Spin Transport in Nanostructures

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Overview

• This effort focuses on the design of alternative geometries and the exploitation of new phenomena to improve on existing spin-dependent transport devices and develop novel ones.

• Review of the ongoing work and discussion of the future work on:
  – Confined Current Path-CPP designs for next generation read heads
  – Fabrication of high quality nanostructures for the investigation of current induced switching and ballistic magnetoresistance by *electrochemical methods* and *glancing angle evaporation*
Calculation of GMR Properties of CCP-CPP Spin Valves

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Funded by NSF-MRSEC

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Conventional CPP Spin Valves

- With increasing miniaturization \( \Delta V = I \cdot \Delta R = I \cdot R \cdot MR \):
  - for CIP sensors, decreases
  - for CPP sensors, increases
- \( R \) of CPP sensors is much smaller, thus the signal is also smaller \( \rightarrow \) need much higher current
- \( \Delta V \) is limited by the capability to dissipate the power generated (P) or by electromigration effects (J), depending on the element size
Confined Current Path CPP Spin Valves

Potential enhancement of $\Delta V$ by:

- Increase of $\Delta RA$: material ($Fe_{50}Co_{50}/Cu^*$)
  SV structure (increase of interface)

- Increase of $J_{\text{Hole}}$: material?

- Decrease of $P$: CCP (Confined Current Path) structure

\[ P = I^2 R \]
\[ \Delta V = I \Delta R \]
\[ \begin{align*}
  P &= (JA_{\text{CCP}})^2 \frac{(RA)_0}{\eta A_{\text{CCP}}} \\
  \Delta V &= JA_{\text{CCP}} \frac{\Delta RA_0}{\eta' A_{\text{CCP}}} \\
  &= \Delta V_0 (= J \cdot \Delta RA_0) \frac{\eta A_{\text{CCP}}}{\eta' A_{\text{CCP}}} \\
\end{align*} \]

$\eta A_{\text{CCP}}, \eta' A_{\text{CCP}}$: effective areas for $R, \Delta R$.

CCP structure can reduce $P$ (& $I_s$) without significant decrease of $\Delta V$ for constant $J$ down to considerable confinement. The suffix 0 denotes the original values without CC-layers. ($A_0/A_{\text{CCP}}>\eta, \eta'>1$)
Modeling CCP-CPP

- 2-D resistor network model: \( J = J(x,y) \). Each element is characterized by 4 contact resistances.
- *Previous work:* Max GMR obtained when CC layers are located in both the magnetic layers. This however degrades their magnetic properties.
Optimization of CC-Layer Locations

Calculation conditions:
CC-Layer: 1/81 Hole
Element size: 40.5×40 (nm²)
$R_{\text{Para}} A$: 80 mΩµm²

- Three CC-layers (CC-L₁, CC-L₂ and CC-L₃) are located outside of the magnetic layers to avoid degradation of their magnetic properties. An optimization process is performed by varying thickness and location of these layers.
- Findings:
  - CC-L₃ should be placed at the CoFe-Cu interface
  - No Cu interlayer is needed between CC-L₁ and CC-L₂
## Optimized Structure for CCP-CPP Spin Valves

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu L3 (1)</td>
<td>Cu</td>
<td>4 nm</td>
</tr>
<tr>
<td>CoFeB [free]</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Cu L1 (1)</td>
<td>Cu</td>
<td></td>
</tr>
<tr>
<td>CoFeB [pinned]</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

- **CC-Layers should be in close contact with the magnetic layers; one on top of the free layer and one between the free and pinned layers.**

- **The thickness of the CC-layers should be made as small as possible, provided that the magnetic coupling between the free and pinned layers is kept negligible.**
Dependence of $\Delta V$ on CCP Width

- Increase of $\Delta V$ by current confinement is substantial
- $\Delta V$ decreases below a critical CCP width

- At constant total CCP width, one hole is better than multiple holes
- Averaging of the signal across the track however may be necessary

<table>
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<tr>
<th>Element</th>
<th>Width (nm)</th>
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<tbody>
<tr>
<td>Cu</td>
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<td>CoFeB [free]</td>
<td>3</td>
</tr>
<tr>
<td>CoFeB [pinned]</td>
<td>4</td>
</tr>
</tbody>
</table>

Element size: 6400 (80x80) nm²
Summary

• Optimum design of a CCP-CPP spin valve has been achieved using a resistor network model
  – 2 CC-layers: on top of the free layer and between free and pinned layer
  – A continuous Cu layer between free and pinned layer is not necessary
  – CC layers should be as thin as possible, while keeping magnetic coupling negligible
• $\Delta V$ decreases rapidly for hole width below ~ 10 nm
• Single hole in the CC layer is preferable from the signal standpoint; averaging across the track however is necessary
• 3D model is under development: a preliminary finding is that square holes are better than rectangular ones
Future work

Modeling

· Further optimization of the CC-layer
  - 3D detail structure, magnetic material parameters
· Modification taking into account of mean free path

Experiment

· Development of a method using STM for fabricating controlled CC-holes.
  - Basic investigation of electro-deposition condition of Cu on some oxide layers.
  - Establishment of a method to determine morphology of the CC-layer
· Investigate actual limits of the current density through the confined current path.
Electrochemical Scanning Probe Fabrication of Nanocontacts and Nanochannels for CCP-CPP Devices

- Al₂O₃/Ni/Si samples in NaOH solution
- Localized Al₂O₃ dissolution by pulsing tip potential
- Flush solution with H₂O and substitute with Ni (Cu) plating solution
- Localized plating of Ni (Cu) by charging tip with Ni (Cu) ions, followed by reduction.

\[ E_{\text{tip}} = -0.7 \, \text{V} \]
\[ \text{Al}_2\text{O}_3 + 6e^- \rightarrow 2\text{Al}^{3+} + 3/2\text{O}_2 \]

Schuster et al. PRL 80, 5599 (1998)
Schindler et al., APL 73, 3279 (1998)
Optimization of Preparation Conditions of IrMn Pinning Layer for CPP Spin Valves

H. S. Jung, K. Nagasaka and H. Fujiwara

Funded by NSF-MRSEC
Cu UL Thickness and Quality of IrMn(111)

A Ta UL > 10 nm with Cu UL has been previously found to increase IrMn(111) orientation

Jung and Doyle, AE-08, Intermag 2003

Si(100)/Ta(20 nm)/Cu(t nm)/IrMn(10 nm)/FeCo(4 nm)/Ta(5 nm)

Strong IrMn(111) orientation and narrow dispersion are achieved for $t_{\text{Cu}} > 10$ nm
Dependence of $H_{eb}$ and $H_{c}$ on Texture of IrMn (111)

Si(100)/Ta(20 nm)/Cu(t nm)/IrMn(10 nm)/FeCo(4 nm)/Ta(5 nm)

The exchange bias field $H_{eb}$ and the coercivity $H_{c}$ of a FeCo layer deposited on top of the IrMn layer are plotted as functions of Cu-underlayer thickness $t_{Cu}$. XRD peak intensity curve is also shown as a reference.

Significant $H_{eb}$ and $H_{c}$ are obtained before a good texture of IrMn evolves.
Effect of Crystallinity of IrMn (111) on Thermal Stability

Si(100)/Ta(20 nm)/Cu(t nm)/IrMn(10 nm)/FeCo(4 nm)/Ta(5 nm)

Annealed at 250 °C for 15 min. with H = 2kOe

The rate of decrease of $H_{eb}$ and blocking temperature $T_B$ of a sample annealed at 250 °C are plotted as functions of $t_{Cu}$. **Better thermal stability and high $T_B$ are obtained for $t_{Cu} > 10$ nm.**
Effect of IrMn Thickness on $H_{eb}$ and $H_c$

Si(100)/Ta(20 nm)/Cu(20 nm)/IrMn(t nm)/FeCo(3 nm)/Ta(5 nm)

$H_{eb}$ and $H_c$'s in the pinned direction $H_{c,EA}$ and transverse direction $H_{c,HA}$ are plotted as functions of IrMn layer thickness $t_{IrMn}$. It is seen a good exchange biasing effect is obtainable for $t_{IrMn} > 8$ nm. This value is much smaller than that necessary for Pt(Pd) Mn.
Spin Valve structures

Si/Ta(20)/Cu(20)/IrMn(10)/FeCo(3)/Cu(5)/FeCo(3)/Ta(5 nm)

Annealing at each T for 10’ with H = 2 kOe

Annealing temperature (°C)

Annealed at 250 °C

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Summary and Future Work

• Strong IrMn(111) texture and better thermal stability are achieved by using a Ta/Cu UL

• Optimum structure for CPP spin valves utilizing IrMn pinning layer:

\[
\text{Si/Ta(20 nm)/Cu(15 nm)/IrMn(8 nm)/FeCo(3 nm)/Cu(4 nm)/FeCo(3 nm)/Ta(5 nm)}
\]

\textit{Annealing at 250 °C for 15 min. with } H = 2 kOe

• Next, we plan to study
  – Effect of current-confining layers
  – Coupling by use of Synthetic AF
  – Fabrication of submicron-sized CPP structures
Fabrication of Nanostructure Using Electrochemical Methods

Jie Gong and Giovanni Zangari

Funded by NSF-MRSEC
Nanochannel templates using alumite

Acid anodized aluminum can form an ordered hexagonal array of pores in amorphous Al$_2$O$_3$ with diameter of 10-200nm.

The aluminum can be chemically etched away, exposing the domed barrier layer.

The domed pores can be opened by ion milling forming nanochannels of variable width.
Alumite templates to grow nanoconstrictions and multilayers for spin-transfer studies

**Nanocontact Device**
Minimal opening of pores followed by Ni sputtering and Ni electrodeposition → controlled contact size

**Spin Transfer Device**
Full opening of pores followed by backside sputtering and deposition of Co/Cu multilayers.

Templates synthesized

Multi-step anodization of Al 99.998 % yields porous oxide structures on top of Al metal.

Pore size can be controlled by composition of the solution and voltage (current) applied.

(COOH)$_2$ 0.3 M, 15°C
60 nm pores

H$_2$SO$_4$ 0.3 M, 1°C
20 nm pores
Opening Holes in the Barrier Layer

Ion Milling

Chemical Etching in H₃PO₄

Non-uniform opening of holes by chemical etching
Focused Ion Beam (FIB) – Selectively Engraving Nanoholes

• Opening of single holes at controlled locations is possible by FIB
• Single nanowires can thus be grown and located by previous lithography

* FIB was performed at the University of Virginia
CPP-GMR by Electrodeposition

- Al oxide templates offer a unique geometry for CPP measurements
- Electrodeposition of Cu/Co MLs yields GMR 55% at room temperature
- Possible fabrication of SVs with SAF (Cu/Co)
- A preferred candidate for fundamental studies of interfaces
Electrodeposition of CoFeNi/Cu MLs on SCs

By pulsing current or potential, it is possible to alternately deposit pure Cu and CoFeNi containing traces of Cu.
• Polycrystalline Cu
• Transition BCC $\rightarrow$ FCC for CoFeNi
• Decrease grain size for increasing cd
Future Work

• Aluminum Oxide Templates
  – Synthesis of porous structures from Al\textit{films} supported on Si

• Electrodeposition of FM/NM multilayers
  – Magnetic and magnetotransport measurements on single magnetic layers and multilayers
  – Electrodeposition on GaAs
  – Electrodeposition into porous structures: multilayers and Co/Cu systems for spin transfer studies
Self-Assembled Nanowires for Spintronics

H. Alouach, S. Al-Ghamdi, H. Fujiwara and G. J. Mankey

Funded by shared equipment from NSF-DMR-0213985
GLAD Growth Mechanism

Substrate

GLAD Film

Deposition Angle

Growth Flux (R)

\[ \Phi = 3 \times 10^{-3} \text{ (s}^{-1}\text{)} \]

Incident Flux

Film

Shadowed Regions

Inclined structure

\( \Phi = 0 \)

Deposited @ \( \alpha = 75^\circ \)

Wires normal to the substrate

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Dependence of the Packing Fraction on the Angle of Deposition

Due to the high mobility of the Cu adatoms ($T_{\text{substrate}} \sim 70^\circ\text{C}$) the atomic shadowing is too low at deposition angles below $45^\circ$ to provide a porous structure.
XRD Investigation of Cu Nanowires Orientation
Angle Movements of the X’Pert MRD Cradle

Wire Orientation @ Ψ, Φ = 0° ; 2θ = 43.295°

Θ is fixed to detect the Cu(111) planes
Cu(111) Peak

For a sample deposited w/o azimuthal rotation Cu(111) intensity is maximum when the nanowires are facing the X-Ray source or the detector.

Inclination angle of the wires can be determined by optimum positioning of the wires relative to the detector.
Effect of the Azimuthal Rotation on the Wire and Cu-(111) Crystal Orientation

*With Azimuthal Rotation*

Wire Orientation

\[ \beta = \alpha - a \sin \left( \frac{1 - \cos(\alpha)}{2} \right) \]

Tait et al., Thin Solid Films 226, 196 (1993)

*Without Azimuthal Rotation*

Wire and Crystal Orientation

\[ \tan(\beta) = \frac{1}{2} \tan(\alpha) \]

Nieuwenhuizen et al., Philips Tech. Rev. 27, 87 (1966)
Conclusions

So far we have demonstrated that:
* Glancing angle deposition with substrate rotation can be used to produce nanowires of different (but limited range) size, diameter and packing fraction.
* There is an azimuthal dependence of the crystal structure and/or the texture due to the oblique wire orientation (dΦ/dt=0) with respect to the film plane.
* Accurate determination of the out-of plane wire orientation angle is only possible when the wire direction is optimal with respect to the X-Ray detector (diffraction angle).
Future Work

* Develop epitaxial processes for producing oriented single-crystal multilayer nanowires and characterize their crystal structure using x-ray diffraction.

* Characterize the magnetic properties of multilayer nanowire arrays with conventional magnetometry.

* Study the spin-dependent transport in nanoscale Giant Magneto-Resistive CPP-GMR devices.
Three dimensional atomic scale characterization using atom probe tomography

- Nanowires obtained by the two methods are of the correct size for atom probe tomography (APT).

- APT allows atomic resolution imaging of whiskers and nanowires, including interfaces in multilayers.

- Local Electrode Atom Probe may allow atomic scale characterization of nanochannels and nanocontacts.

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Role of Interfacial Energy in Nanoscale Pattern Formation during Aluminum Electropolishing

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Objectives

• To investigate the mechanism of pattern formation.

• To investigate the effect of anisotropic interfacial energy and anisotropic surface diffusion on pattern formation.

• Study the ability to make hexagonal patterns for perpendicular media.
Polycrystalline Experiment Results

- Three patterns obtained on the same sample
- Electropolished at 56 V for 30 s
- 3 \( \mu m \times 3 \, \mu m \) AFM images
Single Crystal Experiment\(^1\)

- Crystallinity gives rise to anisotropic properties.
- Proven in morphological instability studies.

\(^1\)Konovalov et al.
What Is The Mechanism of the Pattern Formation??

• Competition between surfactant adsorption, interfacial energy, and reaction rate.
• Depends on crystal properties and orientation

Polishing Solution (Acid)

\[ \text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^- \]

Aluminum
Mathematical Analysis

- Poisson-Boltzmann’s Equation
- Electric field dependence on surface height
- Dissolution rate of aluminum
- Surface coverage of surfactant
- Adsorption rate of surfactant
- Interfacial energy changes the total Gibbs Free Energy of anode reaction
The Isotropic Evolution Equation

\[ H_t - \alpha \nabla H_t^2 = - \left( \nabla H \right)^2 - \left( 1 - \frac{\beta}{\alpha} \right) \nabla H - \left( 1 + \beta \right) \nabla^4 H - \nabla^2 \left( \nabla H \right)^2 + 2 \xi \left( \nabla^2 H \right)^2 \]

- \( H_t \) derivative of height with respect to time
- \( \alpha \) ratio of activation energy of dissolution rate to that of adsorption rate
- \( \beta \) ratio of surface energy to the activation energy of dissolution rate
- \( \xi \) operating parameter (applied voltage)

\(^2\)Yuzhakov et al., 1997, 1999
The Anisotropic Evolution Equation

\[
\frac{\partial H}{\partial \tau} - \alpha \nabla \cdot \left( D_s^0 \cdot \nabla \left( \frac{\partial H}{\partial \tau} \right) \right) = -\nabla^2 H - (\nabla H)^2 - \nabla \cdot \left( D_s^0 \cdot \nabla (\nabla^2 H) \right) \\
- \nabla \cdot \left( D_s^0 \cdot \nabla (\nabla H)^2 \right) + 2 \xi_0 (\nabla^2 H)^2 + \frac{\beta}{\alpha} (H_{xx} + \gamma_2 H_{yy}) + \xi_1 (H_{xx} H_{xx} - H_{xy} H_{yx} - 2H_{y} H_{yx}) \\
- \beta \nabla \cdot \left( D_s^0 \cdot \nabla (H_{xx} + \gamma_2 H_{yy}) \right) - \xi_2 \nabla \cdot \left( D_s^0 \cdot \nabla (H_{xx} H_{xx} - H_{xy} H_{yx} - 2H_{y} H_{yx}) \right)
\]

- \( H_{\tau} \) derivative of height with respect to time
- \( D_s^0 \) anisotropic surface diffusion tensor
- \( \alpha \) ratio of activation energy of dissolution rate to that of adsorption rate
- \( \beta \) ratio of surface energy to the activation energy of dissolution rate
- \( \xi_0 \) operating parameter (applied voltage)
- \( \xi_1, \xi_2 \) parameters related to anisotropic interfacial energy
The Effect of Interfacial Energy: Conclusions from Theoretical Model

- Hexagonal patterns are stable only when interfacial energy is considered.
- Patterns are restricted when anisotropic interfacial energy is considered.
  - [100] crystal lead to competition between stripe and hexagons: same as isotropic case
  - [110] crystal only gives striped pattern
  - [111] crystal only gives hexagons
- Theory agrees completely with experimental results.
Numerical Simulations of Isotropic Interfaces
Controlling Pore Size

- Low temperature makes hexagonal pattern more stable.
- Choice of surfactant can significantly change pore size.
- Controlling pore size is important for hard-drive technology (pattern media).
Conclusions

• Interfacial energy is needed to make the hexagonal pattern stable.

• New theory qualitatively predicts both single crystal and polycrystalline experimental patterns.

• Single crystal orientation can give rise to anisotropic properties that will change the pattern evolution.

• Anisotropic surface diffusion may be a key factor in interpreting lower applied voltage in single crystal experiment.