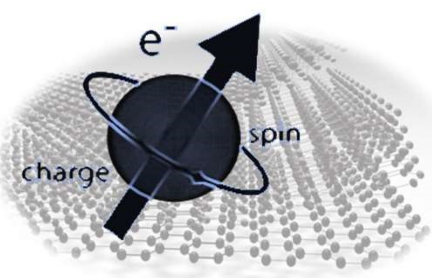
Spintronics with Topological Insulator Heterostructures

Saroj P. Dash

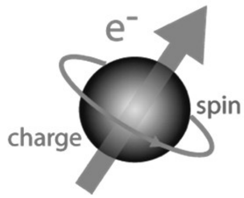


Chalmers University of Technology, Sweden

Research group

MC2 CHALMERS

Quantum Device Physics Laboratory
Microtechnology and Nanoscience Dept. (MC2)



Spin transport

- Silicon
- Graphene
- 2D semiconductors
- Topological insulators
- 2D materials heterostructures

Andre Bogdan Dmitrii Anamul

Venkata Johan Johannes Priyamvada

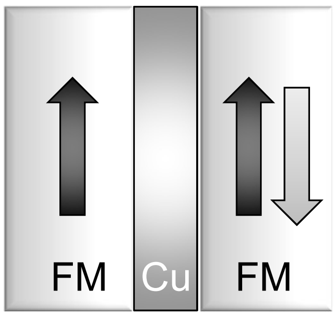
Lennart Madhushanker Ravi Parham

Christian, Wajid

NANOSCIENCE AND NANOTECHNOLOGY A CHALMERS AREA OF ADVANCE
MARIE CURIE ACTIONS
Vetenskapsrådet
VINNOVA
FLAG-ERA
GRAPHENE FLAGSHIP

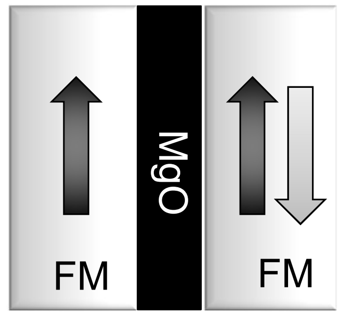
Spintronic effects

GMR



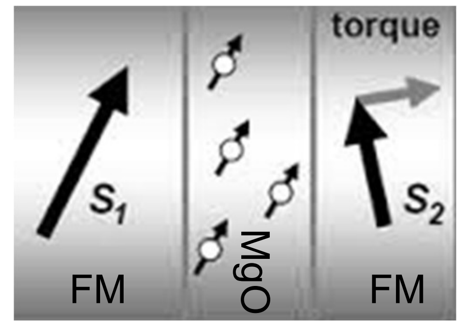
PRL 61, 2472(1988)
PRB 39, 4828 (1989)

TMR



PRL 74 3273 (1995)
Nature Mater 3, 868 (2004)

STT



Slonczewski, Berger (1996)

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2007
Nobel prize for Physics

Hard disk

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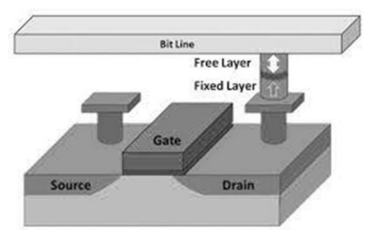
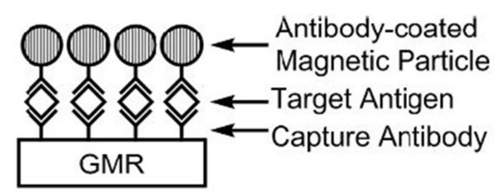
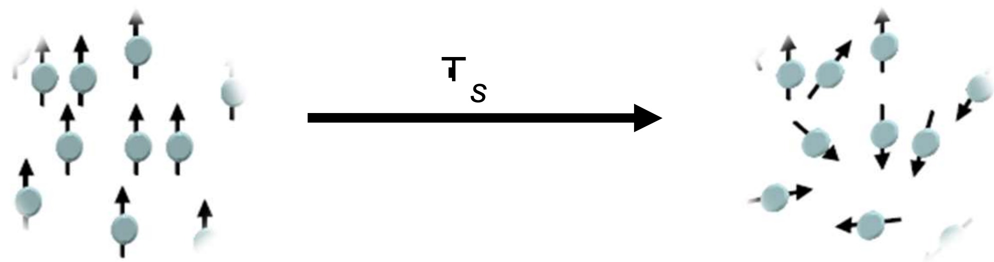
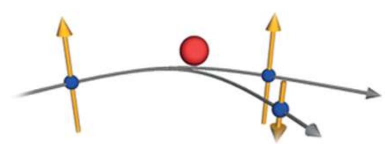


Bio sensors

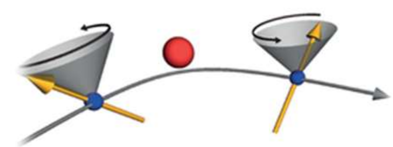


Spin relaxation

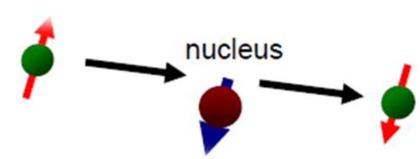




Elliott-Yafet - Momentum scattering by phonons or non-magnetic impurities.

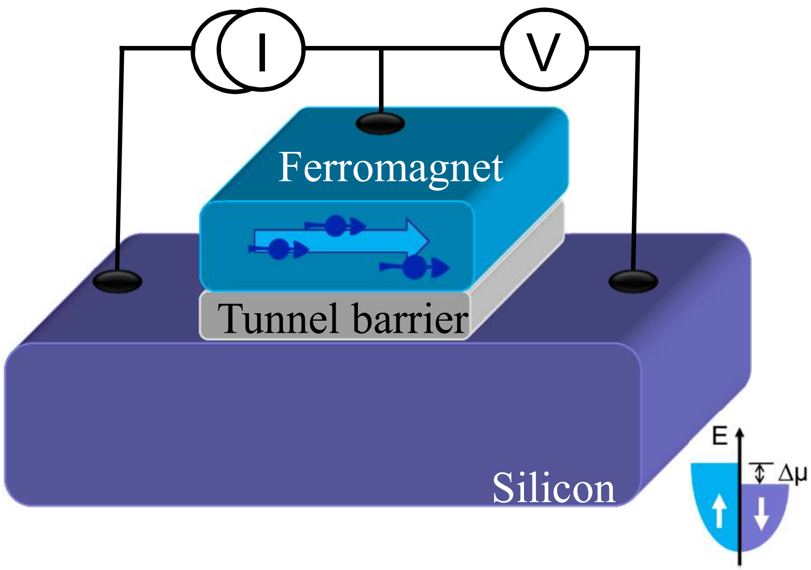


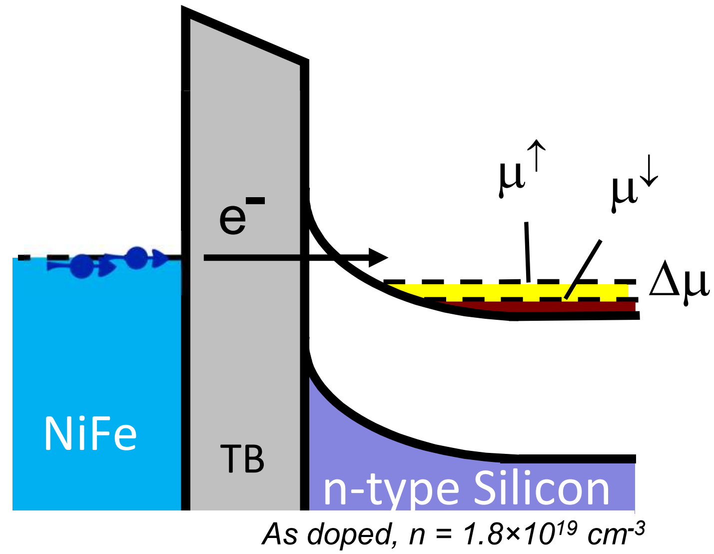
D'yakonov-Perel' - Absence of inversion symmetry is equivalent to the presence of an effective magnetic field.



Hyperfine-interaction – Interaction between the magnetic momentum of nuclei and electrons.

Silicon Spintronics



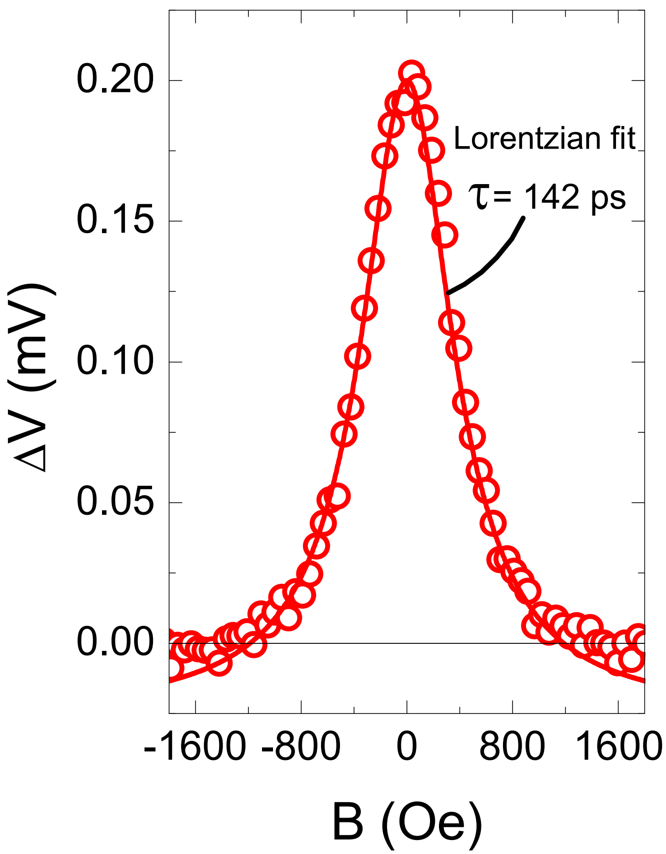


Longer spin lifetime expected in Silicon

- Low spin–orbit coupling : Inversion symmetry of lattice structure
  and low atomic number Z=14
- Low hyperfine interaction: Zero nuclear spin for 96 % of Si

S. P. Dash et al. **Nature** 462, 491 (2009)

Spin injection and detection in Si



S. P. Dash et al. **Nature** 462, 491 (2009)

Stationary spin-accumulation

$$\Delta\mu(B) = \frac{\Delta\mu(0)}{1+(\omega_L.\tau_s)^2}$$

Spin dephasing time (lower limit)

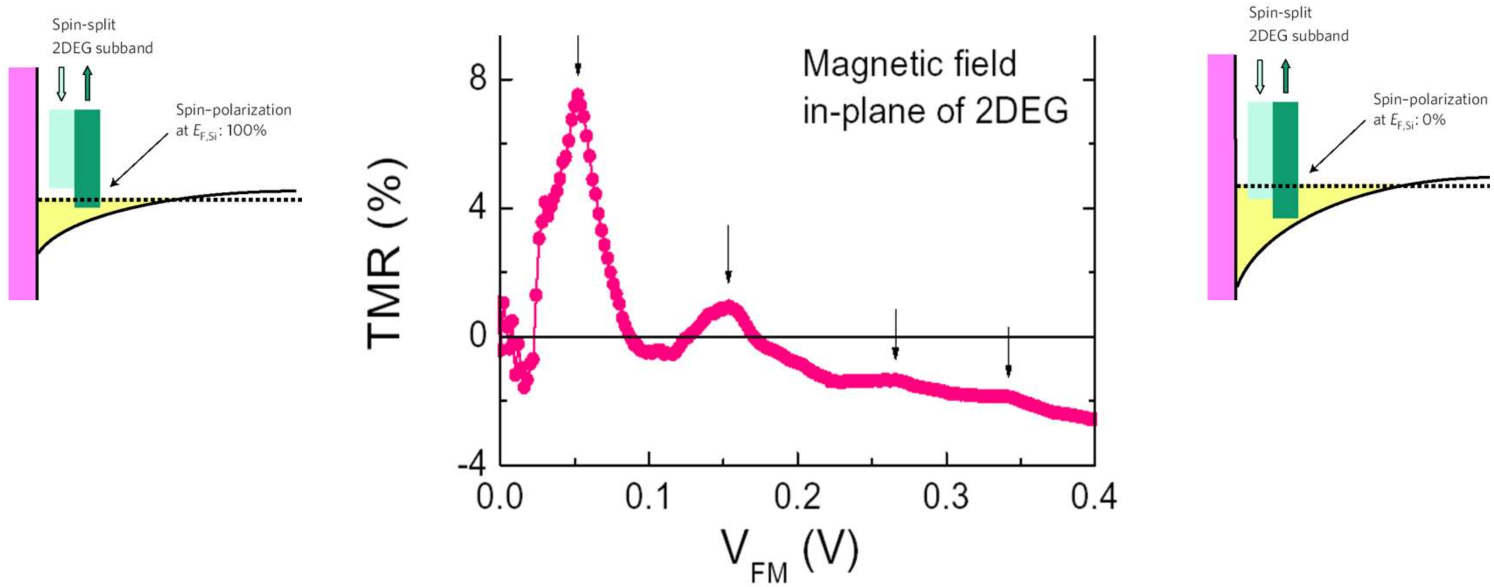
$$\tau_S = \frac{1}{\omega_L} = \frac{\hbar}{g\mu_B(HWHM)} = 140\,ps$$

Spin diffusion length (lower limit)

$$L_{SD} = \sqrt{D\tau_s} = 230nm$$

A. Dankert *et al.* Sci. Rep. 3, 3196 (2013)

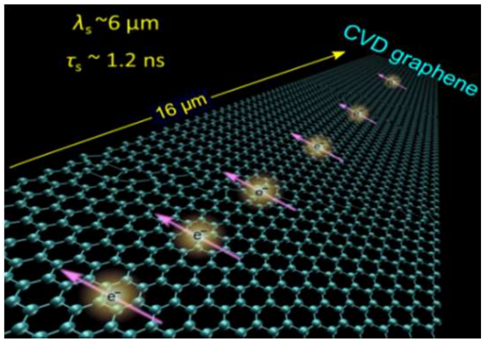
Spin injection into Si quantum well

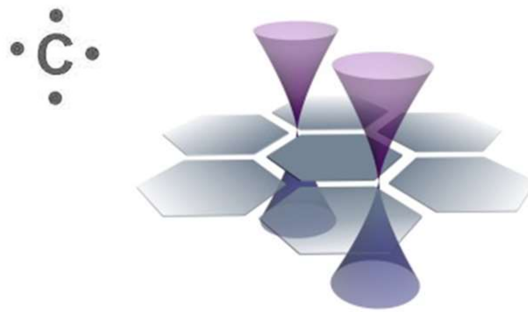


- Electrostatic modification of the magnitude of spin polarization in a Si 2DEG
- Detection by means of tunneling to a ferromagnet, producing prominent oscillations of tunnel magnetoresistance of up to 8%.

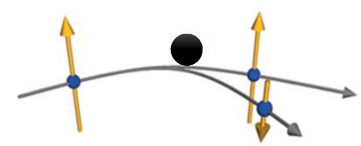
Jansen, Min, Dash, **Nature materials** 9, 133 (2010)

Graphene Spintronics

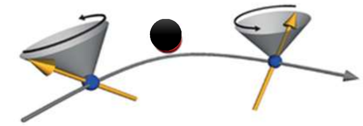




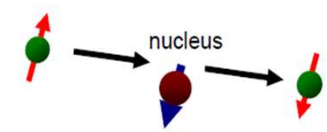
Elliott-Yafet



D'yakonov-Perel'



Hyperfine-interaction



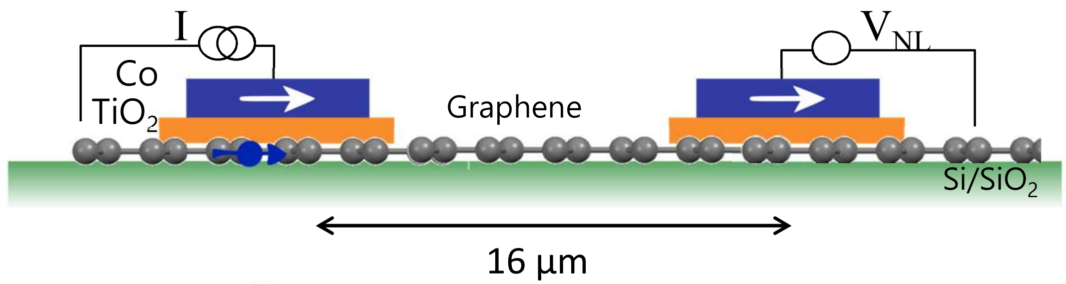
Graphene for long spin coherence

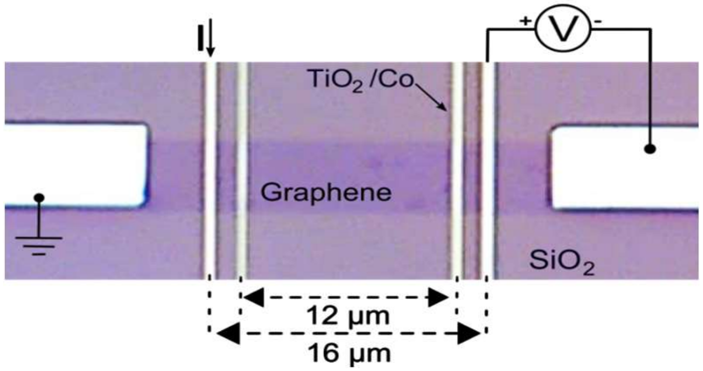
- High mobility
- Low spin-orbit coupling
- No hyperfine interaction

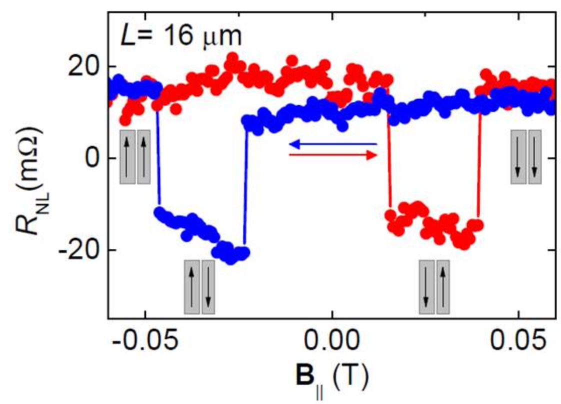
- Spin diffusion length 100 µm
- Spin lifetime 1µs

Kamalakar et al., **Nature Communications 6,** 6766 (2015)

Long distance spin transport in CVD graphene





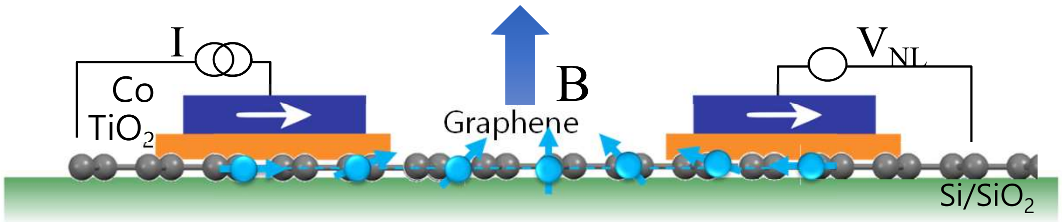


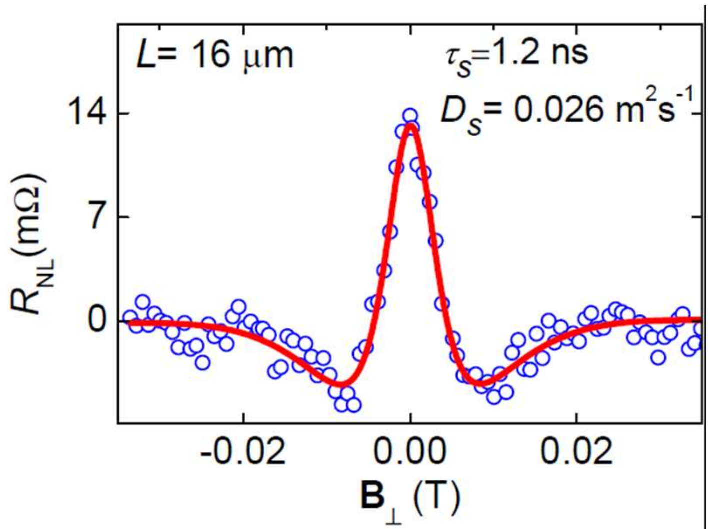
- **Spin transport L=16 µm,**
- Higher than previous reports on CVD graphene
- Highest at room temperature - graphene on SiO_2/Si substrates

Kamalakar et al., **Nature Communications 6,** 6766 (2015)

Long distance spin transport in CVD graphene

Spin Precession in Graphene – Hanle effect



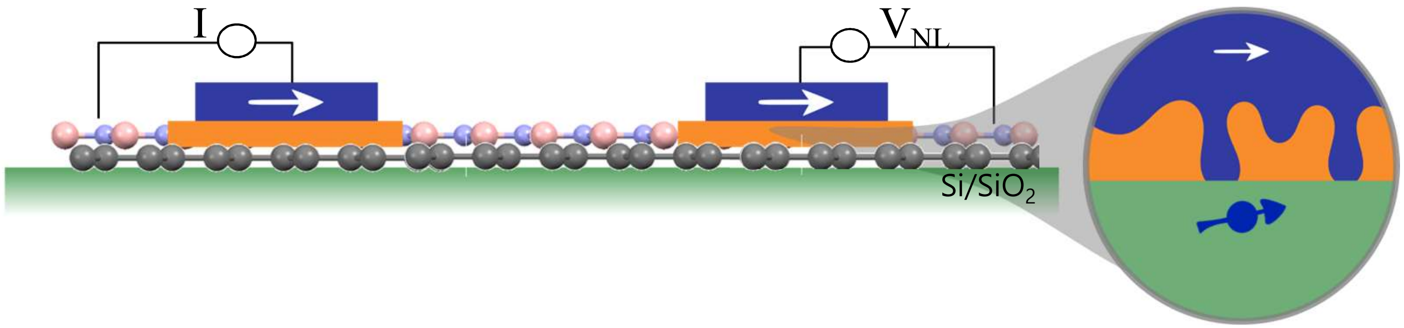


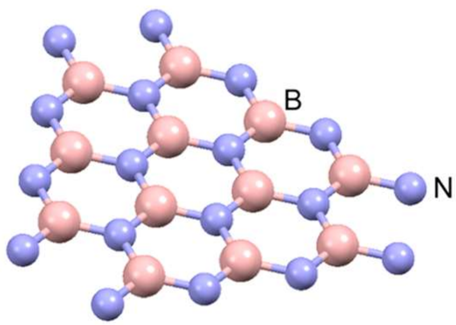
- **Spin parameters L=16 µm, τ = 1.2 ns, λ ~ 6 µm**
- Higher than previous reports on CVD graphene
- Highest at room temperature
  - graphene on SiO_2/Si substrates

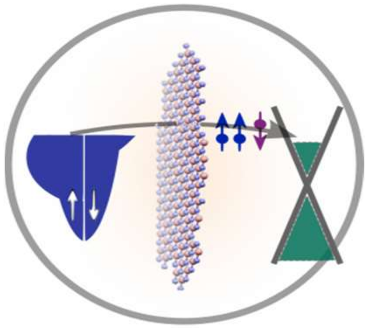
Kamalakar et al., **Nature Communications 6,** 6766 (2015)

Graphene/h-BN heterostrutures

h-BN tunnel barrier for efficient spin injection into Graphene



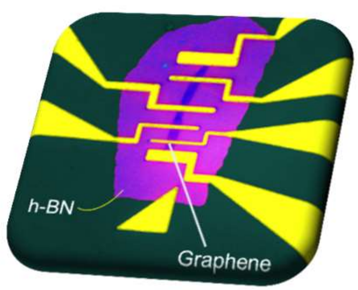


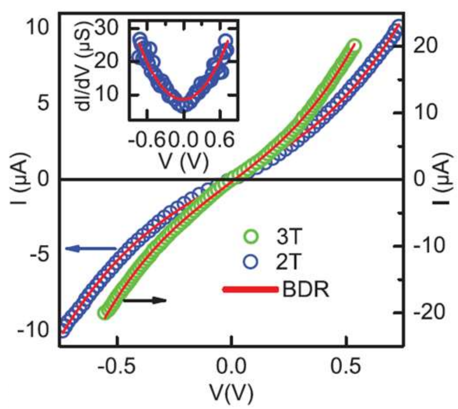


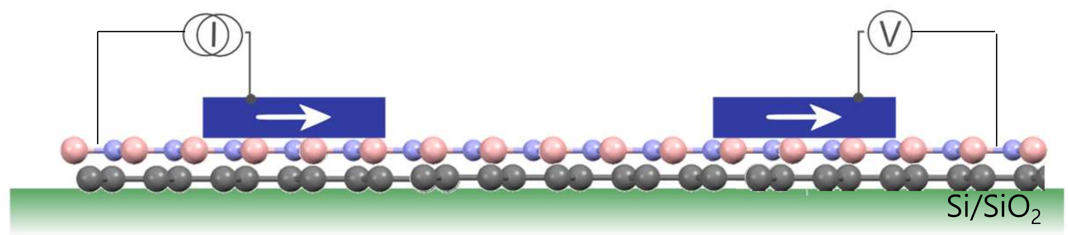
Hexagonal boron nitride (h-BN)

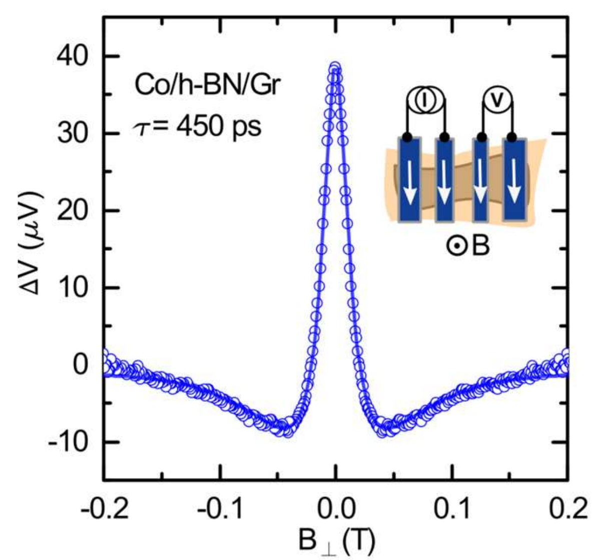
- Atomically thin insulator E_g = 6 eV
- 2D structure → No dangling bonds or interface states.
- Tunnel barrier resistance can be tailored by varying the number of layers

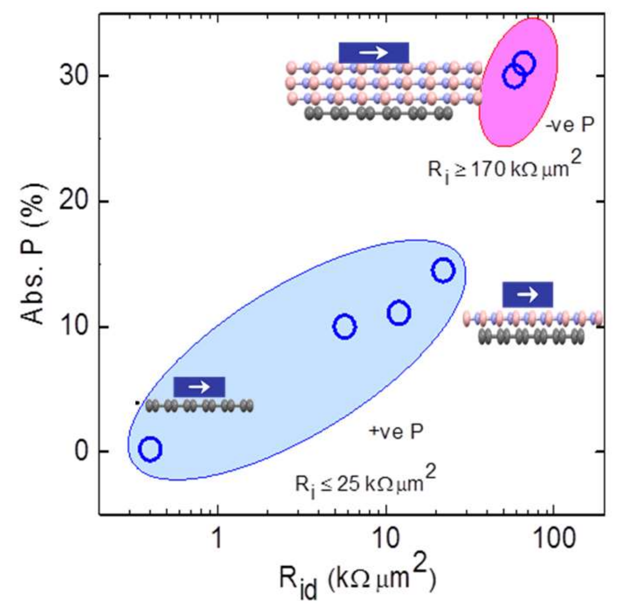
Graphene/h-BN heterostrutures









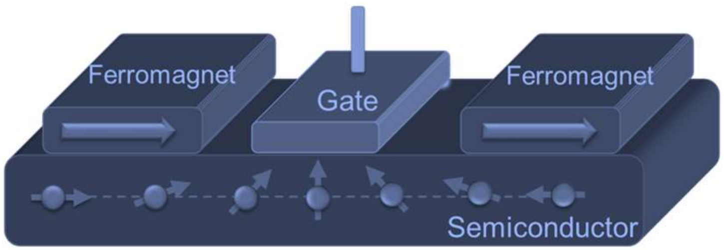


- Improved spin lifetime up to 450 ps
- Larger spin polarization for thicker h-BN barrier

Kamalakar et. al., Scientific Reports 4, 6146 (2014)
Scientific Reports 6, 21168 (2016)

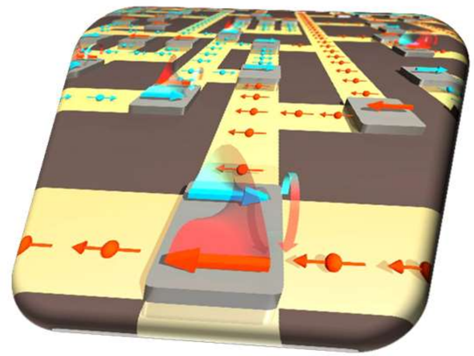
New perspectives for spintronics

Spin transistor



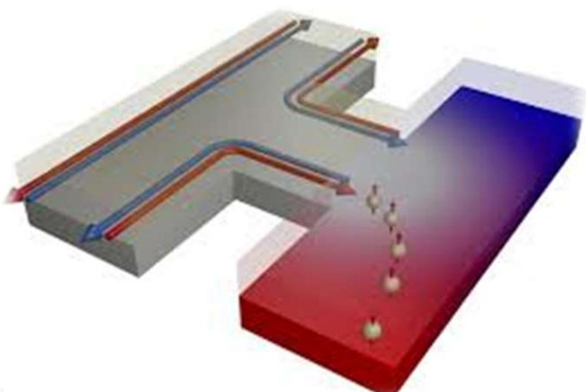
Datta, Das; APL. 56, 665 (1990)

Spin logic



Dery et al. Nature 447, 573 (2007)

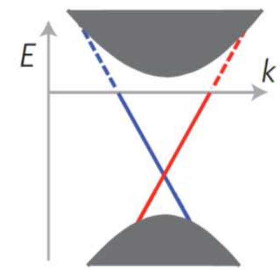
Spin Hall
Quantum spin Hall

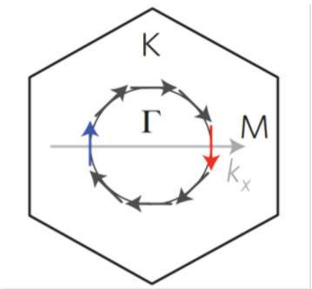


König et al., Science (2007)

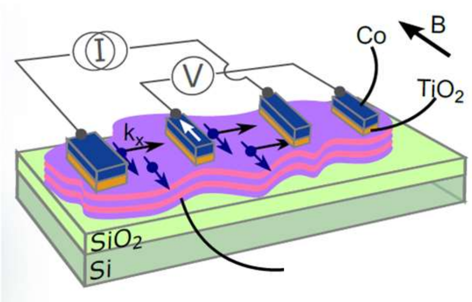
Outline

- Spin-momentum locking in topological insulators

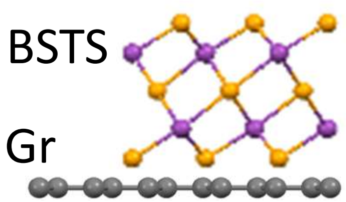




- Electrical detection of spin-momentum locking up to room temperature
    - ➢ Bi_2Se_3
    - ➢ $Bi_{0.75}Sb_{1.25}Te_{0.5}Se_{2.5}$ (BSTS)

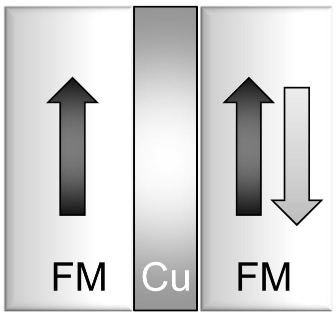


- Dirac material heterostructures of Graphene/Topological insulators



Spintronic effects

GMR



PRL 61, 2472(1988)
PRB 39, 4828 (1989)

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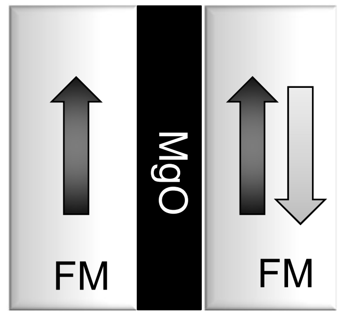

PRL 74 3273 (1995)
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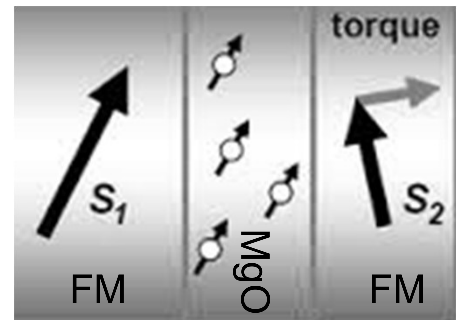

Slonczewski, Berger (1996)

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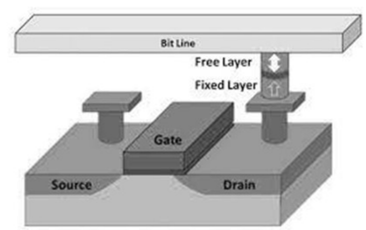
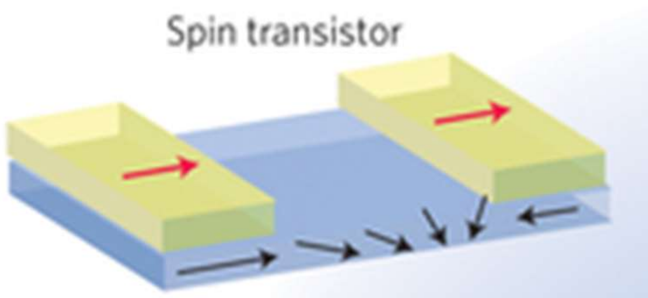
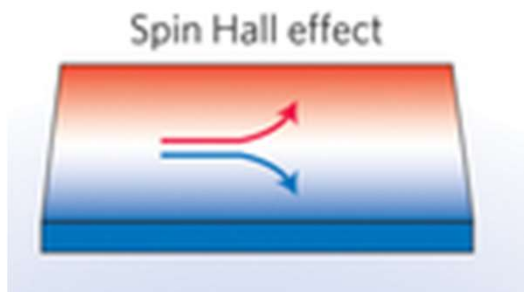
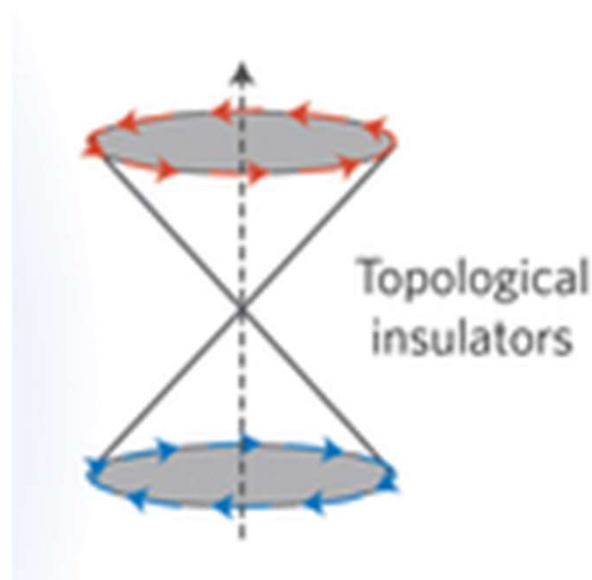


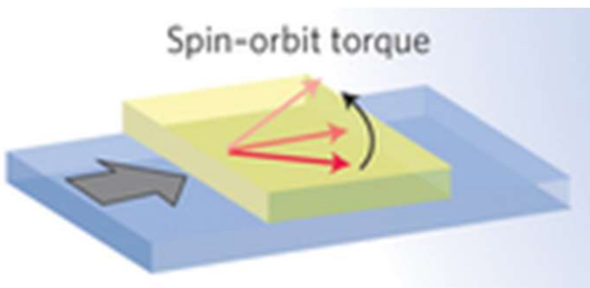
New perspectives for spintronics

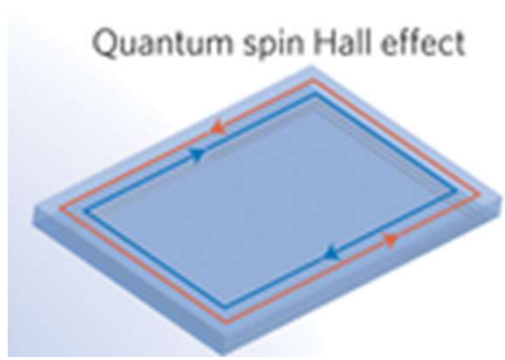
Spin–orbit coupling





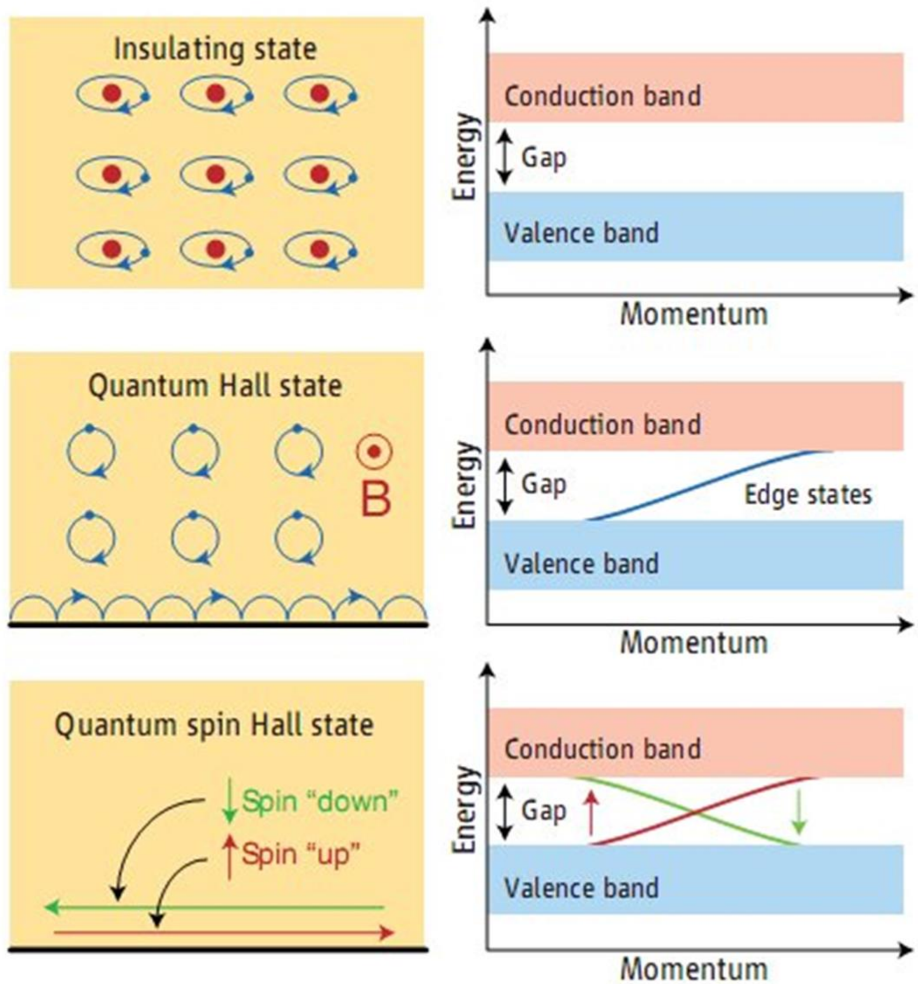






Nature mater (2016)

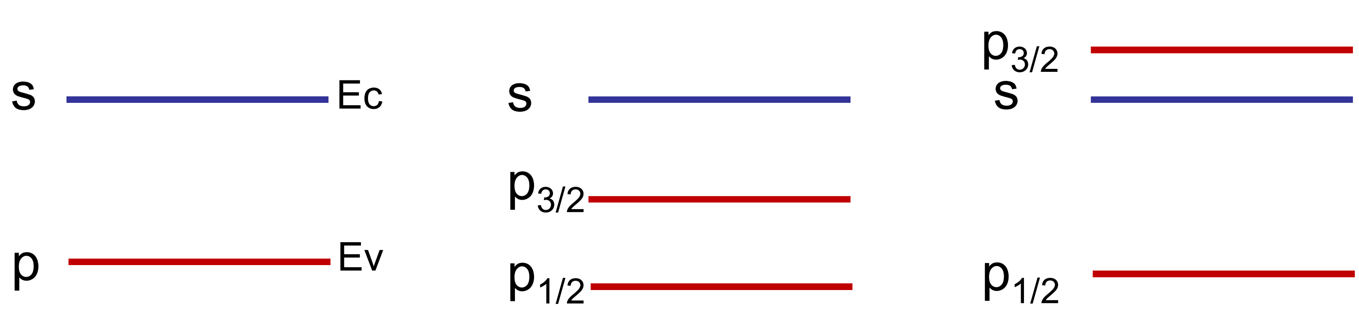
Topological Insulator



Topological Insulator

Spin-Orbit coupling
(Band inversion)

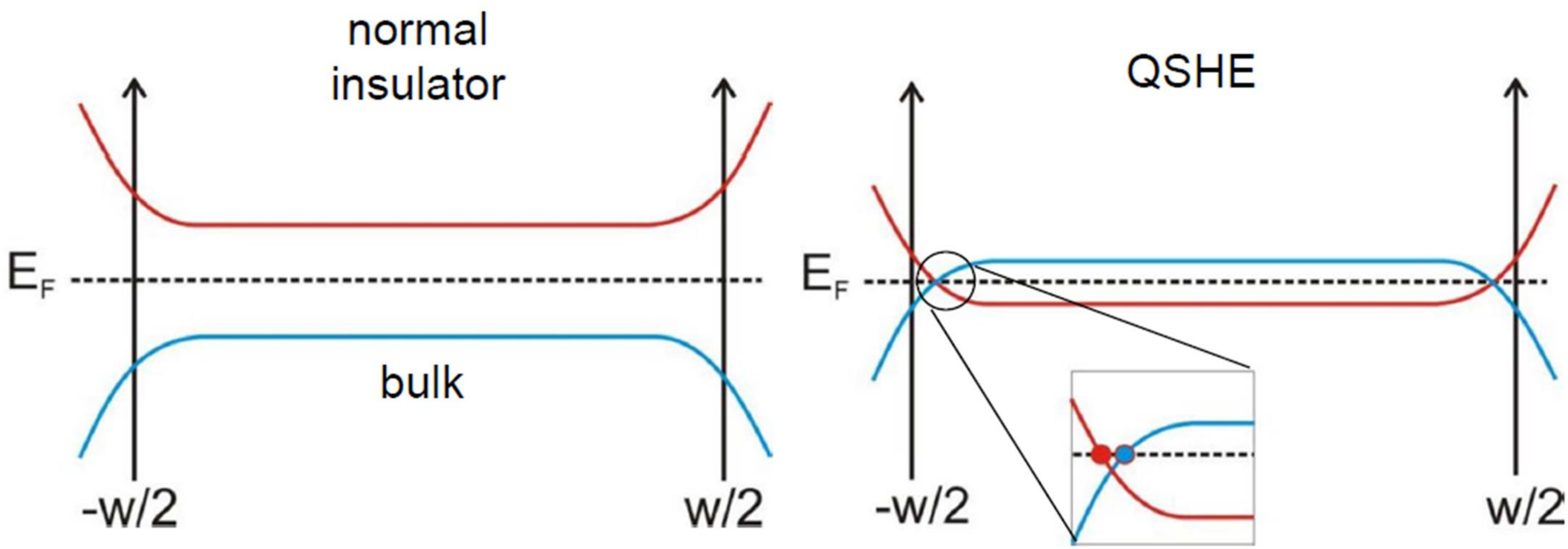
No Spin-Orbit | Small Spin-Orbit | Large Spin-Orbit



Band gap $E_g = s - p$

HgTe, Bi_2Se_3, Bi_2Te_3

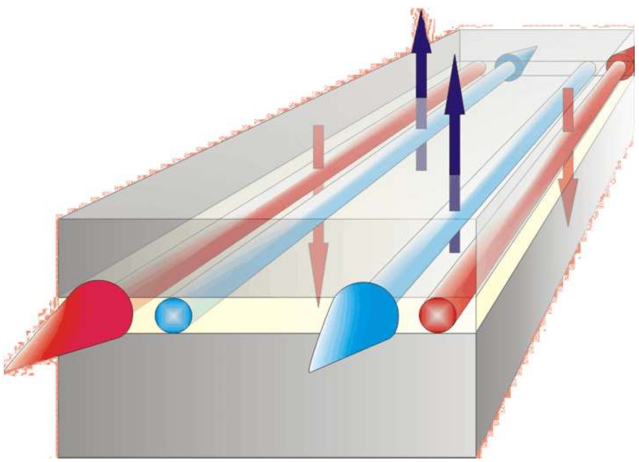
Topological Insulator



Science 318, 766-770 (2007)

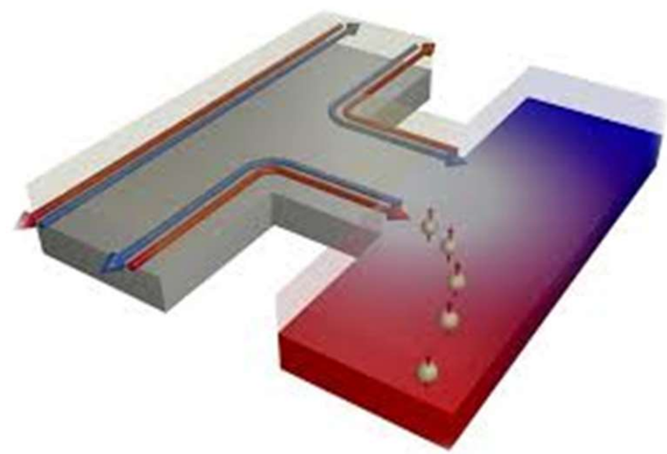
2D Topological Insulators

Quantum Spin Hall Insulator State
in HgTe Quantum Wells



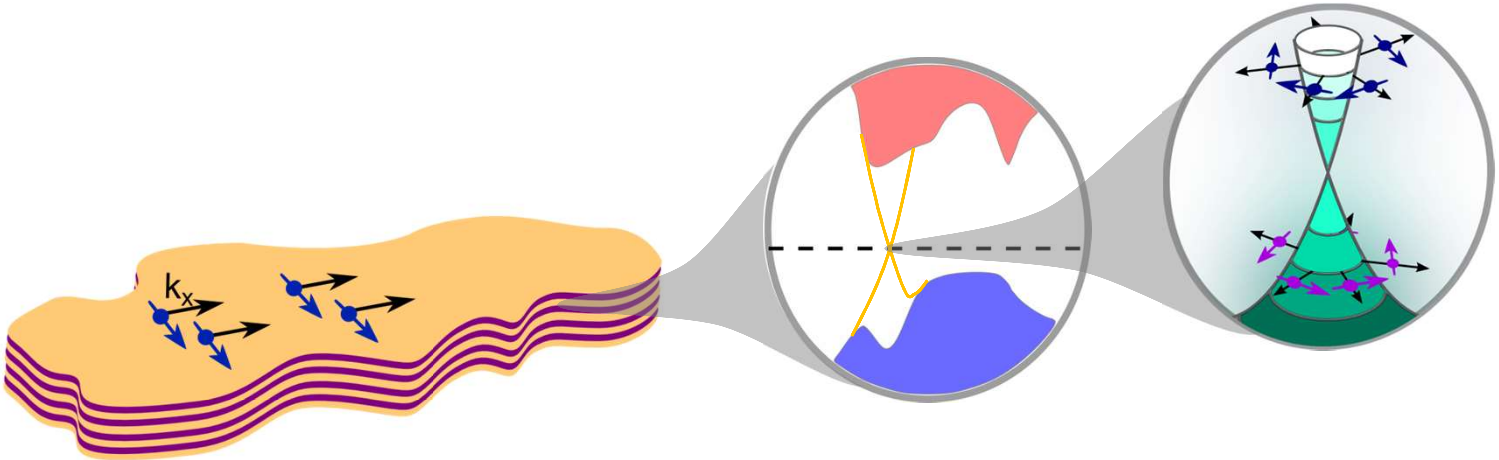
Science 318, 766-770 (2007)

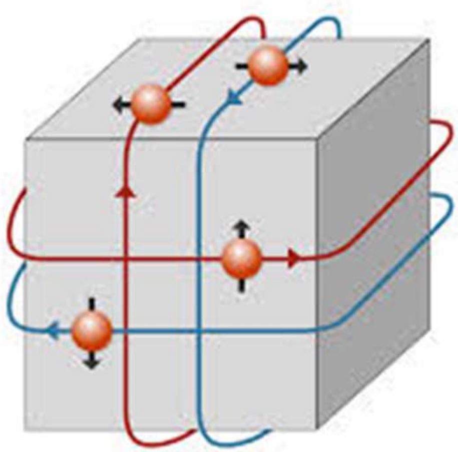
Spin polarization of the
quantum spin Hall edge states



Nature Physics 8, 486–491 (2012)

3D Topological Insulators



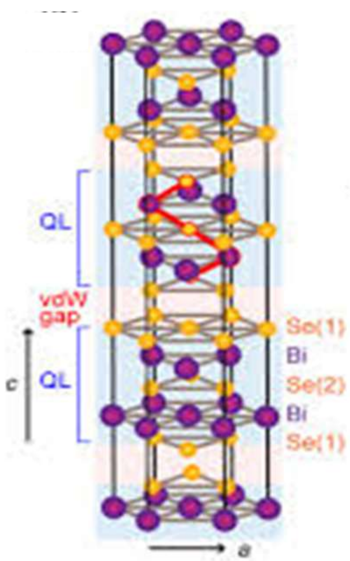


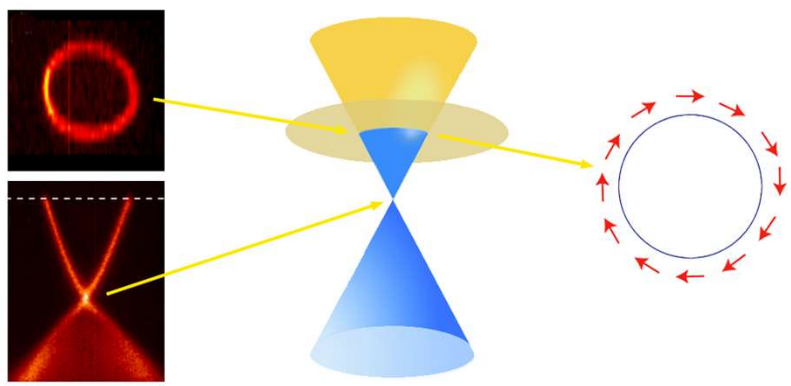
- Insulating bulk band structure
- Dirac state formation at the surface
- Spin and momentum direction are locked (SML)

- Novel measurement techniques possible

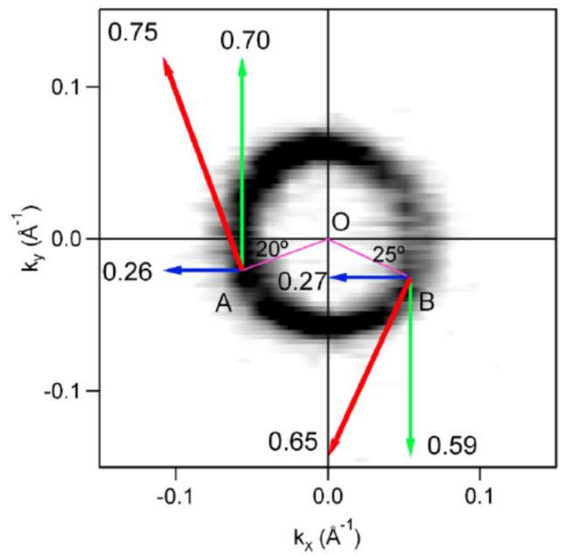
3D Topological Insulators

Angle and spin resolved photo emission spectroscopy





Hsieh *et al. Nature* **460,** 1101 (2009)



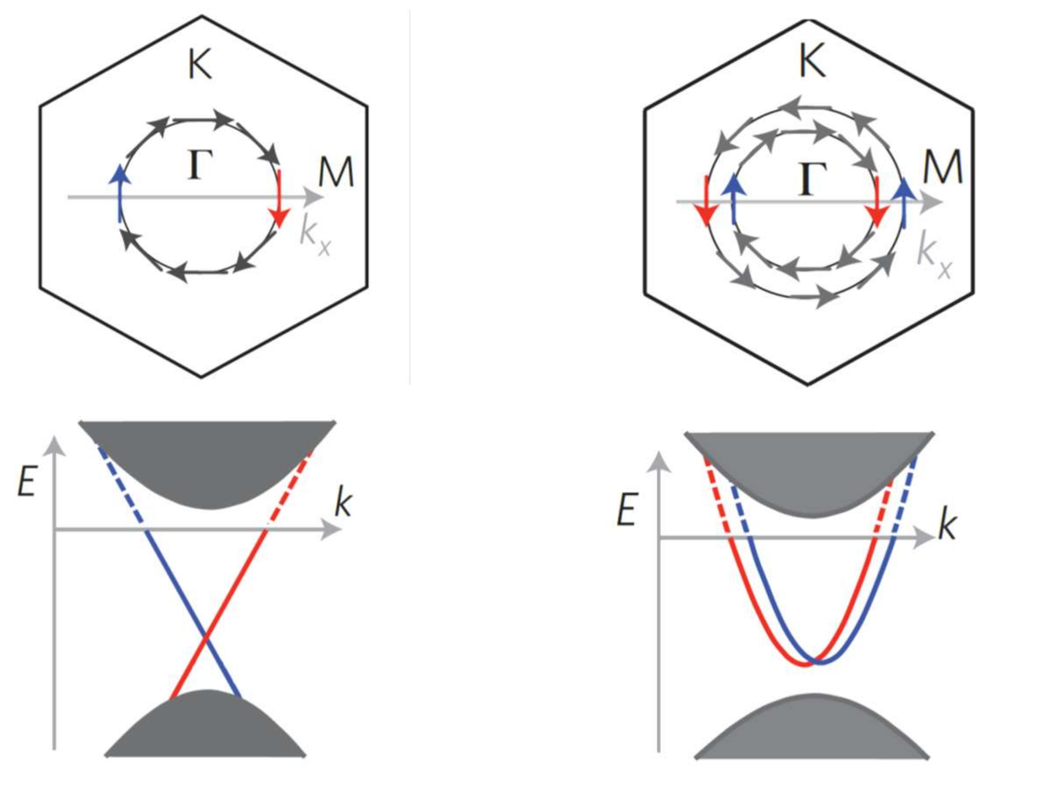
Pan *et al. Phys. Rev. Lett.* **106,** 257004 (2011)

- Bi_2Se_3, Bi_2Te_3, Sb_2Te_3 are 3D topological insulators with robust states on surface under room temperature conditions.
- Surface and spin state detected by spin-resolved ARPES

M. Z. Hasan, C. Kane,
Rev. Mod. Phys. 82, 3045 (2010)

Difference with Rashba effect

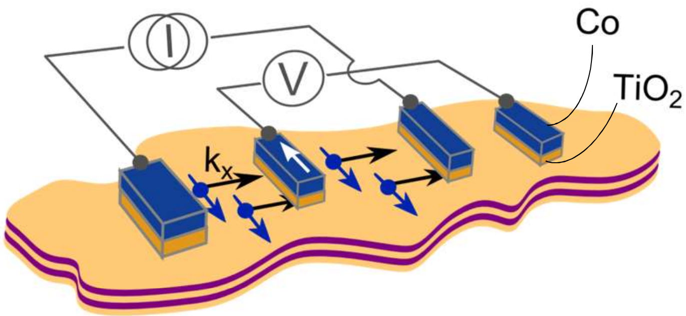
SML Rashba



Jozwiak *et al. Nat. Phys.* **9,** 293 (2013)

Potentiometric measurements

CHALMERS

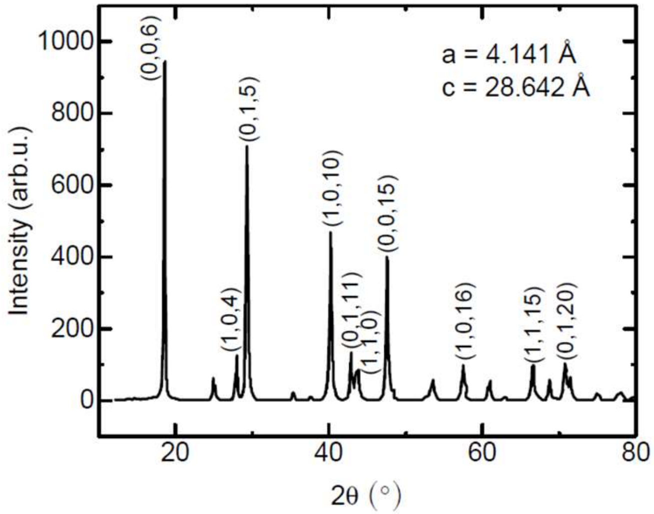


- Applied direct current induces momentum-locked spins
- Detect spins with ferromagnetic tunnel contact
- Net spin polarization can be detected under the contact

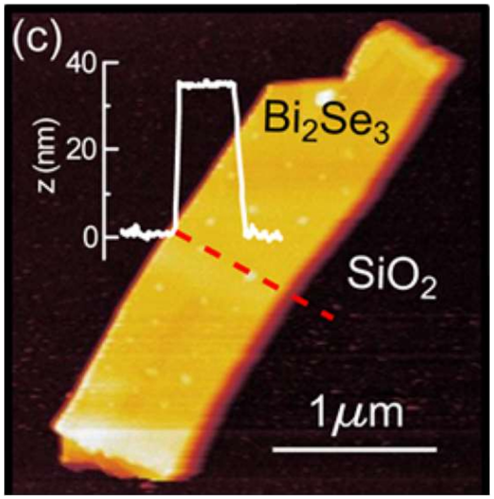
Hong et al., PRB 86, 085131 (2012)

Devices with Bi_2Se_3

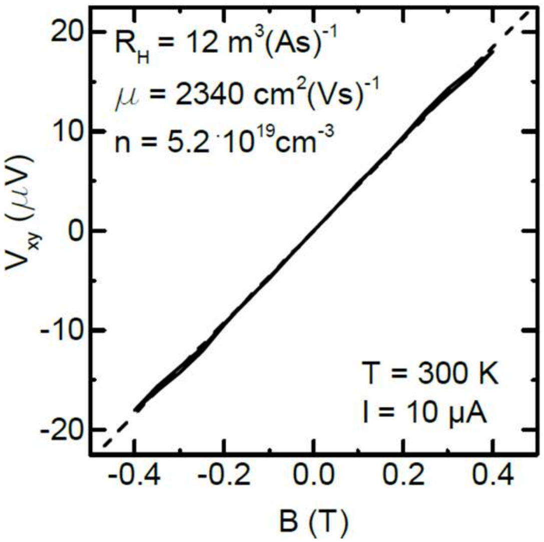
XRD



AFM



Hall



- Crystal grown by Bridgemen method
- Bi_2Se_3 flakes of 20 – 70 nm thickness
- Mobility 2000 $cm^2 V^{-1} s^{-1}$

Dankert, ..., Dash, Nano Letters 15 (12), 7976 (2015)

Magnetotransport in Bi_2Se_3

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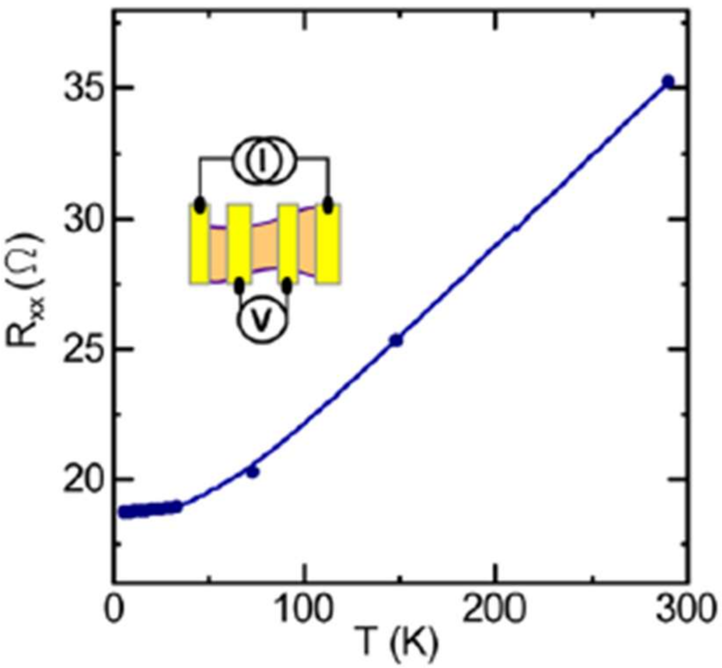
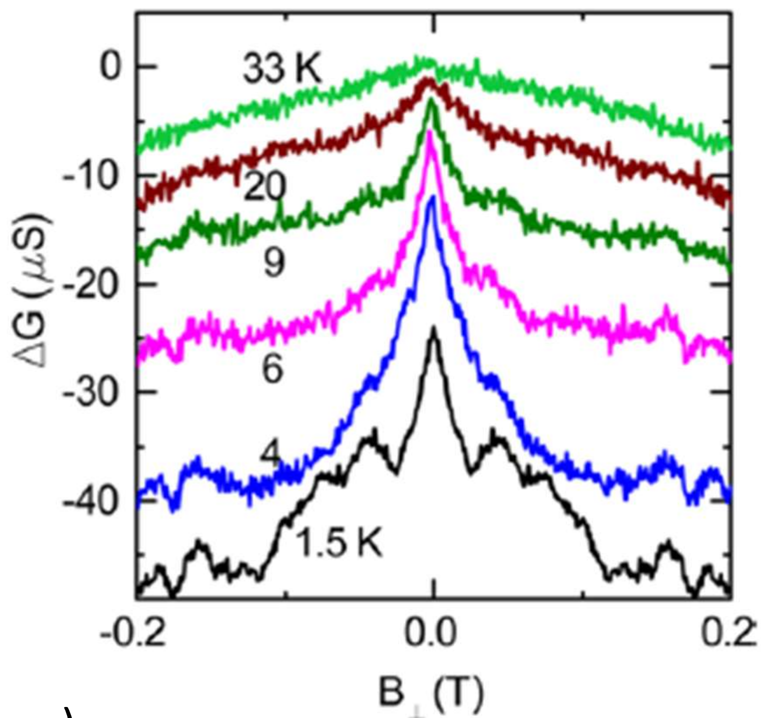
Resistance



Weak localization



- Metallic behavior of Bi_2Se_3 flakes (20 – 100 nm)
- Waek localization indicates strong spin-orbit coupling in Bi_2Se_3

Dankert, ..., Dash, Nano Letters 15 (12), 7976 (2015)

Ferromagnetic tunnel contacts on Bi_2Se_3

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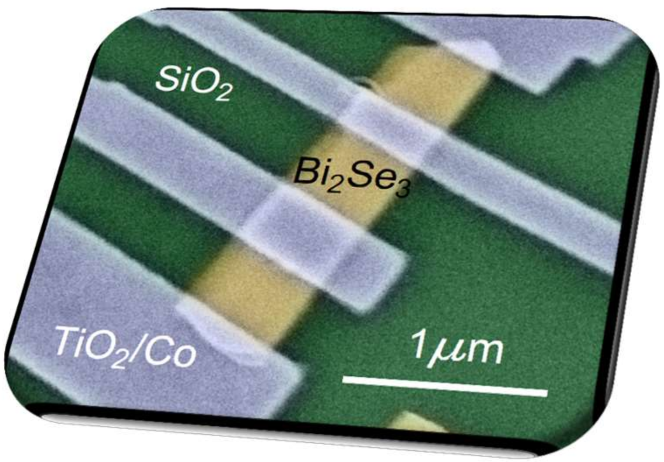
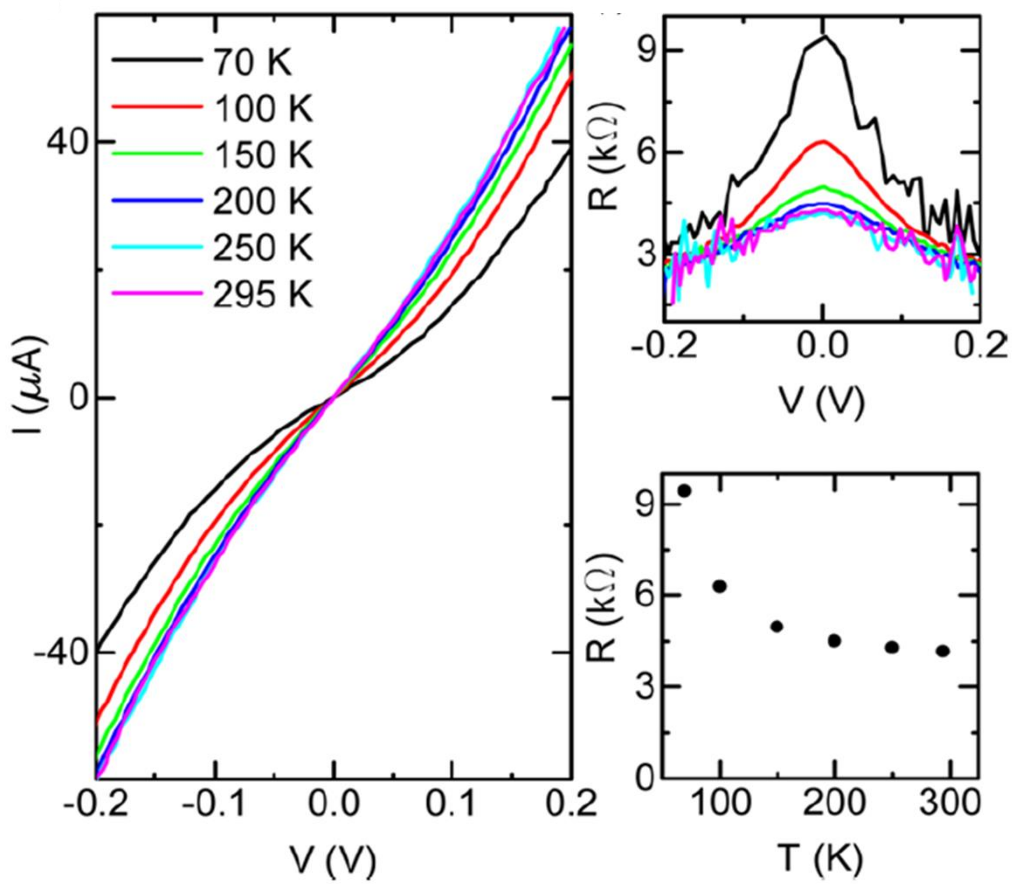


- Exfoliated Bi_2Se_3 on Si/SiO_2
- TiO_2/Co tunnel contacts
- Good tunneling behavior of the contacts



Dankert, ..., Dash, Nano Letters 15 (12), 7976 (2015)

Detection of spin-momentum locking

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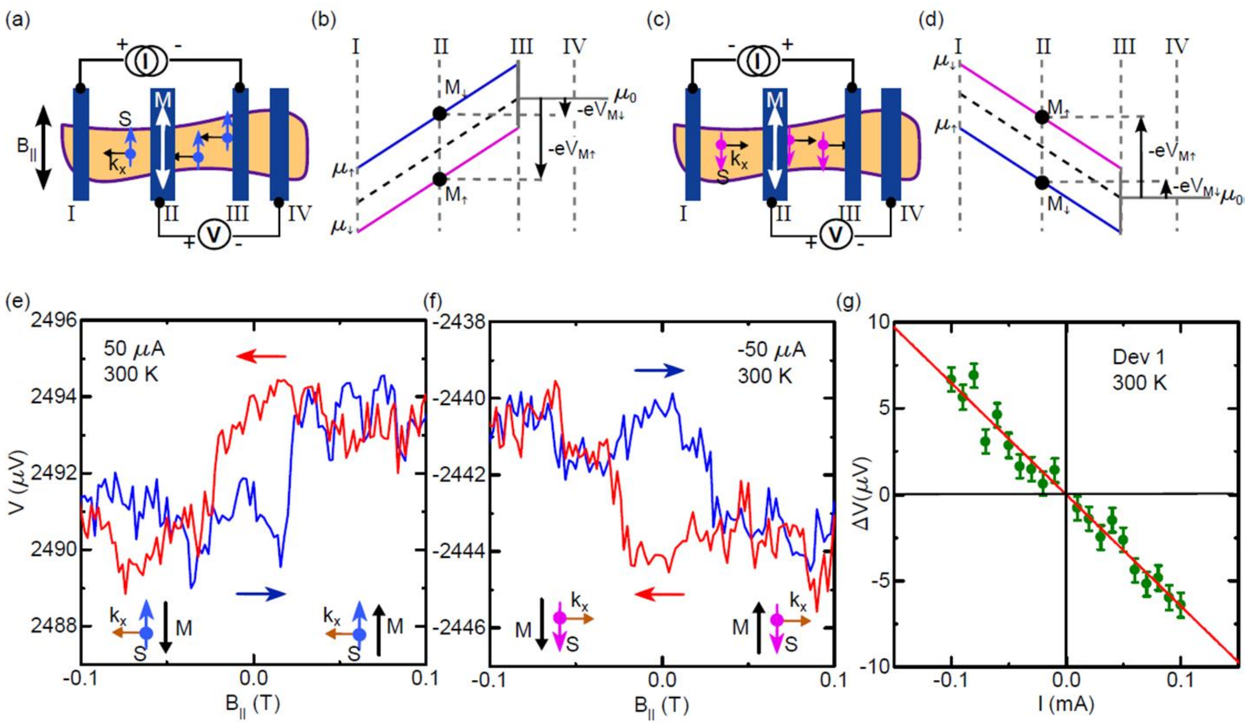
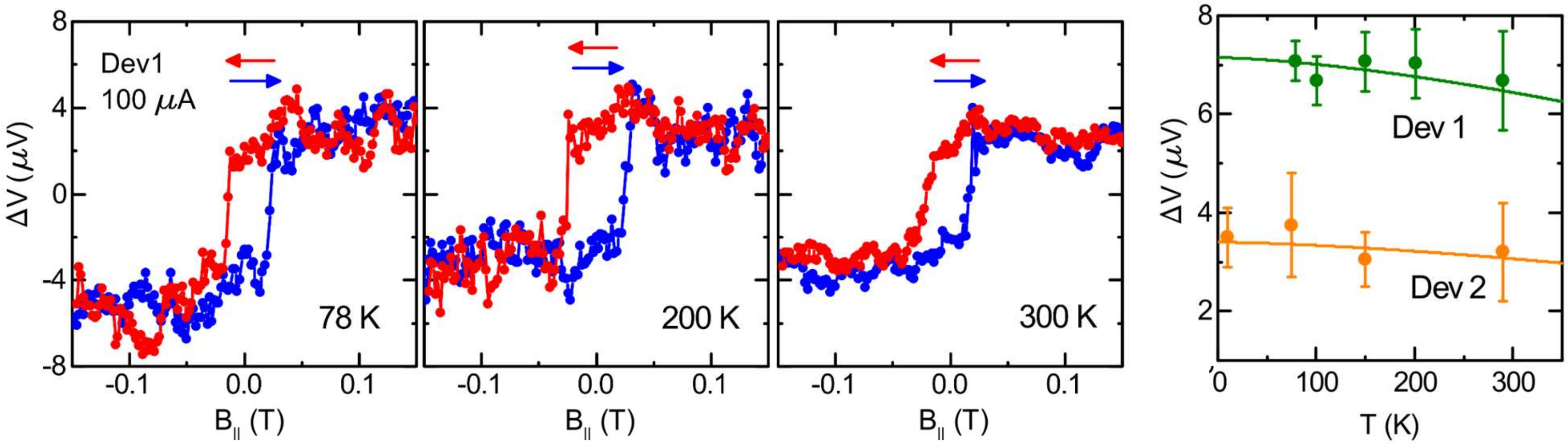


- Potentiometric measurement of spin-polarized surface current
- Spin valve signal between ferromagnet and net surface spins under the contacts
- Spin polarization in surface up to **room temperature**
- Spin-current density ∝ applied current
- Rules out contributions from thermal effects

Dankert, Nano Letters 15 (12), 7976 (2015)

Temperature dependence



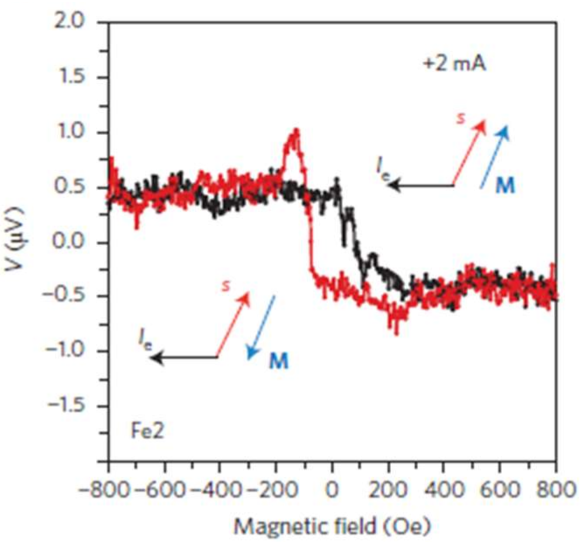
- Very weak temperature dependence
  → can be influenced by several factors of Bi_2Se_3 (bulk/surface contribution, doping, mobility of Bi_2Se_3) and ferromagnetic tunnel contacts

- Bi_2Se_3 thickness: Dev1 (40nm) vs. Dev2 (70nm) → Surface origin of signal

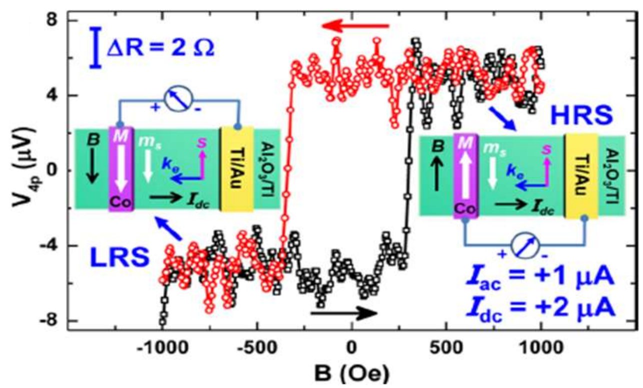
Dankert, Nano Letters 15 (12), 7976 (2015)

Literature

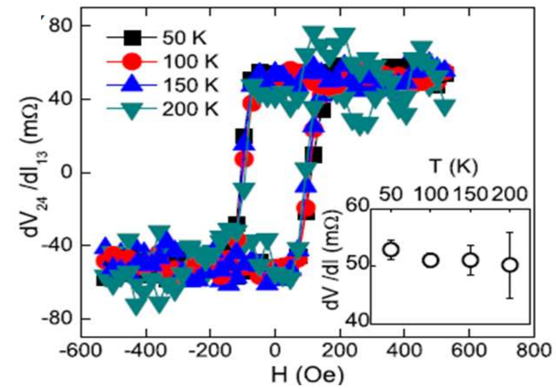
Li et al. Nature Nano 9, 218 (2014)



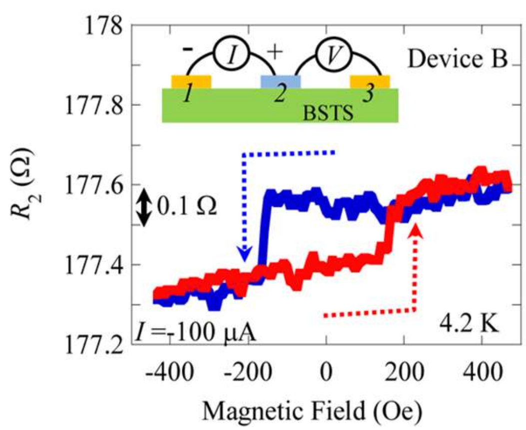
Tang et al. Nano Lett. 14, 5423 (2014)



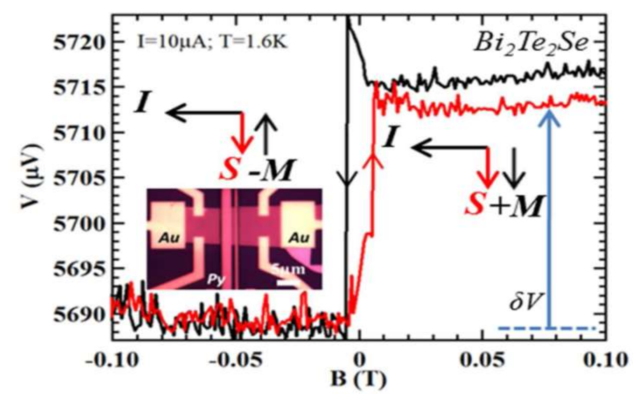
Liu et al. PRB 91, 235437 (2015)



Shiraisi et al. Nano Lett. (2014)

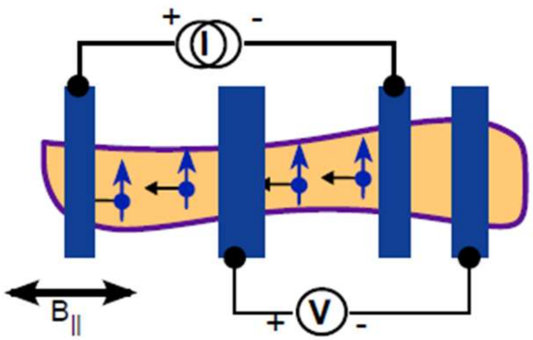


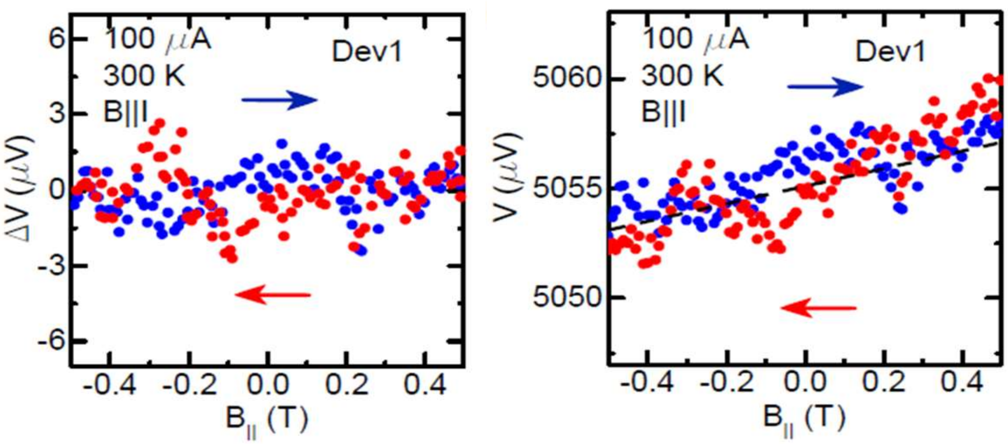
Tian et al. Sci. Rep. 5, 14293 (2015)



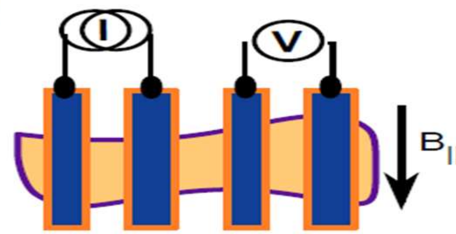
Control Experiments

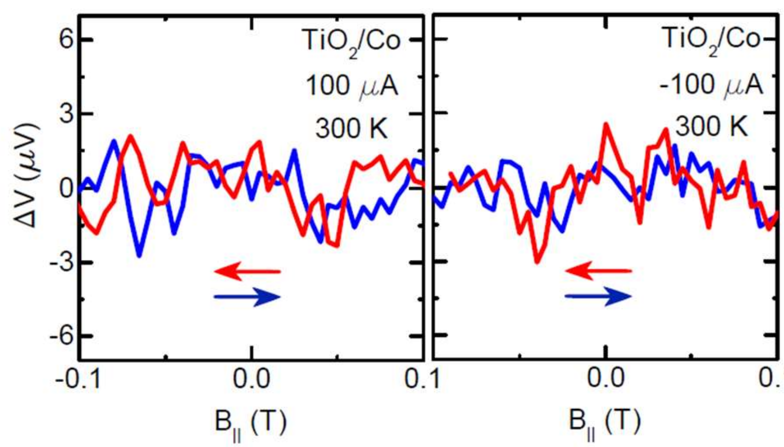
90^0 B_{in} Sweep





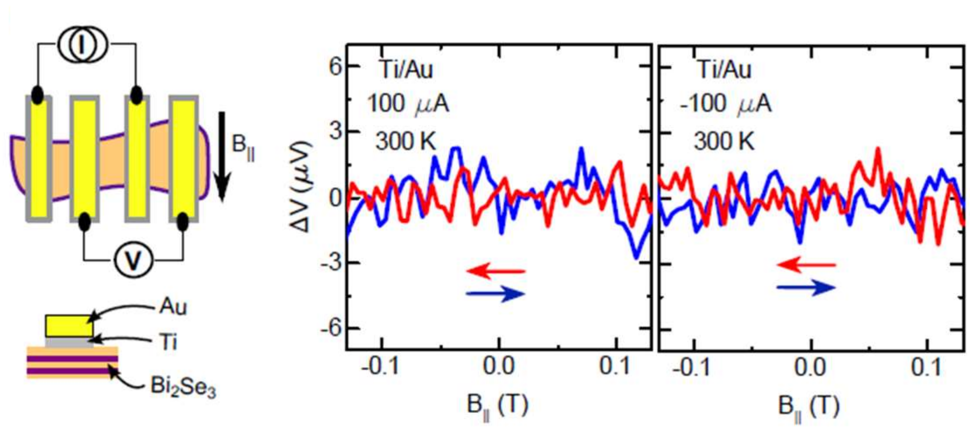
Non-local measurement





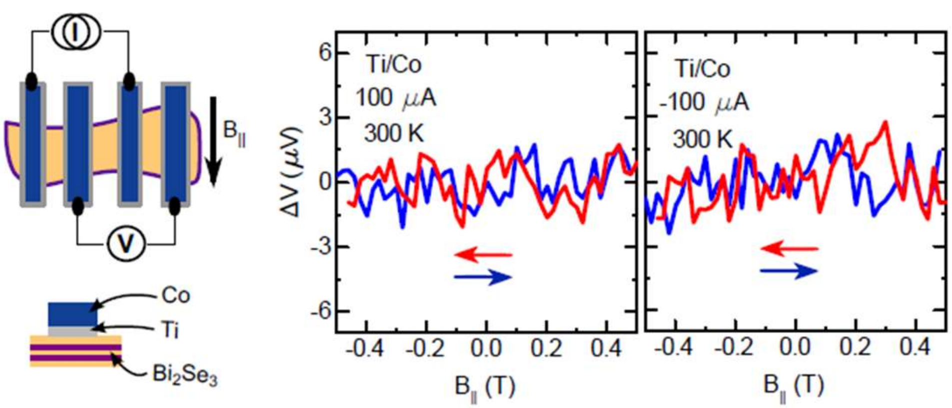
Dankert, ..., Dash, Nano Letters 15 (12), 7976 (2015)

Control Experiments



Non-magnetic Ti/Au contacts

- No signal means, no artifacts from Bi_2Se_3



Magnetic Co contact with non-magnetic Ti interlayer

- No signal means, no artifacts from ferromagnetic electrode

Dankert, ..., Dash, Nano Letters 15 (12), 7976 (2015)

Summary

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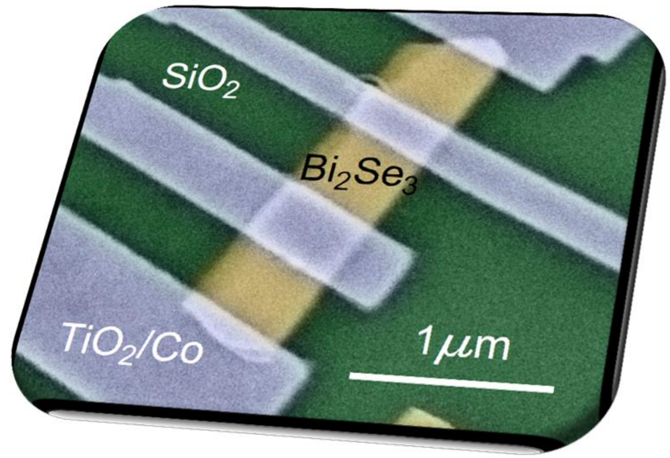
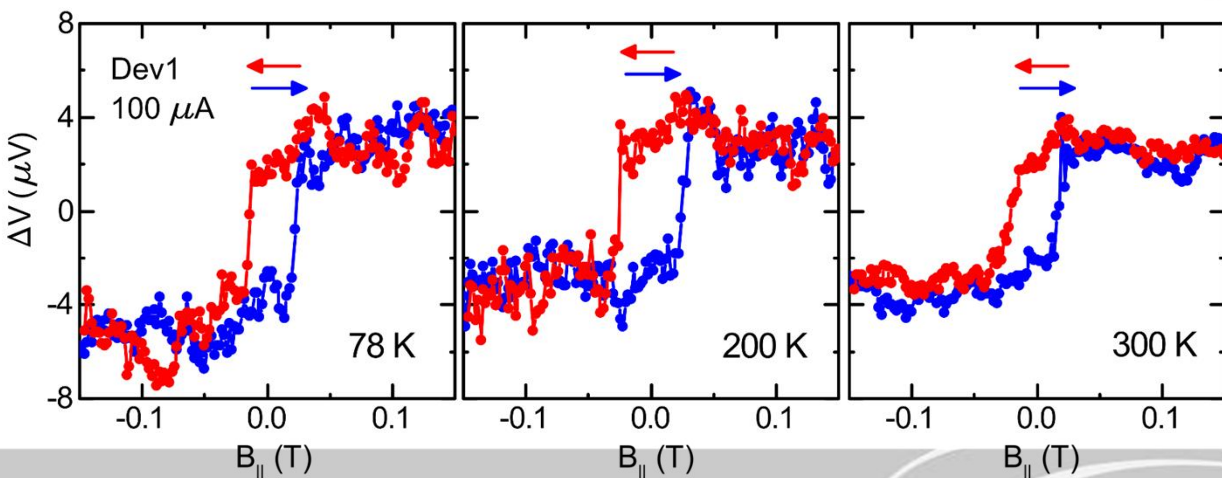
- Observation of spin-momentum locking up to room temperature in Bi_2Se_3 and BSTS
- Higher signal in BSTS in comparision to Bi_2Se_3
- Stronger temperature dependence of signal in BSTS





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