All-electric Spin Transistors

Tse-Ming Chen

Department of Physics, NCKU

What is transistor (or MOSFET)?

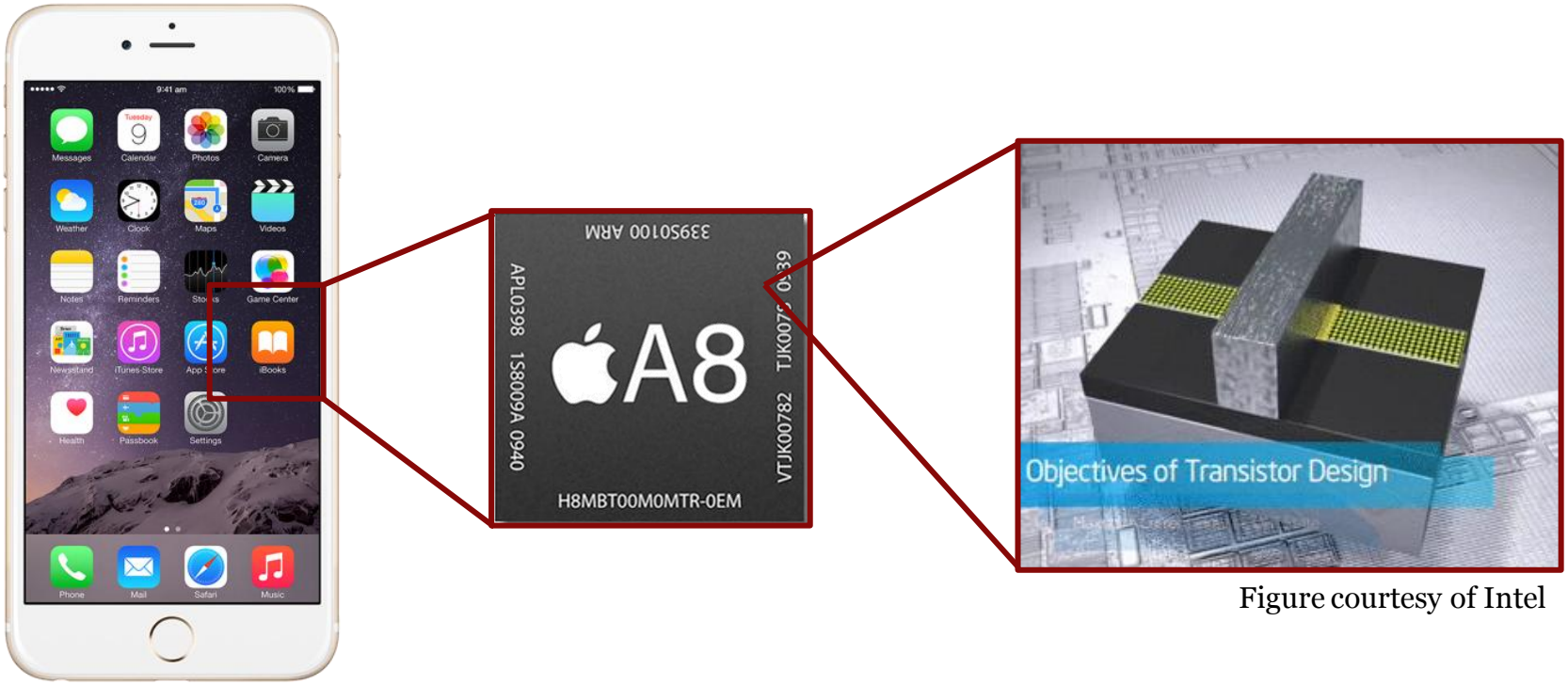
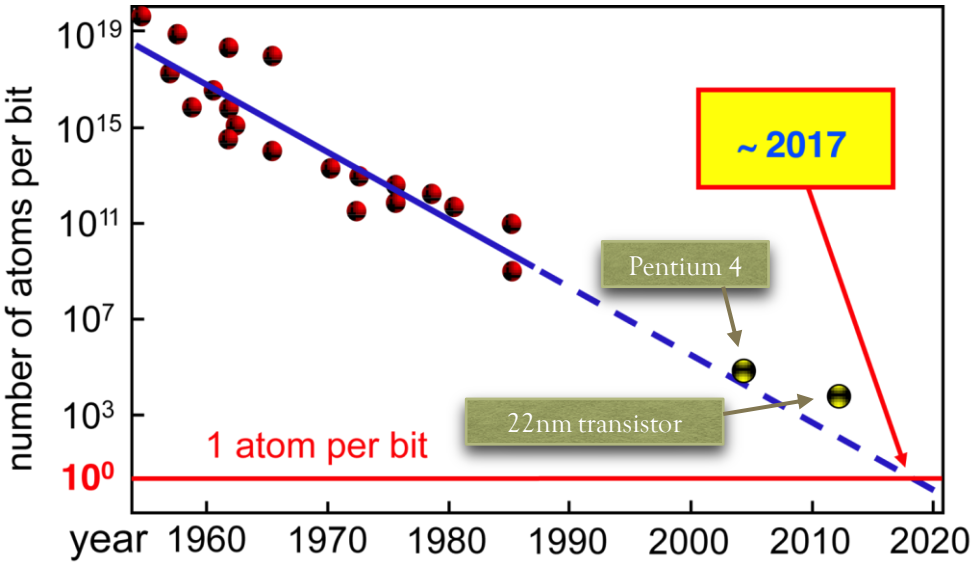


Figure courtesy of Intel

If is said that if a cell is the building block of life, then a transistor is the building block of the digital era.

Semiconductor Scaling

William Shockley, John Bardeen
and Walter Brattain
1956 Nobel Prize



R. W. Keyes, IBM J. R&D 32, 26 (1988).

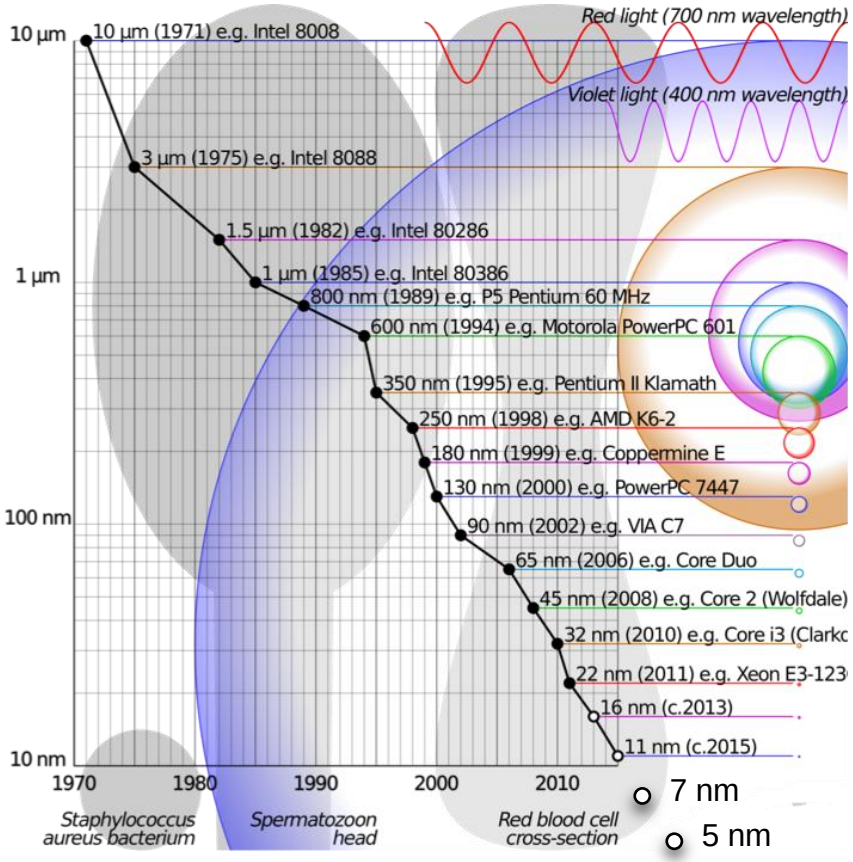


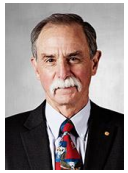
Figure courtesy of wiki

Doom of Moore' s Law (and the semiconductor industry)???

Beyond MOSFET

MOSFET

Quantum Computing
(superposition & entanglement)

Serge Haroche and David J. Wineland
2012 Nobel Prize

Photo courtesy of NASA

Spintronic Computing
(spin)

1. Spin switch faster than THz
2. New functionality
3. Less energy consumption


Giant Magnetoresistance (GMR)
Albert Fert and Peter Grünberg
2007 Nobel Prize

Spin-transfer torque RAM
STT-RAM

Datta-Das spin FET

nature MILESTONES SPIN

MILESTONES TIMELINE

1896	Zeeman effect (1)
1922	Stern–Gerlach experiment (2)
1925	The spinning electron (3)
1928	Dirac equation (4)
	Quantum magnetism (5)
1932	Isospin (6)
1940	Spin–statistics connection (7)
1946	Nuclear magnetic resonance (8)
1950s	Development of magnetic devices (9)
1950–1951	NMR for chemical analysis (10)
1951	Einstein–Podolsky–Rosen argument in spin variables (11)
1964	Kondo effect (12)
1971	Supersymmetry (13)
1972	Superfluid helium-3 (14)
1973	Magnetic resonance imaging (15)
1975–1976	NMR for protein structure determination (16)
1978	Dilute magnetic semiconductors (17)
1988	Giant magnetoresistance (18)
1990	Functional MRI (19)
	Proposal for spin field-effect transistor (20)
1991	Magnetic resonance force microscopy (21)
1996	Mesoscopic tunnelling of magnetization (22)
1997	Semiconductor spintronics (23)

http://www.nature.com/milestones/milespin/index.html

Outline

- What is spin FET and Why realization of it still seems to be impossible?

- Our contribution to spin FET, and probably many other spintronic devices

MOSFET vs SpinFET

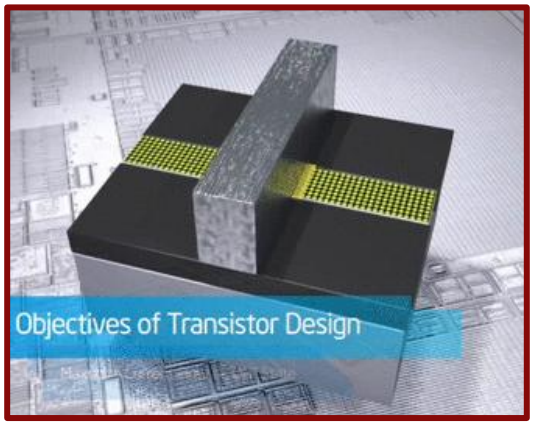
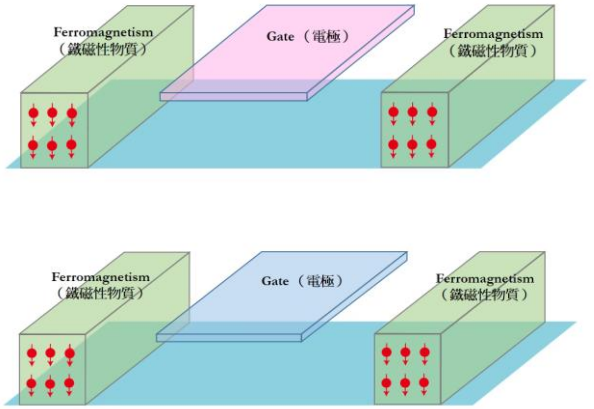
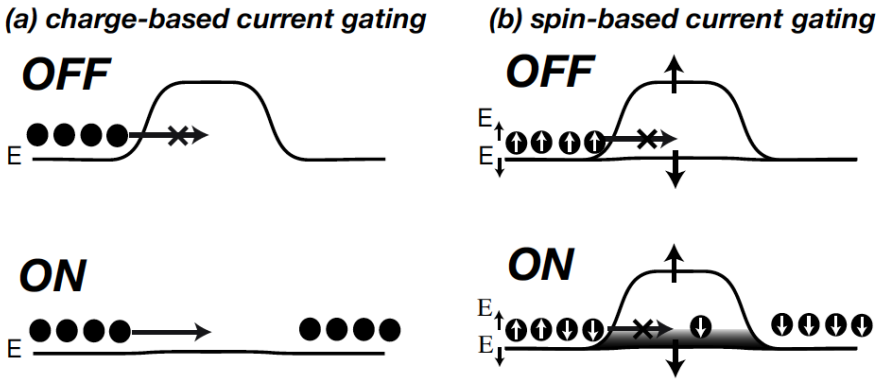


Figure courtesy of Intel





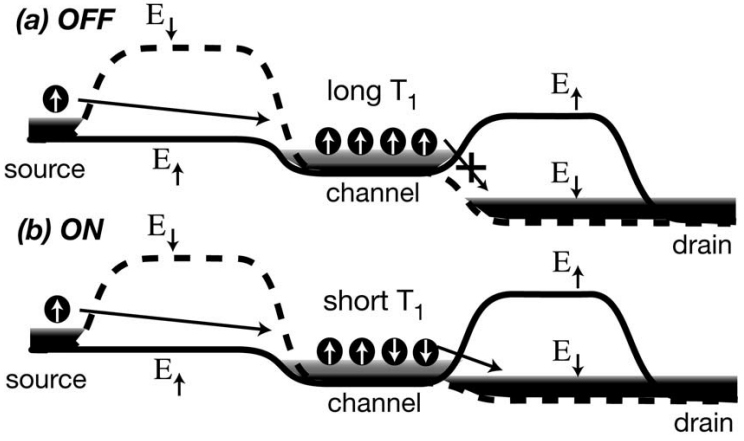


Figure adapted from Hall and Flatte, APL 2006.

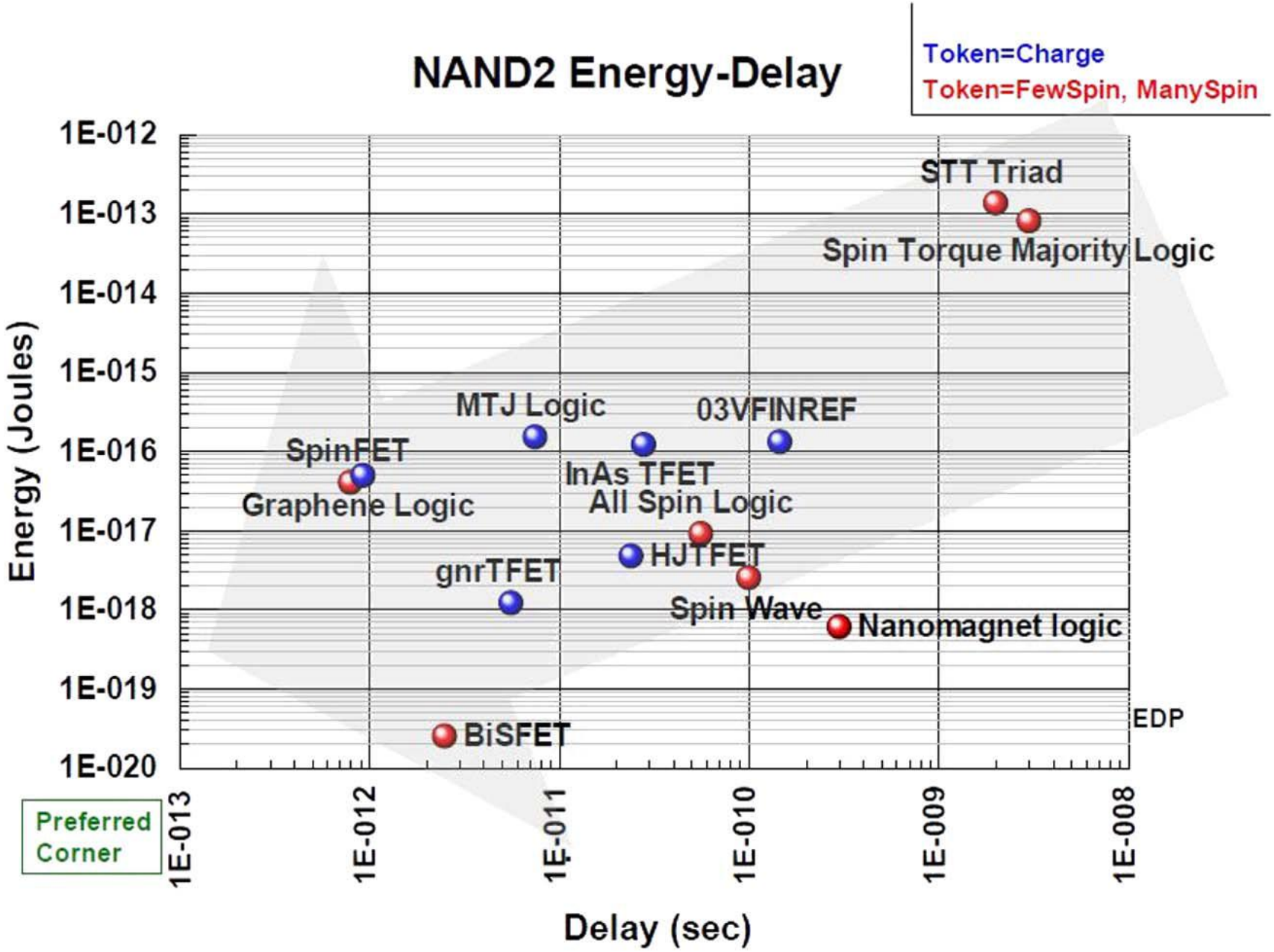


Figure adapted from Nikonov, Proceedings of the IEEE 101, 2498 (2013).

Datta-Das Spin-FET

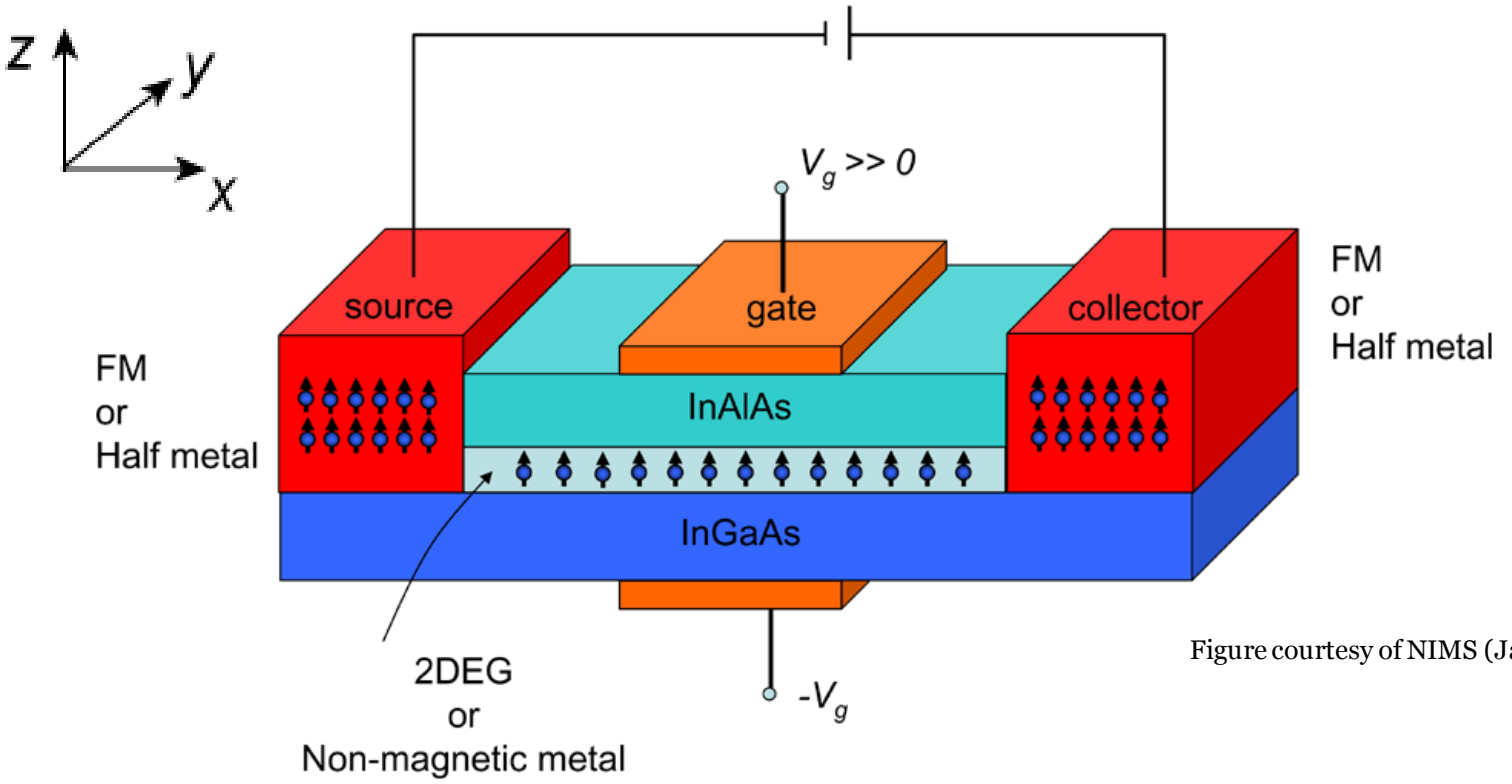
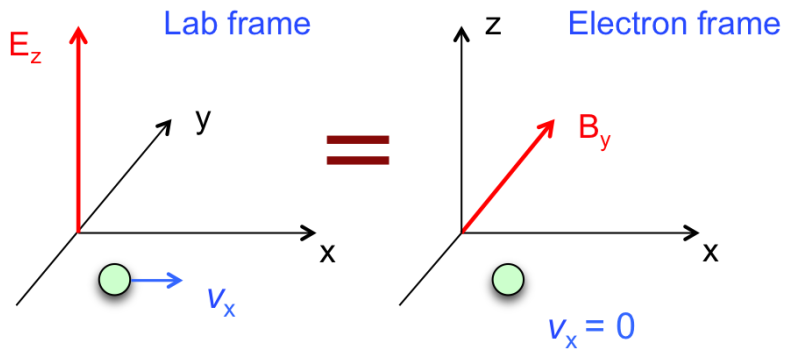


Figure courtesy of NIMS (Japan)

Key components of spin FET (proposed by Datta and Das in 1990)

- Spin injection/detection – using ferromagnetism
- Spin control – using electric field to control the spin rotation

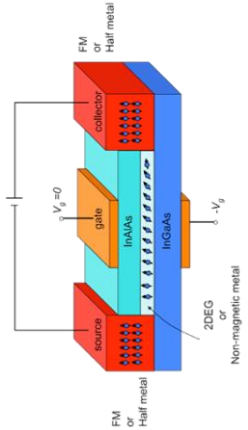
Rashba spin-orbit coupling

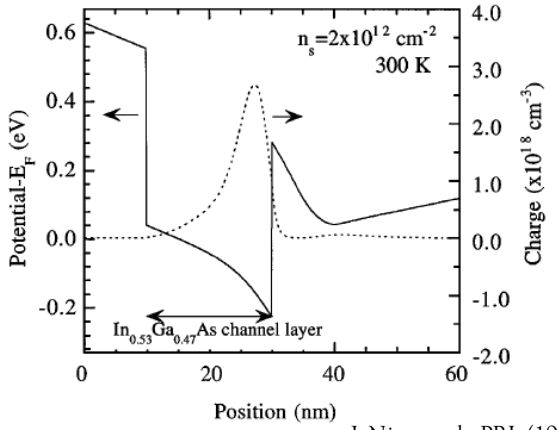


$$\mathbf{B}^{\mathrm{SO}} = -(\hbar/mc^2)(\mathbf{k} \times \mathbf{E})$$

$$H^{\mathrm{SO}} = -\boldsymbol{\mu} \cdot \mathbf{B}^{\mathrm{SO}} = -\beta\boldsymbol{\sigma} \cdot (\mathbf{k} \times \mathbf{E})$$

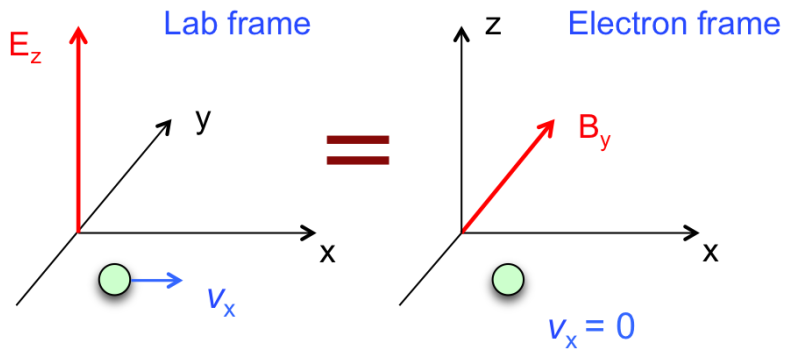
$$= \alpha(-k_x\sigma_y + k_y\sigma_x)$$





J. Nitta et al., PRL (1997).

Rashba spin-orbit coupling & spin precession



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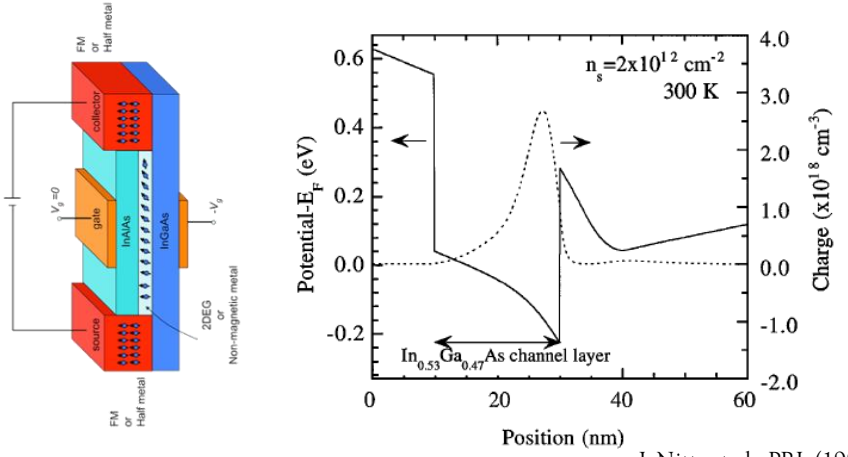
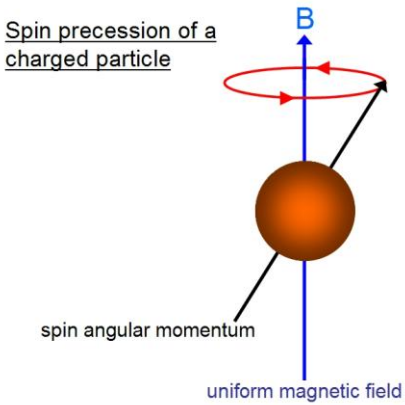
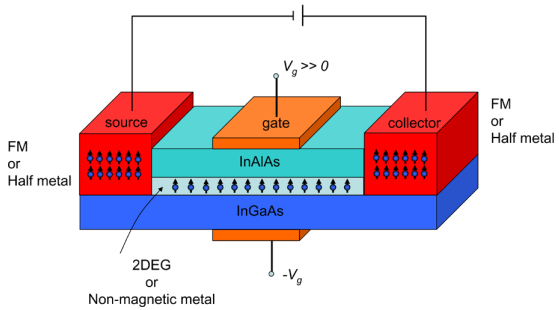


J. Nitta et al., PRL (1997).





Datta and Das showed in APL 56, 665 (1990) that for electron spins travelling in a 1D channel

the precession frequency is

$$\omega_{\mathrm{L}} = 2\alpha k_x/\hbar$$

and the phase shift for spins **ballistically** travelling in a distance L is

$$\Delta\theta = \omega_{\mathrm{L}} t = 2m^*\alpha L/\hbar^2$$

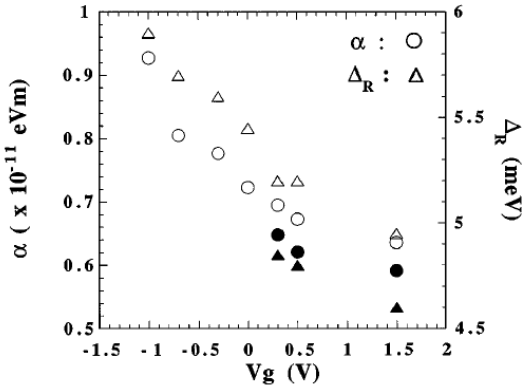
Spin Transistor Research Roadmap

Proposal for spin FET

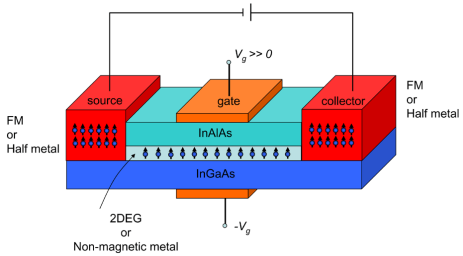
1990

Gate control of spin-orbit coupling

1997



Nitta *et al.* PRL 78, 1335 (1997)



$$\Delta\theta = \omega_L t = 2m^*\alpha L/\hbar^2$$

In order to achieve $\Delta\theta = 2\pi$, L must be at least 2 μm for $\Delta\alpha$ = 3E-12 eVm

Proposal for spin FET

1990

Gate control of spin-orbit coupling

1997

Proposal for nonballistic spin FET

2003

2002

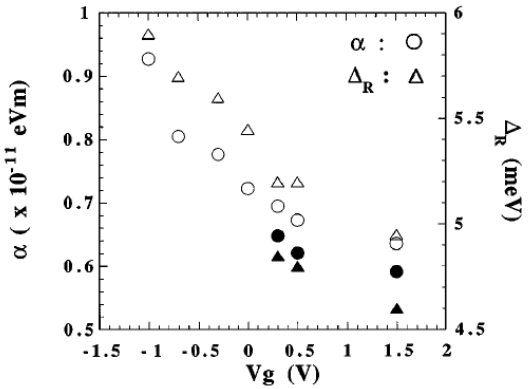
Spin rotation in metals by B-field

VOLUME 90, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 11 APRIL 2003

Nonballistic Spin-Field-Effect Transistor

John Schliemann, J. Carlos Egues,* and Daniel Loss
Department of Physics and Astronomy, University of Basel, CH-4056 Basel, Switzerland
(Received 26 November 2002; published 8 April 2003)

We propose a spin-field-effect transistor based on spin-orbit coupling of both the Rashba and the Dresselhaus types. Different from earlier proposals, spin transport through our device is tolerant against spin-independent scattering processes. Hence the requirement of strictly ballistic transport can be relaxed. This follows from a unique interplay between the Dresselhaus and the Rashba coupling; these can be tuned to have equal strengths, leading to *k-independent* eigenspinors even in two dimensions. We discuss two-dimensional devices as well as quantum wires. In the latter, our setup presents strictly *parabolic* dispersions which avoids complications from anticrossings of different bands.



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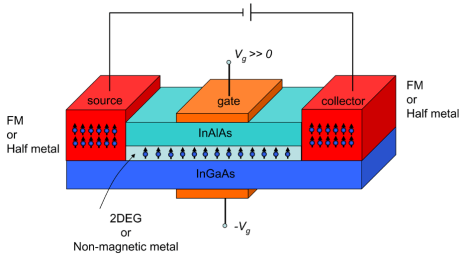
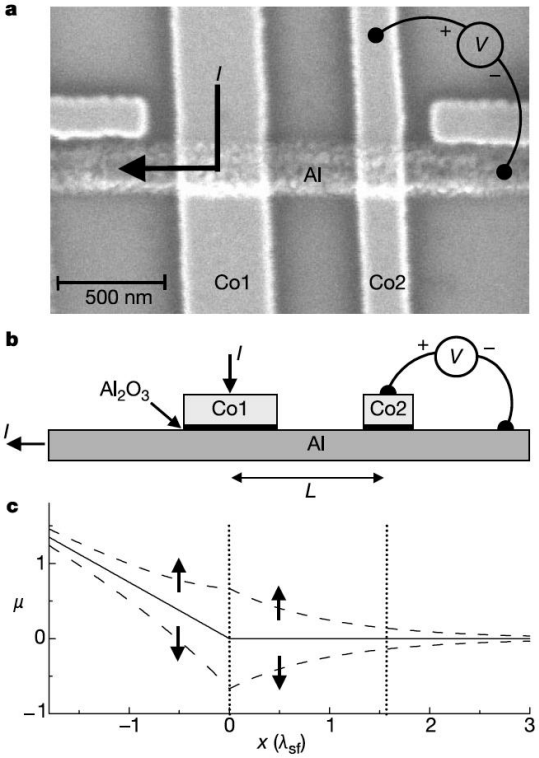
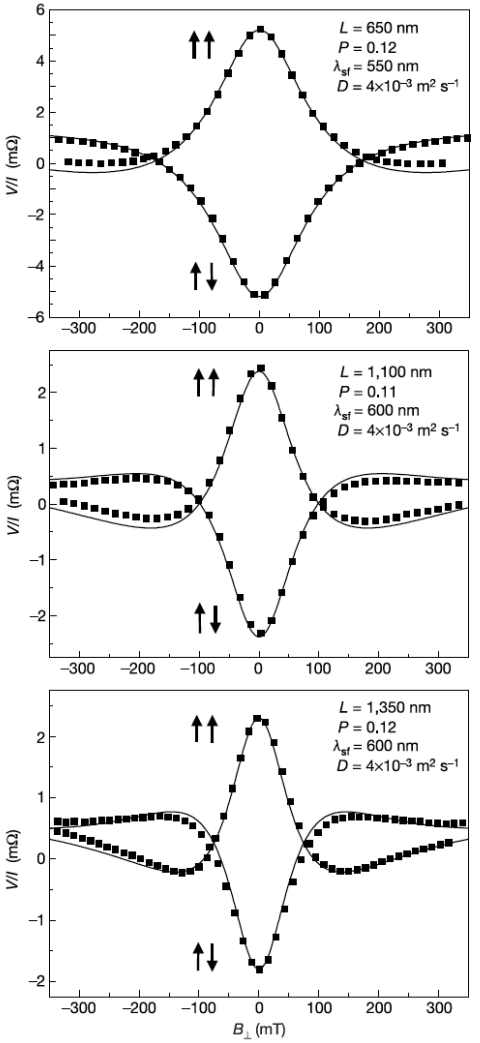


$$\Delta\theta = \omega_L t = 2m^*\alpha L/\hbar^2$$

In order to achieve $\Delta\theta = 2\pi$, L must be at least 2 μm for $\Delta\alpha$ = 3E-12 eVm

Jedema *et al.* Science 416, 713 (2002)





Proposal for spin FET

1990

Gate control of spin-orbit coupling

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Proposal for nonballistic spin FET

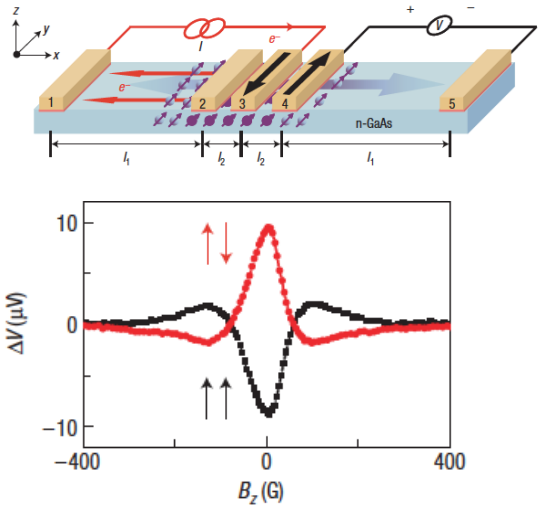
2003

2002

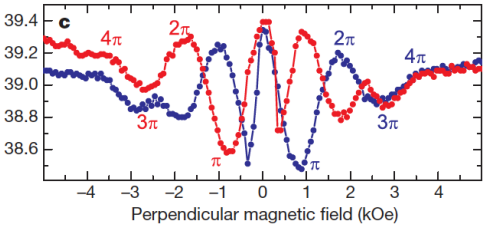
Spin rotation in metals by B-field

2007

Spin rotation in semiconductors by B-field



Lou et al., Nature Physics 3, 197 (2007).



Appelbaum et al., Nature 447, 295 (2007)

Proposal for spin FET

1990

Gate control of spin-orbit coupling

1997

Proposal for nonballistic spin FET

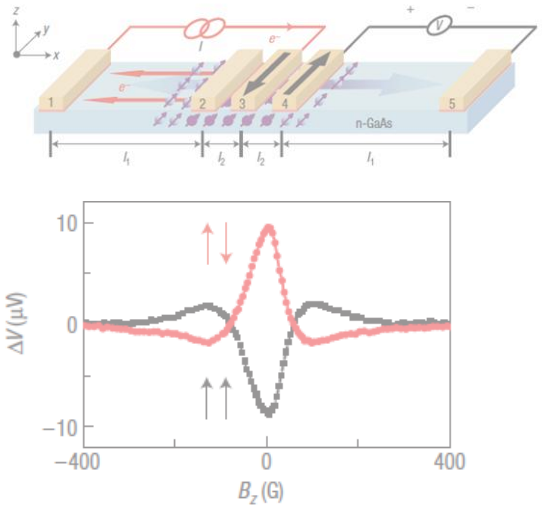
2002

2003

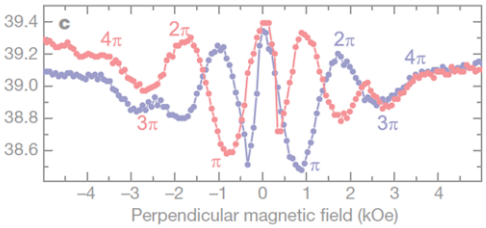
Spin rotation by spin-orbit coupling

2007

2009



Lou et al., Nature Physics 3, 197 (2007).



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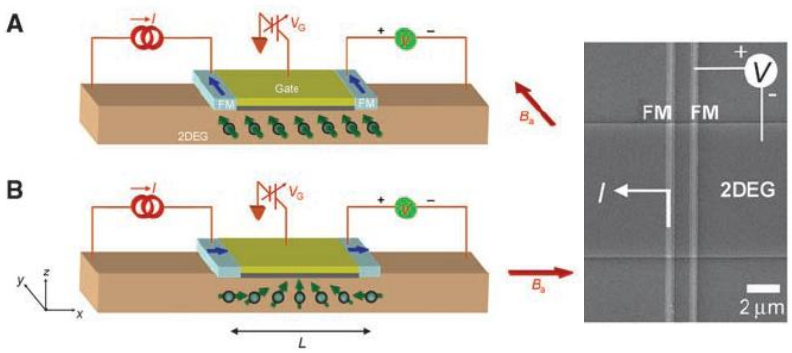
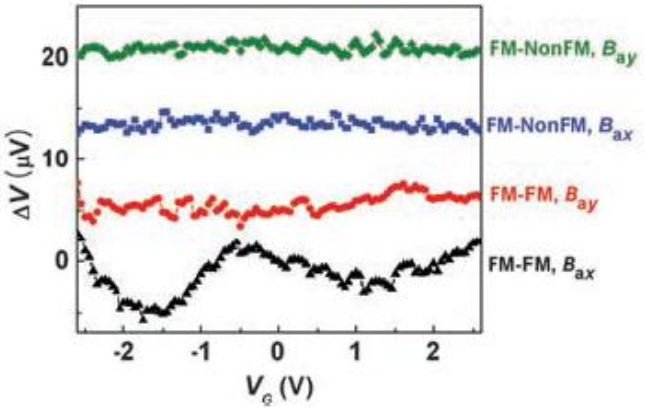




Koo et al., Science 325, 1515 (2009)

- Mean free path is ~1.6 μm when T < 10 K
- Distance between two contacts is 1.6 and 1.2 μm.

However, the oscillatory resistance (on/off) variation is extremely small,

V/I is only 0.01 Ω

Datta-Das spin transistor reach a dead end?

Obstacles to the realization of spin FET…

- low spin-injection efficiency
  due to resistance mismatch [Schmidt et al., PRB 62, R4790 (2000)]

- limited spin lifetime
  picoseconds, due to D'yakonov-Perel' scatterings

- phase spread of accumulated spins
  due to various precession angles resulted from different paths from source to drain

Obstacles again…

- low spin-injection efficiency
  due to resistance mismatch

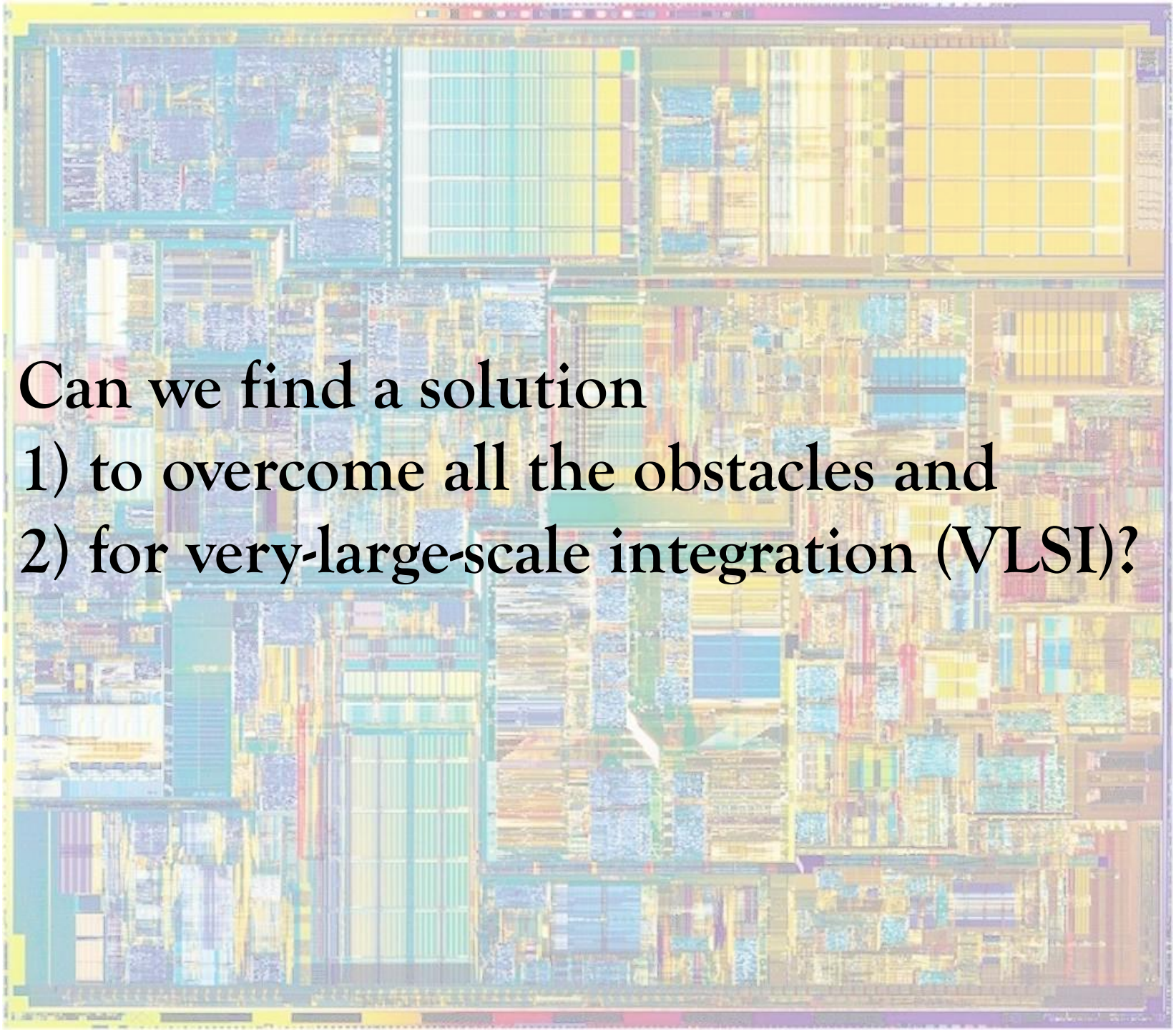
1. Increase spin injection efficiency of FM
2. Optical spin injection
3. ?

- limited spin lifetime
  picoseconds, due to D'yakonov-Perel' scatterings

1. Improve material quality to reduce scatterings, or
2. ?

- phase spread of accumulated spins
  due to various precession angles resulted from different paths from source to drain

1D transport


Can we find a solution
1) to overcome all the obstacles and
2) for very-large-scale integration (VLSI)?

Our proposed solution is to employ

Quantum Point Contacts

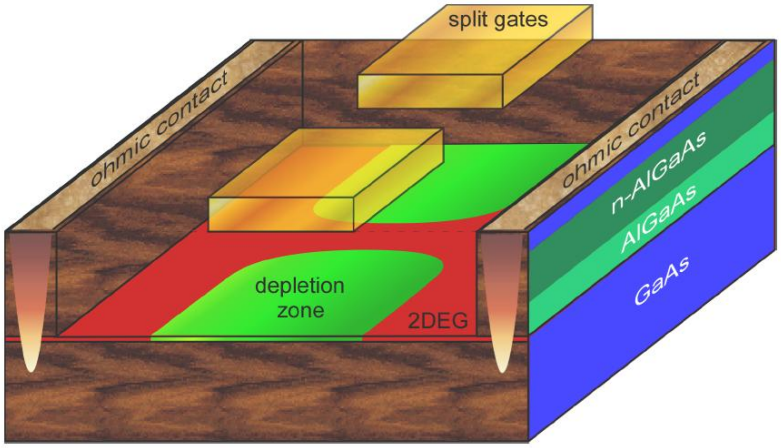
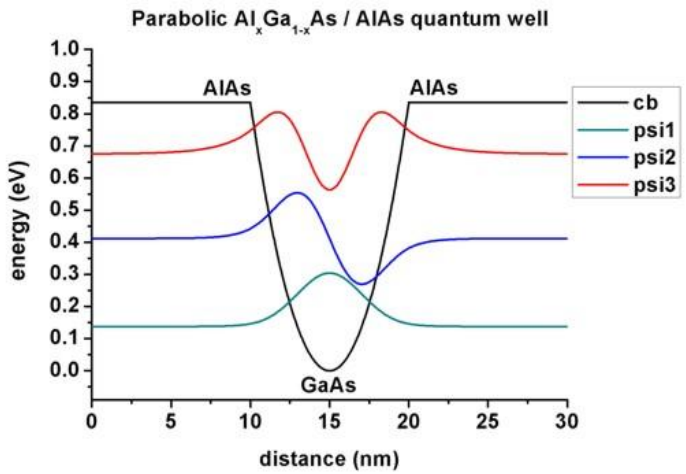
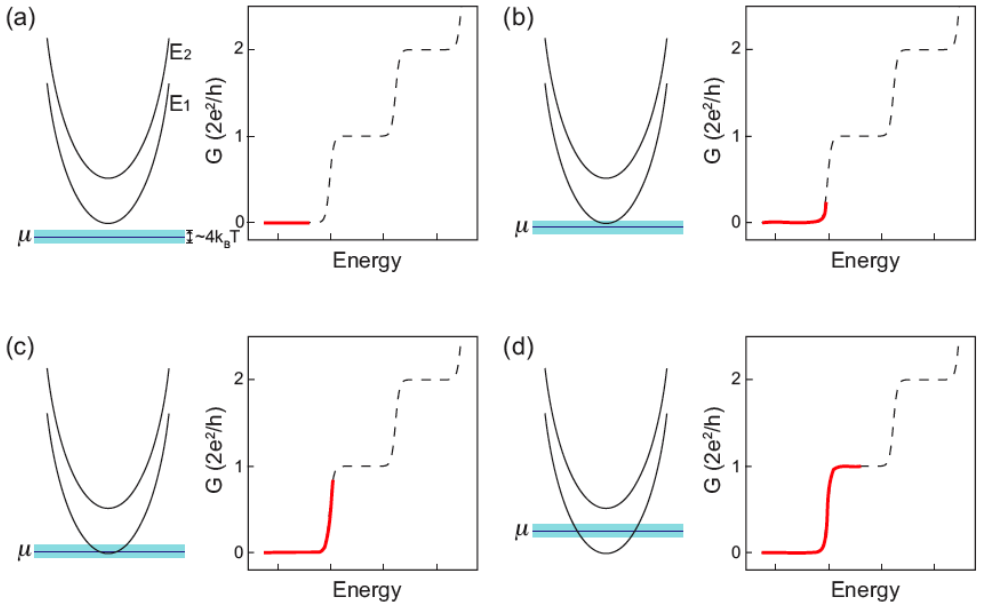


Figure courtesy of M. Switkes





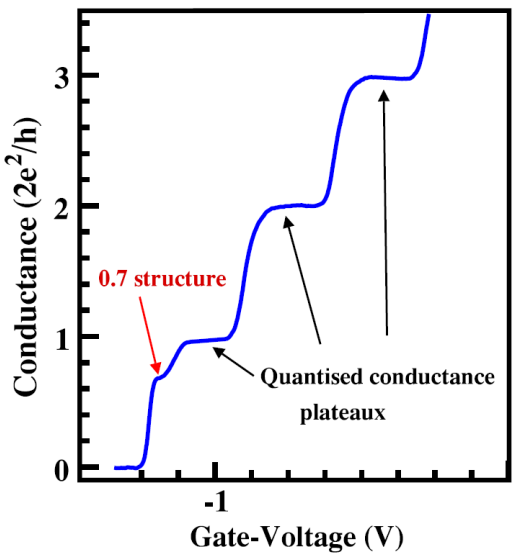
- 1D transport
- conductance quantization at integer multiples of $2e^2/h$

Quantum point contacts & Spin injection

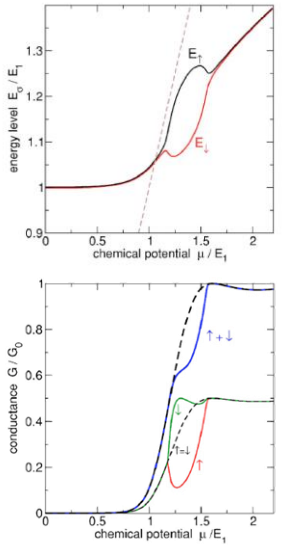
QPC spin injection through e-e interaction

- 0.7 structure – implying spin polarization.

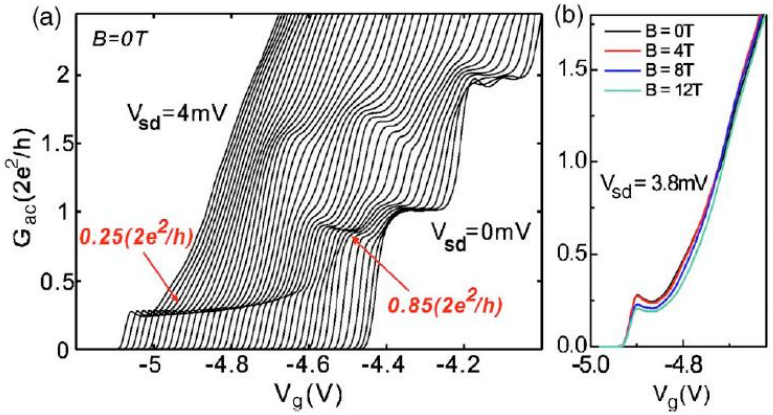
- Possible fully spin polarization (manifested as the 0.25 structure) was first proposed by T.-M. Chen *et al.*, APL 93, 032102 (2008), and then was verified by T.-M. Chen *et al.*, PRL 109, 177202 (2012).

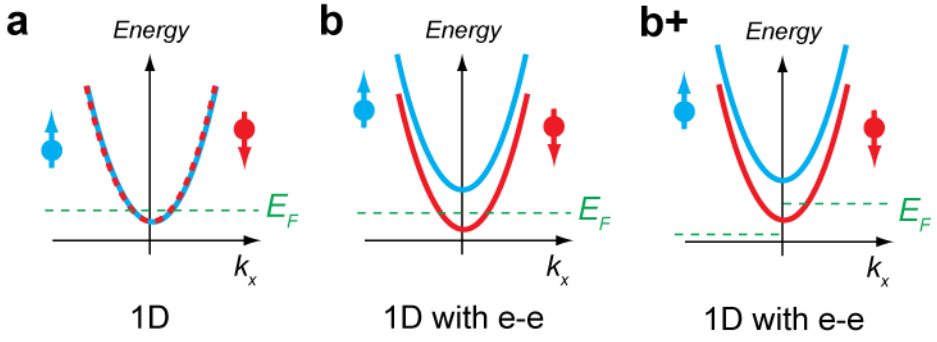


K. J. Thomas et al., PRL (1996).



A. Lassl et al., PRB (2007).



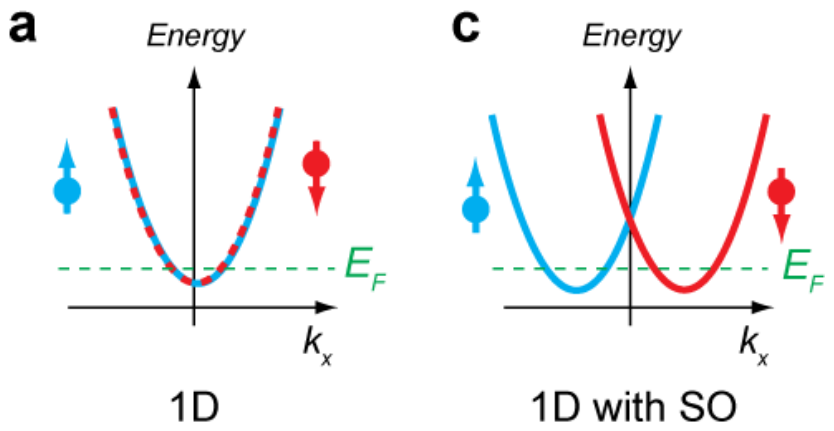


Quantum point contacts & Spin injection

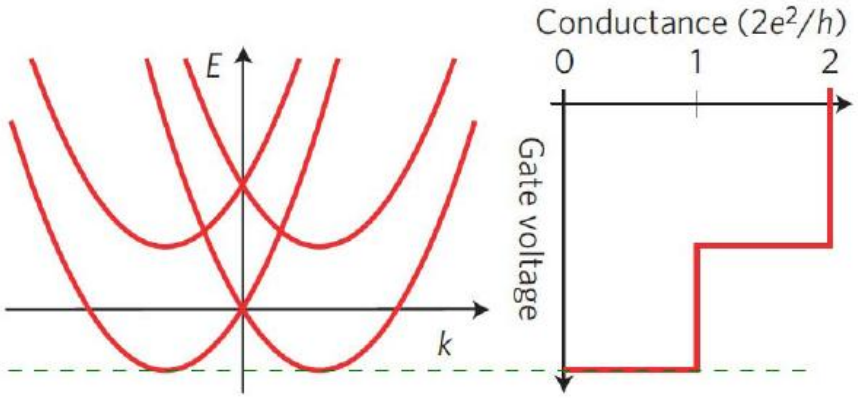
QPC spin injection through spin-orbit coupling

- SO coupling results in two spin-polarized 1D subbands shifted horizontally along the k_x wavevector.

$$E_{\pm} = \frac{\hbar^2}{2m^*}(k \pm \frac{m^*\alpha}{\hbar^2})^2 - \frac{m^*\alpha^2}{2\hbar^2}$$



- Only one spin-species is present in the either right- ($+k_x$) or the left- ($-k_x$) moving direction if the Fermi energy lies below the crossing point, thereby allowing for spin injection/detection.

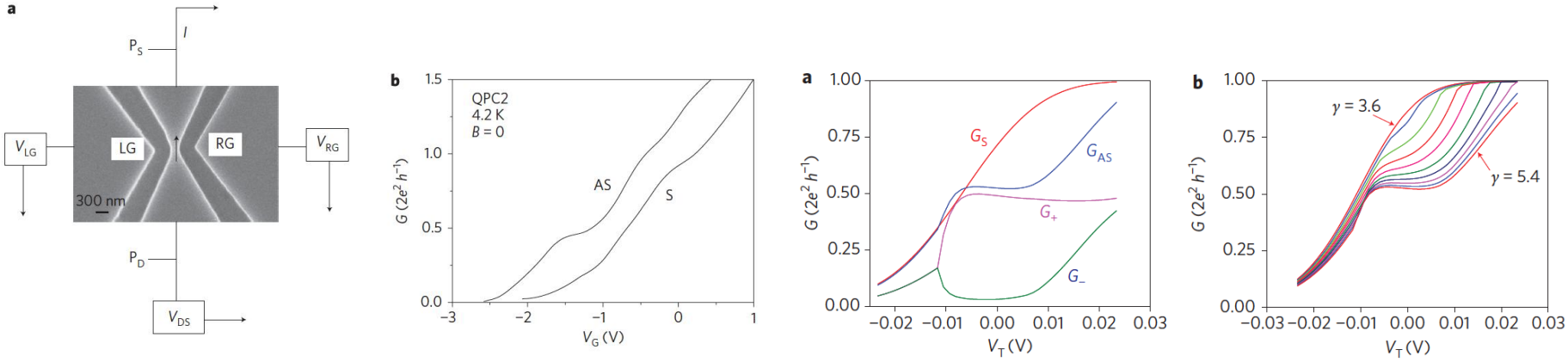


- Unable to tell from QPC conductance.

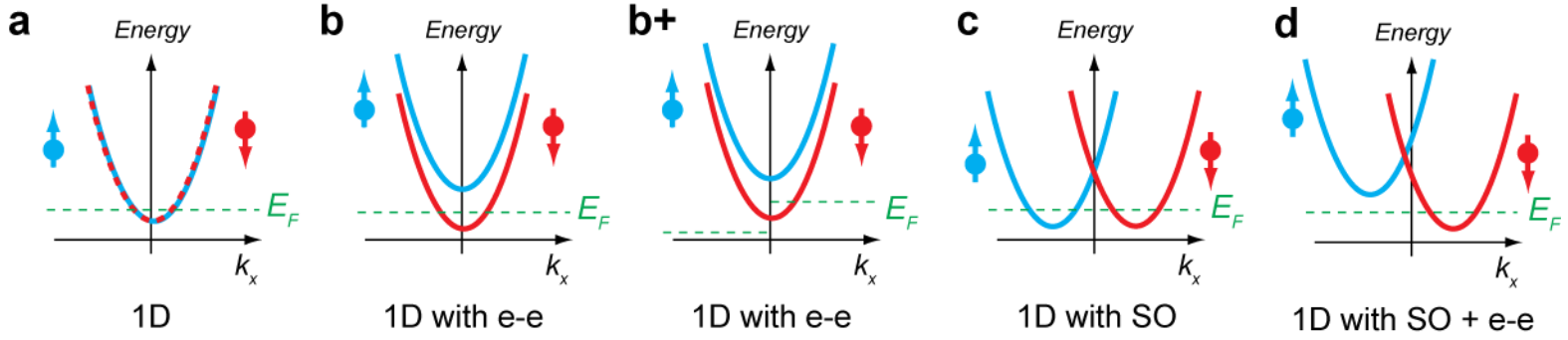
Quantum point contacts & Spin injection

QPC spin injection through spin-orbit coupling & e-e interaction

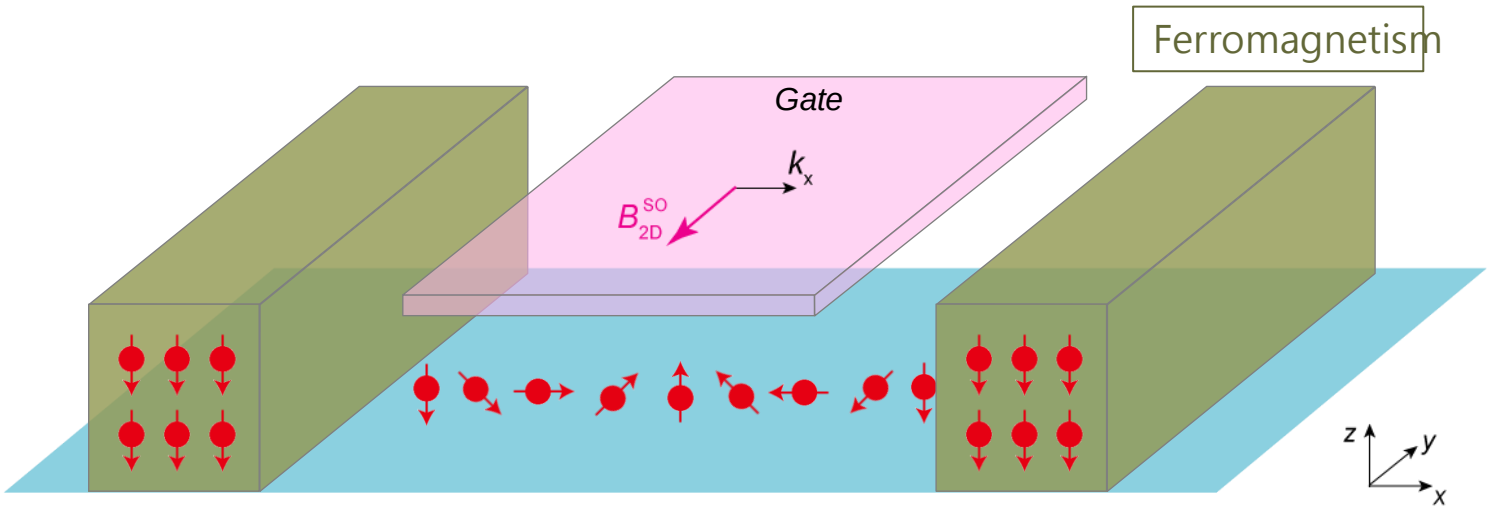
- Debray et al. in Nature Nanotech. 4, 759 (2009) proposed that the e-e interaction coexist with SOI when QPCs are operated near threshold.



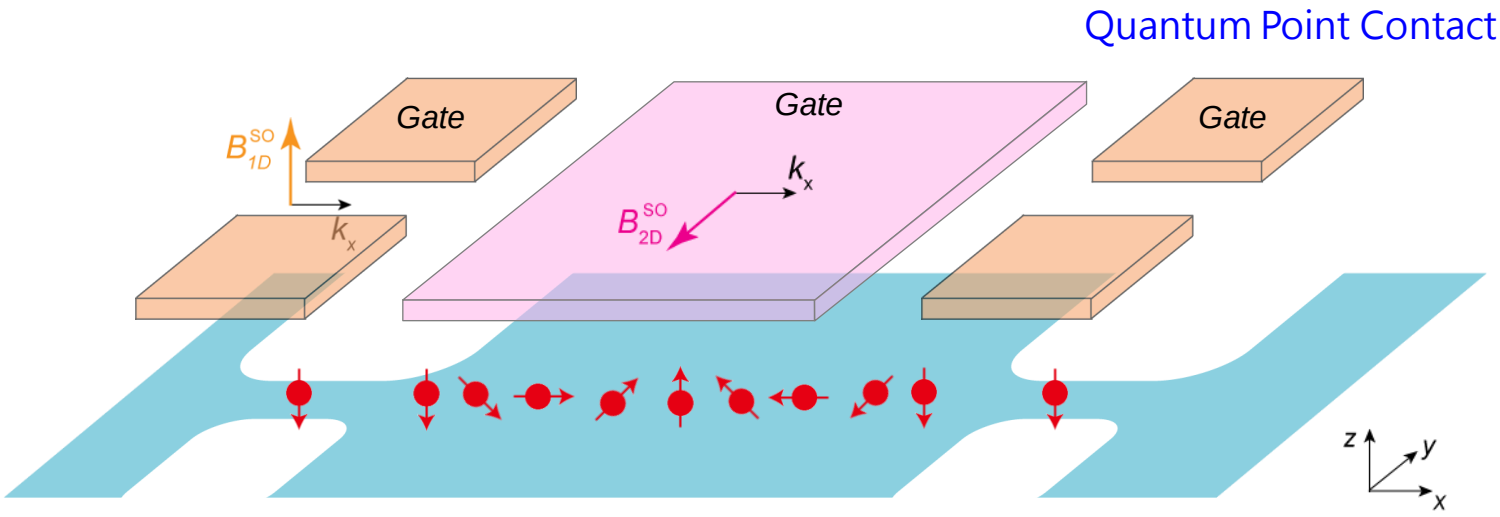
Debray et al., Nat Nanotech (2009).

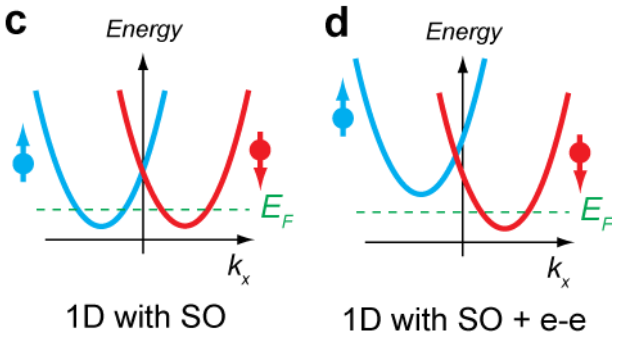


Datta-Das Spin FET



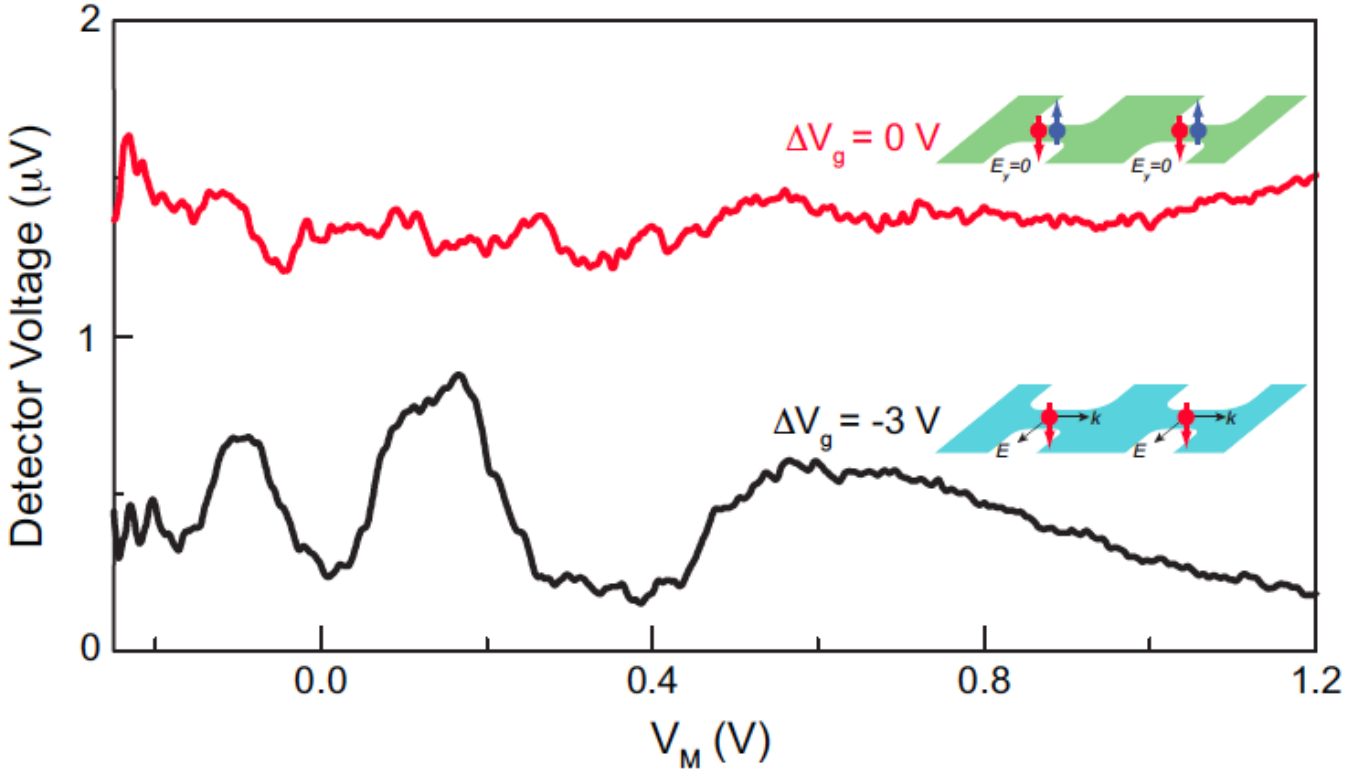
All-electric all-semiconductor Spin FET



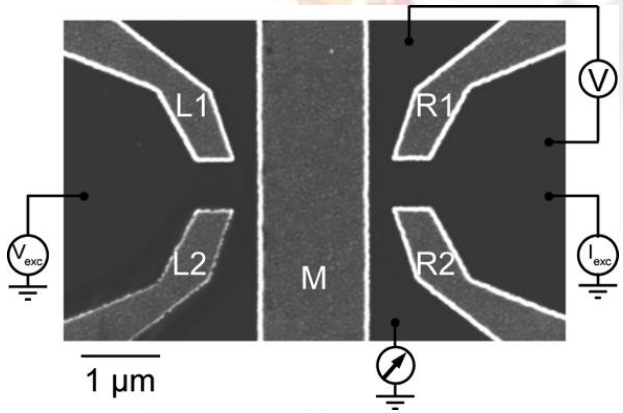


- Asymmetrically biasing the QPCs to generate a lateral SO coupling
- QPC spin injector/detector with 100% efficiency is created

Spin FET



- Oscillatory on/off modulation up to **500%**
- Resistance modulation is **100,000 times greater** than that observed by Koo et al. (Science 2009)



QPC as a spin injection/detection with 100% efficiency; all-electric

Obstacles resolved…

- low spin-injection efficiency
  due to resistance mismatch

Two aligned QPCs collect ballistic transport electrons only

- limited spin lifetime
  picoseconds, due to D'yakonov-Perel' scatterings

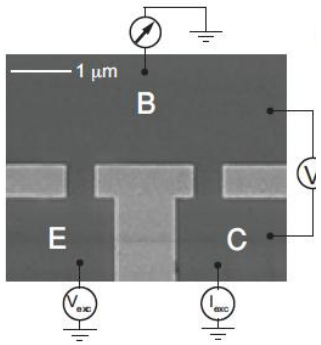
Two aligned QPCs set up a quasi-1D path

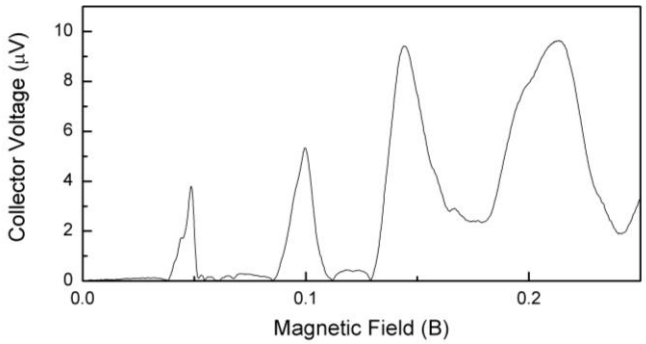
- phase spread of accumulated spins
  due to various precession angles resulted from different paths from source to drain

Spatial spin separation

- The magnetic field, B_f, required to focus electrons at a distance L is

$$B_{\mathrm{f}}^{(p)} = \left(\frac{2\hbar k_{\mathrm{F}}}{eL}\right) p$$

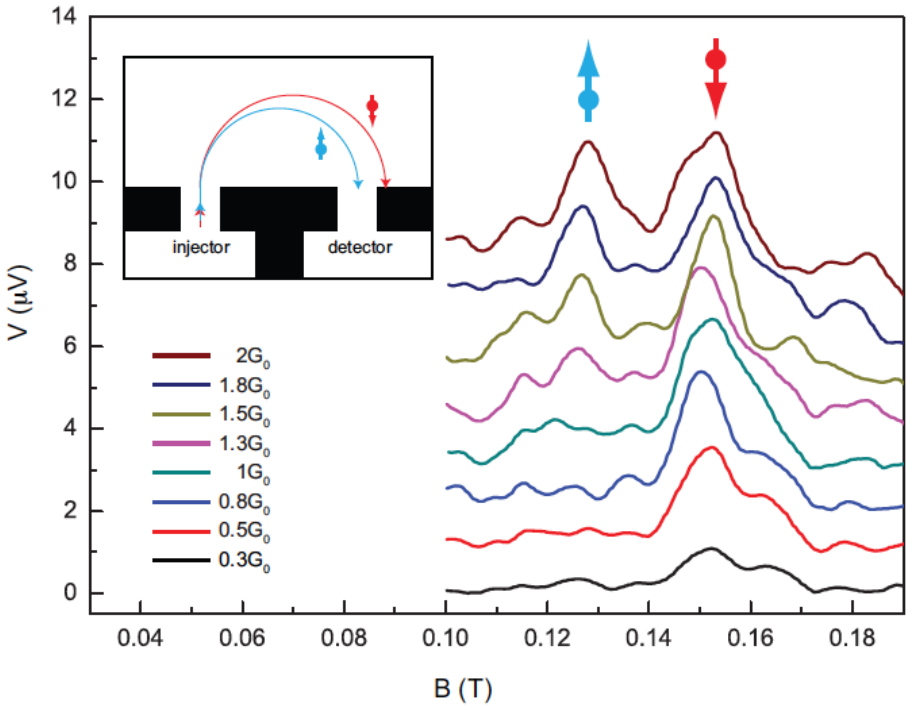




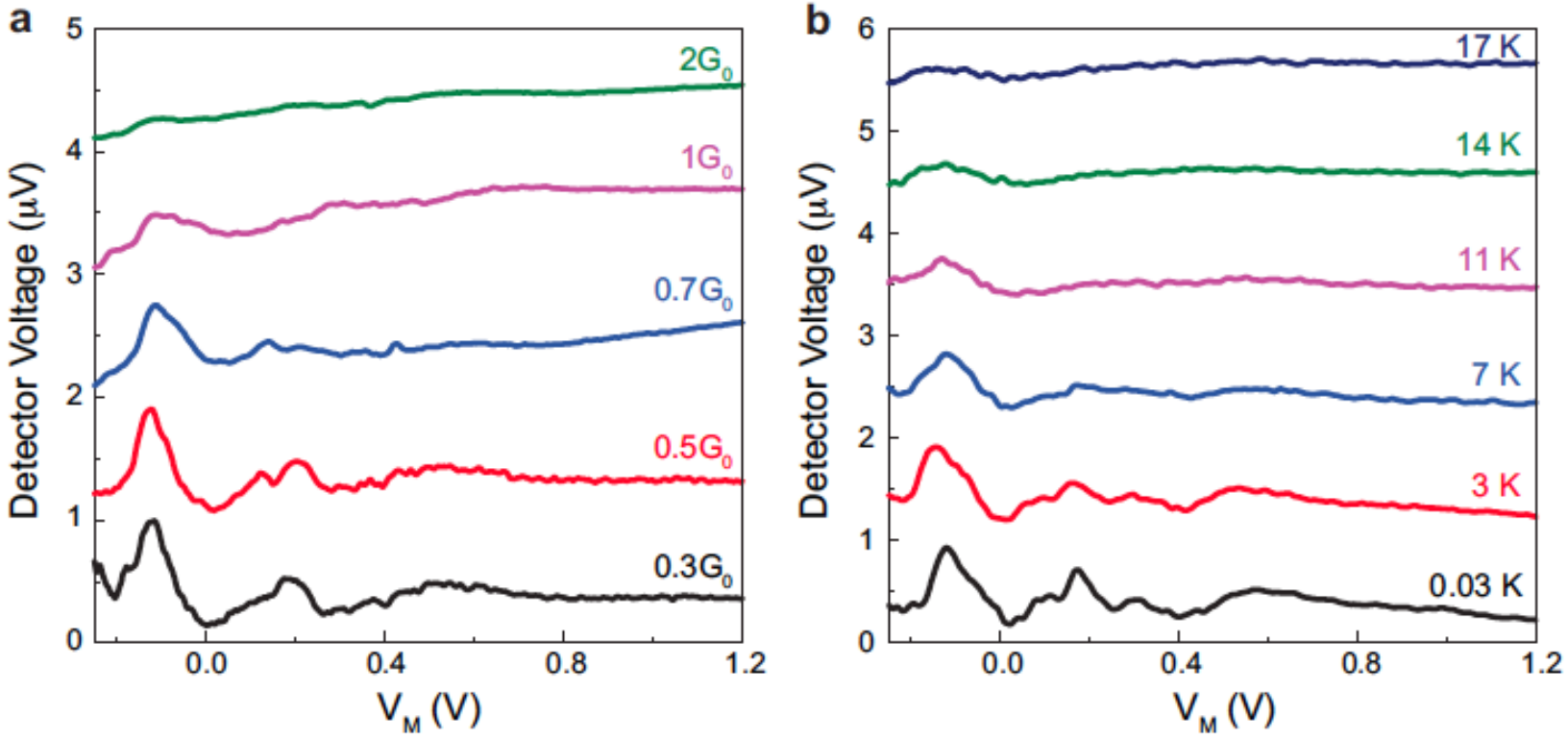
- In the presence of SO, up- and down-spin electrons have different momenta, leading to different cyclotron orbits and focusing peaks.

$$k_{F,\downarrow} = k_0 + m^*\alpha/\hbar^2$$

$$k_{F,\uparrow} = k_0 - m^*\alpha/\hbar^2$$

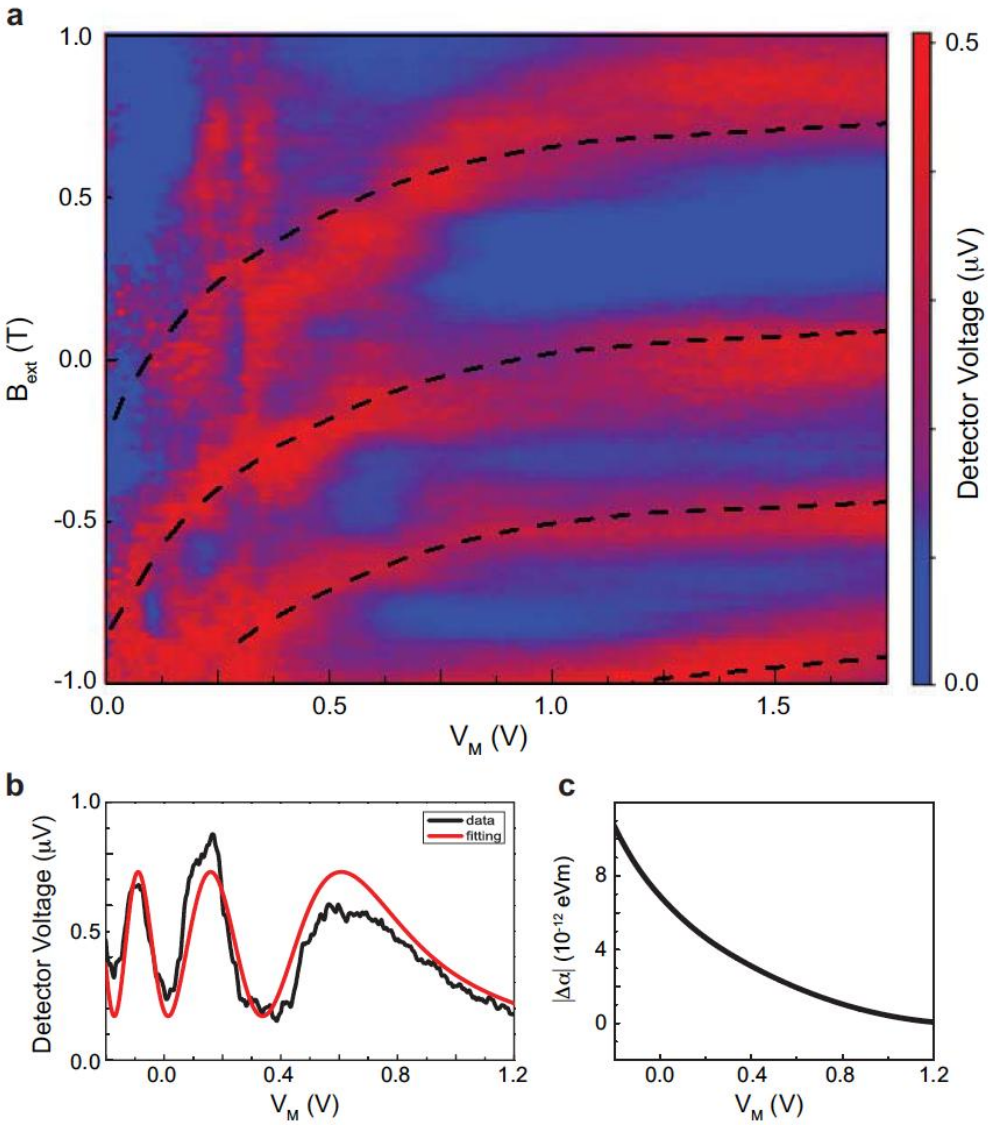


Influence of QPC conductance & temperature



- Oscillation amplitude decreases with increases QPC conductance, consistent with the model of 1D + SO coupling
- Our prototype spin FET survives up to ~ 17 K only
- Working temperature could be improved by introducing a larger spin splitting using wet-etched QPC or InAs nanowires

Simultaneous magnetic and electrical control of spin precession



$$\omega_{\mathrm{L}} = (2\alpha k_x - g\mu_{\mathrm{B}} B_{\mathrm{ext}})/\hbar$$

$$\Delta\theta = \omega_{\mathrm{L}} t = 2m^*\alpha L/\hbar^2 - g\mu_{\mathrm{B}} B_{\mathrm{ext}} m^* L/k_x\hbar^2$$

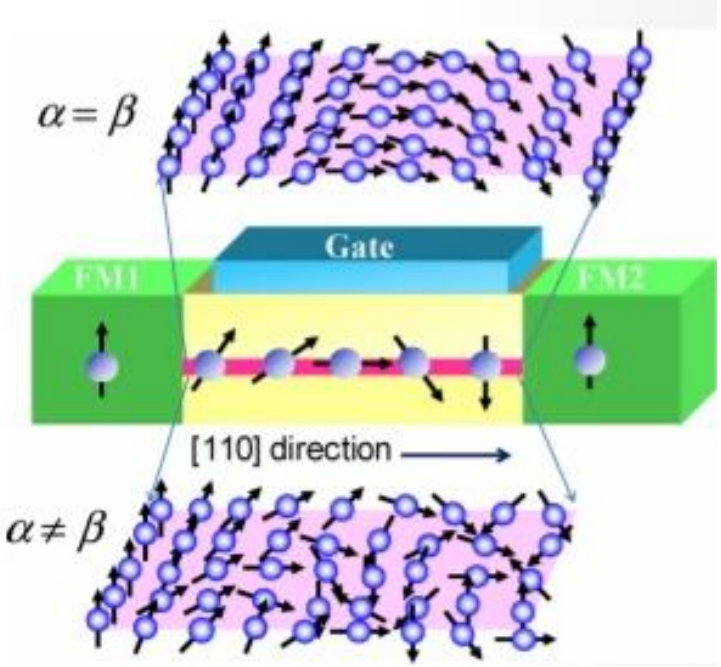
- Our spin FET allows us to combine magnetic and electrical controls of spin precession.
- Theoretical simulations performed
- Good quantitative agreement obtained between experiment and theory

Challenges remain…

- on/off ratio still not large enough
- working temperature still low

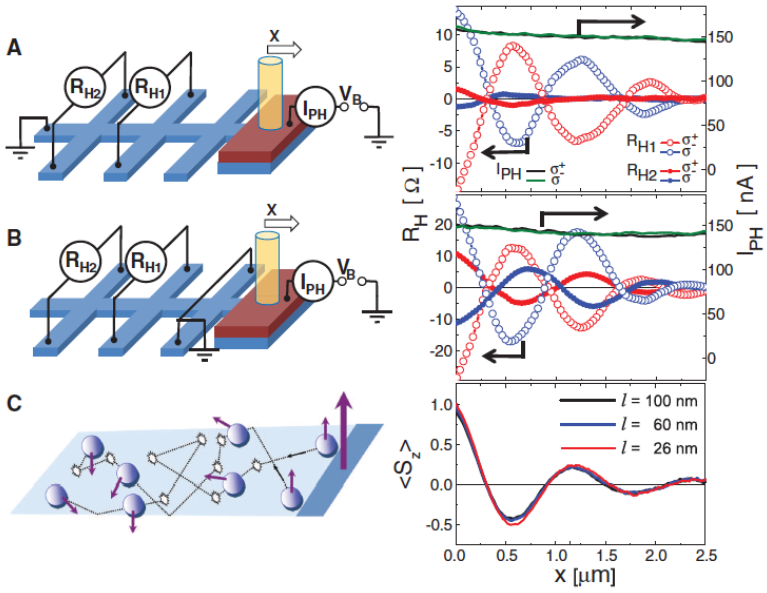
QPC spin filter used in other spin transistors

Non-ballistic spinFET



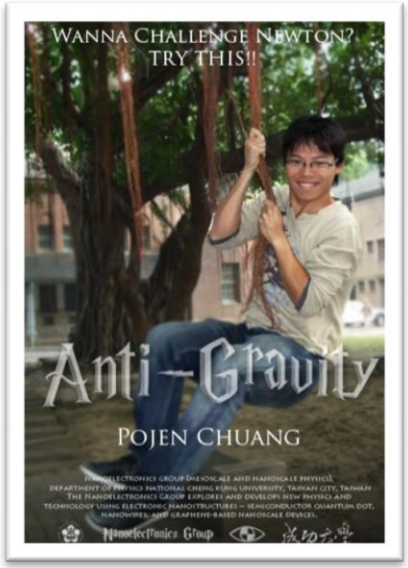
Schliemann et al., Phys. Rev. Lett. 90, 146801 (2003).

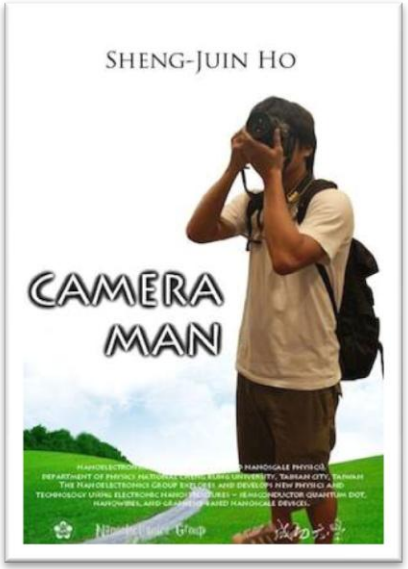
Spin Hall Effect Transistor

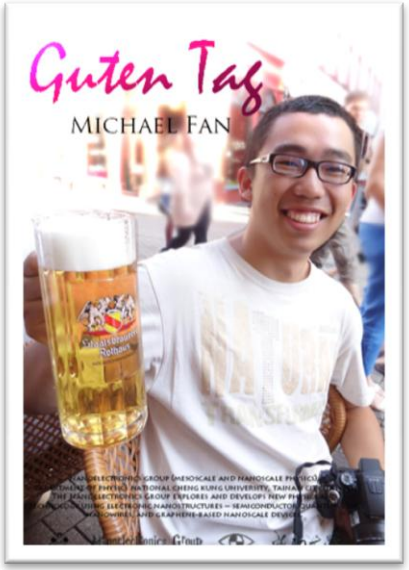


Wunderlich et al., Science 330, 1801 (2010).

Acknowledgement







Material growth & Device fabrication

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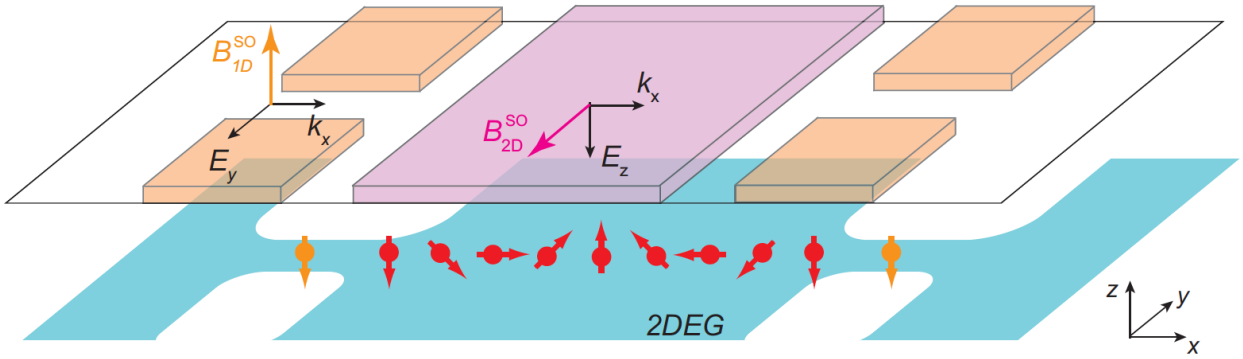
I. Farrer, H. E. Beere, D. A. Ritchie. T.-M. Chen

Summary

- The world's first working spin FET realized by utilizing QPCs.

- The world's first all-electric all-semiconductor spin transistor



THANK YOU!!