Spin Hall Effect

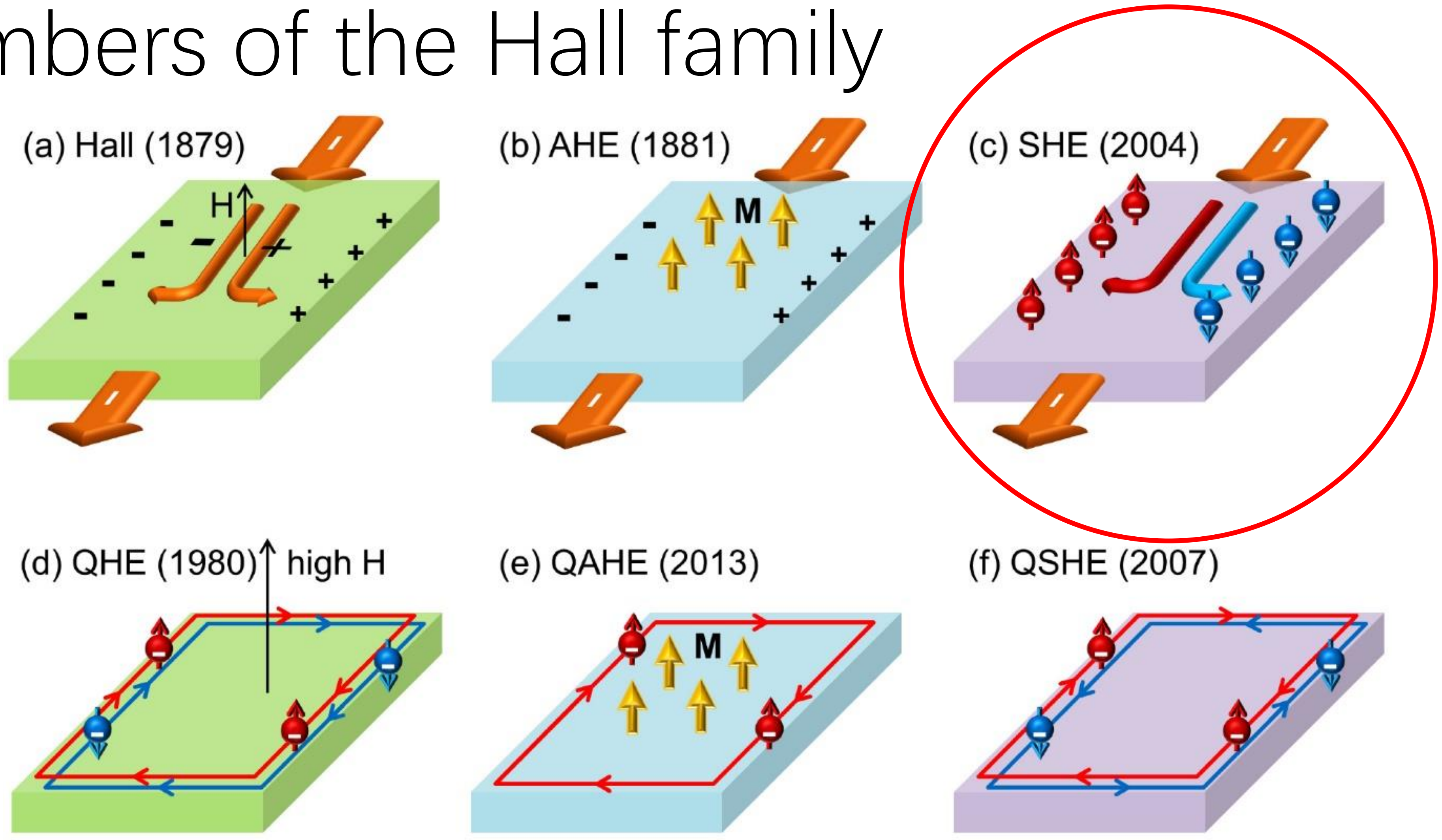
A brief introduction of
theoretical and experimental research

赵利利，王善，闫姣婕，齐少勉，李龙飞，刘震

Outline

- SHE and related phenomena
- Mechanisms of SHE
- Optical experiments of SHE
- Transport experiments of SHE
- Magnetization dynamics and SHE
- Quantum spin Hall effect

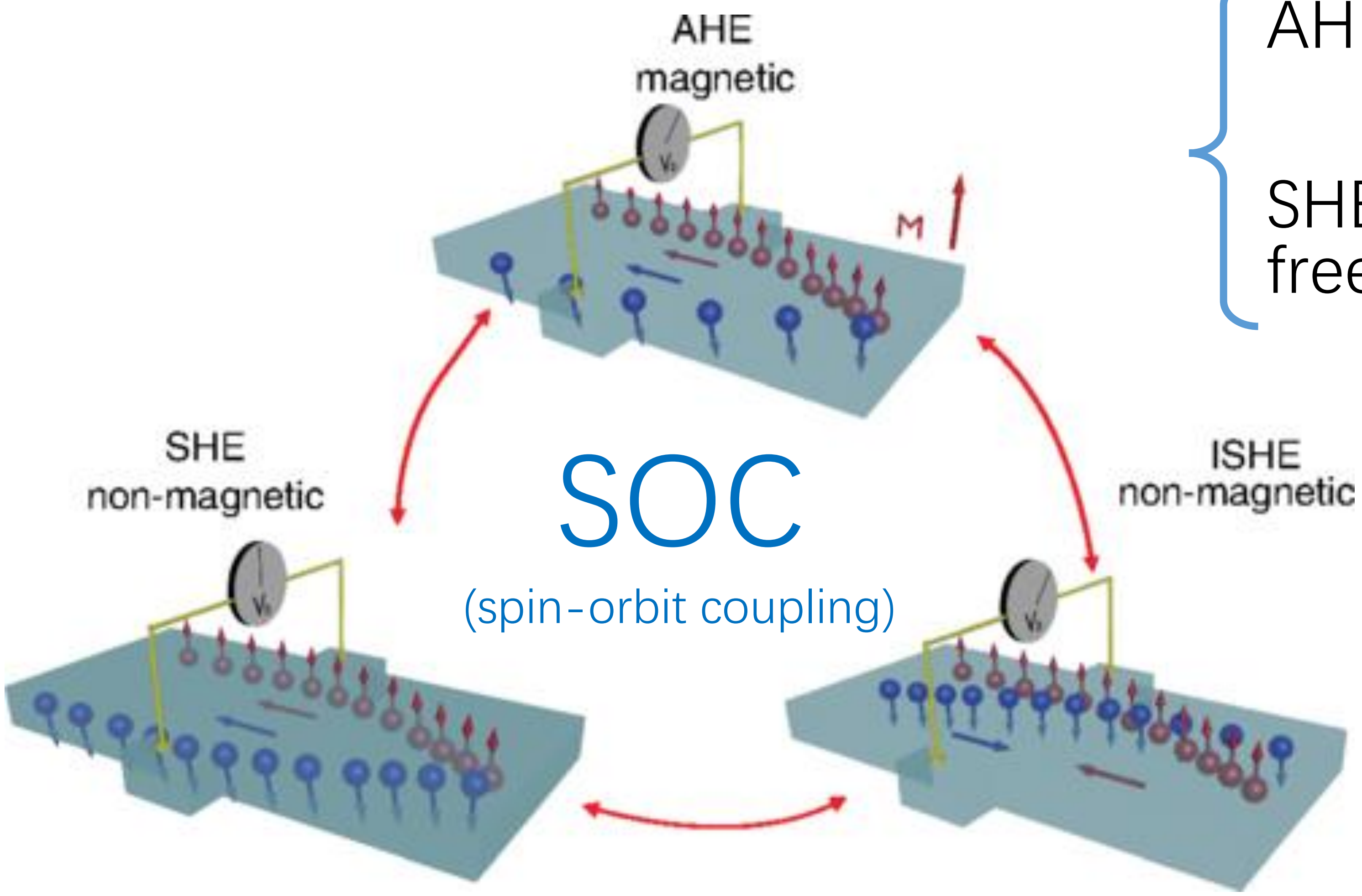
Members of the Hall family



(a) Hall effect. (b) AHE. (c) SHE. (d) QHE, (e) QAHE. (f) QSHE.

Cui-Zu Chang and Mingda Li 2016 *J. Phys.: Condens. Matter* **28** 123002

AHE, SHE and ISHE



AHE: charge degree of freedom

SHE: charge and spin degrees of freedom

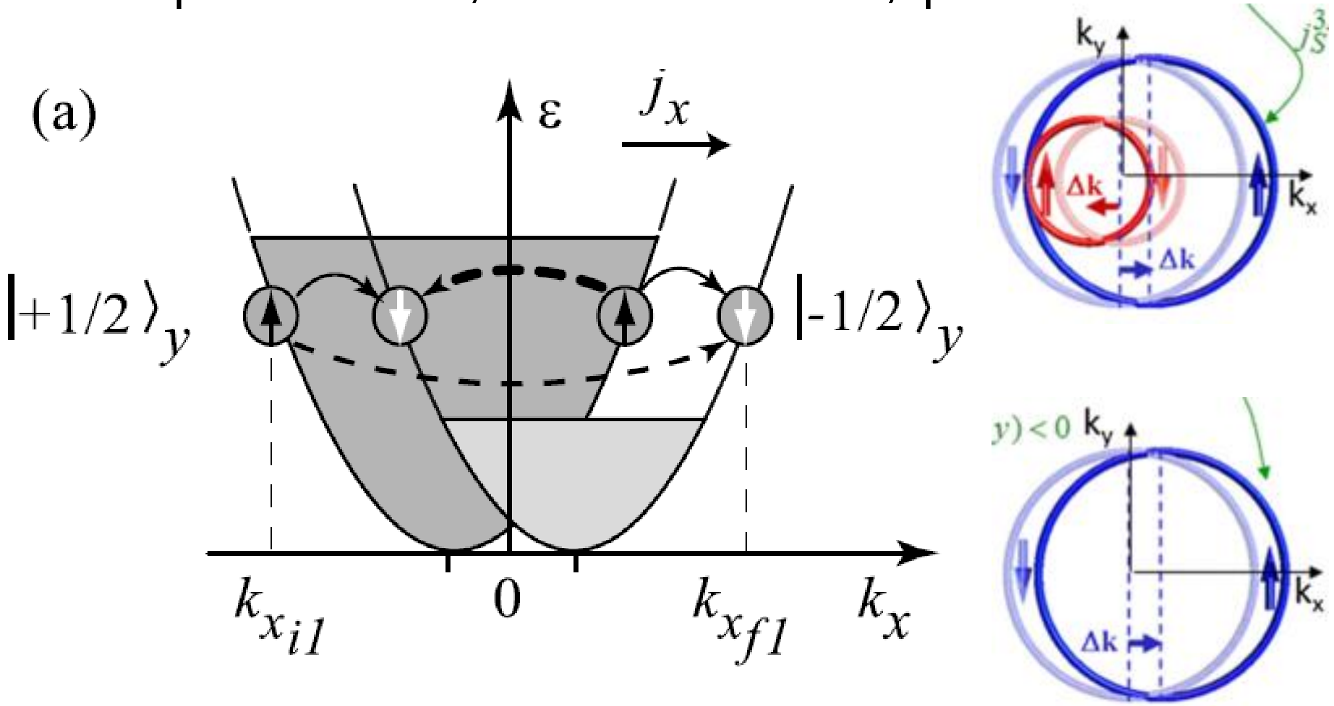
SHE: charge to spin

ISHE: spin to charge

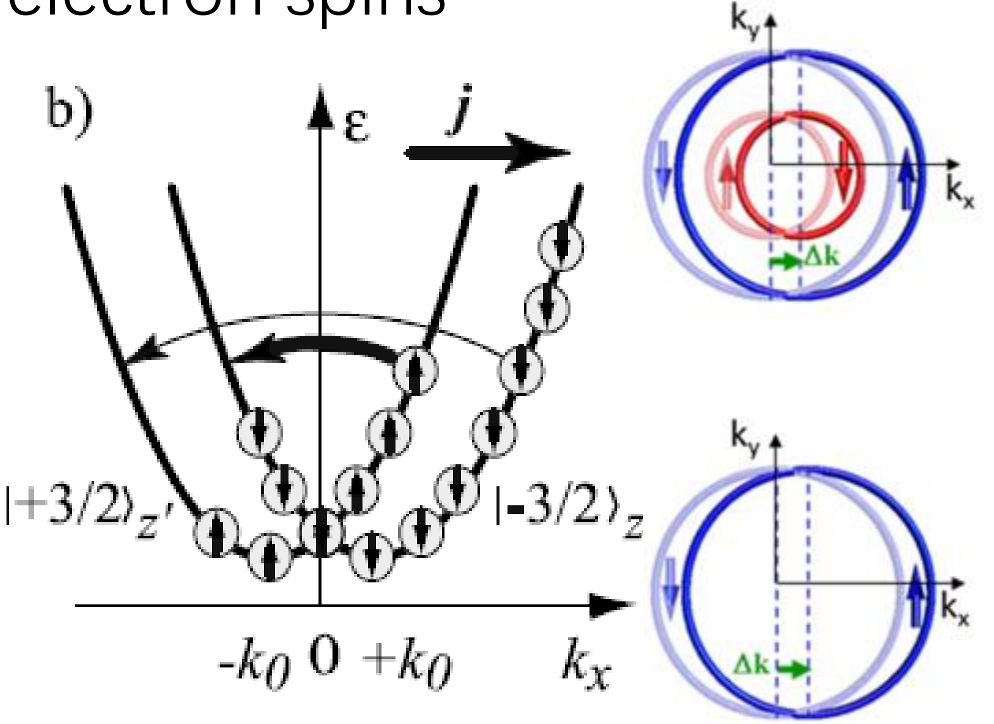
SHE and ISGE

SHE and ISGE(inverse spin galvanic effect) (or REE, Rashba Edelstein effect) are known as companion phenomena

key signature of the SGE is the electrical current-induced by a non-equilibrium, but uniform, polarization of electron spins



SGE(IREE)

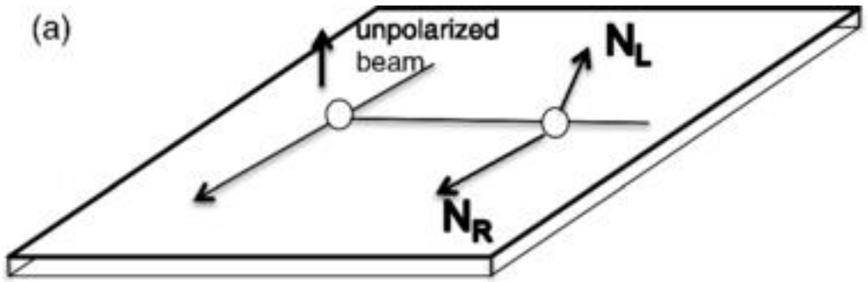


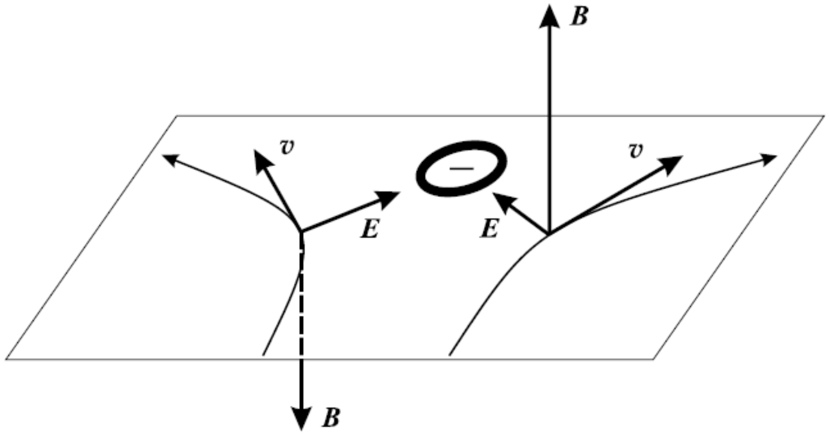
ISGE(REE)

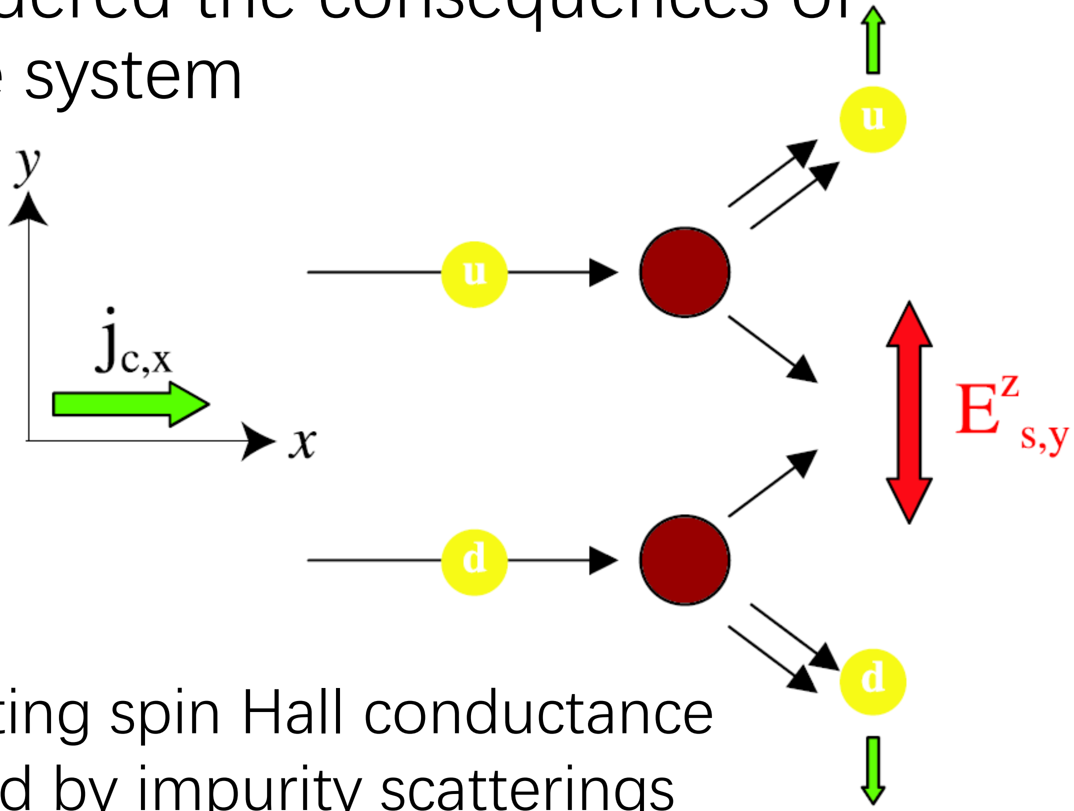
Extrinsic mechanism: skew scattering

originated in the Mott scattering by Mott in 1929 and 1931

phenomenological theory that considered the consequences of chiral Mott scattering in a solid-state system

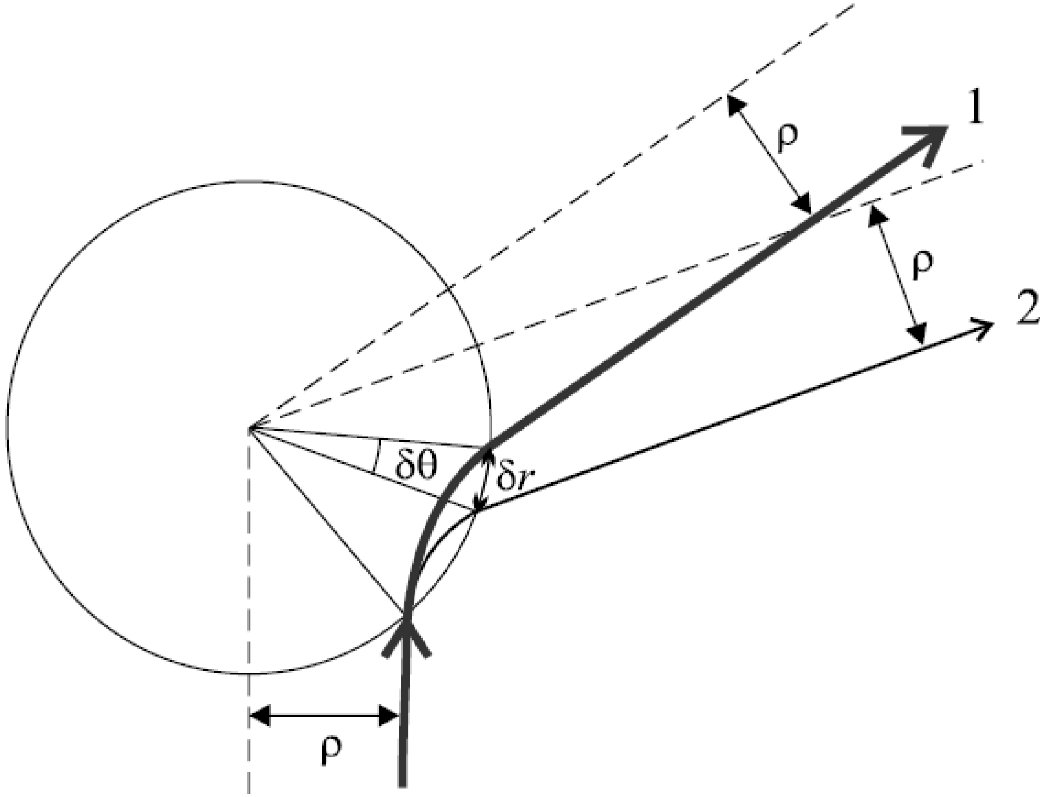




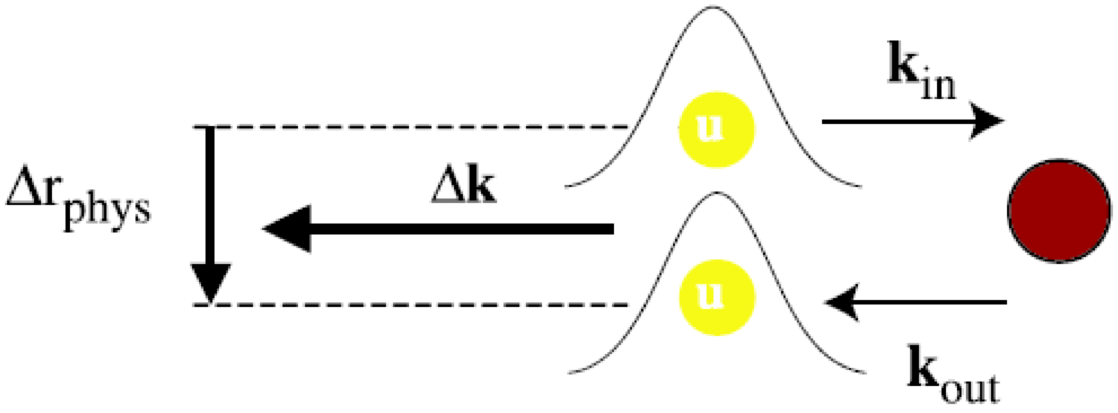


for evaluating spin Hall conductance contributed by impurity scatterings

Extrinsic mechanism: side jump



scattering of a spinning particle by a hard sphere: 1. with SOC, 2. without SOC
the side jump ***δr***



Wave packet scattering

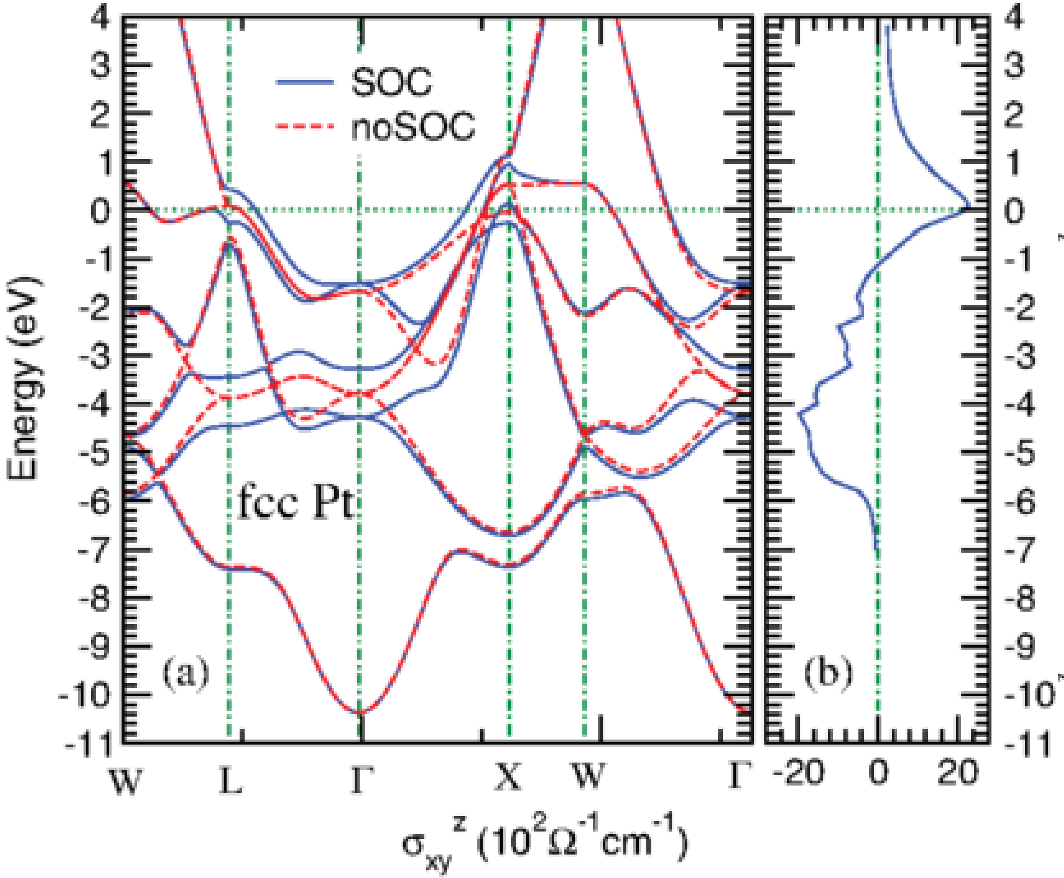
introduced by Berger in 1964

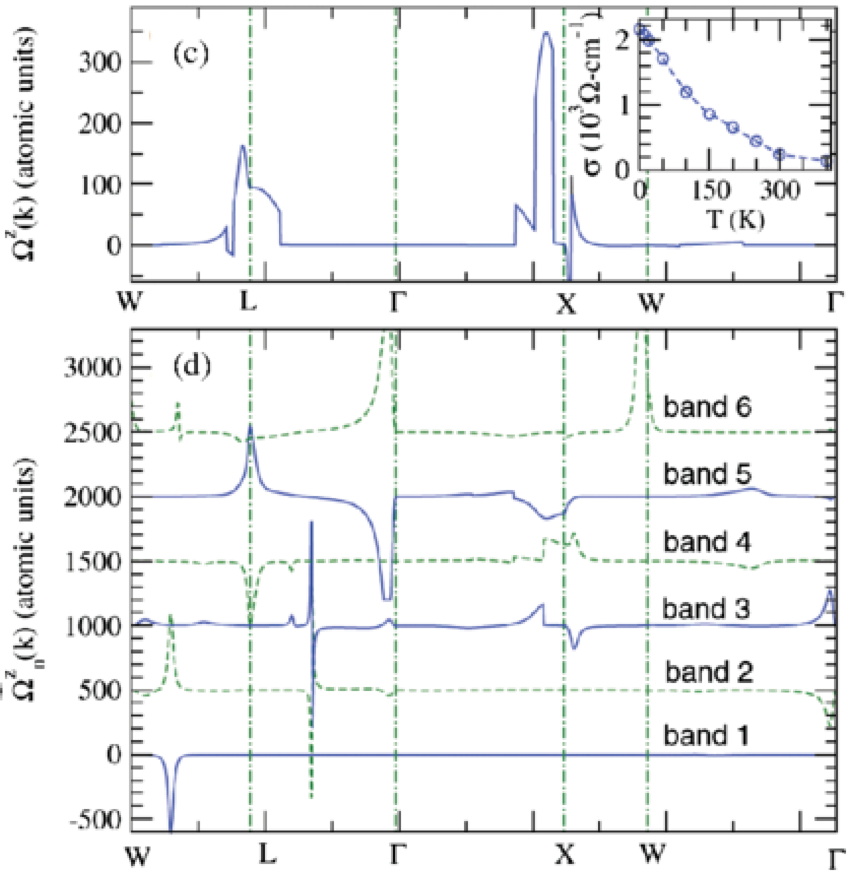
depending on specific material parameters, particularly in systems with complex band structures

Intrinsic mechanism

first derived by Karplus and Luttinger in 1954

dependent only on the band structure of the perfect crystal





materials with relatively complex electronic band structure

using microscopic *ab initio* theory

strong SOC materials especially metals

Theory of SHE

Semi-classical

Intrinsic: band structure

Extrinsic: skew scattering

Extrinsic: side jump

→

Quantum mechanical

Kubo formalism

(exact expression for the spin Hall conductivity in linear response theory)

Optical tools in spin Hall experiments

1. Optical detection of the spin Hall effect
   A. Magneto-optical Kerr effects
   B. Circularly polarized electroluminescence

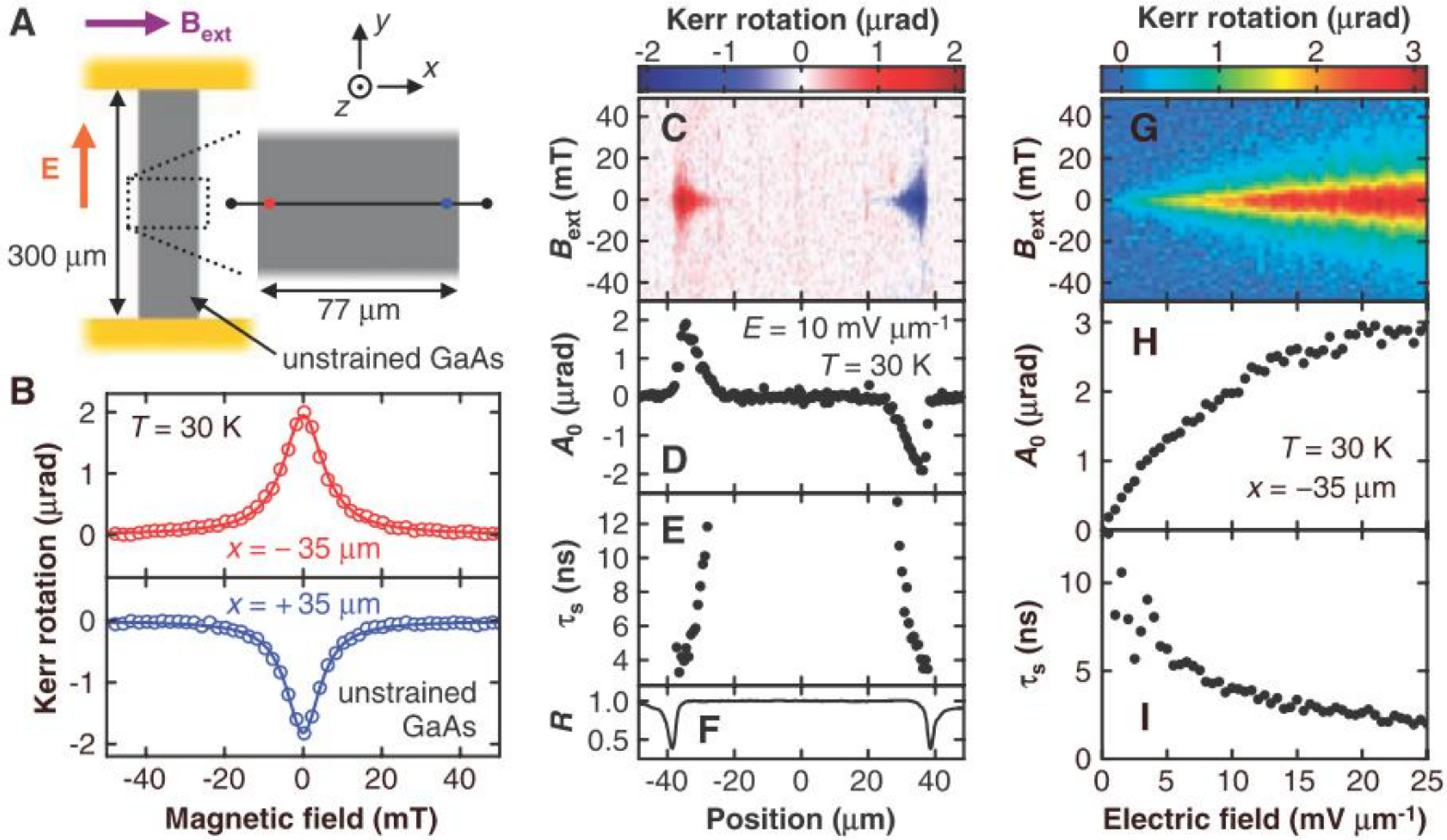
2. Optical generation of the inverse spin Hall effect
   Absorption of circularly polarized light

Magneto-optical Kerr effects

Polarized light

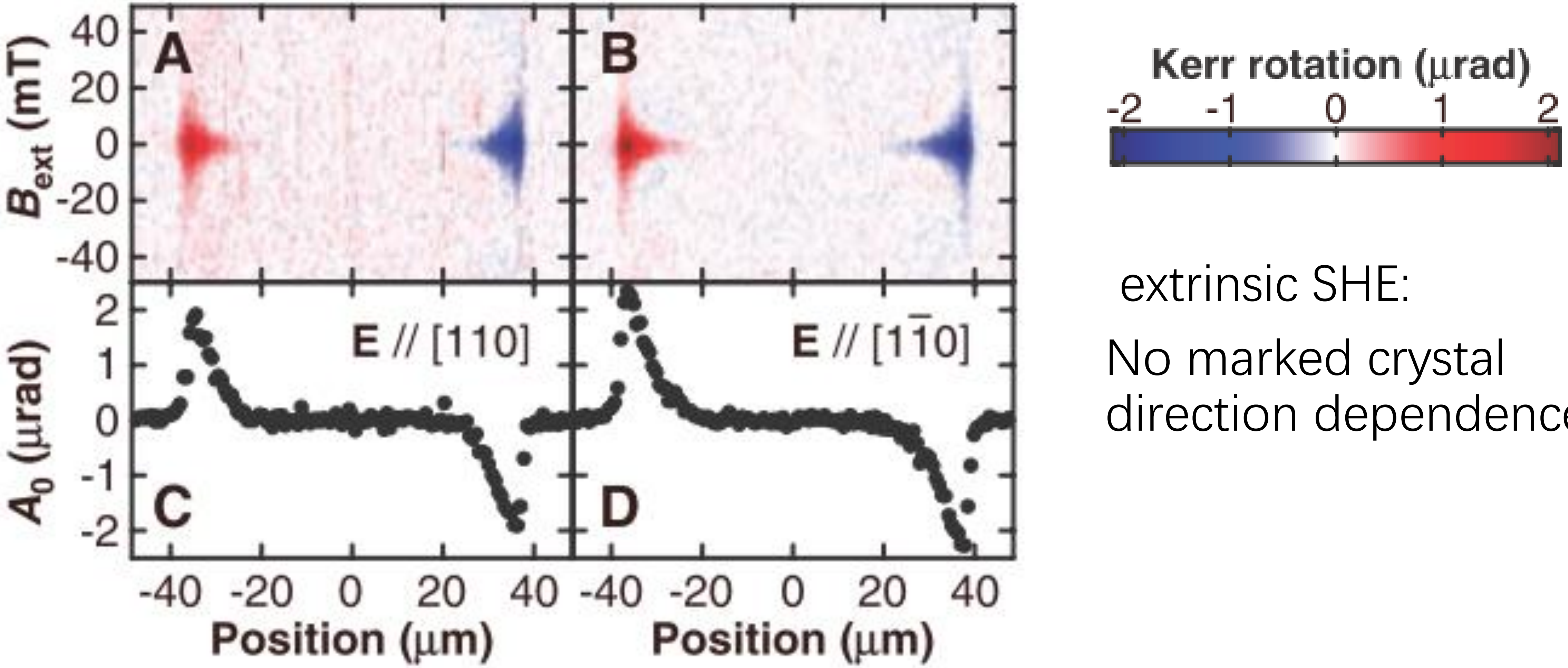
Sample

Rotated polarized reflected light



Kato, Y. K., R. C. Myers, A. C. Gossard, and D. D. Awschalom, 2004a, Science 306, 1910

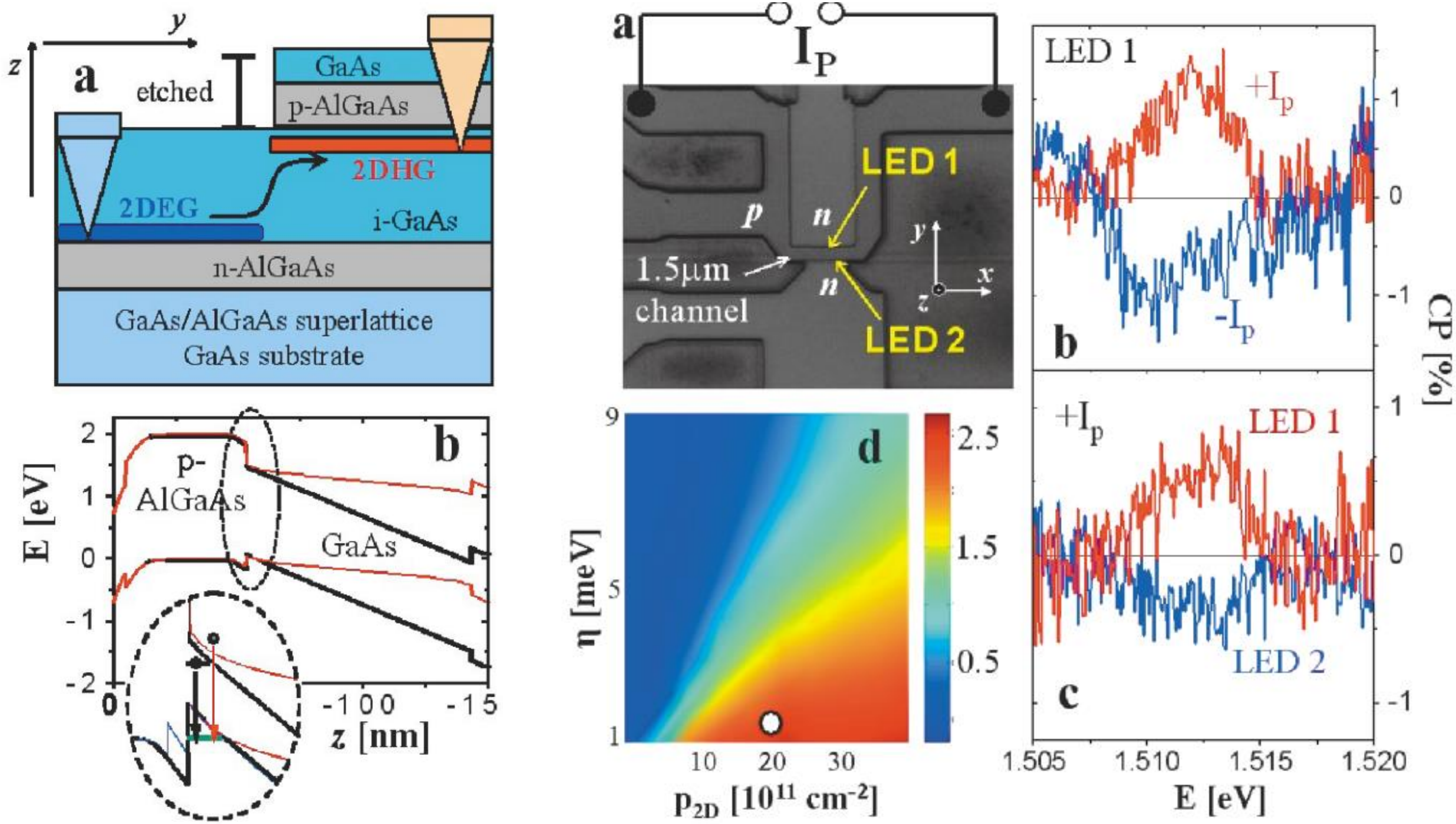
Magneto-optical Kerr effects



extrinsic SHE:

No marked crystal direction dependence

Circularly polarized electroluminescence



intrinsic
SHE

Wunderlich, J., B. Kaestner, J. Sinova, and T. Jungwirth, 2005, Phys.Rev. Lett. 94, 047204.

Absorption of circularly polarized light

NM-semiconductor hybrid structure

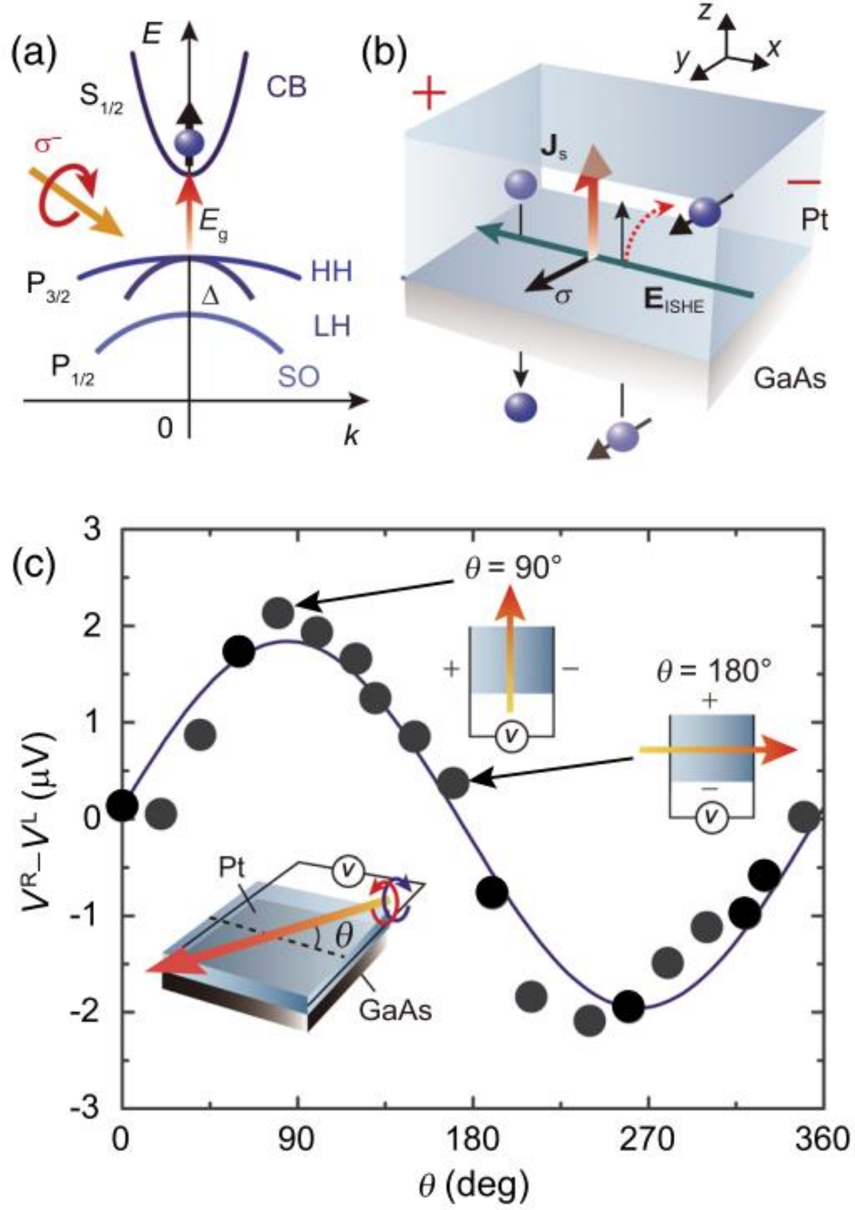
Circularly polarized light

↓ GaAs

spin-polarized carriers

↓ Pt ISHE $\mathbf{E}_{\text{ISHE}} = D_{\text{ISHE}} \mathbf{J}_s \times \boldsymbol{\sigma}$

Electrical voltage



Transport experiments

Concepts of nonlocal spin transport

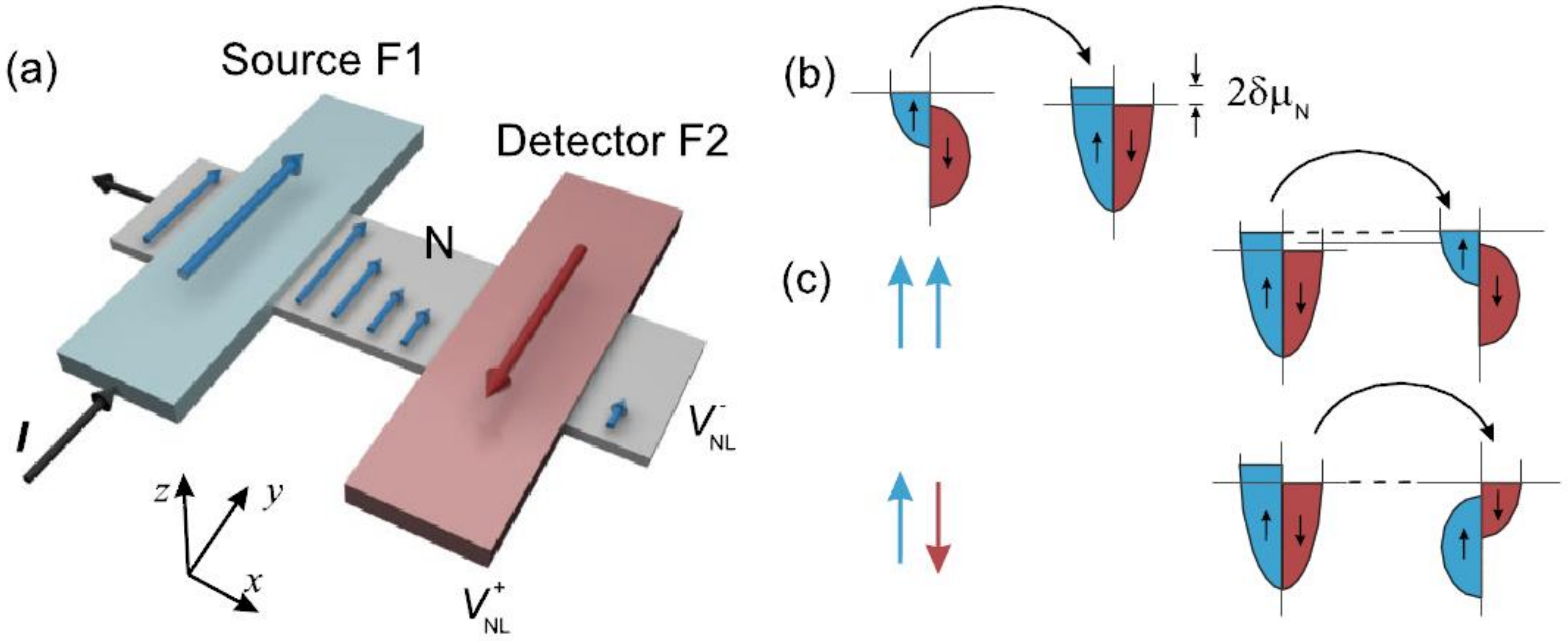


Fig.1. Nonlocal spin detection and spin accumulation.

Jairo Sinova et al. *Rev. Mod. Phys.* **87**, 1213 (2015). Johnson et al *Phys. Rev. Lett*. **55**, 1790. （1985）

Nonlocal detection with lateral spin current

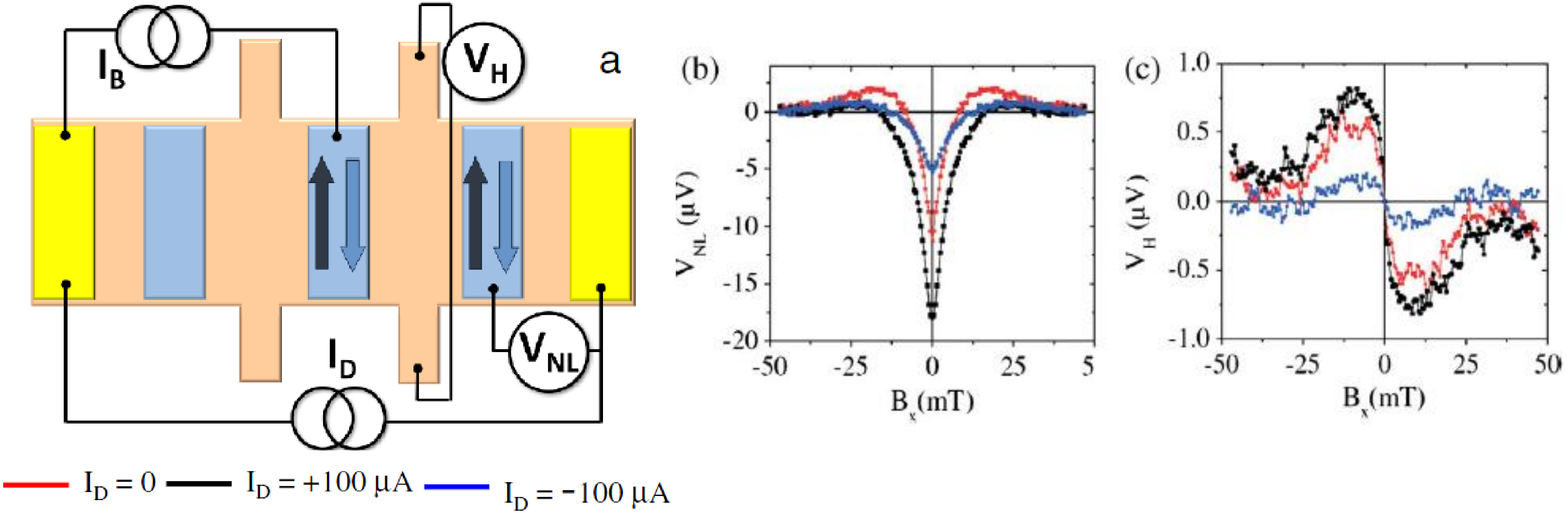


Fig.2. (a) experimental setup. (b) and (c) show the experimental symmetrized nonlocal spin-valve and antisymmetrized ISHE signals

Jairo Sinova et al. *Rev. Mod. Phys.* **87**, 1213 (2015). Olejník et al Phys. Rev. Lett. 109, 076601 (2012)

Nonlocal detection with vertical spin current

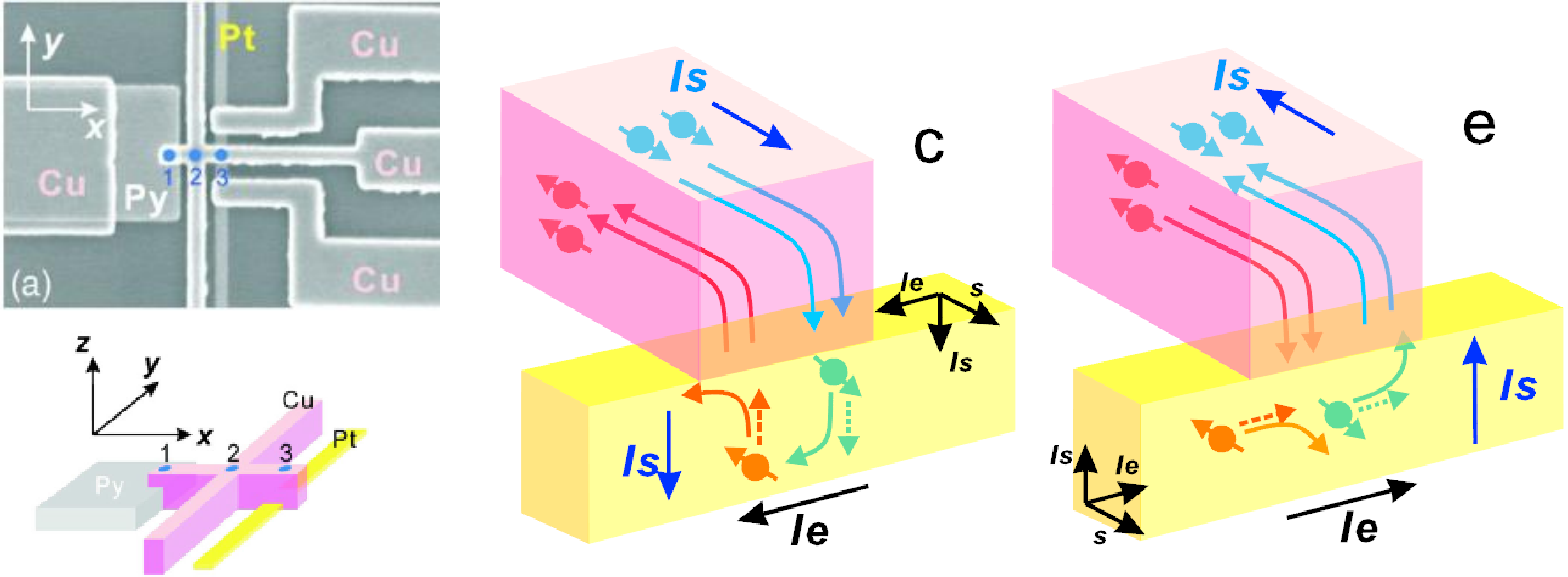


Fig.3. (a) experimental setup; (c) show charge accumulation process in the Pt wire (e) charge to spin-current conversion

Jairo Sinova et al. *Rev. Mod. Phys.* **87**, 1213 (2015). T. Kimura et al. Phys. Rev. Lett. 98, 156601 (2007)

Nonlocal detection with vertical spin current

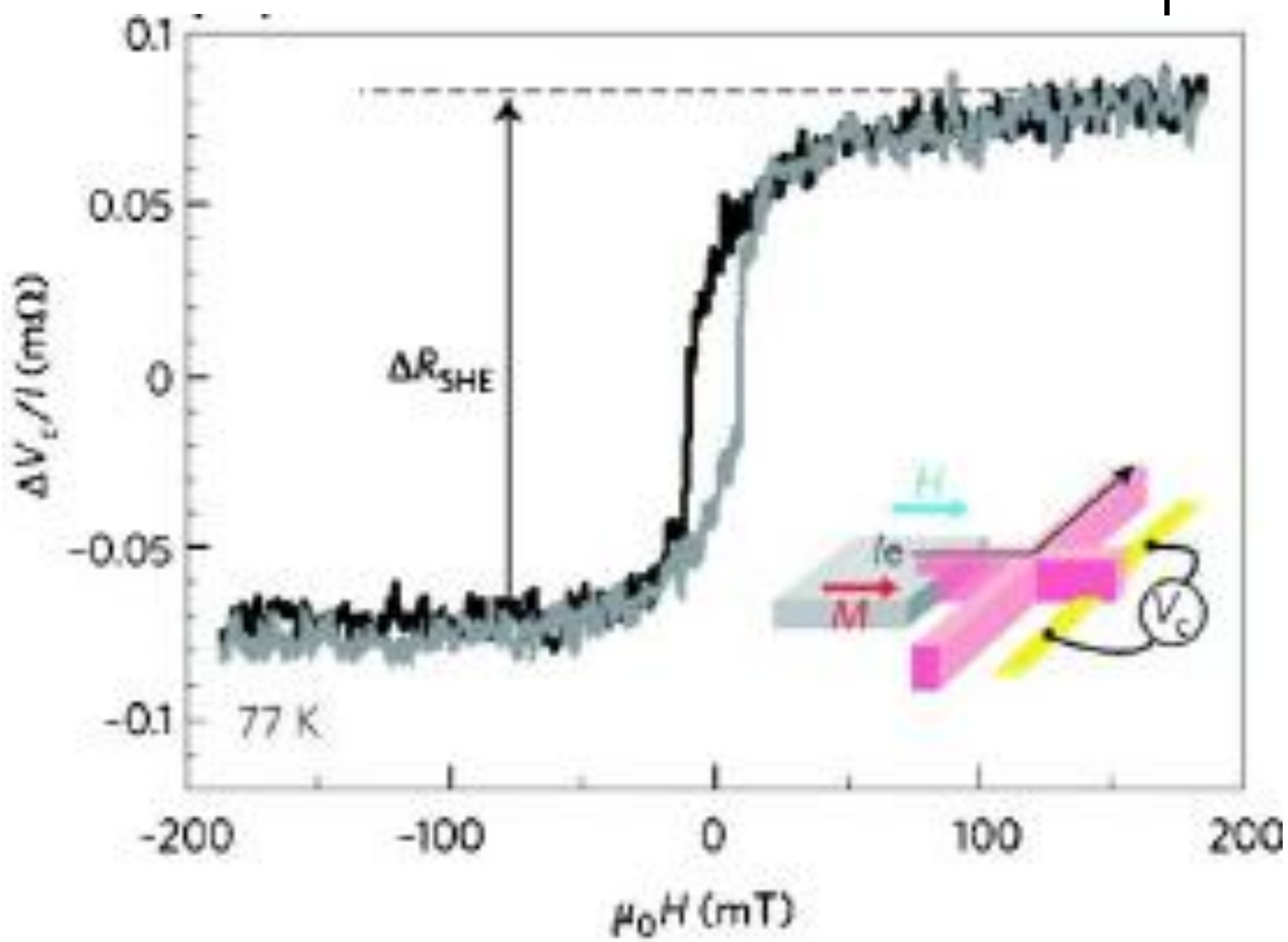
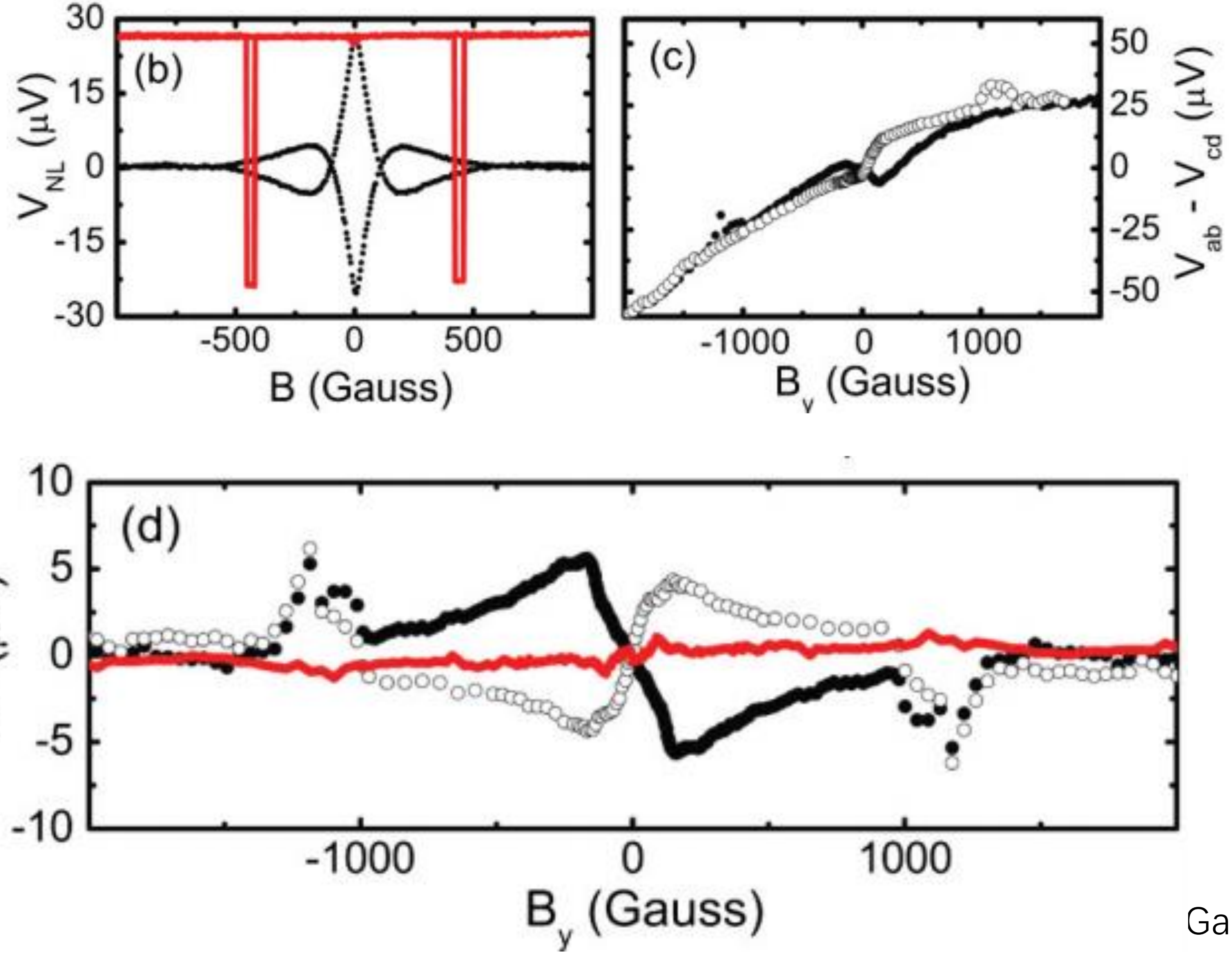
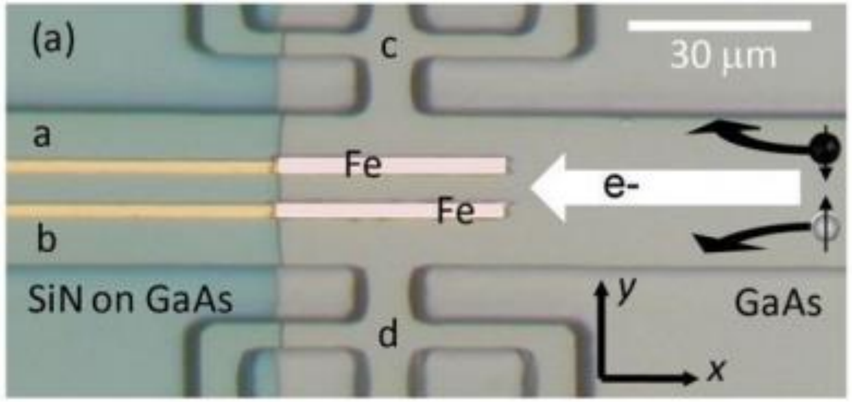


Fig.3. (b) shows the change in Hall △Vc/I due to the inverse spin Hall effect(SHE)

Jairo Sinova et al. *Rev. Mod. Phys.* **87**, 1213 (2015). T. Kimura et al. Phys. Rev. Lett. 98, 156601 (2007)

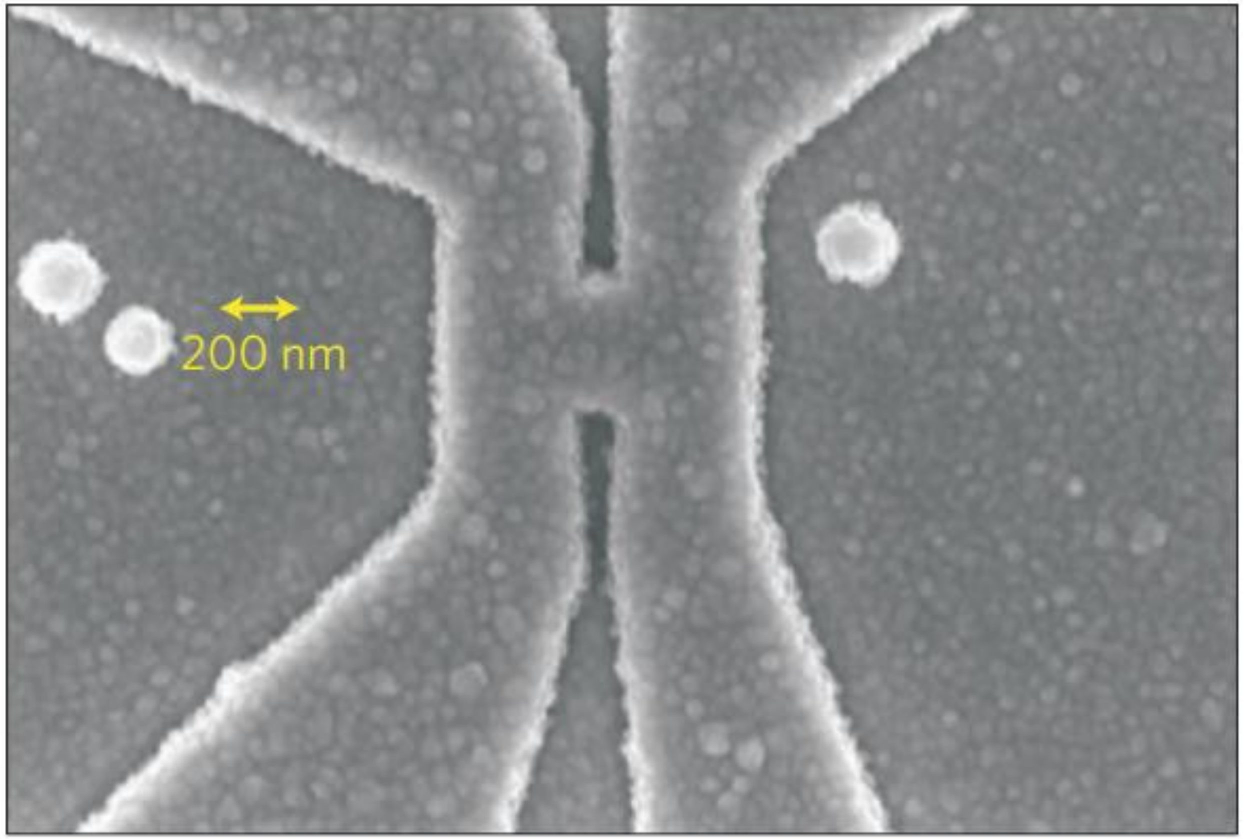
Direct detection of the spin Hall induced spin accumulation

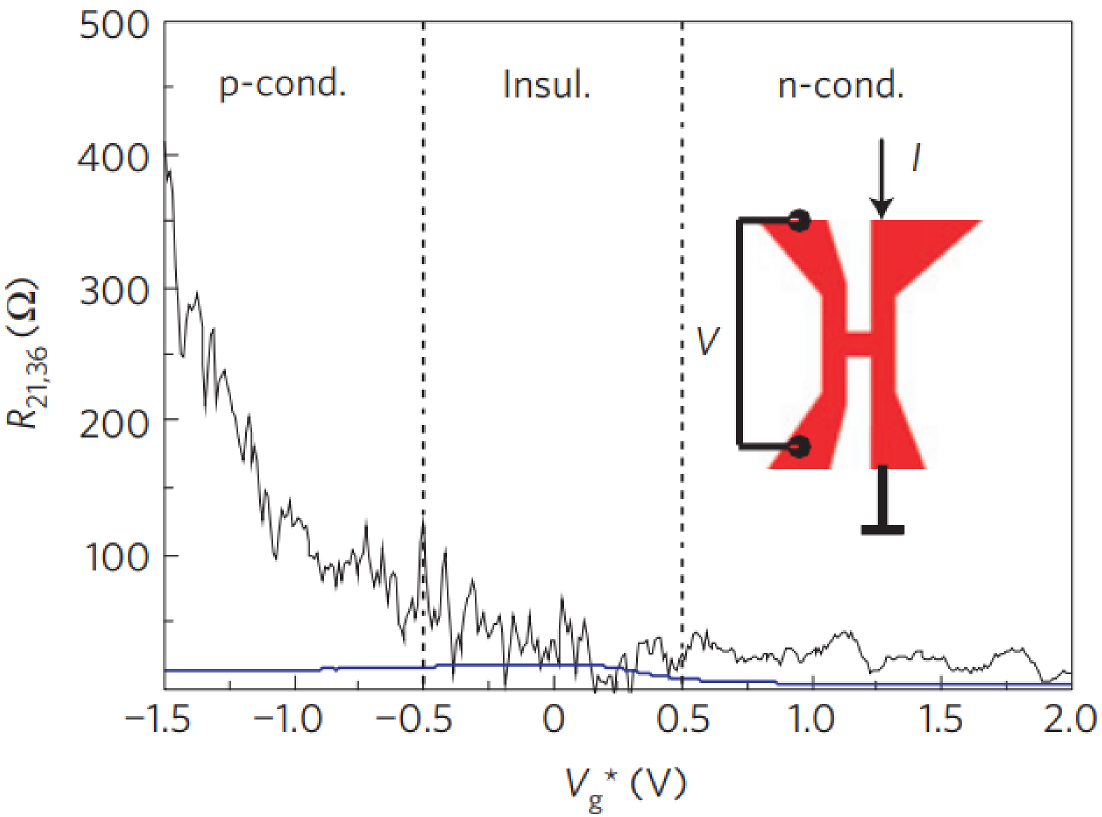




Garlid et al. Phys. Rev. Lett. 105, 156602 (2010)

Detection without ferromagnets





C. Brüne et al. Nat. Phys. 6, 448 (2010)

Spin Hall effect coupled to magnetization dynamics

Ferromagnetic resonance spin pumping

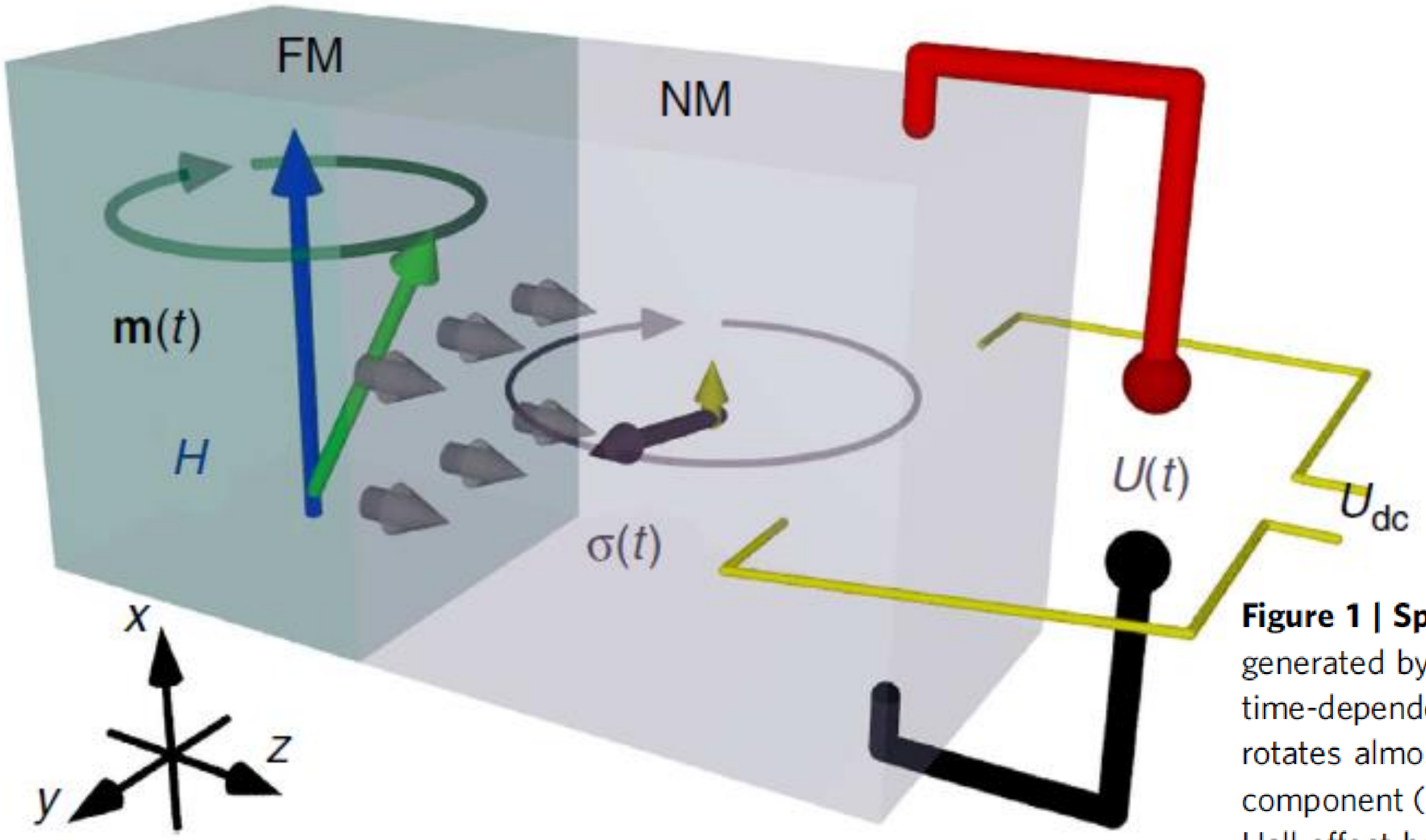
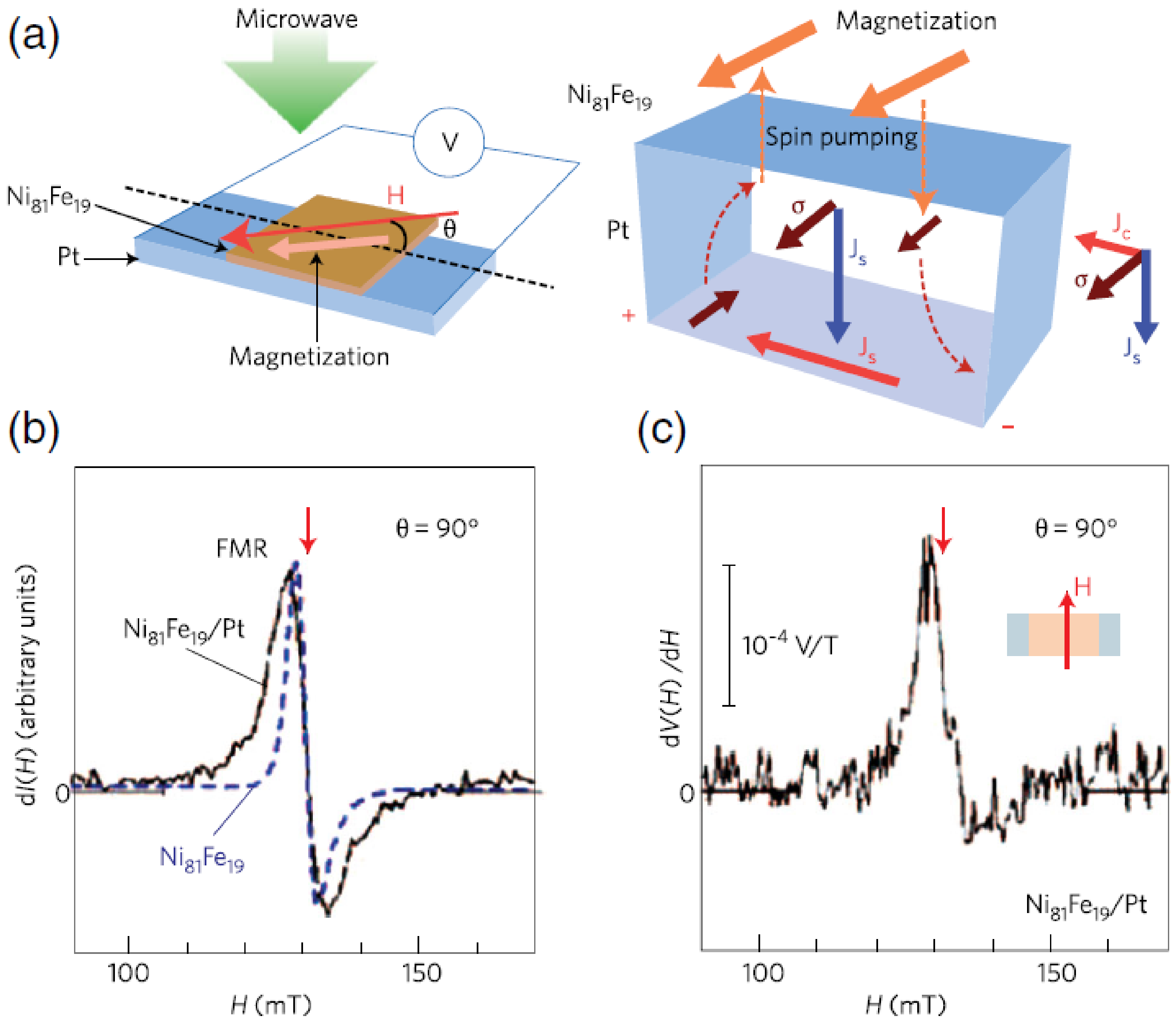


Figure 1 | Spin pumping and ISHE voltage signal. A spin current is generated by spin pumping at the FM–NM interface (grey arrows). The time-dependent spin polarization of this current (indicated as purple arrow) rotates almost entirely in the *y*–*z* plane. The small time-averaged d.c. component (yellow arrow) appears along the *x* axis. Due to the inverse spin Hall effect both components lead to charge currents in NM and can be converted into a.c. and d.c. voltages by placing probes along the *x* and *y* directions, respectively.

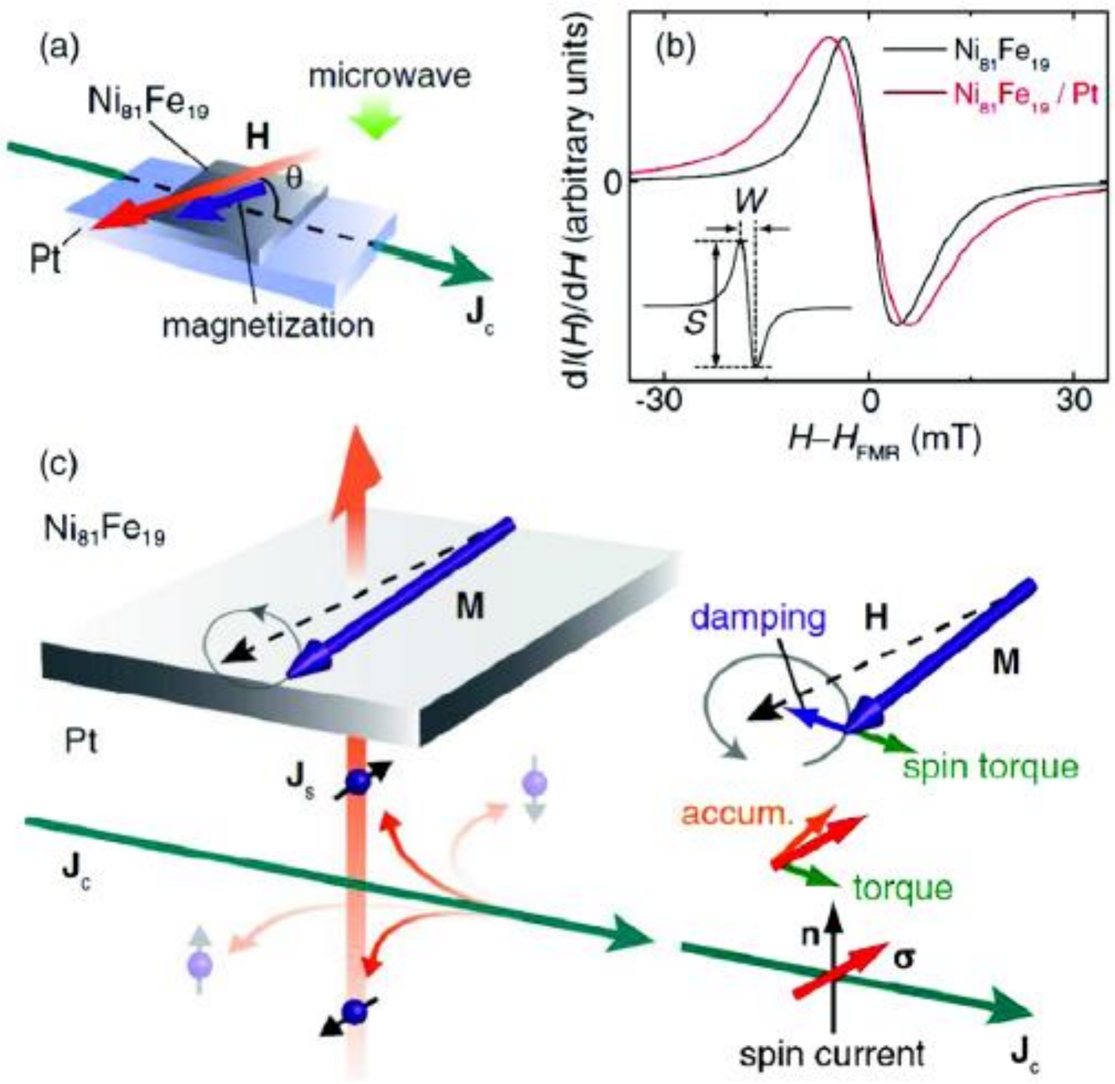
Dahai Wei， et al, NComms 2014

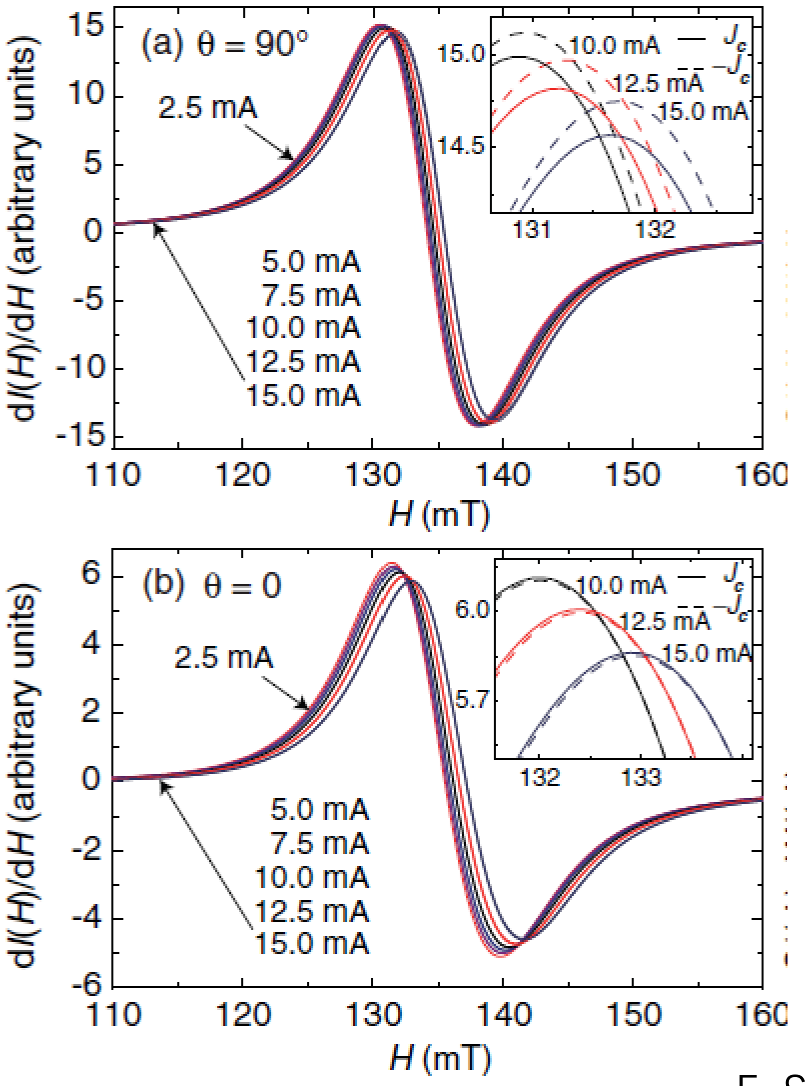
Ferromagnetic resonance spin pumping

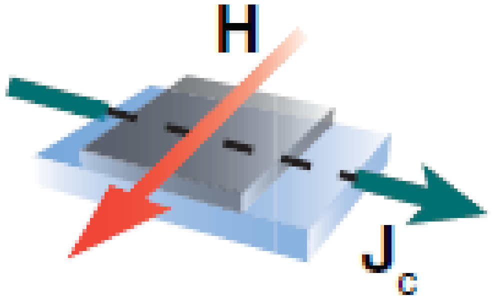


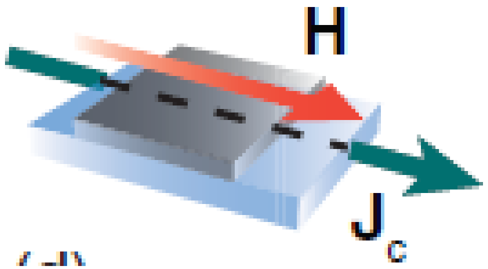
E. Saitoh， et al, APL 2006

Spin Hall effect modulation of magnetization damping









E. Saitoh， et al, PRL 2008

Spin-transfer torque

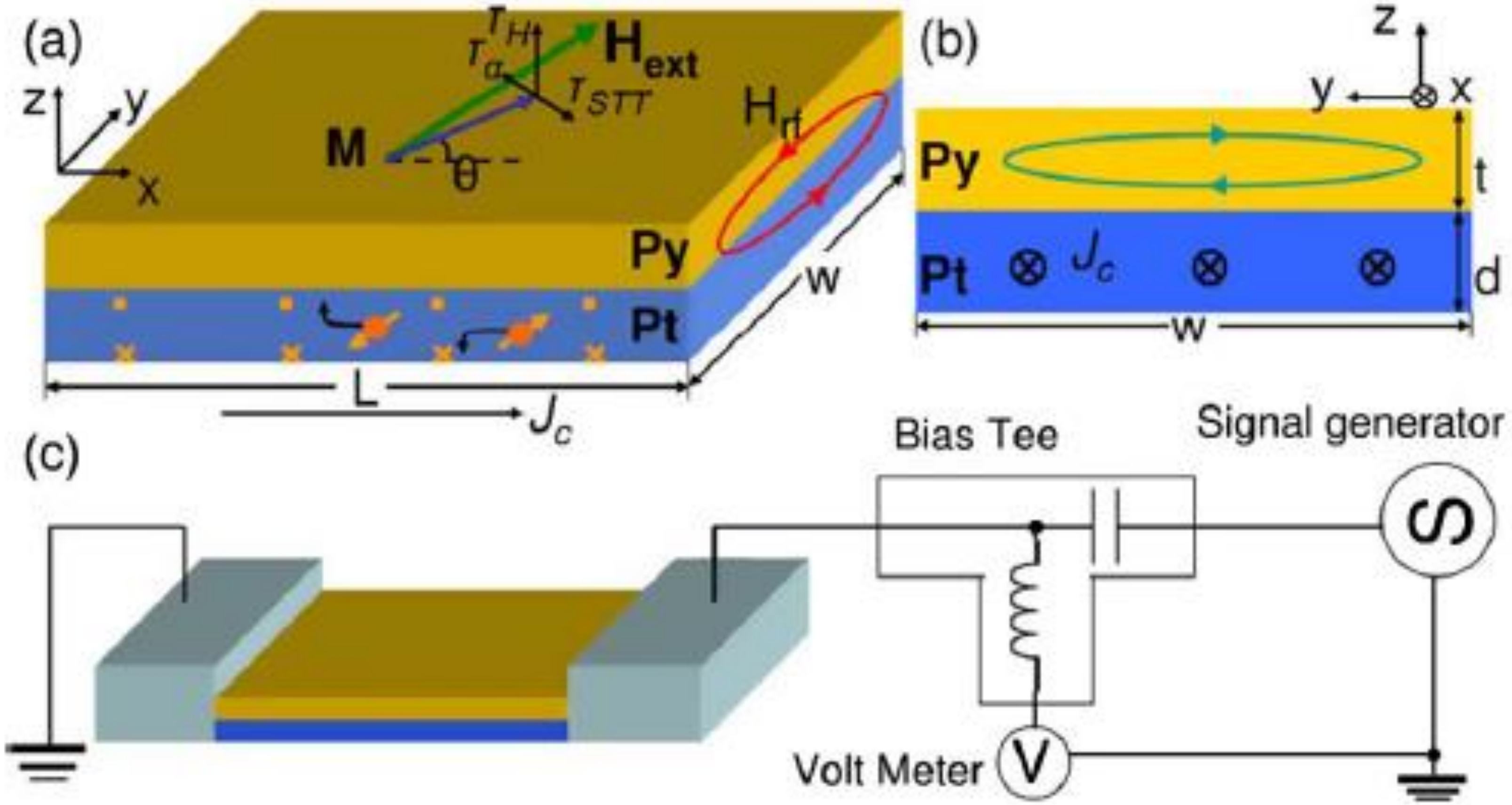
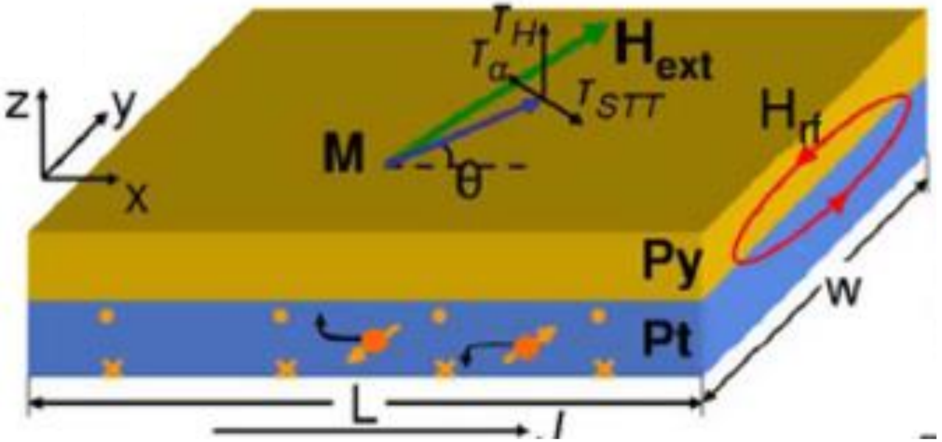
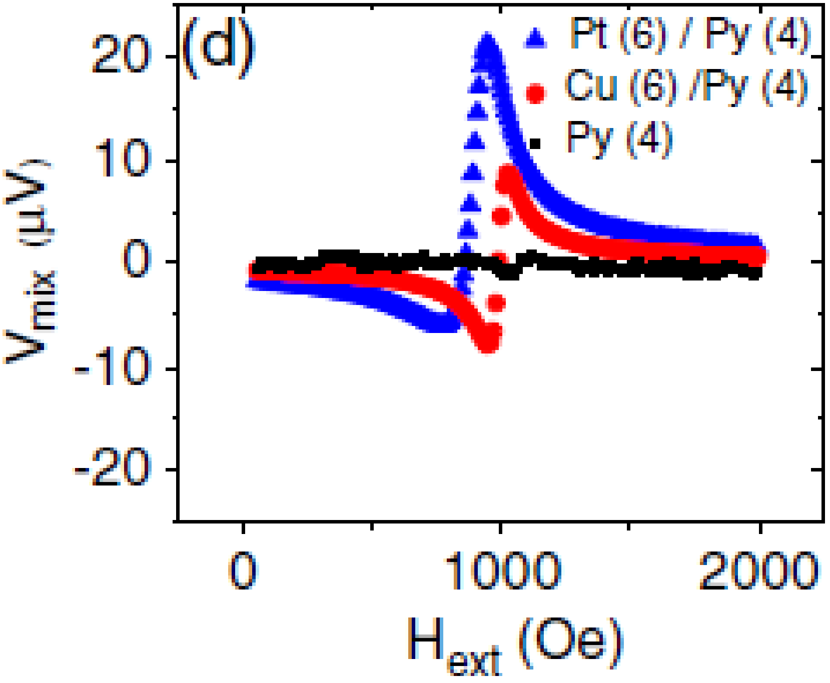


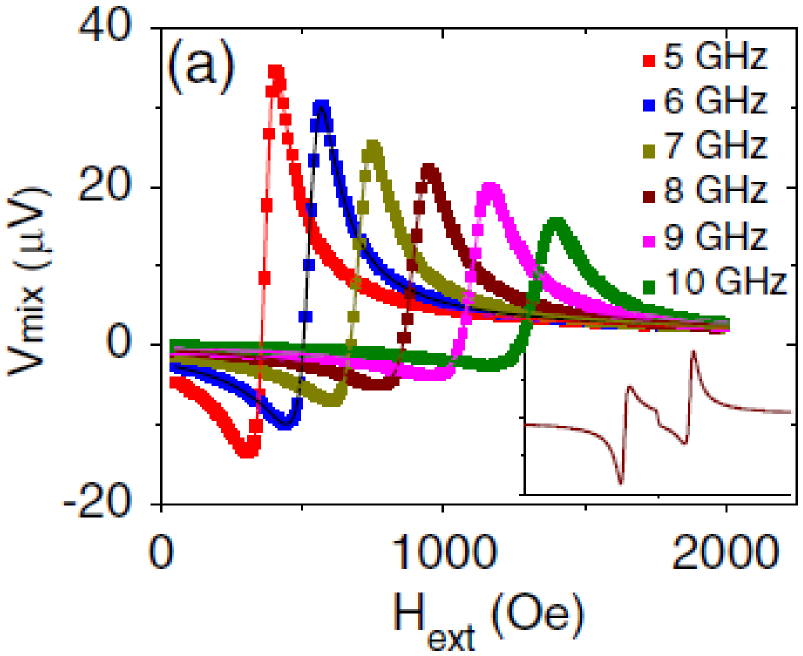
FIG. 1 (color online). (a) Schematic of a Pt/Py bilayer thin film illustrating the spin transfer torque τ_{STT}, the torque τ_H induced by the Oersted field H_{rf}, and the direction of the damping torque τ_α. θ denotes the angle between the magnetization $\boldsymbol{M}$ and the microstrip. H_{ext} is the applied external field. The spin Hall effect causes spins in the Pt pointing out of the page to be deflected towards the top surface, generating a spin current incident on the Py. (b) Left-side view of the Pt/Py system, with the solid line showing the Oersted field generated by the current flowing just in the Py layer, which should produce no net effect on the Py anisotropic magnetoresistance. (c) Schematic circuit for the ST-FMR measurement.

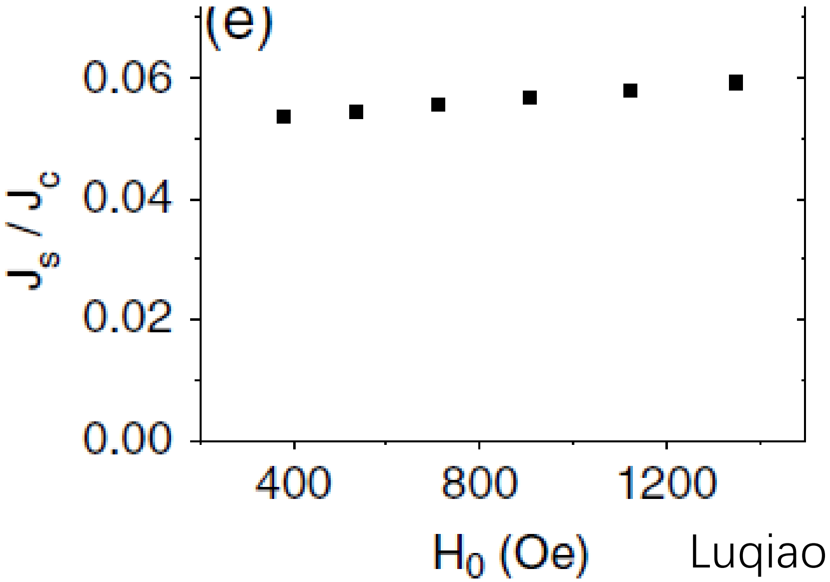
Luqiao Liu， et al, PRL 2011

Spin-transfer torque



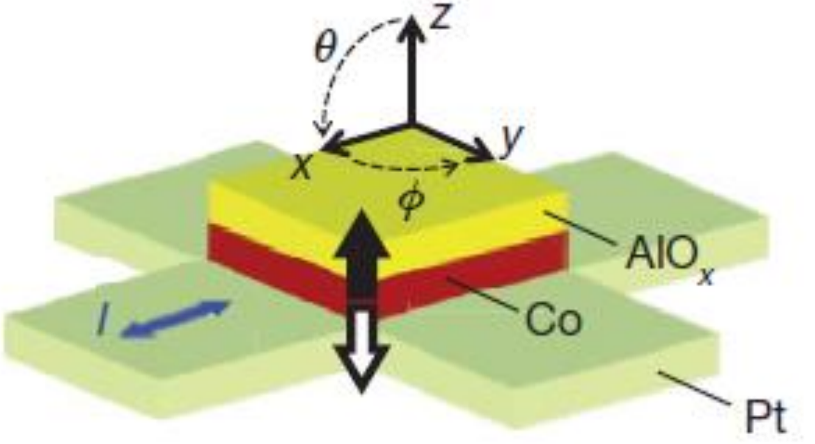


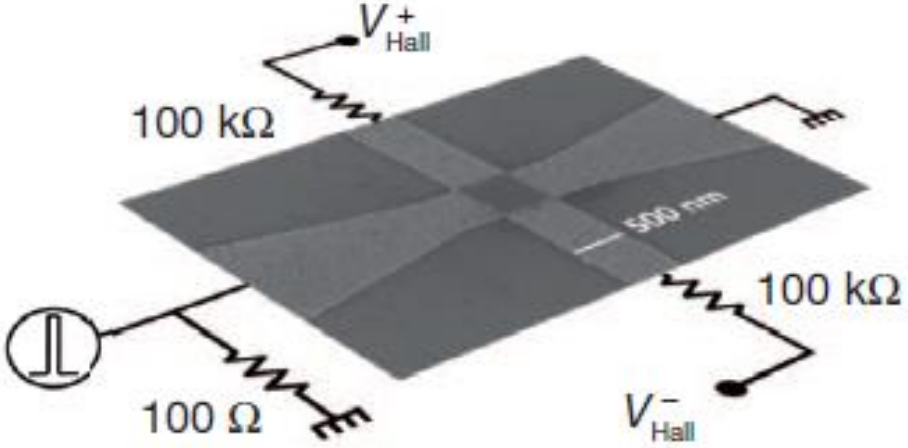


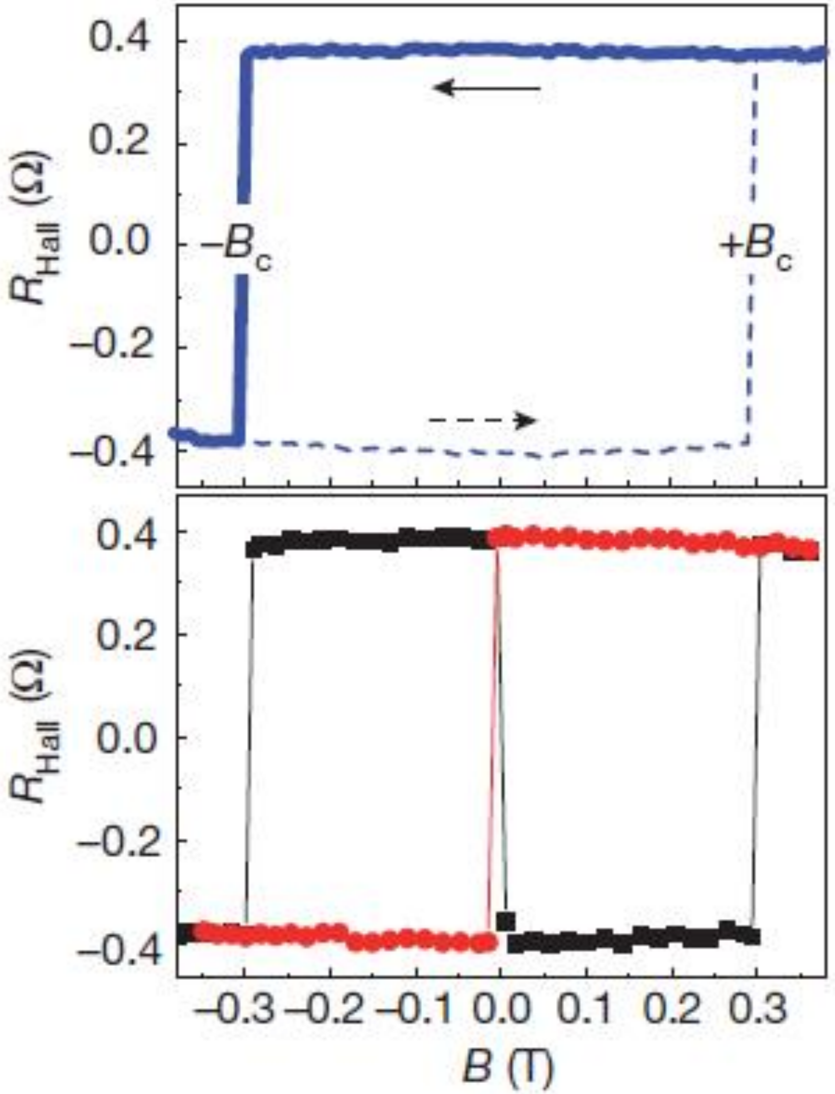


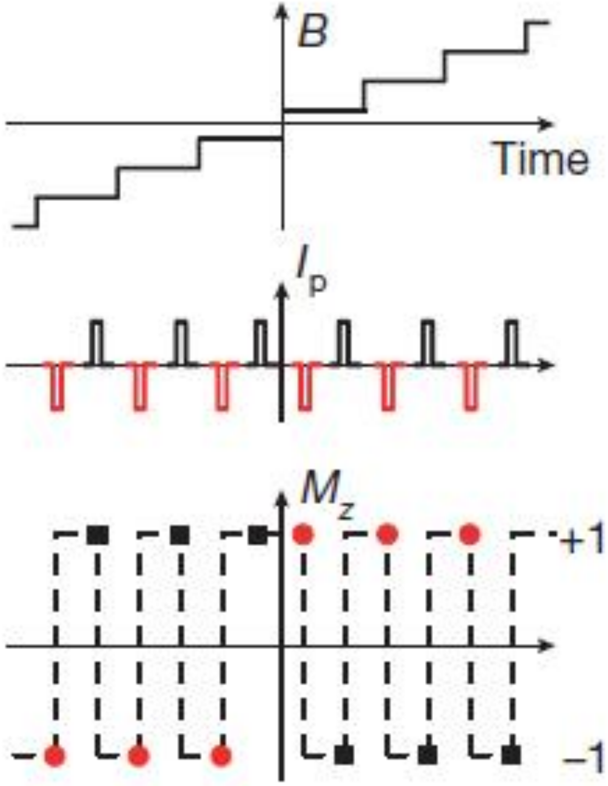
Luqiao Liu， et al, PRL 2011

Spin Hall effect induced switching of the magnetization



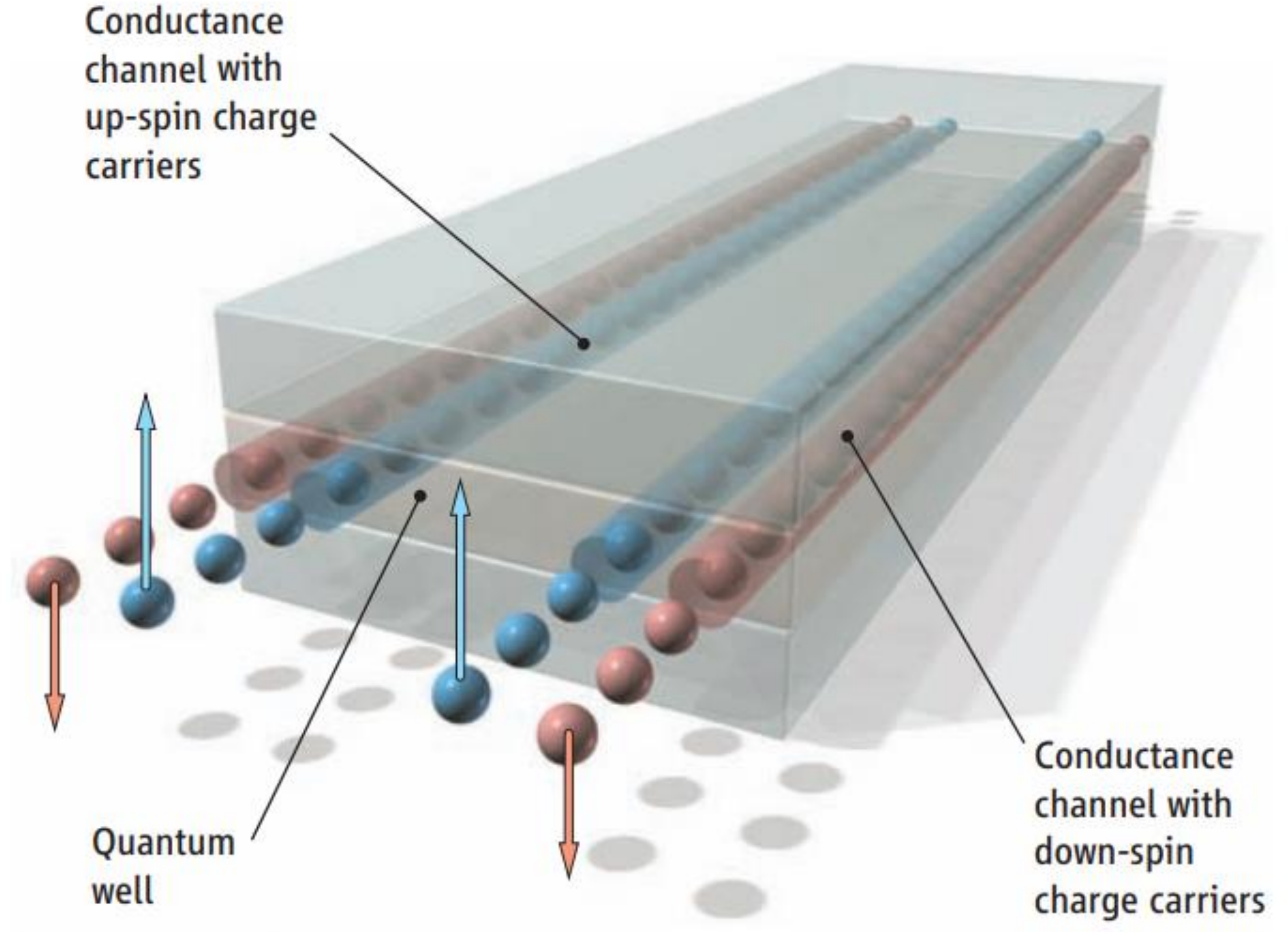






Ioan Mihai Miron， et al, Nature 2011

QSHE

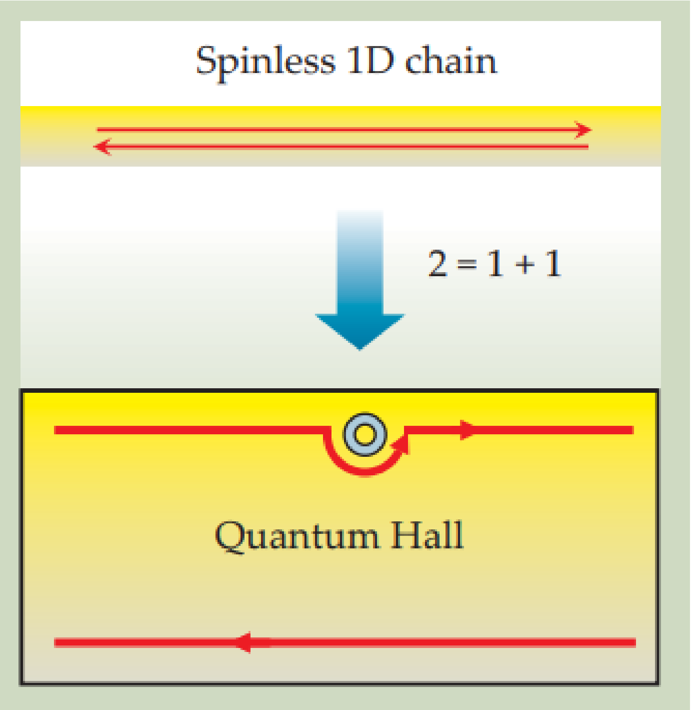


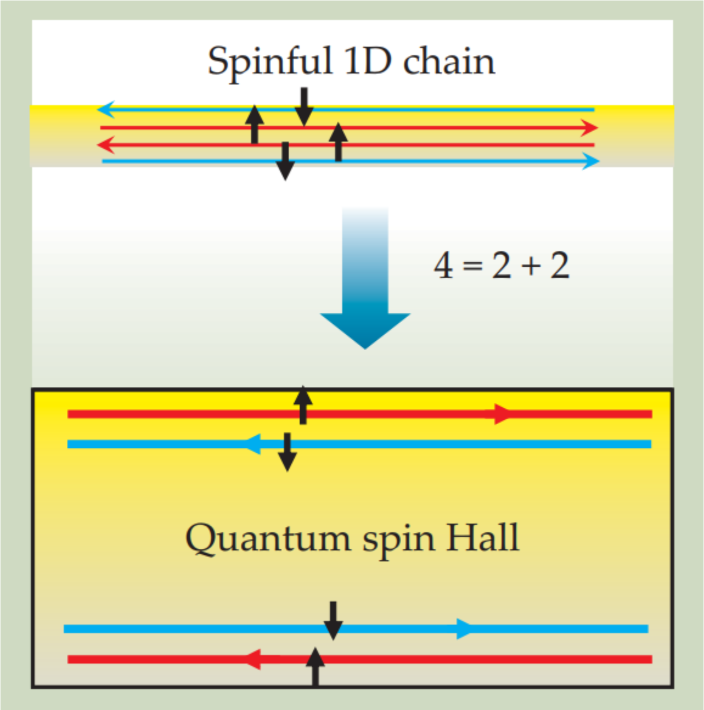
Schematic of the spin-polarized edge channels in a quantum spin Hall insulator.

Carriers with opposite spins move in opposite directions on a given edge

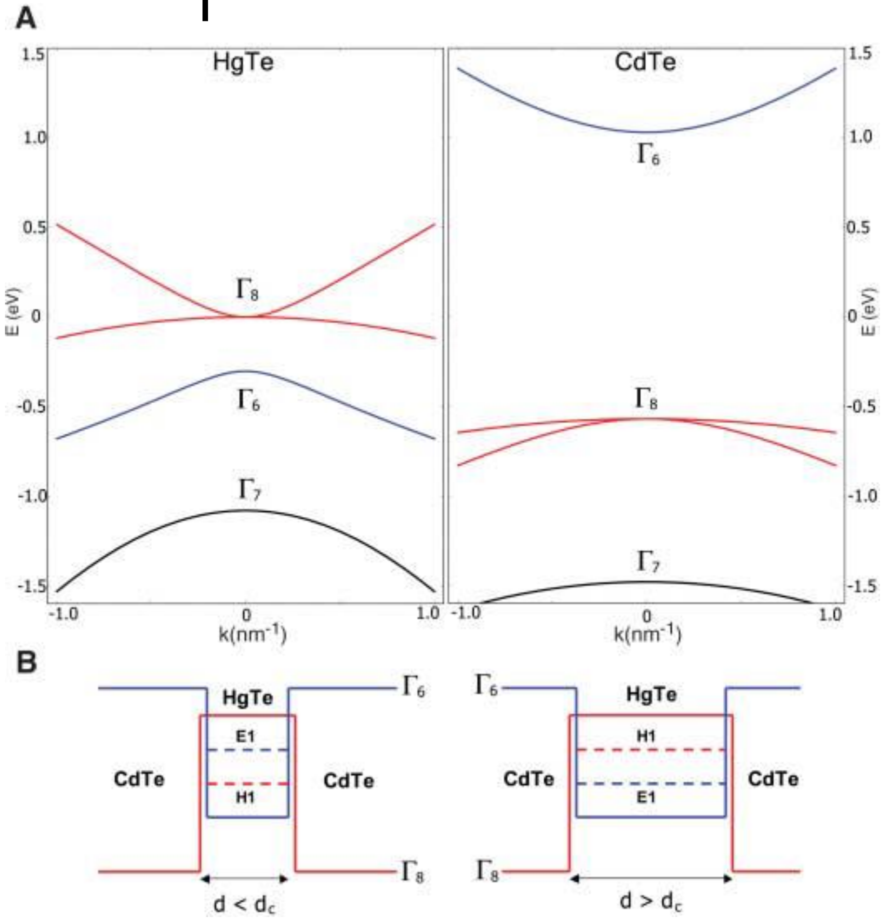
QSHE

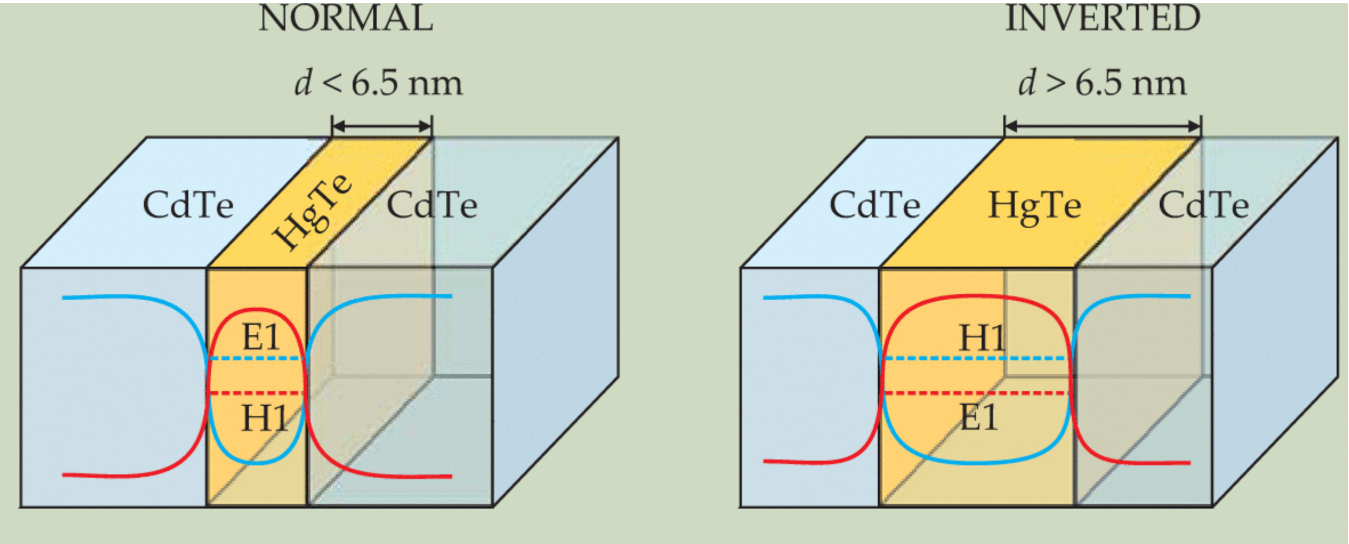
- Insulating in the bulk
- Gapless edge or surface states
- Time-reversal symmetry

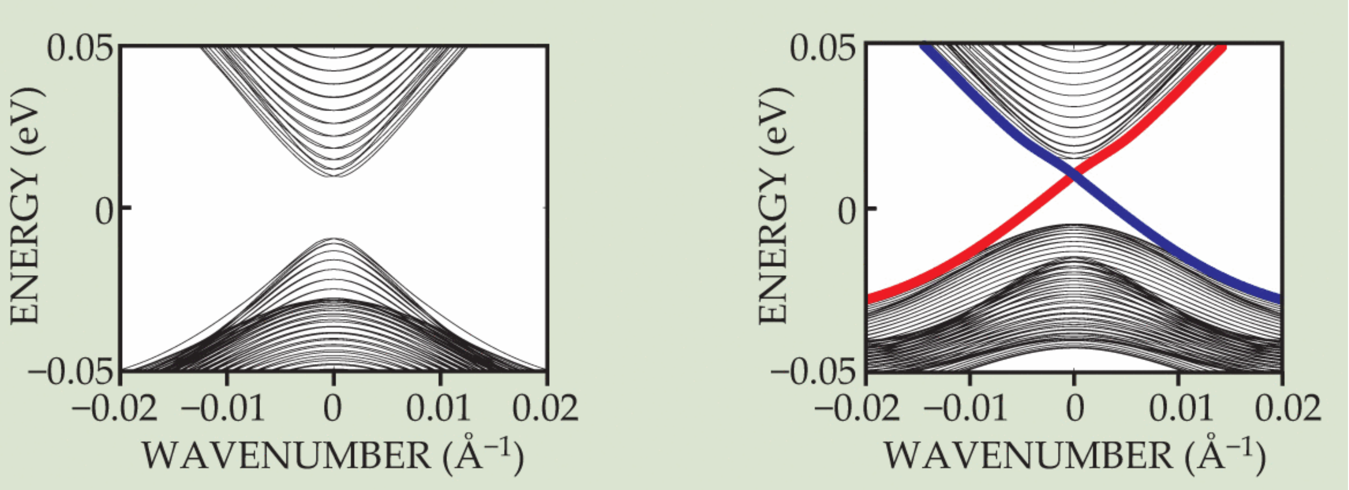




Proposal







HgTe QW

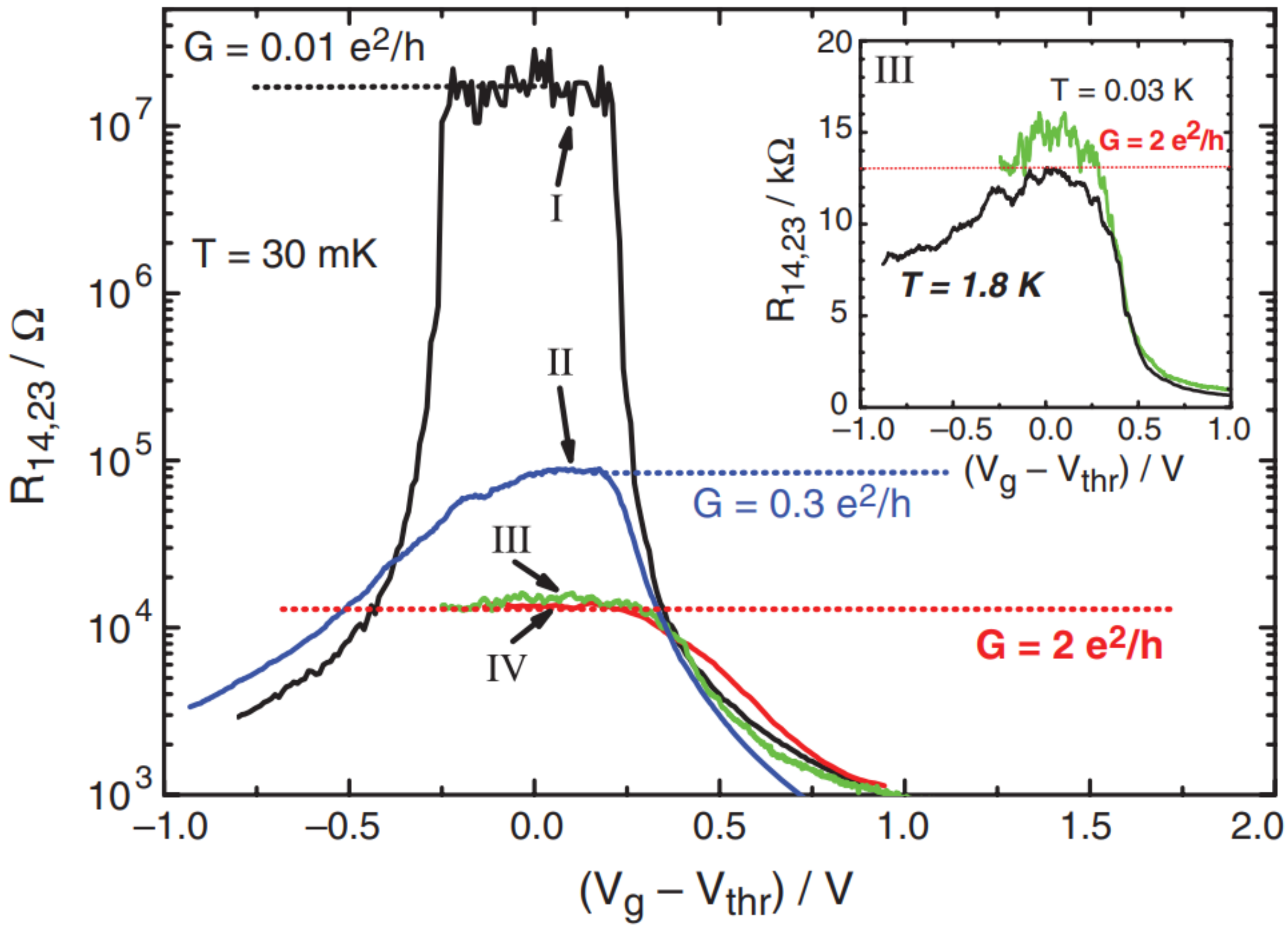
Bulk HgTe has inverted band, CdTe normal band.

The thickness of HgTe has a critical value 6.5nm.

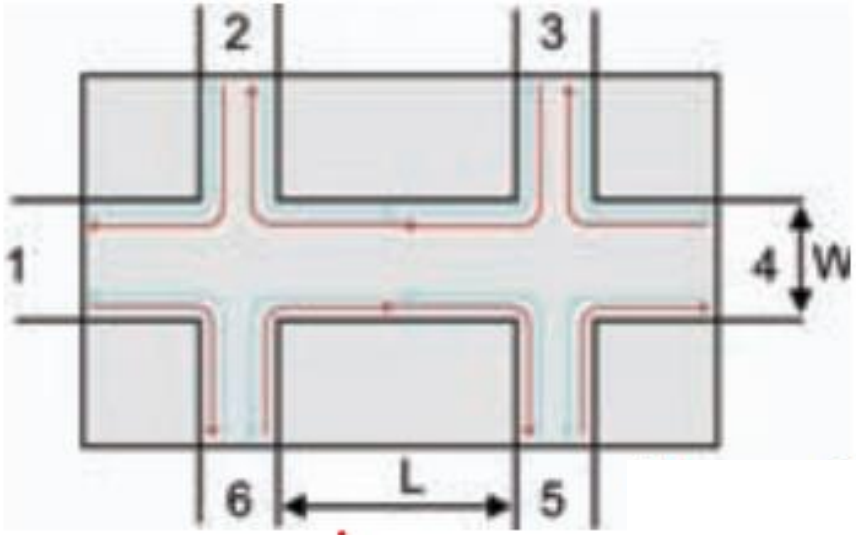
B. A. Bernevig et al. Science 314 (5806), 1757-1761 (2006).

Experiment

HgTe/CdTe Quantum well



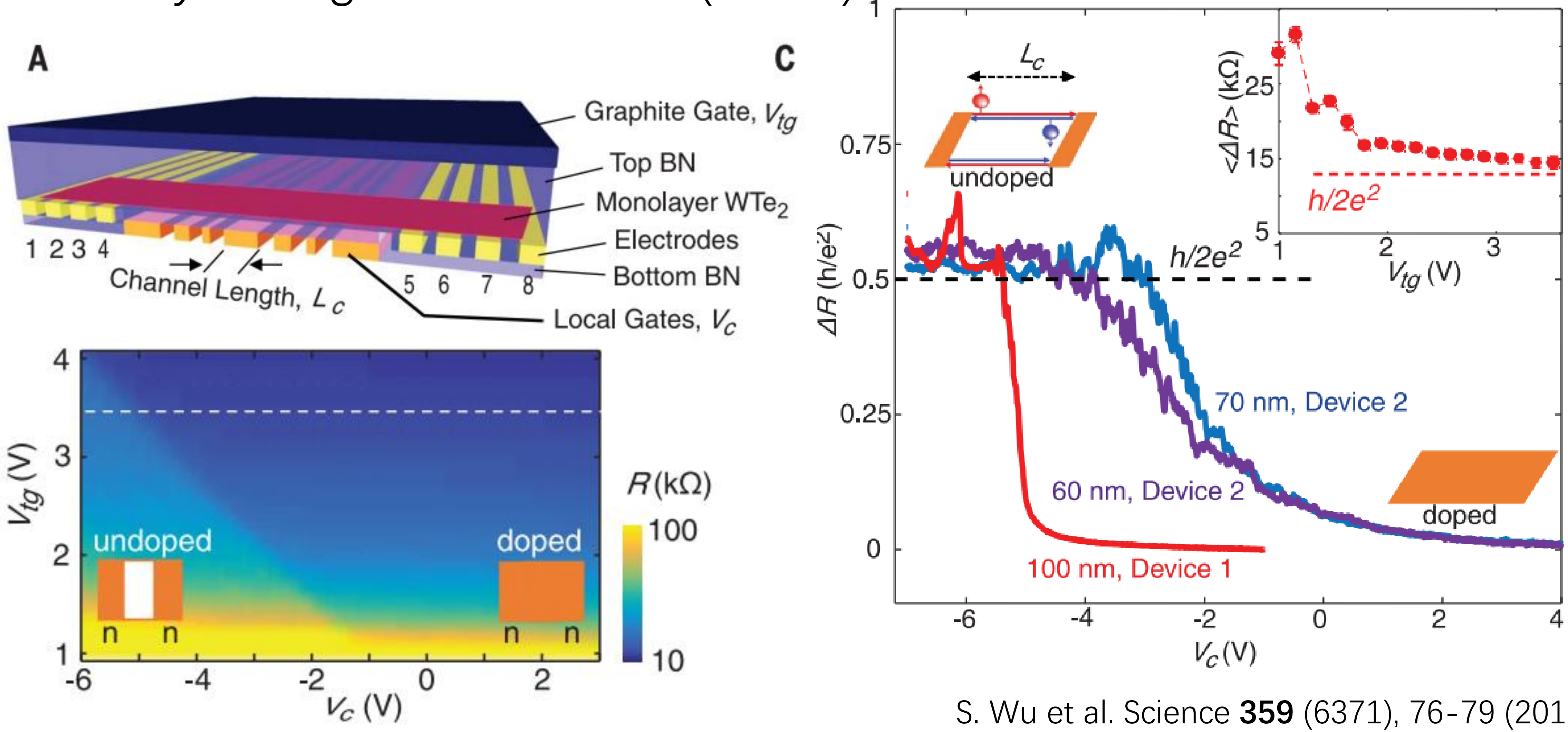
	Length/ um	Width/ um	d /nm	Band structure
I	20.0	13.3	5.5	Normal band
II	20.0	13.3	7.3	Inverted band
III	1.0	1.0	7.3	
IV	1.0	0.5	7.3	



M. Konig et al. Science **318** (5851), 766-770 (2007).

QSHE

monolayer tungsten ditelluride (WTe2)



S. Wu et al. Science **359** (6371), 76-79 (2018).

Question Time

Thanks for your attention!