Science
AAAS

Spin Hall Effect Transistor
Jörg Wunderlich, *et al.*
Science **330**, 1801 (2010);
DOI: 10.1126/science.1195816

The Spin Hall Effect Transistor

QO Group Meeting Jan 12^{th} 2011, by Nathan Cheng

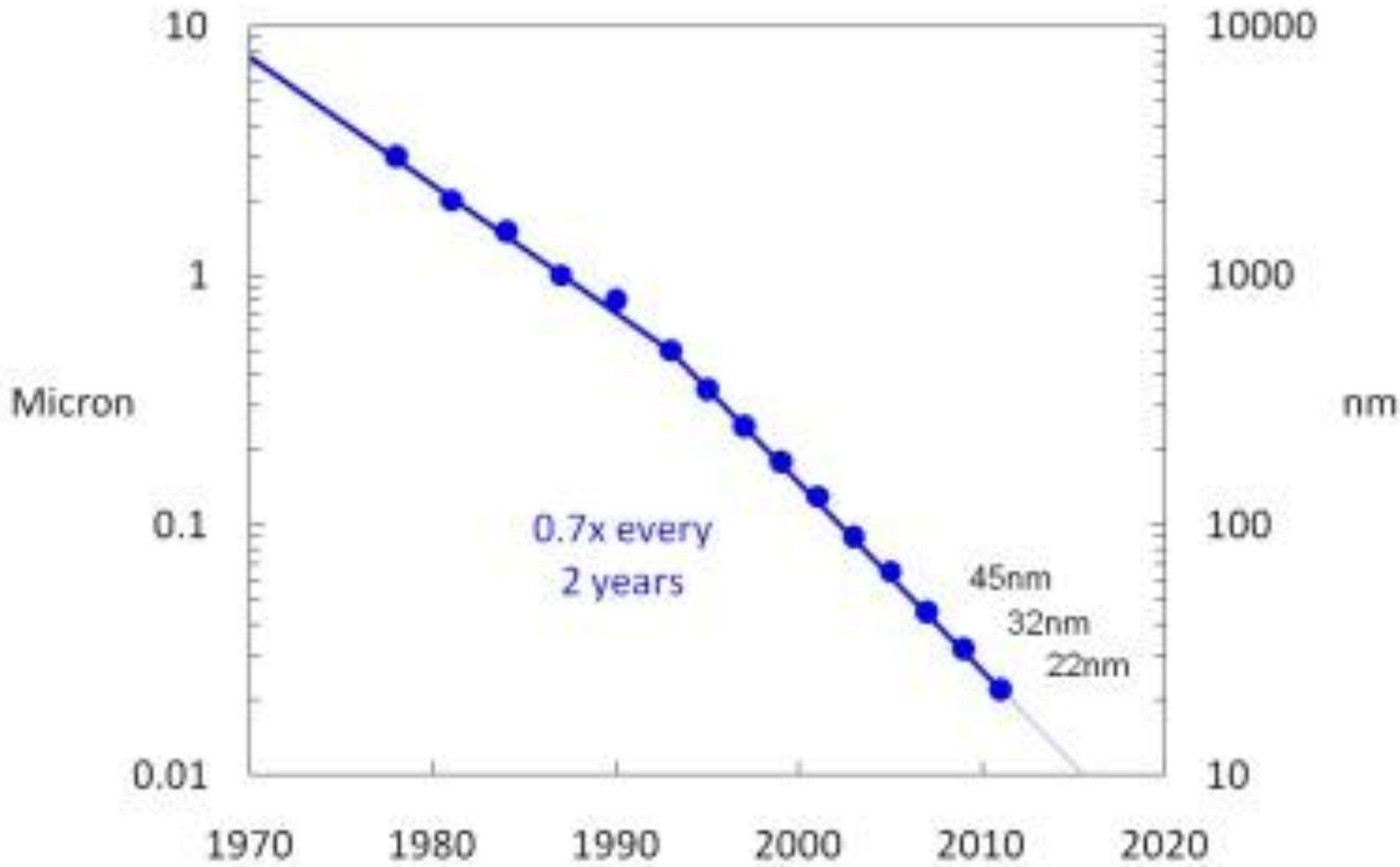
Outline of this talk….

- 1. End of the Silicon Road Map / Why Research Spintronics
- 2. Spin Transistor Basics: Datta-Das Paradigm
- 3. The Paper: Experimental Realization at High-T
- 4. Future Implications?

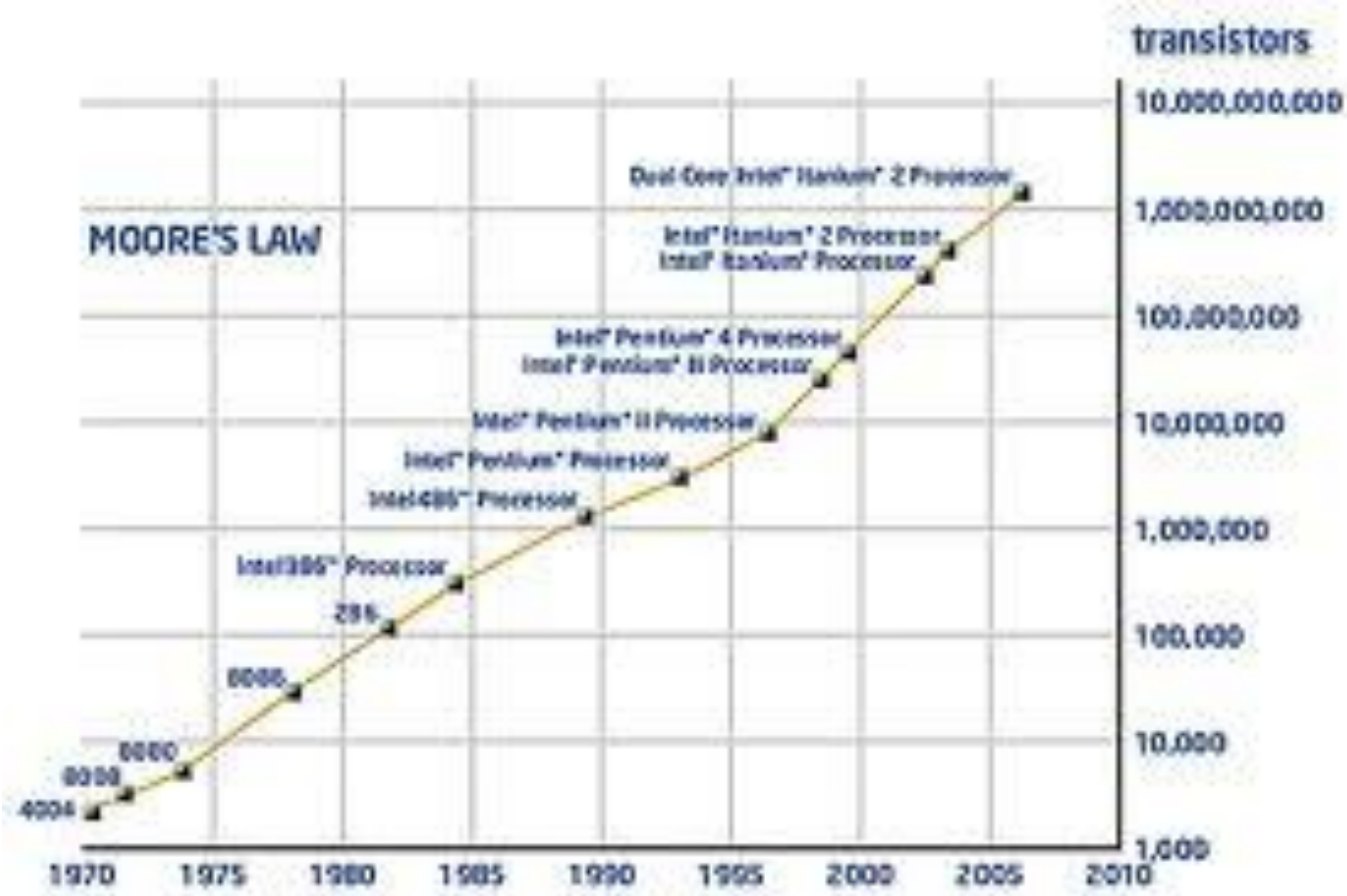
End of the road for silicon…

- First transistor built in 1947 by Shockley, Brattain, Bardeen.
- Metal-Oxide Semiconductor Field Effect Transistor (MOSFET) are ubiquitous!
- Transistors keep getting smaller
  - Moore's Law: Transistors per chip doubles every 2 years
  - ("Moore" like a self fulfilling prophecy!)

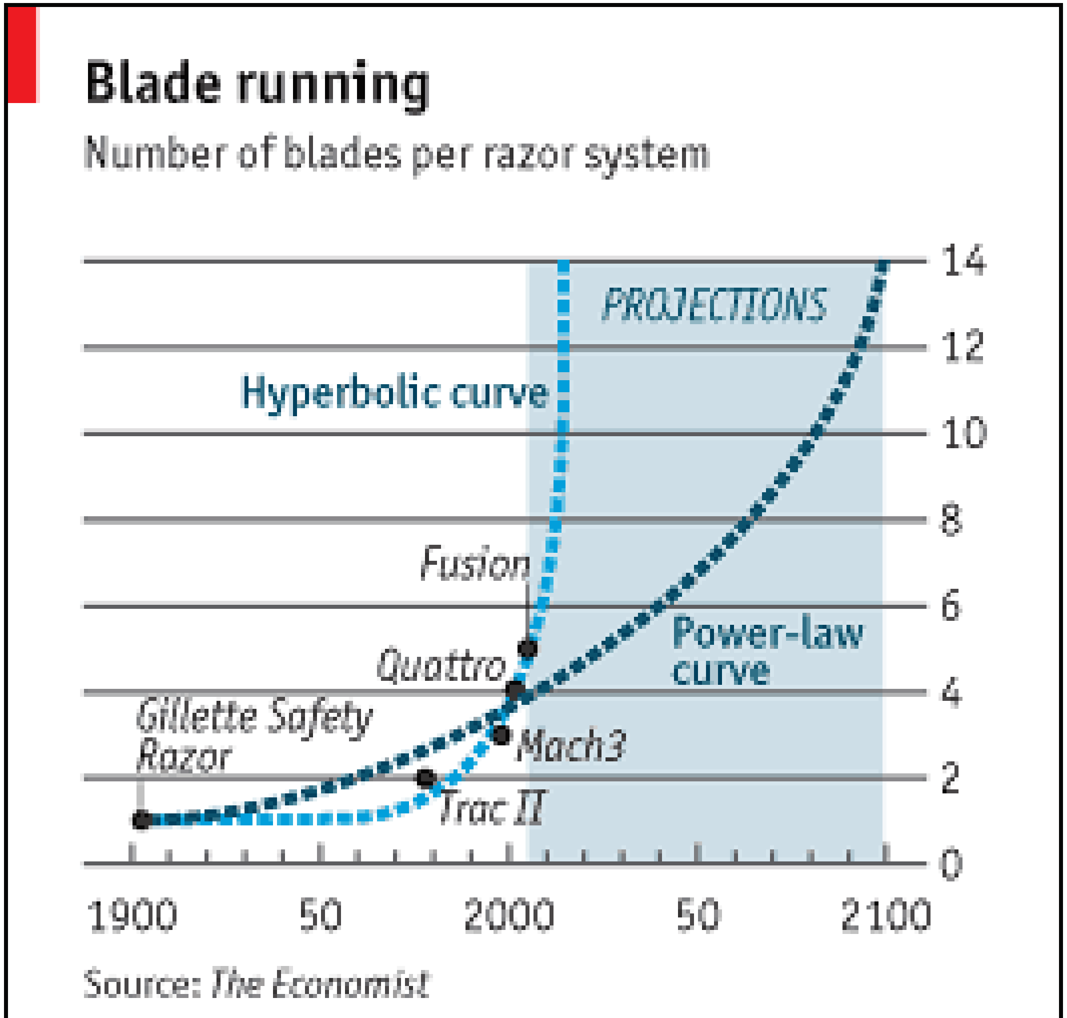
Intel: Transistor Size



Transistors per chip

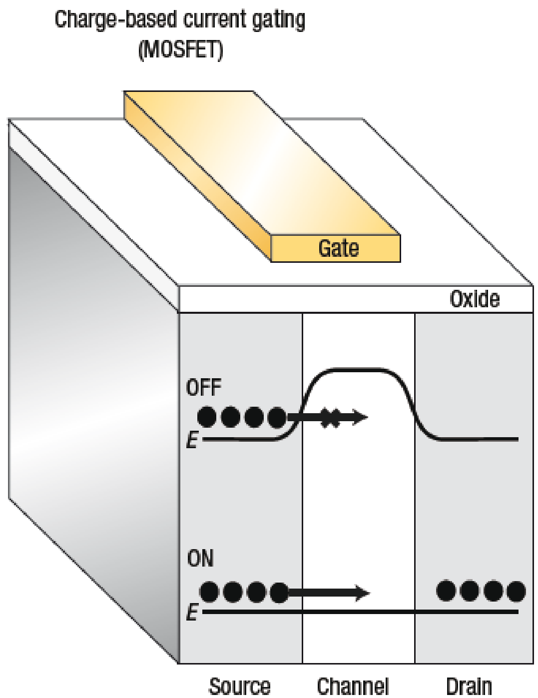


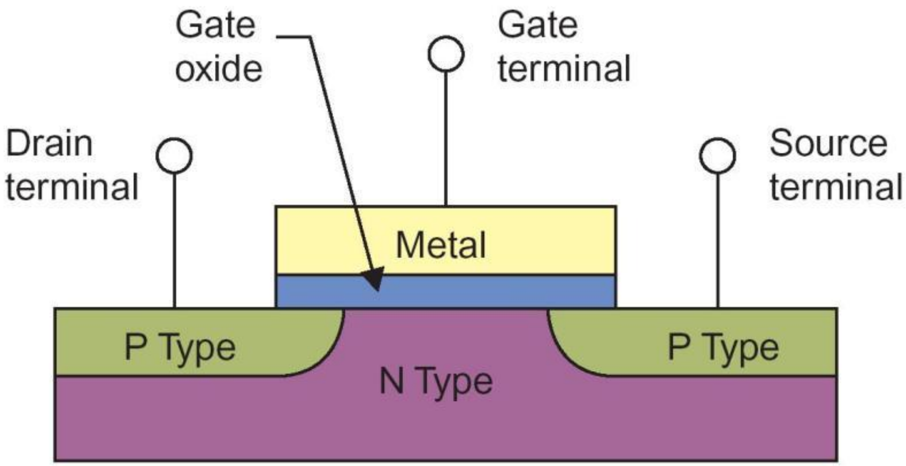
Moore's Law of Razor Blades



Main Challenges to MOSFET Miniaturization

- Gate-Channel Tunneling
- Heat dissipation
- Better lithography techniques





What's Next? Spintronics?

- Current microelectronics only utilize the charge of electrons

- Novel functionality by exploiting electron spin
  - MRAM
  - GMR / TMR magnetic read heads in hard drives
  - Transistors, logic, gates
  - Quantum computing???? (NOT covered today)

Motivation for Spintronics

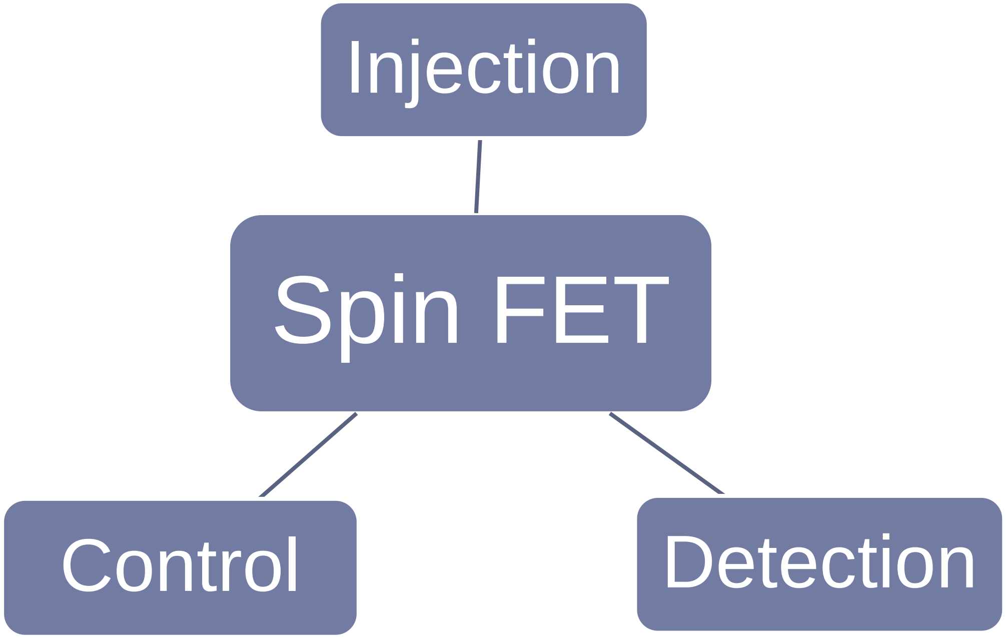
- **Potential** Benefits Spintronics

- Uses less energy
  - Charge-based devices fundamental limits ~ $E \geq kT \ln(2)$
- More easily scaled
- Faster (debateable)

- Integrate with existing semiconductor technology
  - Extend Moore's Law for a bit longer

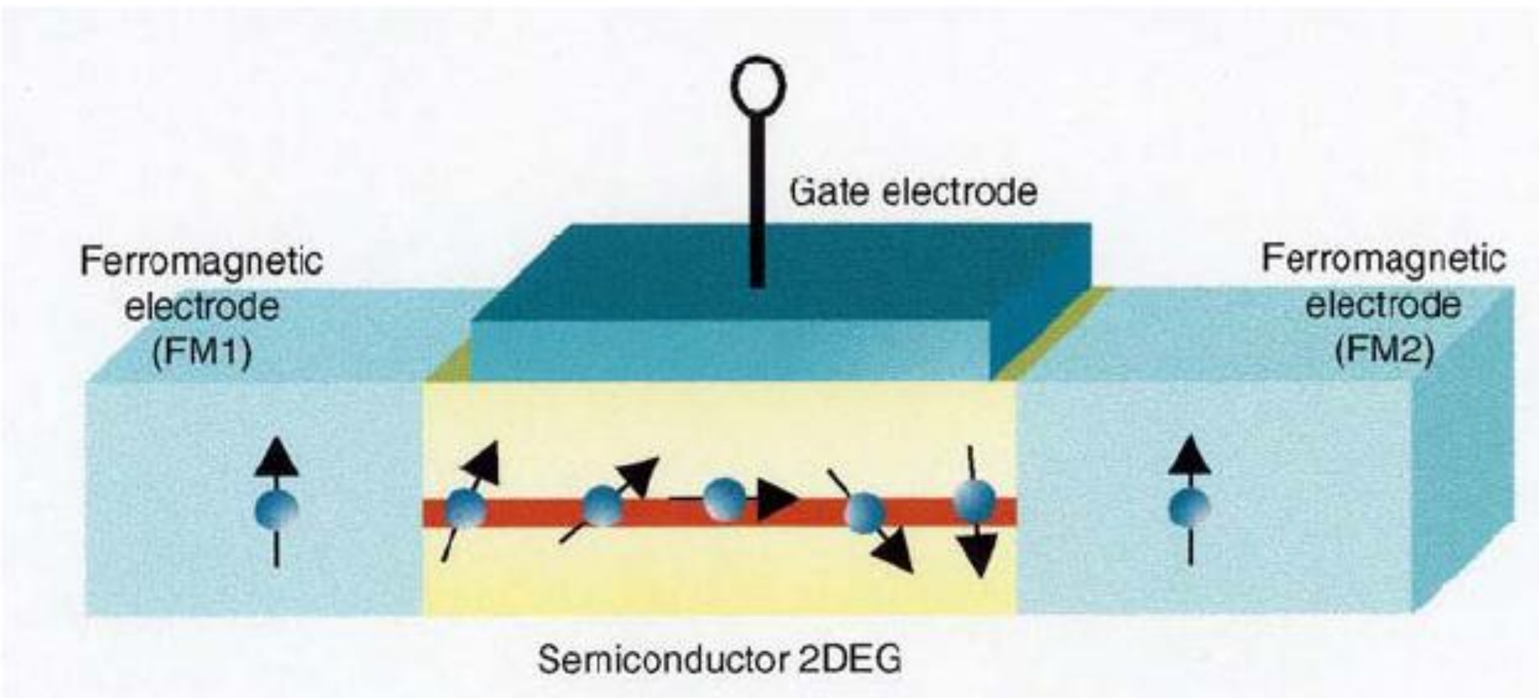
Datta-Das Spin FET: Brief Overview

- (1990) Datta-Das paper spurs new research direction
- Unrealized… OR IS IT?



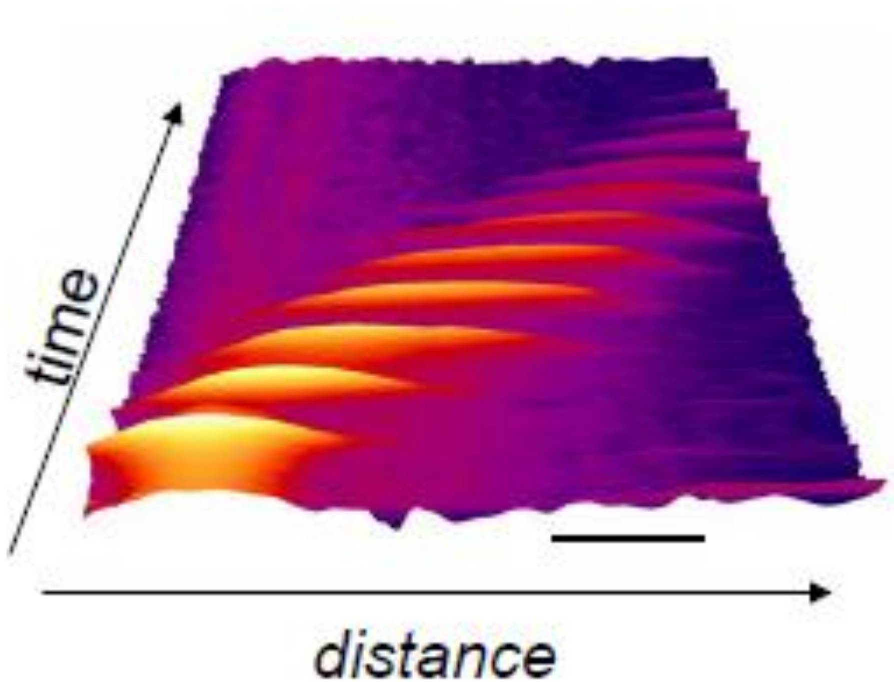
Ideal Datta-Das Spin FET

- Injection: pass current through FM electrode
- Control: Spin precession through Rashba field
- Detection: Spin polarizer



What about spin coherence?

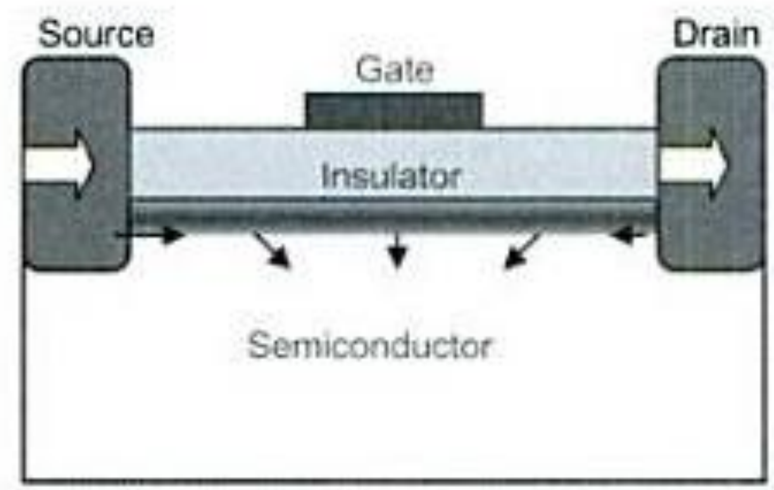
- Can be pretty good in semiconductors
  - $\tau \sim 100$ ns
  - Coherence length ~ 100 um >> typical transistor channels



Kikkawa and Awschalom, Nature 397, 139 (1999)

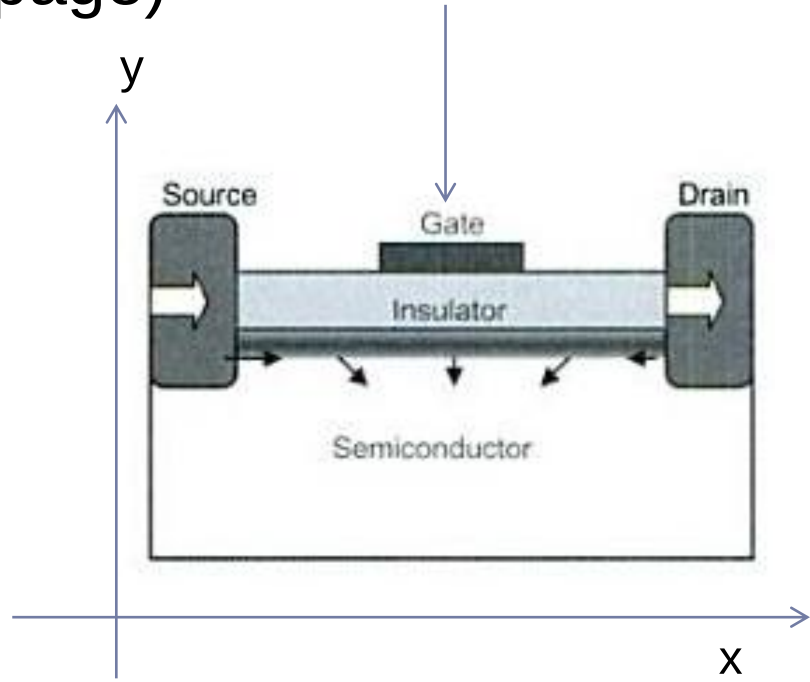
Spin Manipulation, SO coupling

- How to change the spin electrically?
- Take advantage of spin-orbit coupling interaction
  - Simplified case: 1D channel, fully polarized spin current



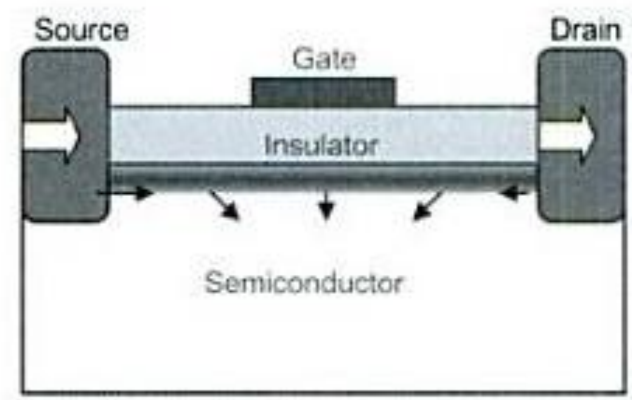
Rashba Field SO

- Electric field (from asymmetry and applied field) is seen as B-field in electron rest frame
- $B_{eff} = \frac{2m^*}{eh^2} \alpha \, E_y \, v_x$ (out of page)
- α = Rashba coefficient
- m = effective mass
- v = drift velocity



Rashba Field

- $B_{eff} = \frac{2m^*}{eh^2} \alpha \, E_y \, v_x$ (out of page)
- B depends on the transverse E-field
  - B is perpendicular to spin
- $< S_x >$ precess about B (Larmor)
- Current ON if Sx aligned to Drain
- Current OFF is Sx is anti-aligned

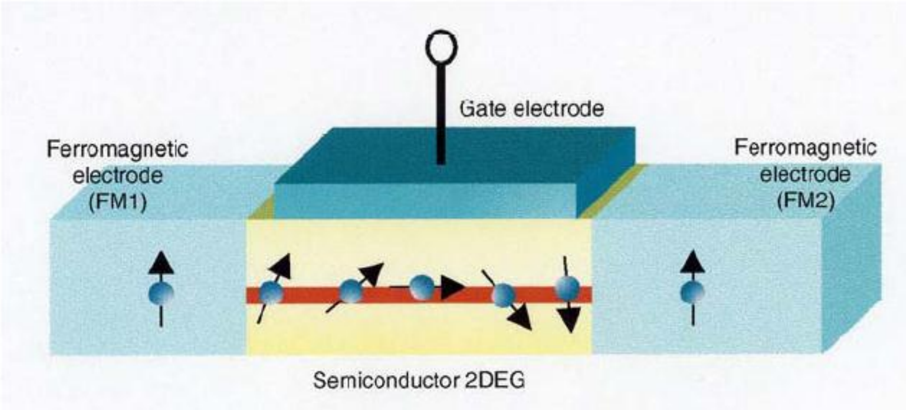


SO coupling in semiconductors

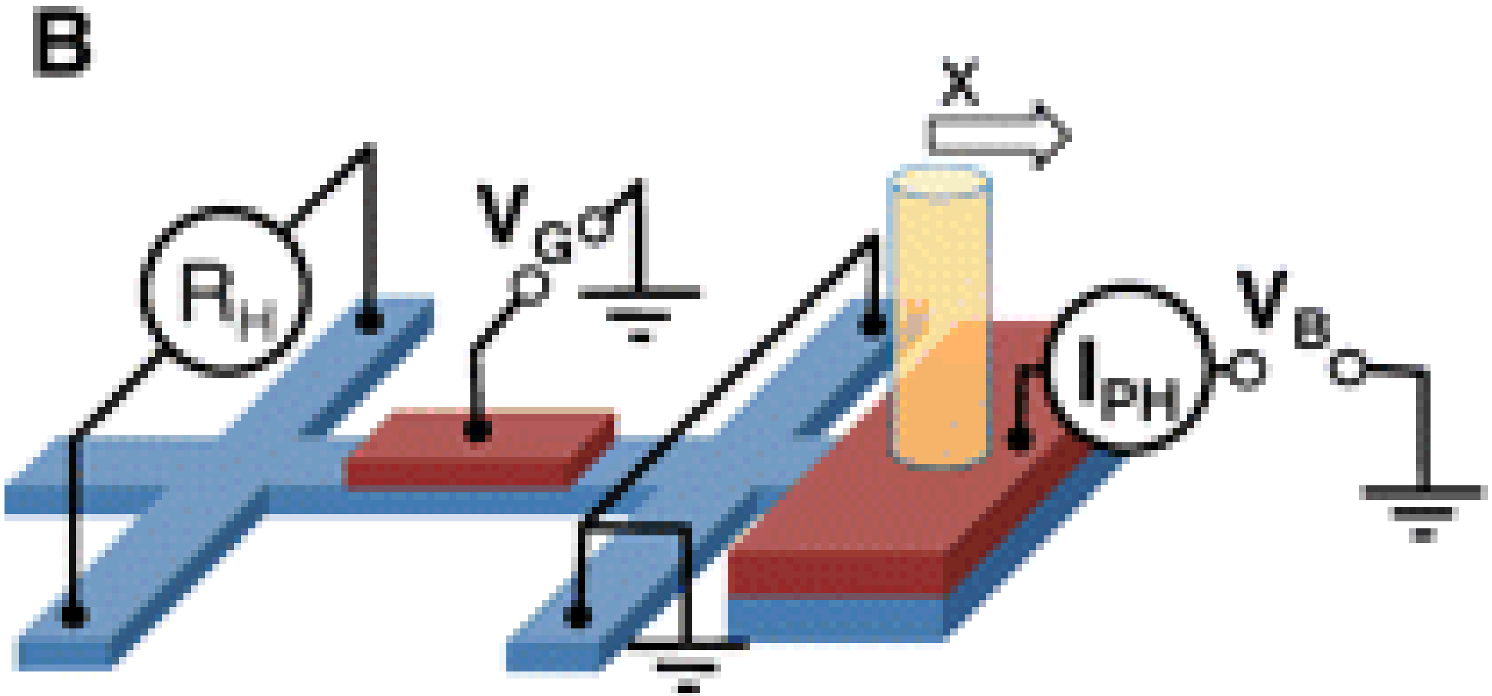
- Actually can be much more complicated
  - Involves Dirac Equation and information on band structure
- Band and crystal structure play an important roles
  - Other effects include Dresselhaus spin-orbit coupling
- Basic qualitative picture remains the same: Electric field can induce precession

Limitations of Datta-Das

- Ferromagnetic contacts introduce stray magnetic fields
- Poor spin injection efficiency going from ferromagnetic contact to semiconductor
  - Lots of research on magnetic semiconductors
  - Difficult to find the right materials at high-T

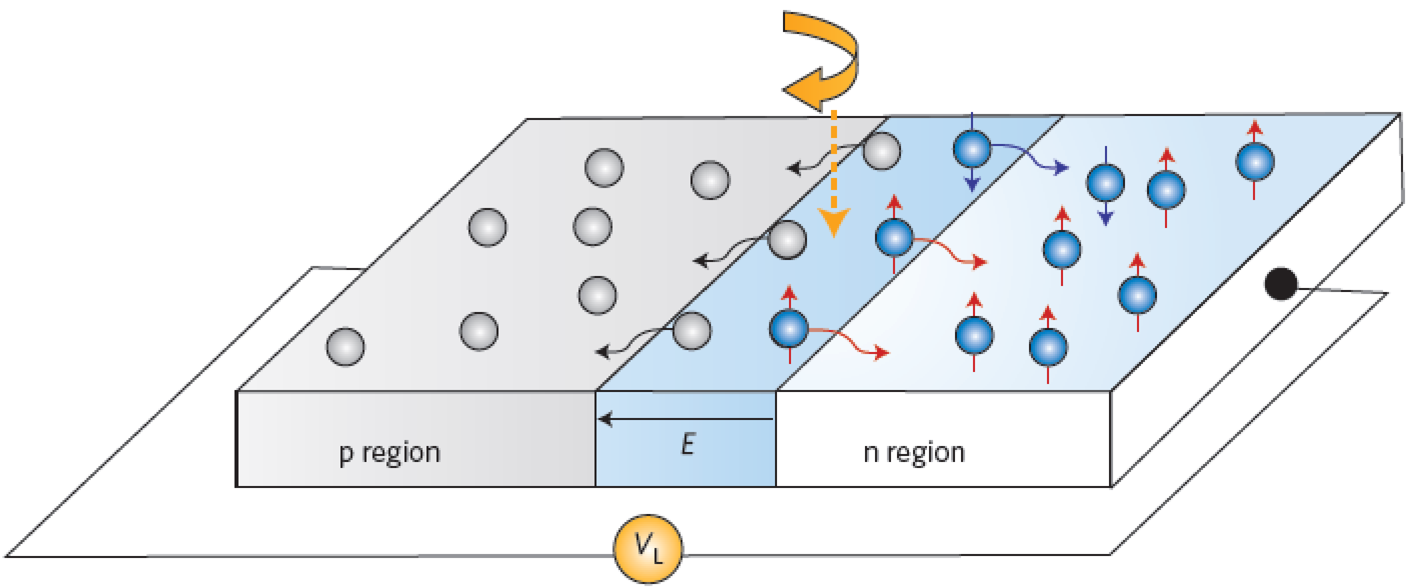


FINALLY: The Spin Hall Effect Transistor

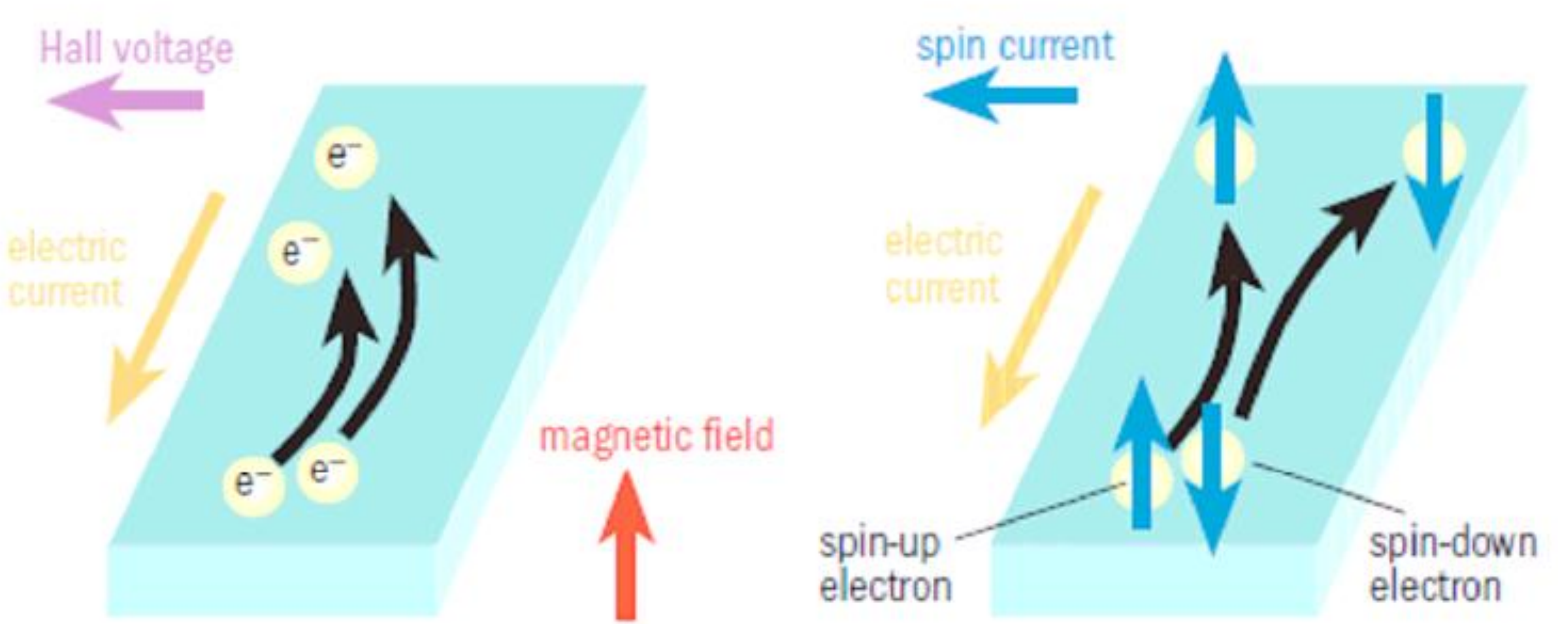


Optical Spin Injection

- Use circularly polarized light!
  - PN junction operated like a photodiode (i.e solar) cell
  - Electron-hole pairs are formed
- E-H spin determined by optical selection rules
  - e- Polarization depends on circularity and sense of light



Spin Hall Effect (SHE)



Intuitively like Magnus effect (i.e Bend it like Beckham)

Detection: Spin Hall Effect (SHE)

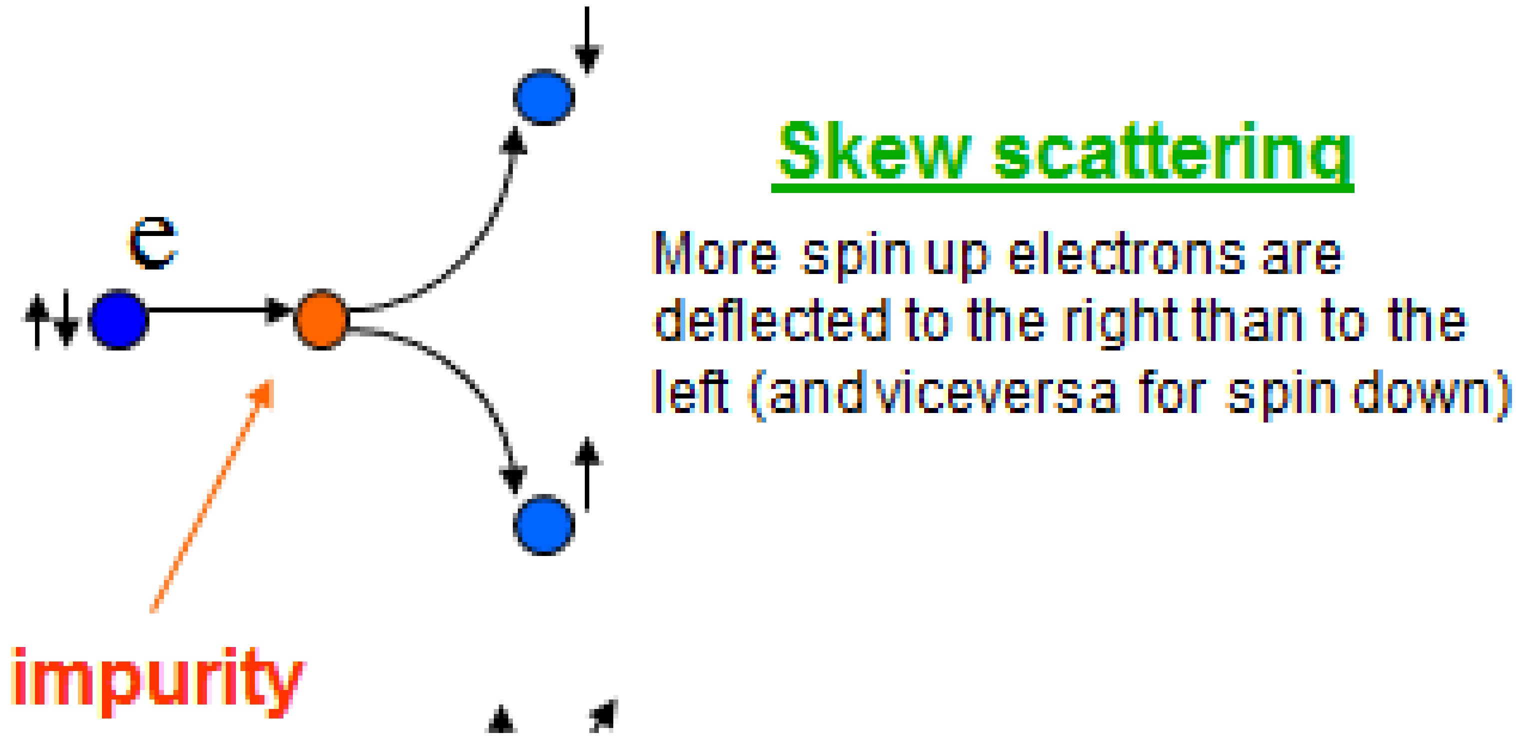
- Predicted by M.I. Dyakonov and V.I. Perel in 1971
  - Always caused by some kind of spin-orbit coupling
  - *Not detected until 2004!*

- *Extrinsic SHE*
  - *Occurs from electrons scattering with impurities*
  - *"Skew-scattering"*
  - *Primary contributor for our device*

- *Intrinsic SHE*
  - *Spin dependent band structure*

Skew Scattering in 2D

- Skew scattering is spin dependent due to spin-orbit coupling interactions between electron and impurity



Electron sees B ~ v x E (relativity)

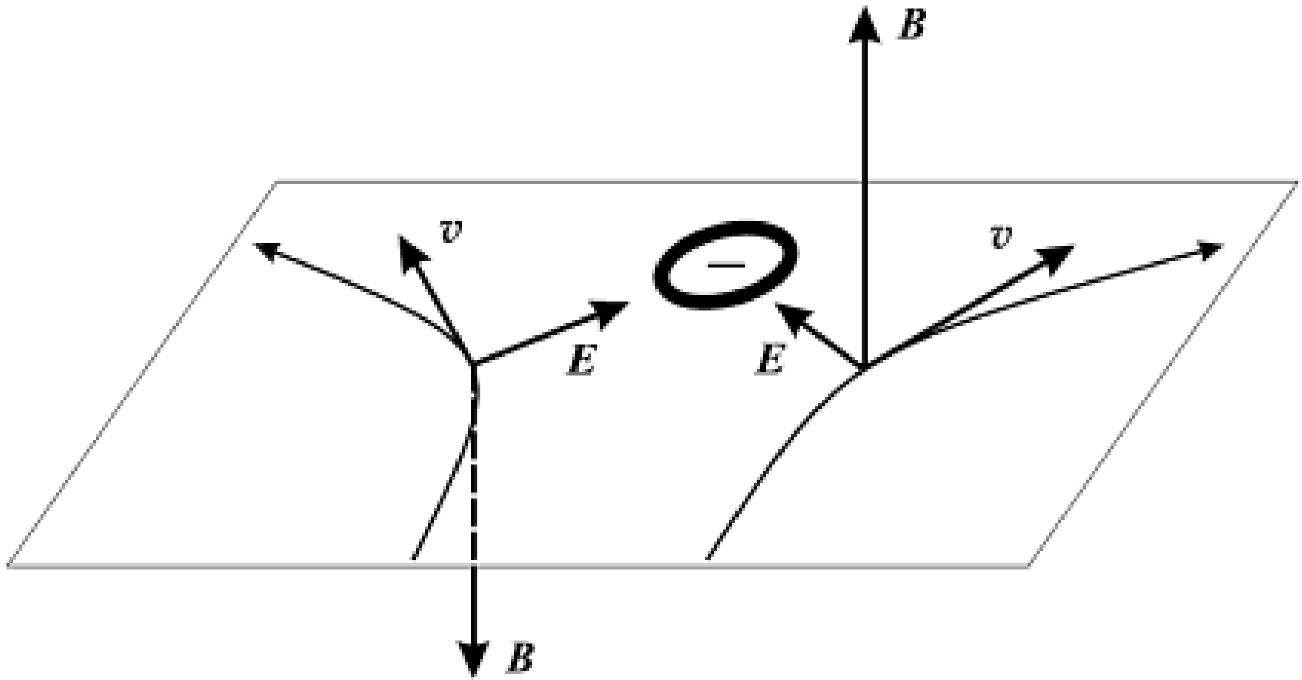
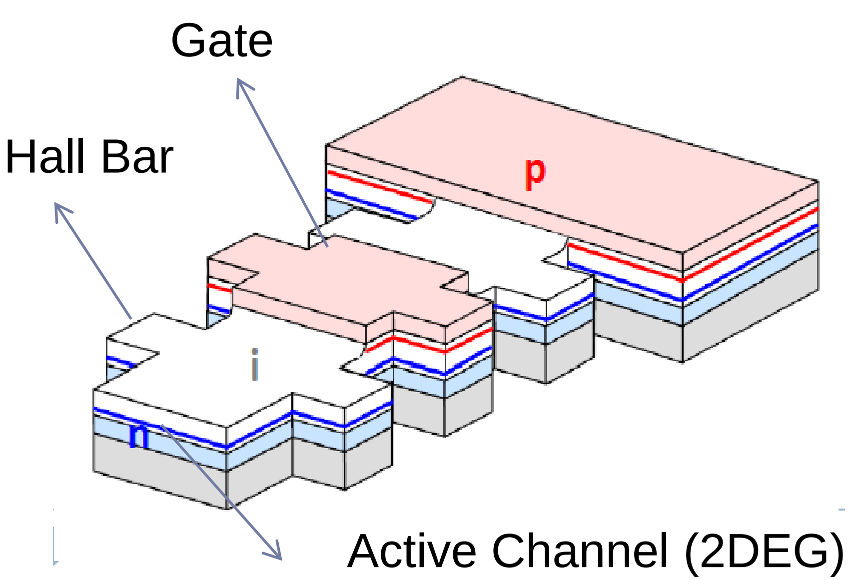
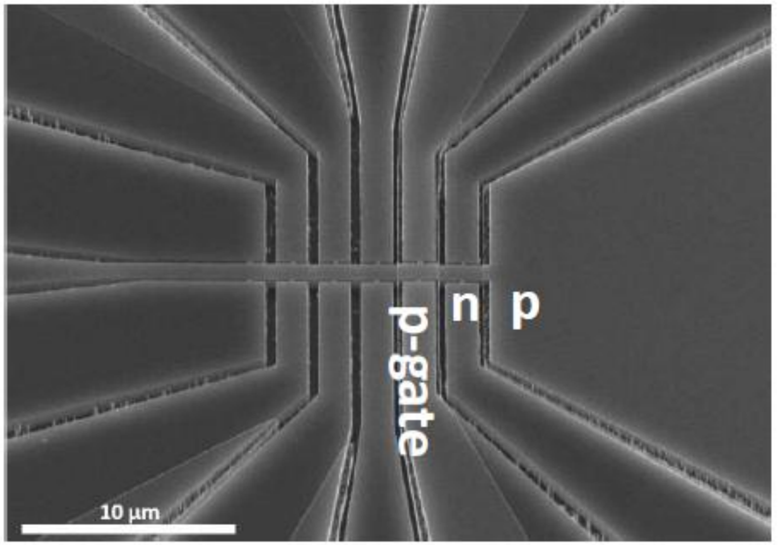


Fig. 8.3. Schematics of electron scattering by a negative charge. The electron spin sees a magnetic field $\boldsymbol{B} \sim \boldsymbol{v} \times \boldsymbol{E}$ perpendicular to the plane of the electron trajectory. Note that the magnetic field has opposite directions for electrons scattered to the left and to the right

Wunderlich et al: Basic idea

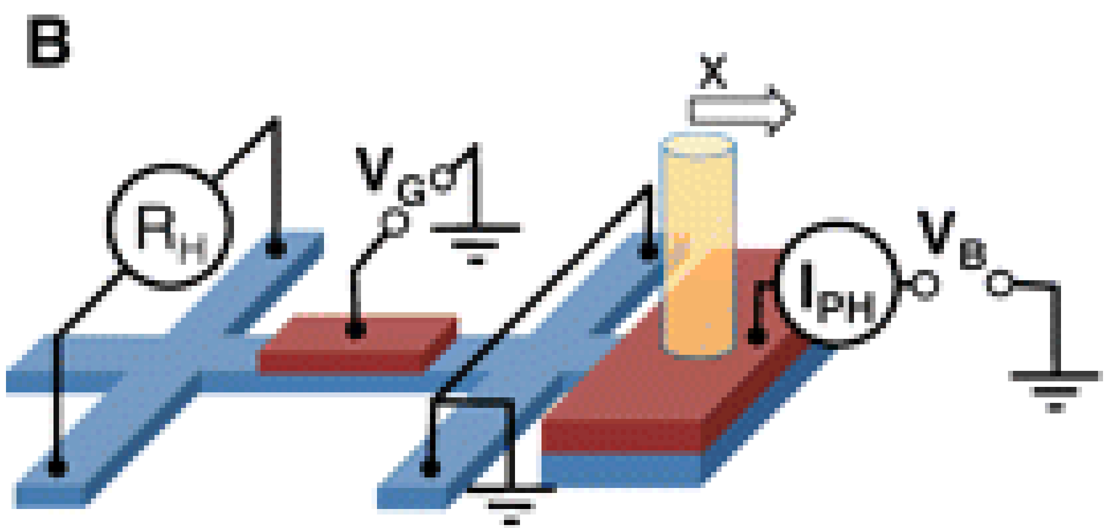
- Similar to the Datta-Das Spin FET
- Complicated doped Al/Ga/As (PIN) heterojunction
  - Tune all those SO coupling interactions
- Optical spin current injection
- Rashba Field Spin precession (same as Datta-Das)





SHE Transistor cont…

- Ti-Saph laser 870 nm (circularly polarized)
- V_b = (reverse) bias voltage = -10V
- I_{PH} = photocurrent
- Twist! *Electric* current is drained off before the gate.
  - Diffusive spin transport

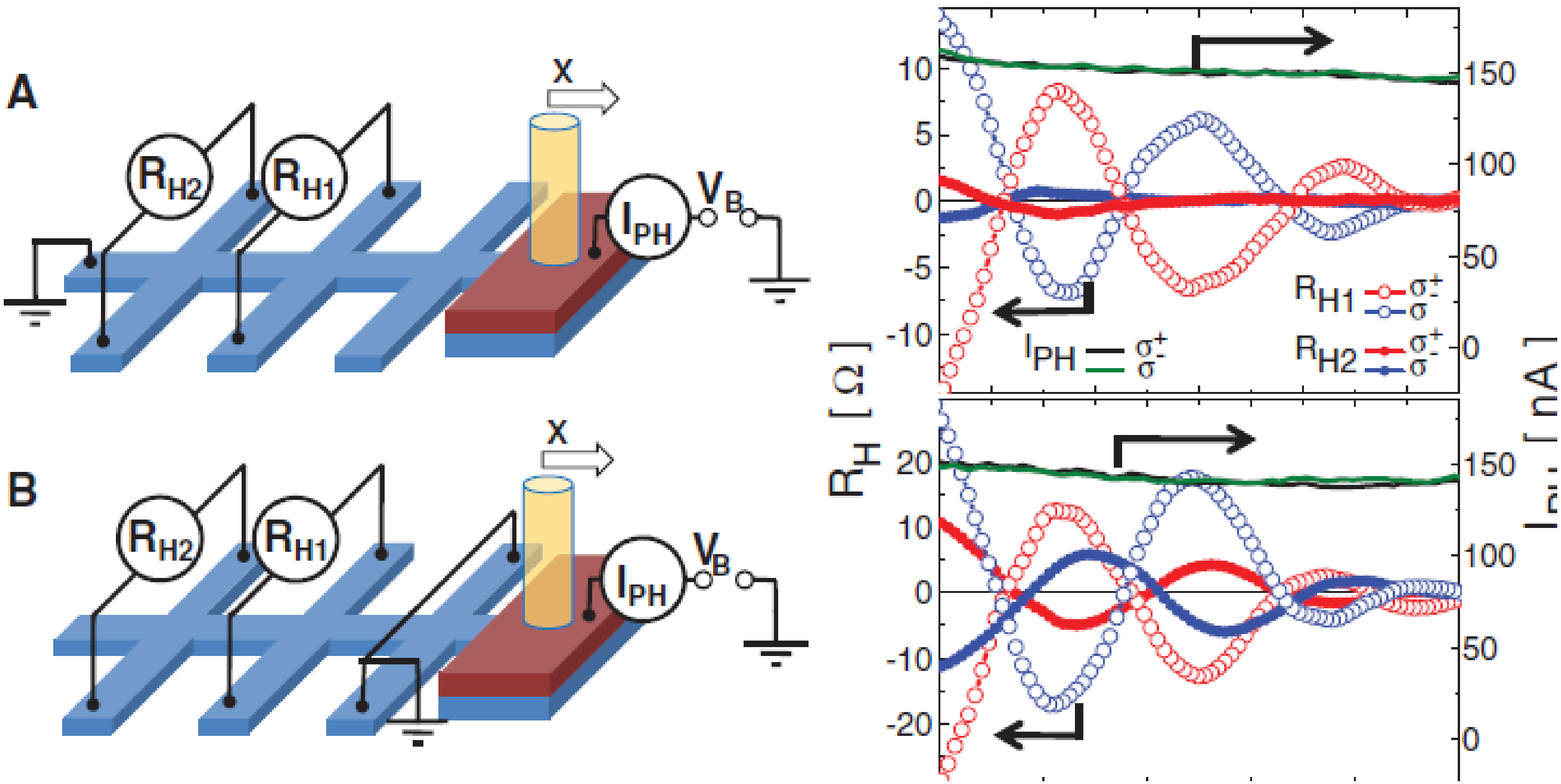


Recap

- 1. Optical spin injection: Spin polarized photocurrent
- 2. Spin current polarization modulated via Rashba field (effective B-field + Larmor precession)
- 3. Spin Hall Effect causes accumulation of different spins to opposite (transverse sides).
- 4. Because we start with a spin polarized current, we get a charge imbalance => electrically detectable

Recap continued….

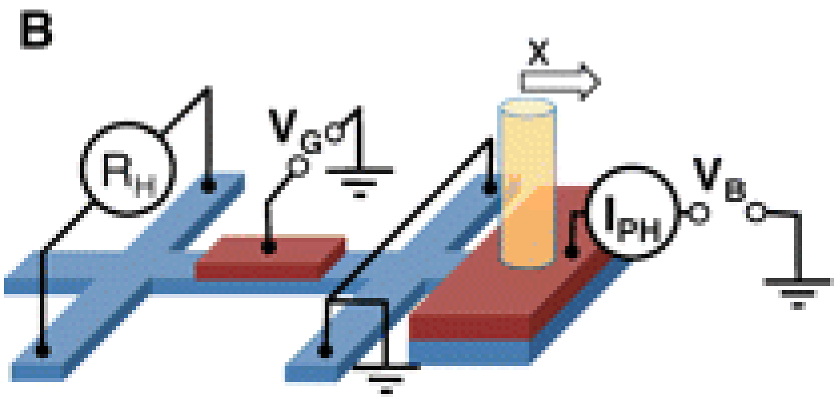
- Typical setups

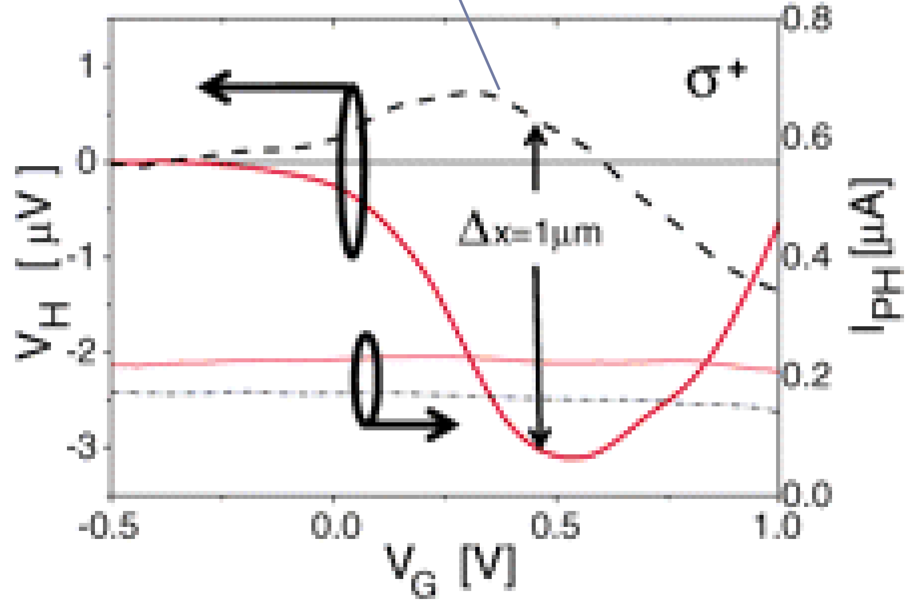


Gate action

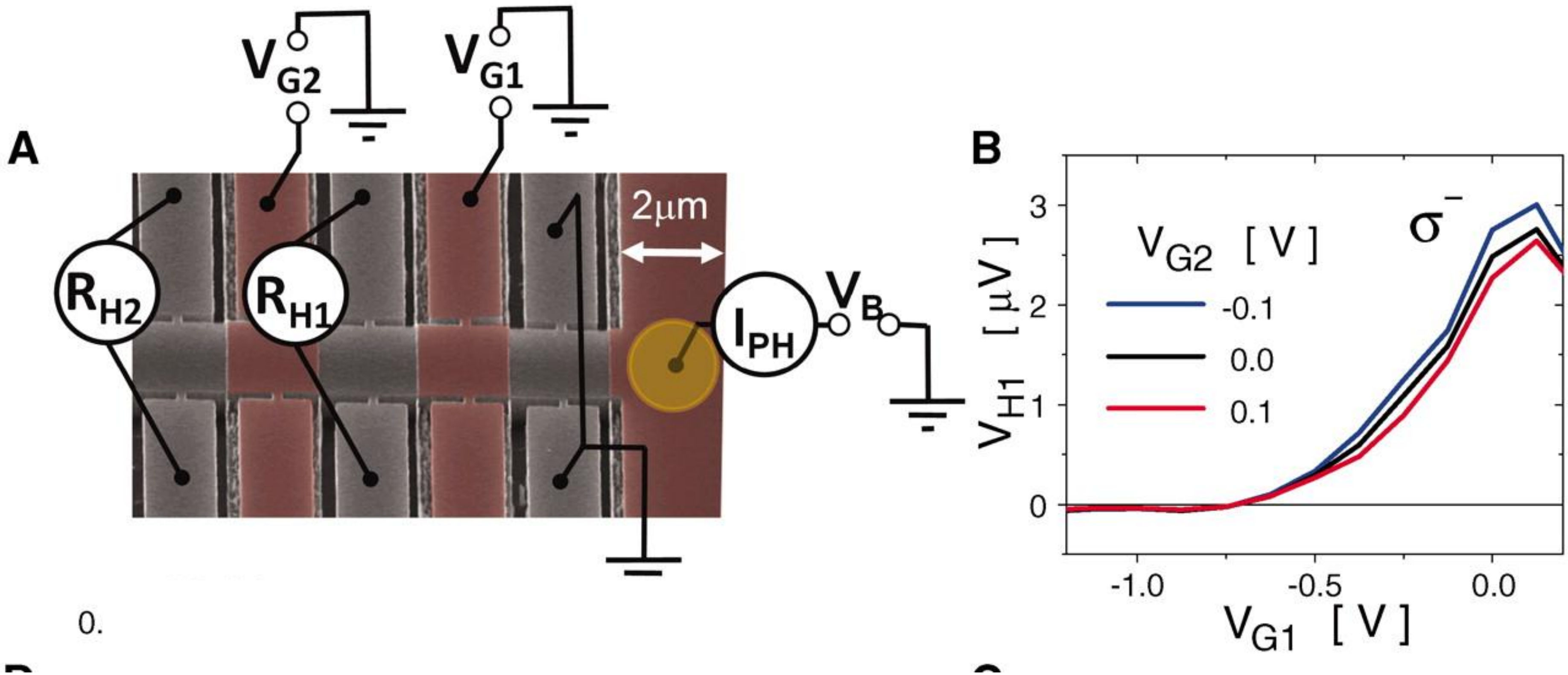
- $R_H = \frac{V_H}{I_{PH}}$
- Vg = gate voltage

Further from detection point

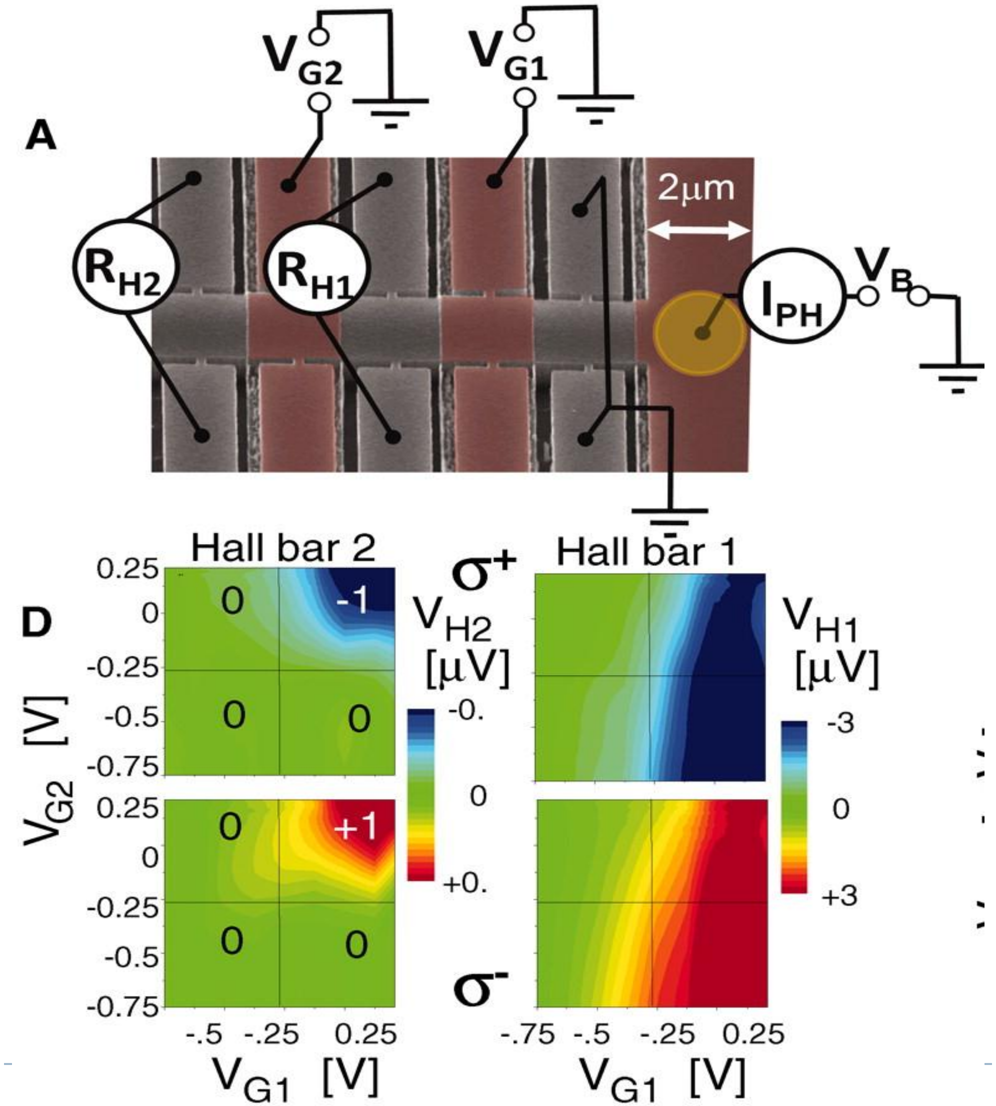




Double Gate Action!



Realization of an AND gate



Impact

- Finally, a (very close) realization Datta-Das spin transistor (proposed 20 years ago)
  - Demonstrable logic function using spin current
- Works at high-temperature
- All semiconductor, electrical detection
  - Possible integration with current technology
- Higher Spin Hall Voltages
  - Usually pretty small

The Future

- Optical injection is not very scalable at the moment
- Two-stage driving requires amplication
- Can use the semiconductor as a solid state polarimeter.
  - Measure blood sugar levels quickly?

THE END

- Thanks for your attention!