Magnetic and Transport Properties of GMR/Spin-Valves and Their Components

H. (Ed) Fujiwara, T. Zhao, K. Zhang, Y. Sakurai

MINT Center and Department of Physics and Astronomy
The University of Alabama

in collaboration with

G. J. Mankey (Physics), M. Sun (Mathematics)

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Subtitles:

1. Confined current path (CCP) CPP-spin valves

2. Thermal effects on magnetic properties of polycrystalline ferro/antiferromagnetic exchange coupled layers

3. Monte Carlo simulation of torque curves and spin-configurations for single-crystalline ferro/antiferromagnetic exchange coupled layers
Design and Preliminary Experiment on CCP-CPP Device

T. Zhao, H. Fujiwara, K. Zhang, and G. J. Mankey

MINT Center
The University of Alabama

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Introduction

Increase of recording density

Higher and higher read head sensitivity

Candidates for replacing CIP-Spin Valves:

TMR-Spin Valves: Too high $R$

CPP-Spin Valves: Too low $R$

Goal: Increase $R$ by confining the current path (CCP) to meet the needs for 0.1~1Tb/in$^2$ recording[1].

$\Delta RA: 15$~$150\,\text{m}\Omega\mu\text{m}^2$ (state of the art: $1$~$2\,\text{m}\Omega\mu\text{m}^2$)

Fujitsu: $20\,\text{m}\Omega\mu\text{m}^2$ (specular CIP type CPP) [2, 3]

\[ \Delta R \propto \frac{w}{(h^{} \cdot t)} \]
\[ \Delta R \propto \frac{t}{(h^{} \cdot w)} \]

Increase recording density (beyond 100Gb/in\(^2\))

Mostly decrease track width (\(r_{bc}\) decreases, \(\sim w/h\) ratio decreases)

CIP output decreases ; CPP output increases
<table>
<thead>
<tr>
<th></th>
<th>TMR</th>
<th>CPP-SV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^*A$</td>
<td>$\sim 10\Omega \mu \text{m}^2$</td>
<td>$\sim 0.01+??\Omega \mu \text{m}^2$</td>
</tr>
<tr>
<td>MR ratio</td>
<td>$\sim 10%$</td>
<td>10~20%</td>
</tr>
<tr>
<td>$\Delta R^*A$</td>
<td>$\sim 2\Omega \mu \text{m}^2$</td>
<td>1~2m$\Omega \mu \text{m}^2$</td>
</tr>
<tr>
<td>Noise</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Resonance</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>frequency</td>
<td></td>
<td></td>
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<tr>
<td>$A=h^*w$</td>
<td></td>
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</tbody>
</table>
Present Status and Goal

$A_{element} = A_{bit}$
$R_{element} = 25 \, \Omega$

$1Tb/\text{in}^2$
$(6.5 \times 10^2 \text{nm}^2)$

$100Gb/\text{in}^2$
$(6.5 \times 10^3 \text{nm}^2)$

$TMR$

$MR (%)$

$RA(\Omega \text{\mu m}^2)$
\[
\Delta R = \left( \frac{\Delta \rho^*}{A} \right) \frac{(1 - \cos \Theta)}{2}
\]

\( \Delta \rho^* \sim 1 \sim 2 \text{ m} \Omega \mu \text{m}^2 \),

\( i_{\text{max}} \sim 10^8 \text{ A/cm}^2 \)

\( V_{\text{out}} \sim 1 \sim 2 \text{ mV} \)

\( A \sim 10^{-11} \text{ cm}^2 (25 \text{ nm} \times 25 \text{ nm} \text{ for } 1 \text{Tb/in}^2) \)

\( W = V_{\text{out}}^2 / (\Delta R(MR)) \)

\( \Delta R \sim \text{several } \Omega \)

\( W \sim 10 \mu \text{W} \text{ (for } (MR)=10\%) \)
Concept of CCP- CPP SV
An Example of CCP-CPP Sensor

Insulator layer with pinholes
with metal embedded

Pinned layer
Substrate
Free layer
Electrodes
Advantages

1. Small $A_{\text{cond}}/A_{\text{element}}$. Reduction of power consumption (keeping output and SNR)

2. Avoid edge effect
Various Conceivable Conductor-Insulator Composite Layers

Lithographic Methods

Single dot

Multiple dots

Natural formation
Self-aligned (or disordered) holes

Mosaic structure
Issues to be studied

- Structure design
- Fabrication method of an insulator layer with pin-hole(s) (artificial: E-beam or SPM lithography/natural: selfassembly or random)
- Metal imbedding (electrodeposition, co-sputtering of metal and insulator)
- Effect of electron confinement in nano-tubes (MR ratio??)
Electrodeposition through pinhole

Inhomogeneous pinholes cause inhomogeneous growth of mushrooms

Sputter method is easier to control.
Designs of CCP-CPP device

(sputtering)

Cu
IrMn
CoFe
SiO₂

CCP1
CCP2
CCP3
CCP4

(Specular Scattering)
Assuming that main contributions to MR come from the interfaces between conducting layer and the free and pinned layers, the insulator layer with pin-holes was inserted at different location and then MR was calculated.

**Cu** 1.0 $\mu\Omega cm$ **CoFe** 10.0 $\mu\Omega cm$
Evaluation of Designs using equivalent circuit (II)
In designs CPP1 and CPP2, both MR and MR ratio increase with the increase of the total resistance. In design CPP3, the increase rate of MR is smaller and the MR ratio is almost constant. In design CPP4, MR has a slight increase but the MR ratio decreases. CPP2 is the prime design for CCP-CPP devices.
Mechanism of $\Delta R/R$ Enhancement

$\Delta R = (r_2 - r_1)$

$R = r_0 + r_1$

$\Delta R/R = (r_2 - r_1)/(r_0 + r_1)$

$\Delta R = 2(r_2 - r_1)$

$R = 4r_0/3 + 2r_1$

$\Delta R/R = (r_2 - r_1)/(2r_0/3 + r_1)$
Fabrication Procedure

1. Make multilayer using magnetron sputtering

2. Define bottom electrode by lithography

3. Define structure near CPP junction by lithography, sputtering and lift off

4. Make top electrode by sputtering and lithography.
Device Geometry

*Mask: top electrode + bottom electrode*
Device Geometry
MR Measurement

Computer

Lock-in Amplifier

Power Source

V

I

Nominal area

Active area?

\[ \Delta R A_{\text{nom}} \approx 500 \text{m} \Omega \mu \text{m}^2 \]
\[ \Delta R / R \approx 0.25\% \]

MR transfer-curve observed for a CCP-CPP structure with a nominal area of 50\(\mu\)m\(^2\). At this moment, it is difficult to evaluate the active area of the sample element.
Conclusion

1. Determined an ideal structure for proposed CCP-CPP by net-circuit model.


\[ \Delta R A_{\text{nom}} \sim 500 \text{ m}\Omega \mu \text{m}^2 \text{ (actual element area?)} \]

\[ \Delta R/R \sim 0.25\% \text{ (cause of very high extra-resistance?)} \]
Future Work

1) Reduce the serial resistance by optimizing the lithography process.

2) Precise control of the effective area of the CPP element.

3) Improve MR by fine adjustment of interfacial structure in the multilayer.

4) Theoretical and experimental evaluation of quantum effect