Spin Transport in the Magnetic Tunneling Transistors

Stuart Parkin
IBM Almaden Research Center, San Jose, California

- Introduction to spin-based electronics
- Introduction to magnetic tunnel transistor (MTT)
- Use MTTs to study spin-dependent hot electron transport
  - spin-dependent electron attenuation lengths in thin films
  - bias voltage dependence of magnetocurrent
  - MTT with a spin-valve base
- Spin injection from MTTs into GaAs
- Spin-based devices

Supported in part by the United States
Defense Advanced Research Project Agency (DARPA)
Spin-Based Electronics

- **Conventional electronics**: utilizing the charge of carriers
- **Spin-based electronics**: utilizing the spin of carriers

**Key components for spintronic devices:**

- **Generate spins**:
  - ferromagnetic metals, diluted magnetic semiconductors etc.

- **Transport spins**:
  - from spin-polarized source into metals or semiconductors

- **Manipulate spins**:
  - electrical field, magnetic field etc.

- **Detect spins**:
  - electrical detection, optical detection
Rashba Effect

- Two dimensional electron gas (2DEG):
  - \( n_s \sim 10^{12} \text{ cm}^{-2} \), \( v_F \sim 10^7 \text{ cm/sec} \)
  - weakly relativistic

- Perpendicular electrical field:
  - due to asymmetry of confining potential
  - due to gate voltage

- Perpendicular electrical field transforms to a magnetic field \( H^* \)
  - conduction band electron spin degeneracy is lifted

- Spin-orbit Hamiltonian:
  - \( H_{SO} = \alpha (\sigma \times k) \cdot z \)


**Datta-Das Spin Transistor**

- **Generation**
  - ferromagnetic (FM) contact FM1

- **Transportation**
  - from FM1 into 2DEG

- **Manipulation**
  - Rashba effect: \( H_{SO} = \alpha (\sigma \times k) \cdot z \)
  - gate voltage controls \( \alpha \)

- **Detection**
  - ferromagnetic contact FM2
**Conductivity Mismatch**

Chemical potential $\mu$

\[
\frac{\partial \mu_{\uparrow,\downarrow}}{\partial x} = -\frac{ej_{\uparrow,\downarrow}}{\sigma_{\uparrow,\downarrow}}
\]

Resistance model:

\[
R_{SC} = x_0 / \sigma_{SC}
\]

\[
R_{FM} = \lambda_{FM} / \sigma_{FM}
\]

Normally,

\[
x_0 > \lambda_{FM}
\]

then,

\[
R_{FM} \ll R_{SC}
\]

$\alpha_2$ – current polarization in parallel alignment

$\beta$ – spin polarization of FM metals

$\lambda_{FM}$ – spin decay length in FM metal

Solution: Tunnel Barrier

- Tunneling current:

\[ J = e \sum_{q,k} \frac{2\pi}{\hbar} |T_{q,k}|^2 \left[ f_k (1 - f_q) - f_q (1 - f_k) \right] \]

q, k: initial and final states
f: Fermi distribution function
T: tunneling matrix element

- **FM metal electrode: density of states (DOS) is spin polarized**
  → tunnel barrier conductance is spin dependent

- **The presence of tunnel barrier can enhance spin injection efficiency**
**Magnetic Tunnel Transistor (MTT) with a Single Base Layer**

- **Emitter (FM1):**
  - Injects spin-polarized hot electrons into the base

- **Base (FM2):**
  - Spin-dependent scattering
  - Serves as a spin filter

- **Collector (GaAs):**
  - Schottky barrier at the interface
  - Only collects electrons when they have enough energy to overcome the Schottky barrier and when there are states available in the semiconductor.

Stuart Parkin
July 9, 2003
**MTT - Parallel Ferromagnetic Moments**

- **Pinned FM Emitter**
- **Tunnel Barrier**
- **Free FM Base**
- **Collector**

**Energy**

**FM Moments Parallel**

Stuart Parkin
July 9, 2003
MTT- Anti-Parallel FM Moments

FM Moments Anti-Parallel

Energy

Pinned FM Emitter

Tunnel Barrier

Free FM Base

Collector

I_E

I_C

Stuart Parkin
July 9, 2003
**Spin Valve Transistor (SVT)**

**Monsma et al. (1995); Jansen et al. (2000)**

Maximum MC observed ~560% at 80 K

- Hot electron energy is limited by emitter Schottky barrier height.
- Collector current is very small (~20 nA)
Ballistic Electron Magnetic Microscopy (BEMM)

Electrons injected from an STM tip
Study spin-dependent hot electron transport in FM thin films

Spin-Resolved Electron Transmission through FM Thin Films

- Electrons generated by photocathod
- Electron polarization parallel to FM film magnetization
  - study spin-dependent electron transmission through FM thin films
- Polarization perpendicular to magnetization
  - spin transfer
  - $\mathbf{M}$ and $\mathbf{P}$ precess about each other
    - current induced magnetization reversal


Magnetic Tunnel Transistor

Magnetic tunnel transistor:

- **Advantages:**
  
  solid state device
  
  high spin polarization (> 95%)
  
  room temperature operation
  
  use tunnel barrier → no conductivity mismatch problem
  
  electron energy can be adjusted by bias voltage: ~ 0.8 – 2.5 eV
  
  high speed

- **Disadvantage:**
  
  small collector current
  
  → increase transfer ratio by reducing interface scattering
  
  → reduce tunnel barrier resistance

Stuart Parkin
July 9, 2003
Fabrication of Magnetic Tunnel Transistors

- Magnetron sputtering and ion-beam sputtering at room temperature
- Three shadow masks
- Active junction area ~100 x 300 mm²
- Base area ~1 x 8 mm²
Magnetocurrent (MC) and Transfer Ratio (TR)

**Magnetocurrent (MC):**

$$MC = \frac{I_{C,P} - I_{C,AP}}{I_{C,AP}}$$

**Transfer Ratio (TR):**

$$TR = \frac{I_C}{I_E}$$

- T = 77 K
- $V_{EB} = 1.0$ V
- MC = 97%

- GaAs (111) / 30 Å Co$_{84}$Fe$_{16}$ / 26 Å Al$_2$O$_3$ / 50 Å
- Co$_{84}$Fe$_{16}$ / 300 Å Ir$_{22}$Mn$_{78}$ / 50 Å Ta

Stuart Parkin
July 9, 2003
Room Temperature Operation

- MC = 64% \( (V_{EB} = 1.4 \text{ V}) \)
- \( I_{C,P} \approx 1.6 \mu\text{A} \)
- MC limited by leakage current from the Schottky barrier

\[
I'_{C,P} = I_{C,P} + I_{LEAK}
\]
\[
I'_{C,AP} = I_{C,AP} + I_{LEAK}
\]
\[
MC' = \frac{I'_{C,P} - I'_{C,AP}}{I'_{C,AP}}
= \frac{(I_{C,P} - I_{C,AP})}{(I_{C,AP} + I_{LEAK})}
= \frac{MC}{1 + \frac{I_{LEAK}}{I_{C,AP}}}
\]

- Leakage current can be greatly reduced by making MTTs with small base area

Stuart Parkin
July 9, 2003
**Collector Current**

- **MTT structure:**
  - Emitter → 50 Å Co$_{84}$Fe$_{16}$ / 25 Å Al$_2$O$_3$
  - Base → $t$ Ni$_{81}$Fe$_{19}$ (25 – 100 Å)
  - Collector → GaAs (001)

- **Collector current:**

\[
I_{C,P(AP)} = I_E \left( \frac{1 + P_E}{2} \right) e^{-t/\lambda_\uparrow(\downarrow)} \alpha_\uparrow(\downarrow) + I_E \left( \frac{1 - P_E}{2} \right) e^{-t/\lambda_\downarrow(\uparrow)} \alpha_\downarrow(\uparrow)
\]

- $I_{C,P(AP)}$: collector current in parallel (anti-parallel) alignment
- $I_E$: emitter current
- $P_E$: spin polarization in the emitter
- $t$: base layer thickness
- $\lambda_\uparrow(\downarrow)$: attenuation length of majority (minority) spins in the base
- $\alpha_\uparrow(\downarrow)$: collection efficiency at the interface for majority (minority) spins
In parallel alignment, transport of minority spins is negligible for thick films:

\[ \frac{I_{C,P}}{I_E} \propto e^{-t/\lambda_{\uparrow}} \]

**Fit:** \( \lambda_{\uparrow} = 67 \pm 3 \text{ Å} \)
Spin-dependence of interface scattering is negligible.

Fit: $\lambda_\downarrow = 13 \pm 2 \text{ Å}$
Energy Dependence of Attenuation Length: NiFe

- Attenuation length of majority electrons decreases with electron energy.
- Attenuation length of minority electrons does not change much.
- Can be explained by strong electron-electron scattering.

Ni$_{81}$Fe$_{19}$ (T=77 K)
Similar result for Co\textsubscript{84}Fe\textsubscript{16} thin films.

Co\textsubscript{84}Fe\textsubscript{16} (T=77 K)
Electron Scattering in FM 3d Transition Metals

- **Electron-electron scattering**
  - spin asymmetry in the DOS of d band
  - minority electrons are strongly scattered due to the abundance of unoccupied states to scatter into

- **Spin-dependent elastic scattering**
  - due to exchange coupling of electron spins to the magnetic moments of ions

- **Spontaneous spin-wave emission**
  - only scatters minority electrons due to angular momentum conservation restraint

- **Thermal spin-wave scattering**
  - causes spin-mixing

- **Phonon scattering**
  - no significant spin-dependence
References for Electron Scattering Mechanisms

According to the conventional Fermi liquid theory*, relaxation time due to electron-electron scattering is:

$$\tau \propto \frac{1}{E_E^2}$$

Then attenuation length is:

$$\lambda \propto \nu \tau \propto \frac{(E_E + E_F)^{1/2}}{E_E^2}$$

Including other scattering processes:

$$\frac{1}{\lambda} = \frac{1}{\lambda_{\text{el-el}}} + \frac{1}{\lambda_{\text{other}}}$$

(assuming $\lambda_{\text{other}}$ is independent of electron energy).

*J. J. Quinn, Phys. Rev. 126, 1453 (1962)
Extrapolated transfer ratio at zero base layer thickness for parallel alignment.

Stronger interface scattering for NiFe/GaAs than for CoFe/GaAs.

Transfer ratio can be improved by minimizing interface scattering.
Spin Polarization vs. Base Layer Thickness

- Required base layer thickness in order to obtain 95% spin-polarized current.
- Emitter polarization is assumed to be 40%.
- MTT promises a highly spin-polarized electron source at room temperature.

Stuart Parkin
July 9, 2003
Bias Dependence of MC in MTTs with GaAs Collectors

MTT structure: Collector / Base / \(\sim 20\ \text{Å} \ \text{Al}_2\text{O}_3 / 50\ \text{Å} \ \text{CoFe} / 300\ \text{Å} \ \text{IrMn} / 50\ \text{Å} \ \text{Ta}\)

Sample Base Collector TMR (%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Base</th>
<th>Collector</th>
<th>TMR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30 Å CoFe</td>
<td>GaAs(001)</td>
<td>46.4</td>
</tr>
<tr>
<td>B</td>
<td>45 Å CoFe</td>
<td>GaAs(001)</td>
<td>40.7</td>
</tr>
<tr>
<td>C</td>
<td>100 Å CoFe</td>
<td>GaAs(001)</td>
<td>31.7</td>
</tr>
<tr>
<td>D</td>
<td>74 Å NiFe</td>
<td>GaAs(001)</td>
<td>14.7</td>
</tr>
<tr>
<td>E</td>
<td>30 Å CoFe</td>
<td>GaAs(111)</td>
<td>29.0</td>
</tr>
</tbody>
</table>

Sample A:

- MC decreases monotonically with bias up to \(\sim 1.1\ \text{V}\)
- MC increases after 1.1 V and then decreases gradually at higher bias

Stuart Parkin
July 9, 2003
Transfer ratio increases with bias due to the opening of GaAs conduction bands for electron collection.

More rapid increase in transfer ratio at $\sim 1.1$ V.
GaAs Conduction Band Structure

**Γ band:**
- lowest energy

**L bands:**
- 0.29 eV above Γ band

**X bands:**
- 0.48 eV above Γ band

Projection of GaAs energy bands on (001) plane
Scattering in the base broadens the energy and angular distribution of hot electrons.
Majority and minority electrons have different energy distribution due to spin-dependent inelastic scattering in the base layer.

At low bias, majority electrons can be more easily collected by the collector because of their narrow energy distribution, which leads to a large MC. At high bias, more minority electrons can also be collected, which leads to a reduced MC.

The opening of the L bands favors the injection of majority electrons and causes the non-monotonic bias dependence of the MC.
Angular distribution: broad for both majority and minority electrons.

→ strong interface scattering

Energy distribution: broader for minority electrons than for majority electrons.

Stuart Parkin
July 9, 2003
For narrow angular distribution, the contribution from the L bands is very small. The non-monotonic bias dependence of MC cannot be reproduced.
The non-monotonic bias dependence of MC cannot be reproduced without assuming different energy distribution for majority and minority electrons.
Bias Dependence of MC in MTTs with a Si Collector

- Monotonic bias voltage dependence of MC
- Conduction band structure of Si is different from that of GaAs
- Assuming broad angular distribution and different energy distribution for majority and minority electrons, the same model can well account for this monotonic bias dependence.
Magnetic Tunnel Transistor with a Spin-Valve Base

- **Nonmagnetic emitter**
- **Spin-valve base**
  - FM1 and FM2 have different coercivity
- **Transmission polarization:**

\[
P = \frac{e^{-t/\lambda_{\uparrow}} - e^{-t/\lambda_{\downarrow}}}{e^{-t/\lambda_{\uparrow}} + e^{-t/\lambda_{\downarrow}}}
\]
Spin-valve: 50 Å Ni$_{81}$Fe$_{19}$ / 40 Å Cu / 50 Å Co$_{70}$Fe$_{30}$

 MC = 3420 %
 IC = 43 pA

 MC = 670 %
 IC = 7.5 µA

V$_{EB}$ = 0.8 V

V$_{EB}$ = 2.5 V

Stuart Parkin
July 9, 2003
**Spin Filtering**

\[ \text{t Å NiFe / 40 Å Cu / t Å CoFe} \]

**Transmission Polarization:**

\[
P = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}} = \frac{e^{-t/\lambda_{\uparrow}} - e^{-t/\lambda_{\downarrow}}}{e^{-t/\lambda_{\uparrow}} + e^{-t/\lambda_{\downarrow}}}
\]

**Magnetocurrent:**

\[
MC = \frac{I_{C,P} - I_{C,AP}}{I_{C,AP}} = \frac{2P_1P_2}{1 - P_1P_2}
\]

*Stuart Parkin  
July 9, 2003*
MC: Single Layer Base MTT vs. Spin-Valve Base MTT

\[ MC = \frac{2P_1 P_2}{(1 - P_1 P_2)} \]

\( P_1, P_2: \) Density of states polarization (~40%) or transmission polarization (>95%)

Single layer base MTT

\[ P_1 = 40\%, \ P_2 = 95\% \]
\[ \rightarrow \ MC = 123\% \]

Spin-valve base MTT

\[ P_1 = 95\%, \ P_2 = 95\% \]
\[ \rightarrow \ MC = 1850\% \]
Hot electron scattering at CoFe/Cu and NiFe/Cu interfaces negligible

Strong hot electron scattering at NiFe/GaAs interface than at CoFe/GaAs interface
**MC: Cu vs. Au Space Layers**

- Similar MC for Cu and Au spacers
  - spin transport in MTTs dominated by bulk effect

- Very different GRM of the spin-valve with Cu and Au spacers
  - GMR effect dominated by interface effect
Strong hot electron scattering at the CoFe/Au and NiFe/Au interfaces
Electrical Spin Injection from MTTs into GaAs

p\textsuperscript+\text{-GaAs} / p\text{-AlGaAs} / i\text{-AlGaAs} / [GaAs / InGaAs QW]\textsubscript{3} / i\text{-AlGaAs} / n\text{-GaAs} / NiFe / CoFe / Al\textsubscript{2}O\textsubscript{3} / CoFe / Ta

Stuart Parkin
July 9, 2003
Spin-polarized electrons recombine with holes in the QWs and emit circularly polarized light. The spin polarization can be determined by measuring the polarization of the light.
Optical Selection Rules

Selection Rules:

- In quantum wells, the degeneracy of heavy and light holes is lifted. As a result, it is possible to measure electron-HH recombination only.

- Electroluminescence (EL) polarization reflects electron spin polarization right before they recombine with heavy holes.
Optical Setup:

- Faraday geometry: magnetic field parallel to light propagation.

- Liquid crystal retarder (LCR) and linear polarizer (A) select the polarization components of the EL.

- Light intensity measured with a charge coupled device (CCD).
Spin Relaxation Mechanism

- **Elliott-Yafet (EY) mechanism:**
  - Spin-orbit coupling mixes electron wave functions with opposite spin states.
  - Momentum scattering can cause spin relaxation.
  - Spin relaxation rate:
    \[ \frac{1}{\tau_s} \propto \frac{1}{\tau_p} \Rightarrow \frac{1}{\tau_p} \text{ being momentum relaxation rate} \]

- **Bir-Aronov-Pikus (BAP) mechanism:**
  - Spin relaxation due to electron-hole interactions.
  - Spin relaxation rate proportional to hole concentration in non-degenerate case.

- **D’yakonov-Perel’ (DP) mechanism:**
  - Effective magnetic field:
    \[ H = - g \frac{\hbar}{2} \left( \sigma \cdot B_{\text{EFF}} \right) \propto E^n \]
  - Spin relaxation due to precession in the effective magnetic field.
  - Spin relaxation rate:
    \[ \frac{1}{\tau_s} \propto \tau_p \]
**DP Relaxation Mechanism**

Injected spin along z-axis, effective magnetic field along x-axis

---

**Large $\tau_p$:**

$\langle S_z \rangle = 0$

Spin relaxation is effective

No momentum scattering

**Small $\tau_p$:**

$\langle B \rangle = 0$

Spin relaxation is suppressed

Before scattering

After scattering

---

Stuart Parkin
July 9, 2003
Electroluminescence

- $T = 1.4 \text{ K}, V_{EB} = -2.06 \text{ V}, V_{CB} = 1.0 \text{ V}$

- EL polarization defined as:

$$P_{EL} = \frac{I_+ - I_-}{I_+ + I_-}$$

$I_+$ and $I_-$ being EL intensities for $\sigma_+$ and $\sigma_-$ components respectively.
Majority Spin Injection

Metal

\[ + \frac{1}{2} \]
\[ - \frac{1}{2} \]

\[ \text{H} (+) \]

GaAs

\[ - \frac{1}{2} \]
\[ + \frac{1}{2} \]

\[ - \frac{3}{2} \]
\[ + \frac{3}{2} \]

- Zeeman splitting

\[ \Delta E = - g \mu_H m_S \]

- Metal: \( g_e \sim 2 \)

- GaAs: \( g_e \sim -0.44 \)

- Positive EL polarization in positive field \( \rightarrow \) majority spin injection

R. Wang

Stuart Parkin
July 9, 2003
Field Dependence of EL Polarization

- Background polarization due to thermalization of spins in the magnetic field.
- After subtracting a linear background, the EL polarization data agrees with the SQUID data very well.
- EL polarization up to ~10%.
Strong bias dependence of EL polarization

Most likely related to spin relaxation process:
- DP mechanism
- BAP mechanism
Spin-Torque Transistor

- $\mu_S$ generates source drain current $I_{SD}$.
  - → spin accumulation in normal metal $N_1$

- Orientation of magnetization $M_B$ in the base influences spin accumulation in $N_1$.
  - → $I_{SD}$ can be modulated by varying $\theta$

- Spin transfer from $N_1$ and $N_2$ into the base produces torque on $M_B$.
  The resulting angle $\theta$ depends on both $\mu_B$ and $\mu_S$.
  - → $I_{SD}$ can be modulated by varying $\mu_B$

- Negative differential resistance and gain can be achieved.

**Magnetic p-n Junctions**

- **n-region (nonmagnetic)**
  - spin-polarized due to spin injection

- **p-region (magnetic)**
  - spin subband splitting in magnetic field
    \[ \Delta E = 2 g \mu_B B \]
  - barrier height for electron current depends on magnetic field
  - current varies exponentially with magnetic field

\[ B^* = 2 k_B T / g \mu_B \]

- \( \alpha \): spin polarization in n-region
- \( \tau \): spin relaxation time
  - red: \( \alpha = 0, \tau = 0.2 \) ns
  - violet: \( \alpha = 1, \tau = 20 \) ns
  - cyan: \( \alpha = 1, \tau = 2 \) \( \mu \)s

Spin-Polarized Solar Battery

- Spin up electrons
- Spin down electrons

- **p-n junction illuminated by circularly polarized light**

- **Depletion region: build-in field**
  - spin-polarized electrons swept into p-region
  - unpolarized holes swept into n-region

- **Generate both charge current and spin-polarized current**

---

Acknowledgments

Xin Jiang¶, Roger Wang¶, Sebastiaan van Dijken
Roger MacFarlane, Bob Shelby
IBM Almaden Research Center, San Jose

Glenn Solomon, Jim Harris
¶Solid State Photonics Laboratory, Stanford University

Stuart Parkin
July 9, 2003