Spin field effect transistor

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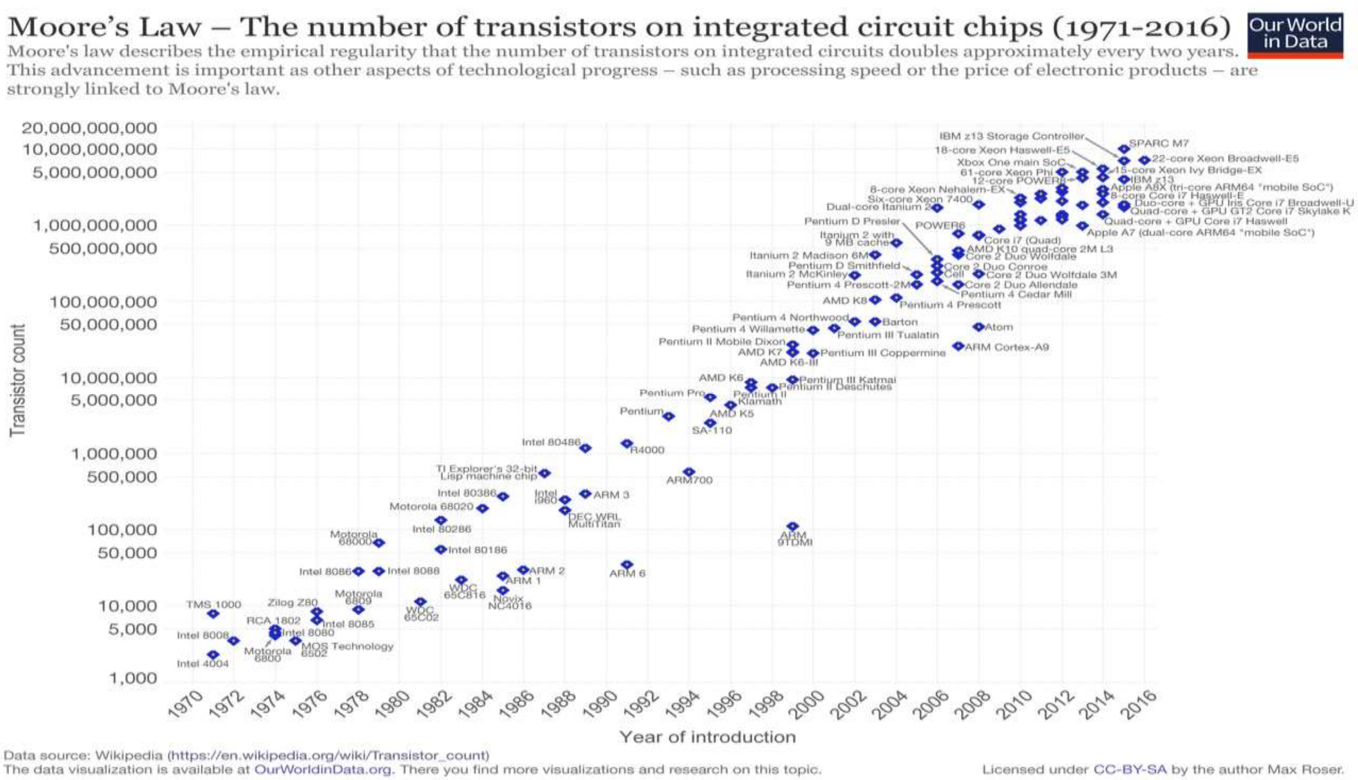
Background

- Moore's law : The number of transistors in a dense integrated circuit doubles about every two years



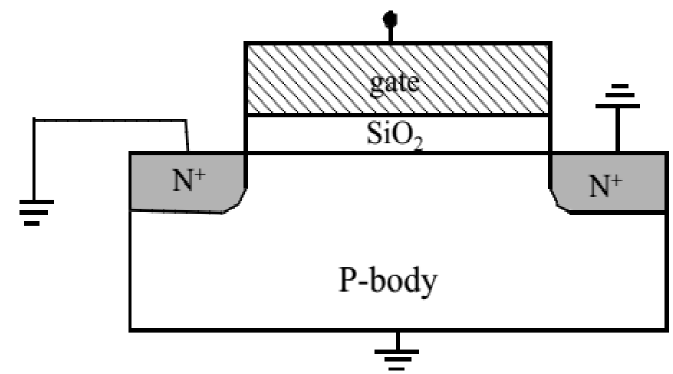
https://en.wikipedia.org/wiki/Moore%27s_lawv

MOSFET

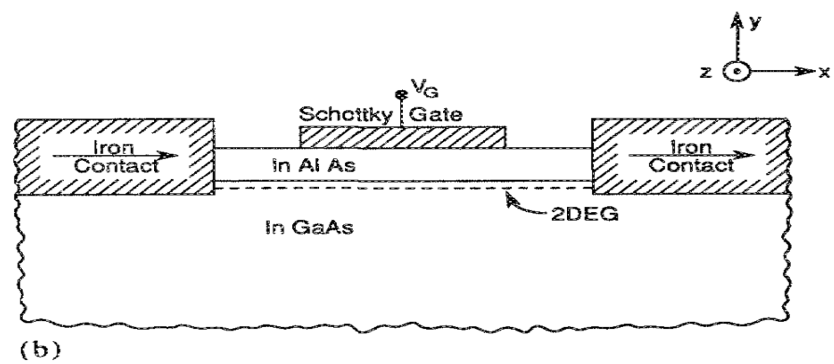
- Challenge for MOSFET

➢ Heat dissipation problems

➢ Quantum tunneling



- One of solutions :spin field effect transistor



Rashba SOC in 2DEG

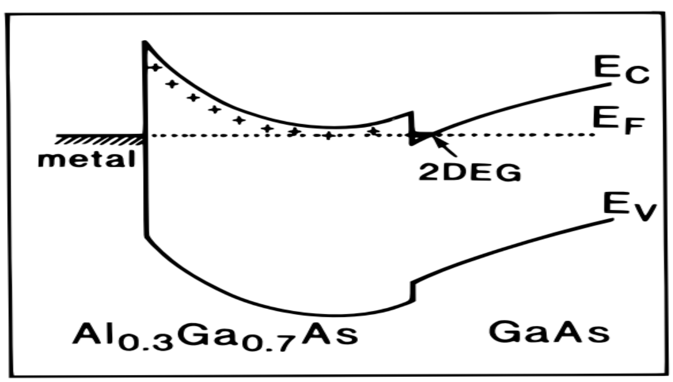
- Rashba spin orbit coupling(structure inversion asymetry):

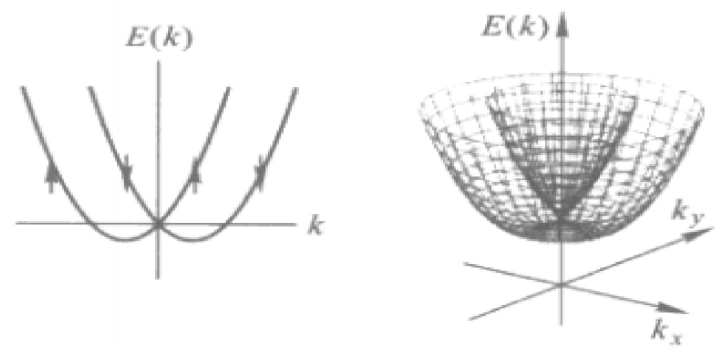
$$H_R = \eta(\sigma_z k_x - \sigma_x k_z)$$

- Spin split energy band:

$$E(z\ \text{pol.}) = \hbar^2 k_{x1}^2 / 2m^* - \eta k_{x1},$$

$$E(-z\ \text{pol.}) = \hbar^2 k_{x2}^2 / 2m^* + \eta k_{x2}$$





(a) (b)

Electro-optic modulator

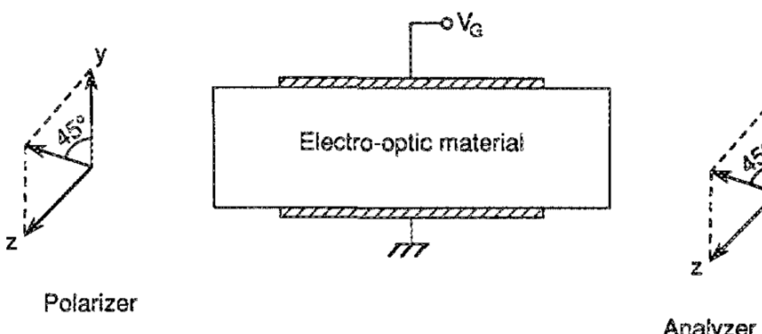
- Different spin polarized electrons have different wave vector

$$k_{x1} - k_{x2} = 2m^*\eta/\hbar^2$$

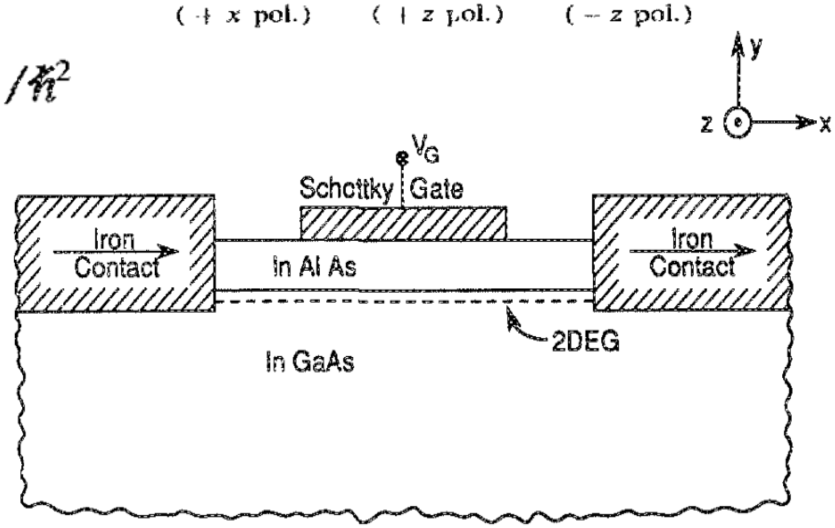
- A differential phase shift

$$\underset{(+x\text{ pol.})}{\begin{pmatrix}1\\1\end{pmatrix}} = \underset{(+z\text{ pol.})}{\begin{pmatrix}1\\0\end{pmatrix}} + \underset{(-z\text{ pol.})}{\begin{pmatrix}0\\1\end{pmatrix}} .$$

$$\Delta\theta = (k_{x1} - k_{x2})L = 2m^*\eta L/\hbar^2$$



(a)



(b)

Datta and Dass.APL.1990

Why choose spin FET?

- Property
  - high speed
  - low power consumption
  - high level integration

III-V semiconductor

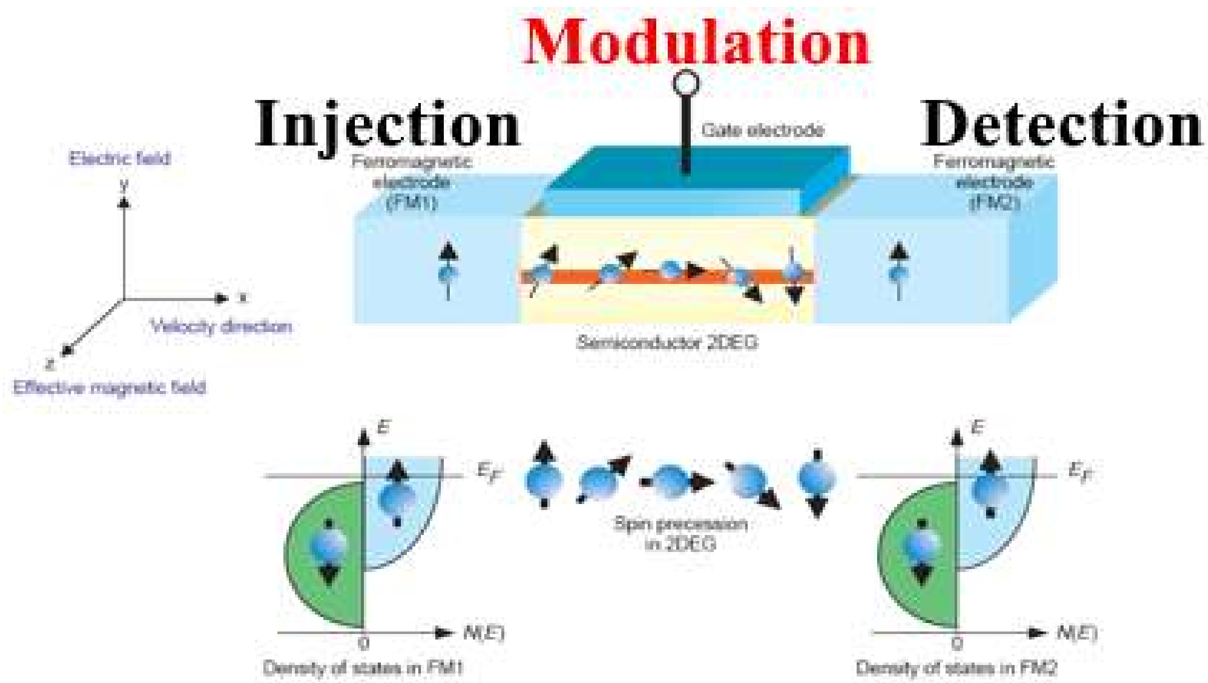
- Curie temperature above RT
- Long spin relaxation time
- Strong spin orbit coupling

Graphene

- Long spin diffusion length
- Weak spin orbit coupling

How to work?

- Spin injection
- Spin modulation
- Spin detection



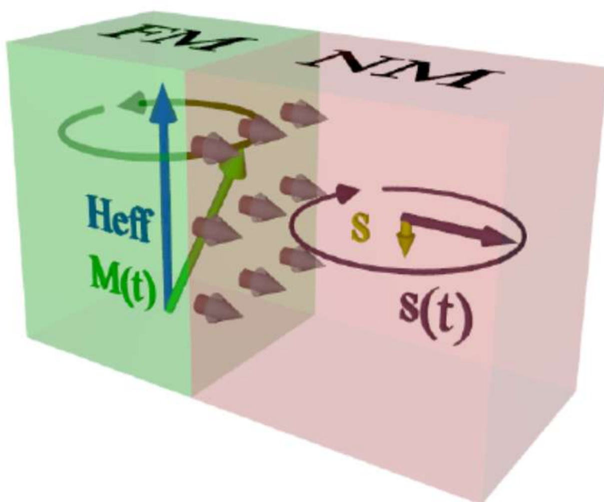
Spin injection

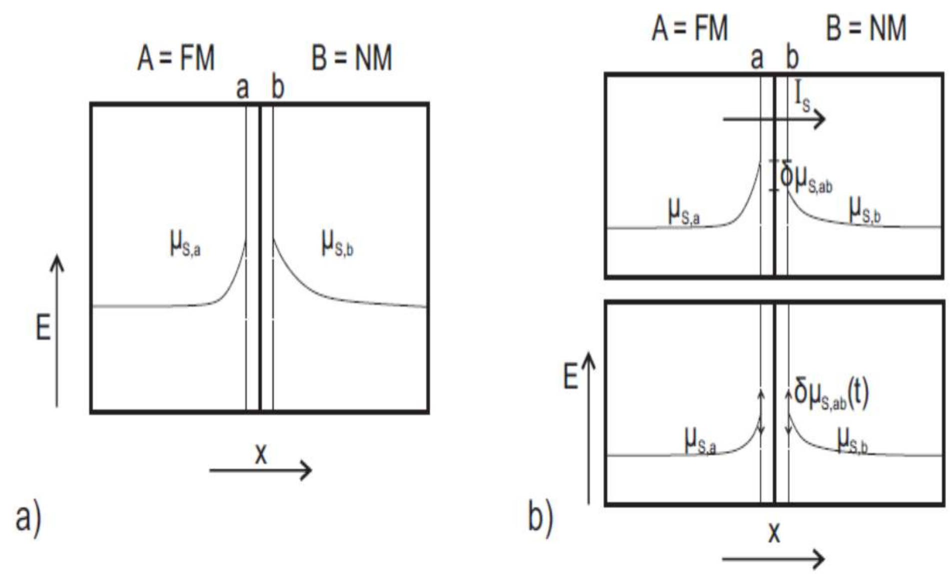
- Spin dynamic pumping
- Electrical injection

➢ Schottky barrier
➢ Oxide tunneling barrier
➢ Spin Esaki diode
➢ Hot electron spin injection

Spin dynamic pumping

- Processing magnetization in FM layer pumps spin current into NM layer.



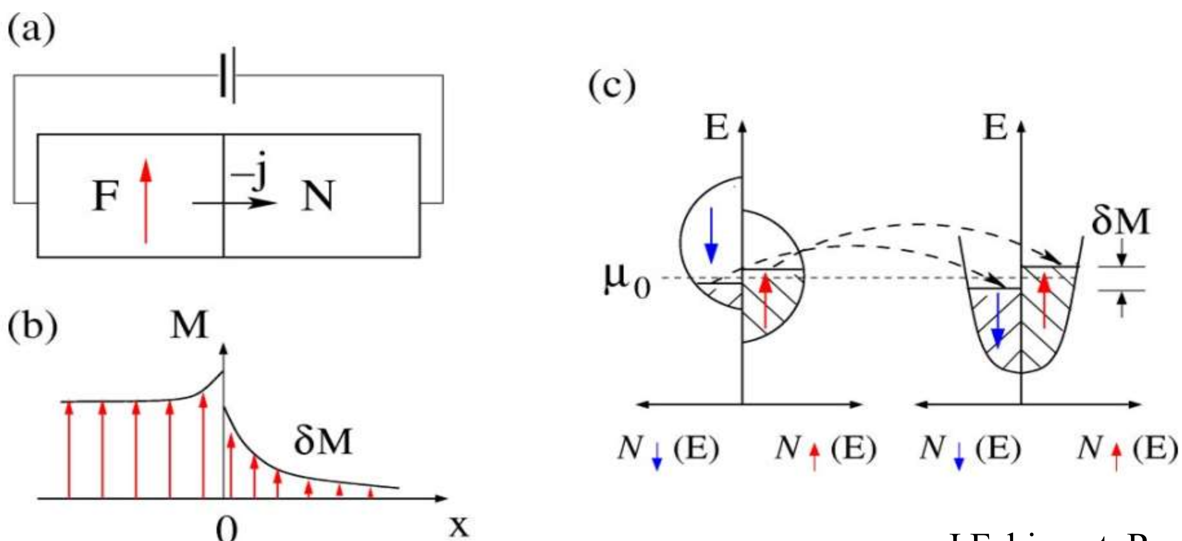


$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha_G}{\mathbf{M}_s}\mathbf{M} \times \frac{d\mathbf{M}}{dt}$$

$$\mathbf{I}_{\text{s, net}}^{\text{pump}} = \frac{\hbar}{4\pi}\left(\Re(\tilde{g}^{\uparrow\downarrow})\mathbf{e}_M \times \frac{d\mathbf{e}_M}{dt} - \Im(\tilde{g}^{\uparrow\downarrow})\frac{d\mathbf{e}_M}{dt}\right)$$

Electrical spin injection theory

- Spin polarized current is injected from FM to semiconductor
- Current spin polarizability $\boxed{P_I = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow}}$
- Main problem :conductance mismatch
- Spin injection efficiency $\boxed{P_j = \frac{R_F P_{\sigma F} + R_c P_\Sigma}{R_F + R_c + R_N}}$



J.Fabian.et. Review of modern physics.2004

Different contact

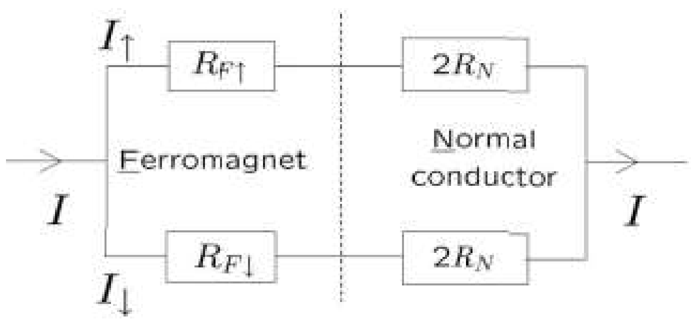
Spin injection efficiency: $\boxed{P_j = \frac{R_F P_{\sigma F} + R_c P_\Sigma}{R_F + R_c + R_N}}$

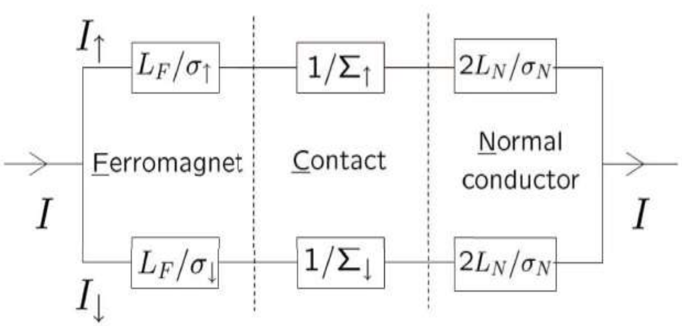
- Transparent contact: $R_c \ll R_N, R_F$

$$\boxed{P_j = \frac{R_F}{R_N + R_F} P_{\sigma F}}$$

- Tunneling contact: $R_c \gg R_F, R_N$

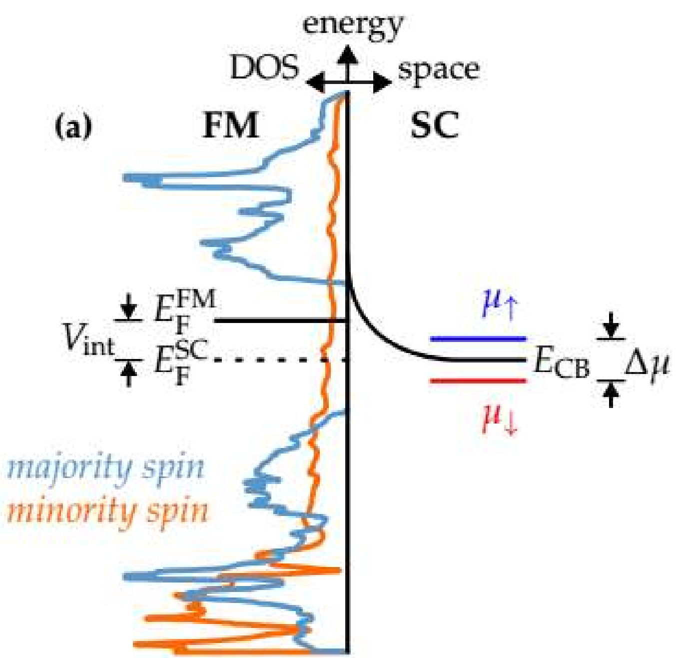
$$\boxed{P_j = P_\Sigma}$$

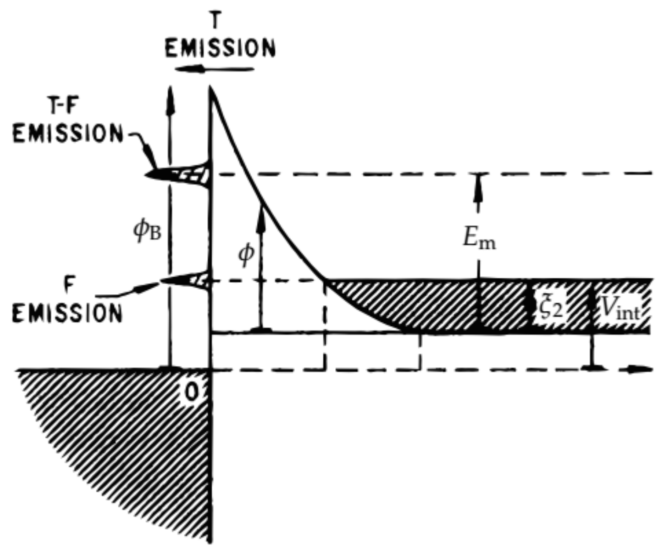




Schottky barrier

- ferromagnetic Heusler alloy Co_2FeSi/n-type GaAs

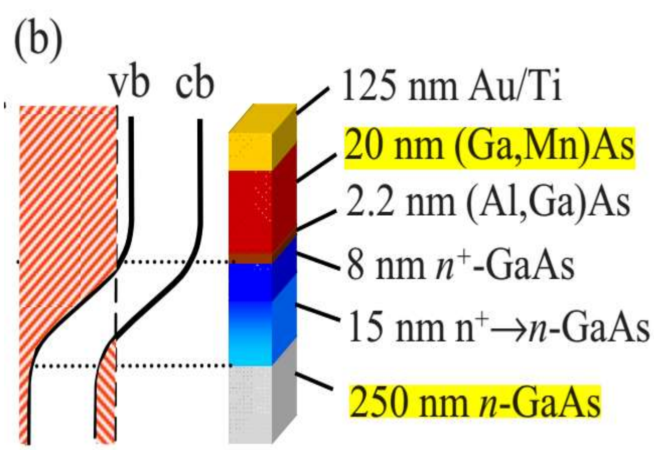


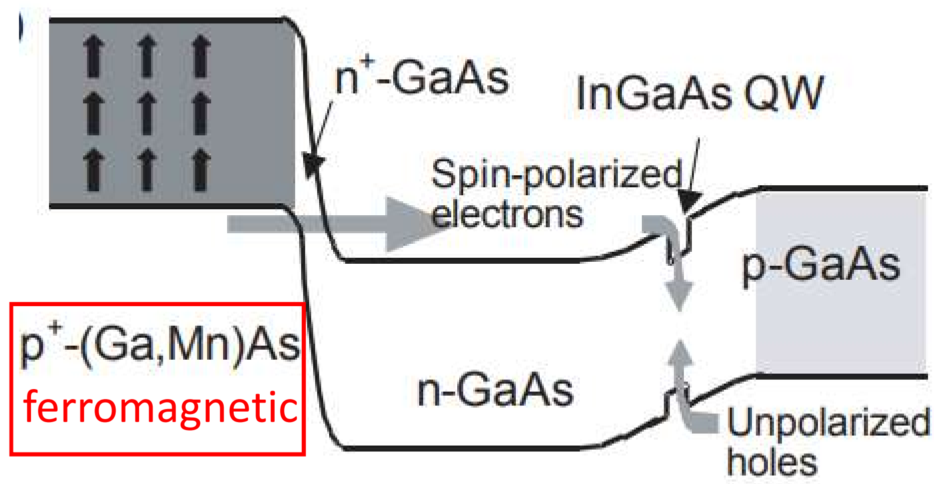


S. Sze .et. Metal-semiconductor contacts.2006

Spin Esaki diode

- ➢Under a small reverse bias electrons from VB of (Ga , Mn)As tunnel to CB of GaAs.
- ➢The conversion of spin-polarized electrons via Esaki tunneling leaves its mark in a bias dependence of the spin-injection efficiency, which at maximum reaches the value of 50%.



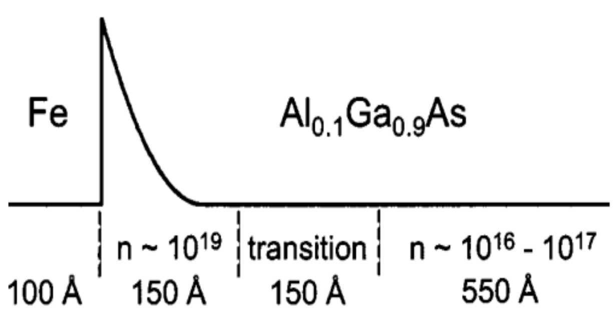


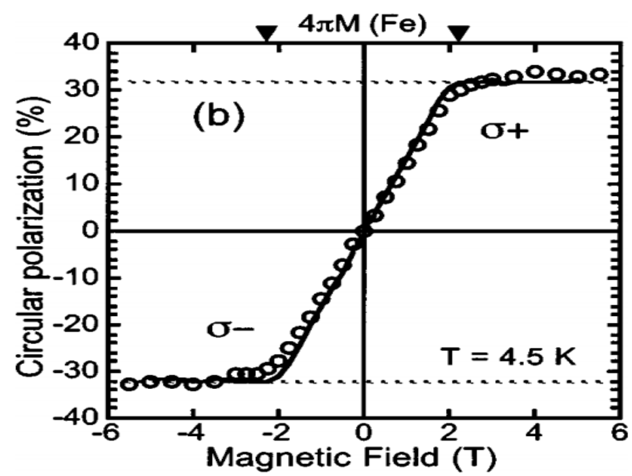
M. Ciorga A.et.prb.2009.

Improvement for depletion region

- The use of a thin, heavily doped surface region reduces the depletion width as well as the effective barrier height, significantly enhancing the probability for tunneling.

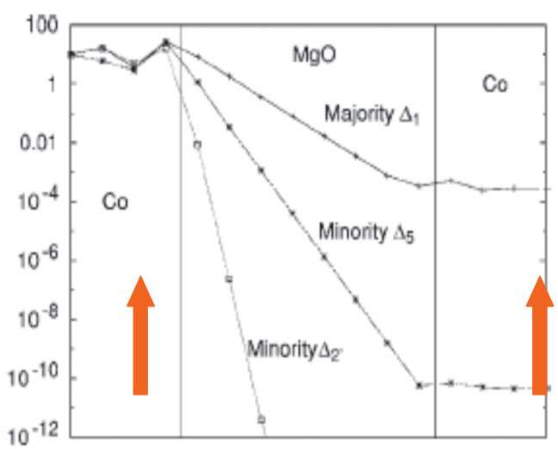
$$\boxed{P = \exp\left(-\frac{4\pi\sqrt{2m\varphi}}{h}d\right)}$$





Oxide barrier

- Spin dependent conductance: $\boxed{G = e^2 \rho(E_{\mathrm{F}}) \tilde{D}}$
- Spin efficiency: $\boxed{P_j \quad = \quad P_{\Sigma}}$



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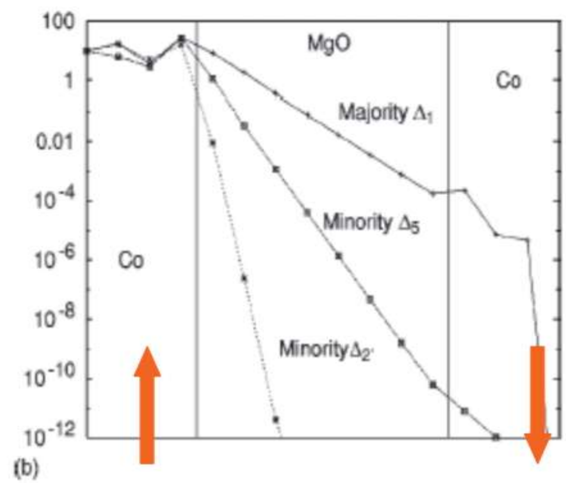
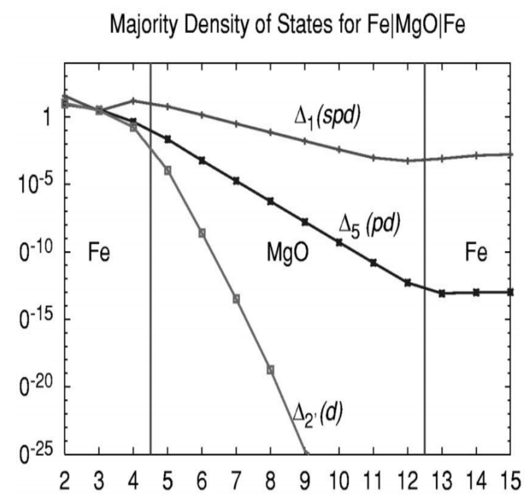
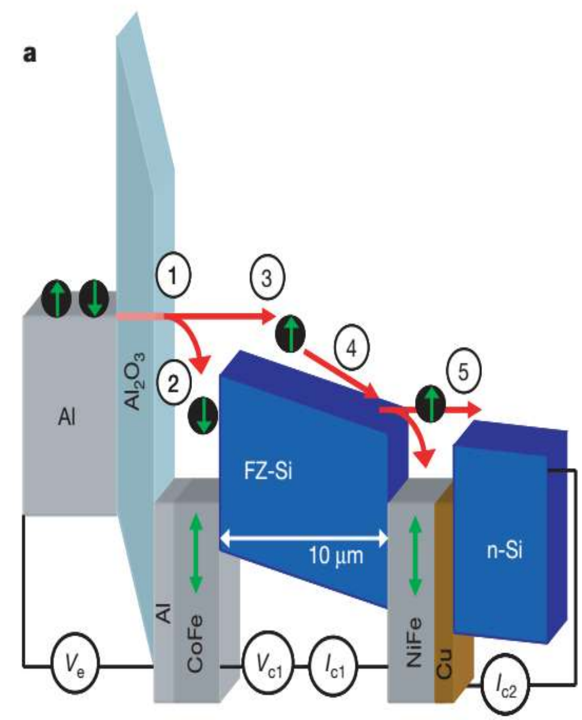




Zhang.et.PRB.2001

Hot electron spin injection

- This method to achieve spin injection is by spin-dependent ballistic hot-electron filtering through ferromagnetic thin films.
- The exponential spin selective mean free path dependence in the ferromagnetic films create very large spin polarizations. In principle ,this can approach 100%,allowing effective injection and detection at cryogenic and room temperature.



Ian Appelbaum.et.nature.2007

Spin detection

- ISHE
- Silsbee-Johnson spin-charge coupling

AHE,SHE and ISHE

- Charge current: $\mathbf{j}_{\mathrm{c}} = \sigma \mathbf{E} + D\nabla n$
- Spin current: $j_{\mathrm{s,ij}} = -\frac{\hbar}{2}\mu E_{\mathrm{i}} s_{\mathrm{j}} - \frac{\hbar}{2} D \frac{\partial s_{\mathrm{j}}}{\partial x_{\mathrm{i}}}$
- Including spin-orbit coupling and anomalous current density

$$j_{\mathrm{c,i}} = \sigma E_{\mathrm{i}} + eD\frac{\partial n}{\partial x_{\mathrm{i}}} - \frac{2e}{\hbar}\zeta\epsilon_{\mathrm{ijk}}\left(\frac{\hbar}{2}\mu E_{\mathrm{j}} s_{\mathrm{k}} + \frac{\hbar}{2} D \frac{\partial s_{\mathrm{k}}}{\partial x_{\mathrm{j}}}\right)$$

$$j_{\mathrm{s,ij}} = \frac{\hbar}{2}\mu E_{\mathrm{i}} s_{\mathrm{j}} + \frac{\hbar}{2} D \frac{\partial s_{\mathrm{j}}}{\partial x_{\mathrm{i}}} - \frac{\hbar}{2e}\zeta\epsilon_{\mathrm{ijk}}\left(\sigma E_{\mathrm{k}} + eD\frac{\partial n}{\partial x_{\mathrm{k}}}\right)$$

$$\mathbf{j}_{\mathrm{c}} = \frac{2e}{\hbar}\alpha_{\mathrm{SH}} \mathbf{j}_{\mathrm{s}} \times \mathbf{e}_{\mathrm{s}}$$

AHE and ISHE

$$\mathbf{j}_{\mathrm{s}} = \frac{\hbar}{2e}\alpha_{\mathrm{SH}} \mathbf{e}_{\mathrm{s}} \times \mathbf{j}_{\mathrm{c}}$$

SHE

ISHE

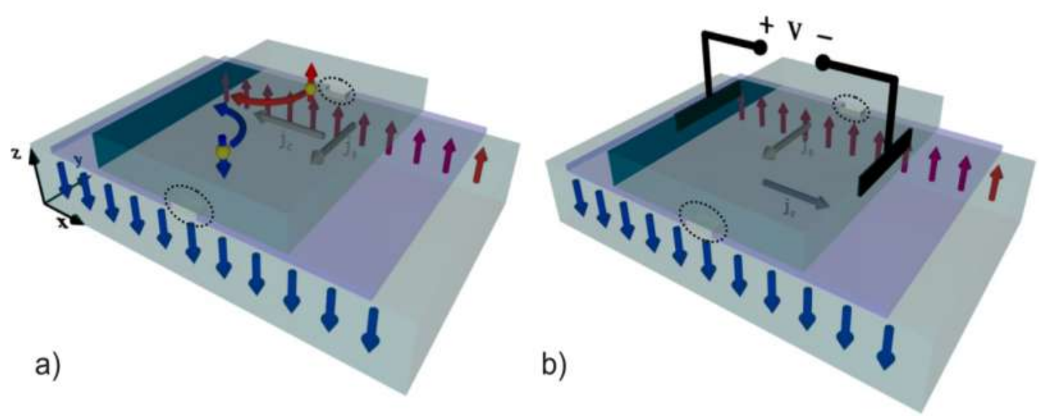
- Spin current convert to charge current:

$$\boxed{\mathbf{j}_{\mathrm{c}} = \frac{2e}{\hbar}\alpha_{\mathrm{SH}}\mathbf{j}_{\mathrm{s}} \times \mathbf{e}_{\mathrm{s}}}$$

- Some challenges:

➢Voltage detectable is small(is proportional to the resistivity and α_{SH})

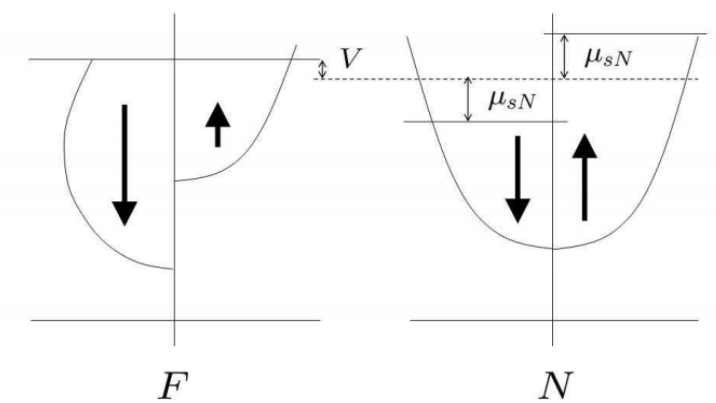
➢The device's dimensions are smaller than λ_{sd}

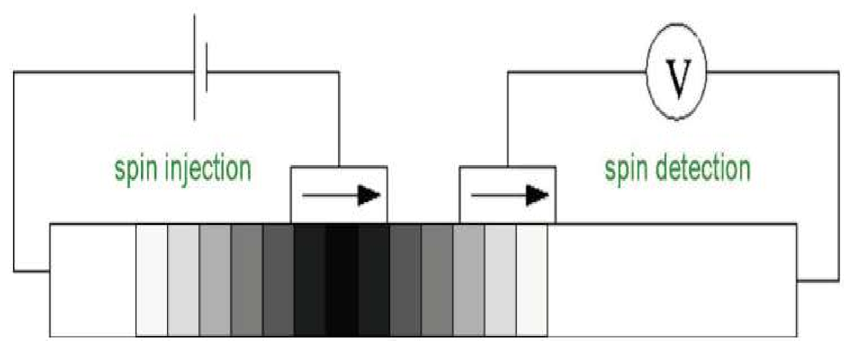


Silsbee-Johnson spin-charge coupling

- If a spin accumulation is generated in a nonmagnetic conductor that is in a proximity of a ferromagnet, a current flows in a closed circuit, or an electromotive force appears in an open circuit.

$$\boxed{\mathrm{emf} = -\frac{R_F P_{\sigma F} + R_c P_\Sigma}{R_F + R_c + R_N}\,\mu_{sN}(\infty) = -P_j\,\mu_{sN}(\infty)}$$





Spin modulation

- Hanle spin procession frequency
- Spin diffusion length
- Conductivity
- Spin dependent barrier
- Magnetoelectric effect

Spin procession frequency

- Spin orbit coupling in 2DEG

$$H_R = \alpha_R\ (\boldsymbol{\sigma} \times \mathbf{k})\ \cdot \hat{\mathbf{n}}$$

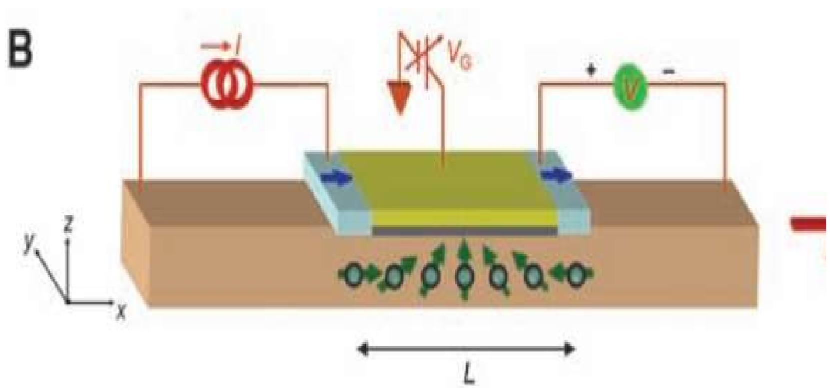
$$B_R(\vec{v}) = \frac{2}{\hbar}\alpha_R(\vec{k} \times \vec{n})$$

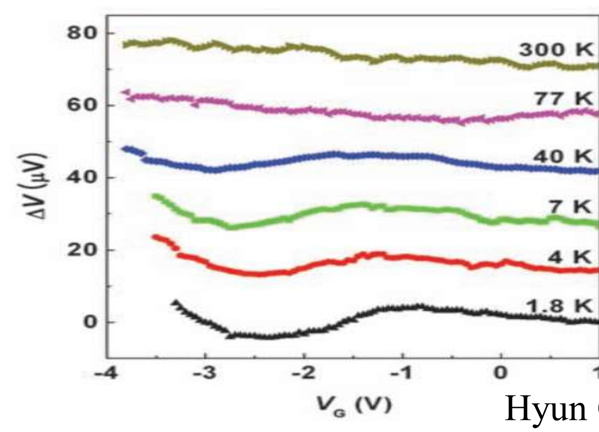
- Gate modulation of Rashba coefficient

$$\alpha_R = \alpha_0 \langle \mathcal{E}_v(\mathbf{r}) \rangle$$

- At low temperature,transport of electrons in 2DEG is ballistic(coherent).

$$V = A\cos(2m^*\alpha L/\hbar^2 + \varphi)$$





Hyun Cheol Koo et. science.2009

Spin diffusion length

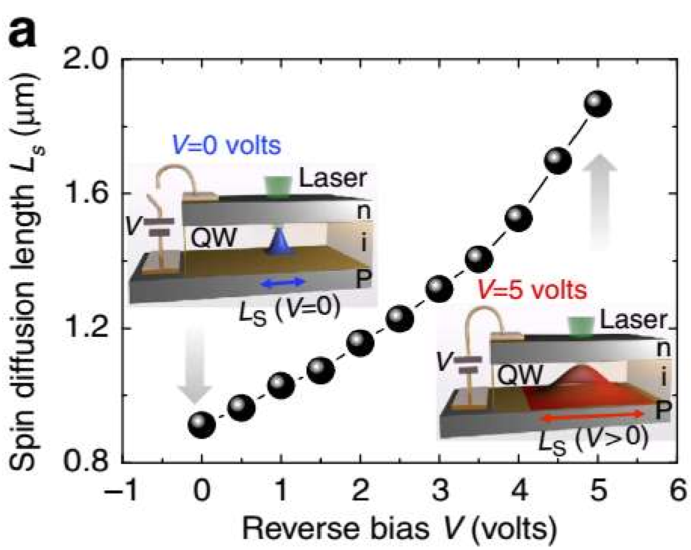
- At RT, in semiconductor(GaAs,GaN),electron spin relaxation dominates by DP mechanism

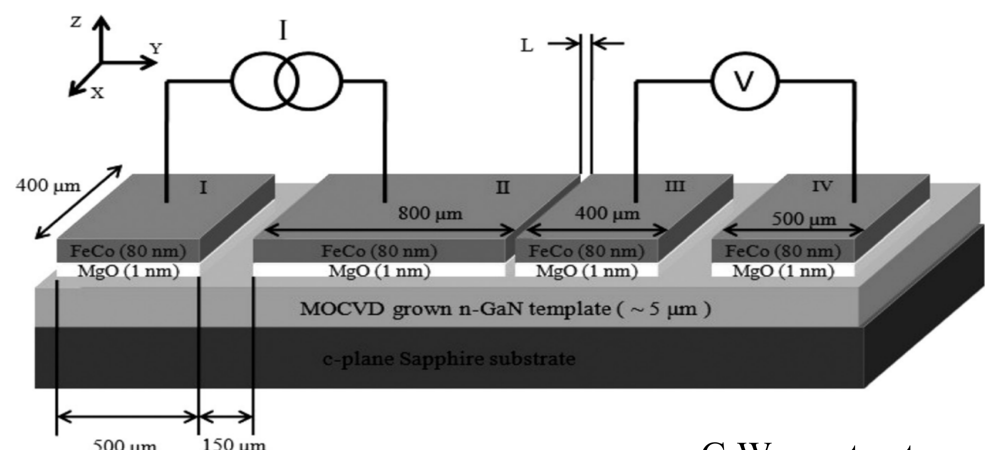
$$\Omega_{Tot}(\mathbf{k}_{//}) = \Omega_{\mathrm{BIA}}(\mathbf{k}_{//}) + \Omega_{\mathrm{SIA}}(\mathbf{k}_{//}) = \left(\frac{\beta}{\hbar} + \frac{2r_{41}E}{\hbar}\right)(k_y, -k_x, 0)$$

$$\frac{1}{\tau_s} = \langle \Omega^2_{\mathrm{Tot}} \rangle \tau^*_p$$

$$\boxed{L_s = \sqrt{D_s T_s}}$$

$$\boxed{\mu_{sN} = \mu_{sN}(0)e^{-x/L_{sN}}}$$

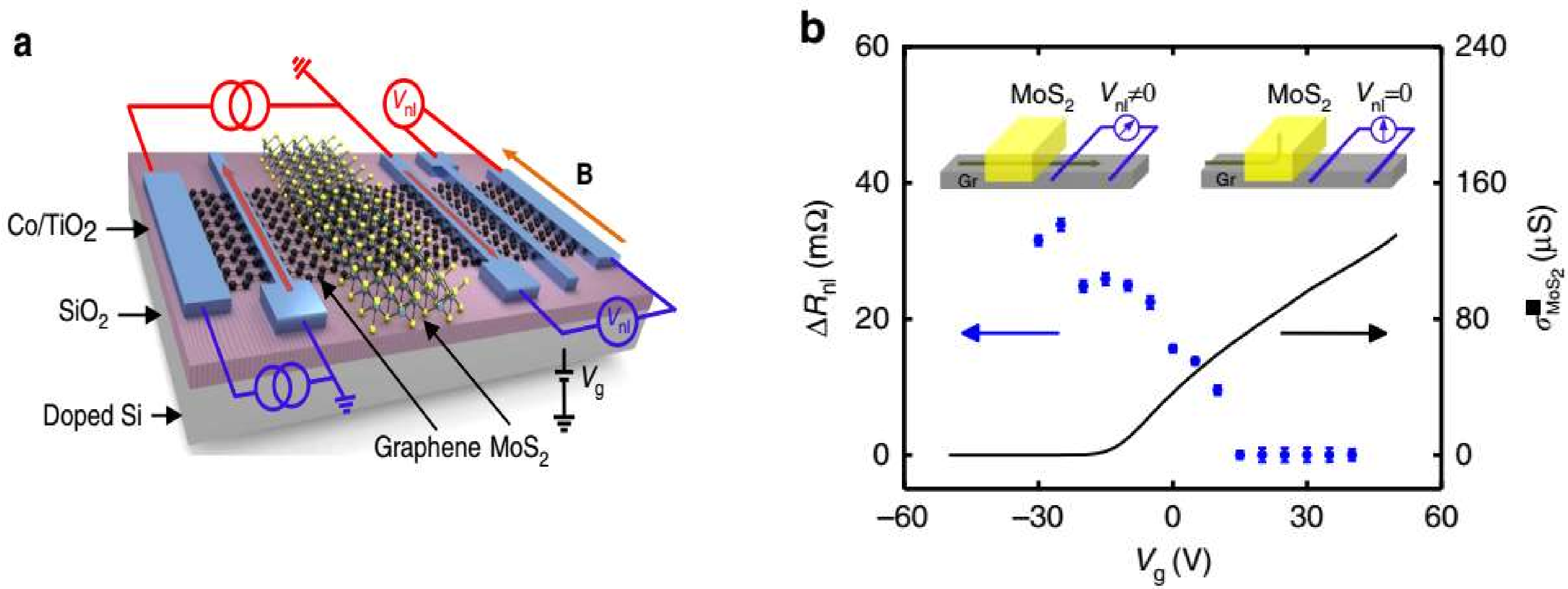




G.Wang.et.nature cm.2013

A spin field-effect switch

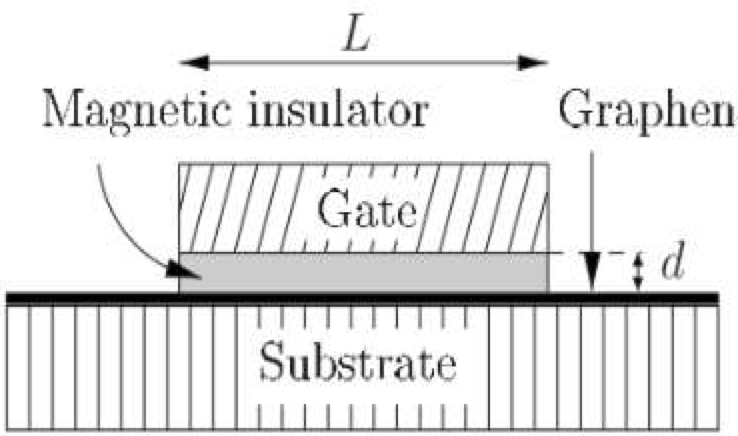
- Gate voltage modulate the conductivity of MoS2



Wenjing Yan.et.nature cm.2016

Spin-dependent barrier

- Using magnetic insulator rather than normal insulator as dielectric layer in FET could induce a spilt according to spin caused by ferromagnetic proximity.



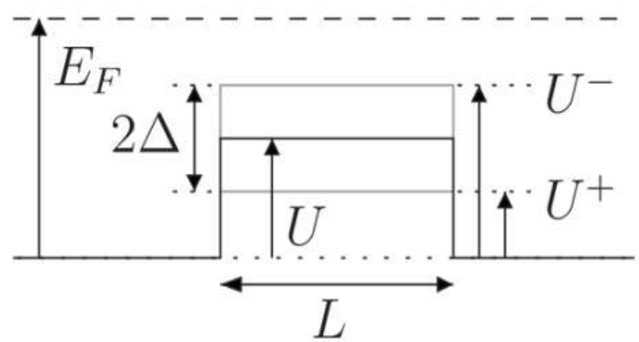
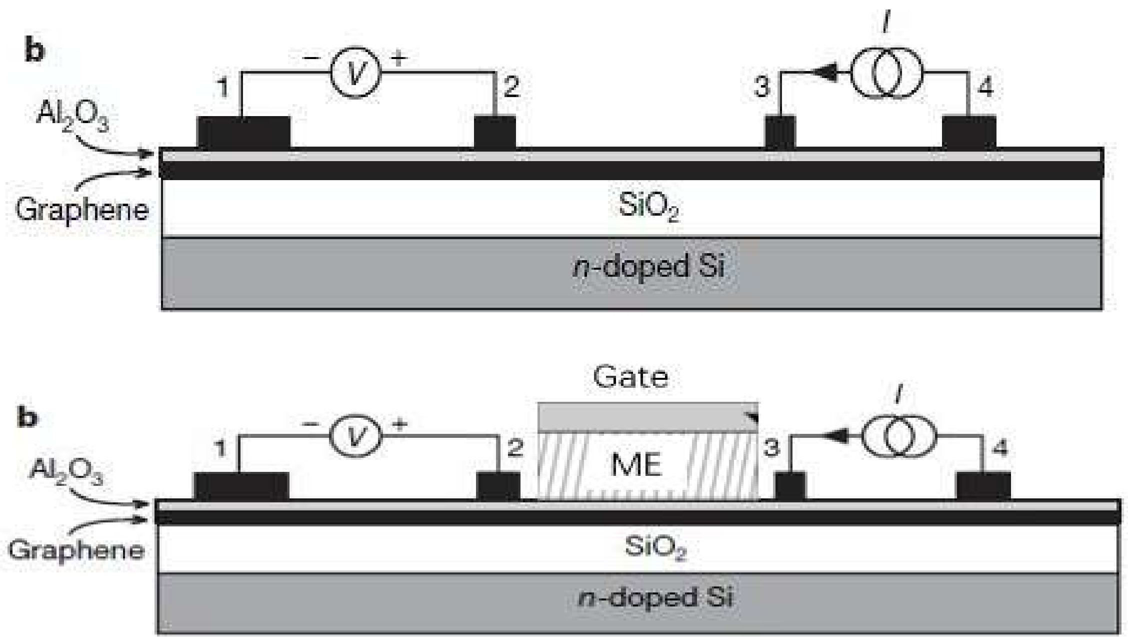


FIG. 4. Ferromagnetic proximity effect splits the barrier according to spin such that $U^{\pm}=U\mp\Delta$.

PHYSICAL REVIEW B 77, 115406 (2008)

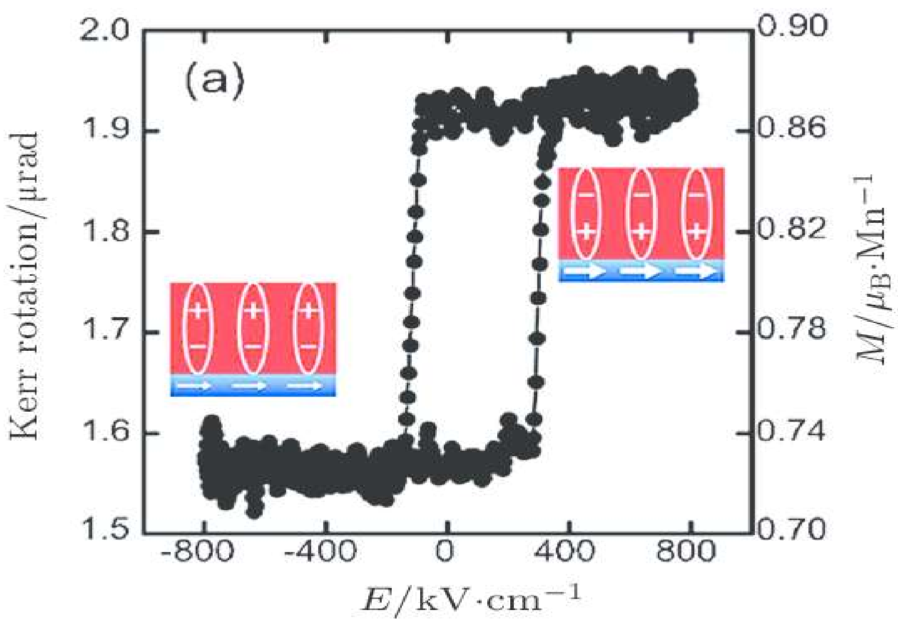
A proposal for spin FET

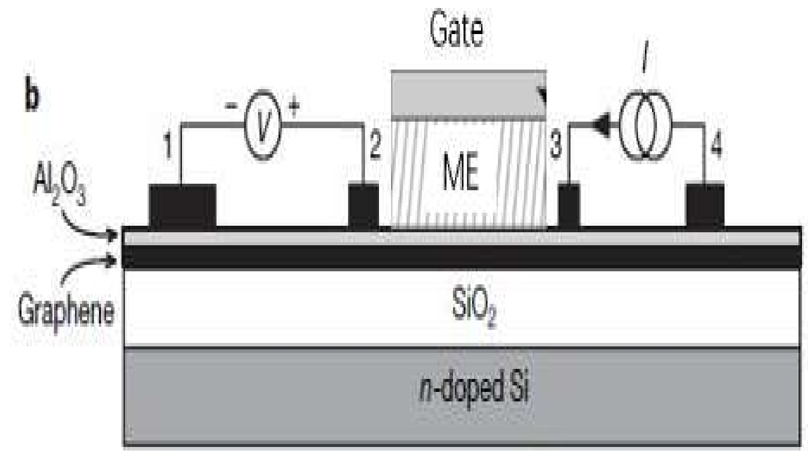
If such structure is deposited on the middle of a non-local spin-valve, the signal would be affected by the gate voltage.



Magnetoelectric effect

- A dielectric material moving through an electric field would become magnetized. A material where such a coupling is intrinsically present is called a magnetoelectric.





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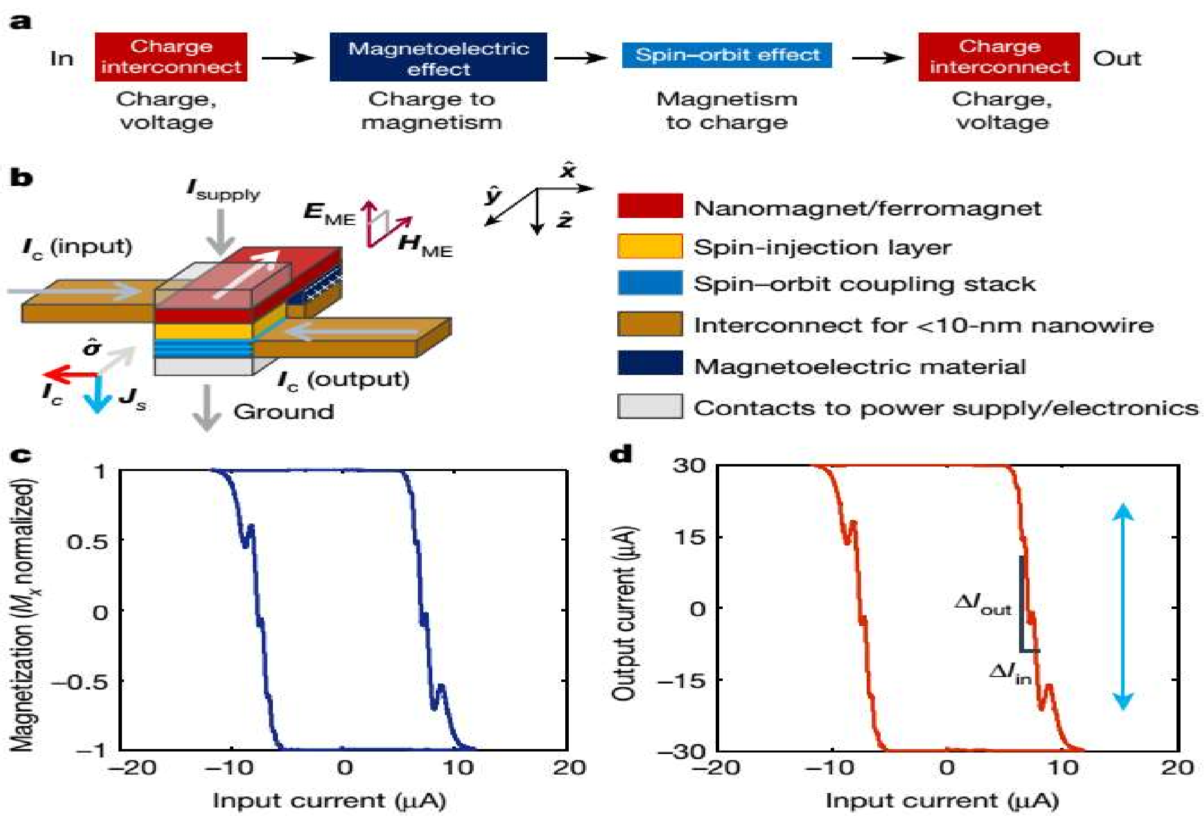
Scalable energy-efficient magnetoelectric spin–orbit logic

Sasikanth Manipatruni[1]*, Dmitri E. Nikonov[1], Chia-Ching Lin[1], Tanay A. Gosavi[1], Huichu Liu[2], Bhagwati Prasad[3], Yen-Lin Huang[3,4], Everton Bonturim[3], Ramamoorthy Ramesh[3,4,5] & Ian A. Young[1]



Thank you