Perpendicular MTJ stack development for STT MRAM on Endura PVD platform

Mahendra Pakala,
Silicon Systems Group, AMAT

Dec 16th, 2014
AVS 2014

*All data in presentation is internal Applied generated data*
OUTLINE

- STT MRAM Background
- Perpendicular Magnetic Tunnel Junction Basics
- Perpendicular Magnetic Tunnel Junction Using Endura PVD
Key Drivers for STT MRAM

Today’s Hierarchy

- CPU/ Register
- L1 Cache - SRAM
- L2, L3 Cache - SRAM
- Main Off Chip Memory - DRAM
- Local Storage - FLASH
- Local Storage - HDD
- Offline Storage - TAPE

Scaling challenges of current RAM
Latency gap between Storage and RAM

STT MRAM
Memory Performance Comparison

- STT RAM attributes: Endurance, Fast Access & Non-Volatility
**STTRAM BIT OPERATION**

**Storing Data**

Magnetic direction of storage layer

<table>
<thead>
<tr>
<th>SL</th>
<th>FM “0”</th>
<th>INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td>FM</td>
<td></td>
</tr>
</tbody>
</table>

Energy

\[ \Delta E = KV \]

\[ K, \text{ Anisotropy is material property and, } V \text{ is the volume of storage layer} \]

<table>
<thead>
<tr>
<th>N-B thermally activated flip probability:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ F(t) = 1 - \exp \left[-N \frac{t}{\tau_0} \exp \left(-\frac{\Delta E}{k_B T} \right) \right] ]</td>
</tr>
</tbody>
</table>

\[ \Delta (= \frac{\Delta E}{k_B T}) \text{ is a measure of length of data retention.} \]

**Reading Data**

Reading is done by sensing the resistance (high or low)

Tunneling Magneto-resistance (TMR):

\[ \text{TMR\%} = \frac{R_{AP} - R_P}{R_P} \times 100 \]

**Writing Data**

Writing is done using Spin Transfer Torque (STT) switching (MRAM, a precursor used magnetic field writing – not scalable)

Switching current:

\[ I_c \propto \frac{\alpha}{\eta} (\Delta) \]

Low \( I_c \) at high \( \Delta \) is one of the tradeoffs in design

**Storing Data**

Magnetic direction of storage layer

<table>
<thead>
<tr>
<th>SL</th>
<th>FM “0”</th>
<th>INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td>FM</td>
<td></td>
</tr>
</tbody>
</table>

Energy

\[ \Delta E = KV \]

\[ K, \text{ Anisotropy is material property and, } V \text{ is the volume of storage layer} \]

<table>
<thead>
<tr>
<th>N-B thermally activated flip probability:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ F(t) = 1 - \exp \left[-N \frac{t}{\tau_0} \exp \left(-\frac{\Delta E}{k_B T} \right) \right] ]</td>
</tr>
</tbody>
</table>

\[ \Delta (= \frac{\Delta E}{k_B T}) \text{ is a measure of length of data retention.} \]

**Reading Data**

Reading is done by sensing the resistance (high or low)

Tunneling Magneto-resistance (TMR):

\[ \text{TMR\%} = \frac{R_{AP} - R_P}{R_P} \times 100 \]

**Writing Data**

Writing is done using Spin Transfer Torque (STT) switching (MRAM, a precursor used magnetic field writing – not scalable)

Switching current:

\[ I_c \propto \frac{\alpha}{\eta} (\Delta) \]

Low \( I_c \) at high \( \Delta \) is one of the tradeoffs in design
Switching Current (Writing) vs. Data Retention

Switching Current ($I_{co}$)

$$I_{co} \propto \frac{\alpha M V}{\eta} (H_{eff})$$

- moment of SL
- damping const.
- Volume of SL
- spin polarization
- effective field

Data Retention / Thermal Stability ($\Delta$)

$$\Delta = \frac{VH_k M_s}{2k_B T}$$

- Anisotropy
- (~ effective field for pMTJ)

Low $I_{co}$ at high $\Delta$ is key challenge for Magnetic Tunnel Junction (MTJ) stack development (along with high TMR, large pinning and thermal stability of stacks)
STT RAM Technology Options

- Perpendicular MTJ preferred for scalability
- Many new thin films (few Å) and, interfaces to control
Key Enabler: Magnetic Tunnel Junctions (MTJ)

- In-plane MTJ manufacturability demonstrated in HDD/MRAM (in products since 2007)
- Current Industry focus is on Perpendicular MTJ to enable high density arrays

**HDD:** First Adopter of MgO MTJ
(WDC, HGST, Seagate, TDK)

**MRAM:**
(Everspin)

**STT MRAM**
Sampling:
Everspin
TDK/Headway
Developing:
Toshiba/Hynix
Samsung
Global Foundries
Micron
Intel

**IN PRODUCTION**

**Pilot/R&D**
OUTLINE

- STT MRAM Background
- Perpendicular Magnetic Tunnel Junction Basics
- Perpendicular Magnetic Tunnel Junction Using Endura PVD
Magnetic Tunneling Junction (MTJ)

- 2 spin independent channel conduction – amorphous barrier
- Spin filtering for tunneling through MgO crystalline barrier

RA(Ω.μm²) = RP × A
TMR% = \( \frac{R_{AP} - R_P}{R_P} \times 100 \)
Growth and Annealing of MgO MTJ

As-deposited
- Cap layer (Ta or Ru)
- Amorphous CoFeB
- Textured MgO(001)
- Amorphous CoFeB
- Ru (spacer of SyF)

After annealing
- Cap layer (Ta or Ru)
- Textured bcc CoFeB(001)
- Textured MgO(001)
- Textured bcc CoFeB(001)
- Ru (spacer of SyF)


Annealing at 300° to 450°C to obtain high TMR%
Anisotropy in Magnetic Films

Anisotropy: Preferred direction/axis of magnetization. Many sources…only 2 shown here

- **Shape Anisotropy (in-plane)**
  - Demagnetizing field ($H_D$)

- **Interfacial Anisotropy (⊥ to plane)**
  - Symmetry breaking
  - Strain
  - Electron hybridization

For a film to have **perpendicular (⊥)** magnetization, need to satisfy:

$$H_K - H_D > 0$$

$$H_K = \frac{2K}{M_S}$$

$$K = K_V + \frac{K_S}{t}$$

- Effective bulk Anisotropy
- Interface

**Metal or Oxides**

**Ferromagnet**
Stray Field Balance in MTJ: SAF

SAF: Synthetic Anti-Ferromagnet

- Reduces stray field on storage layer.
- Increases pin layer stability.

RKKY Oscillatory Coupling in non-magnetic spacer layer (Ru, Ir, Cr,...)

Eg., CoFe\Ru\CoFe(FCC)

\[ j > 0 \] Ferromagnetic coupling

\[ j < 0 \] Anti-ferromagnetic coupling
STT MRAM: pMTJ Stack Engineering Summary

PMA
Interface & Bulk PMA

Basic MTJ
Spin Dependent Coherent tunneling

SyAF /SAF Pin MTJ
RKKY coupling

- Sub Å control of film thickness and interface roughness
- MgO growth condition for crystal texture/quality (low impurity, OH) and anneal
- Crystalline texture for magnetic materials

RKKY coupling as function of Ru thickness

Atomic level matching across interface

Thickness and thermal budget control

Applied Materials at AVS TFUG 2014
OUTLINE

- STT MRAM Background
- Perpendicular Magnetic Tunnel Junction Basics
- Perpendicular Magnetic Tunnel Junction Using Endura PVD
Perpendicular MTJ Stack Deposition

Endura PVD Platform
Perpendicular MTJ Stack Blanket Film Performance: Transport/Tunneling (CIPT)

High TMR and BEOL Thermal Budget Compatibility for MTJ Stack Dep
Perpendicular MTJ Stack Blanket Film Performance, Magnetics (VSM)

- Large pinning strength for SAF and square loop for Free Layer
Patterned pMTJ Performance Metrics

1) Quasi Static Test (measure MTJ resistance as field is scanned),
2) Pulse current measurements

High TMR for fast read
Low $H_{off}$ for reliability
Low $R_P$ sigma for yield
High $H_c$ ($\propto H_k$) for data retention

\[ TMR = \frac{R_{AP} - R_P}{R_P} \times 100\% \]
MTJ Size Dependence (Patterned): Top Pin

- High TMR and $H_C$ can be achieved by MTJ stack optimization and etch process tuning.
- 20nm bits with highest TMR of ~153% and $H_C$ ~ 850 Oe.
Switching Current (Ic) & Scalability

- Low switching current (~20uA) obtained by pMTJ stack optimization
- Δ (data retention) ~50 for ~20nm.
Summary

- STT MRAM offers good endurance, speed and non-volatility. Hence being considered for embedded, cache and stand alone memory.

- One key challenge for making high density STT MRAM is developing materials with low switching current (I_{co}) at high thermal stability (Δ), with high TMR% & pinning.

- Using Endura PVD system, perpendicular MTJ stacks with performance suitable for dense arrays were demonstrated.
  - 20nm patterned MTJ: I_{co} of ~ 20uA, Δ > 50, patterned TMR of ~ 153%

Thanks for your attention!
Turning innovations into industries.