Spin Transport in the Magnetic Tunneling Transistors

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- **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**

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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:

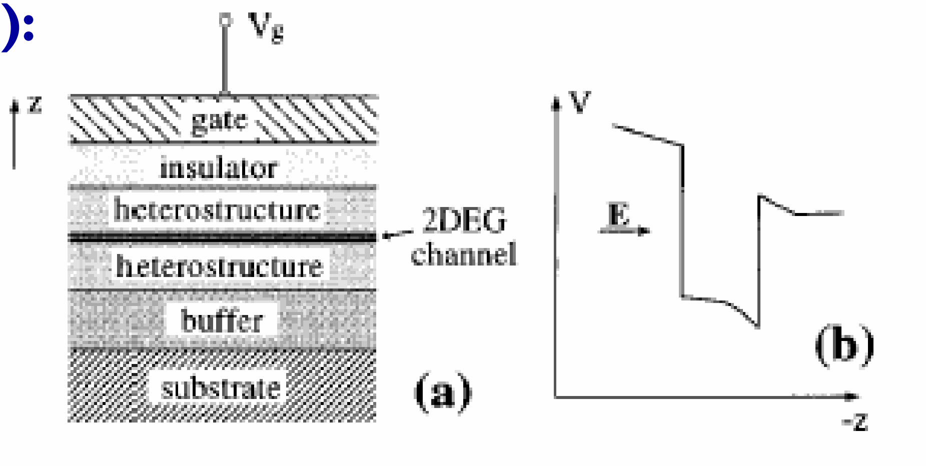
  → electrical field, magnetic field etc.

- Detect spins:

  → electrical detection, optical detection

Rashba Effect

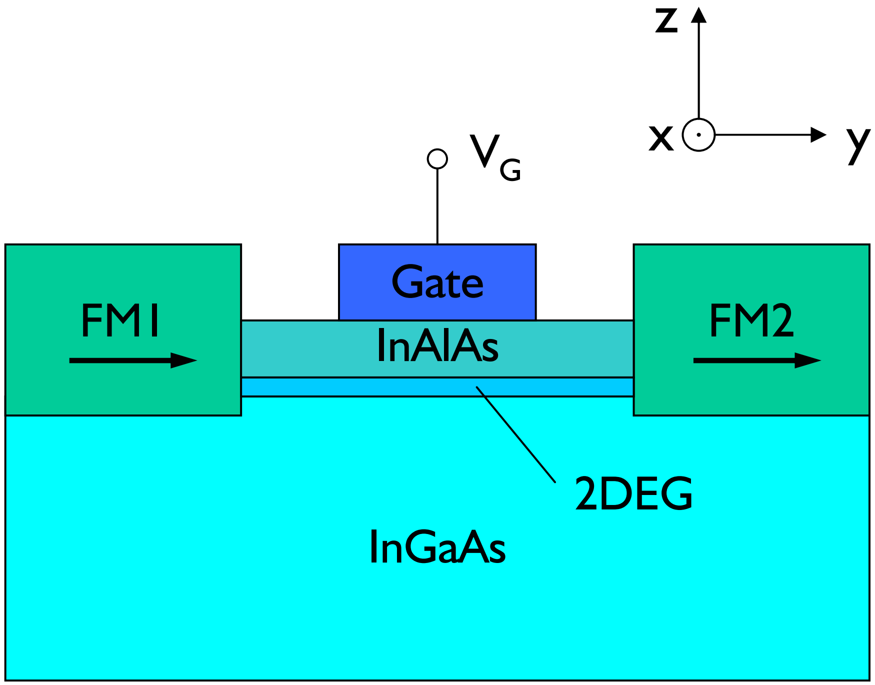
- **Two dimensional electron gas (2DEG):**
  - $n_s \sim 10^{12}\ cm^{-2}$, $v_F \sim 10^7\ cm/sec$
  - weakly relativistic



M. Johnson, Phys. Rev. B **58**, 9635 (1998)

- **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:**
  - $H_{SO} = \alpha\ (\sigma \times \mathbf{k}) \bullet \mathbf{z}$
  - Yu. A. Bychkov and E. I. Rashba, J. Phys. C **17**, 6039 (1984).

Datta-Das Spin Transistor



S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990)

- **Generation**

  - ferromagnetic (FM) contact FM1

- **Transportation**

  - from FM1 into 2DEG

- **Manipulation**

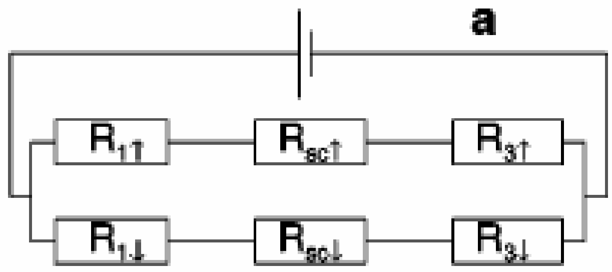
  - Rashba effect: $H_{SO} = \alpha\,(\sigma \times \mathbf{k}) \bullet \mathbf{z}$

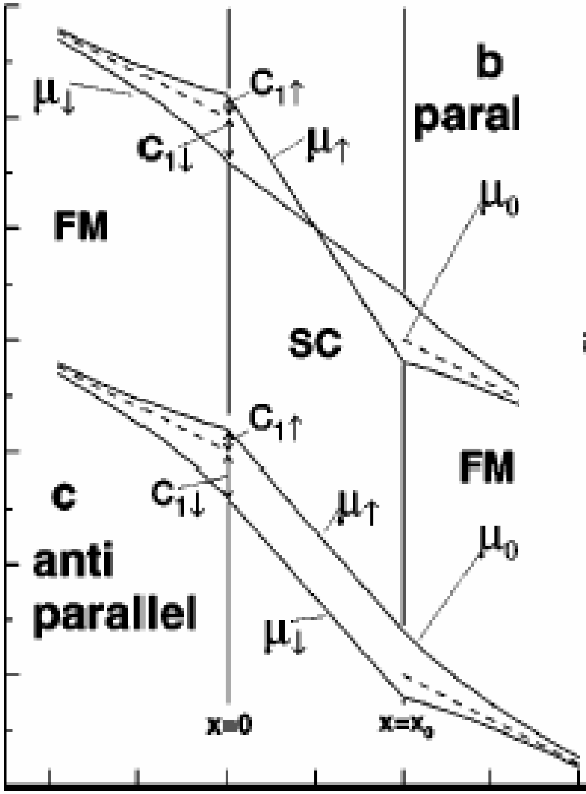
  - gate voltage controls α

- **Detection**

  - ferromagnetic contact FM2

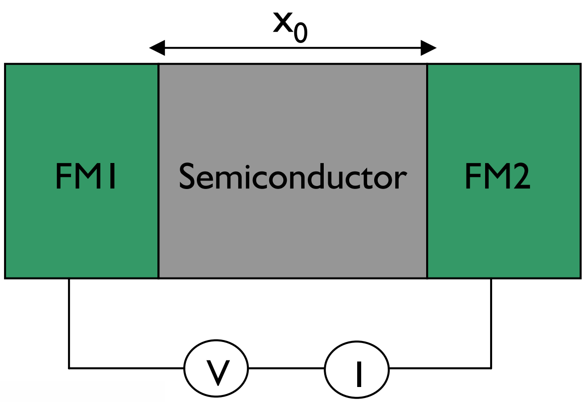
Conductivity Mismatch

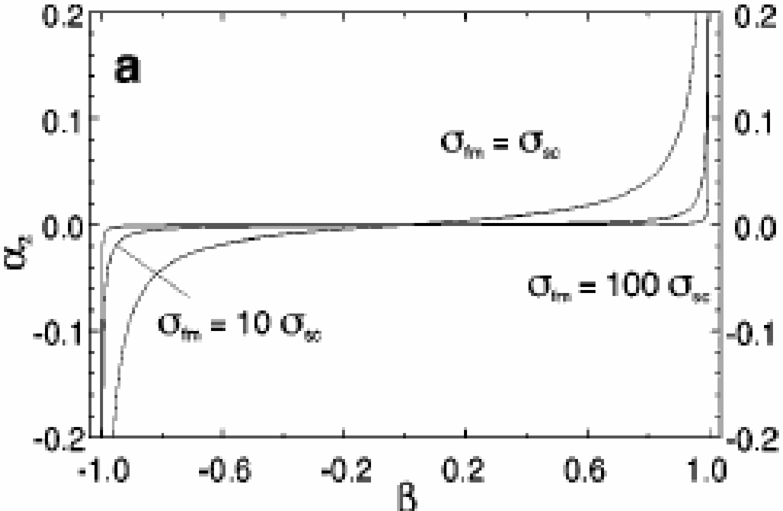




Chemical potential μ

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





α_2 – current polarization in parallel alignment

β – spin polarization of FM metals

λ_{FM} – spin decay length in FM metal

Resistance model:

$R_{SC} = x_0 / \sigma_{SC}$

$R_{FM} = \lambda_{FM} / \sigma_{FM}$

Normally,

$x_0 > \lambda_{FM}$

$\sigma_{SC} \ll \sigma_{FM}$

then,

$R_{FM} \ll R_{SC}$

G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).

Solution: Tunnel Barrier

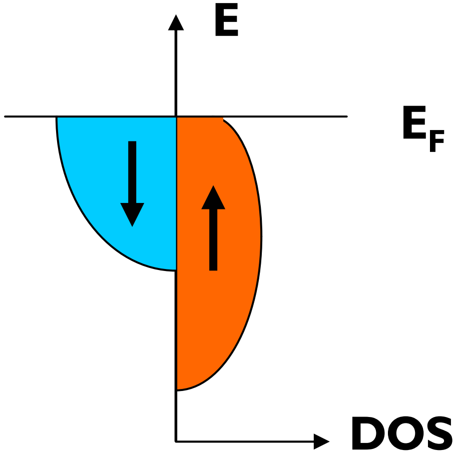
- **Tunneling current:**

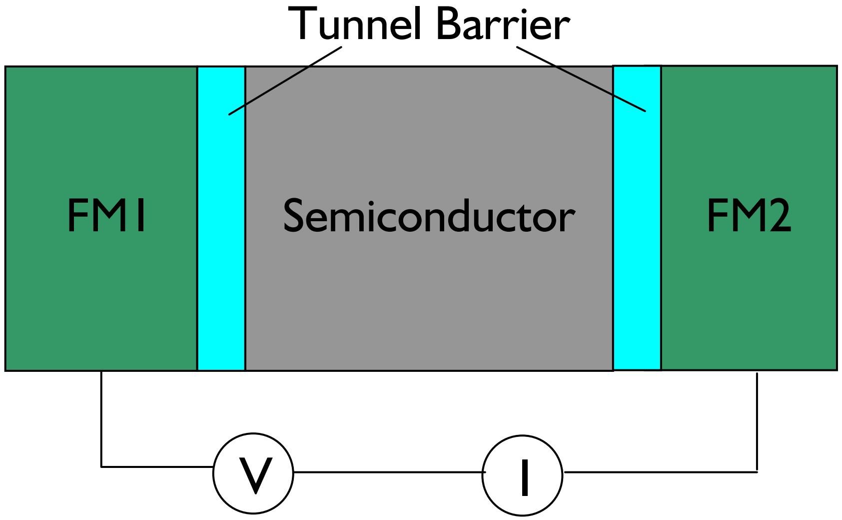
$$J = e\sum_{q,k} \frac{2\pi}{\hbar} \left| T_{q,k} \right|^2 \left[f_k (1 - f_q) - f_q (1 - f_k) \right]$$

q, k: initial and final states

f: Fermi distribution function

T: tunneling matrix element





- **FM metal electrode: density of states (DOS) is spin polarized**

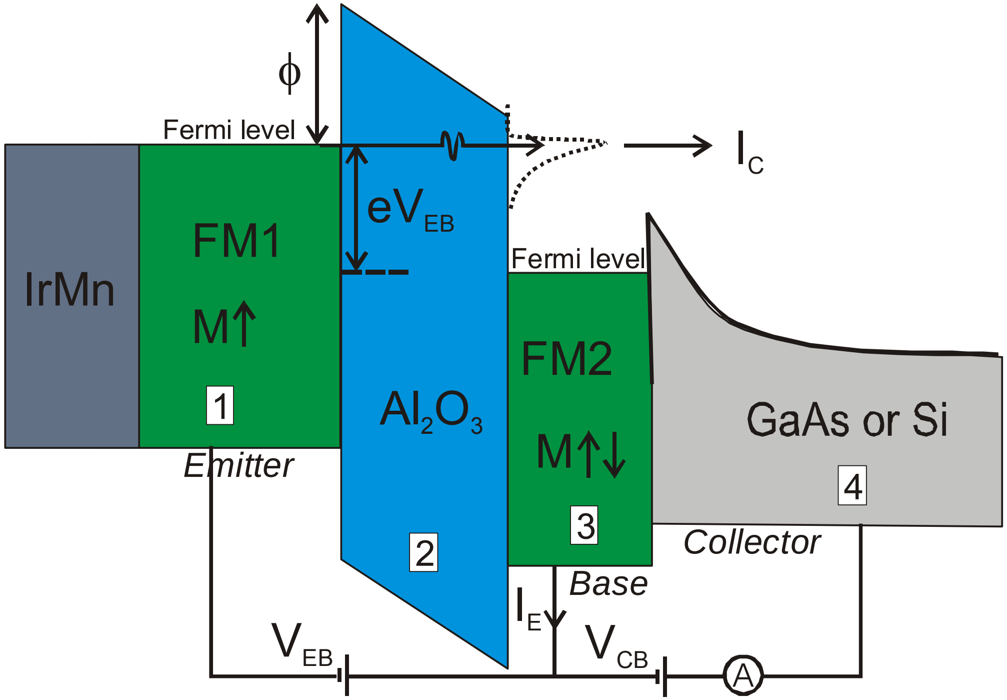
→ tunnel barrier conductance is spin dependent

- **The presence of tunnel barrier can enhance spin injection efficiency**

- E. I. Rashba, Phys. Rev. B **62**, R16267 (2000).

- V. Ya. Kravchenko and E. I. Rashba, Phys. Rev. B **67**, 121310 (R) (2003)

Magnetic Tunnel Transistor (MTT) with a Single Base Layer



Emitter (FM1):

- Injects spin-polarized hot electrons into the base

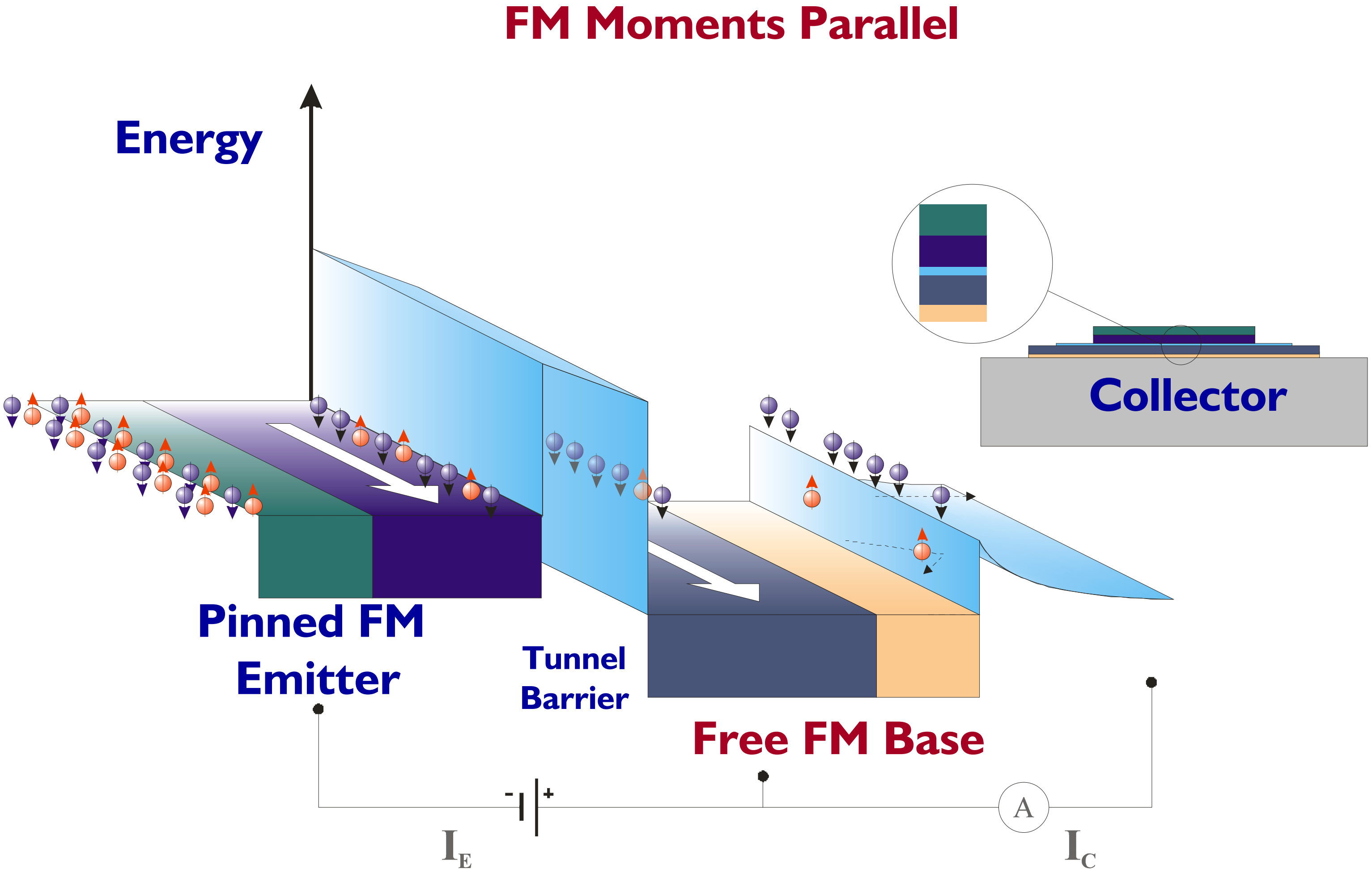
Base (FM2):

- Spin-dependent scattering
- Serves as a spin filter

Collector (GaAs):

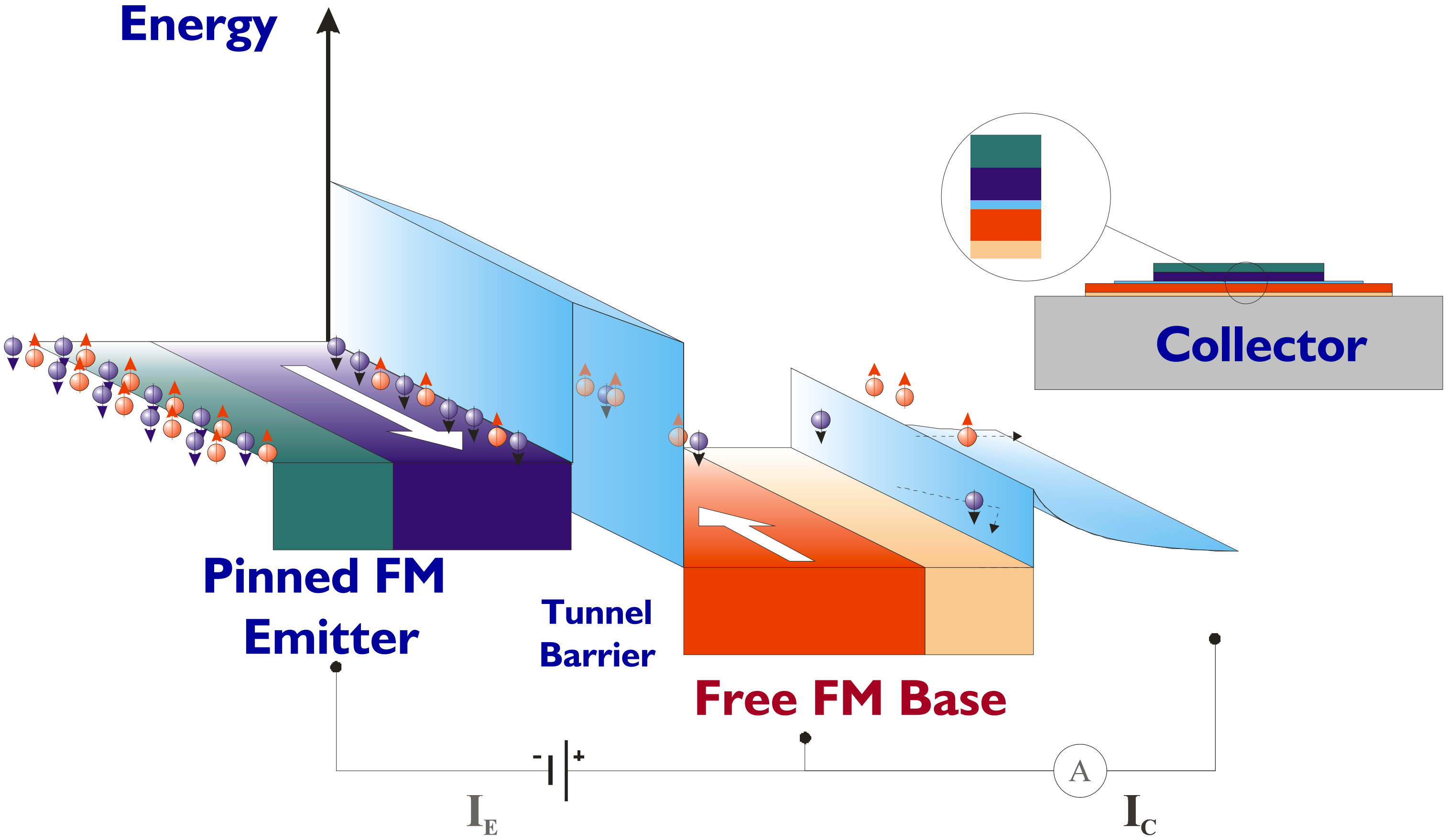
- Schottky barrier at the interface
- Only collects electrons when they have enough energy to overcome the Schottky barrier and when there are states available in the semiconductor.

MTT- Parallel Ferromagnetic Moments



MTT- Anti-Parallel FM Moments

FM Moments Anti-Parallel



Energy

Collector

Pinned FM Emitter

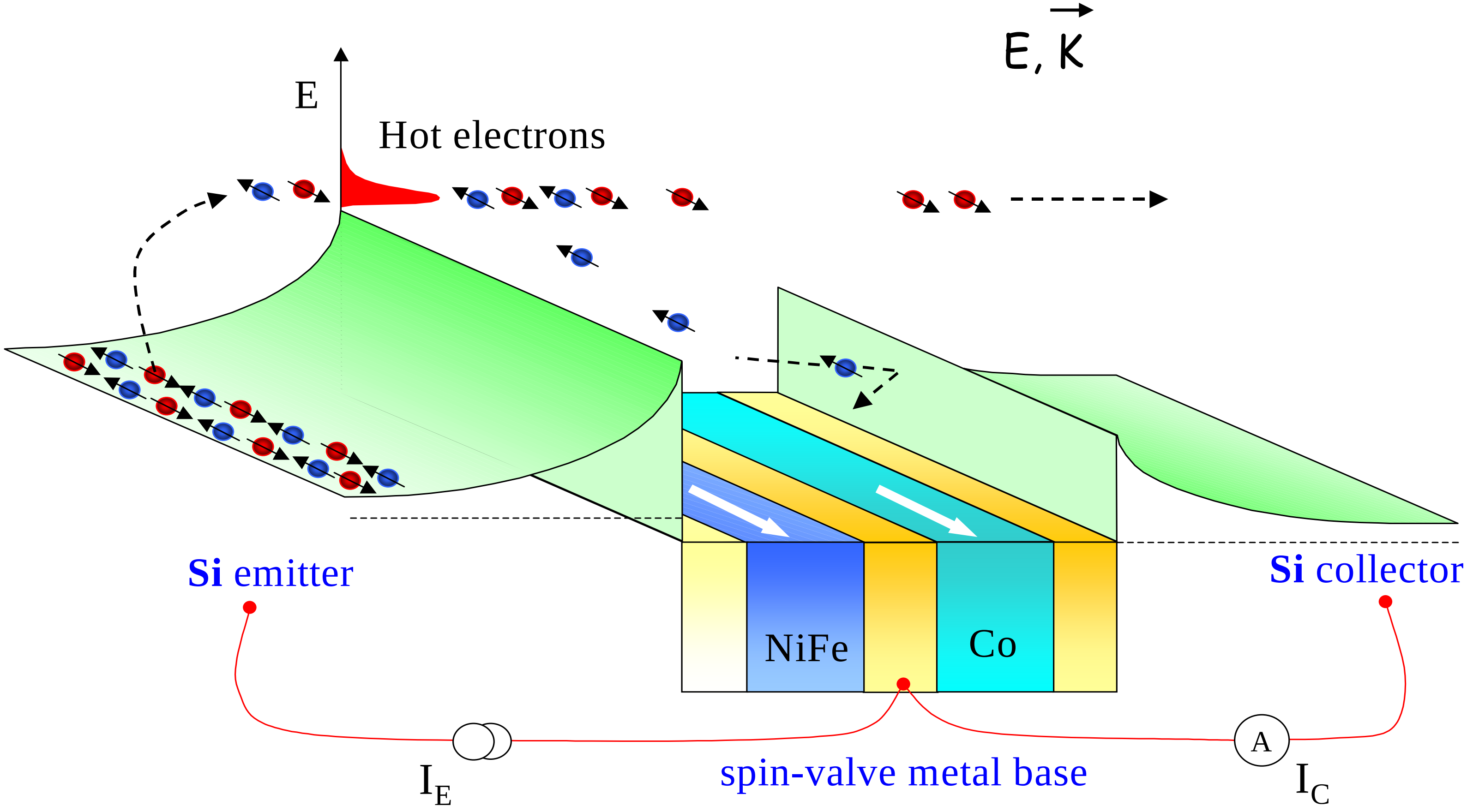
Tunnel Barrier

Free FM Base

Spin Valve Transistor (SVT)

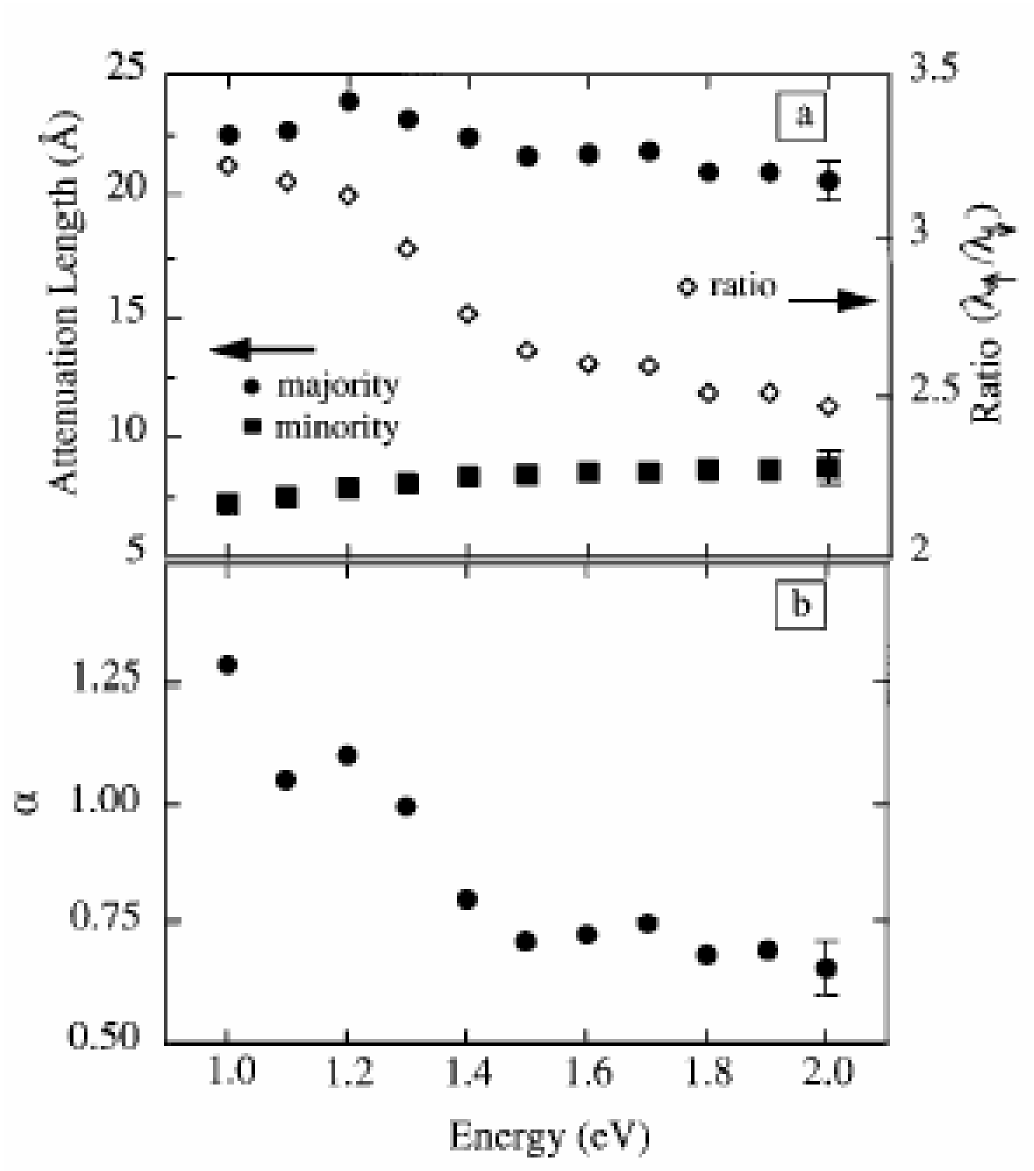
Monsma et al. (1995); Jansen et al. (2000)

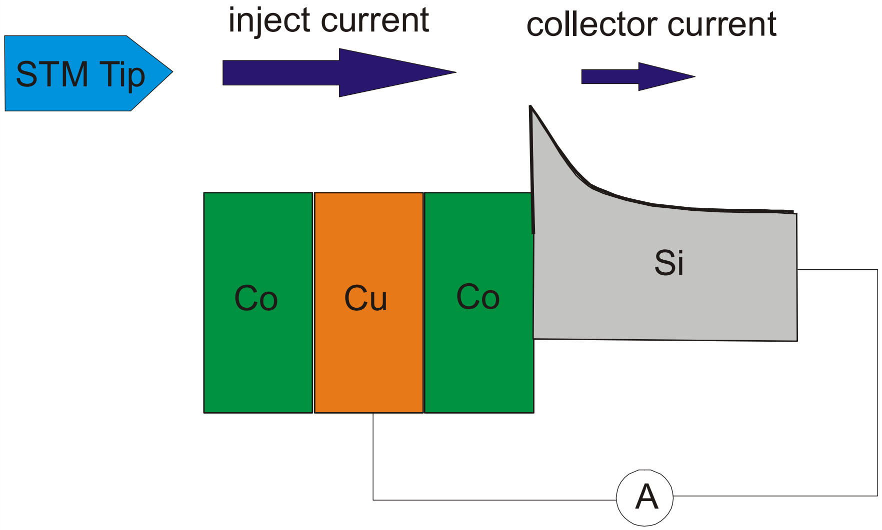
Maximum MC observed ~560% at 80 K



- **Hot electron energy is limited by emitter Schottky barrier height.**
- **Collector current is very small (~20 nA)**

Ballistic Electron Magnetic Microscopy (BEMM)

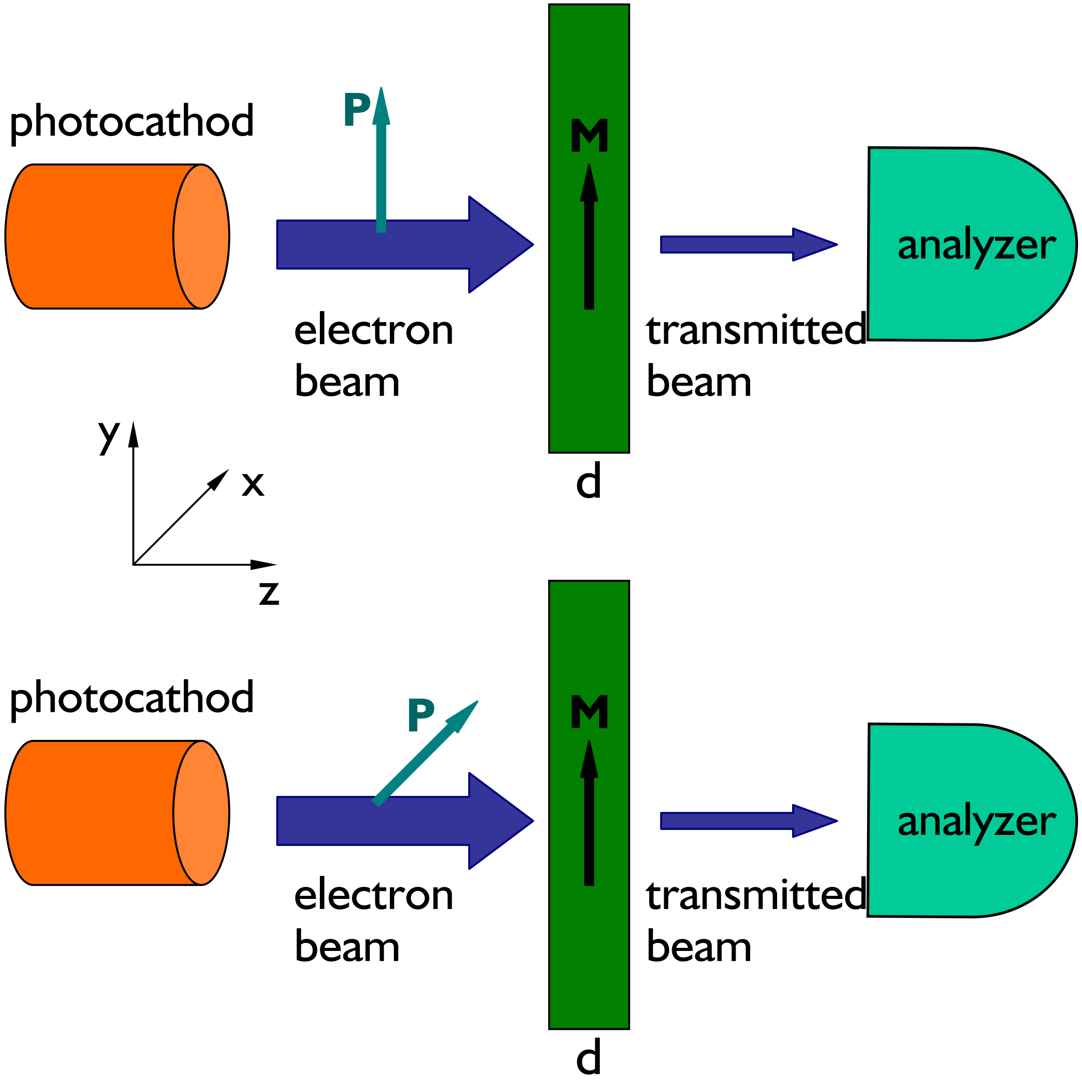




- **Electrons injected from an STM tip**
- **Study spin-dependent hot electron transport in FM thin films**

W. H. Rippard and R. A. Buhrman, Phys. Rev. Lett. **84**, 971 (2000).

Spin-Resolved Electron Transimission 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**

  - **M** and P precess about **each other**

    → current induced magnetization reversal

D. Oberli, R. Burgermeister,S. Riesen, W. Weber, and H. C. Siegmann, Phys. Rev. Lett. **81**, 4228 (1998).

W. Weber, S. Riesen, and H. C. Siegmann, Science **291**, 1015 (2000).

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

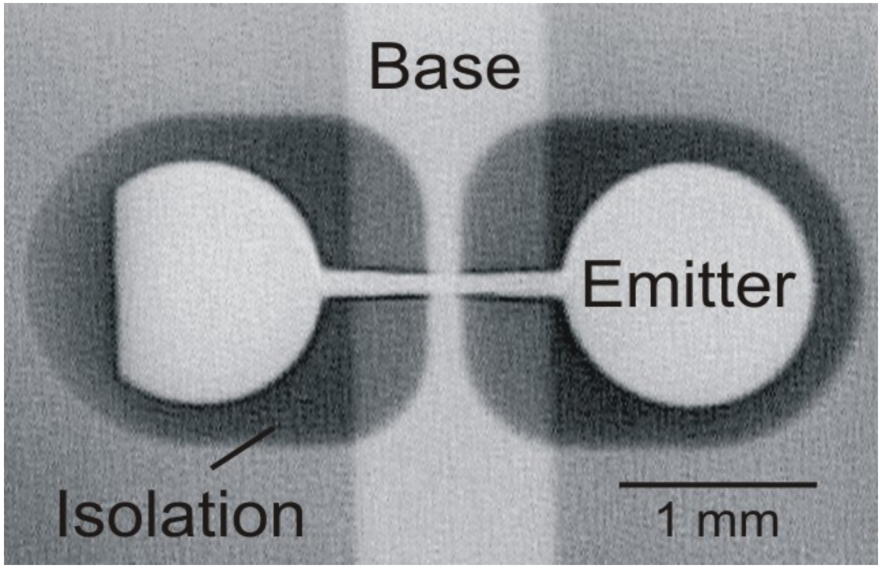
- Disadvantage:

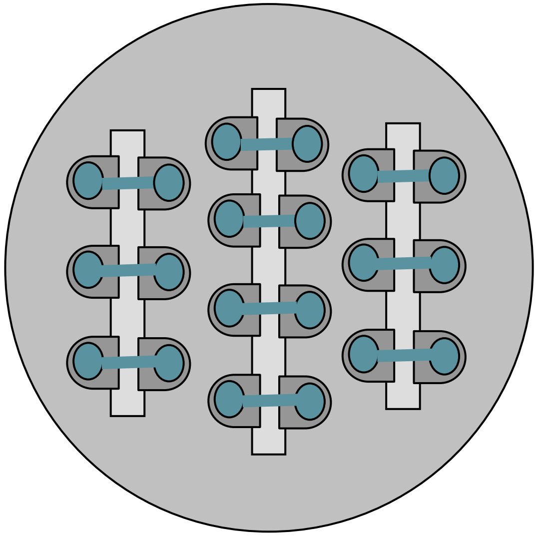
small collector current

→ increase transfer ratio by reducing interface scattering

→ reduce tunnel barrier resistance

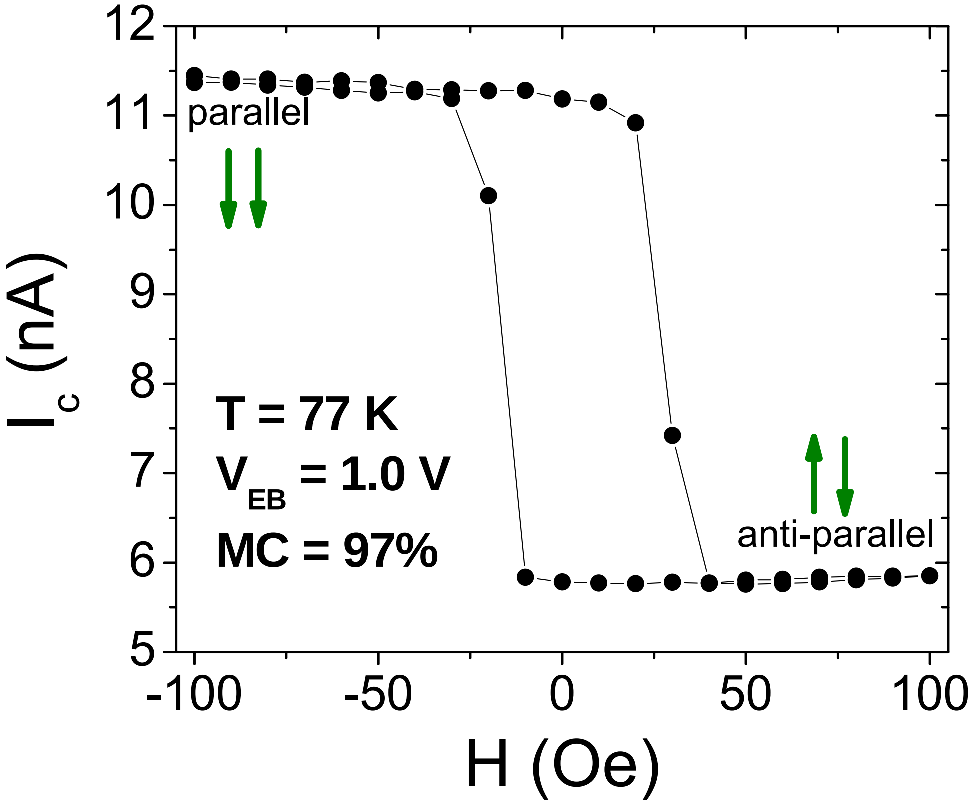
Fabrication of Magnetic Tunnel Transistors





- Magnetron sputtering and ion-beam sputtering at room temperature
- Three shadow masks
- Active junction area ~100 x 300 mm^2
- Base area ~1 x 8 mm^2

Magnetocurrent (MC) and Transfer Ratio (TR)



GaAs (111) / 30 Å $Co_{84}Fe_{16}$ / 26 Å Al_2O_3 / 50 Å
$Co_{84}Fe_{16}$ / 300 Å $Ir_{22}Mn_{78}$ / 50 Å Ta

- **Magnetocurrent (MC):**

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

- **Transfer Ratio (TR):**

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

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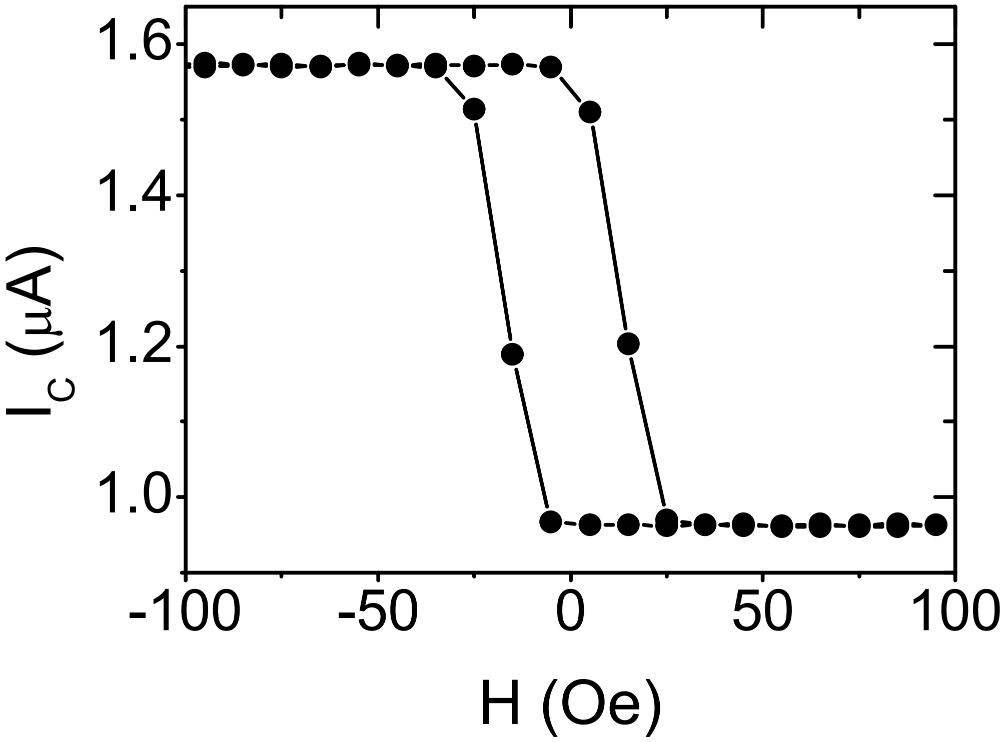
Room Temperature Operation



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

$$I'_{C,P} = I_{C,P} + I_{LEAK}$$

$$I'_{C,AP} = I_{C,AP} + I_{LEAK}$$

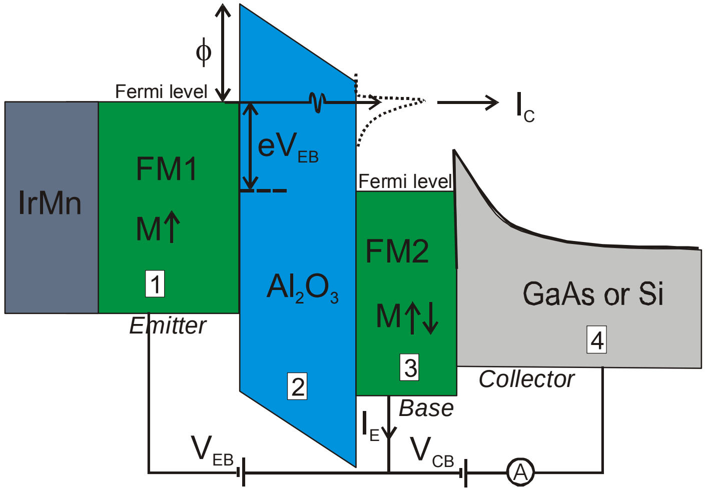
$$MC' = (I'_{C,P} - I'_{C,AP}) / I'_{C,AP}$$

$$= (I_{C,P} - I_{C,AP}) / (I_{C,AP} + I_{LEAK})$$

$$= MC / (1 + I_{LEAK} / I_{C,AP})$$

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

Collector Current



- **MTT structure:**

  Emitter → 50 Å $Co_{84}Fe_{16}$ / 25 Å Al_2O_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

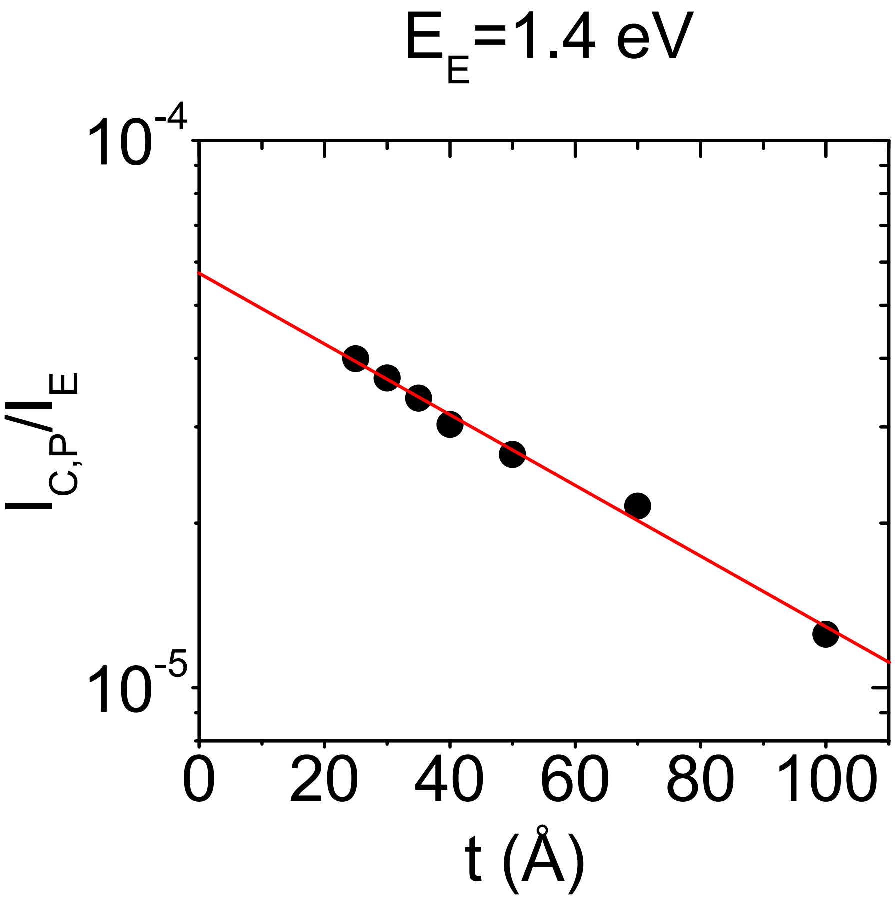
P_E: spin polarization in the emitter

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

Majority Electron Attenuation Length

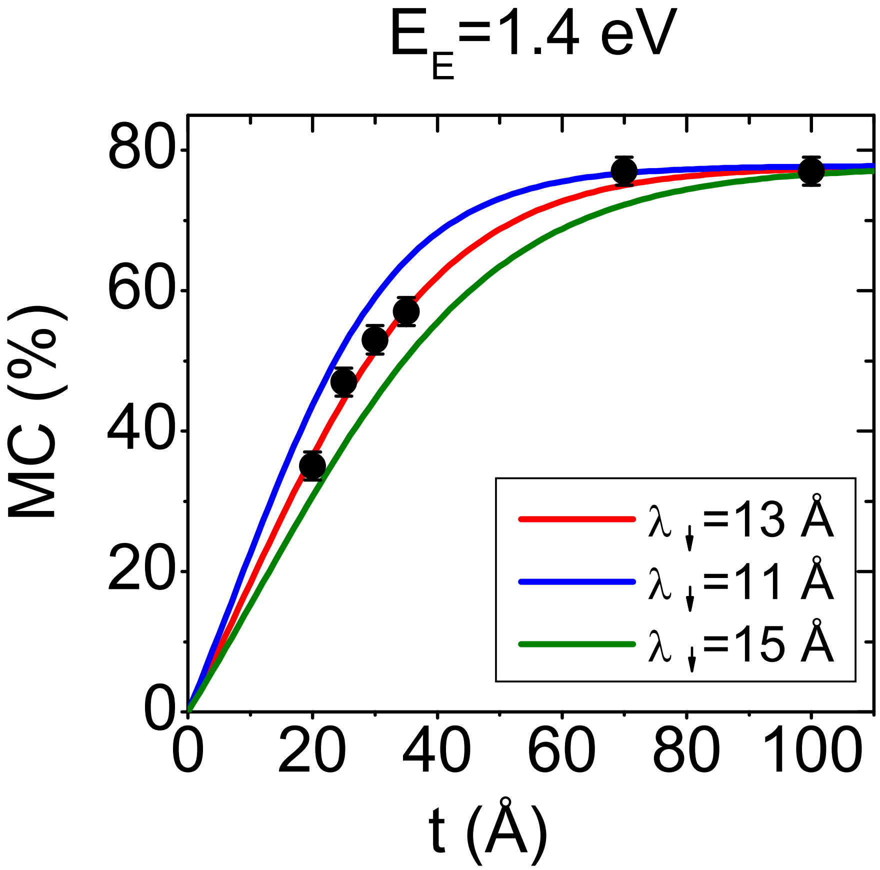


In parallel alignment, transport of minority spins is negligible for thick films:

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

Fit: $\lambda_\uparrow = 67 \pm 3$ Å

Minority Electron Attenuation Length



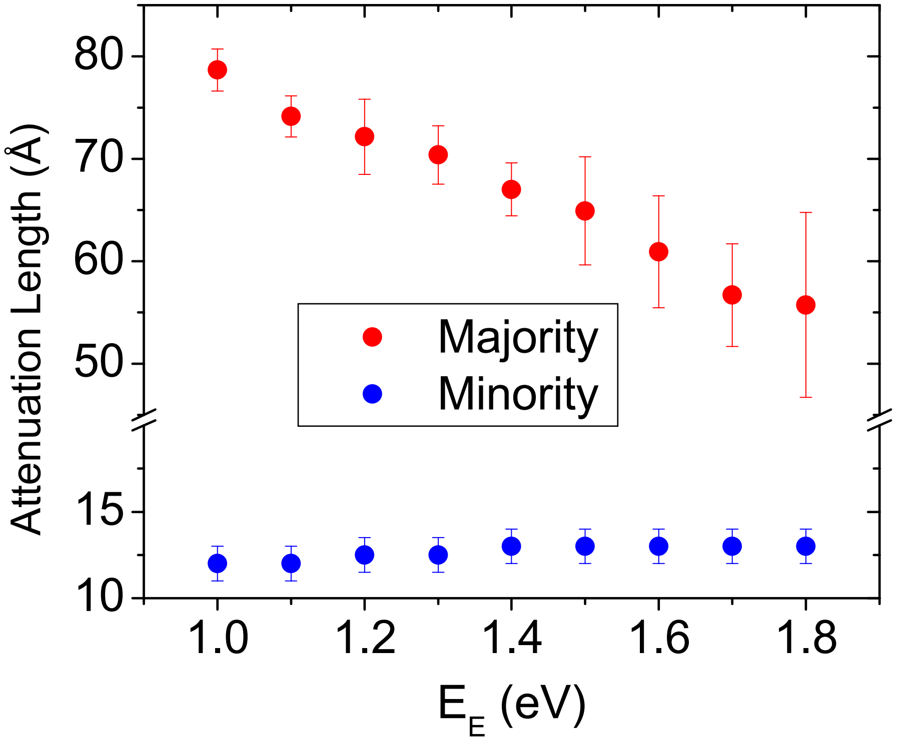
Spin-dependence of interface scattering is negligible.

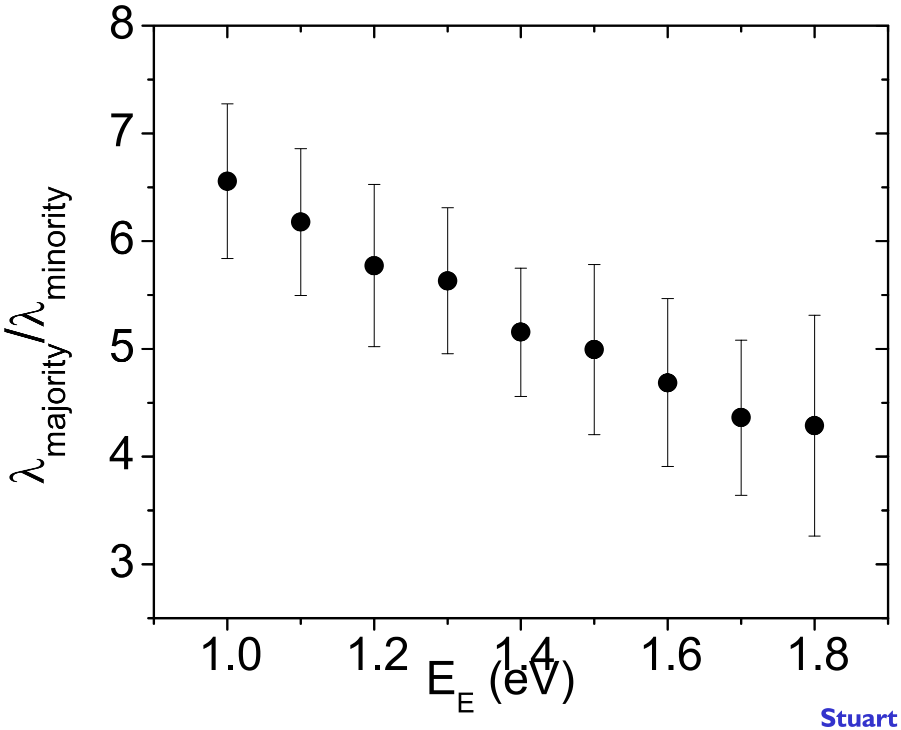
Fit: $\lambda_\downarrow = 13 \pm 2$ Å

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)





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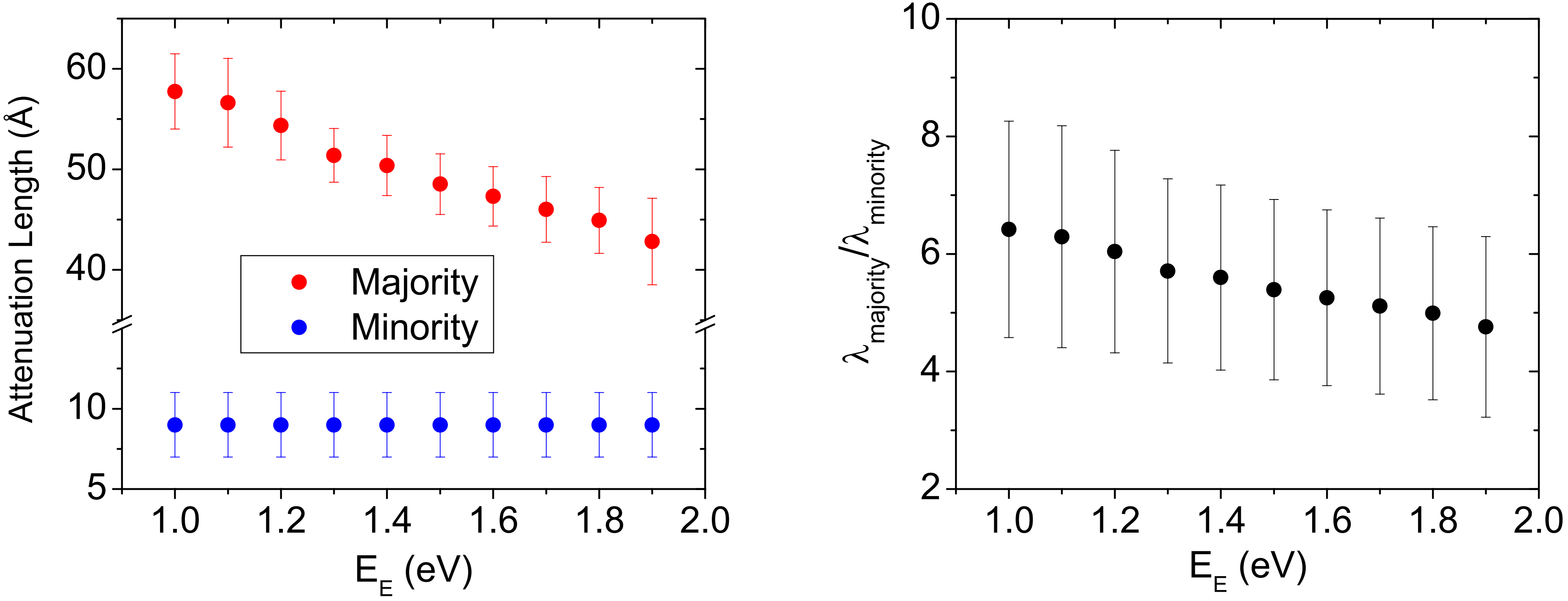
Energy Dependence of Attenuation Length: CoFe

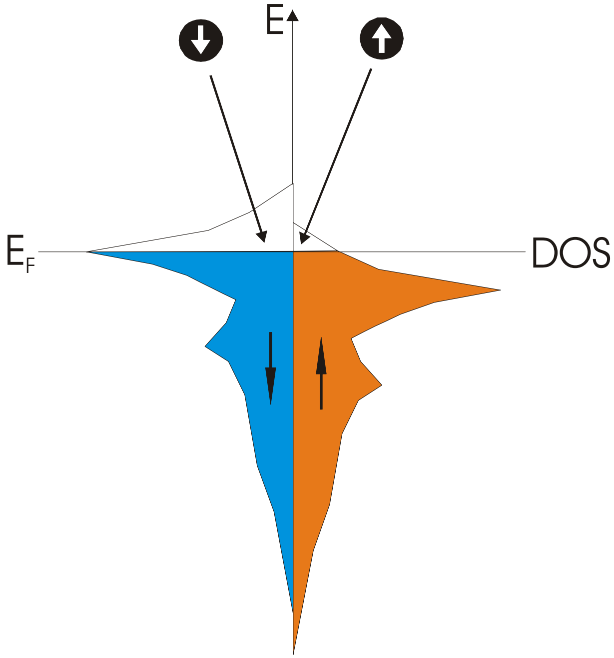
- **Similar result for $Co_{84}Fe_{16}$ thin films.**

$Co_{84}Fe_{16}$ (T=77 K)

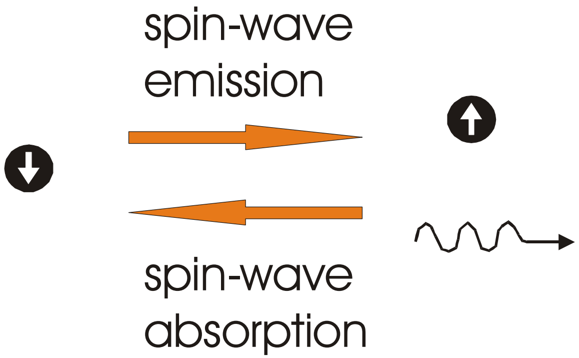


Electron Scattering in FM 3d Transition Metals

electron-electron scattering



Spin-wave scattering



- **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

J. J. Quinn, Phys. Rev. **126**, 1453 (1962).

R. K. Nesbet, Phys. Rev. B **32**, 390 (1985).

A. Ormeci, B. M. Hall, and D. L. Mills, Phys. Rev. B **42**, 4524 (1990).

D. P. Pappas et al., Phys. Rev. Lett. **66**, 504 (1991).

M. P. Gokhale and D. L. Mills, Phys. Rev. Lett. **66**, 2251 (1991).

G. Schönhense and H. C. Siegmann, Ann. Phys. (Leipzig) **2**, 465 (1993).

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J. Hong and D. L. Mills, Phys. Rev. B **59**, 13840 (1999).

E. Zarate, P. Apell, and P. M. Echenique, Phys. Rev. B **60**, 2326 (1999).

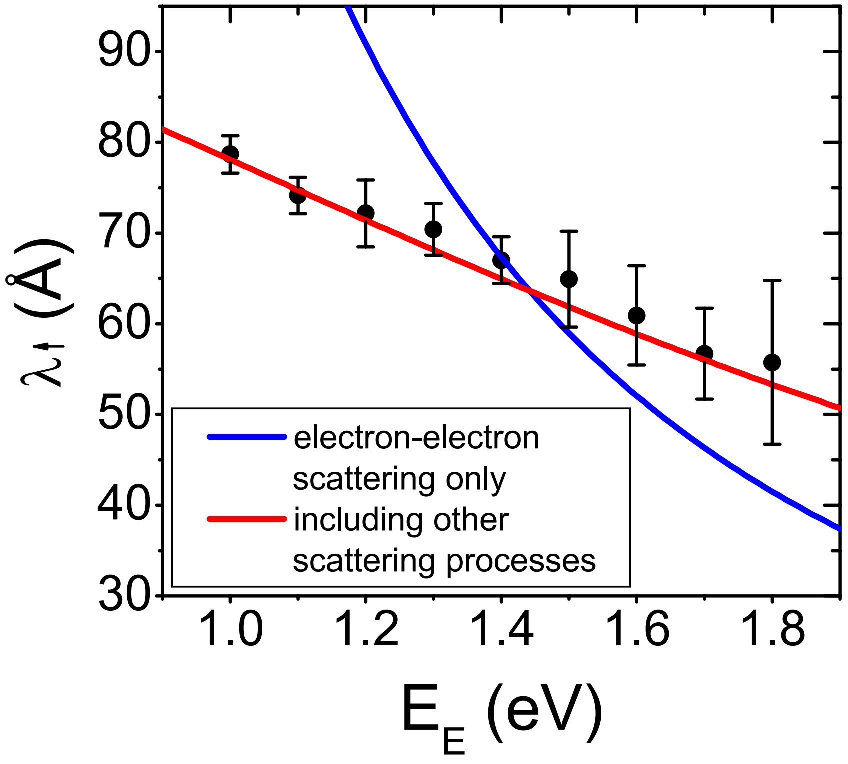
R. Jansen et al., Phys. Rev. Lett. **85**, 3277 (2000).

R. Knorren et al., Phys. Rev. B **61**, 9427 (2000).

H. –J. Drouhin, Phys. Rev. B **62**, 556 (2000).

H.-J. Drouhin, J. Appl. Phys. **89**, 6805 (2001).

Energy Dependence of Majority Electron Attenuation Length



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

$$\tau \propto 1/E_E^2$$

Then attenuation length is:

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

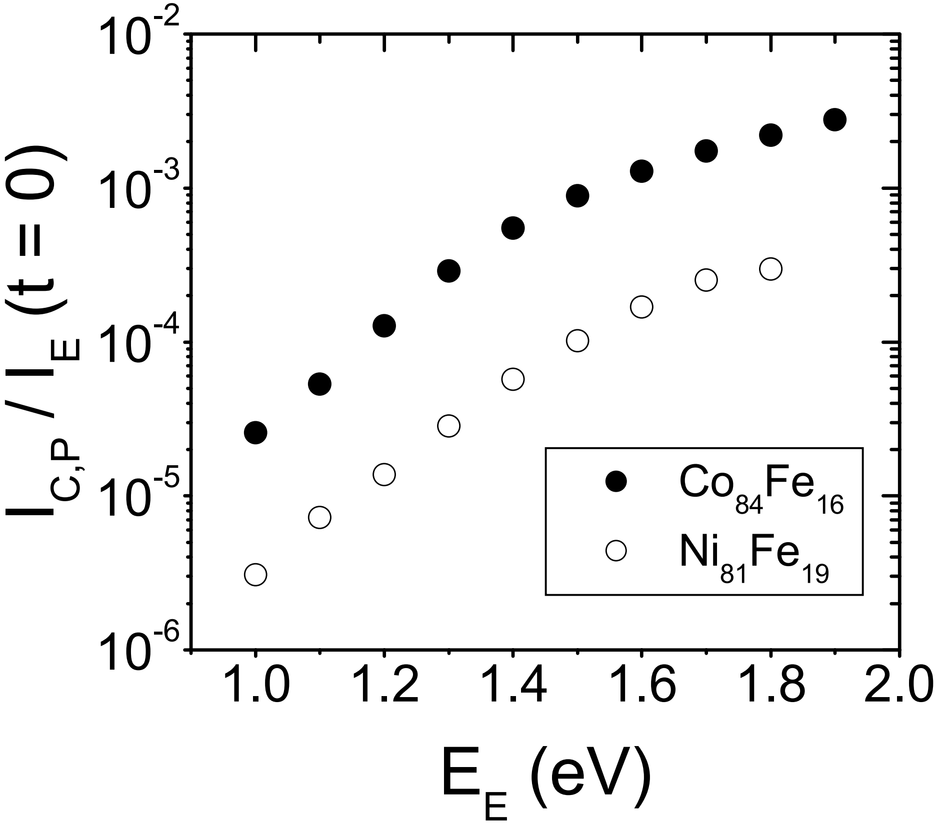
Including other scattering processes:

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

(assuming λ_{other} is independent of electron energy).

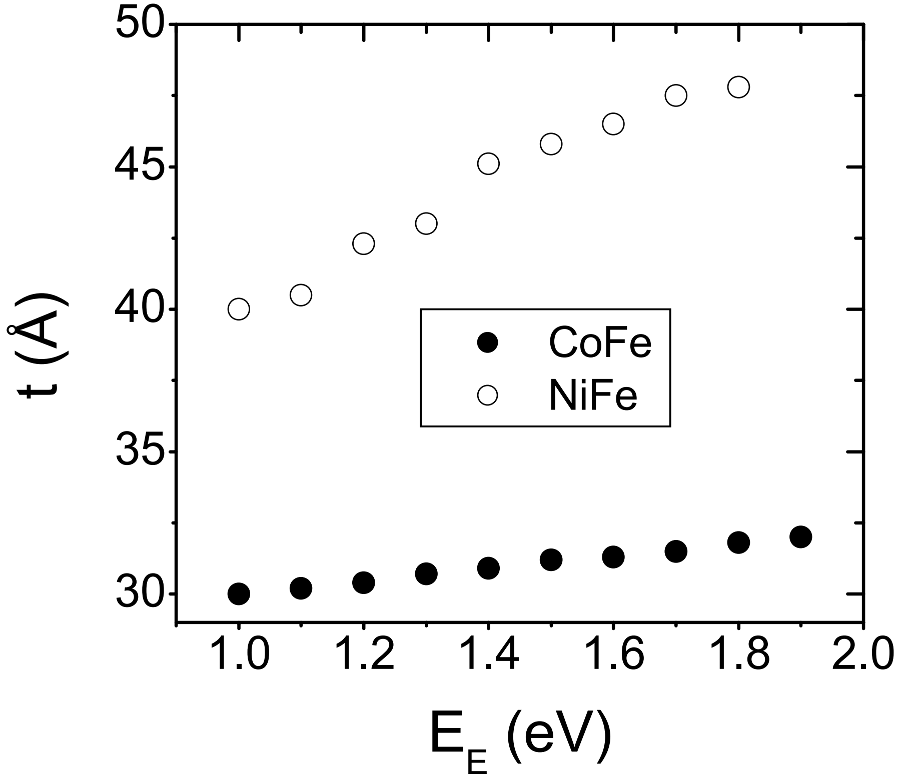
*J. J. Quinn, Phys. Rev. **126**, 1453 (1962)

Interface Scattering: CoFe vs. NiFe



- Extrapolated transfer ration 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

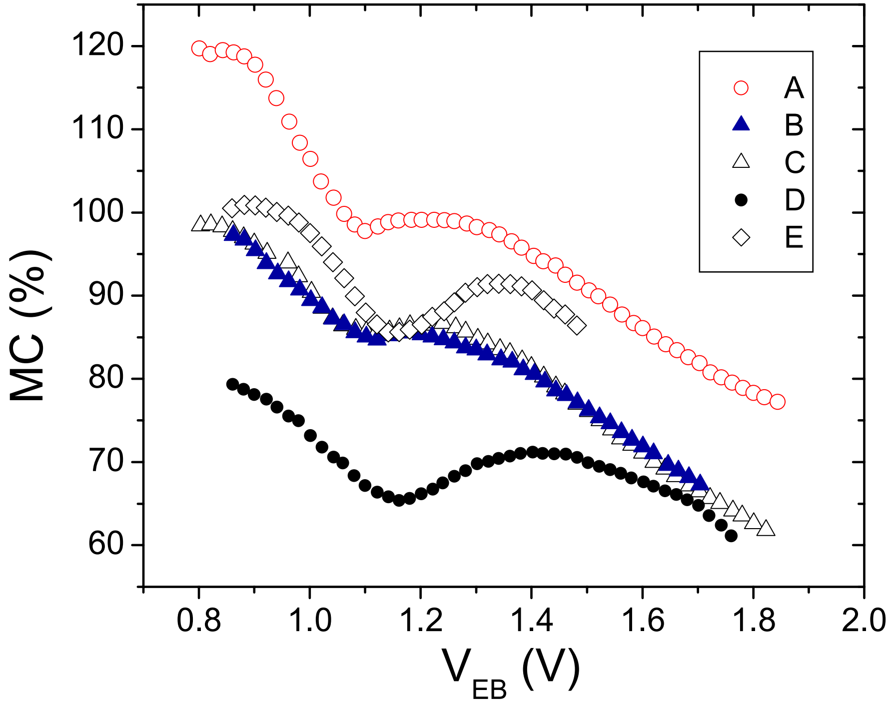
Spin Polarization vs. Base Layer Thickness



- 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.

Bias Dependence of MC in MTTs with GaAs Collectors

MTT structure: Collector / Base / ~20 Å Al_2O_3 / 50 Å CoFe / 300 Å IrMn / 50 Å Ta



Sample	Base	Collector	TMR (%)
A	30 Å CoFe	GaAs(001)	46.4
B	45 Å CoFe	GaAs(001)	40.7
C	100 Å CoFe	GaAs(001)	31.7
D	74 Å NiFe	GaAs(001)	14.7
E	30 Å CoFe	GaAs(111)	29.0

Sample A:

- MC decreases monotonically with bias up to ~ 1.1 V
- MC increases after 1.1 V and then decreases gradually at higher bias

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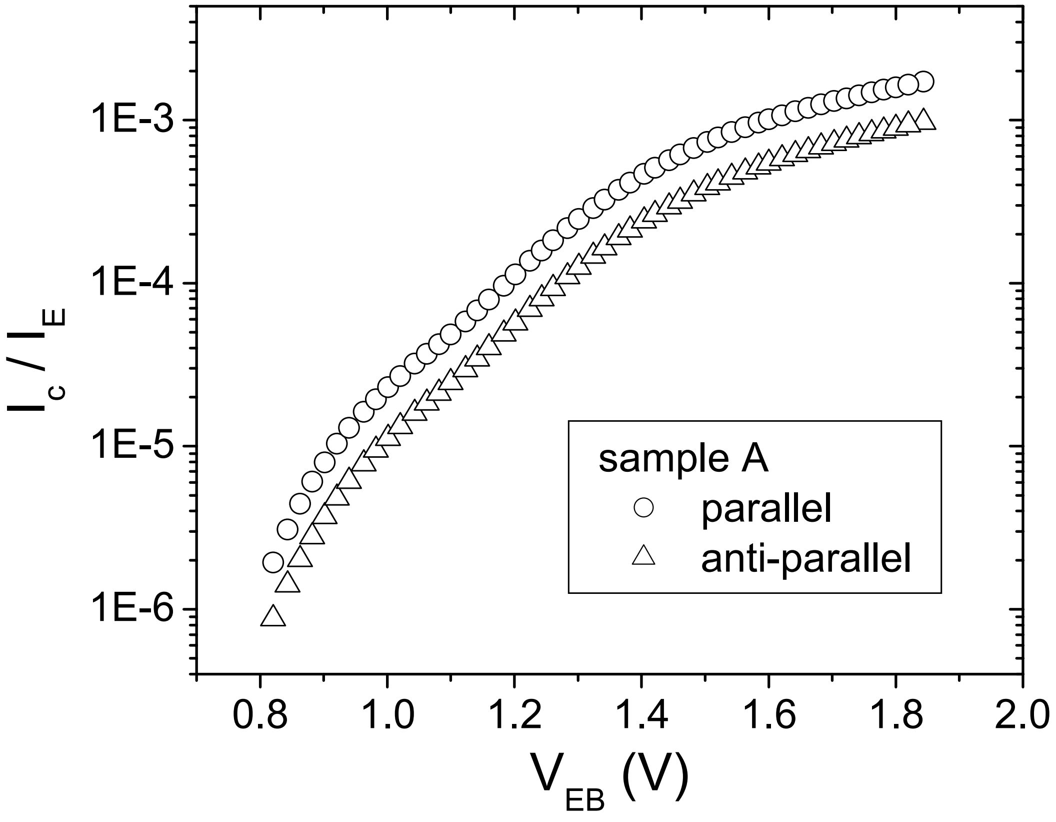
Bias Dependence of Transfer Ratio



- Transfer ratio increases with bias due to the opening of GaAs conduction bands for electron collection.
- More rapid increase in transfer ratio at ~ 1.1 V.

GaAs Conduction Band Structure

Γ band:

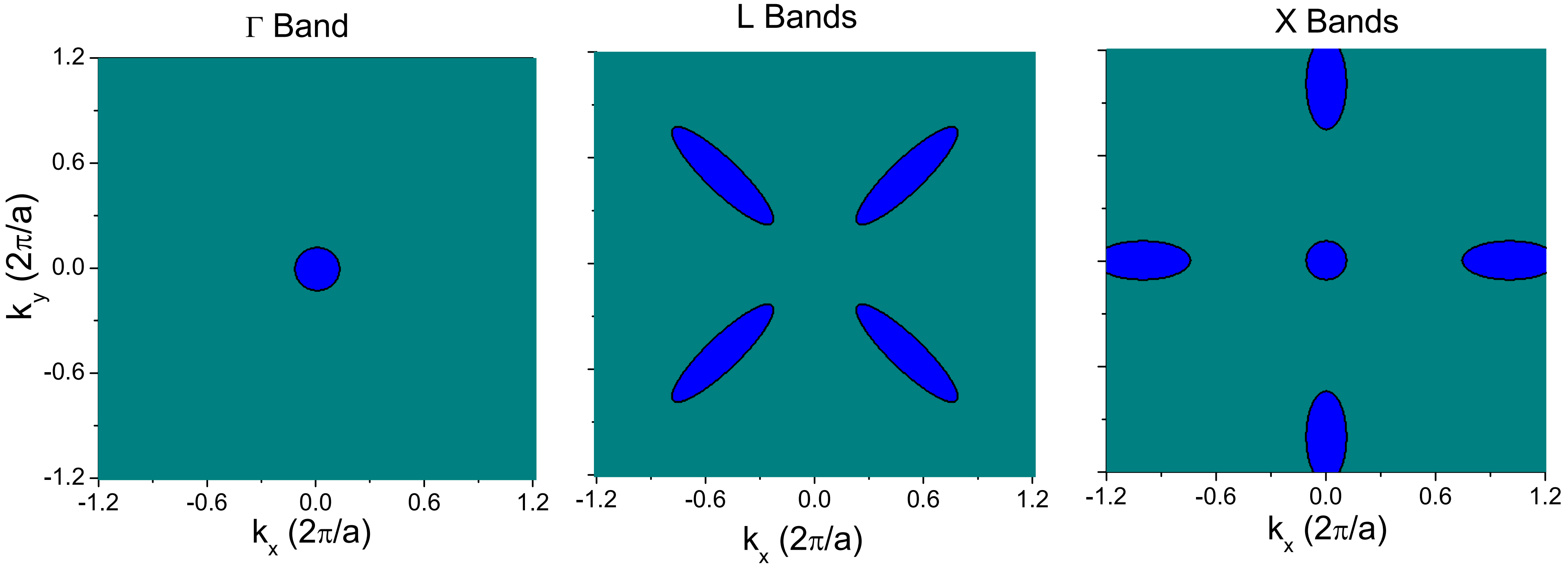
→ lowest energy

L bands:

→ 0.29 eV above Γ band

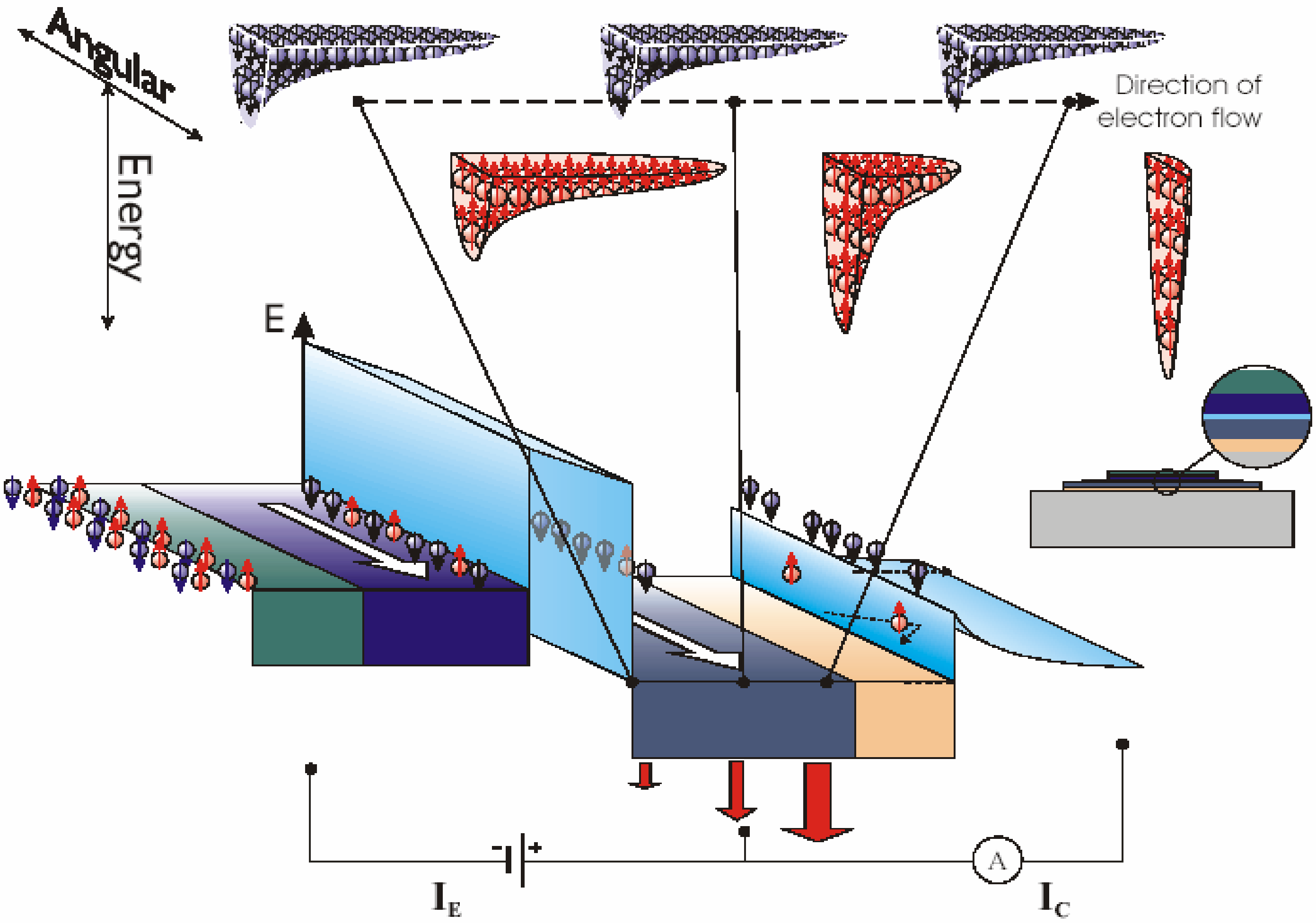
X bands:

→ 0.48 eV above Γ band



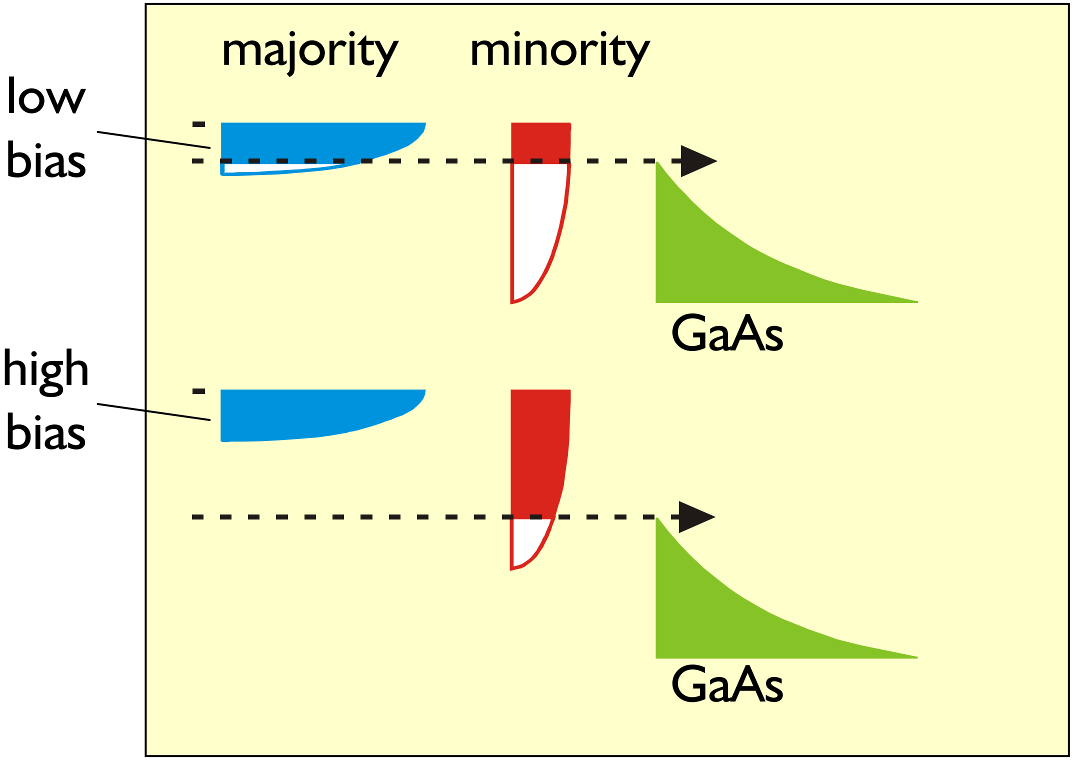
Projection of GaAs energy bands on (001) plane

Energy and Angular Distribution of Hot Electrons



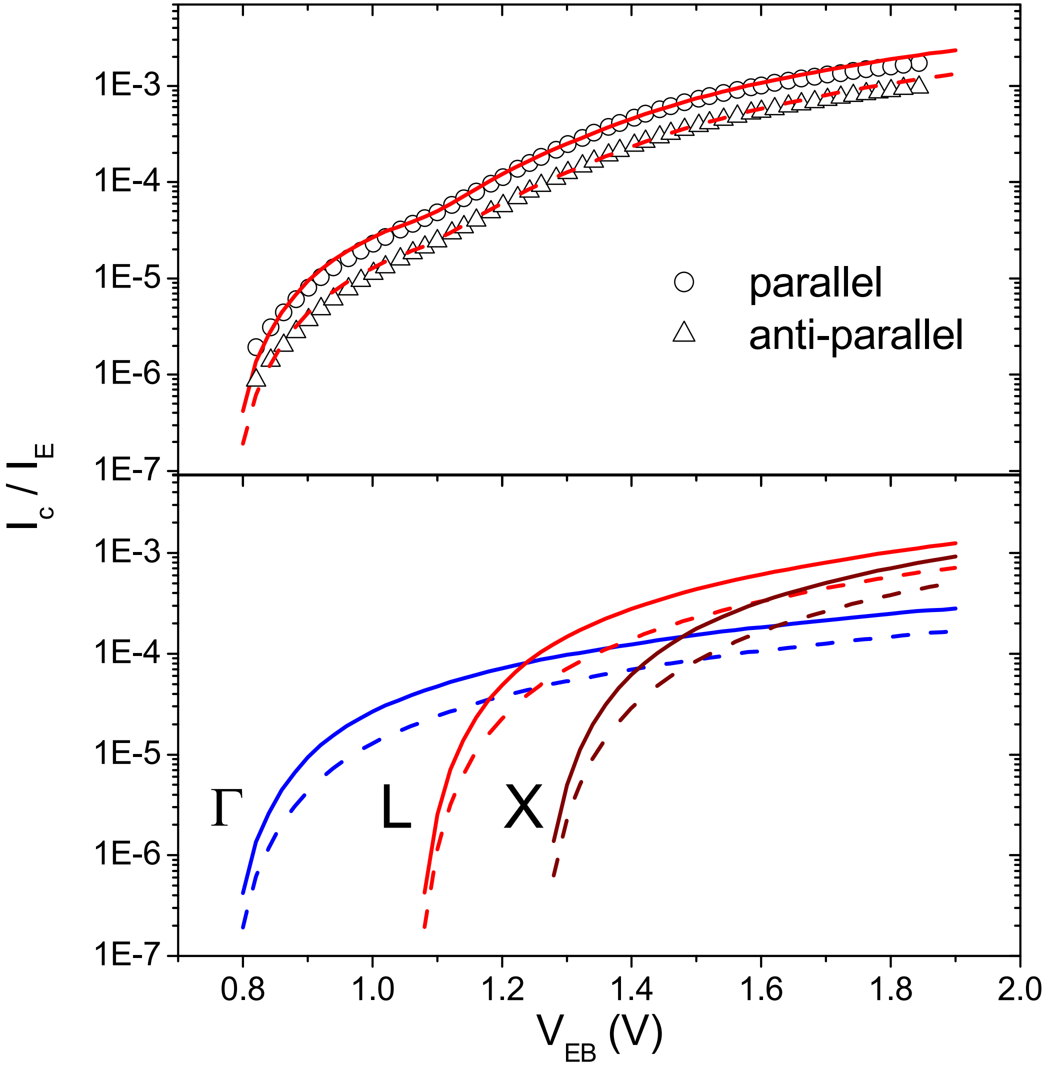
Scattering in the base broadens the energy and angular distribution of hot electrons.

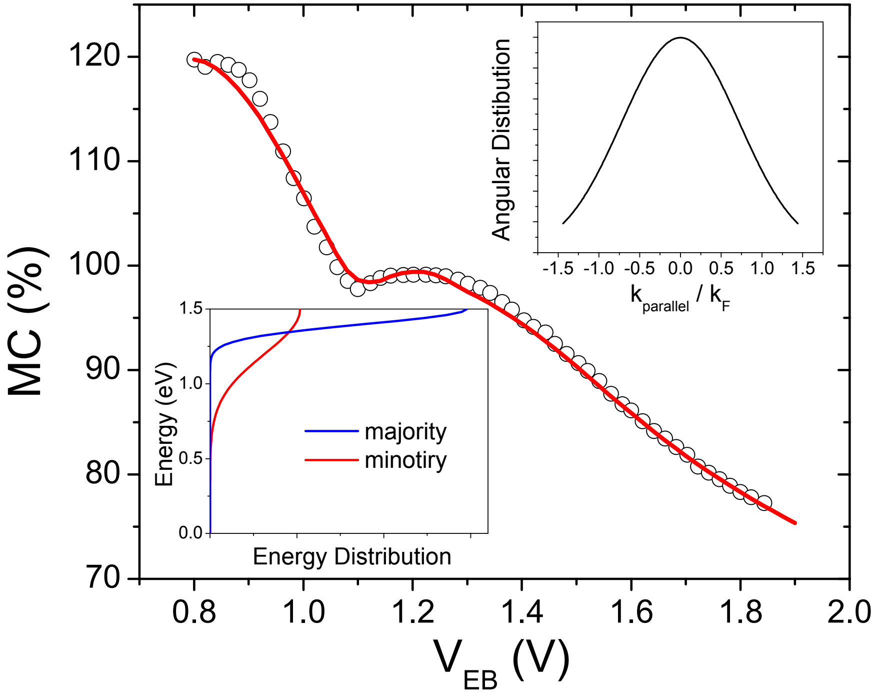
Model



- 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.

Calculation Results



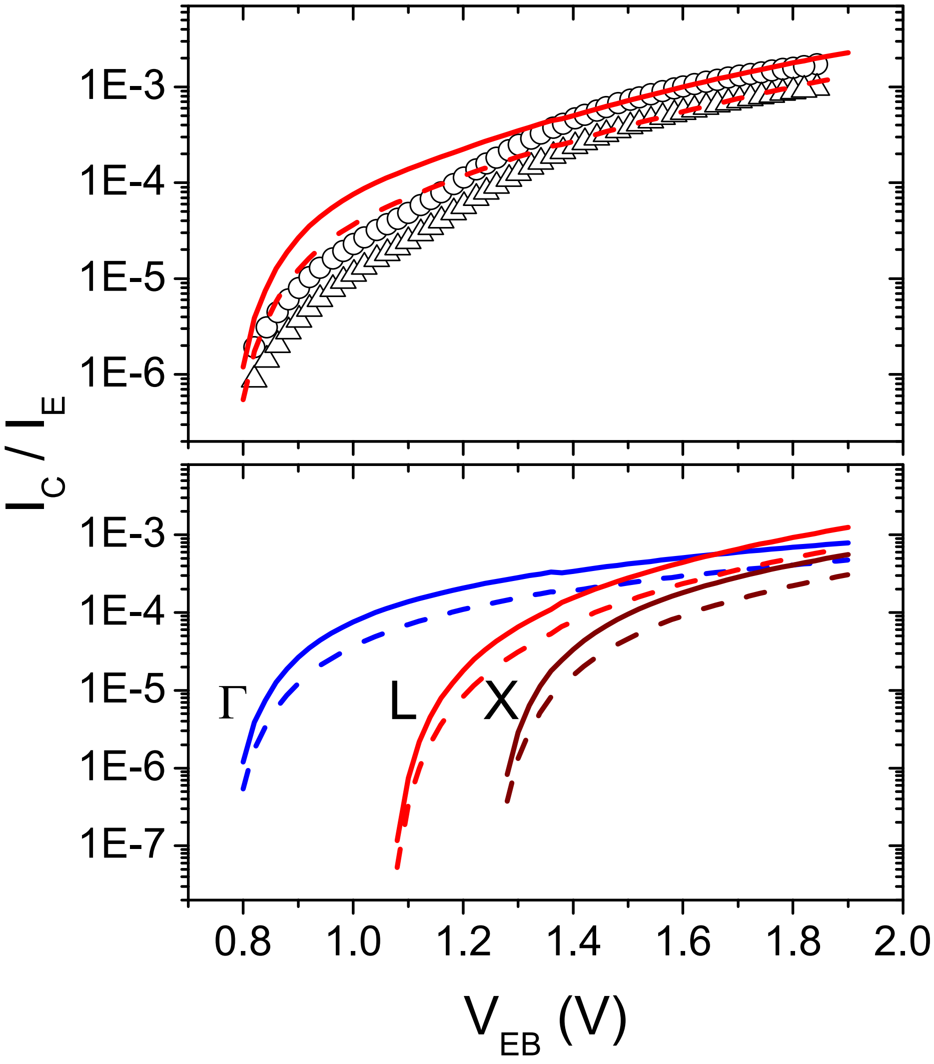


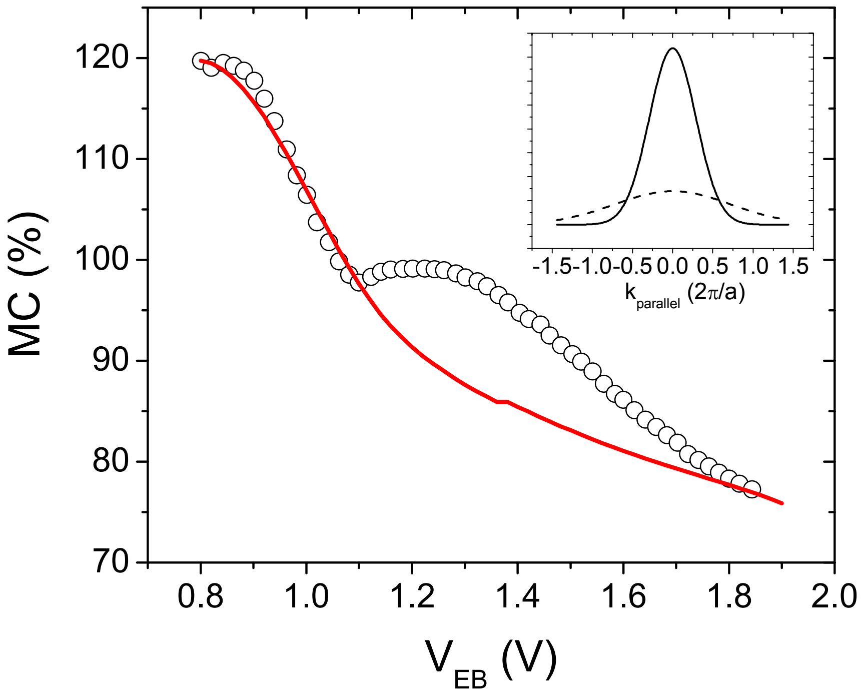
- Angular distribution: broad for both majority and minority electrons.

  → strong interface scattering

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

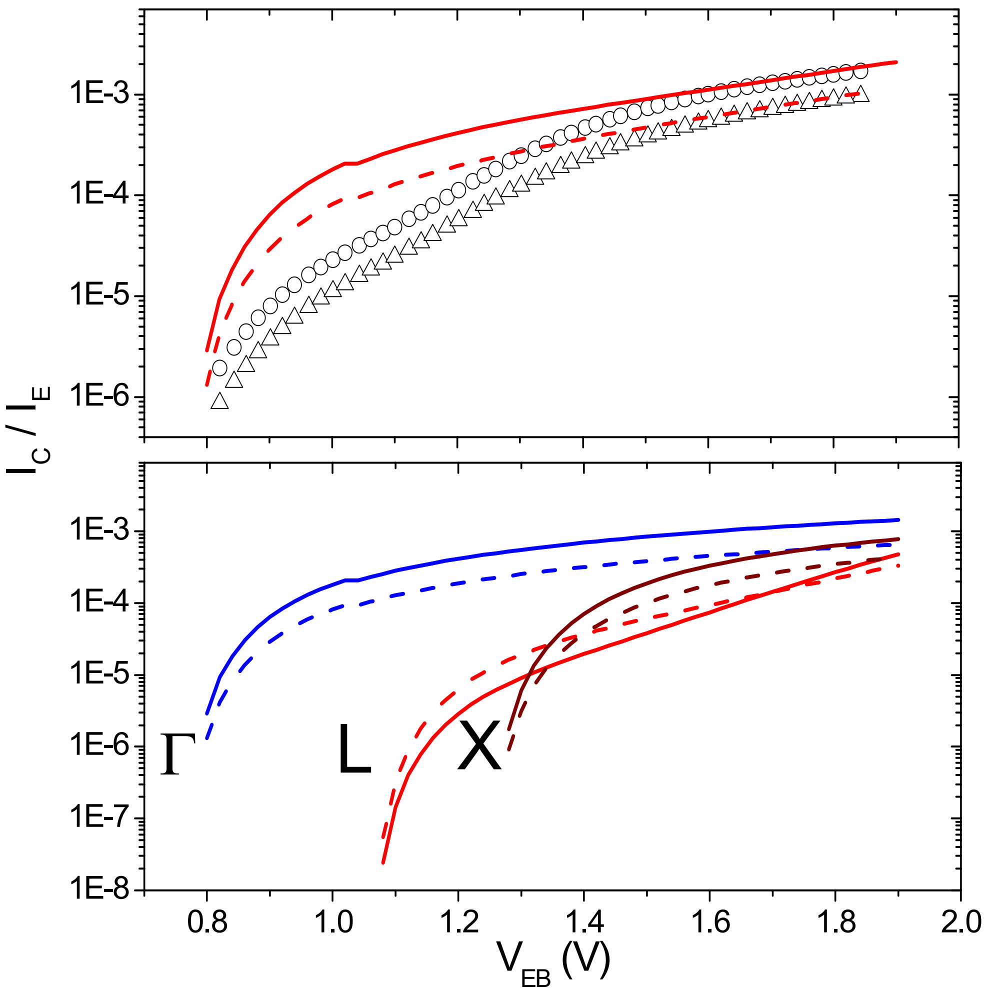
Narrow Angular Distribution

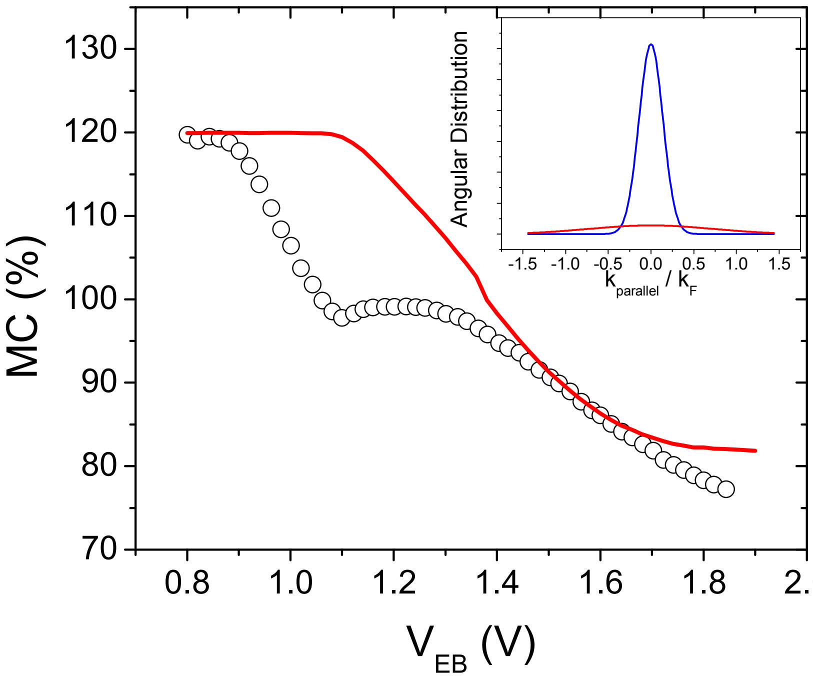




For narrow angular distribution, the contribution from the L bands is very small. The non-monotonic bias dependence of MC cannot be reproduced.

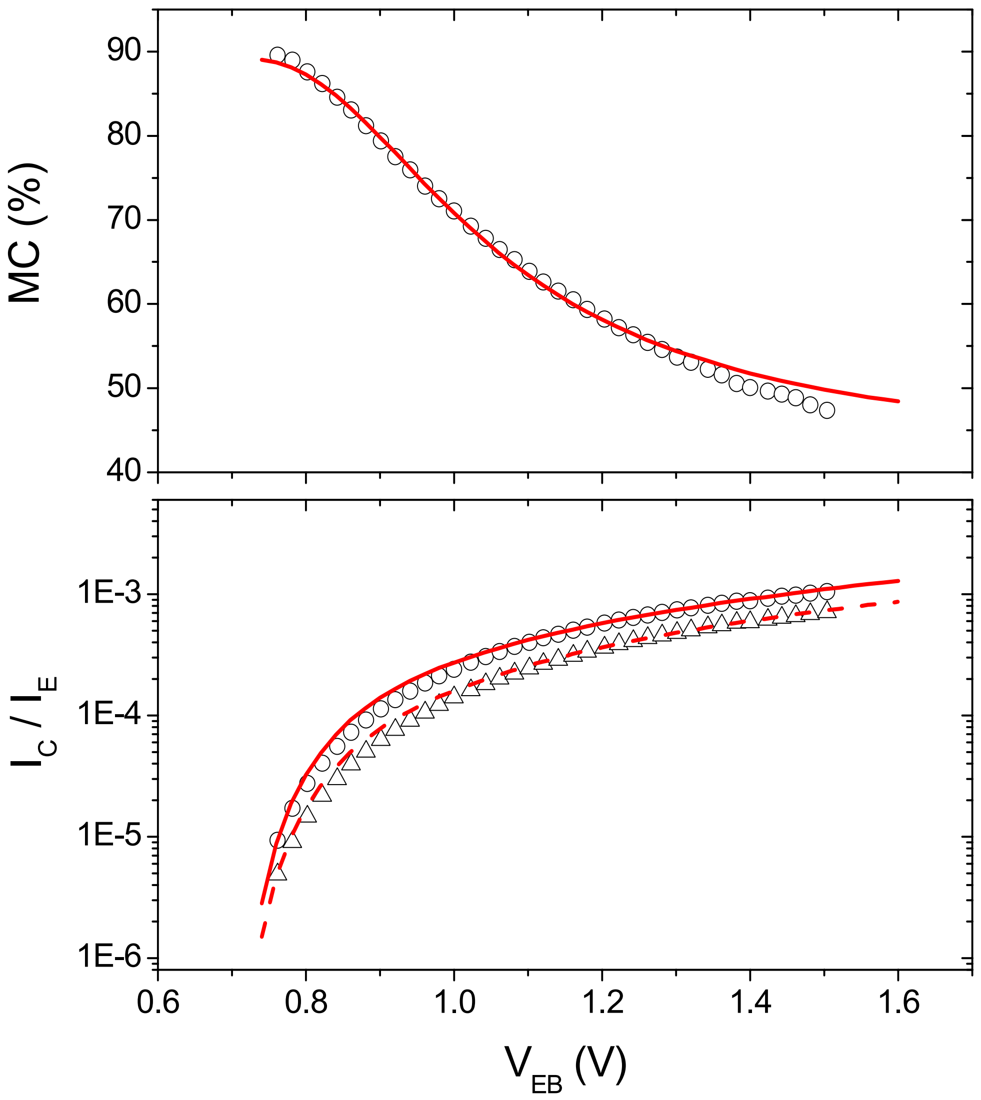
Same Energy Distribution





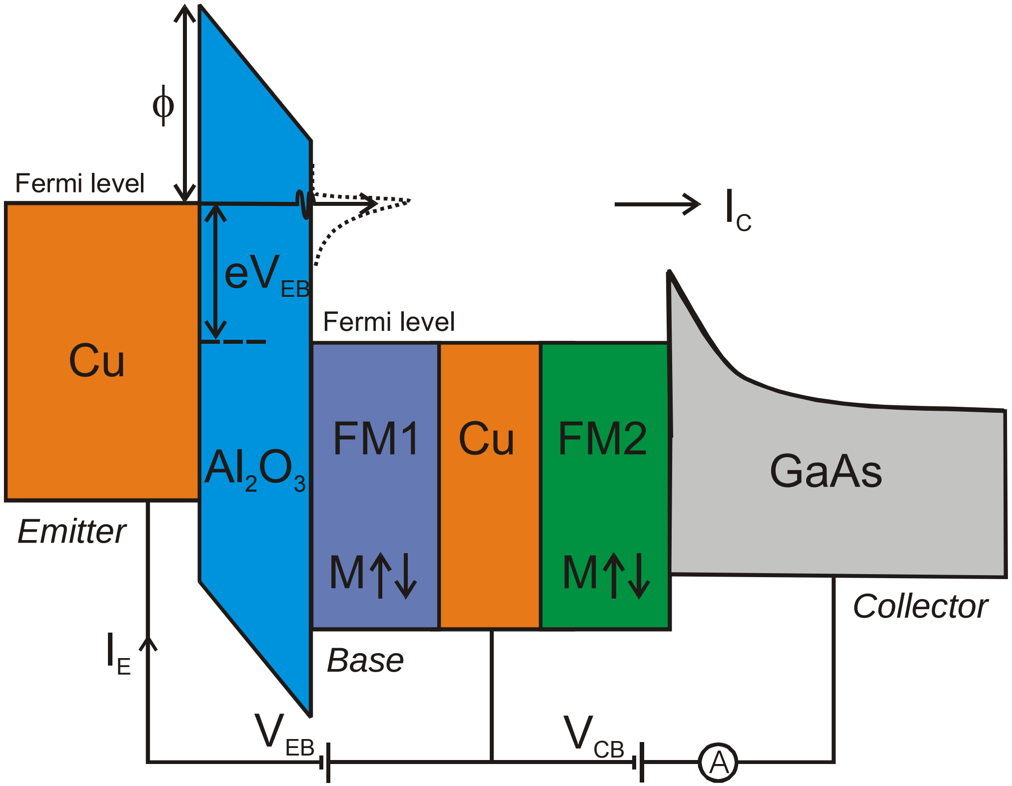
The non-monotonic bias dependence of MC cannot be reproduced without assuming different energy distribution for majority and minority electrons.

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

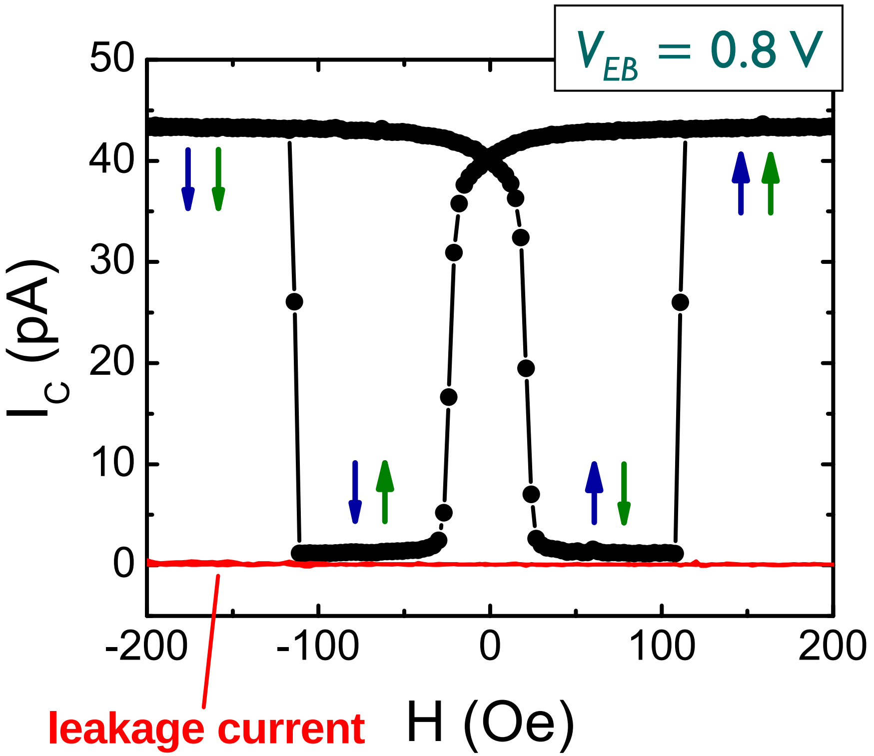
- **Transmission polarization:**

$$P = \frac{e^{-t/\lambda_\uparrow} - e^{-t/\lambda_\downarrow}}{e^{-t/\lambda_\uparrow} + e^{-t/\lambda_\downarrow}}$$

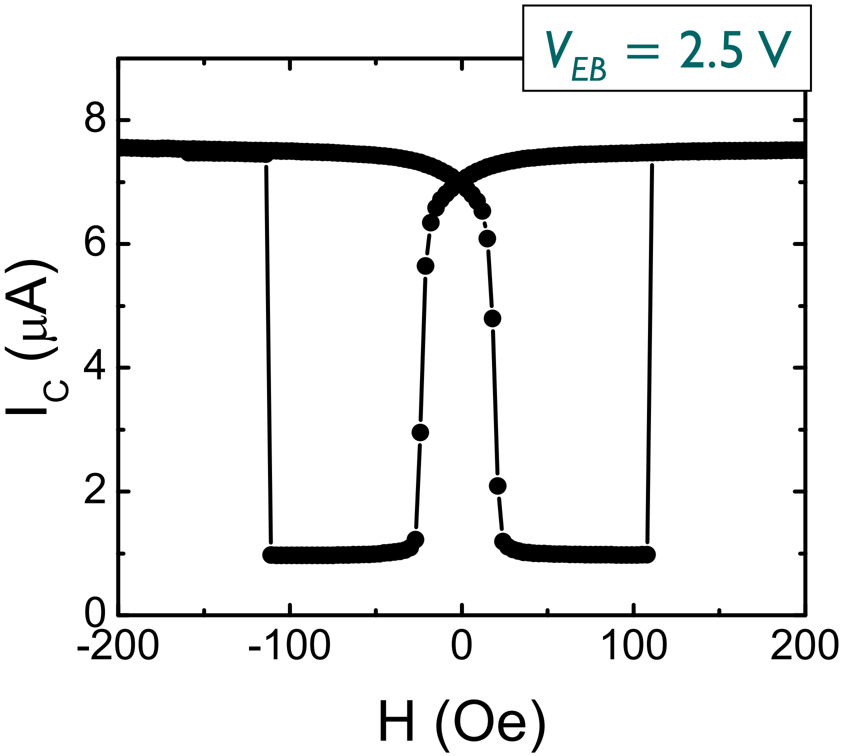
3400% MC

Spin-valve: 50 Å $Ni_{81}Fe_{19}$ / 40 Å Cu / 50 Å $Co_{70}Fe_{30}$

MC = 3420 %
I_C = 43 pA

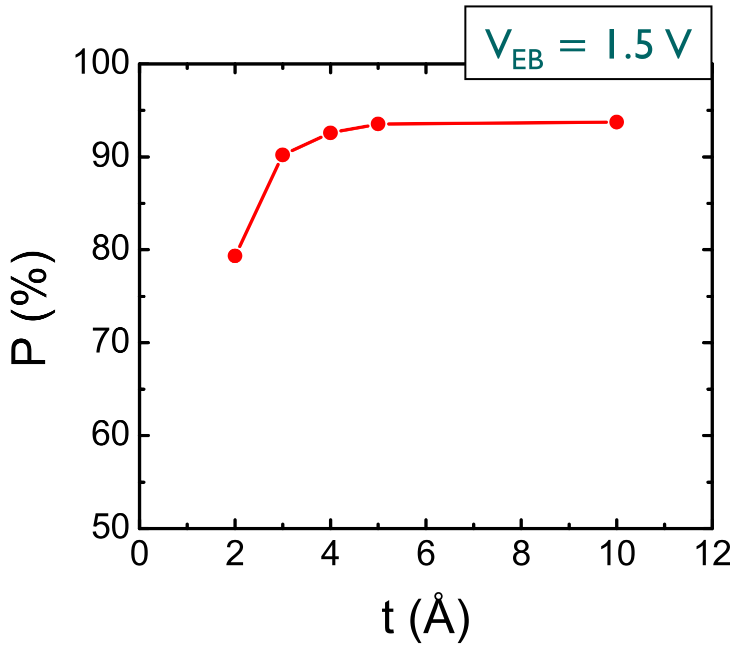


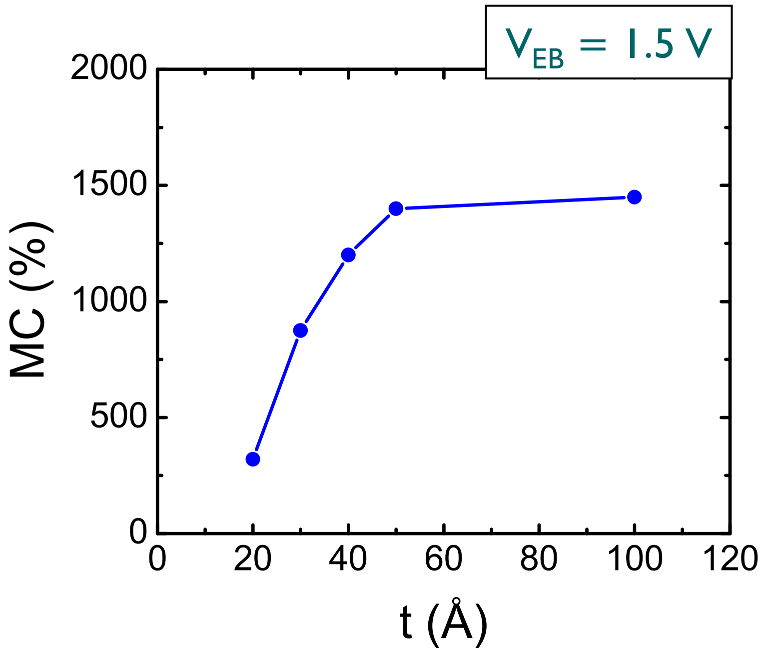
MC = 670 %
I_C = 7.5 μA



Spin Filtering

t Å NiFe / 40 Å Cu / t Å CoFe





Transmission Polarization :

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

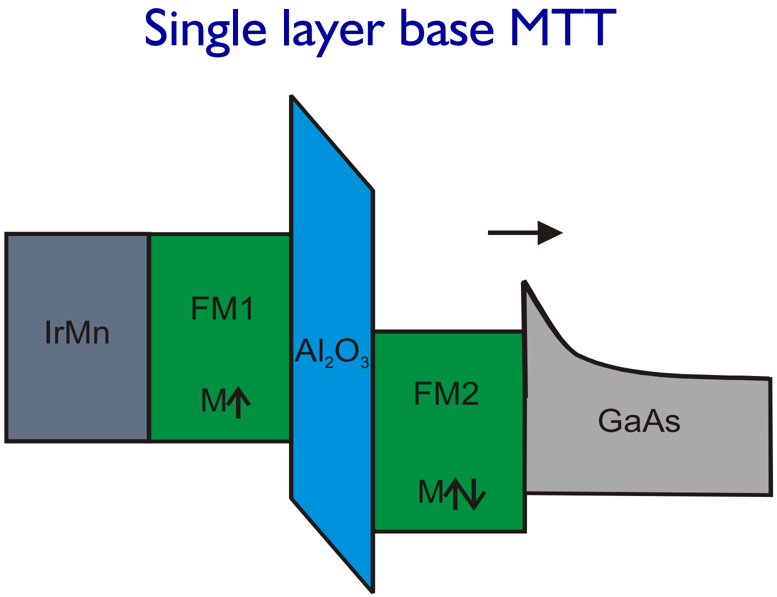
Magnetocurrent :

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

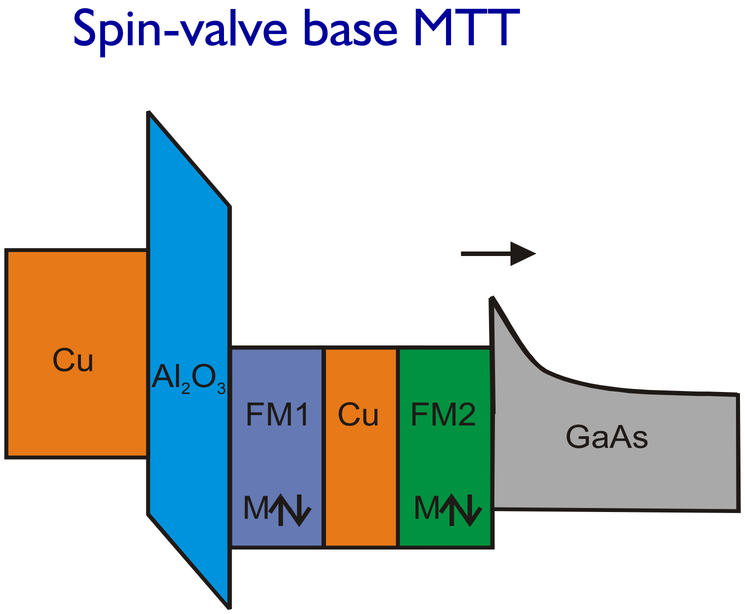
MC: Single Layer Base MTT vs. Spin-Valve Base MTT

$$MC = 2P_1P_2 / (1 - P_1P_2)$$

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

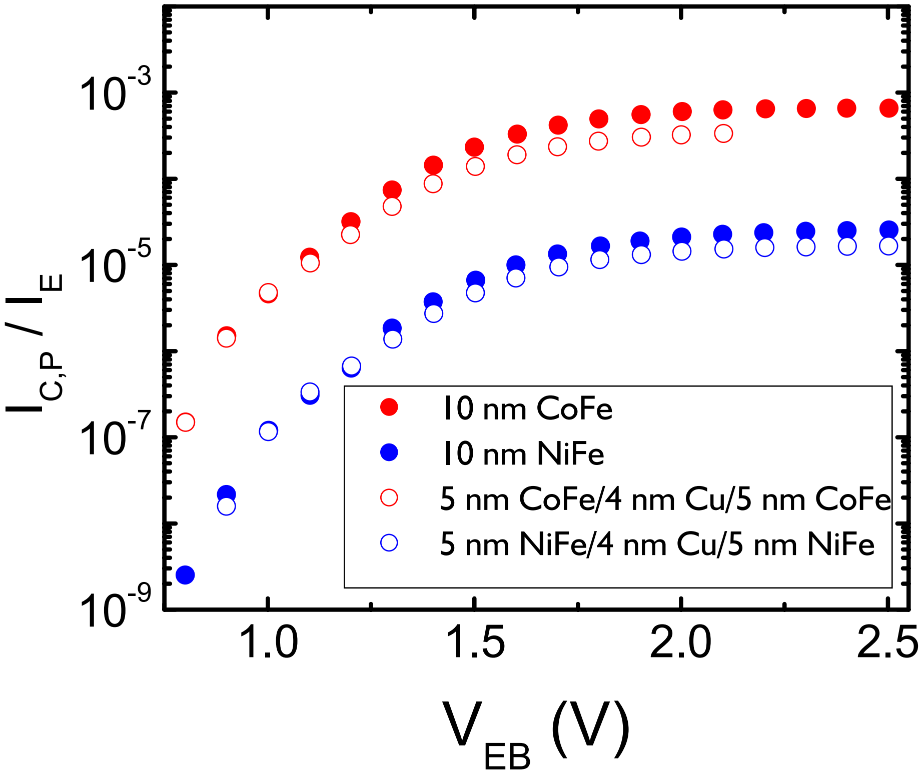

Single layer base MTT

$P_1 = 40\%, P_2 = 95\%$
→ MC = 123 %


Spin-valve base MTT

$P_1 = 95\%, P_2 = 95\%$
→ MC = 1850 %

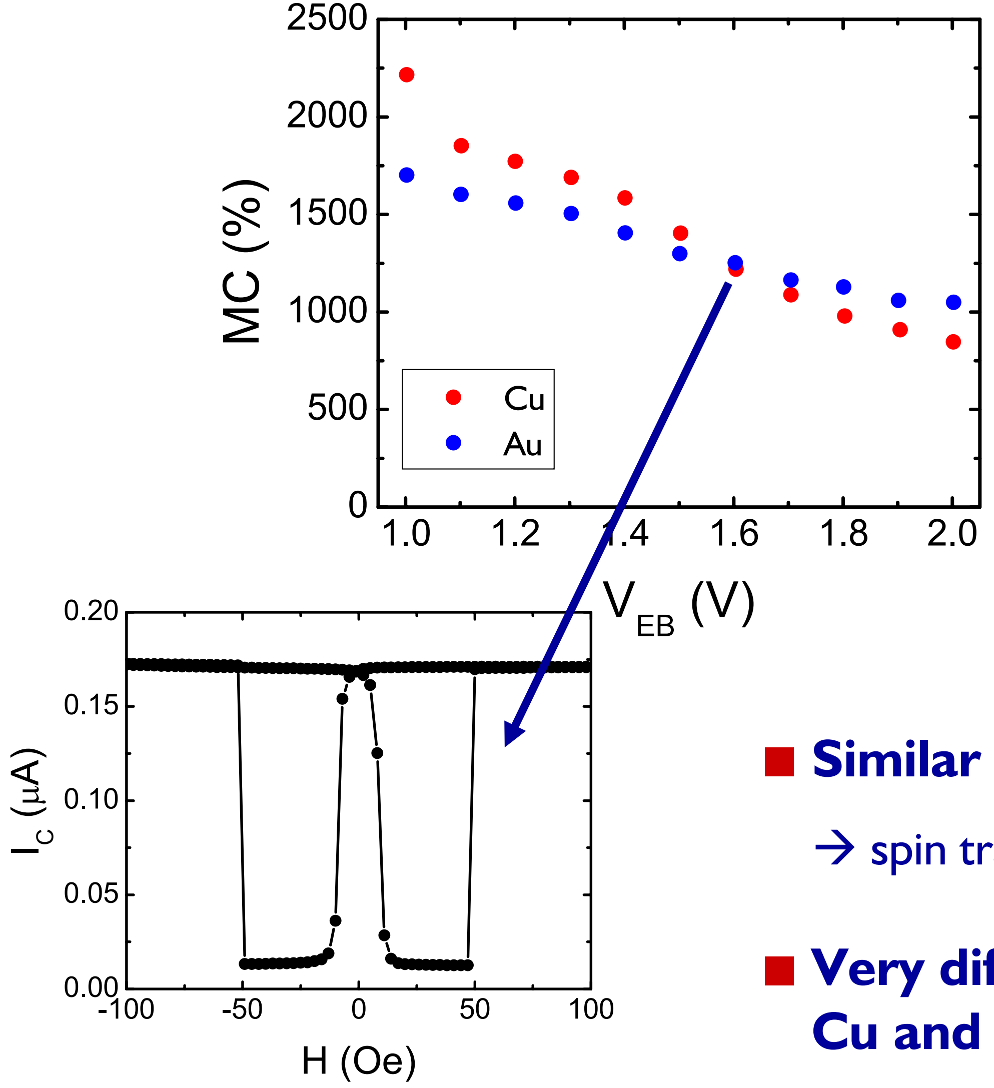
Interface Scattering



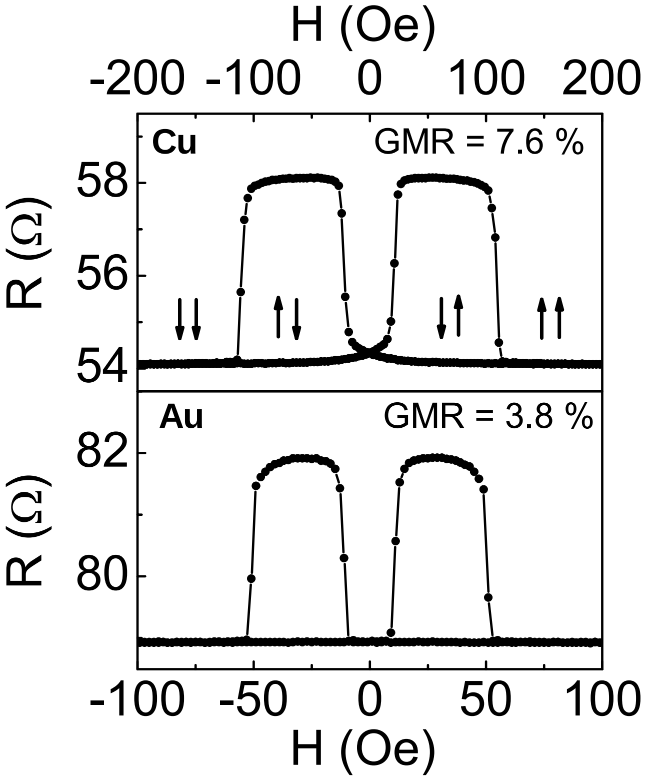
- Hot electron scattering at CoFe/Cu and NiFe/Cu interfaces negligible
- Strong hot electron scattering at NiFe/GaAs interface than at CoFe/GaAs interface

MC: Cu vs. Au Space Layers

50 Å NiFe / 40 Å Au or Cu / 50 Å CoFe



50 Å NiFe/40 Å Au/50 Å CoFe



- **Similar MC for Cu and Au spacers**

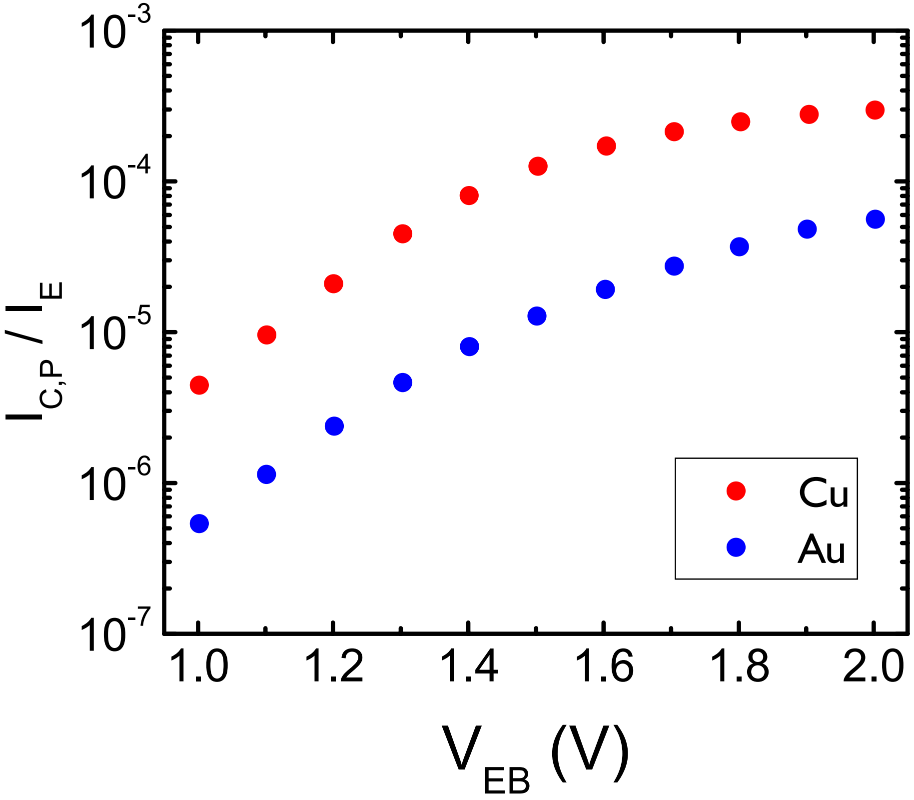
  → spin transport in MTTs dominated by bulk effect

- **Very different GRM of the spin-valve with Cu and Au spacers**

  → GMR effect dominated by interface effect

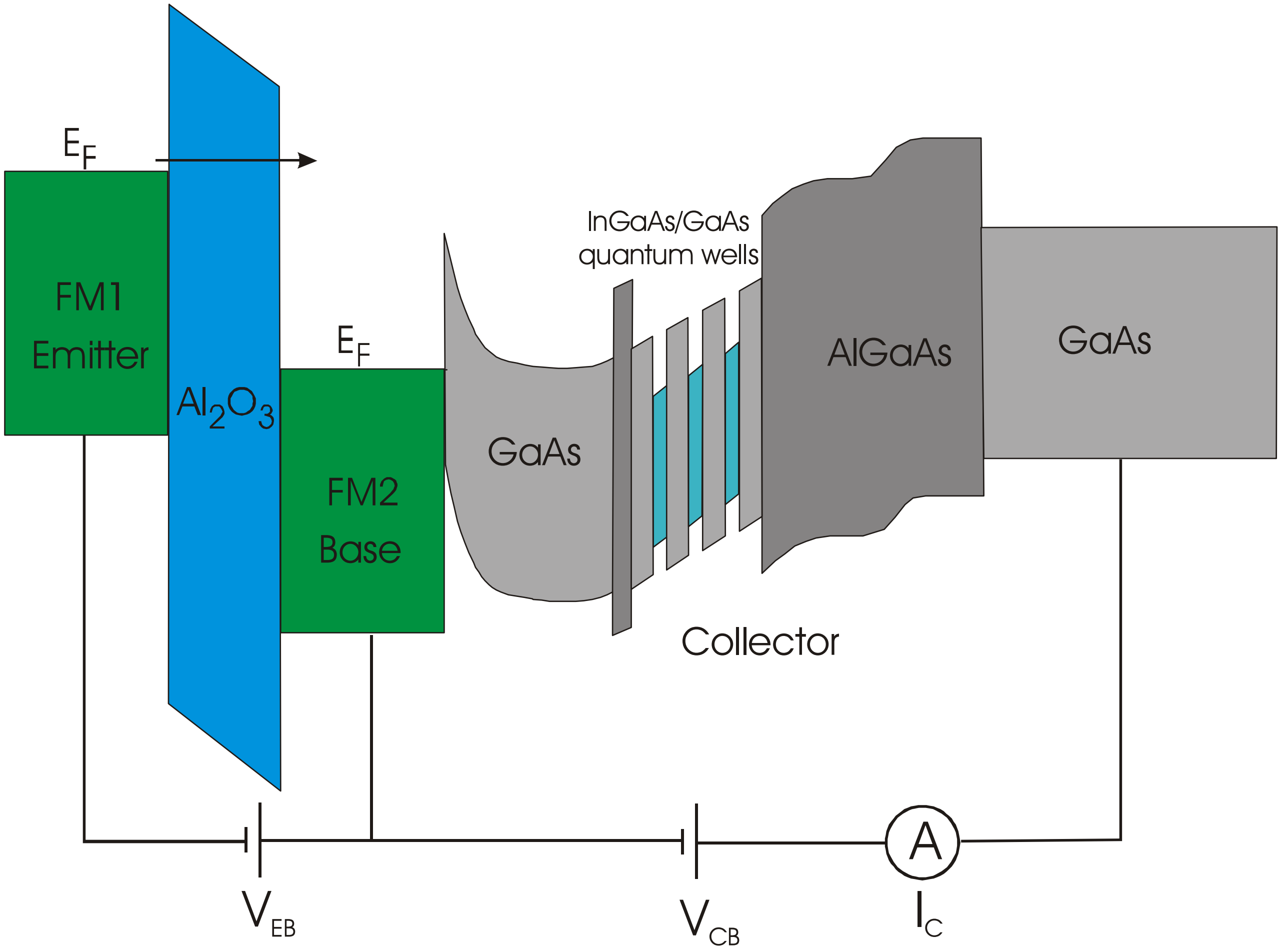
TR: Cu vs. Au Space Layer

50 Å NiFe / 40 Å Au or Cu / 50 Å CoFe



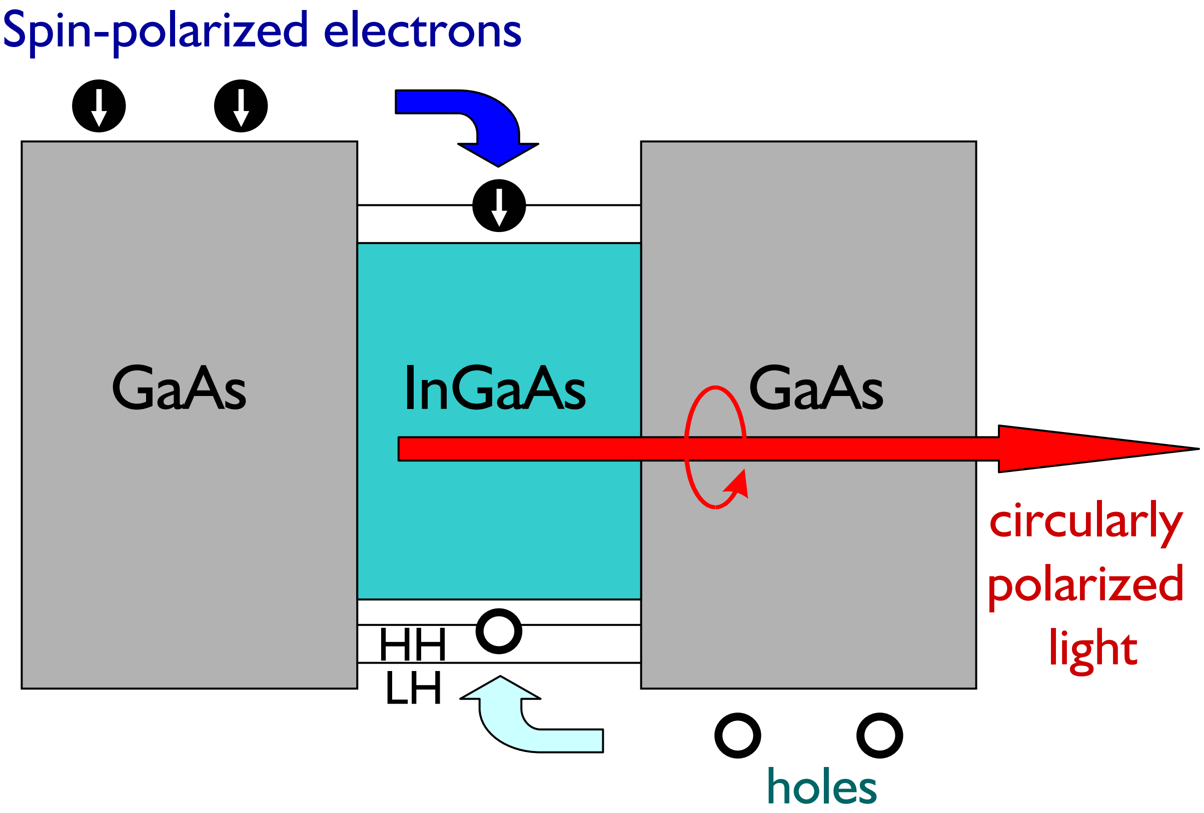
Strong hot electron scattering at the CoFe/Au and NiFe/Au interfaces

Electrical Spin Injection from MTTs into GaAs



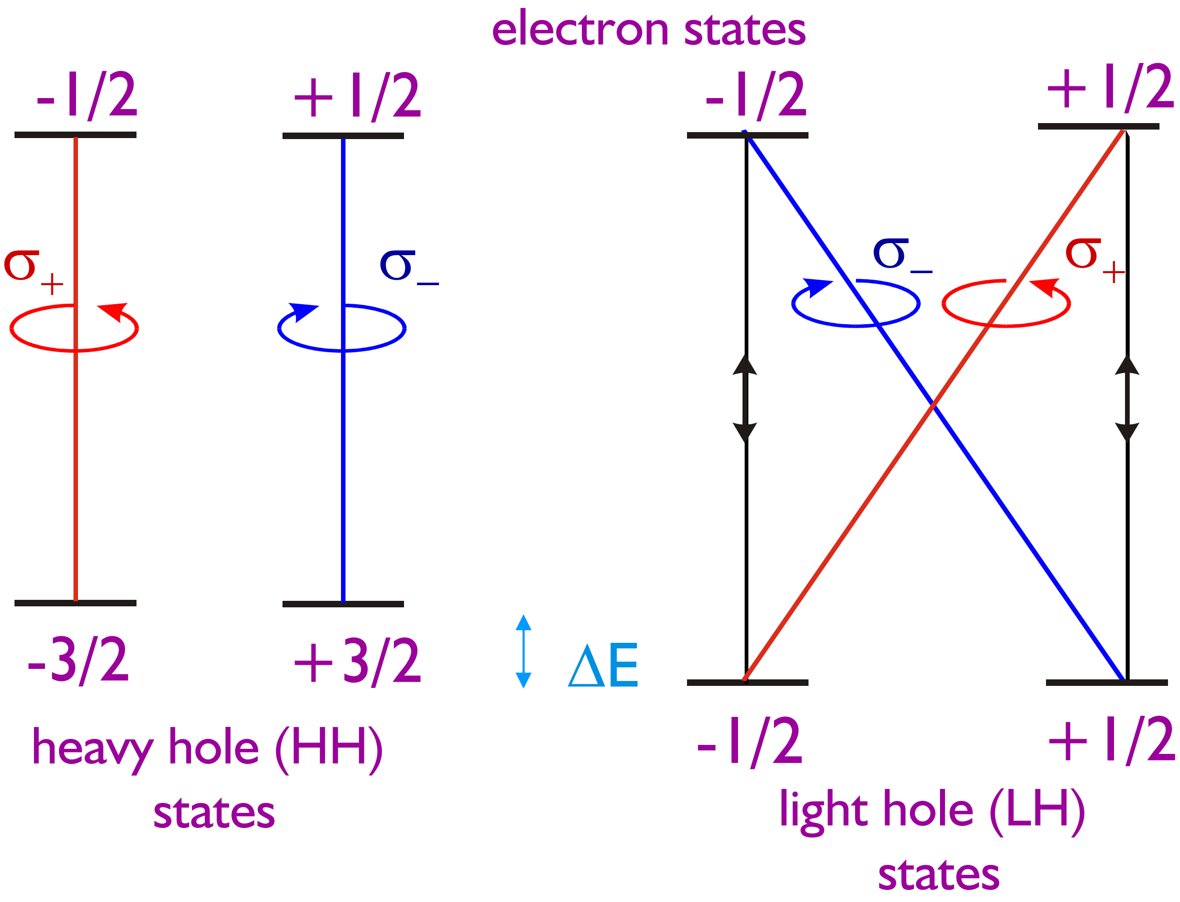
p^+-GaAs / p-AlGaAs / i-AlGaAs / [GaAs / InGaAs QW]$_3$ / i-AlGaAs / n-GaAs / NiFe / CoFe / Al_2O_3 / CoFe / Ta

Electron-Hole Recombination in Quantum Wells



- 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

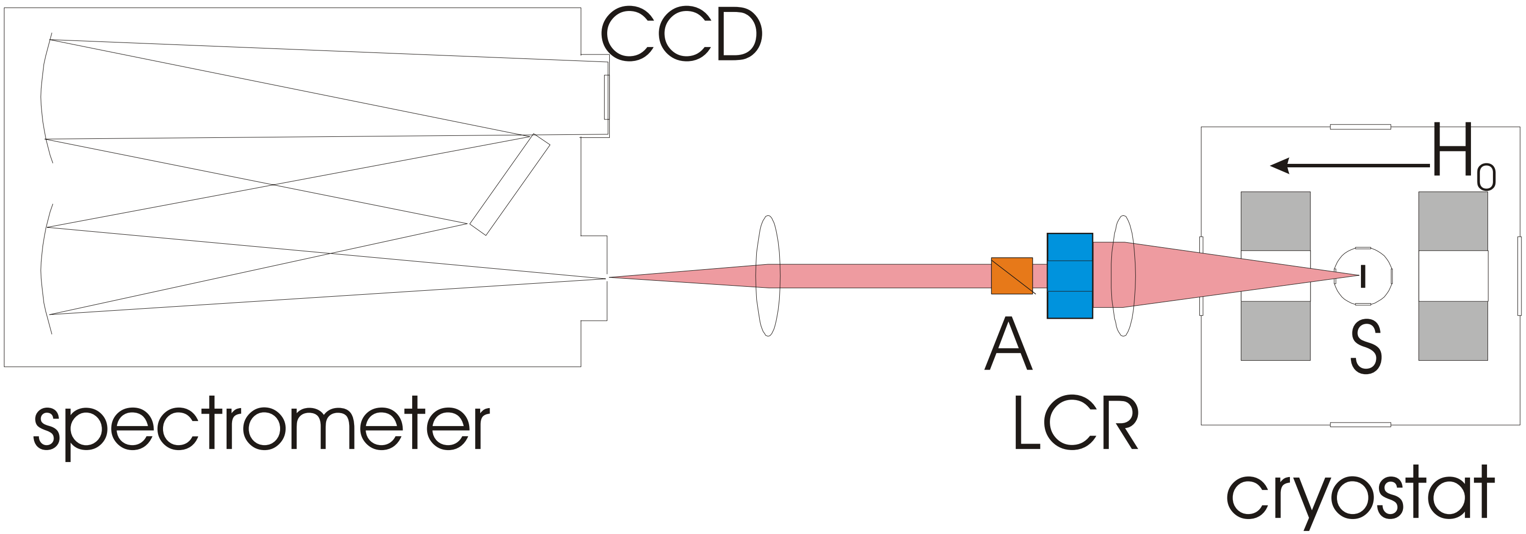


Selection Rules:

- 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.

Experiment Set-up



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:

  $1 / \tau_S \propto 1 / \tau_p$ → $1 / \tau_p$ 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:**

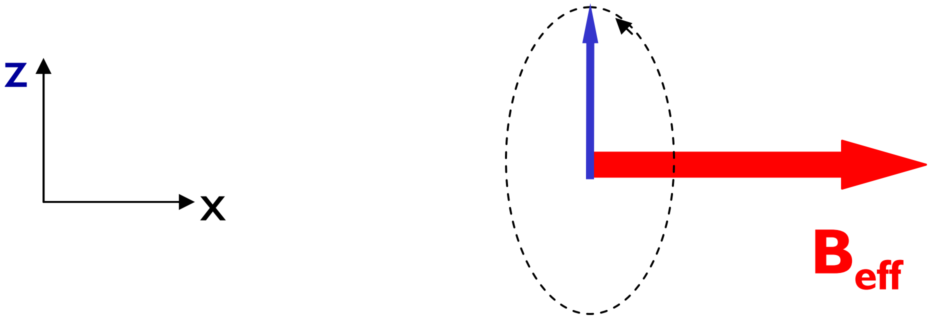
  - Effective magnetic field: $H = - g \hbar (\sigma \bullet \mathbf{B}_{EFF}) / 2$, $B_{EFF} = B_{EFF} (\mathbf{p}) \propto E^n$

  - Spin relaxation due to precession in the effective magnetic field

  - Spin relaxation rate: $1 / \tau_S \propto \tau_p$

DP Relaxation Mechanism

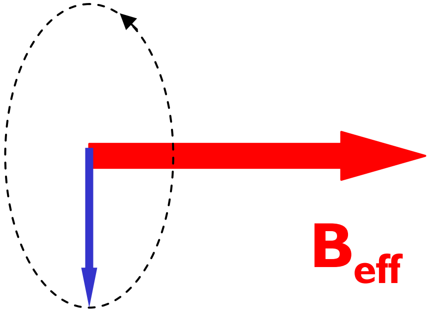
Injected spin along z-axis, effective magnetic field along x-axis



large τ_p:

$\langle S_z \rangle = 0$

spin relaxation is effective

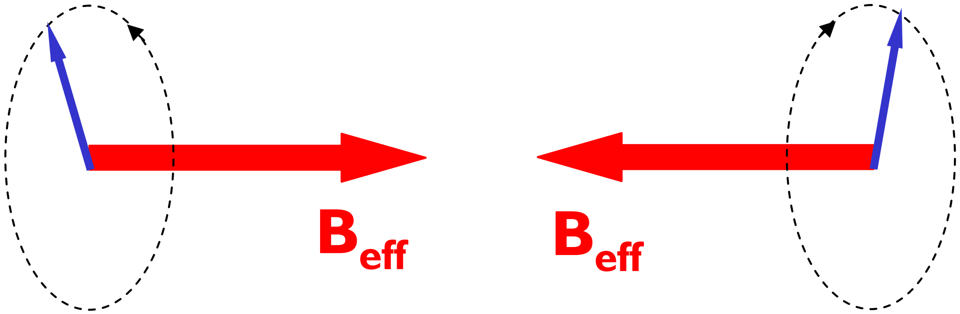


no momentum scattering

small τ_p:

$\langle B \rangle = 0$

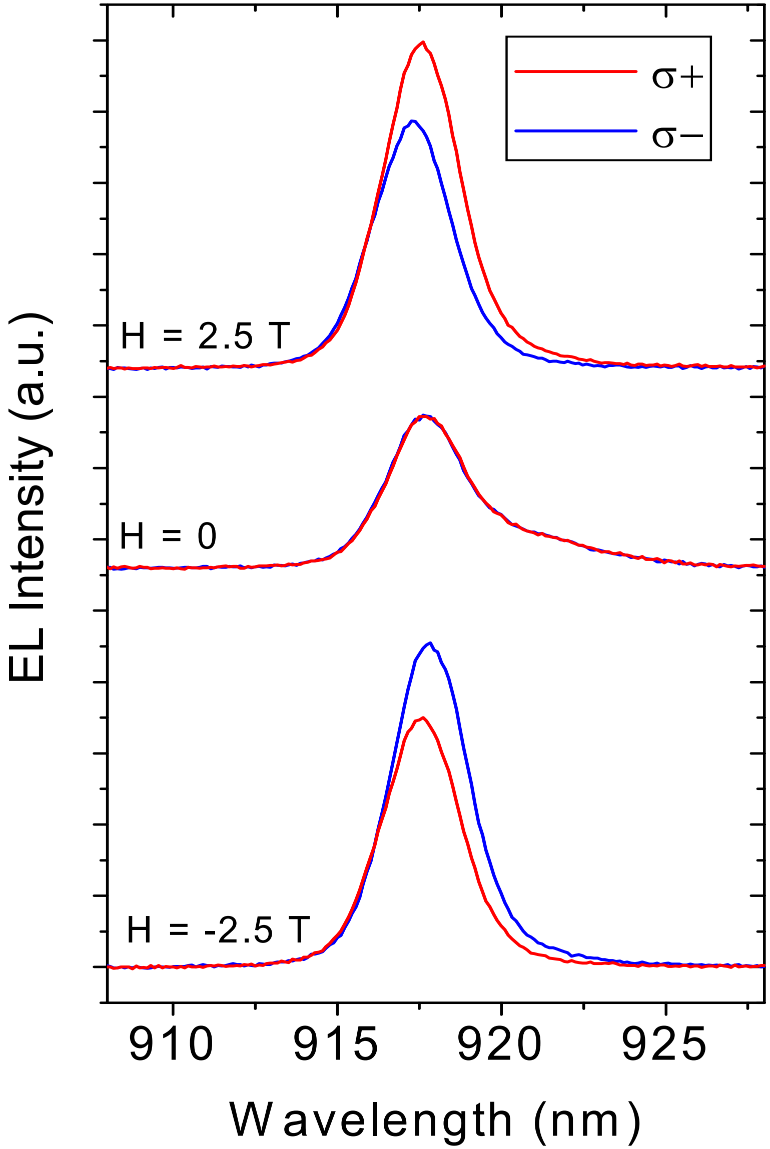
spin relaxation is suppressed



before scattering

after scattering

Electroluminescence

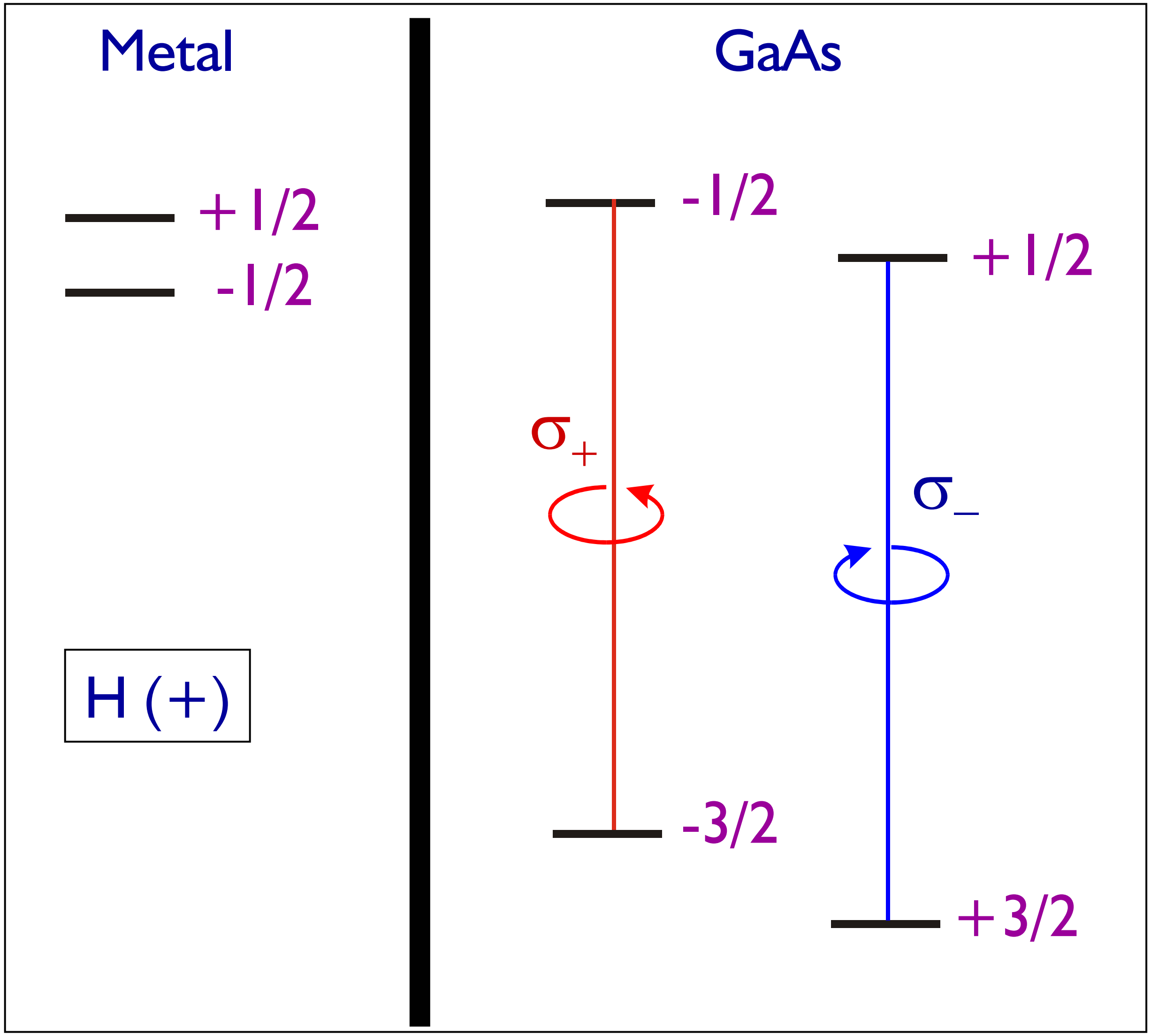


- T = 1.4 K, V_{EB} = -2.06 V, V_{CB} = 1.0 V
- EL polarization defined as:

$$P_{EL} = (I_+ - I_-) / (I_+ + I_-)$$

I_+ and I_- being EL intensities for σ_+ and σ_- components respectively.

Majority Spin Injection



R. Wang

- Zeeman splitting

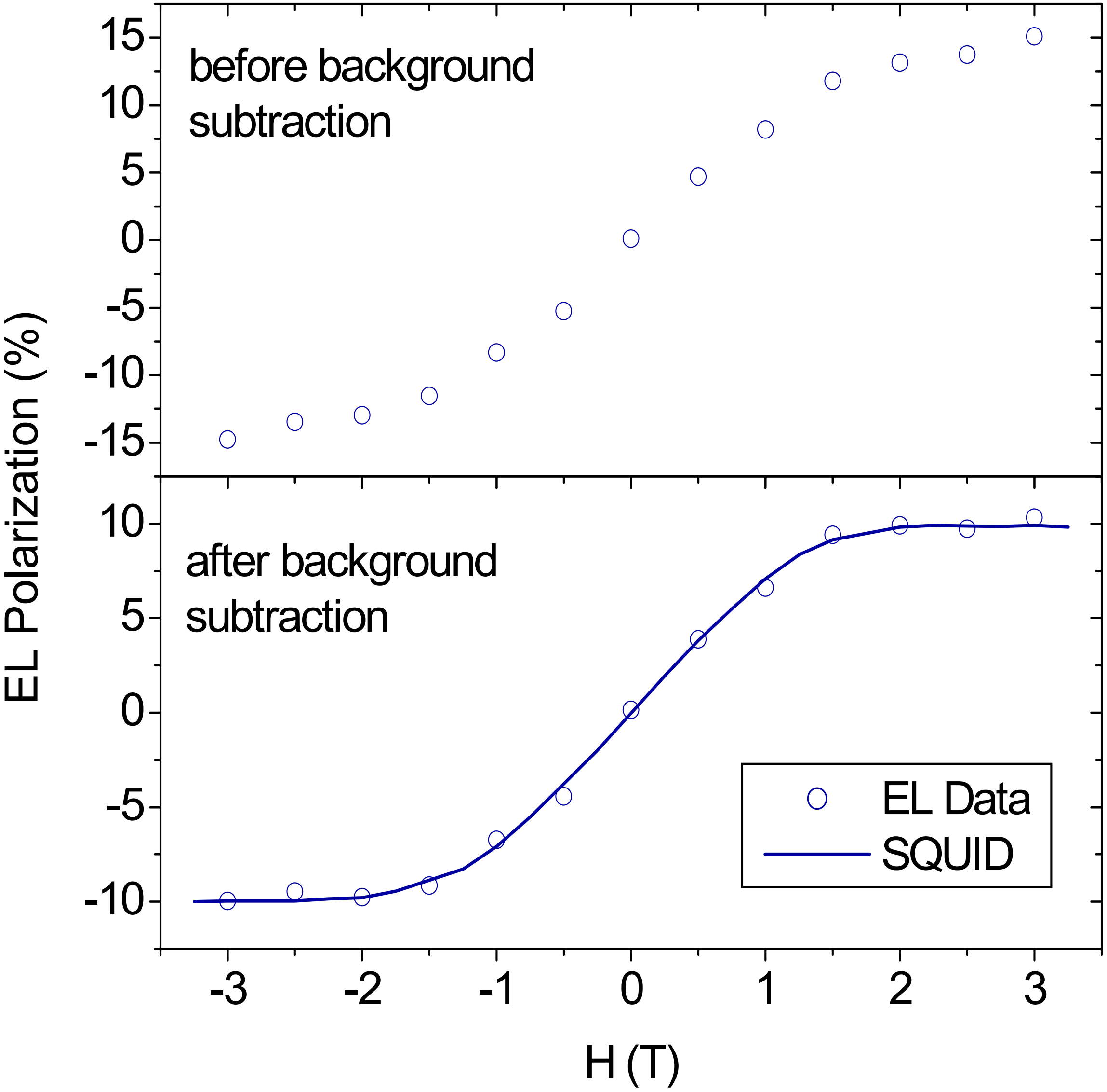
  $\Delta E = - g \mu H m_s$

- Metal: $g_e \sim 2$

  GaAs: $g_e \sim -0.44$

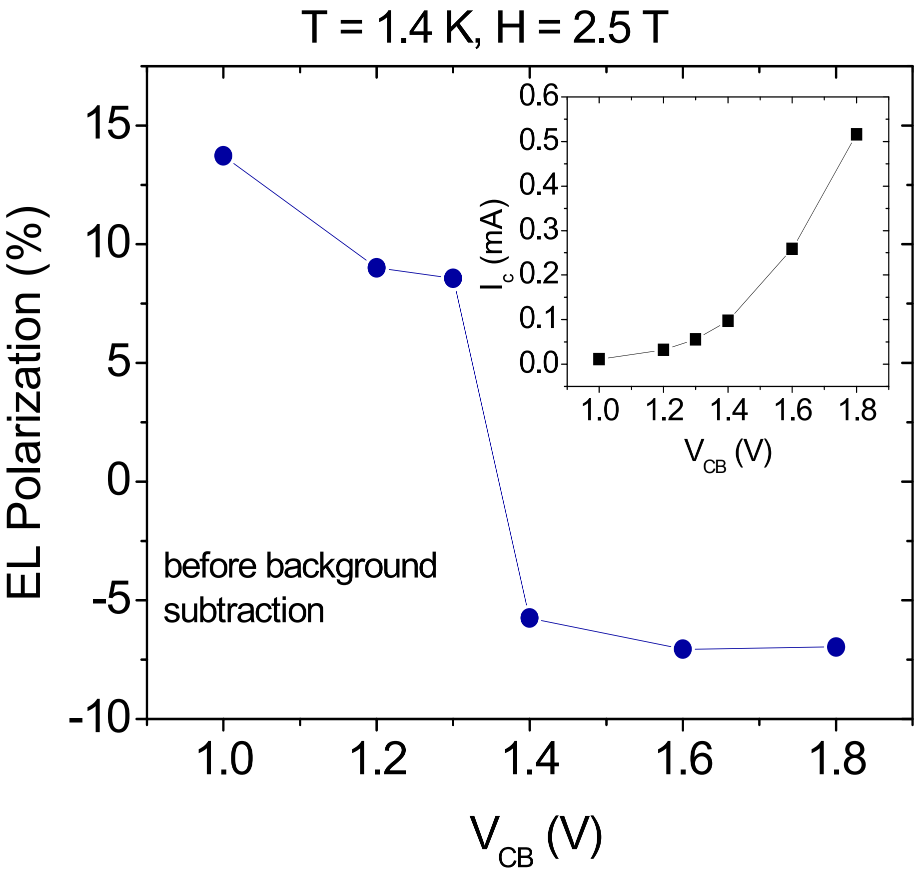
- Positive EL polarization in positive field → majority spin injection

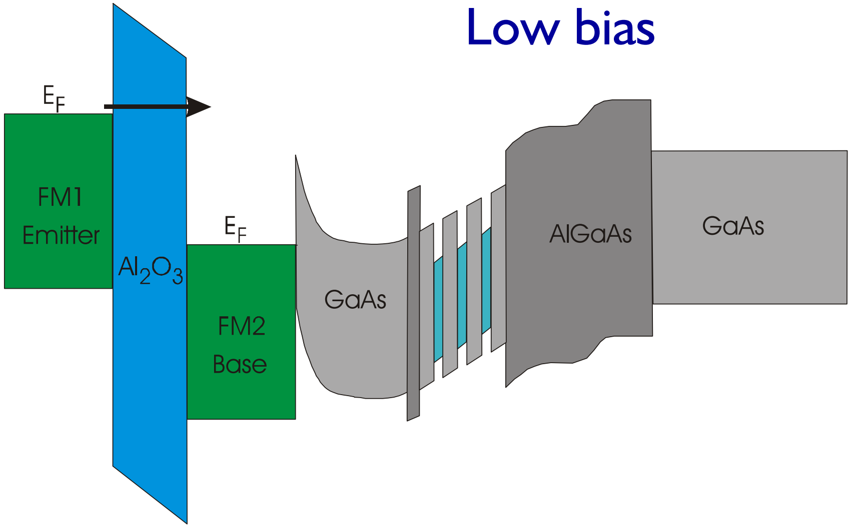
Field Dependence of EL Polarization

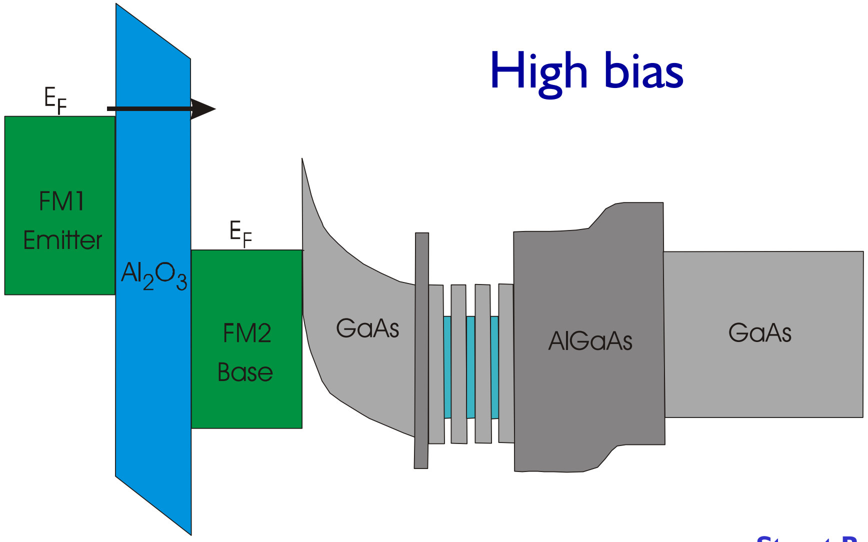


- Background polarization due to thermalization of spins in the magnetic field.
- After subtracting a linear background, the EL polarization data agrees with the SQUID data very well.
- EL polarization up to ~10%.

Bias Dependence of EL Polarization

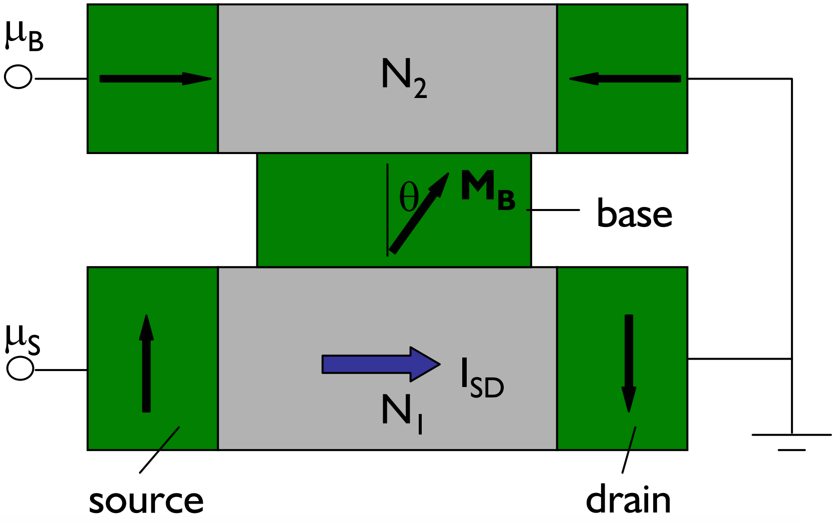


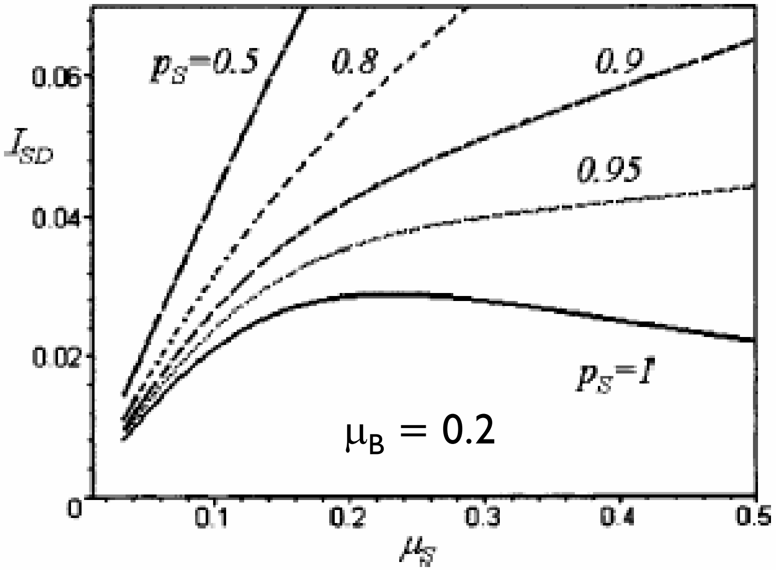




- **Strong bias dependence of EL polarization**
- **Most likely related to spin relaxation process:**
  - DP mechanism
  - BAP mechanism

Spin-Torque Transistor





G. E. W. Bauer, A. Brataas, Y. Tsekovnyak, and B. J. van Wees, Appl. Phys. Lett. **82**, 3928 (2000).

- **μ_S generates source drain current I_{SD}.**

  → spin accumulation in normal metal N_I

- **Orientation of magnetization M_B in the base influences spin accumulation in N_I.**

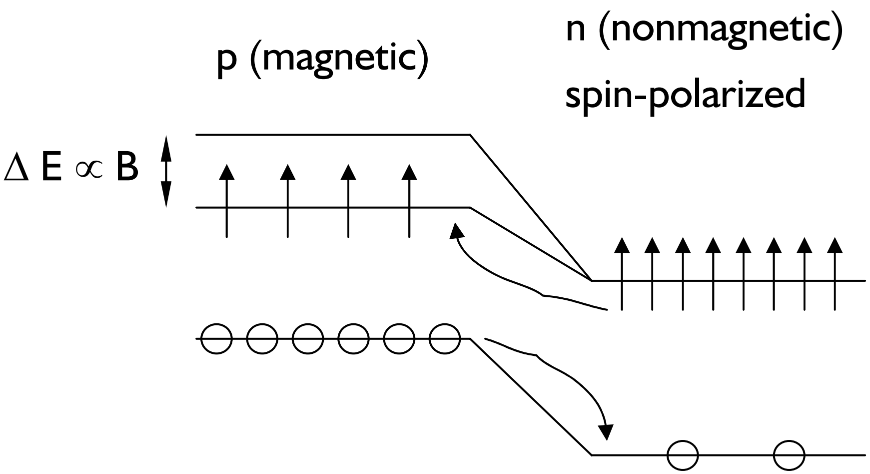
  → I_{SD} can be modulated by varying θ

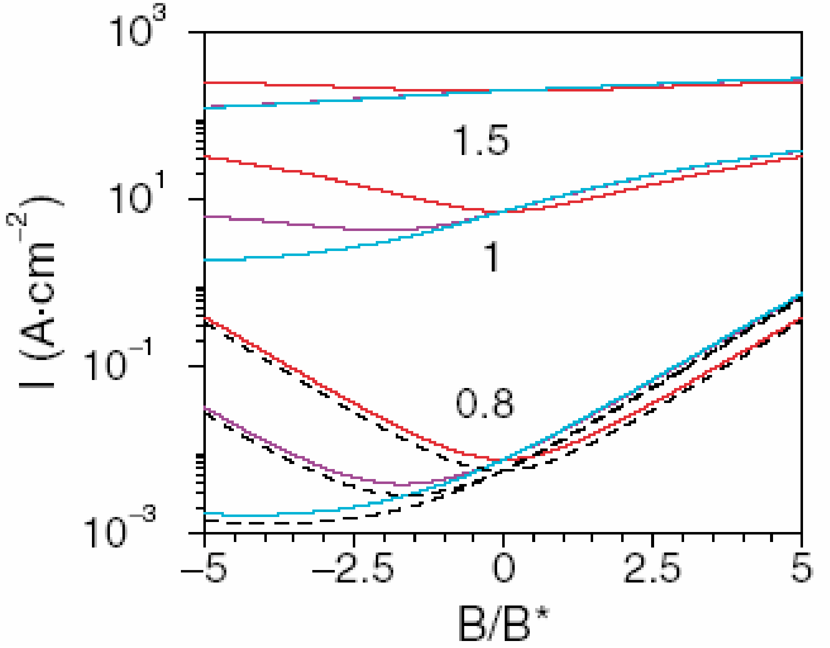
- **Spin transfer from N_I and N_2 into the base produces torque on M_B. The resulting angle θ depends on both μ_B and μ_S.**

  → I_{SD} can be modulated by varying μ_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

$B^* = 2 k_B T / g \mu_B$

α: spin polarization in n-region

τ: spin relaxation time

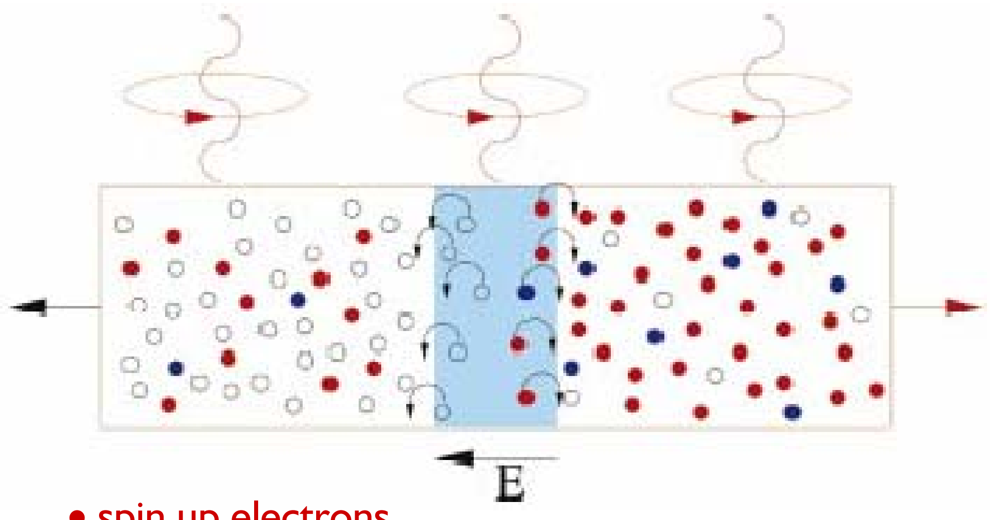
red: $\alpha = 0$, $\tau = 0.2$ ns

violet: $\alpha = 1$, $\tau = 20$ ns

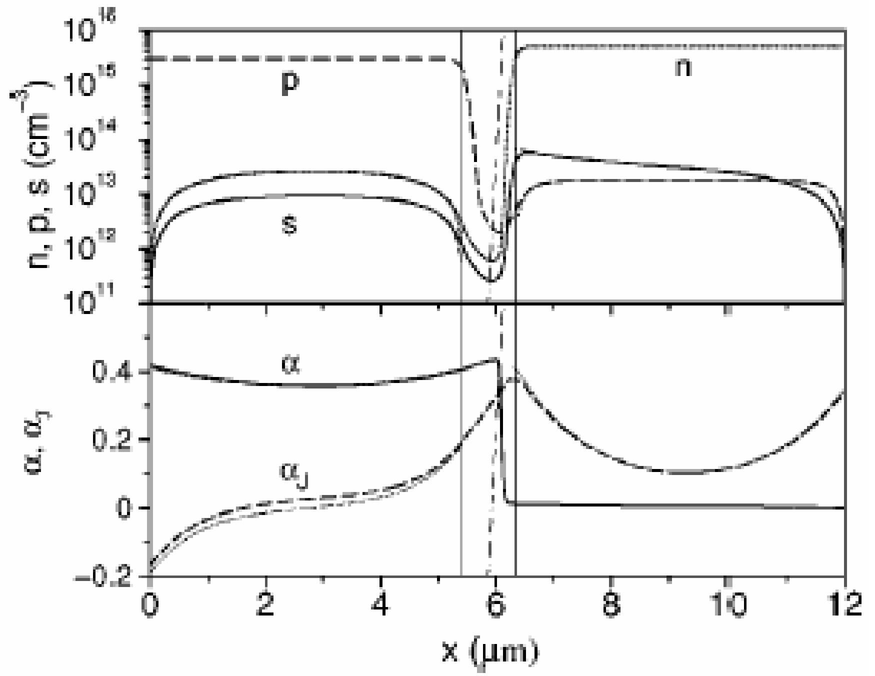
cyan: $\alpha = 1$, $\tau = 2$ μs

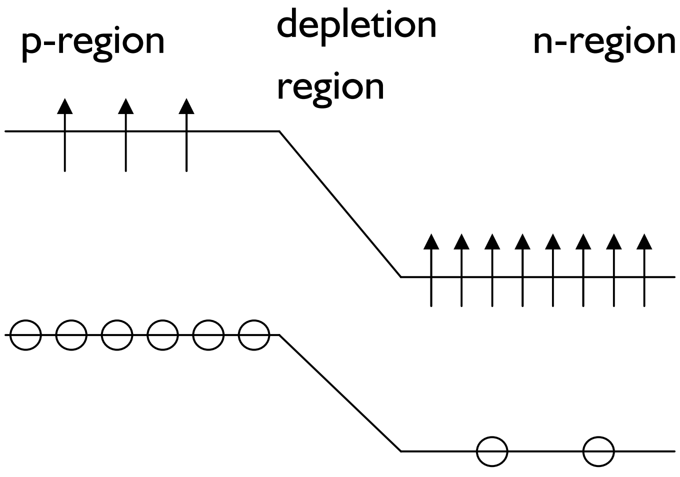
I. Žutić, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. **88**, 066603 (2002).

Spin-Polarized Solar Battery



- spin up electrons
- spin down electrons





p-region

depletion region

n-region

I. Žutić, J. Fabian, and S. Das Sarma, Appl. Phys. Lett. **79**, 1558 (2001).

- **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

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Glenn Solomon, Jim Harris

¶Solid State Photonics Laboratory, Stanford University