Fabrication and Transport properties of nanostructured magnetic tunnel junctions

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Introduction
Tunnel junctions

Experiment
Nanofabrication

Results and Discussion
Fabrication of nano-pillars and $R(T)$

Summary
What’s Tunneling
Types of Tunneling Mechanism

- Emission (Hot electron tunneling)
- Trapping assisted tunneling (hopping)
- Elastic trapping assisted tunneling
- Inelastic trapping assisted tunneling
- Direct tunneling

Current through tunneling barrier

\[ j \sim \int_0^{E_m} dE \left\{ D_1(E) D_2(E + eV) T(E) \left[ f(E) - f(E + eV) \right] \right\} \]

\begin{align*}
H \psi(x) &= E \psi(x) \\
H &= \frac{p^2}{2m} + \phi(x)
\end{align*}

\begin{align*}
I: \psi(x) &= A e^{ikx} + B e^{-ikx} \\
II: \psi(x) &= C e^{ix} + D e^{-ix} \\
III: \psi(x) &= F e^{ikx}
\end{align*}
Introduction

I-V Characteristic of Direct Tunneling

I-V Characteristic

Conductance $dI/dV = G$

Low bias

Linear

Constant

Non-linear

Parabolic

Vacuum level

$E_F, \phi, E$

Weak insulating-like temperature dependence of the conductance (or resistance)
Introduction

The Electrode Effect of Tunneling

Other than NM/I/NM

First observation of TMR at RT

**Introduction**

*MR*

**MTJ 130×230 nm**

**MR**

**MR ratio ~ 130%**

**RA ~ 9 Ω μm²**

- Ru (10nm)
- MnIr (7.5nm)
- CoFeB/Ru/CoFe (3.6/0.85/3nm)
- Mg/MgO (0.45/0.64nm)
- CoFeB (4nm)
- Ta/Ru/Ta (5/40/5nm)

\[ TMR = \frac{2P_I P_{II}}{1 - P_I P_{II}} \]

*M. Julliere, Phys. Lett. 54A, 225 (1975)\]
Introduction

Applications

Signal
Time

read head
write head

Read head

Data storage

Reading a bit
Writing '1'
Writing '0'

word line
bit line
Giant tunneling magnetoresistance up to 410% at room temperature in fully epitaxial Co/MgO/Co magnetic tunnel junctions with bcc Co(001) electrodes

Review

Field switching

Spin-transfer torque switching
**Temp-dependent resistance of Al₂O₃ Based MTJ**

The quality of barrier


The effect of electrodes

J. Ventura et al, APL 90, 032501 (2007)
J. Ventura et al, JPCM 19, 176207(2007)

L. Yuan et al, PRB 73, 134403 (2006)
**Temp-dependent resistance of MgO Based MTJ**

The quality of barrier

\[ G(\theta) = G_T\{1 + P_1 P_2 \cos(\theta)\} + G_{SI} \]


The evidence of non-direct tunneling in MTJ

\[ G(\theta) = G_T\{1 + P_1 P_2 \cos(\theta)\} + G_{SI} \]

Model for Temperature Dependent Conductance

\[ G(T) = G_T(T) \left(1 \pm P_1 P_2 \cos \theta\right) + G_{SI} \]

Spin-dependent term
M. Julliere, Phys. Lett. 54A, 225 (1975)

Spin-independent term

\[ G_T(T) = G_0 \frac{CT}{\sin(CT)} \]

\[ C = 1.387 \times 10^{-4} \frac{d}{\sqrt{\phi}} \]

Bloch’s Law
\[ P(T) = P_0 (1 - \alpha T^{3/2}) \]

Dominant

Weak insulating-like temperature dependence of the conductance (or resistance)
Key equipment for nanofabrication

SEM modified for direct writing system
**Experiment**

**Electron-beam lithography**

- **spin coating PMMA**
- **e-beam exposure**
- **development**

**Single layer: PMMA**

**Bi-layer: PMMA / PMMA-MAA**
**Electron-beam lithography**

Experiment

- Thermal evaporation
  - 100nm

- Lift-off
  - 300nm

- 29-Oct-04 4300SE WD15.1mm 15.0kV x35k 1um
Bottom-up process for MTJ Cells

(a) Open the metal mask through ion milling

(b) Create the undercut through wet etching

(c) Deposit multilayer and in situ contact

(d) Pattern the layout through lithography

(e) Top electrode and bottom electrode with active layer, 200 nm scale
Top-down process for MTJ cells

Two-step ion-milling


P. G. Glöersen, J. Vac. Sci. Technol. 12, 28 (1975)
Top-down process for MTJ Cells-I

Open-trench technique

Top-down process for MTJ Cells-II

**Etch-back technique**


Top-down process for Nano-MTJ Cells-III

Sheet film

E-beam lithography
Two steps ion-milling etching

(a) Photo-resist (ZEP520A)
MTJ
Bottom electrode

Self-aligned Technique

(b) Capping insulator to isolate electrodes
SiO_x

(c) Remove PR to open a window for nano-contact

(d) Capping top electrode

100 nm
Results and Discussion

Nanopillars

100 nm device after etching
Results and Discussion

Nanopillars

Sub-100 nm device after etching

High density MTJ array
Diameter 55 nm
Nano-pillars and devices

Results and Discussion
Layer Structure and Magnetic Properties of MgO MTJ

Sub./Ta(5)/Ru(40)/Ta(5)/CoFeB(3)/MgO(0.78)/CoFeB(3)/CoFe(0.5)/Ru(0.85)/CoFe(2.5)/MnIr(7.5)/Ru(10)
(unit: nm)

Free layer
(green + black) SAF

0.3 μm x 0.5 μm
RA=7.06 Ω μm²

Results and Discussion
Results and Discussion

Magnetoresistance

MTJ 140% MR

Resistance (Ω)

H (Oe)

500 nm
Results and Discussion

Current-Induced Switching

Set at AP

H=0 Oe

Pulser
Results and Discussion

**Temperature Dependent TMR, R(T)**

![Graph showing Temperature Dependent TMR, R(T)](image)

<table>
<thead>
<tr>
<th>Shape</th>
<th>Dimension (nm)</th>
</tr>
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<tbody>
<tr>
<td>OD</td>
<td>ellipse 300x500</td>
</tr>
<tr>
<td>R1</td>
<td>ellipse 200x400</td>
</tr>
<tr>
<td>R3</td>
<td>ellipse 200X800</td>
</tr>
<tr>
<td>R3-2</td>
<td>ellipse 200X800</td>
</tr>
</tbody>
</table>
1. Various processes for making MTJ cells  
2. Fabrication of nano-scaled MTJ cells using electron beam lithography.  
3. Field switching and current-induced switching on nano-scaled MTJ cells.  
4. Interesting temperature dependent resistance at Low/High state of nano-scaled MTJ cells.
Thanks for your attention