Magnetic and Transport Properties of GMR/Spin-Valve Structures

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Objectives

High density magnetic recording

Goal: 100 Gb/in²  →  1 Tb/in²

Spintronics

(Electronics in which a new freedom of spin is incorporated)

Extension of work on carbon-nanotubes utilizing a confirmed long spin-relaxation length (>0.4 µm).
Projects

Spin valves
A new type of CPP spin-valves (for 0.1~1 Tb/in²)
Magnetization behavior in exchange coupled layers.
(A key component of spin-valves:
Find controlling factors)
Determination of magnetic parameters of very thin AF-layers (Numerical analysis of experimental data)

Magnetic nanostructures (DOD)
Observation techniques of nanoscopic magnetization structures
(Reconstruction of magnetization distribution from MFM images)

Spin transport through carbon-nanotubes (NSF)
(Extension of work on spin-resoled STM)
Subtitles

1. Design and preliminary experiment on CCP-CPP device.

2. Training effect of F/AF couple systems.
   a. AF-layer thickness dependence.
   b. Annealing effect.

3. MFM observation of magnetization reversal process of F/AF coupled layers.

4. Data driven mathematical models and their application to magnetic parameter determination.
Why CPP?, State of the Art of CPP

Increase of recording density  →  Decrease in CIP output
TMR: Too high a resistance!  Δρ*<10 Ωμm²

\[ \Delta R = \left( \frac{\Delta \rho^*}{S} \right) \frac{(1-\cos \Theta)}{2} \]

Δρ* ~ 1~2 mΩμm²,

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

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

\( S \sim 10^{-11} \text{cm}^2 \) (30nm × 30nm for 1Tb/in²)

→ \( R \sim \) several Ω

\( W \sim 1\mu W \)

* TMR: \( R > 10 \text{k } \Omega \)

Fujitsu (~10 mΩμm²; variation of specular SV)
Present Status and Goal

GOAL

CPP

RA ($\Omega \mu m^2$)

$S_{element} = S_{bit}$

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

$1Tb/in^2$

$100Gb/in^2$

TMR

$MR (%)$

$RA(\Omega \mu m^2)$

$S_{element} = S_{bit}$

$R_{element} = 25 \, \Omega$
Concept of CCP- CPP SV

- Substrate
- Conductor
- Insulator
- Pinned layer
- Free layer
- Electrodes
Advantages

1. Increase of the element resistance
   \[ R \rightarrow 20 - 200 \, \Omega \]

2. Reduction of power consumption
   \[ \rightarrow \frac{S}{S_0} \]

3. Edge effect avoidance
   (insensitive parts, etc.)
Designs of CCP-CPP device

CCP2CPP1
(CCu
IrMn
CoFe
SiO2
CCP3
(Specular Scattering)
CCP4

Cu
IrMn
CoFe
SiO2
Simulation Results

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.
Geometry of Device
MR measurement

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

MR transfer-curve observed for a CCP-CPP structure with a nominal area of 50µm². However, at this moment, it is difficult to evaluate the active area of the sample element.
Training effect-Type I
Si/Cu/NiFe(12nm)/IrMn(3.2nm)/Cu

M (a. u.)

H (Oe)

Magnetic properties (Oe)

|H_{sw}^+|

|H_{sw}^−|

Training cycle (n)

The University of Alabama
Training effect ratios $\omega$ as a function of $t_{AF}$

$$\omega = \frac{(H_{sw}-(0) - H_{sw}-(20))}{H_{sw}-(0)}$$

A: NiFe(12nm)/IrMn ($t$ nm)
B: IrMn ($t$ nm)/NiFe(12nm)
Mechanism of Causing $H_{eb}$ and $H_c$-Enhancement

Magnetization of F layer $M$

$AF$ surface net moment $S_{net}$

$r = J/2Kt < 0.5$

$H_{eb}$

Switched AF grains

$r = J/2Kt > 0.5$

$H_c$
Mechanism of Training Effect

$H_{eb} < H_c$

Type 1

$J < K_{AF}t_{AF}$

$J > K_{AF}t_{AF}$

initial

trained

switched by training

fixed by training

$H_{eb} > H_c$

Type 2
Effect of AF-AF Coupling

(33x33 10nm cubes, $\beta = 30^\circ$, $J_{AF-AF}^{\text{mean}}=0.05\text{ergs/cm}^2$, $r=0.45$)

$J_{AF-AF}^{\text{mean}} = 0.001\text{ergs/cm}^2$

$0.01$

$0.05$

$0.1$
Fitted curves for $H_{sw}^-$ vs annealing time for different energy barriers

- $E_1 = 1.13$ eV is obtained from fitting, $E_2$ is negligible.

- The distribution of activation energy might be rather narrow.
Vacancy relocation model
Sample preparation for MFM observation

Problems of MFM:
1. The observable area of a commercialized MFM (about 100 $\mu m \times 100$ $\mu m$) is too small to capture the whole reversal process in a sheet film.

2. Tip-sample interaction, especially during the near-surface scan (1st pass) at Lift Mode, may disturb the “real” domain structure in the sample.

Solutions:
1. Thin film samples were made into arrays of circular elements (60 $\mu m$ in diameter) by photolithography.

2. Put a relatively thick capping layer (Cu 45nm) on top of the magnetic layers.
Domain structures in CoFe(10nm)/IrMn(5nm)

The magnetic reversal process is rather localized because of the distributed pinning fields at the F/AF interface so that the hysteresis loops of the sheet film and the element array are very much alike. 360° walls were formed indicating that the reversal process proceeded through incoherent rotation.
Suggested Model II

With increasing applied field
Domain structures in CoFe(20nm)/IrMn(5nm)

The reverse domains were formed both inside and at the edge of the sample, separated by \(180^\circ\) Néel walls from the remaining parts. These reverse domains expanded through wall motion. The enhancement of the exchange coupling inside the F layer with the increase in the F layer thickness causes the change of reversal mechanism.
Conclusion
CCP-CPP: Determined an ideal structure for proposed CCP-CPP by net-circuit model.
Succeeded in measuring MR response curve for a preliminary experimental sample. \[ \Delta R A_{\text{nom}} \sim 0.5 \Omega \mu m^2, \Delta R/R \sim 0.25\% \]
(actual element area: unknown!),
Very high extra-resistance?

F/AF effect: Training effect (AF-thickness, annealing).
Strong dependence on AF-layer thickness
Recoverable by annealing but not totally
(narrow \( \Delta E \sim 1.1 \text{eV}: \text{different mechanism from spin-switching} \))

MFM observation of magnetization reversal
Systematic dependence on F-layer thickness
Future work

CCP-CPP: Determine the actual element area and seek for cause for the extra-resistance.

Lithographic control of current confinement.

Effect of the current-driven spin excitation and other quantum effects.

Feasibility for MRAM use including the thermal stability improvement.

F/AF effect: Detailed mechanism of the training effect with a help of simulation.

Experimental confirmation of the presumed mechanism.