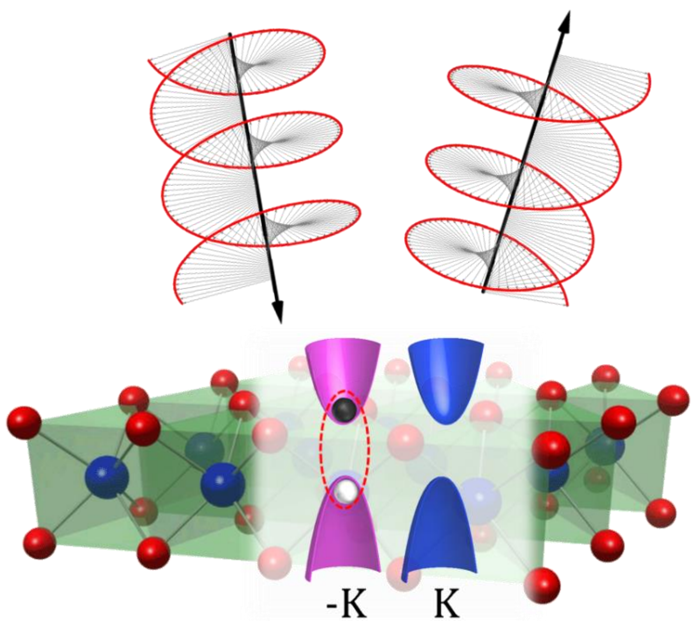
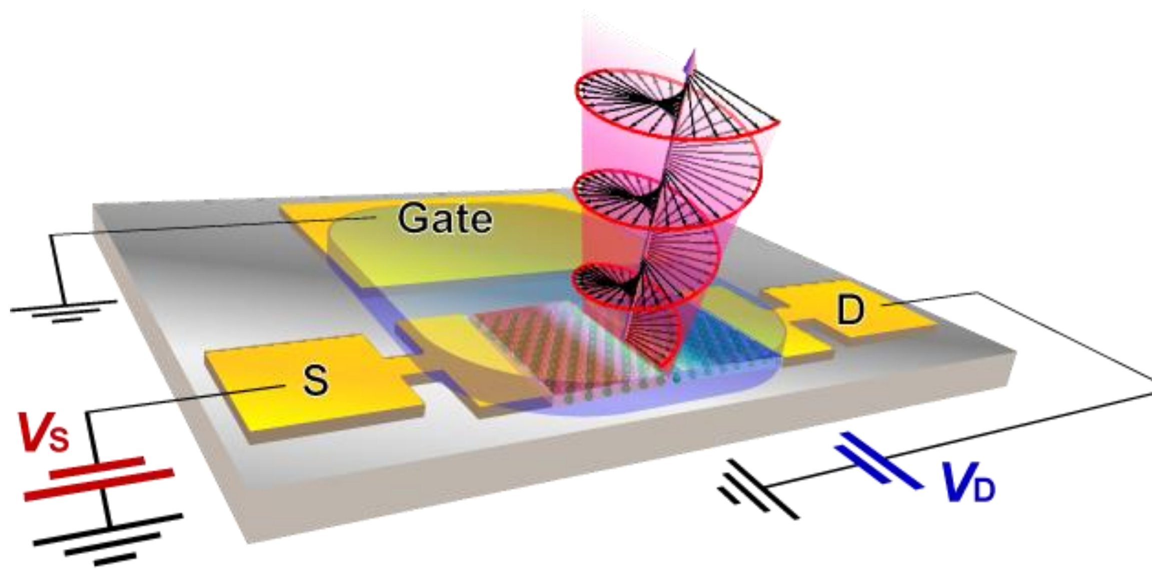
Chiral electroluminescence from 2D material based transistors

Y. Iwasa

University of Tokyo & RIKEN CEMS





Acknowledgements

Materials/Devices

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Y. Kasahara (Kyoto)

SARPES

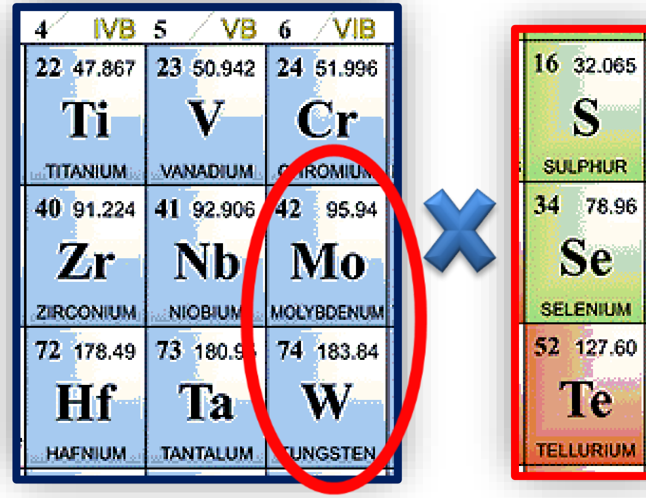
M. Sakano, K. Ishizaka (Tokyo)
S. Shin, K. Yaji(ISSP)
K. Miyamoto, T. Okuda (HIroshima)

Theory

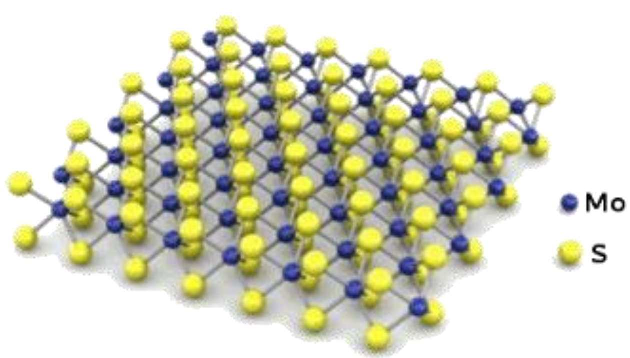
T. Oka (Tokyo)

Transition Metal Dichalcogenides (TMD, MX_2)

MoS_2 known as lubricant

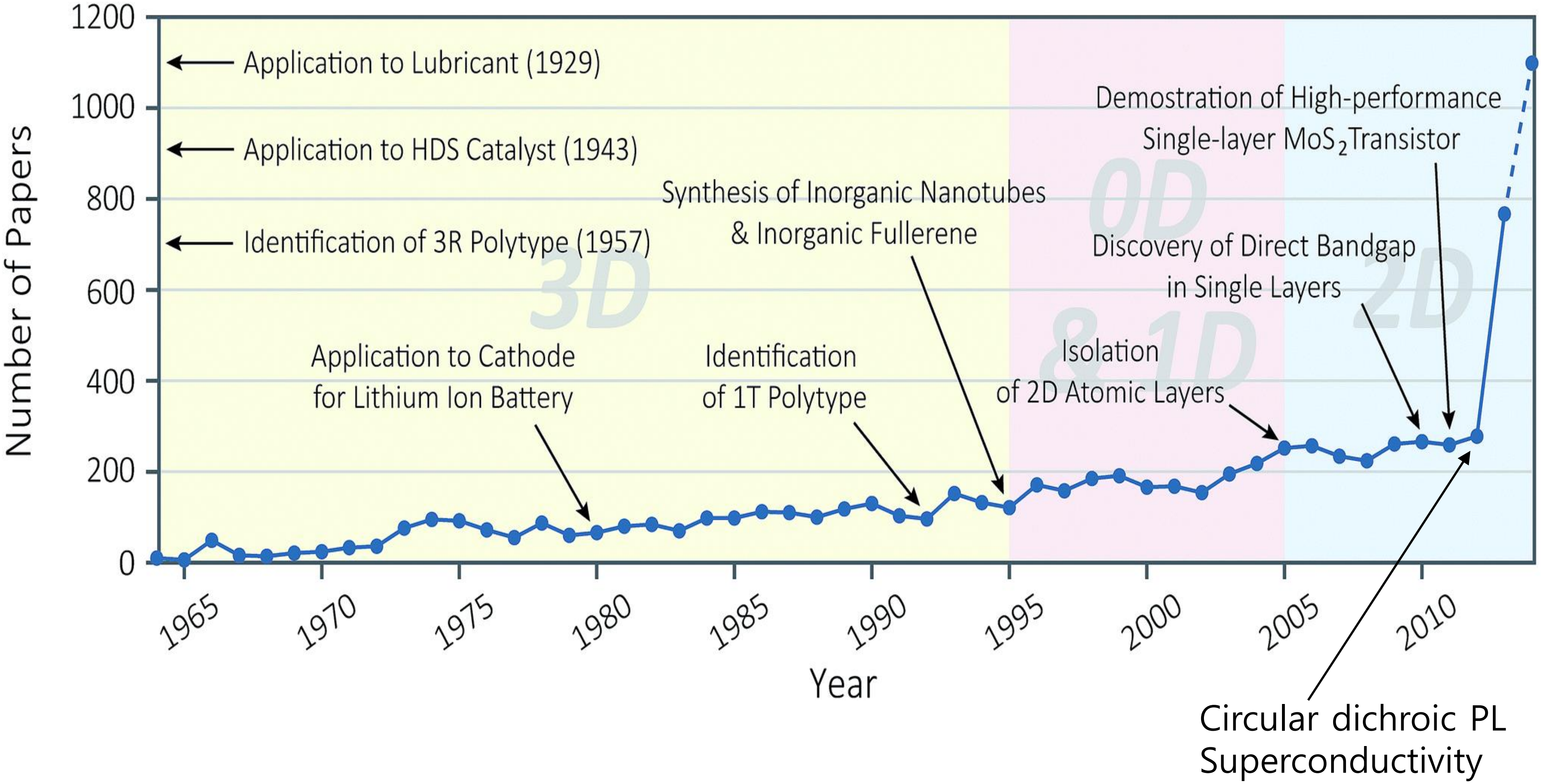


mono/multilayer



- Monolayer Isolation (2005)
- Photoluminescence (2010)
- Monolayer FET(2011)
- Valleytronics (2012)
- Superconductivity (2012)
- Photodetectors (2013)
- Light Emitting Diodes (2014)
- Piezoelectic (2014)
- Laser (2015)
- Thermolelectrics

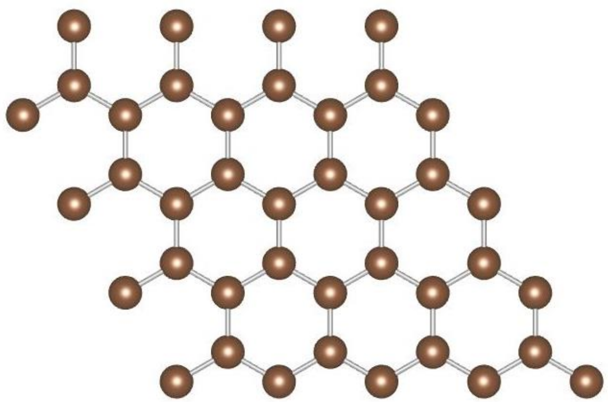
History of MoS_2 researches

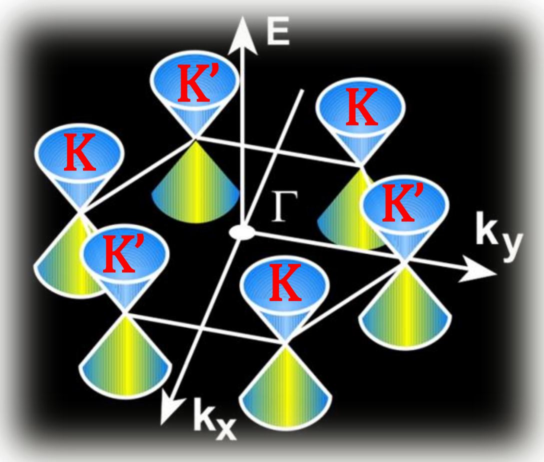


I. Song et al., RSC Adv. **5**, 7495 (2015)

Broking Inversion Symmetry in Graphene

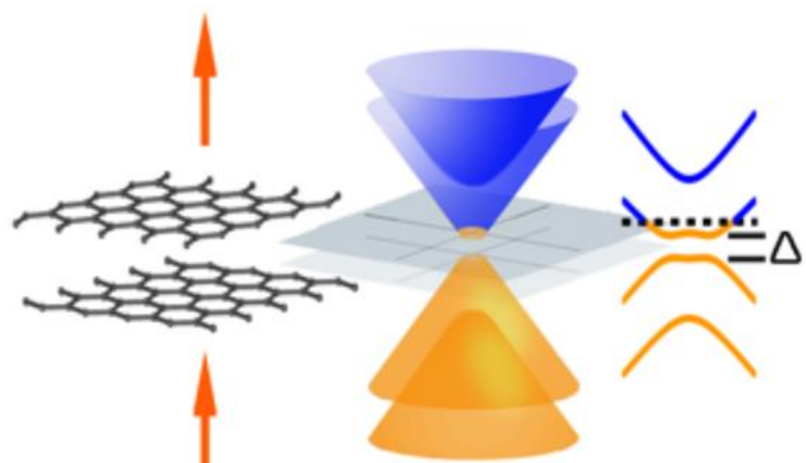
Graphene



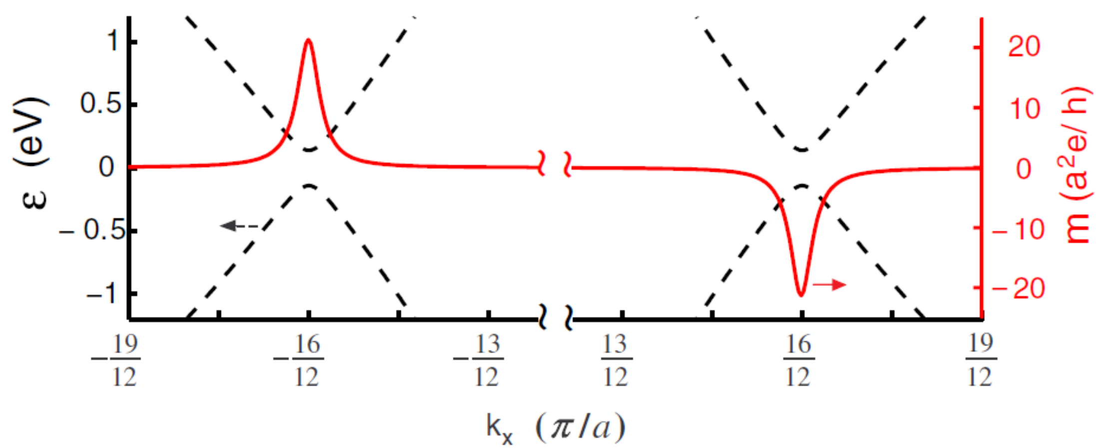


http://www2.fkf.mpg.de/klitzing/hom

Double layer graphene under E

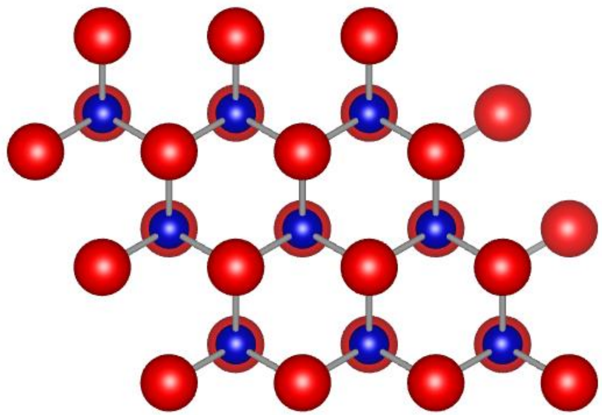


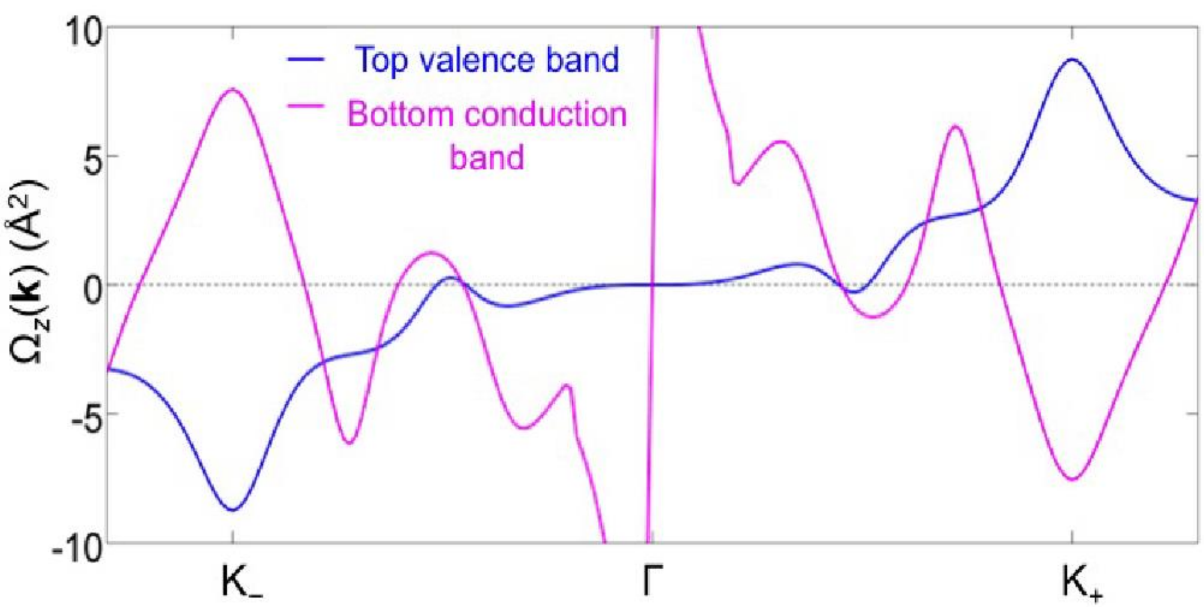
Zhang, Nature 459, 820 (2009).



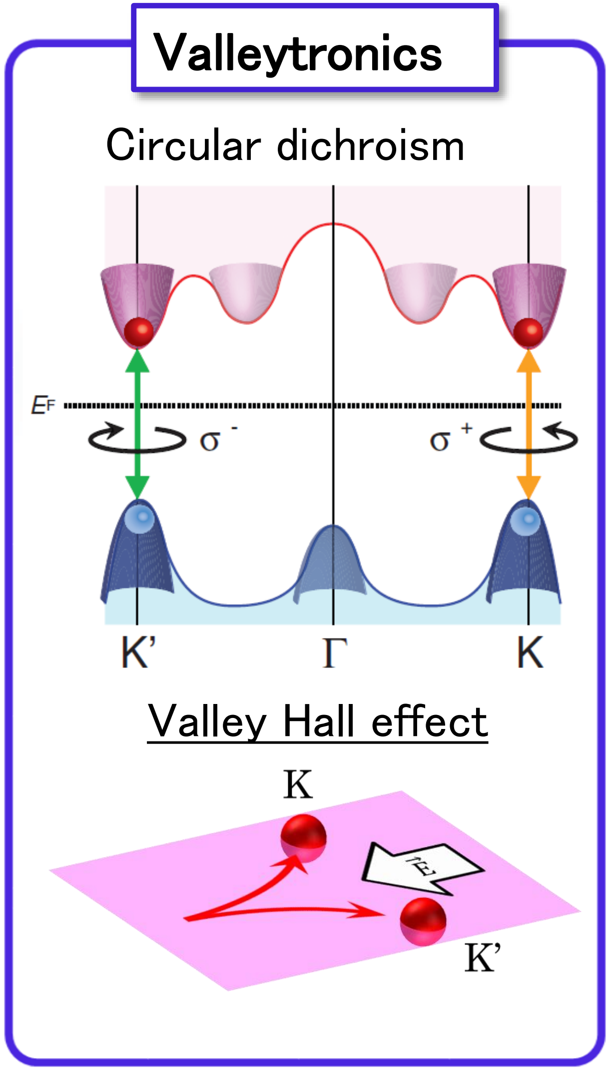
Xiao, Yao, Niu, PRL 99, 236809 (2007).

Valley curvature in monolayer TMDs



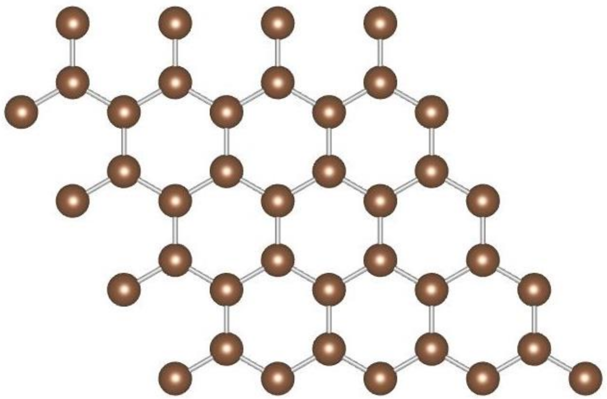


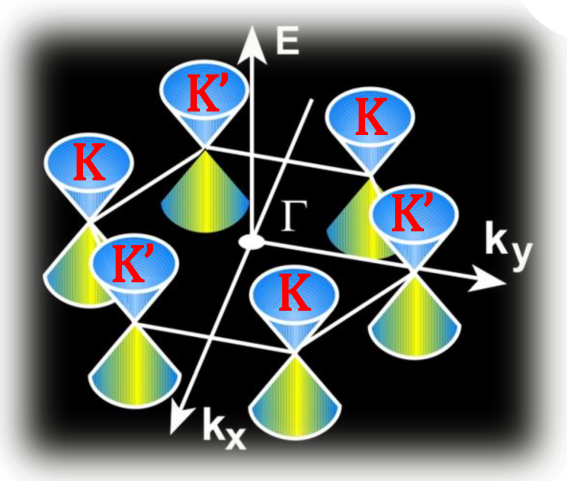
T. Cao, *et al.*, Nature Communication, **3**, 887 (2012).



Broken Inversion Symmetry + SOI in TMD

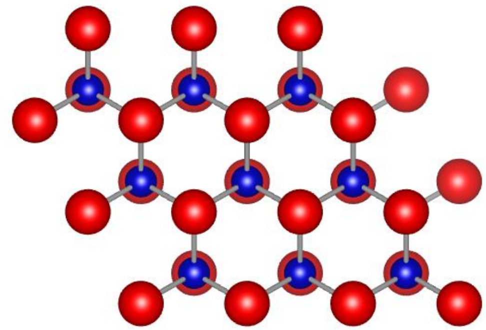
Graphene



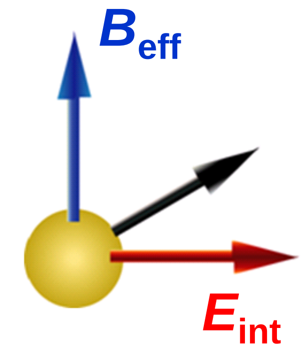


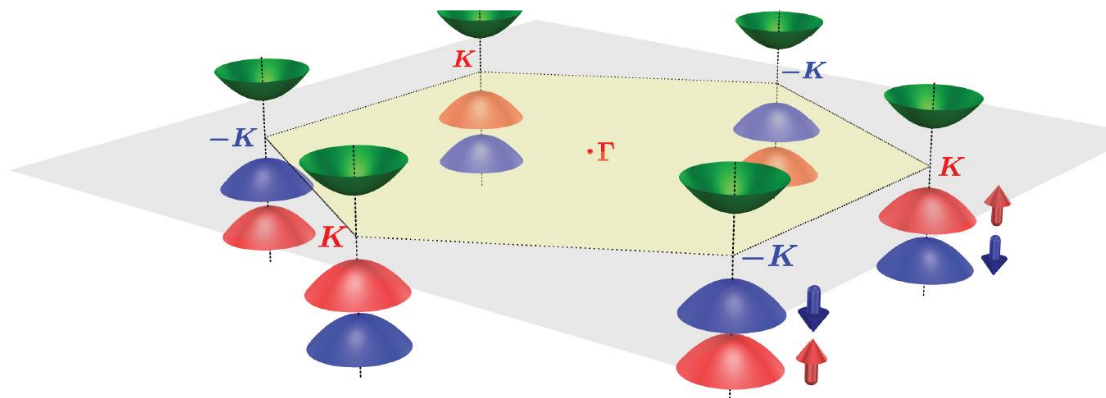
http://www2.fkf.mpg.de/klitzing/home.php

TMD



Spin-Orbit Interaction

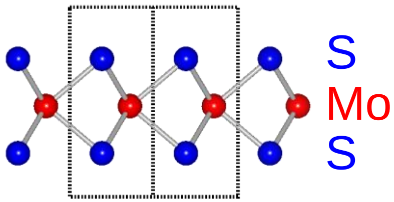




D. Xiao *et al*., PRL **108**, 196802 (2012).

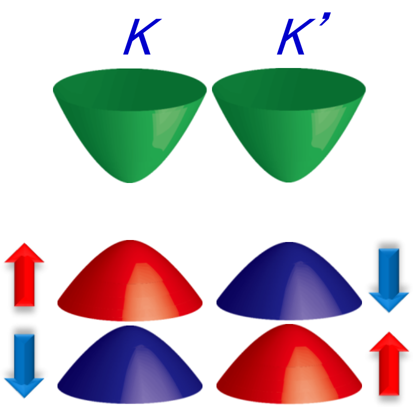
Monolayer and Bulk MoS_2

1ML MoS_2 ($P\bar{6}m2$)

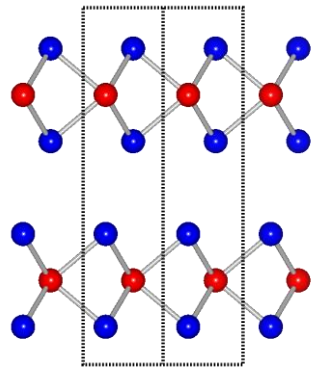


3-fold

Noncentro-symmetric

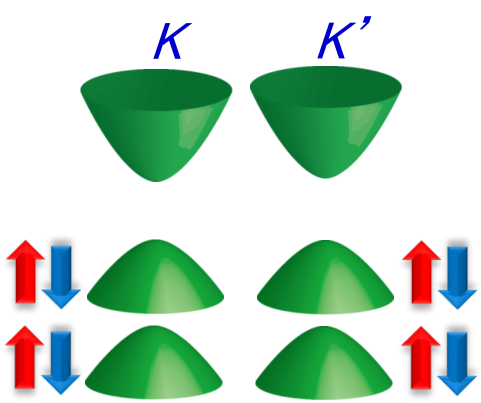


2H-MoS_2 ($P6_3/mmc$)

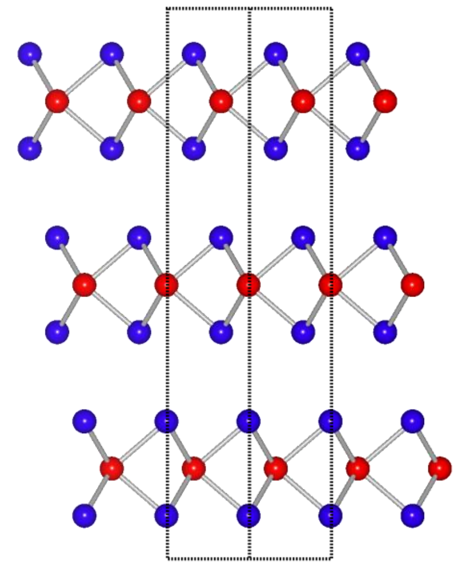


6-fold

Centro-symmetric



Bulk 3R-MoS_2($R3m$)

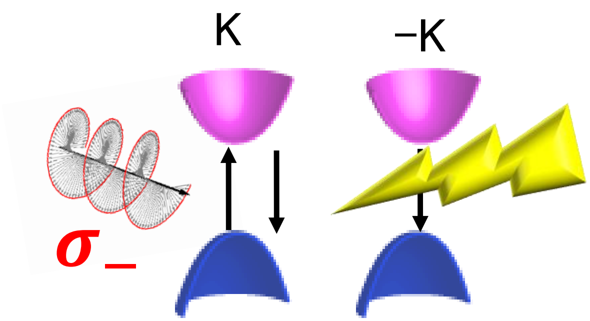


3-fold

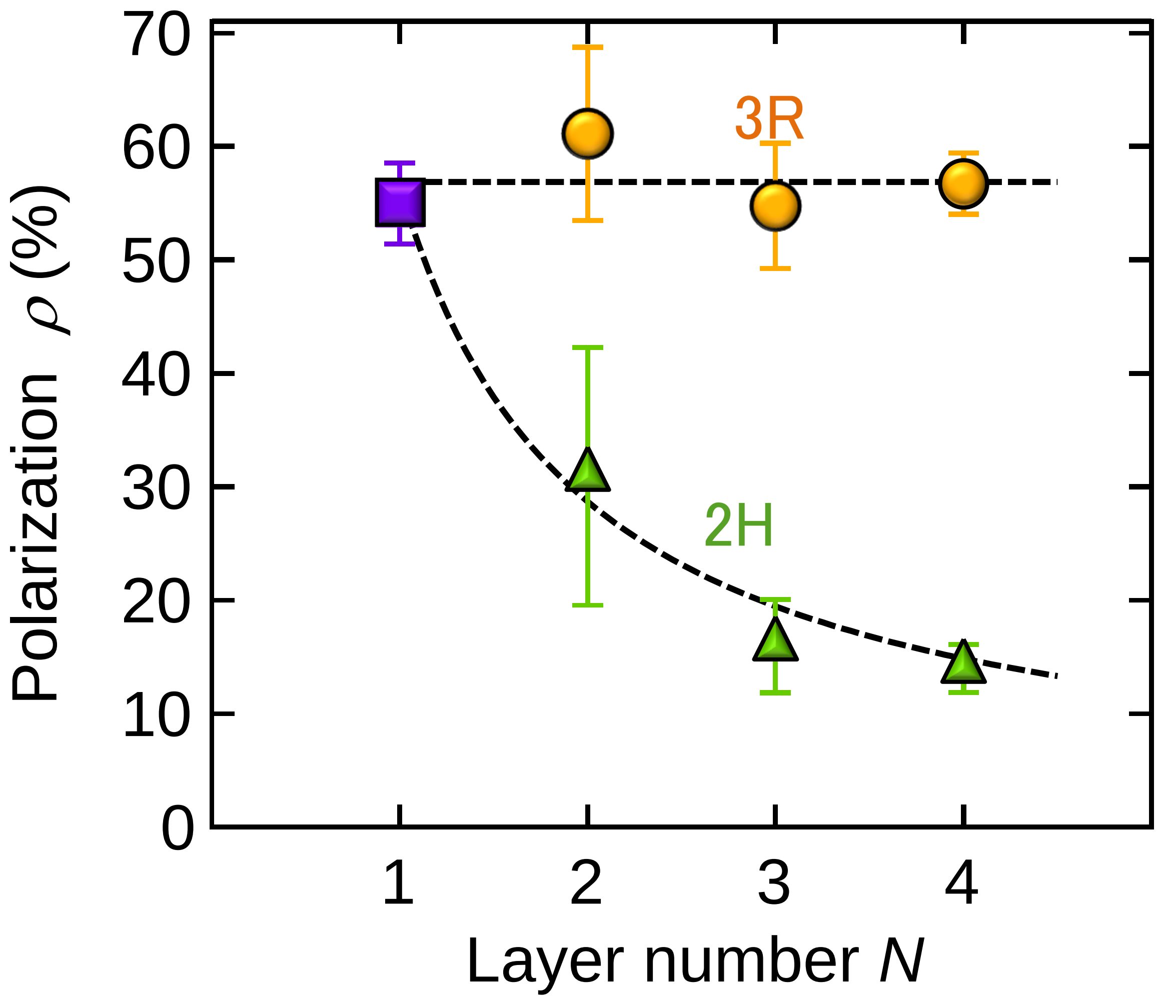
Noncentrosymmetric

Spin-Valley coupling in bulk

Layer number dependence of PL Circular Polarization

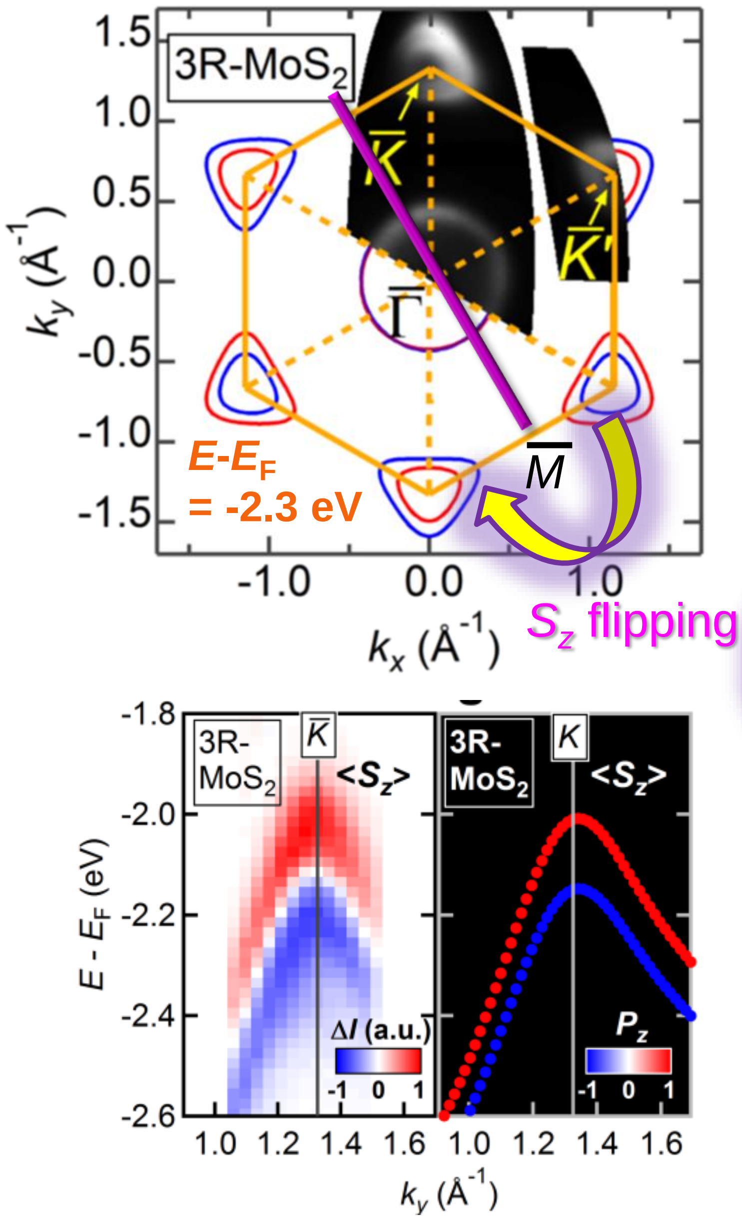


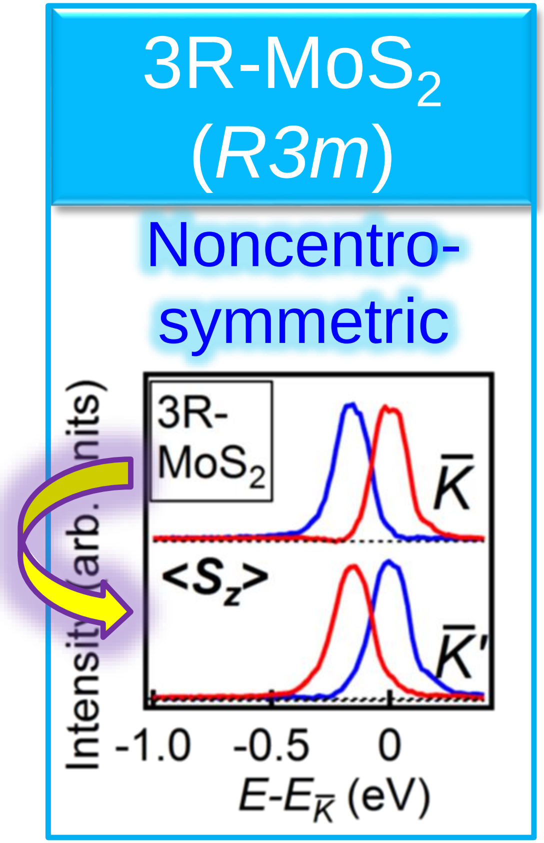
$$\rho = \frac{I(\sigma -) - I(\sigma +)}{I(\sigma -) + I(\sigma +)}$$

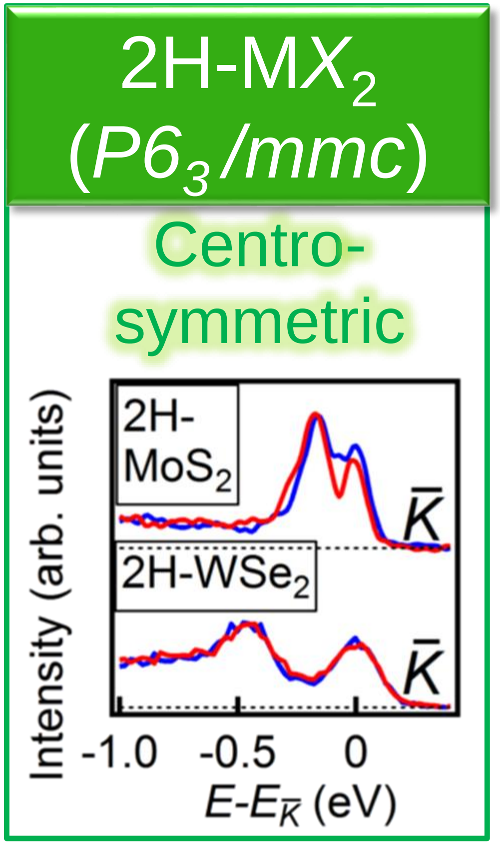


R. Suzuki et al., Nat Nanotech 9, 611 (2014)

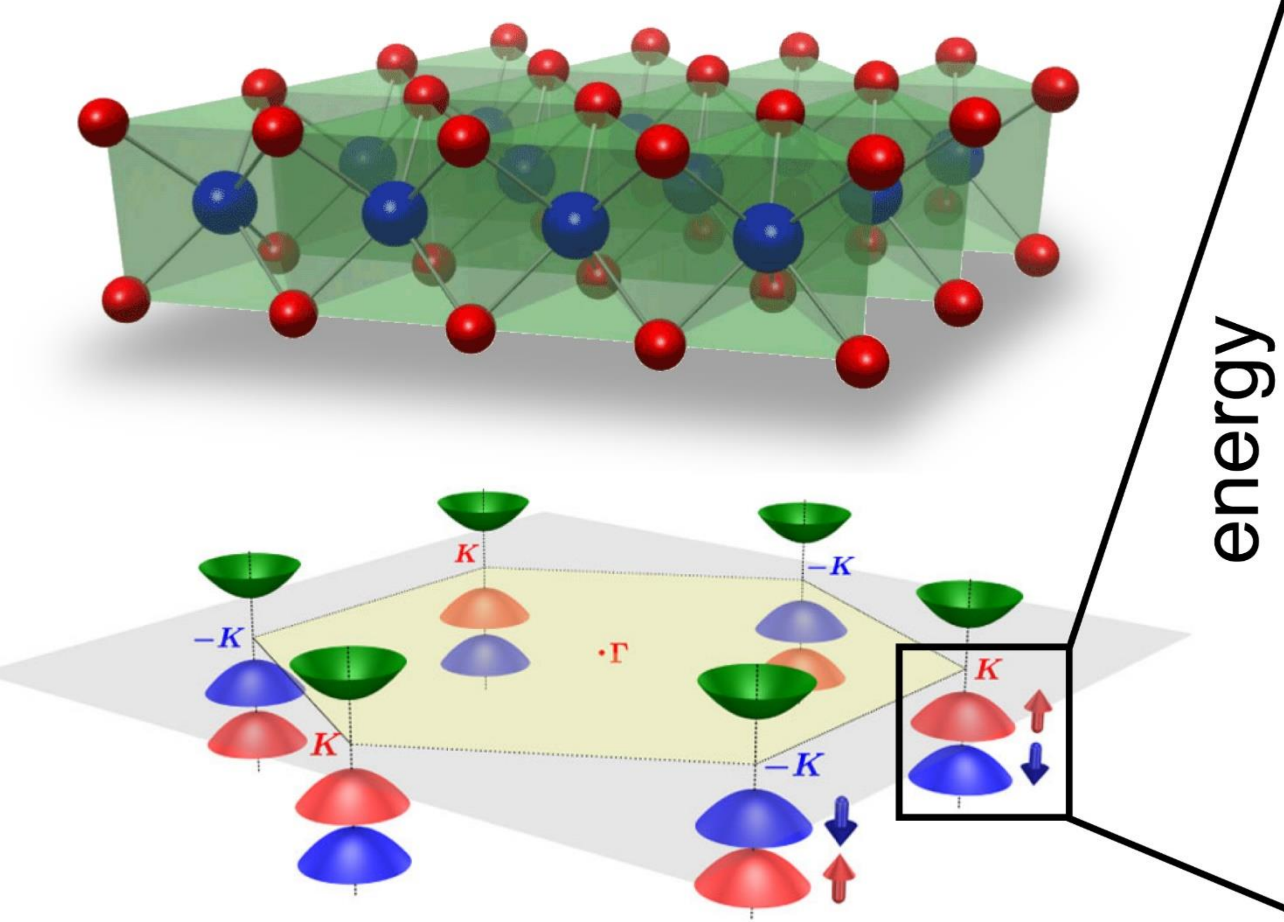
Spin-Polarized Valence band in 3R-MoS_2

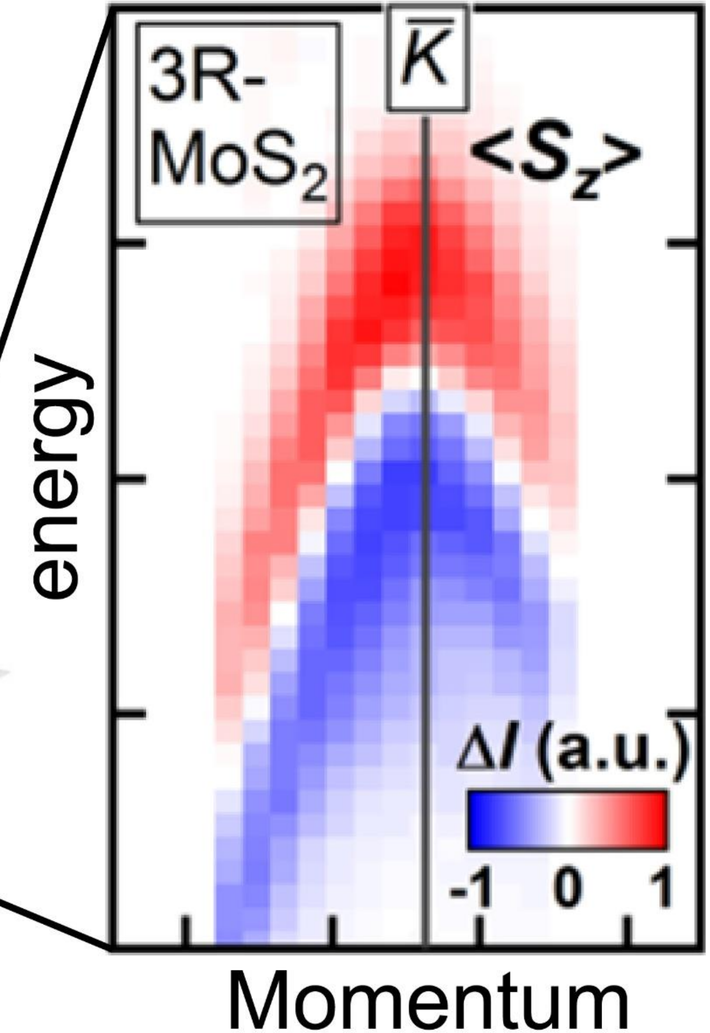






Valley-dependent spin polarization observed by SARPES





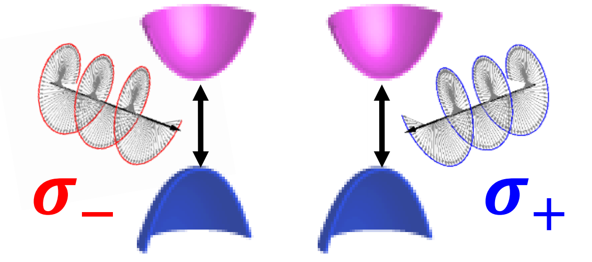
D. Xiao et al., PRL 108, 196802 (2012)

R. Suzuki et al., Nat Nanotech 9, 611 (2014)

Opto-valleytronics in monolayer TMDs

- Circular dichroic PL

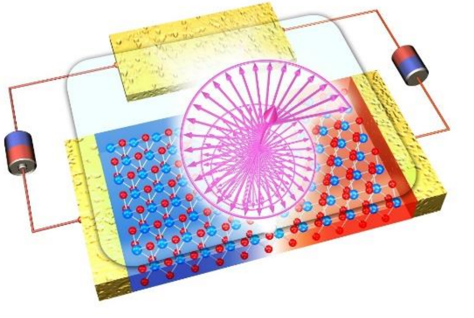
  H. Zeng et al., *Nat Nano* 7, 490 (2012).
  K. F. Mak et al., *Nat Nano* 7, 494 (2012).



- EO conversion

  Current→ Circularly polarized light
  (Chiral Light Emitting Transistor)

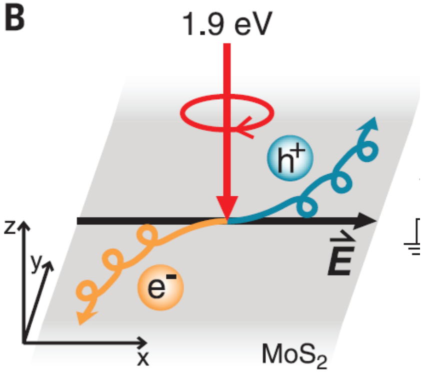
  Y. J. Zhang et al., *Science* 344, 725 (2014)



- OE conversion

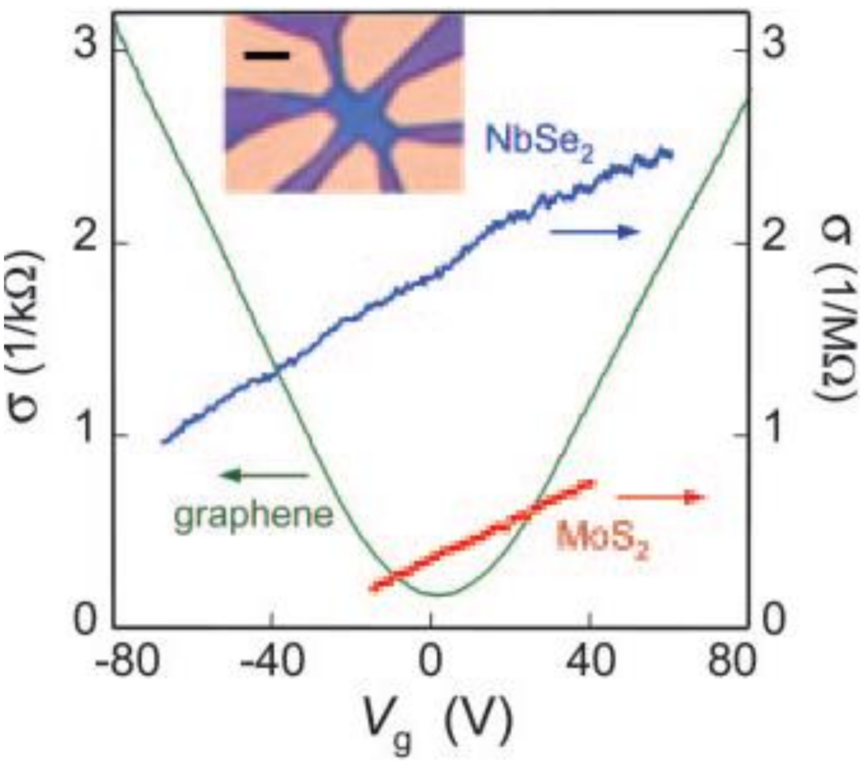
  Circularly polarized light
  →Valley-polarized current (Valley Hall Effect)

  K. F. Mak *et al. Science* 344, 1489 (2014)

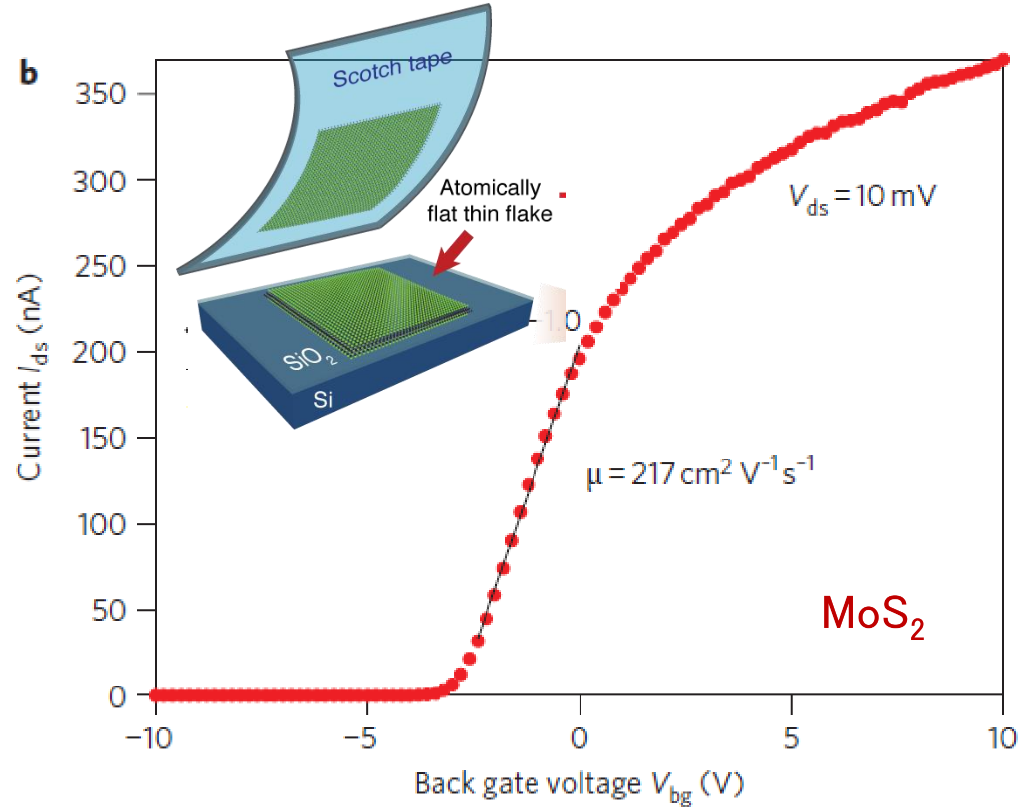


Monolayer FET of MoS_2

WSe2: V. Podzorov, APL **84**, 3301 (2004)

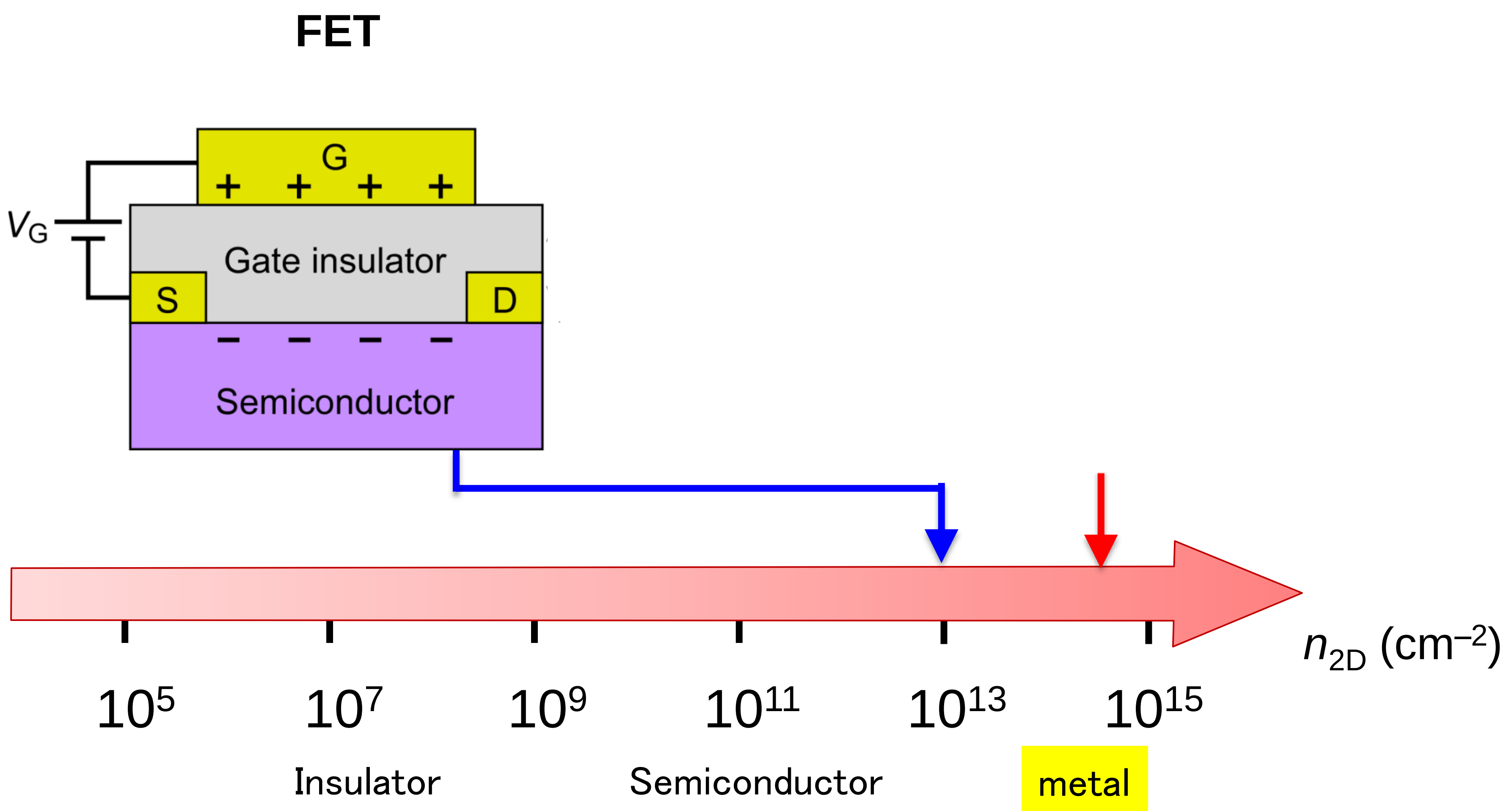


K. S. Novoselov et al., PNAS. 102, 10451 (2005)

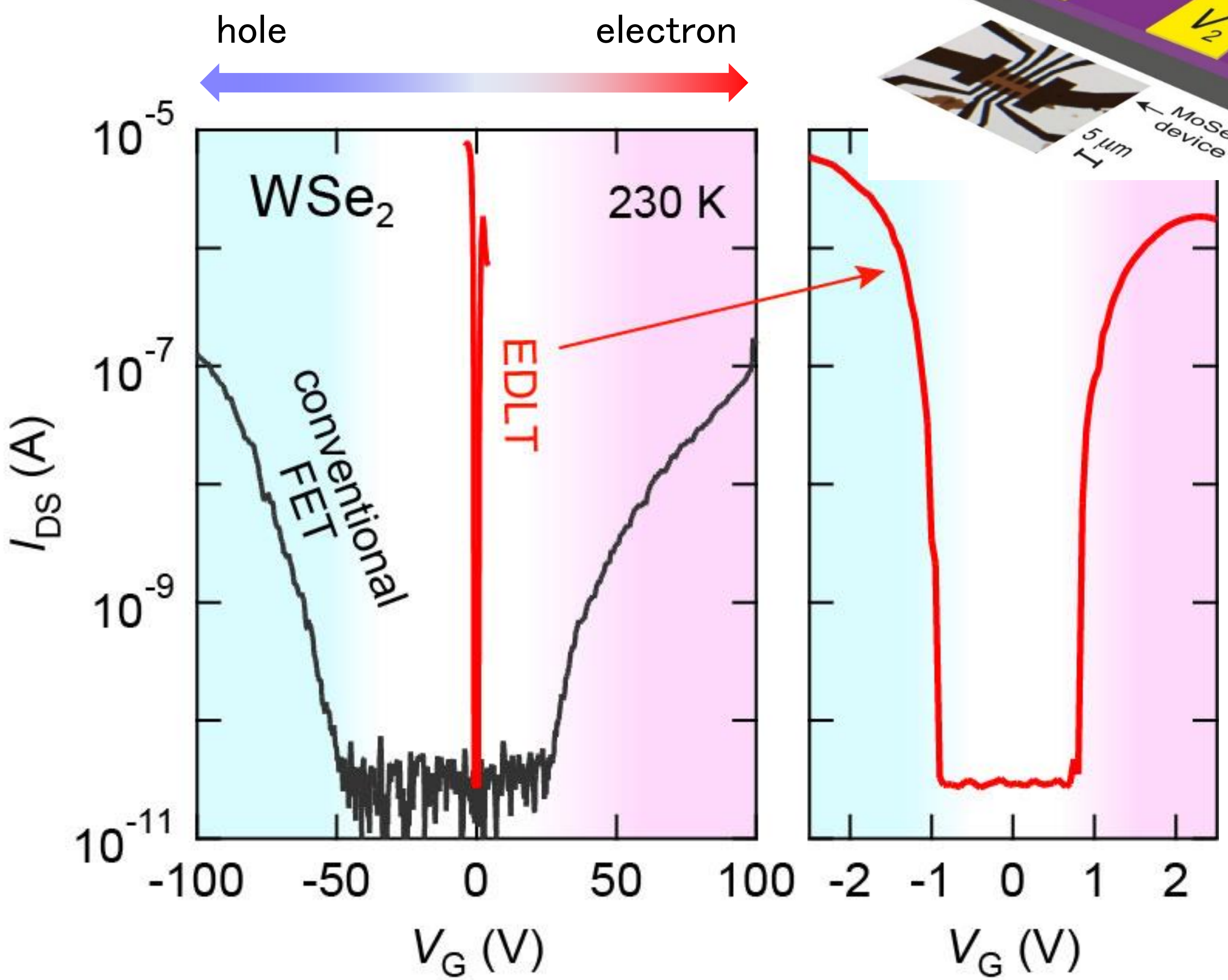


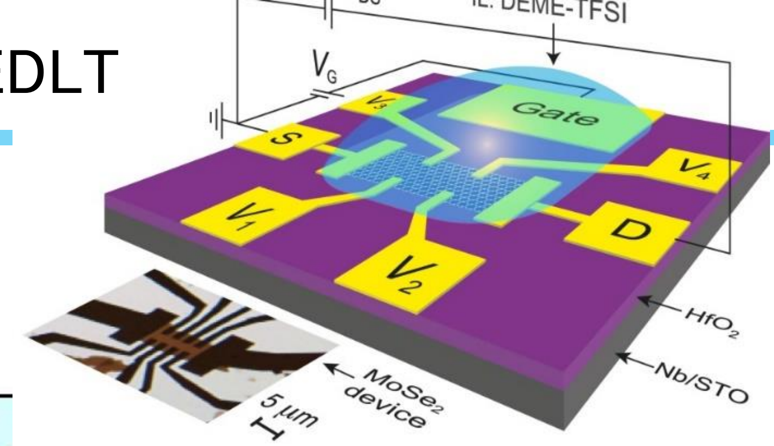
B. Radisavljevic et al., Nat. Nanotech. 6, 147 (2011)

From FET to EDLT (Electric Double Layer Transistor)

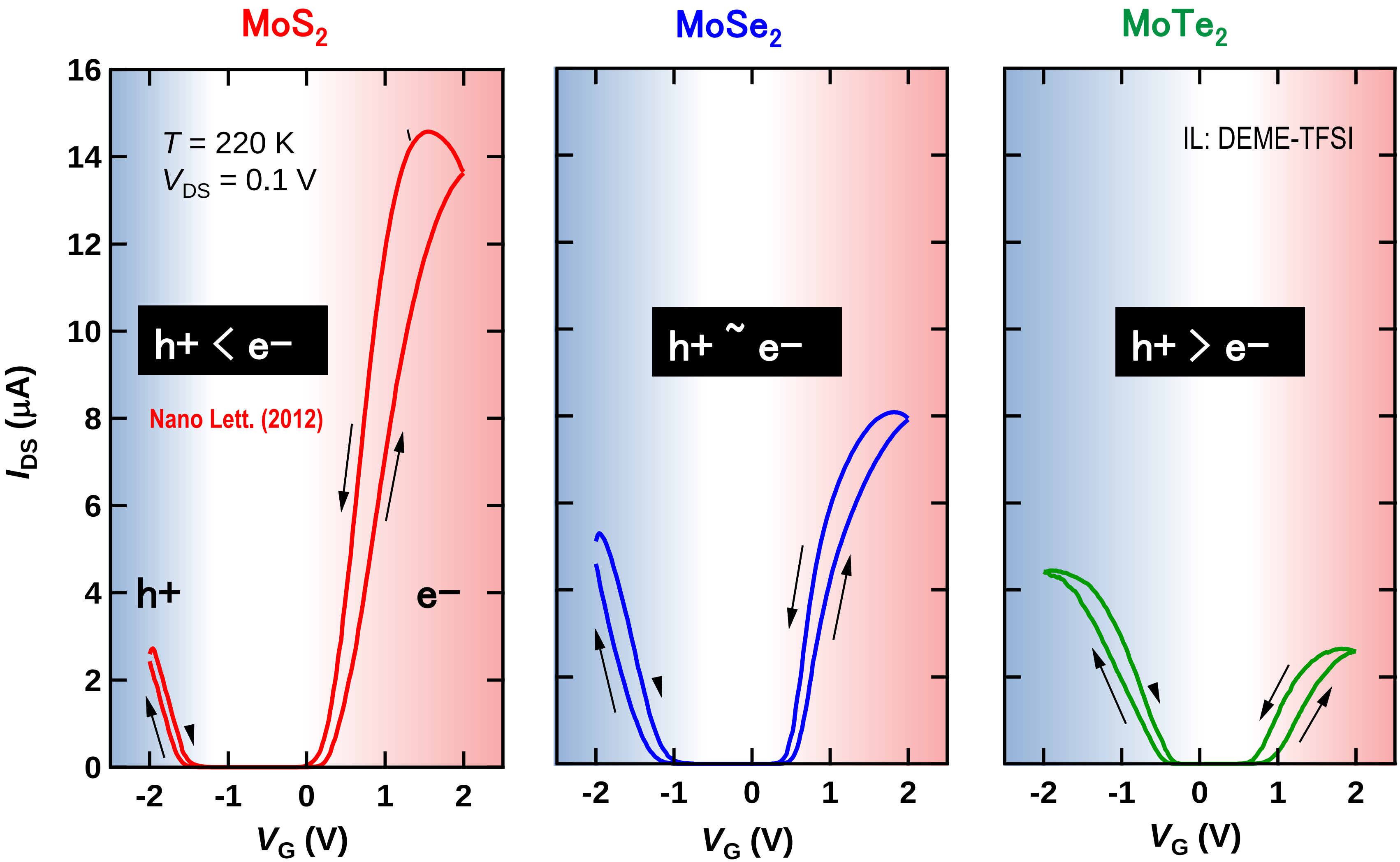


Ambipolar transport in WSe2: FET vs EDLT



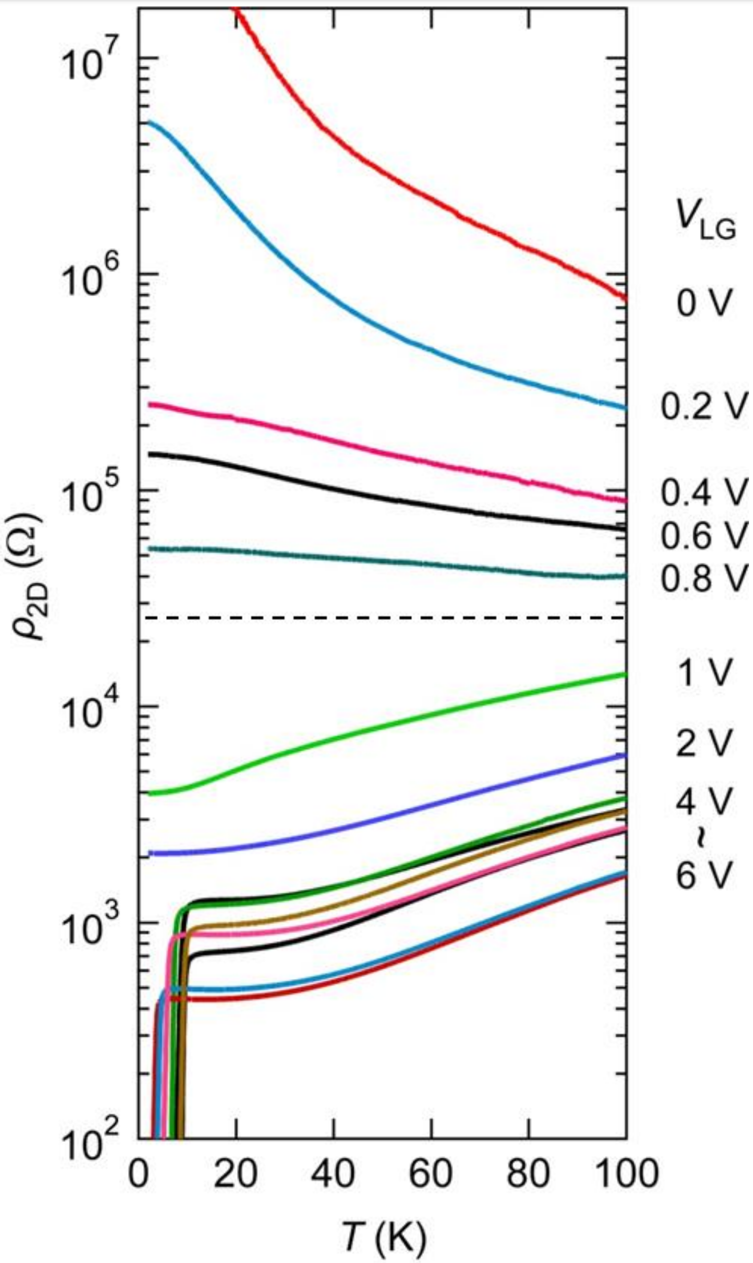


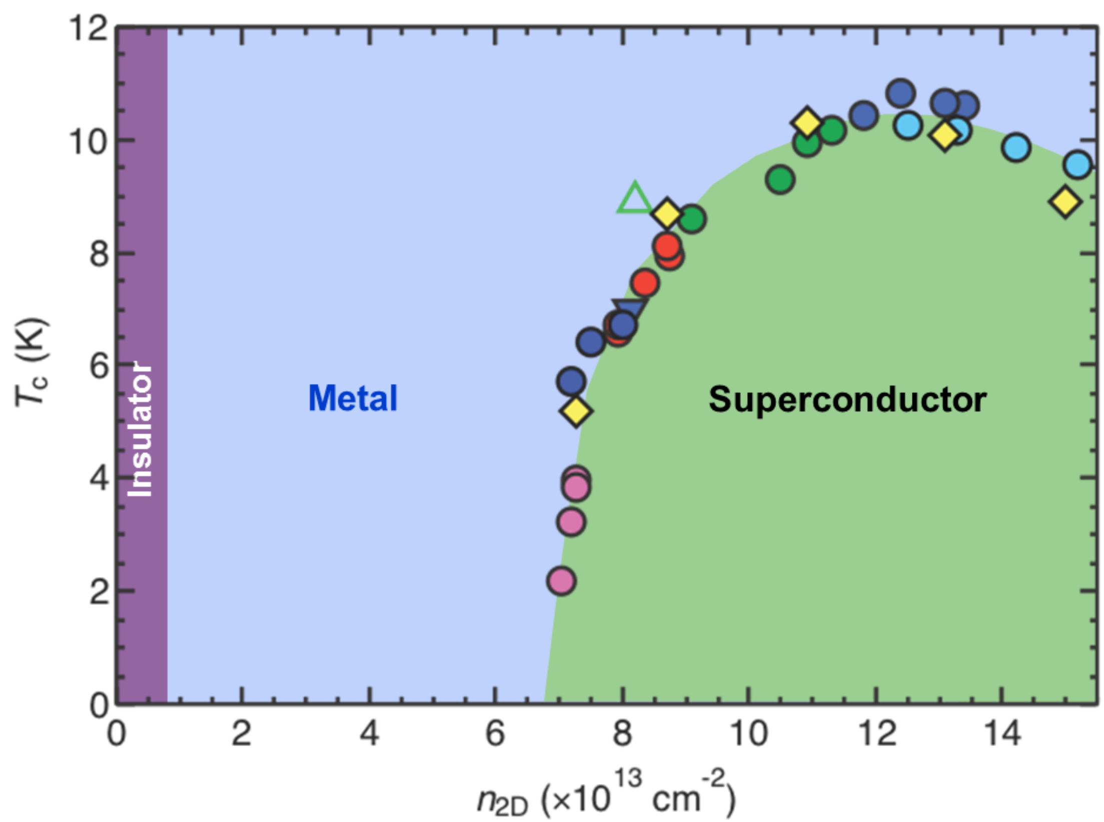
Transistor Characteristics of MoX2 EDLTs



❖ ***Systematic Evolution of Ambipolar Transistor Operation in MoX_2***

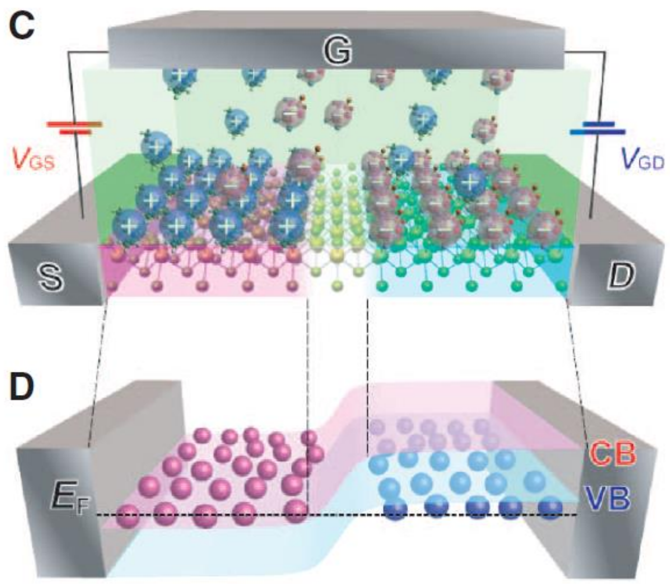
Gate induced superconductivity in MoS_2

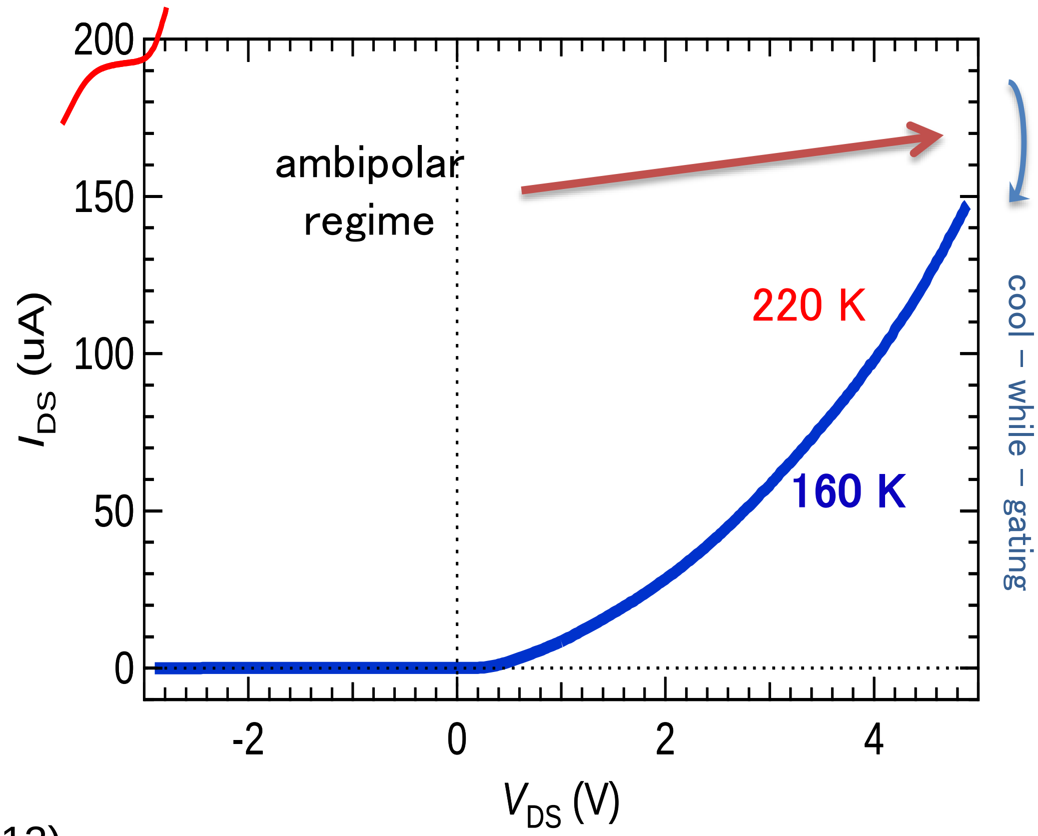




Ye *et al*. **Science** 338, 1193 (2012)

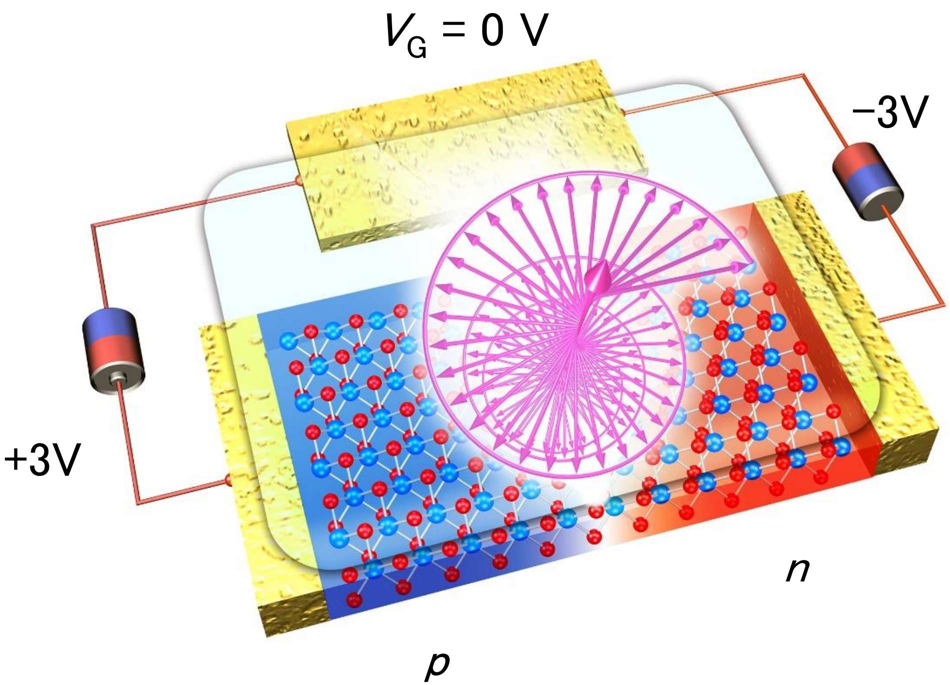
Ambipolar transport and Stable *p-i-n* Junction in MoS_2-EDLT





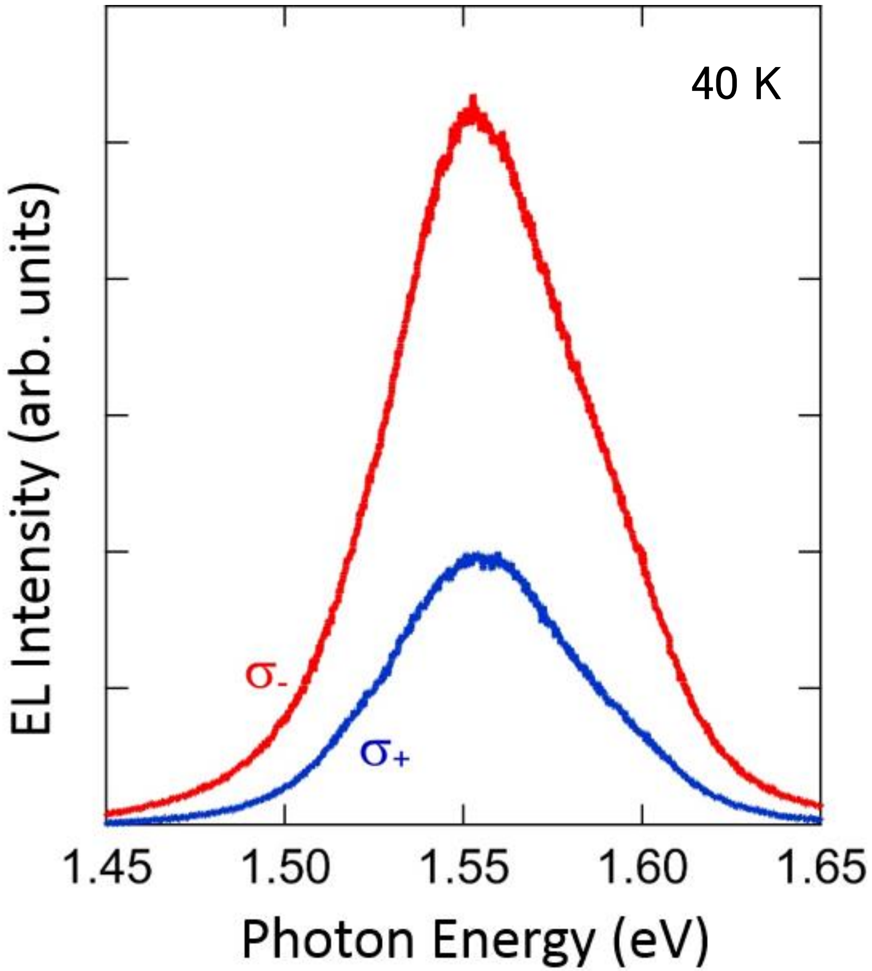
Y. J. Zhang et al., *Nano Lett.* **12** 1136 (2012)
Y. J. Zhang et al., *Nano Lett.* **13** 3023 (2013)

Circularly polarized EL in monolayer WSe_2–EDLT



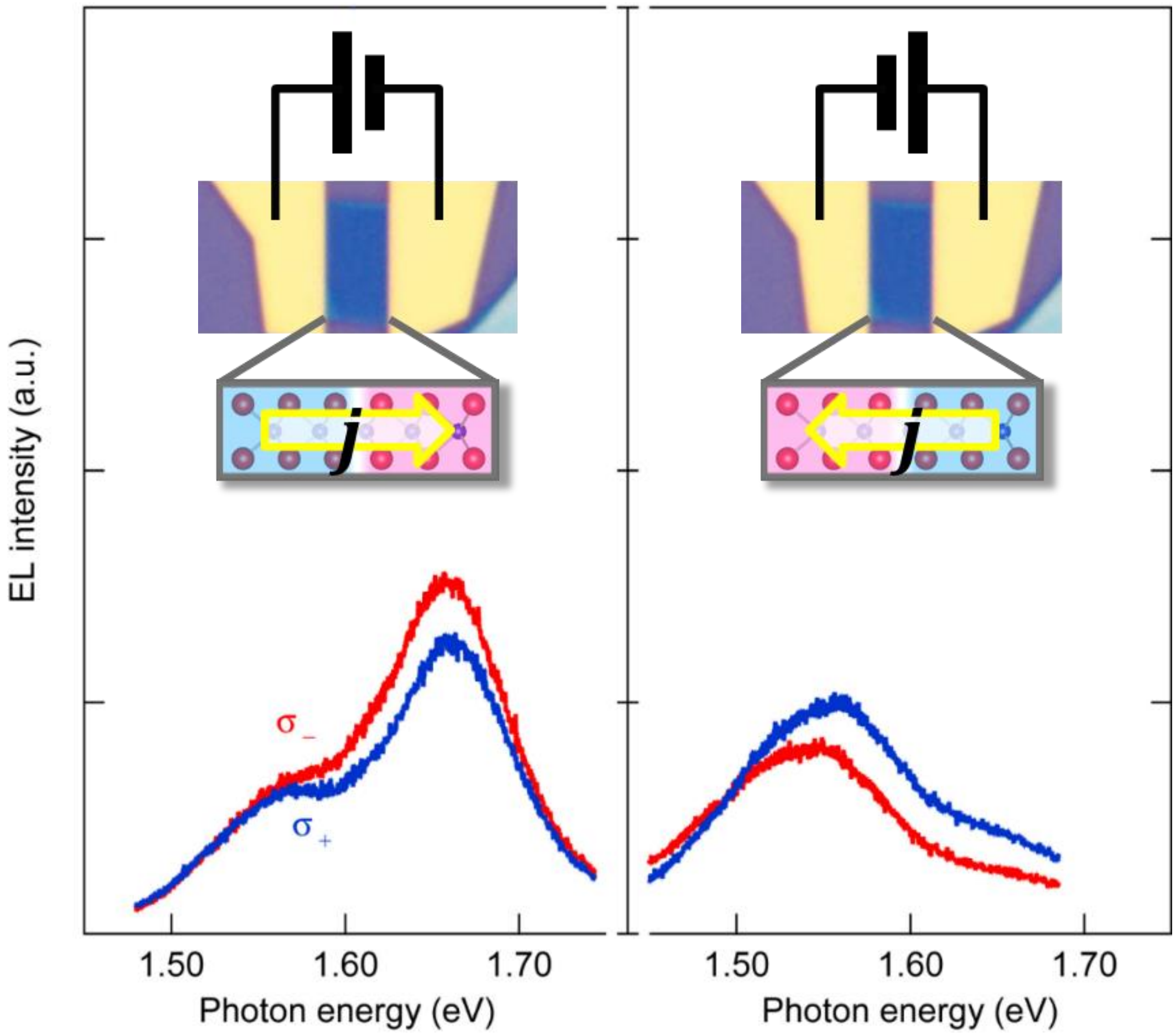
Light Emitting Transistor with solid gate

Popischil et al. *Nature Nano* **9**, 257 (2014)
Baugher *et al.*, *Nature Nano* **9**, 262 (2014)
Ross *et al.*, *Nature Nano* **9**, 262 (2014)



Y. J. Zhang *et al.*, *Science* **344**, 725 (2014)

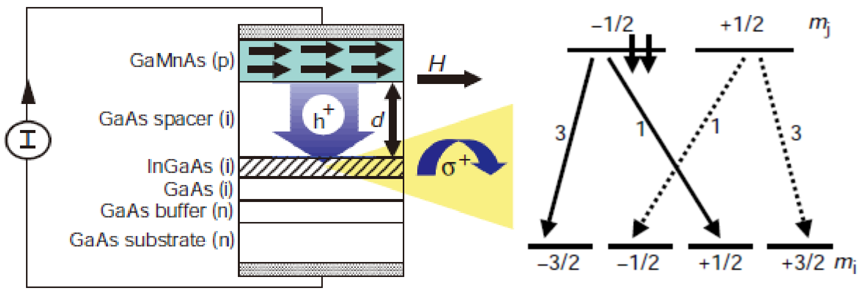
Polarization switching by current direction in WSe_2



Zhang *et al.*, *Science* **344**, 725 (2014)

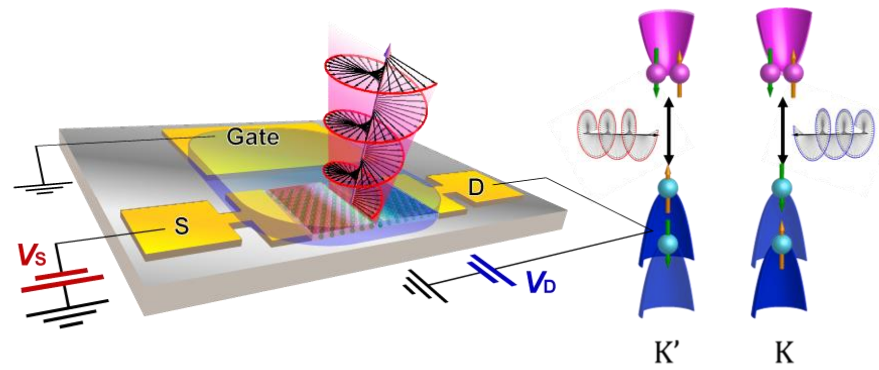
Switchable chiral light source

Spin LED



Nature **402**, 787/790 (1999)

Valley LET



Chemically doped *p-n* junction

Field-induced *p-n* junction

Spin circular dichroism

Valley circular dichroism

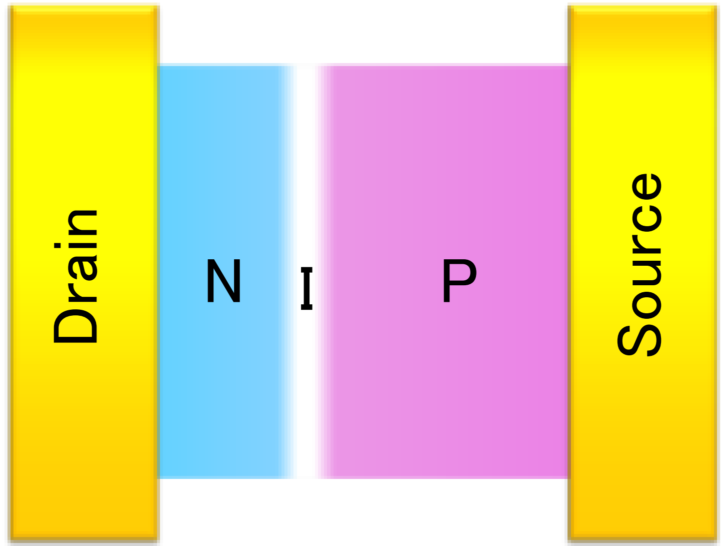
Circular emission requires spin injection

Valley injection is not necessary

Helicity is controlled by magnetic field

Helicity can be controlled by **electric field**

Potential Mechanisms



Model 1; Polarization is produced at I–region

Y. J. Zhang *et al.*, *Science* 344, 725 (2014)

Model 2: Polarization is produced at P–region

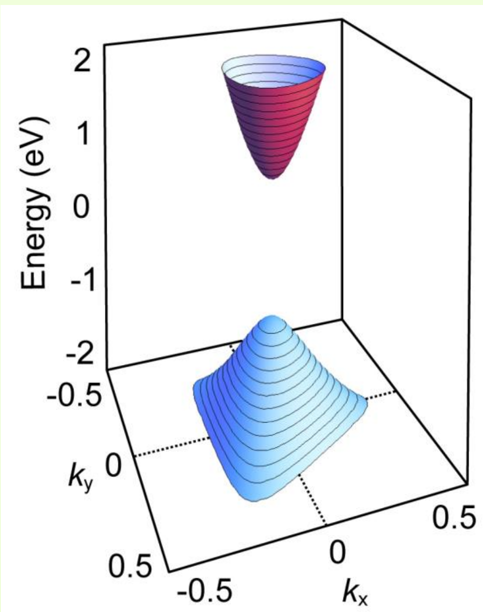
H. Yu et al., *PRL* 113, 156603 (2014)

Source of circularly polarized EL is
non–parabolicity (trigonal warping) of valence bands

Mechanism 1: Produced at *PIN* Junction

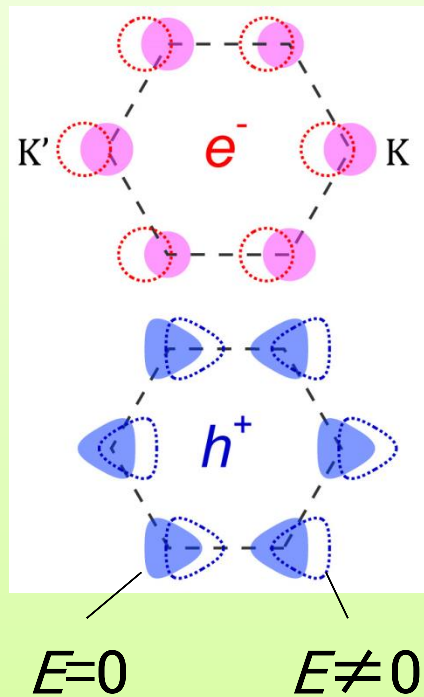
Valley dependent overlap of electron and hole distributions

Trigonal warping

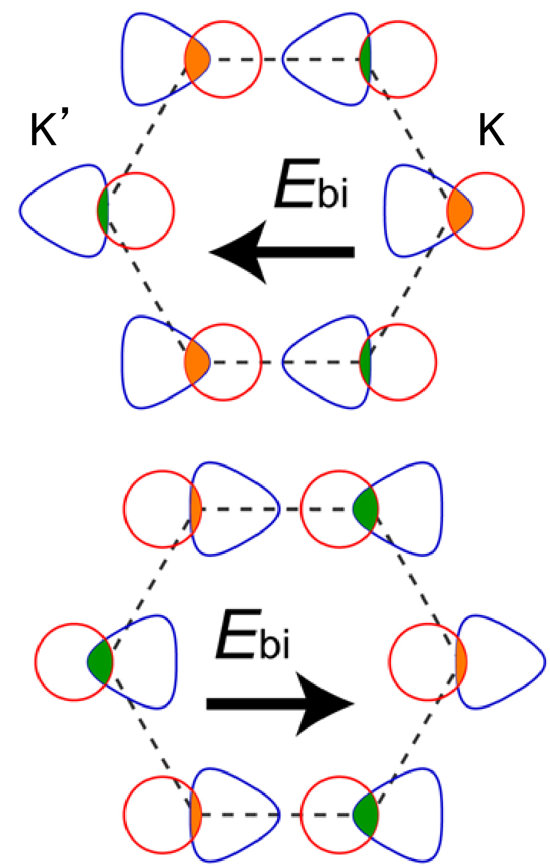


A. Kormányos *et al.*,
Phys. Rev. B **88**, 045416 (2013).

Built-in potential



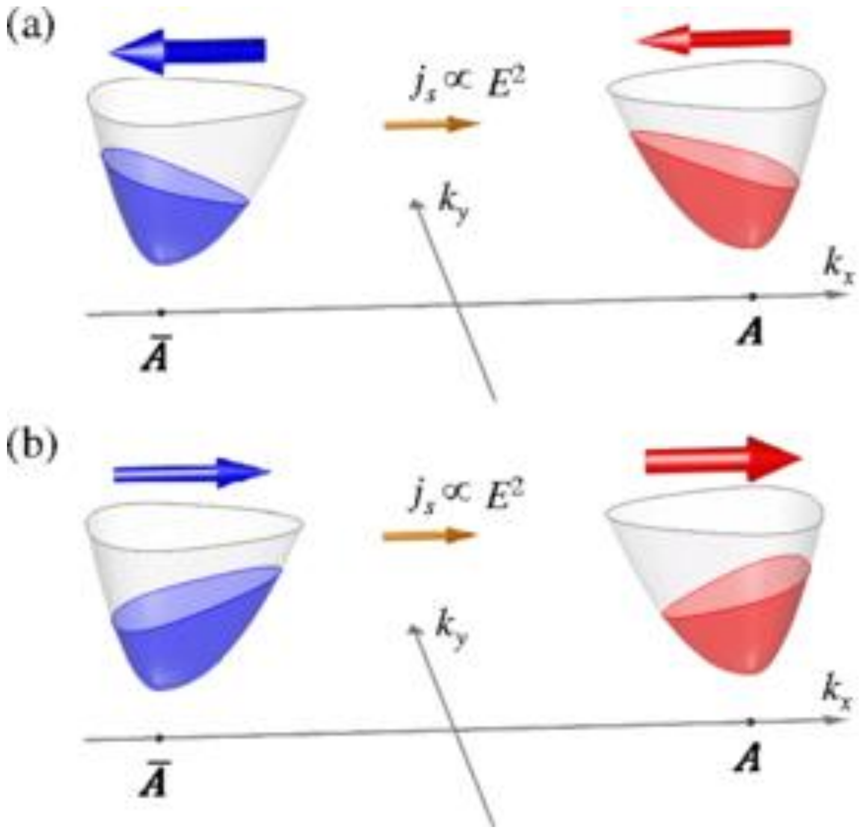
Field direction depended
valley overlap polarization



Y. J. Zhang, T. Oka *et al.*, *Science* **344**, 725 (2014)

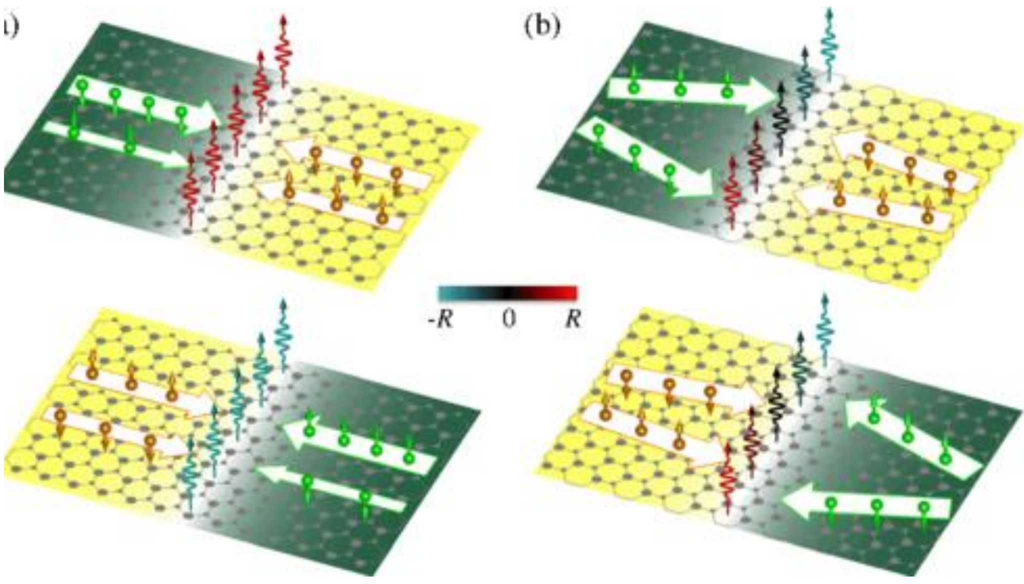
Mechanism 2: Produced at *P* channels

Nonlinear current produces valley polarization



Along arm chair edge

Along zigzag edge



H. Yu et al., Phys. Rev. Lett. 113, 156603 (2014)

Summary

TMD for valleytronics: interface valley and spin/light

1. Experimental detection of valley-dependent spin polarization
2. Switchable chiral light emitting transistor