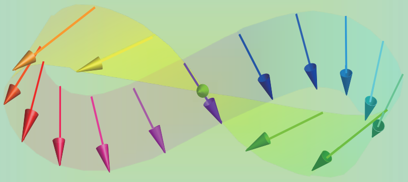
Information Storage and Spintronics

16



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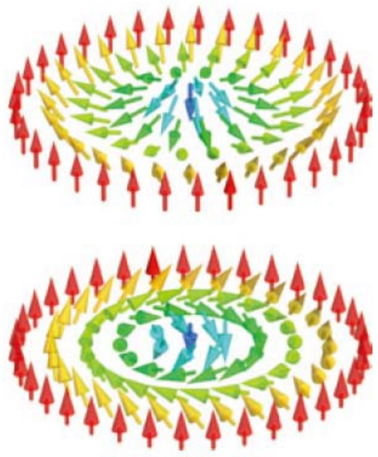
14:00 Friday, 25/November/2022 (SLB 101)

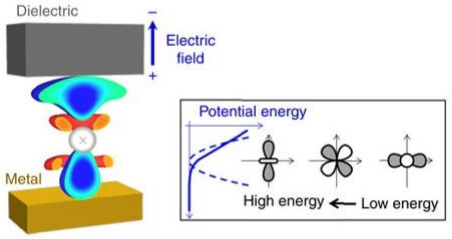
Quick Review over the Last Lecture

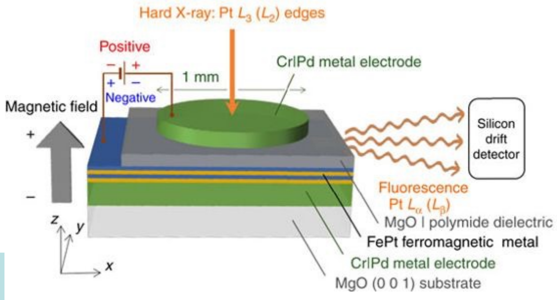
Magnetic skyrmions : *



	Skyrmions	Domain walls
Size [nm]		
Velocity [m/s]		
Critical current density [A/cm^2]		

Voltage-controlled memory : *





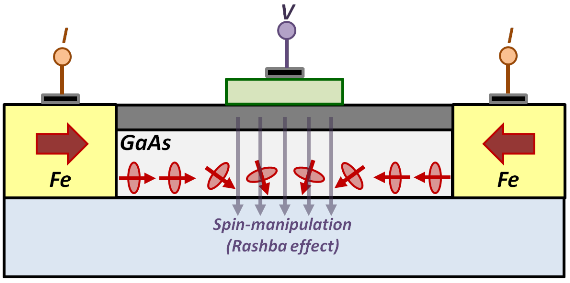
* A. Fert *et al.*, *Nature Nanotechnol.* **8**,152 (2013);
** S. Miwa *et al.*, *Nat. Commun.* **8**, 15848 (2017).

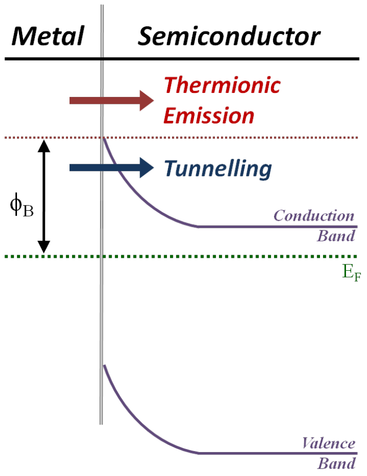
16 Three-Terminal Devices

- Spin-polarised transistors
- Lateral spin-valves
- Spin injection
- Spin accumulation
- Johnson transistors

Spin-Polarised Field Effect Transistor

- Spin transistor was originally proposed by Datta and Das.
- Fe/GaAs is one of the leading systems for obtaining efficient spin-polarised injection into a semiconductor (SC). **
- GaAs has long carrier spin lifetimes and large spin diffusion lengths.
- Fe is an ideal injector as it has:
  - high Curie temperature
  - low coercivity
  - good lattice matching with GaAs
- The intrinsic Schottky barrier that forms at the Fe/SC interface overcomes the limitations due to the conductivity mismatch.



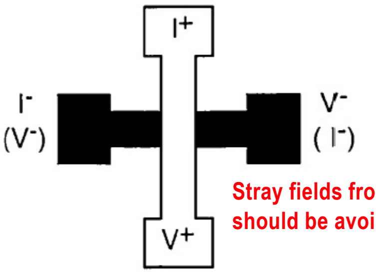


* S. Datta and S. Das, *Appl. Phys. Lett.* **56**, 665 (1990);
** G. Wastlbauer and J. A. C. Bland, *Adv. Phys.* **54**, 137 (2005); D. Hagele *et al.*, *Appl. Phys. Lett.* **73**, 1580 (1998); J. M. Kikkawa and D.D. Awschalom, *Nature* **397**,139 (1999); E. I. Rashba, *Phys. Rev. B* **62**, R16267 (2000).

Spin Transport - *Spin-pol'd electrons* → *SC* → *Spin-pol'd electrons*

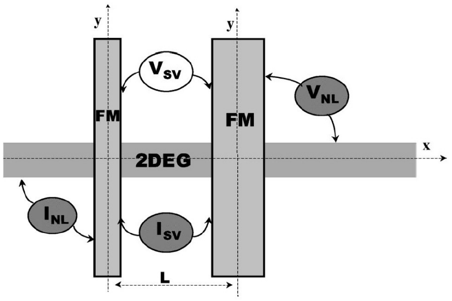
Spin FET structures :

Hall bar geometry



Stray fields from FMs should be avoided.

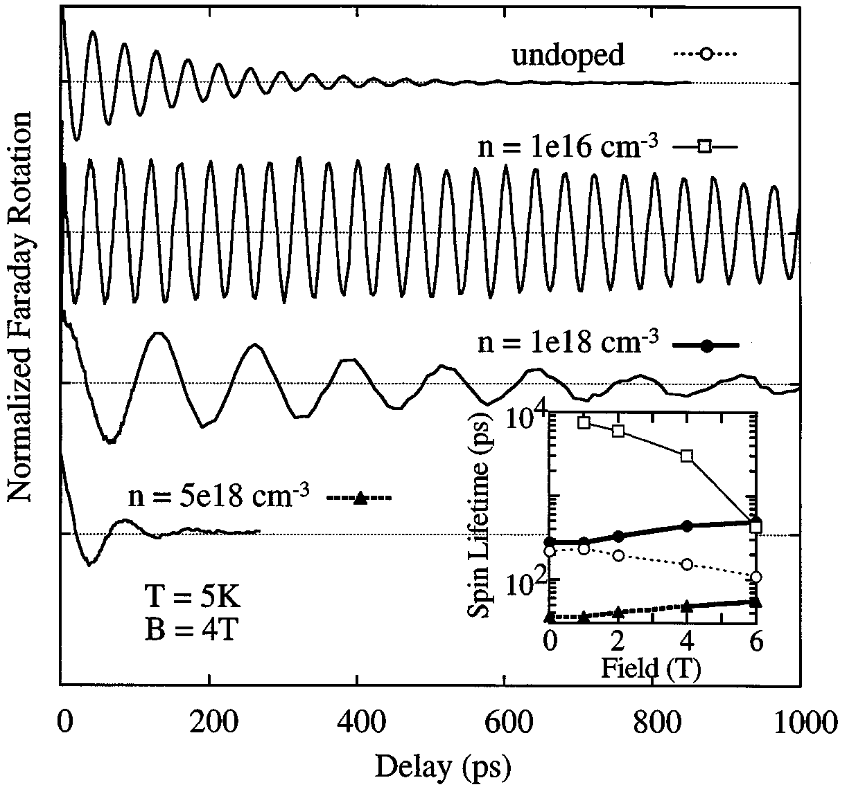
Asymmetric multi-terminal geometry



Structures	Spin polarization	Refs.
FM / 2DEG Hall-bar-type structures :		
86 nm NiFe / 25 nm AlGaSb / 15 nm InAs 2DEG / … / GaAs	~ 1% @ 75 K	P. R. Hammar *et al.*, *Phys. Rev. Lett.* **83**, 203 (1999); *Phys. Rev. B* **61**, 7207 (2000).
NiFe / 750-6400 nm InAs QW / NiFe	Hall effect @ 4.2 K	F. G. Monzon and M. L. Roukes, *J. Magn. Magn, Mater.* **198-199**, 632 (1999).
FM / 2DEG asymmetric structures :		
NiFe & Co / InAs 2DEG / NiFe & Co	AMR @ 4.5 K	A. T. Filip *et al.*, *Phys. Rev. B* **62**, 9996 (2000).
60 nm NiFe / InAs 2DEG / GaAs	~ 0.2% @ < 10 K	C.-M. Hu *et al.*, *Phys. Rev. B* **63**, 125333 (2001).
Schottky (tunnel) diodes (FM / SC) :		
3.5 nm Fe / 2 nm **Oxide** / *n*-GaAs	~ 5% @ <RT	A. Filipe *et al.*, *Phys. Rev. Lett.* **80**, 2425 (1998).

Spin-Polarised Electrons in GaAs

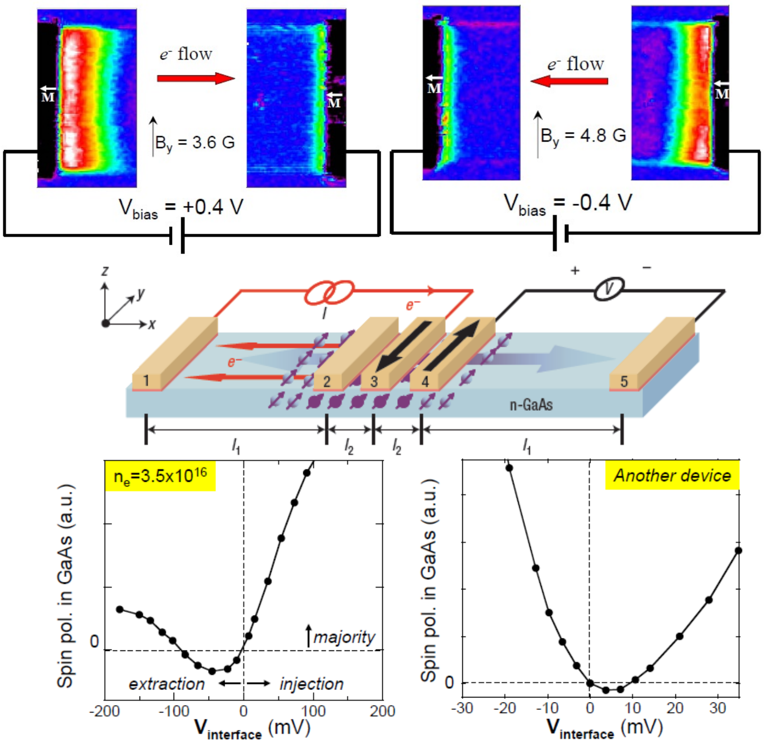
> 100 μm spin diffusion length : *



* J. M. Kikkawa and D. D. Awschalom, *Phys. Rev. Lett.* **80**, 4313 (1998).

Spin Transport Measurements in GaAs

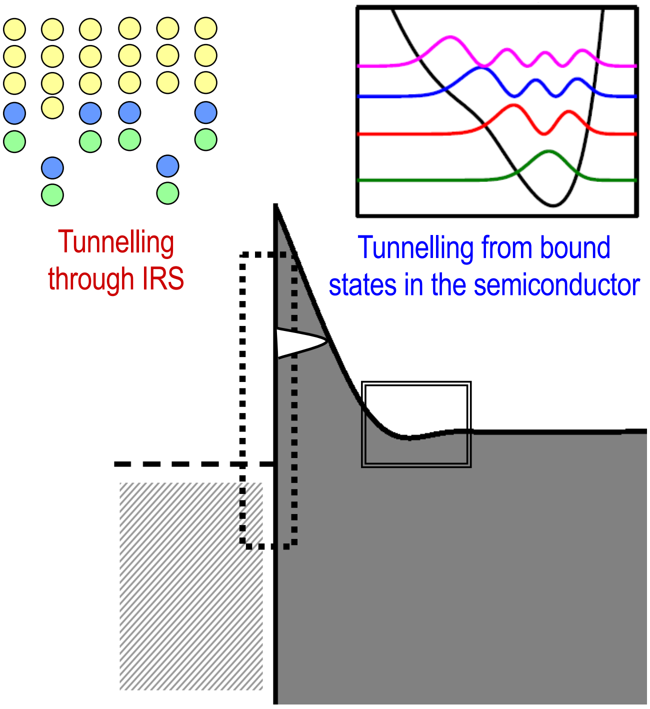
- Experimental studies have shown that spin injection can be achieved leading to a majority spin accumulation.
- Spin injection / extraction has been observed using both optical * and electrical ** techniques.
- A bias dependant polarisation inversion has been observed, the origin of which remains unknown.
- Knowledge of the mechanism(s) responsible for the polarisation inversion required for the development of future devices.



* S.A. Crooker *et al.*, *Science* **309**, 2191 (2005);
** X. Lou *et al.*, *Nature Phys.* **3**, 197 (2007).

Possible Origins of Spin Polarisation Reversal

- There are two promising candidates to explain the polarisation inversion:
  - Tunnelling through interface resonance states (IRS). *
  - Tunnelling from bound states in the semiconductor. **
- It has been shown that the contribution arising from bound states can be varied through control of the doping profile.
- The strength and position of IRS is sensitive to the atomic interface structure. *

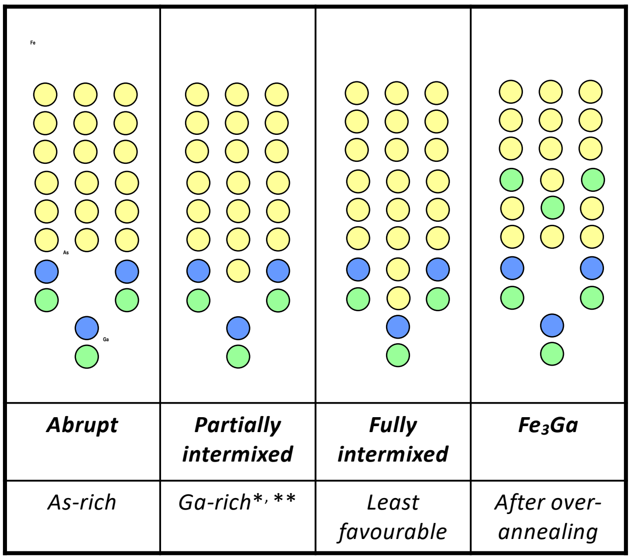


* S Honda *et al.*, *J. Phys. D: Appl. Phys.* **43**, 135002 (2010);
** H. Dery and L.J. Sham, *Phys. Rev. Lett.* **98**, 046602 (2007).

Fe / GaAs (001) Interface Structures

- There are several proposals for the interface structure of Fe / GaAs (001) films.
- Calculations suggest that the abrupt interface is energetically favourable for As-terminated surfaces (often used to limit diffusion).
- Previous calculations predict that minority carrier interface states lie 0.3 eV below the top of the Schottky barrier.

  - These are yet to be observed experimentally.
- Calculations are yet to be performed for inter-atomic spacings measured experimentally.

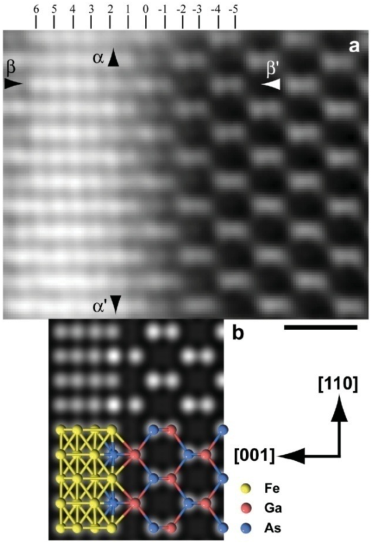


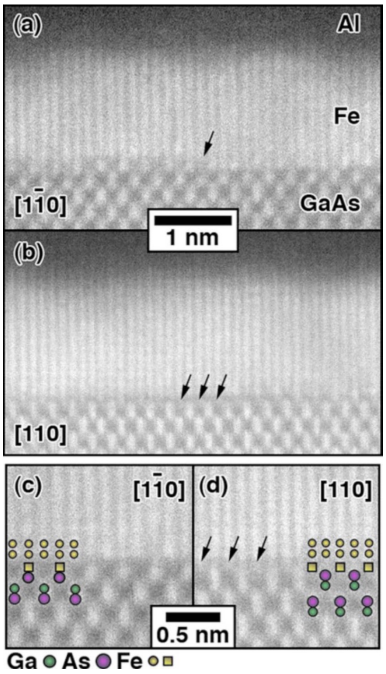
Abrupt	**Partially intermixed**	**Fully intermixed**	**Fe_3Ga**
As-rich	*Ga-rich*, ***	*Least favourable*	*After over-annealing*

* T. J. Zega *et al.*, *Phys. Rev. Lett.* **96**, 196101 (2006);
** J. M. LeBau *et al.*, *Appl. Phys. Lett.* **93**, 121909 (2008).

Previous Experimental Observations

- There have been two previous reports on experimental observations of the Fe/GaAs interface. *,**
- The two studies reported different interfacial structures.
- Both reports did not observed the abrupt interface.
- Experimental values for the Schottky barrier height range from eV. ***, ****

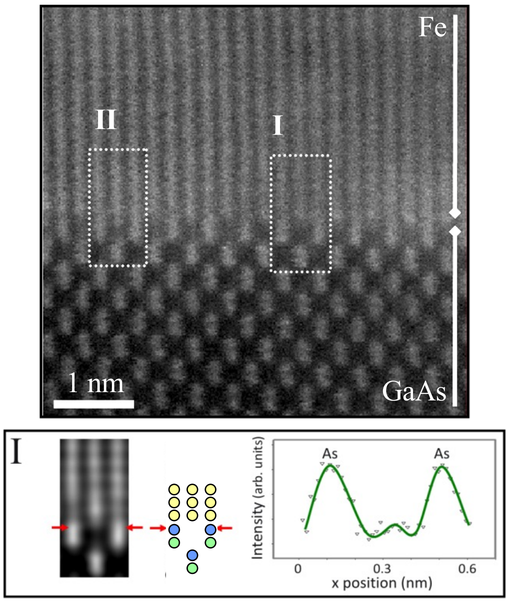




* T. J. Zega *et al.*, *Phys. Rev. Lett.* **96**, 196101 (2006);
** J. M. LeBau *et al.*, *Appl. Phys. Lett.* **93**, 121909 (2008);
*** H. Kurebayashi *et al.*, *Appl. Phys. Lett.* **91**, 102114 (2007);
**** B. T. Jonker *et al.*, *J. Appl. Phys.* **81**, 4362 (1997).

HAADF STEM Observation on Fe/GaAs Interfaces

- The figure shows an unfiltered HAADF-STEM image the Fe / GaAs interface.
- Two different interfacial structures are observed.
  - Abrupt (first report) **
  - Partially mixed (as reported previously) *
- Analysis of the intensity profiles (z-contrast) taken across the interfaces suggest that Fe is responsible for the partially mixing.
- From the areas observed the film is ~ 95% abrupt.



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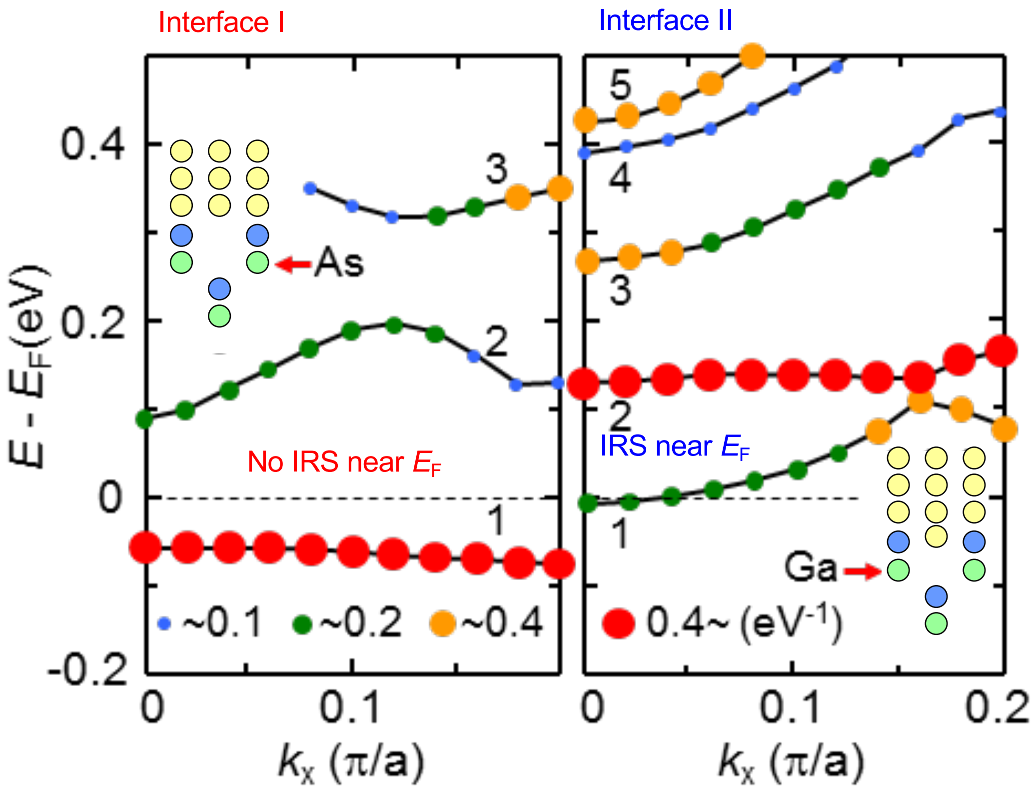
* L. R. Fleet *et al.*, *IEEE Trans. Magn.*, **47**, 2756 (2011);
** L. R. Fleet *et al.*, *Phys. Rev. B* **87**, 024401 (2012).

Peak Positions of IRSs



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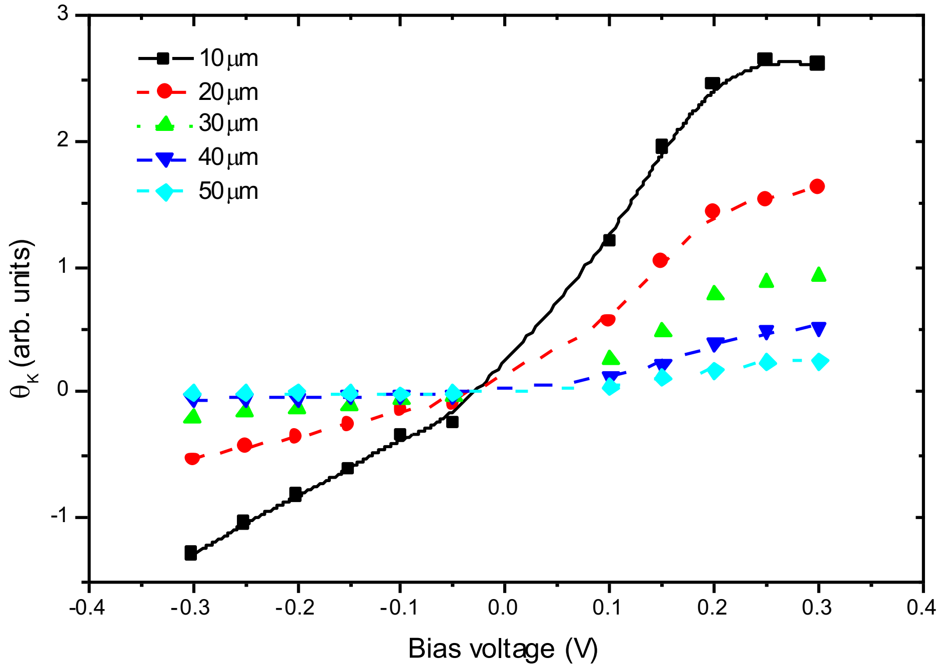
* L. R. Fleet *et al.*, *Phys. Rev. B* **87**, 024401 (2012).

Bias Dependence

- No spin polarisation reversal induced by a bias voltage.

  → Agrees with calculations.



Rashba Effect for Gating

Gate operation in a spin FET : *

For the modulation of spin-polarised electrons in a semiconductor, the spin-orbit interaction Hamiltonian can be derived from the Dirac equations :

$$H_{\mathrm{SO}} = \frac{q\hbar^2}{4m^2c^2}\left(\vec{\boldsymbol{\sigma}} \cdot \left[\vec{\boldsymbol{E}} \times \vec{\boldsymbol{p}}\right]\right)$$

where q, $\hbar$, m, c, $\vec{\boldsymbol{\sigma}}$, $\vec{\boldsymbol{E}}$ and $\vec{\boldsymbol{p}}$ are the electron charge, Planck constant, electron mass, speed of light, Pauli matrices, electric field and electron momentum, respectively. By comparison with the Rashba Hamiltonian $H_{\mathrm{R}} = \eta_{\mathrm{SO}}\left(\vec{\boldsymbol{\sigma}} \times \vec{\boldsymbol{k}}\right) \cdot \vec{\boldsymbol{v}}$ ($\vec{\boldsymbol{k}}$: wave vector and $\vec{\boldsymbol{v}}$: unit vector perpendicular to plane),

$$H_{\mathrm{R}} = \frac{q\hbar^2}{4m^2c^2}\left(\vec{\boldsymbol{\sigma}} \cdot \left[\vec{\boldsymbol{E}} \times \vec{\boldsymbol{p}}\right]\right) = \frac{q\hbar^2}{4m^2c^2}\frac{V_{\mathrm{G}}}{d}\left(\vec{\boldsymbol{\sigma}} \times \vec{\boldsymbol{k}}\right) \cdot \vec{\boldsymbol{v}}$$

The spin-orbit interaction constant η_{SO} can be obtained by using a gate voltage V_{G} and distance between an electron path and a gate length d :

$$\eta_{\mathrm{SO}} = \frac{q\hbar^2}{4m^2c^2}\frac{\quad}{\quad}$$

* A. Hirohata *et al.*, *J. Magn. Magn. Mater.* **509**, 166711 (2020).

Gate Dimensions

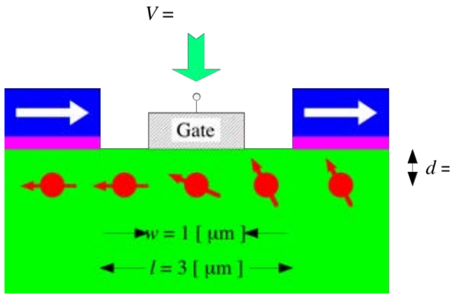
Gate operation in a spin FET : *

For commonly-used InGaAs 2DEG, a 180º phase shift can be achieved for a separation between an injector and a detector :

$$l = \frac{\Delta\theta\hbar^2}{2m^*\eta_{\mathrm{SO}}} \approx \quad \mu\mathrm{m},$$

and gate length :

$$w = \frac{\hbar^2}{2m^*\eta_{\mathrm{SO}}} \approx \quad \mu\mathrm{m}.$$



The corresponding electric field required is estimated to be

$$\frac{V_{\mathrm{G}}}{d} = \frac{4m^{*2}c^2\eta_{\mathrm{SO}}}{q\hbar^2} \approx 4.3 \times 10^{10}\ \mathrm{V/m}$$ (m^* is the electron effective mass).

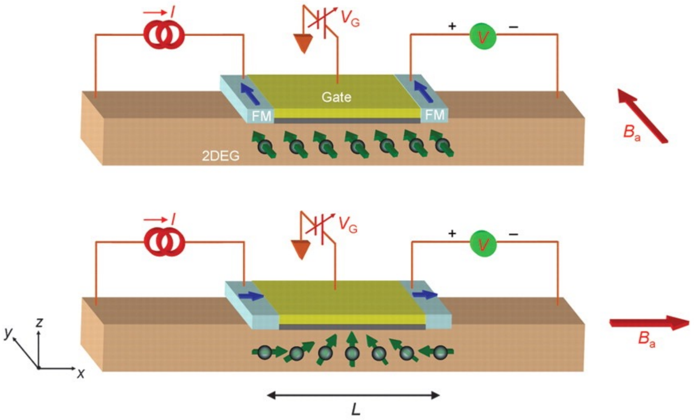
This provides $d \sim 1$ nm and $V_{\mathrm{G}} \sim 43$ V.

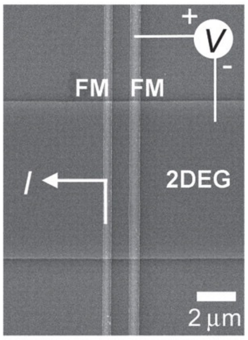
These values are very difficult to realise with present nano-fabrication techniques and requires a further improvement of the spin-orbit interaction constant η_{SO}.

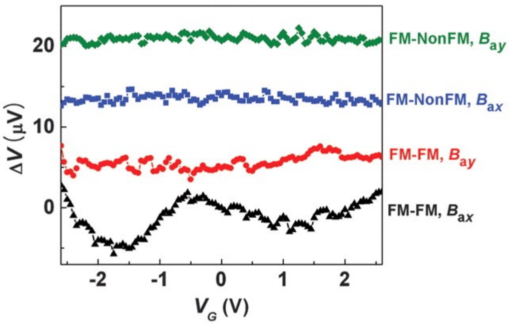
* A. Hirohata *et al.*, *J. Magn. Magn. Mater.* **509**, 166711 (2020).

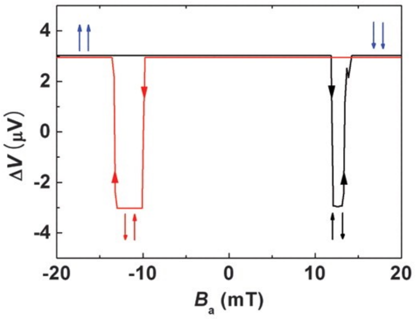
Recent Demonstration of Spin FET Operation

Gate operation in a NiFe / InGaAs / NiFe spin FET : *









* H. C. Koo *et al.*, *Science* **325**, 1515 (2009).

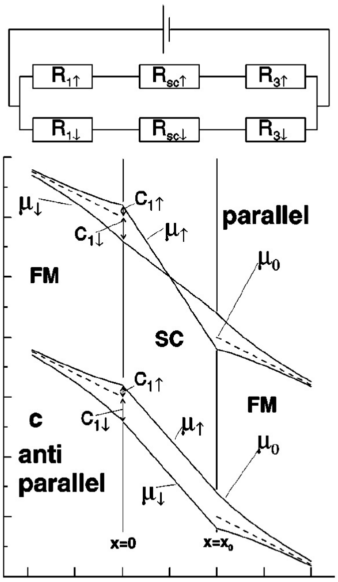
Theoretical Studies - *FM* → *SC*

FM / SC Interfaces :

Ohmic contacts :

- Diffusive process : 100 % spin polarisation in FM is crucial.
  → DMS, Heusler compounds and half-metallic FM as FM

G. Schmidt *et al.*, *Phys. Rev. B* **62**, R4790 (2000).



Schottky / tunnel barrier contacts :

- Ballistic process :

E. I. Rashba, *Phys. Rev. B* **62**, 16267 (2000).

P. Mavropoulos *et al.*, *Phys. Rev. B* **66**, 024416 (2002).

Spin coherence length :

- Spin life time :

M. E. Flatté and G. Vignale, *Appl. Phys. Lett.* **78**, 1273 (2001).

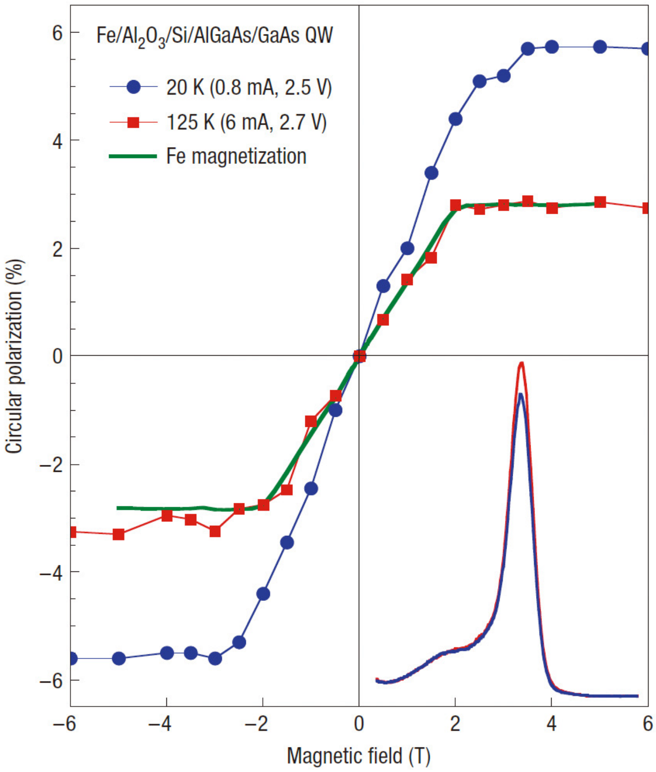
Spin modulation :

- Spin orientation ∝ gate voltage

A. Bournel *et al.*, *Mater. Sci. Forum* **297**, 205 (1999).

Spin Injection into Si

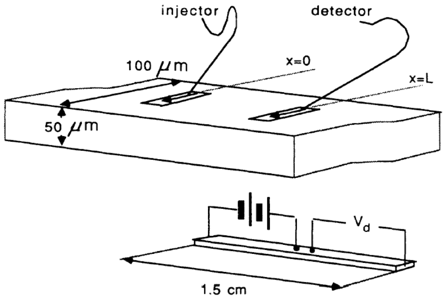
Ballistic spin injection into Si : *

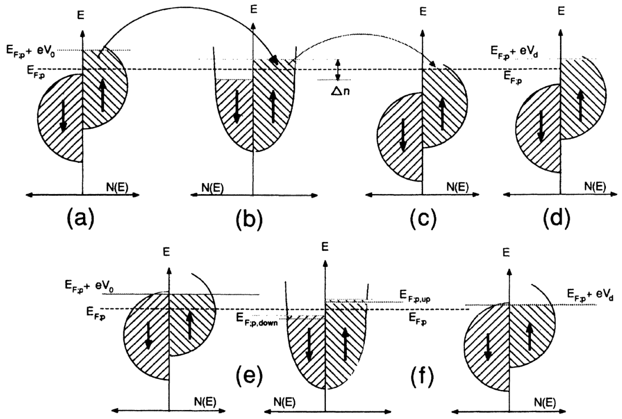


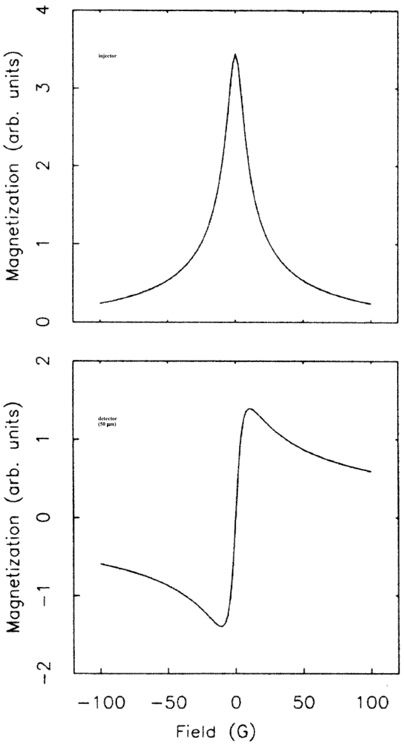
* B. T. Jonker *et al.*, *Nature Phys.* **3**, 542 (2007).

Johnson Transistors

All-metallic transistors : *



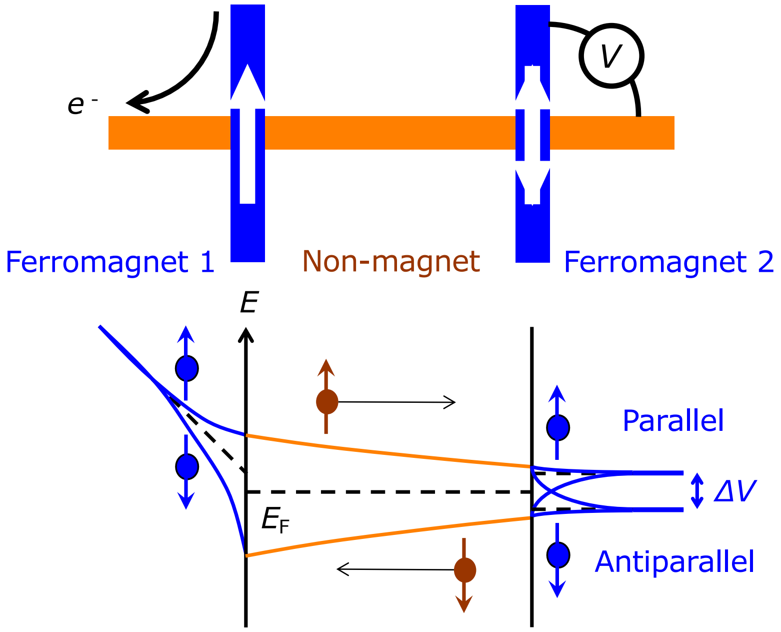


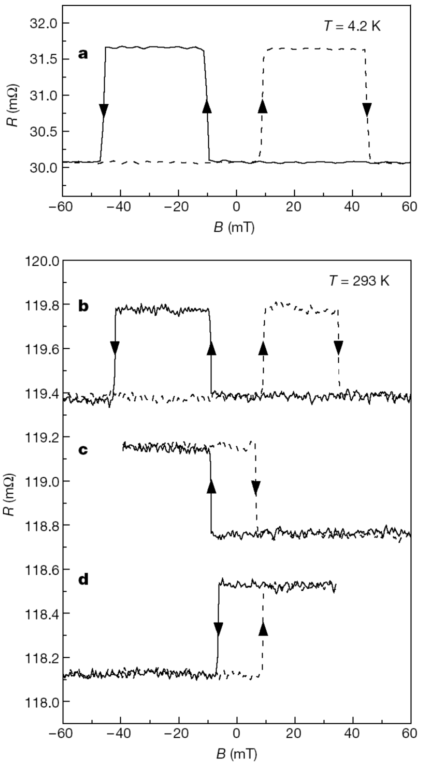


* M. Johnson and R. H. Silsbee, *Phys. Rev. Lett.* **56**, 1790 (1985), *Phys. Rev. B* **37**, 5312 (1988).

Recent Improvement

Lateral spin-valve structures with Co / Al / Co nano-wires : *





* F. J. Jedema *et al.*, *Nature* **410**, 345 (2001).

Generation of a Pure Spin Current

In a lateral spin-valve structure, a pure spin current can be generated : *

A spin current $\overrightarrow{J_s}$ and a charge current $\overrightarrow{J_c}$ can be expressed as

$$\overrightarrow{J_s} = -\frac{\hbar}{2e}\left(\overrightarrow{j_\uparrow} - \overrightarrow{j_\downarrow}\right),$$

$$\overrightarrow{J_c} = \overrightarrow{j_\uparrow} + \overrightarrow{j_\downarrow}.$$

These currents follow the diffusion equation. For the spin current, the spin diffusion equation is written as

$$\nabla^2(\mu_\uparrow - \mu_\downarrow) = \frac{1}{D\tau_{\mathrm{sf}}}(\mu_\uparrow - \mu_\downarrow) \equiv \frac{1}{\lambda^2}(\mu_\uparrow - \mu_\downarrow),$$

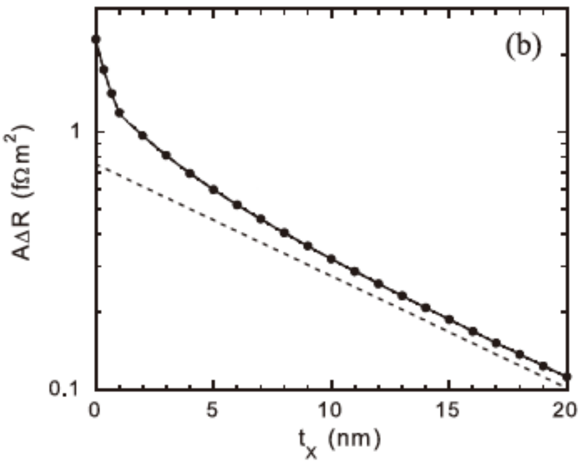
where λ is the spin diffusion length (= $\sqrt{\qquad}$) and τ_{sf} is the spin flip time.

* A. Hirohataet *al.*, *J. Magn. Magn. Mater.* **509**, 166711 (2020).

Spin Diffusion Length

Spin diffusion length determines the distance without spin flip : *

Materials	Spin diffusion length [nm] (300 K)	Resistivity [μΩ·cm] (300 K)
Al	350 ~ 600 (293 K)	3.2 ~ 9.1
Cu	350 ±50 (293 K)	2.9
Ag	132 ~ 152 (298 K)	4.9 ~ 5.5
Au	60 (293 K)	5.2
Pt	3.8 +0.7/-0.3	18 ±0.7
Ta	1.9 +0.3/-0.5	200±15
CoFe	6.2 +0.3/-0.7	20 ±1.3
NiFe	5.2 +1.8/-0.9	30 ±3
Co	7.7 +1.8/-2.2	25 ±2.4



$$\boldsymbol{\Lambda R_{\mathrm{NL}} = 4\frac{P^2 R_{\mathrm{FM}}^2}{(1-P^2)^2 R_{\mathrm{NM}}} \frac{\exp\left(-\frac{d}{\lambda_{\mathrm{NM}}}\right)}{\left[1 = \frac{2R_{\mathrm{FM}}}{(1-P^2)R_{\mathrm{NM}}}\right]^2 - \exp\left(-\frac{2d}{\lambda_{\mathrm{NM}}}\right)}}$$

where $P = I_\uparrow - I_\downarrow / I_\uparrow + I_\downarrow$: current polarisation of FM, λ_{NM} : spin diffusion length in NM and $R_{\mathrm{NM}} = \rho_{\mathrm{N}}\lambda_{\mathrm{N}}/w_{\mathrm{N}}t_{\mathrm{N}}$ and $R_{\mathrm{FM}} = \rho_{\mathrm{FM}}\lambda_{\mathrm{FM}}/w_{\mathrm{FM}}w_{\mathrm{N}}$: NM and FM spin resistances.

- J. Bass and W. P. Pratt, Jr. *J. Phys.: Condens. Matter* **19**, 183201 (2007); G. Zahnd *et al.*, *Phys. Rev. B* **98**, 174414 (2018);

** L. O'Brien *et al.*, *Nat. Commun.* ***5***, 3927 (2014).