-memory) using the leading edge technology node, there are still issues to be addressed.

**ISSUES**

- High output (TMR ratio $> 100\%$)
- Low switching current ($I_C < F \mu A$)
- Thermal stability for nonvolatility ($E/k_B T > 40$)
- Annealing stability in back-end-of-line process ($T_a > 350^\circ C$)

- MTJs have to satisfy these requirements with scalability at the same time.
- In order to satisfy these requirements, we focus on the MTJs with perpendicular anisotropy electrodes.
Progress of MTJs

MgO-barrier MTJs

604%@RT(1144%@5K)

Tohoku Univ. & Hitachi

MgO-barrier MTJs

In-plane anisotropy
pseudo-SV

Perpendicular anisotropy
pseudo-SV

Nat. Mat., 9, 721 (2010)
M-H curves of CoFeB/MgO stack samples with different $t_{\text{CoFeB}}$

<table>
<thead>
<tr>
<th>CoFeB($t_{\text{CoFeB}}$)</th>
<th>MgO(1)</th>
<th>Ta(5)</th>
<th>Ru(10)</th>
<th>SiO$_2$/Si sub.</th>
</tr>
</thead>
</table>

$T_a = 300 \, ^\circ\text{C}$, 4 kOe, 1h

$s_{\text{in-plane}} = 0.34 \, \text{T}$

$M_s = 1.58 \, \text{T}$

$K = 2.1 \times 10^5 \, \text{J/m}^3$

$t_{\text{CoFeB}}$ dependence of $Kt_{\text{CoFeB}}$ in CoFeB/MgO stack

\[ Kt_{\text{CoFeB}} = (K_b - M_s^2/2\mu_0) t_{\text{CoFeB}} + K_i \]

- From the y-intercept, $K_i = 1.3$ mJ/m$^2$.
- The CoFeB/MgO interfacial anisotropy $K_i$ is dominant in the perpendicular anisotropy because $K_b$ is negligible.

$T_a = 300^\circ\text{C}$

$t_{\text{MgO}}$ dependence of $M_s$ and $K$

Saturation magnetization $M_s$ and effective magnetic anisotropy energy density $K$ are evaluated from the out-of-plane $M-H$ curves.

More than 3 monolayers of MgO is required to stabilize the perpendicular anisotropy induced by CoFeB-MgO interface.

Possible factor of the perpendicular anisotropy in CoFeB/ MgO stack

- $3d_{z^2}$ band of Fe is pushed up above the Fermi energy.
- The contribution of $3d_{z^2}$ orbital of Fe becomes small, resulting in appearance of perpendicular anisotropy.

TMR properties in CoFeB-MgO p-MTJs

Clear hysteresis -> top and bottom CoFeB electrodes have perpendicular anisotropy.

Junction size dependence of $I_{c0}$

$F = 40 \sim 76\text{nm} \phi$

$T_a = 300^\circ\text{C}$

$S \cdot t_{\text{CoFeB}}$

Critical current, $I_{c0}$ ($\mu\text{A}$)

Recording layer volume, $V_{\text{rec}} (\text{nm}^3) = S \cdot t_{\text{CoFeB}}$

$I_{c0}$ linearly decreases with junction area $S$

(volume $V_{\text{rec}}$).

We confirmed scalability of switching current for spin transfer torque.

Junction size dependence of $E/k_B T$

$E/k_B T$ maintained almost constant values even though the junction diameter was varied from 40 nm to 80.

$I_{c0}$ reduces in proportion to the volume of the recording layer but the $E/k_B T$ values are not affected much by the volume down to 40 nm in diameter.

Origin of the junction size dependence of $I_{C0}$ and $E/k_BT$ 

No clear reduction in $E/k_BT$ with different junction size

Nucleation type magnetization reversal

$E/k_BT = \frac{K_{eff}\pi(D_n/2)^2}{k_BT}$

$Nucleation diameter$: $D_n$

$D_n$ showed almost constant values of 40 nm in diameter, which is almost independent of junction size.

$I_{C0} = J_{C0}S = J_{C0}(\pi(D^2-D_n^2)/4)+\pi(D_n/2)^2 \propto S$

$E/k_BT = K_{eff}\pi(D_n/2)^2/k_BT \propto D_n^2$

$J_{c0}$ and $E/k_B T$ of MTJs with 40 nm diameter

- $J_{c0}$ and $E/k_B T$ are maintained after annealing at 350$^\circ$C.
- This MTJ system has a back end of the line (BEOL) compatibility.

### Table

<table>
<thead>
<tr>
<th>$T_a$ (°C)</th>
<th>TMR ratio (%)</th>
<th>$RA$ ($\Omega \mu$m$^2$)</th>
<th>$J_{c0}$ (MA/cm$^2$)</th>
<th>$E/k_B T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>124</td>
<td>18</td>
<td>3.9</td>
<td>43.1</td>
</tr>
<tr>
<td>350</td>
<td>113</td>
<td>16</td>
<td>3.8</td>
<td>39.1</td>
</tr>
</tbody>
</table>

K. Miura et al., MMM 2010, HC-02.
### Comparison of MTJs

<table>
<thead>
<tr>
<th>Type</th>
<th>Stack structure (nm)</th>
<th>Size (nm)</th>
<th>MR (%)</th>
<th>RA (Ωμm²)</th>
<th>J₀ (MA/cm²)</th>
<th>I₀ (μA)</th>
<th>ΔE/kₐT</th>
<th>I₀/Δ</th>
<th>Tₘ (°C)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-MTJ</td>
<td>CoFeB(2)/Ru(0.65)/CoFeB(1.8)</td>
<td>100x200</td>
<td>&gt;130</td>
<td>~10</td>
<td>2</td>
<td>~400</td>
<td>65</td>
<td>~6.2</td>
<td>300-350</td>
<td>J. Hayakawa et al., IEEE T-Magn., 44, 1962 (2008)</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>L₁₀-FePt(10)/Fe(t)/MgO(0.4)/MgO(1.5)/L₁₀-FePt(t)</td>
<td>Blanket</td>
<td>120 (CIPT)</td>
<td>11.8k</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>500</td>
<td>M. Yoshizawa et al., IEEE T-Magn., 44, 2573 (2008)</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>L₁₀-FePt/CoFeB/MgO(1.5)/CoFeB/Co based superlattice</td>
<td>Blanket</td>
<td>202 (CIPT)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>H. Yoda et al., Magnetics Jpn. 5, 184 (2010) [in Japanese].</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>[Co/Pt]CoFeB/CoFe/MgO/CoFe/CoFeB/TbFeCo</td>
<td>Blanket</td>
<td>85-97 (CIPT)</td>
<td>4.4-10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>225</td>
<td>K. Yakushiji et al., APEX 3, 053033 (2010)</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>[CoFe/Pd]/CoFeB/MgO/CoFeB/[CoFe/Pd]</td>
<td>800x800 N (113)</td>
<td>100 (113)</td>
<td>18.7k (20.2k)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>350 (325)</td>
<td>K. Mizunuma et al., MMM&amp;INTERMAG2010</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>CoFeB (1)/TbCoFe (3)</td>
<td>130 φ</td>
<td>~15</td>
<td>4.7</td>
<td>650</td>
<td>107</td>
<td>6.08</td>
<td>-</td>
<td>-</td>
<td>M. Nakayama et al., APL 103, 07A710 (2008)</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>L₁₀-alloy</td>
<td>50-55 φ</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>49</td>
<td>56</td>
<td>0.88</td>
<td>-</td>
<td>T. Kishi et al., IEDM 2008</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>Fe based L₁₀ (2)/CoFeB (0.5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>H. Yoda et al., Magnetics Jpn. 5, 184 (2010) [in Japanese].</td>
</tr>
<tr>
<td>p-MTJ</td>
<td>CoFeB/MgO/CoFeB</td>
<td>40 φ (124)</td>
<td>113 (16)</td>
<td>3.8 (3.9)</td>
<td>48 (49)</td>
<td>39 (43)</td>
<td>1.23 (1.14)</td>
<td>350 (300)</td>
<td>S. Ikeda et al., Nat. Mat. 9 (2010) 721. K. Miura et al., MMM2010,HC-02</td>
<td></td>
</tr>
</tbody>
</table>

These p-MTJ technologies will be a promising building block for nonvolatile VLSIs using spin-transfer torque switching.
Issue for p-MTJs

Bit Information “0”
- Parallel state
- Low resistance
- Different polarity = Stable
- Free Reference

Bit Information “1”
- Antiparallel state
- High resistance
- The same polarity = Unstable

The thermal stability $\Delta_p = E/k_B T$ of anti-parallel state in p-MTJs becomes low by comparison with parallel state.
Enhancement of thermal stability

$$\Delta P_{AP} = \Delta \left[ 1 \pm \frac{H_s}{H_{c0}} \right]^2$$

**Conventional structure**

- $H_s$ decreases by employing step structure with large reference layer.
- $\Delta P_{AP}$ increases with decreasing diameter of reference layer.

**Stepped structure**

- $H_s$ decreases by employing step structure with large reference layer.
- $\Delta P_{AP}$ increases with decreasing diameter of reference layer.
Two types of p-MTJs

Conventional structure

Stepped structure

$F$: Feature size

K. Miura et al., 2011 VLSI Technology, 11B-3.
$H_s$ in two types of p-MTJs

<table>
<thead>
<tr>
<th></th>
<th>Conventional structure</th>
<th>Stepped structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMR ratio (%)</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>$RA$ (Ωµm²)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>$H_s$ (mT)</td>
<td>22</td>
<td>5</td>
</tr>
</tbody>
</table>

$H_s$ can be reduced by using stepped structure.

K. Miura et al., VLSI Technology 2011, 11B-3.
ΔP and ΔAP in two types of p-MTJs

\[ \text{Probability} = 1 - \exp \left\{ 1 - \frac{\tau_p}{\tau_0} \exp \left[ \Delta \left( 1 - \frac{H - H_s}{H_{c0}} \right) \right] \right\} \]

\[ \Delta_{P,AP} = \Delta \left( 1 \pm \frac{H_s}{H_{c0}} \right)^2 \]

### Table

<table>
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<tr>
<th></th>
<th>Conventional structure</th>
<th>Stepped structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔP</td>
<td>71.2</td>
<td>72.9</td>
</tr>
<tr>
<td>ΔAP</td>
<td>46.5</td>
<td>70.1</td>
</tr>
</tbody>
</table>

ΔAP in stepped structure increases.
Cell area of stepped structure

Cell area of 0.09 $\mu\text{m}^2$ (300nm$\phi$) in the stepped structure corresponds to SRAM cell area at 32 nm technology node.

Cell area can be down to 0.04 $\mu\text{m}^2$ (200nm$\phi$) without degrading the retention time over 10 years, which corresponds to SRAM cell area at 20 nm technology node.
Summary

- We have demonstrated that the critical current $I_{c0}$ in CoFeB/MgO perpendicular anisotropy MTJs (p-MTJs) can be scaled down with decreasing recording layer volume.

- The thermal stability factor $E/k_B T$ can be maintained at about 40 even though the recording volume was reduced to 40 nm. The magnetization reversal in CoFeB/MgO p-MTJs is dominated by nucleation type magnetization reversal (nucleation diameter ~40 nm).

- CoFeB/MgO p-MTJs show the high TMR ratio of more than 100%, high thermal stability at dimension as low as 40 nm diameter and a low switching current of 49 $\mu$A at the same time.

- CoFeB/MgO p-MTJ with step structure shows the enhancement of thermal stability in antiparallel state, which achieves thermal stability for data retention time over 10 years.