2D Valley-Spin Transport in Transition Metal Dichalcogenides

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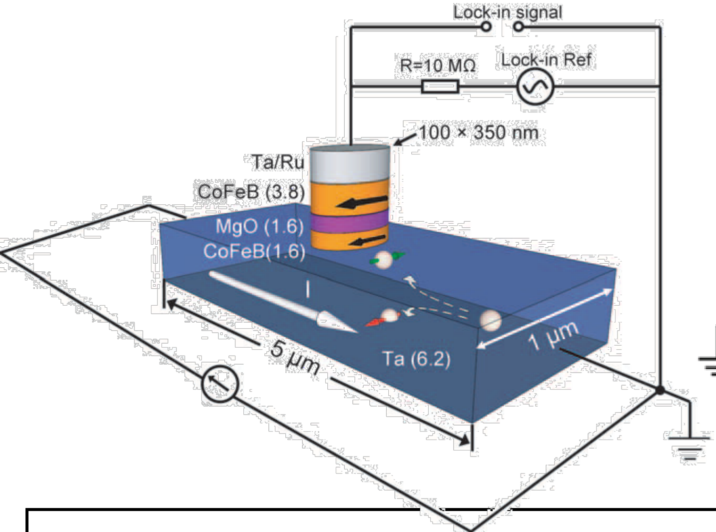
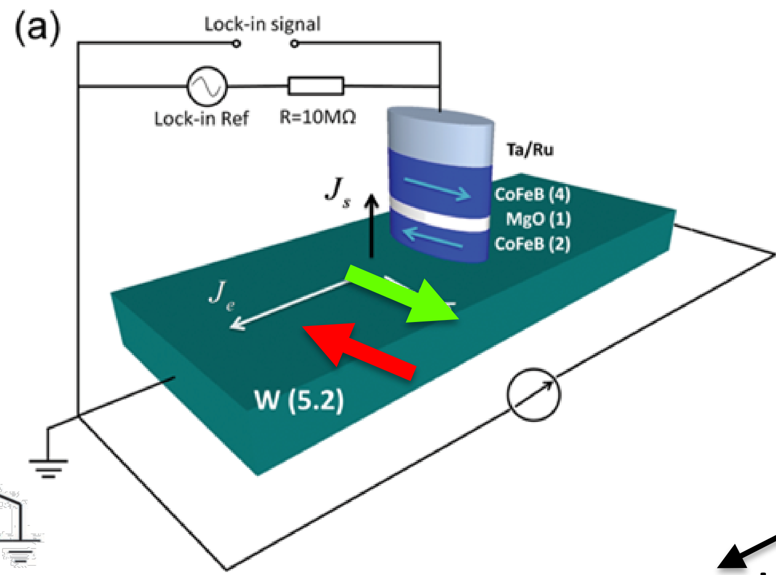
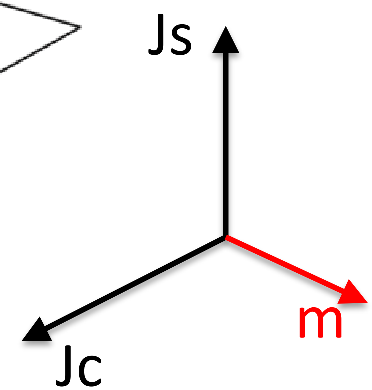
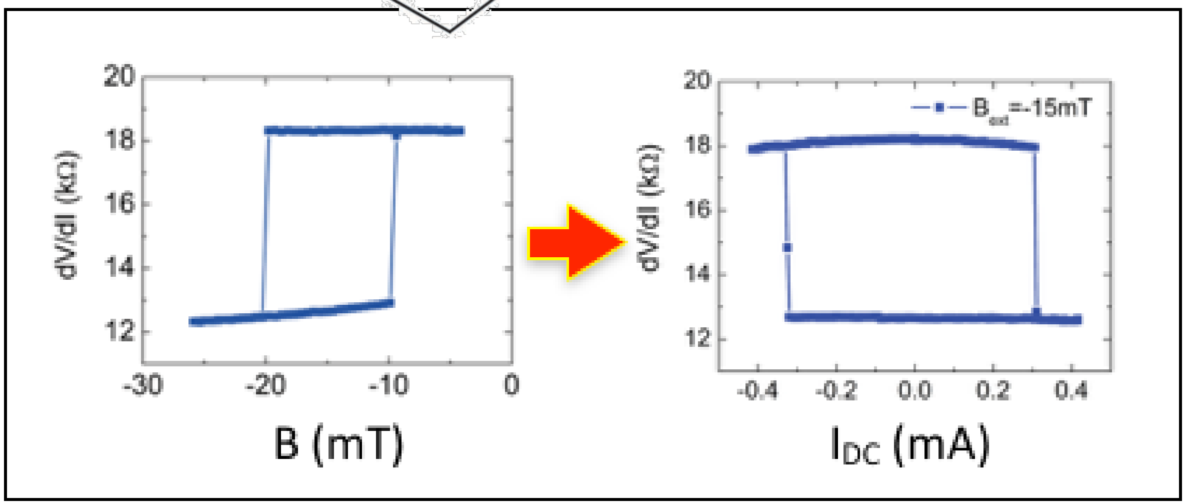
Spintronics Workshop
September 11, 2019





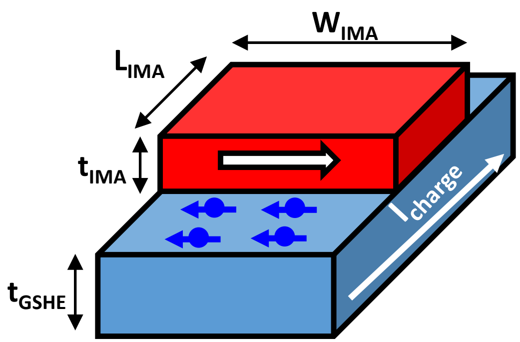




Liu et al., *Science* **336**, 555 (2012)
Pai et al., *APL* **101**, 122404 (2012)
Liu et al., *PRL* **109**, 096602 (2012)

Switching Current of SOT Switching Based Write Unit

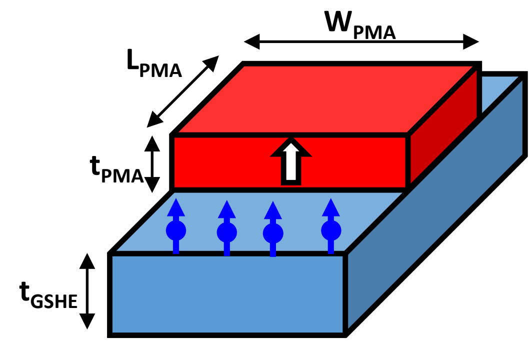
IMA on in-plane GSHE



$$J_{C,WRITE} = \frac{2e}{\hbar}\mu_0 M_S H_K t \alpha \left(1 + \frac{H_D}{H_K}\right)\frac{1}{\theta_{SH}}$$

IMA switched by in-plane GSHE

PMA on out-of-plane GSHE

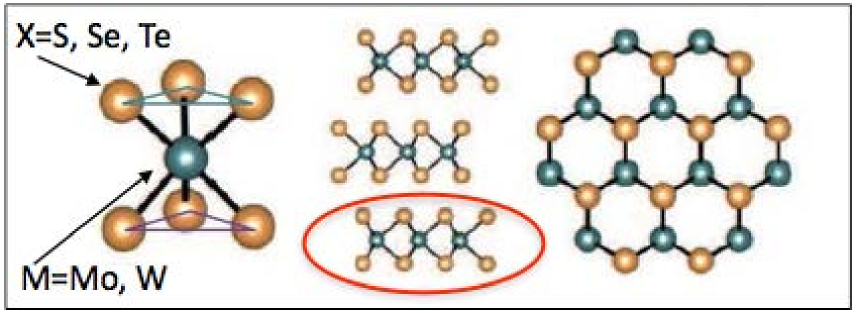


$$J_{C,WRITE} = \frac{2e}{\hbar}\mu_0 M_S H_K t \alpha \frac{1}{\theta_{SH}}$$

PMA switched by out-of-plane GSHE

Switching Energy

Transition Metal Dichalcogenides (2H – MX_2)



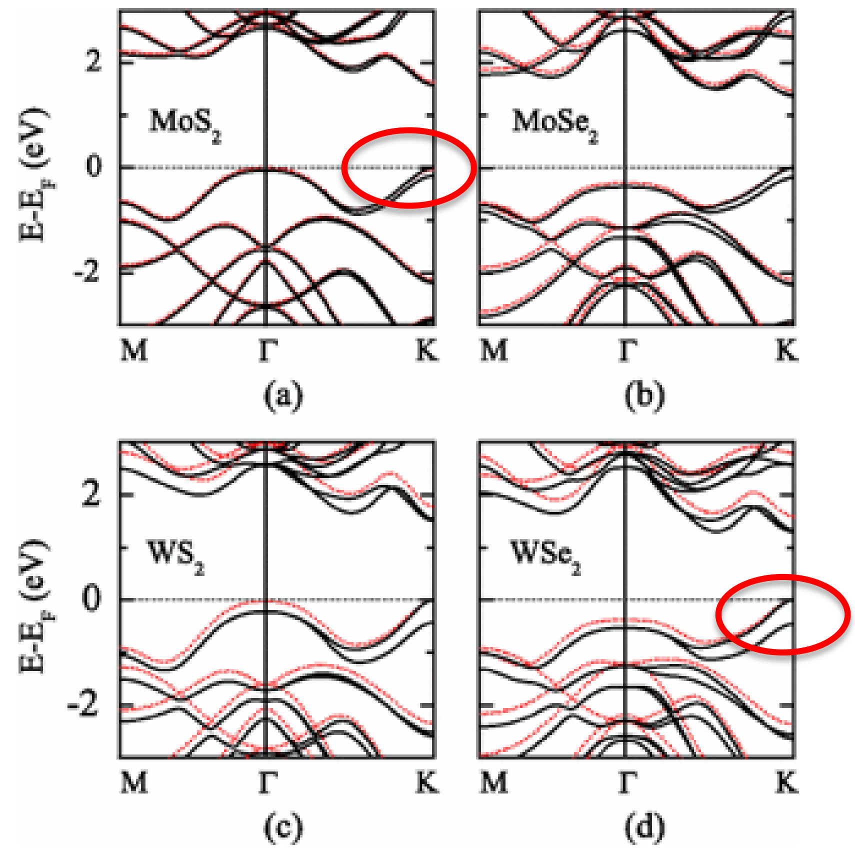
Bulk —> Monolayer: D6h —> D3h
Loss of inversion symmetry

Time reversal symmetry + Inversion symmetry

$$E^{\uparrow}(\vec{k}) = E^{\downarrow}(-\vec{k}) \qquad E^{\uparrow}(\vec{k}) = E^{\uparrow}(-\vec{k})$$

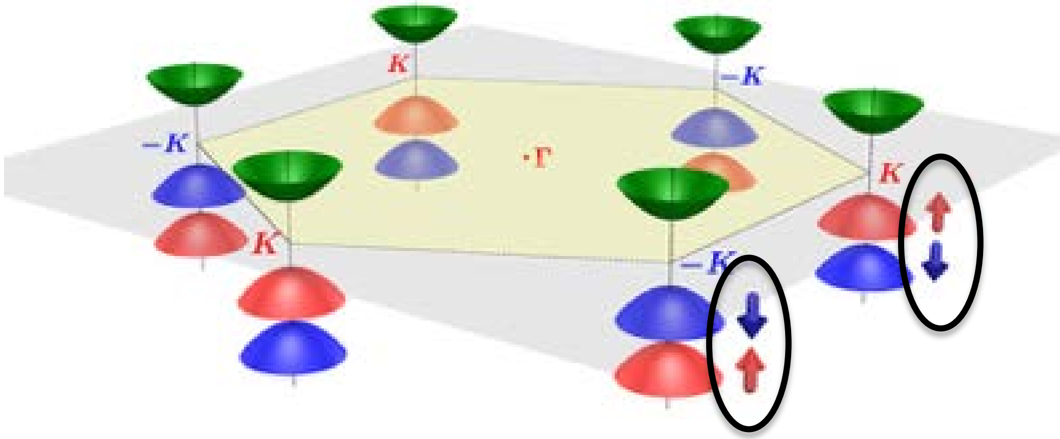
Kramer's degeneracy

$$E^{\uparrow}(\vec{k}) = E^{\downarrow}(\vec{k})$$



Z. Y. Zhu, et al., PRB **84**, 153402 (2011)

- Spin orbit interaction breaks the spin degeneracy in monolayer TMD.
- Spin polarization is out-of-plane due to in-plane electron motion and in-plane potential gradient asymmetry



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

Berry curvature:

$$\Omega(\vec{k}) = \nabla_k \times \langle u_n(\vec{k}) | i\nabla_k | u_n(\vec{k}) \rangle$$

Analogous to: $\vec{B} = \nabla \times \vec{A}$

Broken inversion symmetry:

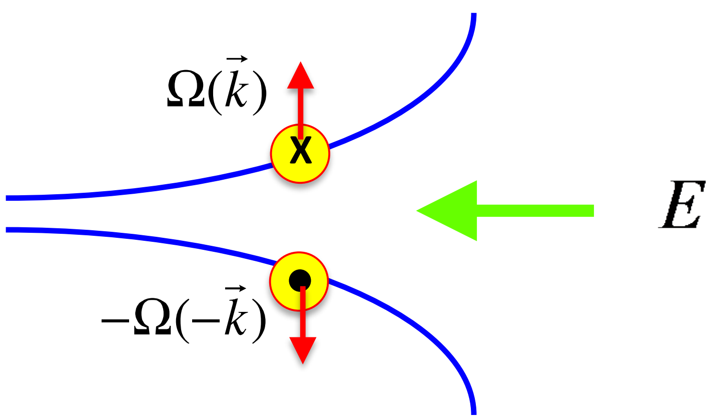
$$\Omega(\vec{k}) \neq 0$$

Valley Spin Hall effect $\hbar\vec{v} = \nabla_k \varepsilon_n(\vec{k}) - e\vec{E} \times \vec{\Omega}$

Time reversal symmetry:

$$\Omega(\vec{k}) = -\Omega(-\vec{k})$$

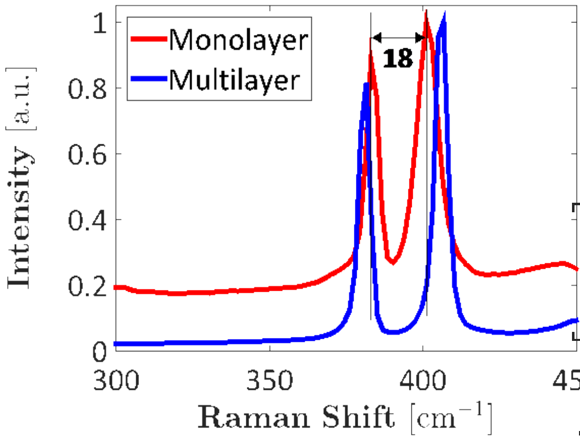
$$E^{\uparrow}(\vec{k}) = E^{\downarrow}(-\vec{k})$$



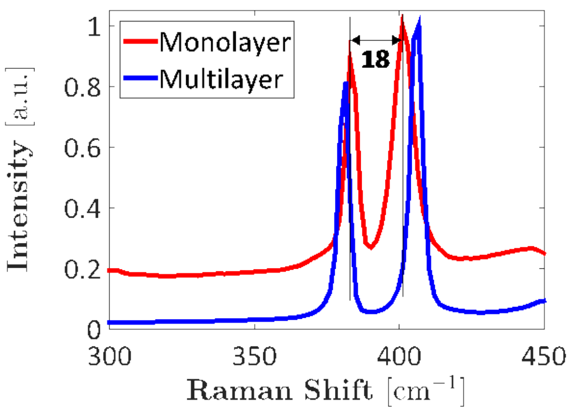
K and –K valleys with opposite Berry curvature develop anomalous velocities with opposite directions!

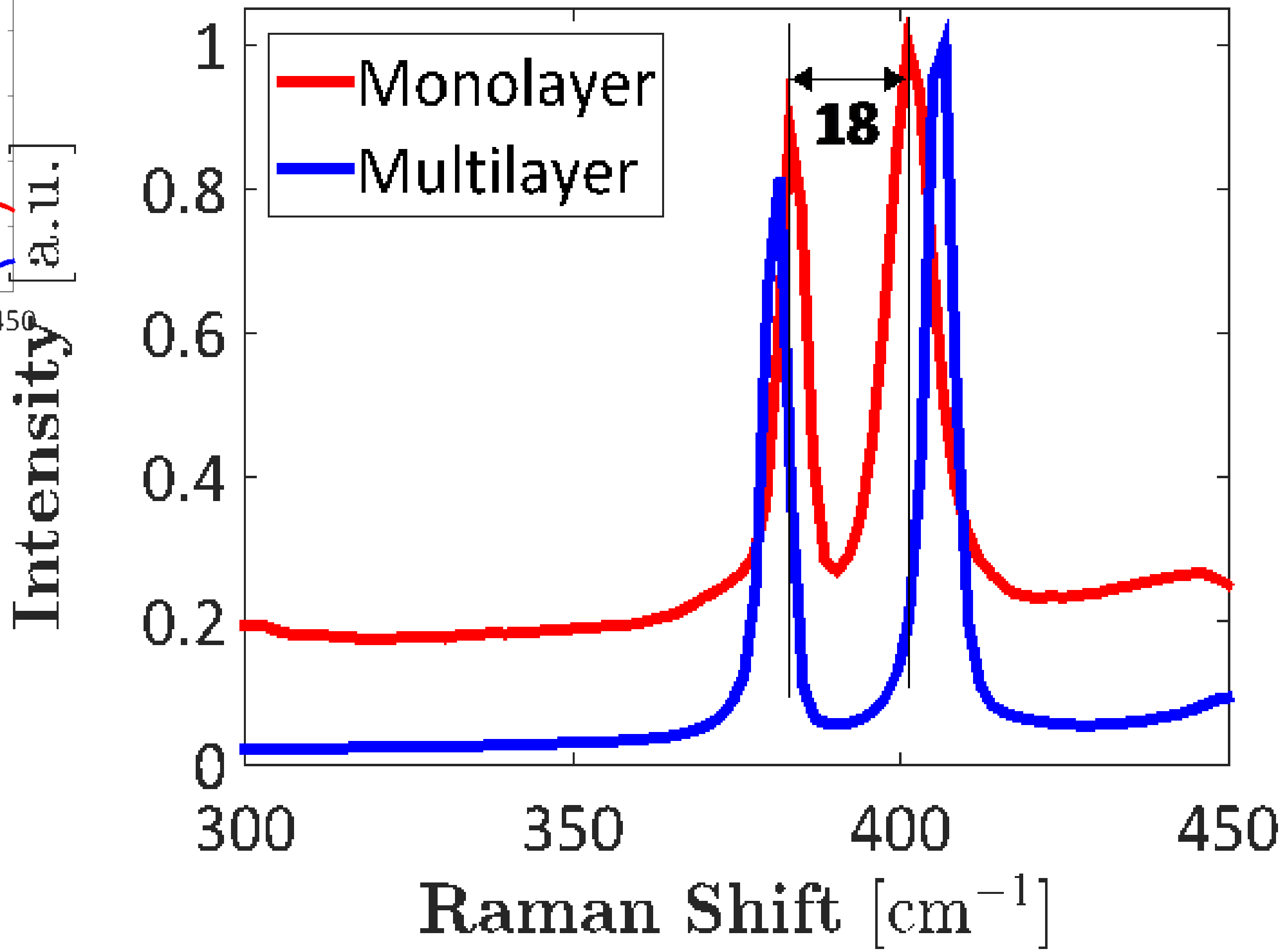
Transfer Characteristics

4-probe Measurements to Extract Rc and Sheet Resistance



Raman

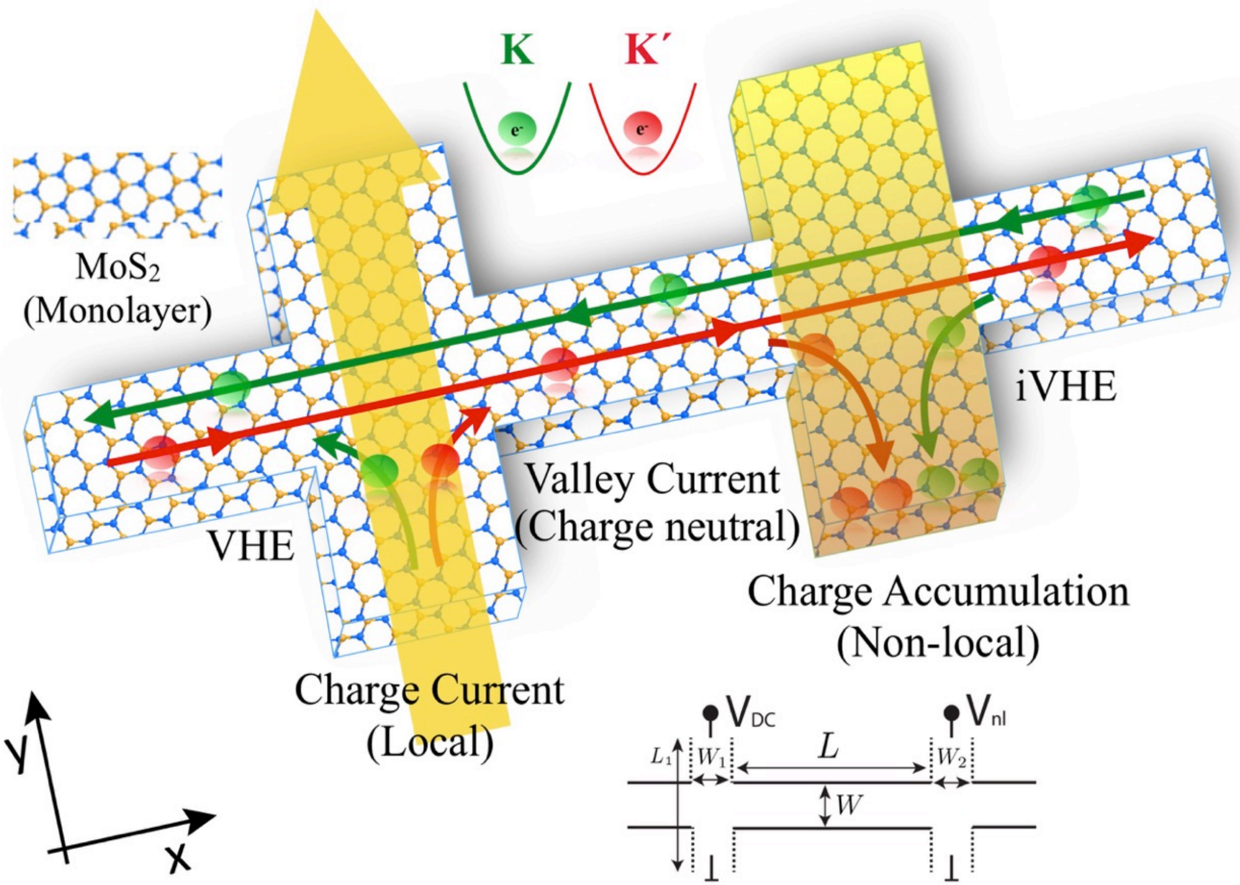


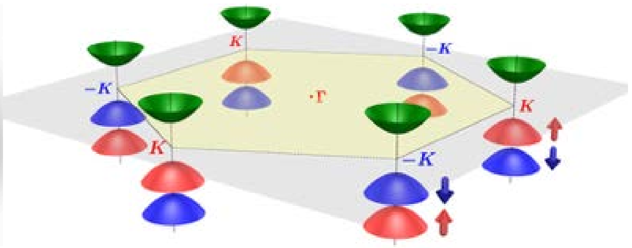


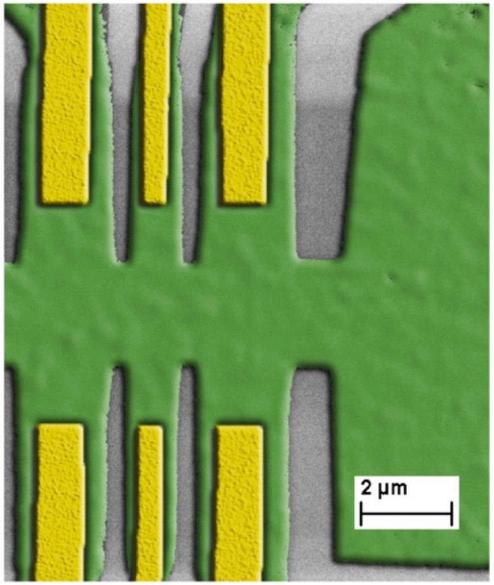
Typical n-type characteristics are observed in MoS_2 FET devices

Non-local Measurement Set-up for Valley Current Detection

L = 0.5μm, L_1 = 4.5μm, W_1 = 1μm, W = W_2 = 2μm

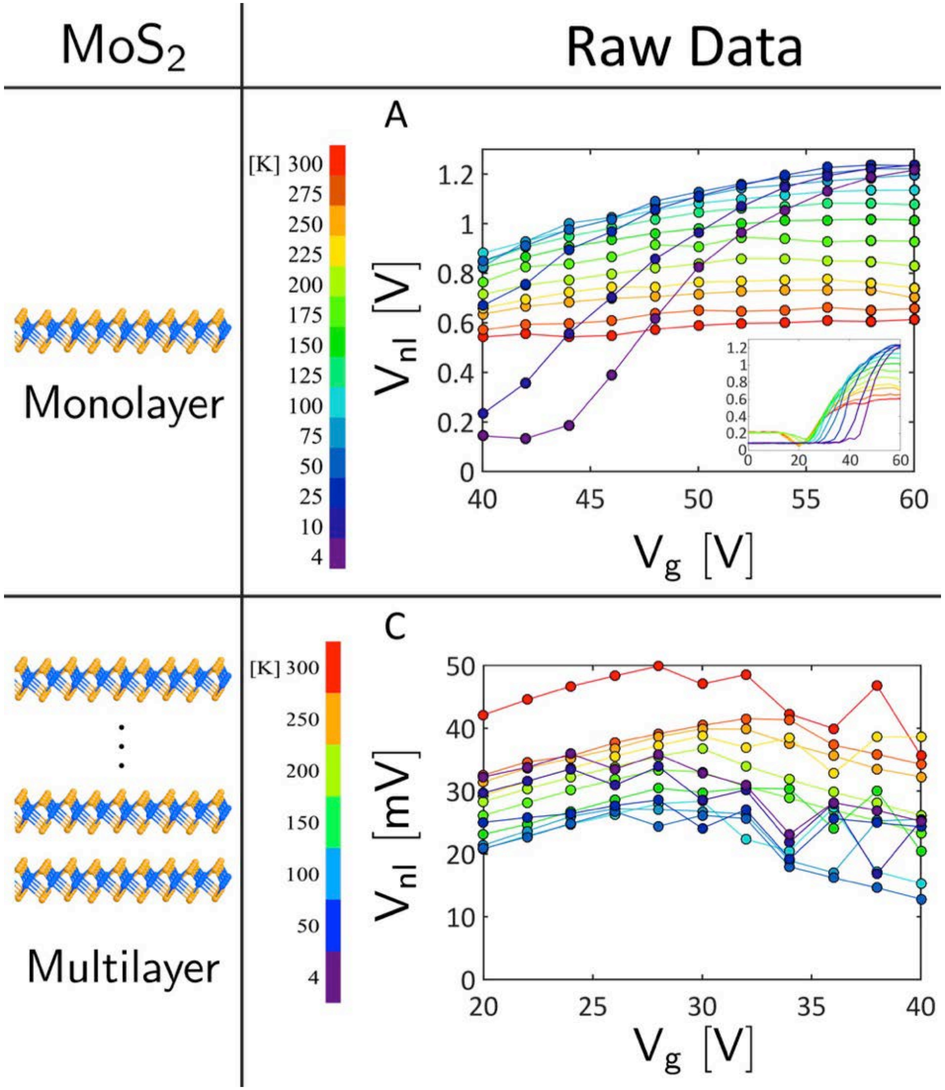


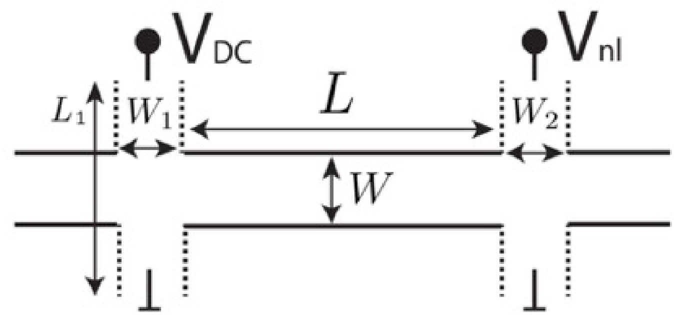




T. Hung, et al., Science Advance, 5, eaau6478 (2019)

Non-local Measurements of Monolayer and Multi-layer MoS_2

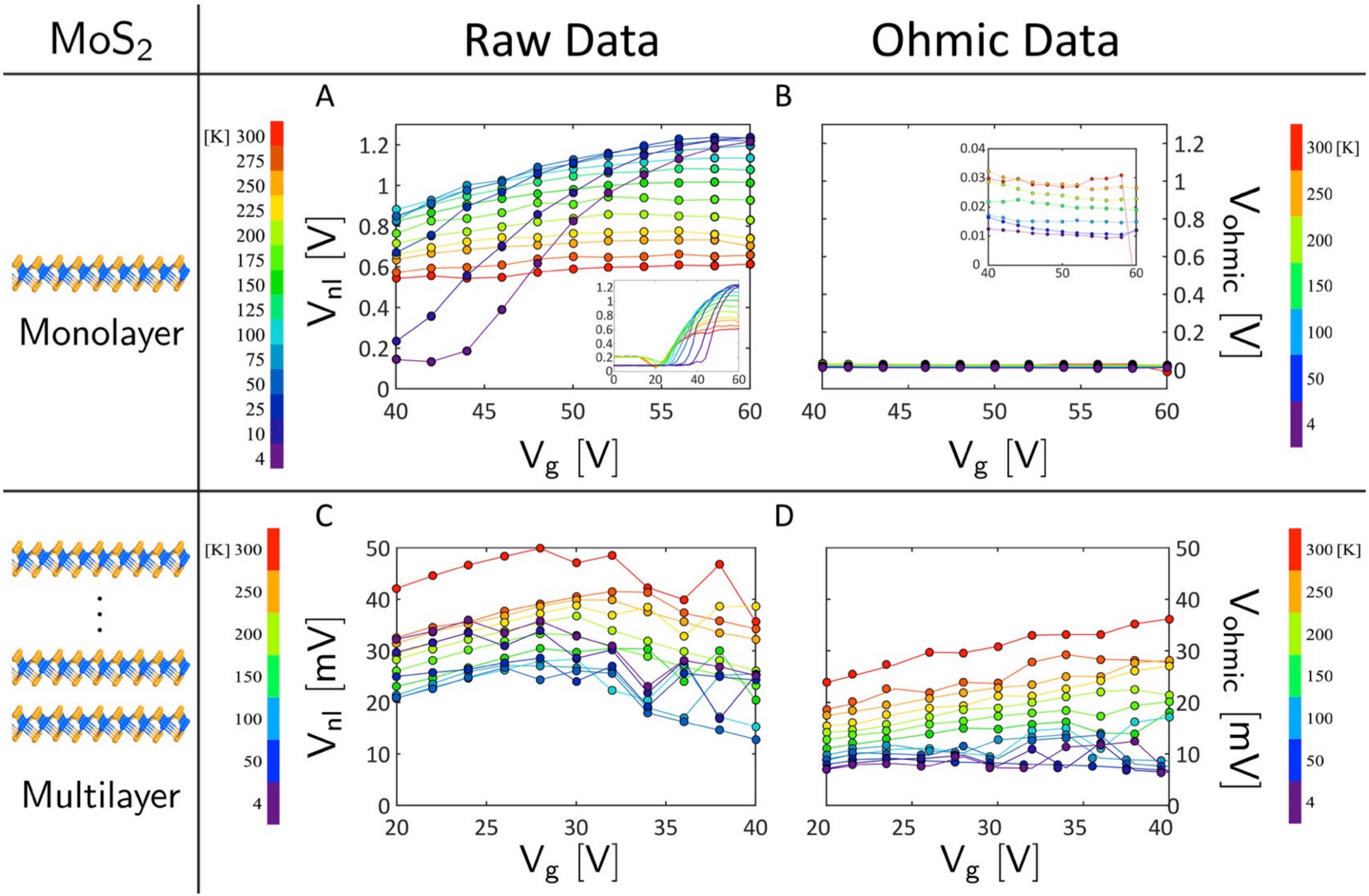




$$V_{Ohmic} = I_{DC}\rho_{sh}\frac{W}{W_1}e^{\frac{-\pi L}{W}}$$

Large non-local Hall voltage measured in monolayer MoS_2

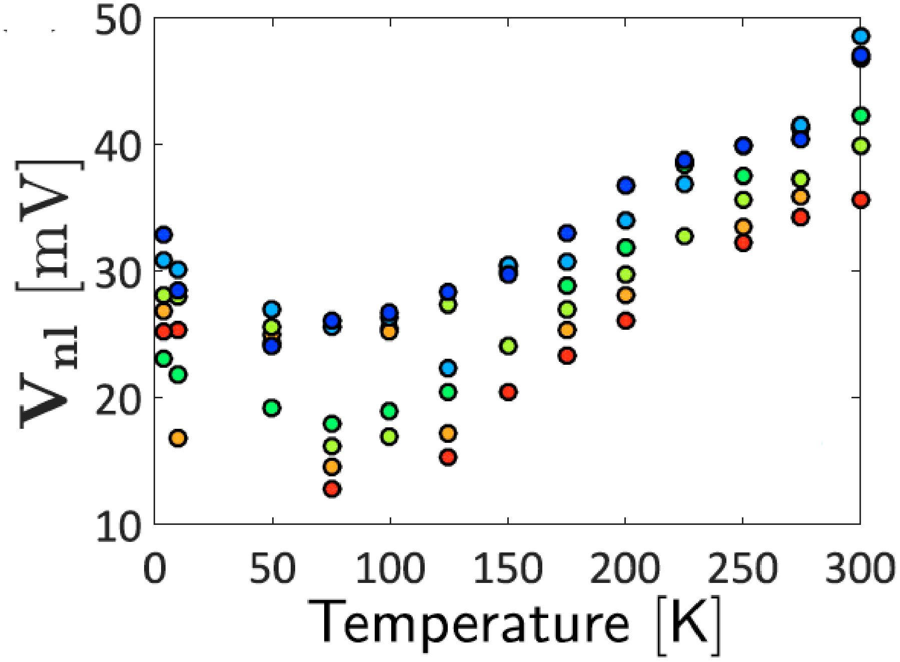
Non-local Measurements of Monolayer and Multi-layer MoS_2



Large non-local valley Hall voltage measured in monolayer MoS_2

Monolayer

Multi-layer



$$V_{Ohmic} = I_{DC}\rho_{sh}\frac{W}{W_1}e^{\frac{-\pi L}{W}}$$

Opposite temperature dependence trends are observed

Temperature Dependence of Non-local Signals

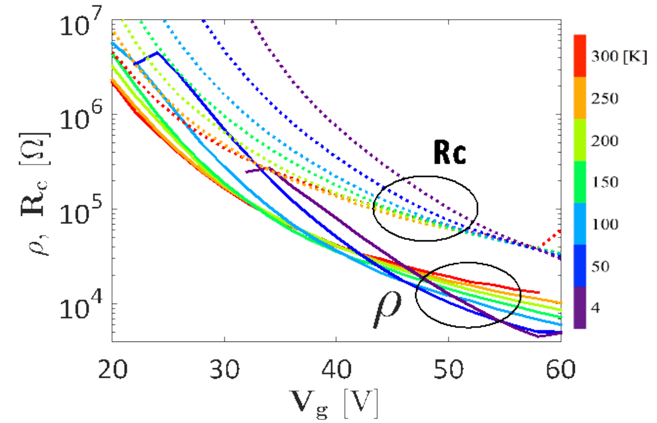
Monolayer

Multi-layer

$$V_{Ohmic}(T) = \frac{V_{ds}}{\left[2R_C(T) + \rho_{sh}(T)\frac{L_1}{W_1}\right]} \rho_{sh}(T) \frac{W}{W_1} e^{\frac{-\pi L}{W}}$$

Opposite temperature dependence trends are observed

Valley Hall Effect Induced Non-local Resistance



$$R_{nl}(T) \rightarrow R_{nl}\left(\rho(T), \lambda(T), \theta(T)\right)$$

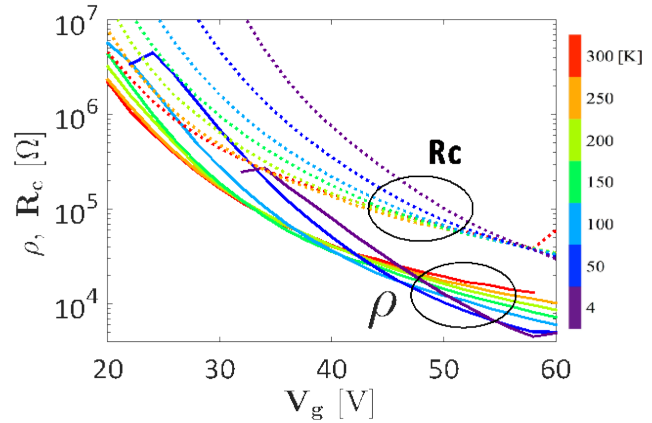
$$R_{nl} = \frac{V_{nl}}{I_{DC}} = \frac{2\rho\lambda W \sinh\left(\frac{W_1}{2\lambda}\right)\sinh\left(\frac{W_2}{2\lambda}\right)\theta^2 e^{-\frac{L}{\lambda}}}{\left(W_1 e^{\frac{W_1}{2\lambda}} + 2\lambda\sinh\left(\frac{W_1}{2\lambda}\right)\theta^2\right)\left(W_2 e^{\frac{W_2}{2\lambda}} + 2\lambda\sinh\left(\frac{W_2}{2\lambda}\right)\theta^2\right)}$$

$\theta^2 \ll 1$

$\frac{W_{1,2}}{\lambda} \ll 1$

$$R_{nl} = \frac{1}{2}\theta^2 \frac{W}{\sigma\lambda} e^{\frac{-L}{\lambda}}$$

Experiment
Empirical



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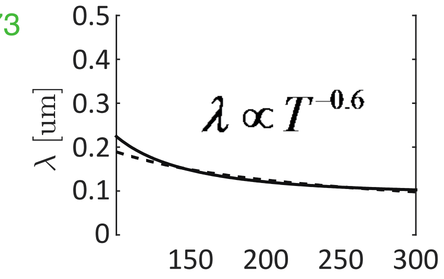
$\frac{W_{1,2}}{\lambda} \ll 1$

$$R_{nl} = \frac{1}{2}\theta^2 \frac{W}{\sigma\lambda} e^{\frac{-L}{\lambda}}$$

Valley Hall Effect Induced Non-local Resistance

Experiment
Empirical

$\lambda \propto T^{-0.73}$



$$R_{nl} = \frac{V_{nl}}{I_{DC}} = \frac{2\rho\lambda W \sinh\left(\frac{W_1}{2\lambda}\right)\sinh\left(\frac{W_2}{2\lambda}\right)\theta^2 e^{-\frac{L}{\lambda}}}{\left(W_1 e^{\frac{W_1}{2\lambda}} + 2\lambda \sinh\left(\frac{W_1}{2\lambda}\right)\theta^2\right)\left(W_2 e^{\frac{W_2}{2\lambda}} + 2\lambda \sinh\left(\frac{W_2}{2\lambda}\right)\theta^2\right)}$$

$\theta^2 \ll 1$

$\frac{W_{1,2}}{\lambda} \ll 1$

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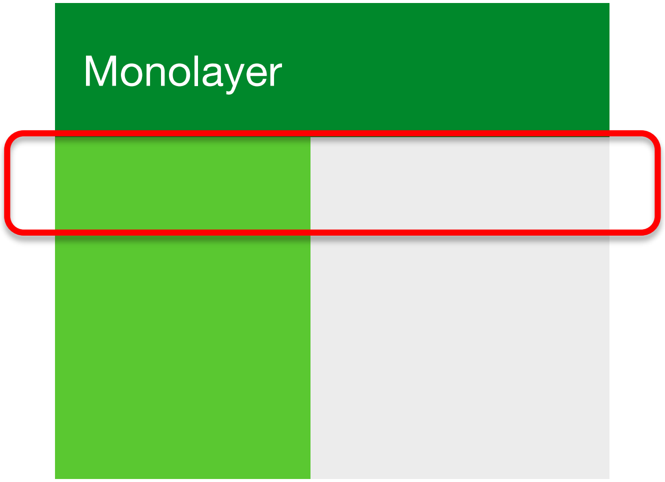
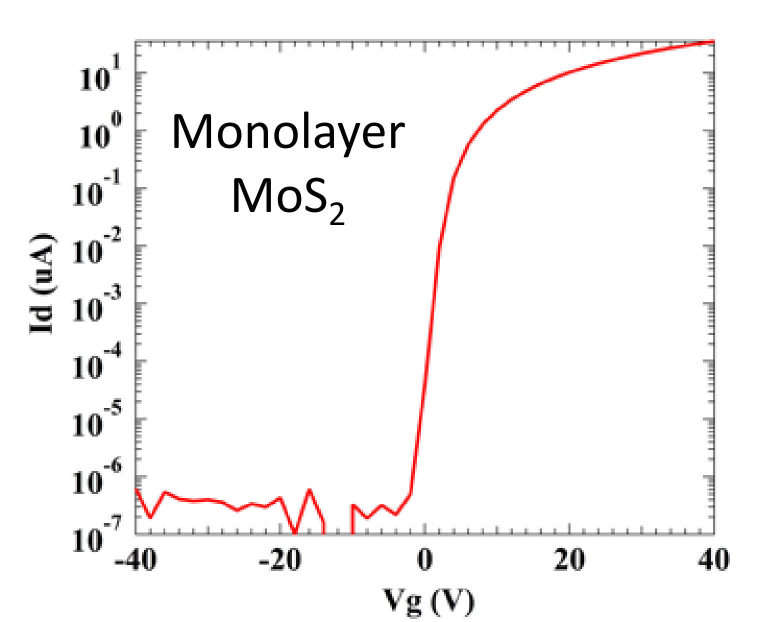
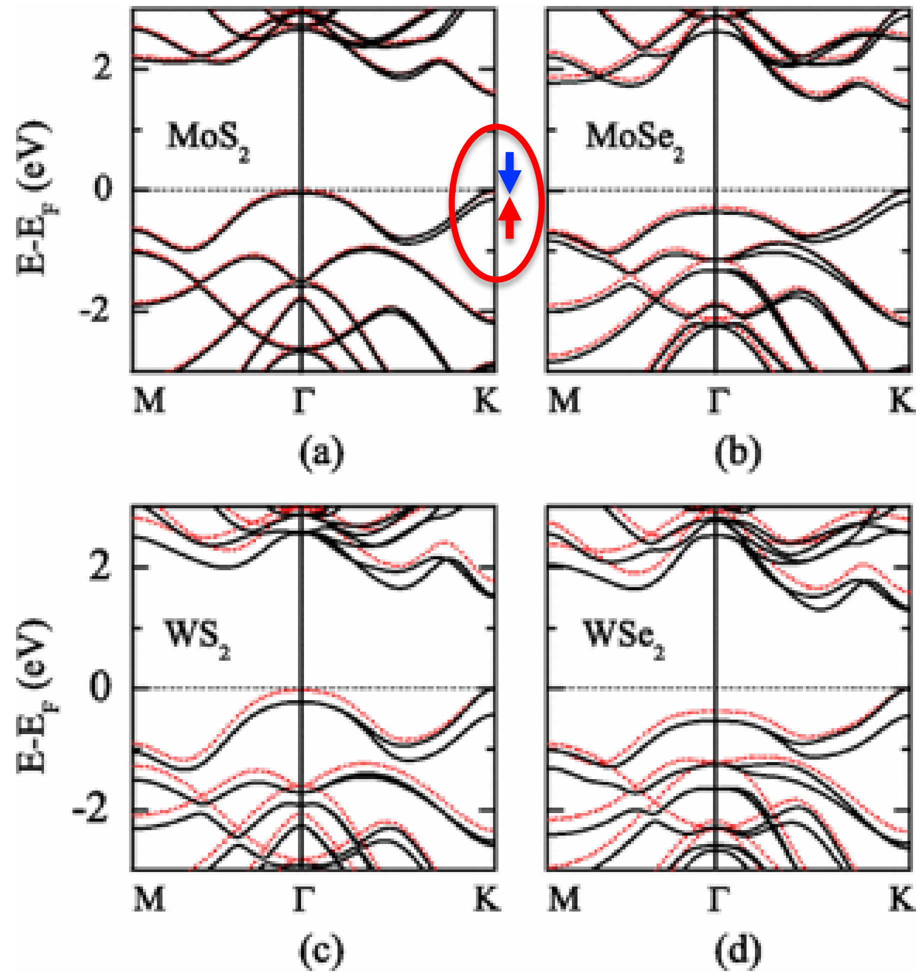
Large Spin Splitting in WSe_2 Valence Band



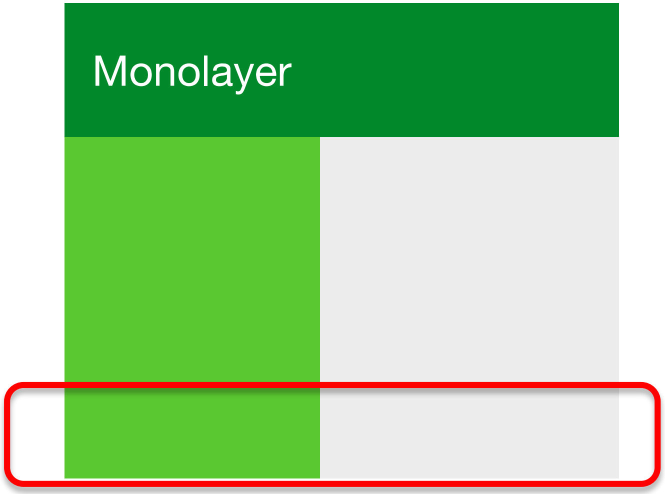


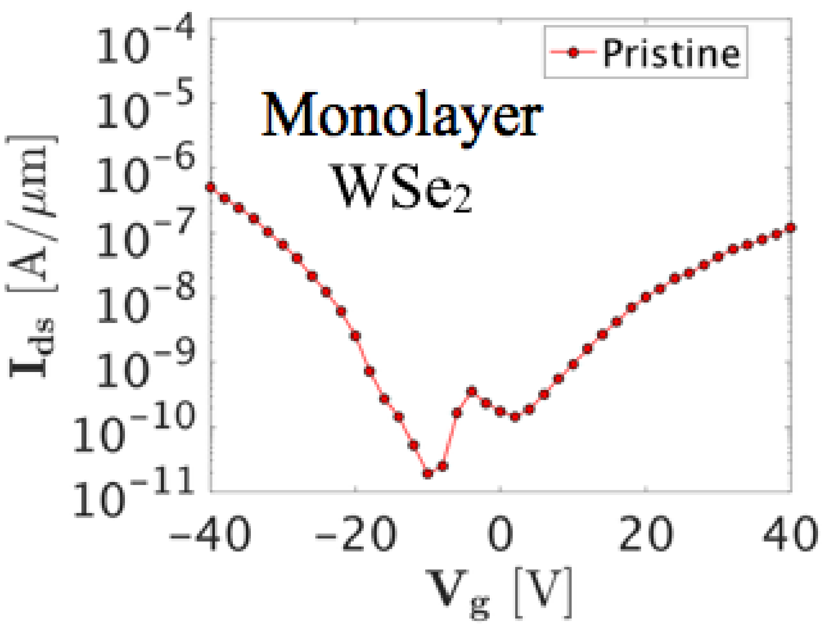


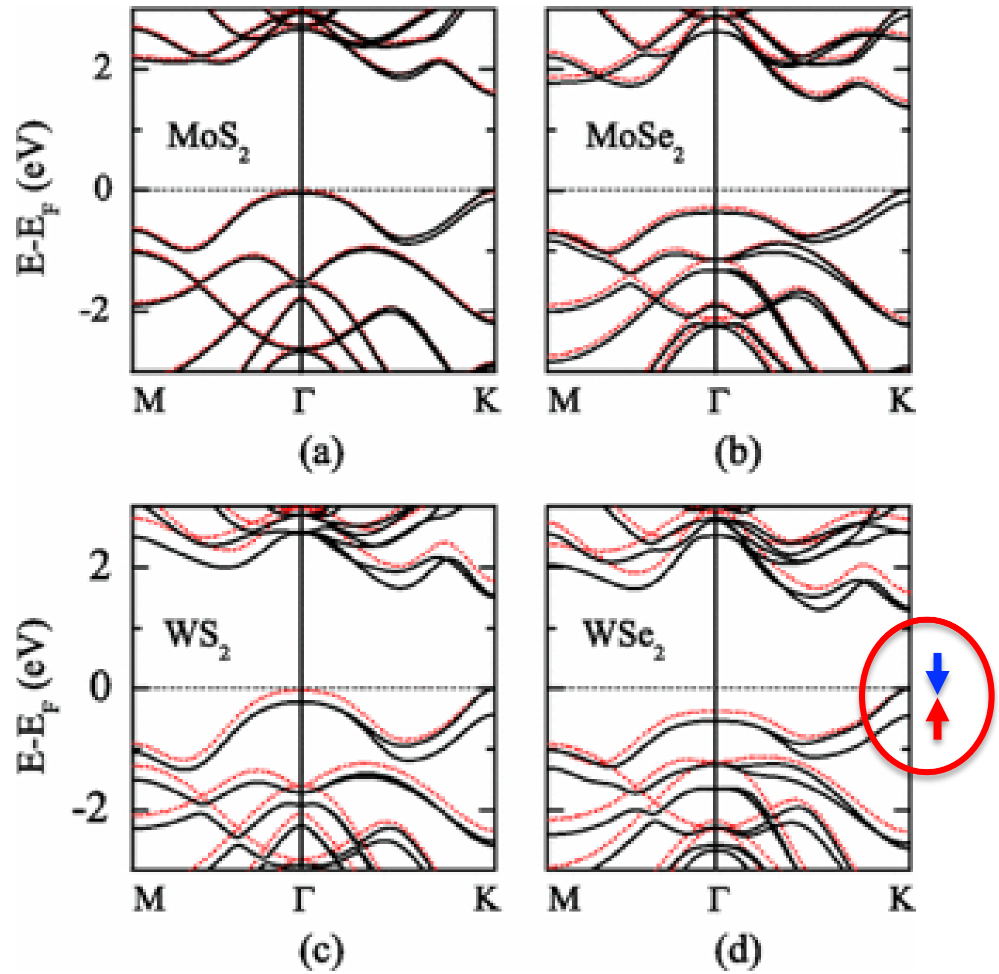
Z. Y. Zhu, et al., PRB **84**, 153402 (2011)

Need to access p-branch, hole carriers

Large Spin Splitting in WSe_2 Valence Band



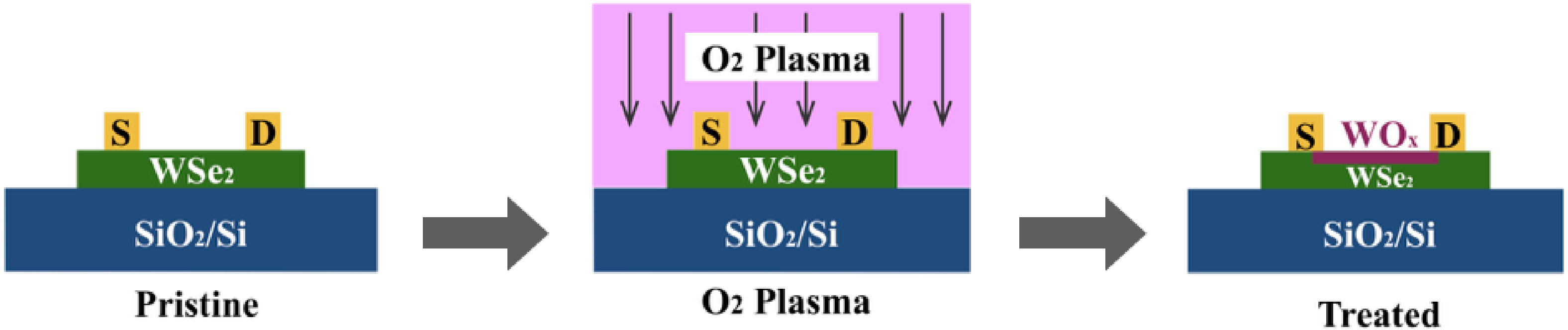


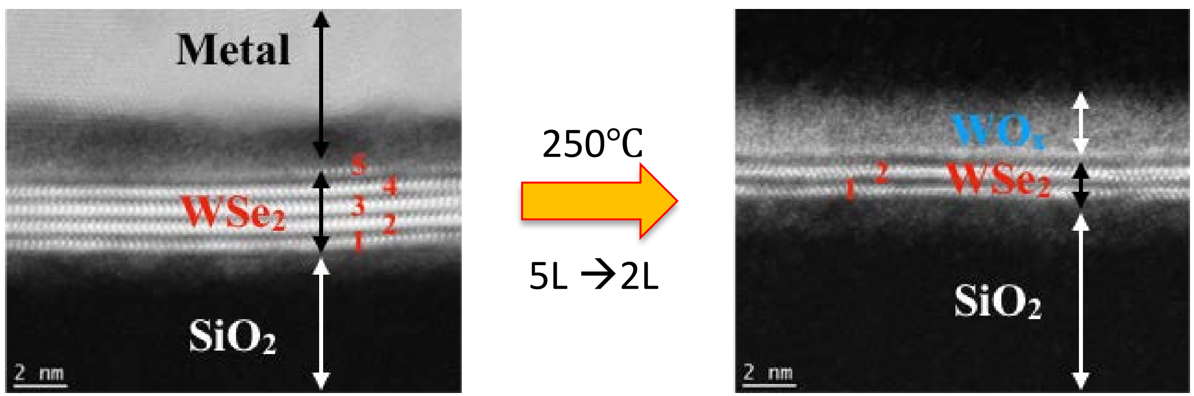


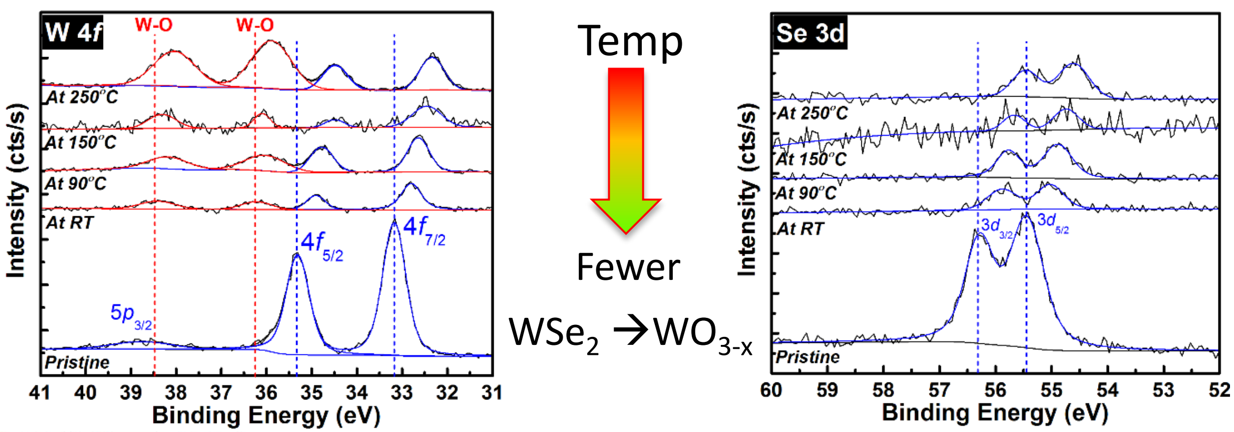
Z. Y. Zhu, et al., PRB **84**, 153402 (2011)

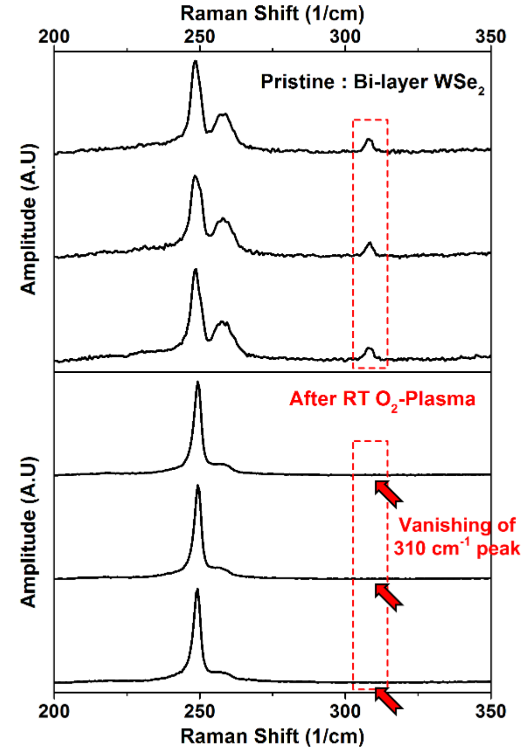
Although p-branch is present, the on-state current needs to be improved!

Air Stable P-type Doping for WSe_2 FETs



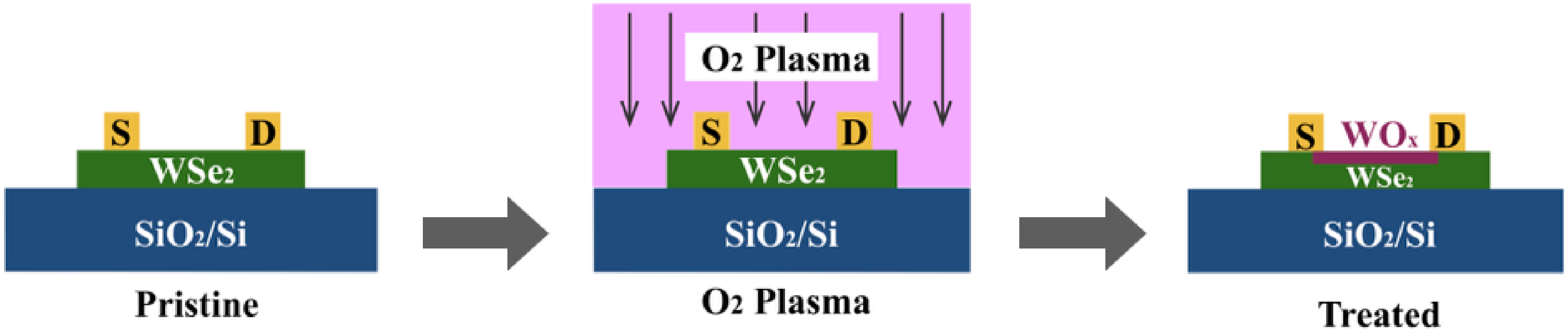






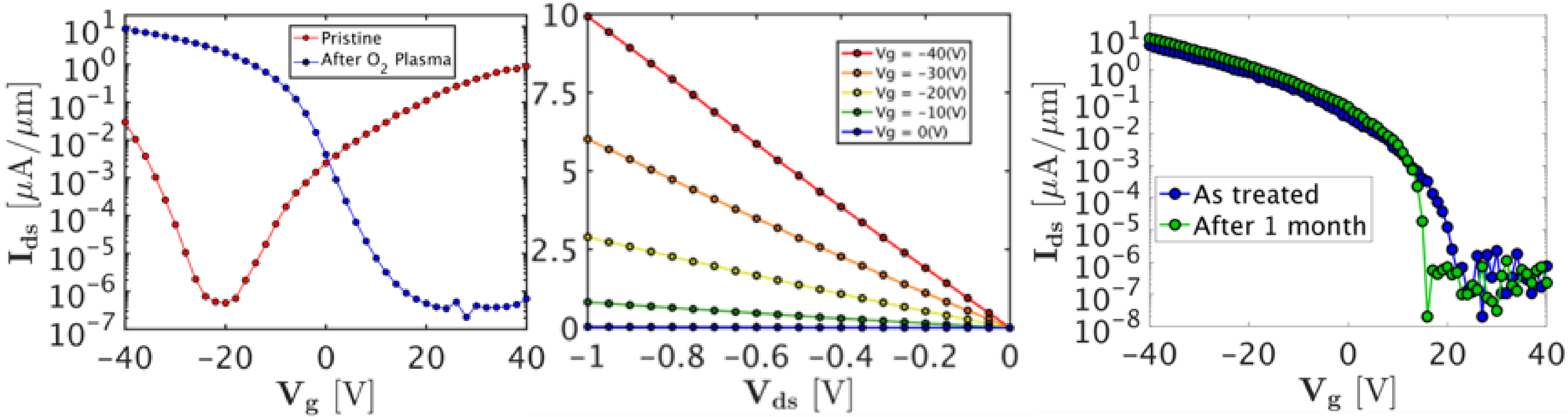
RT Bilayer → Monolayer

Air Stable P-type Doping for WSe_2 FETs



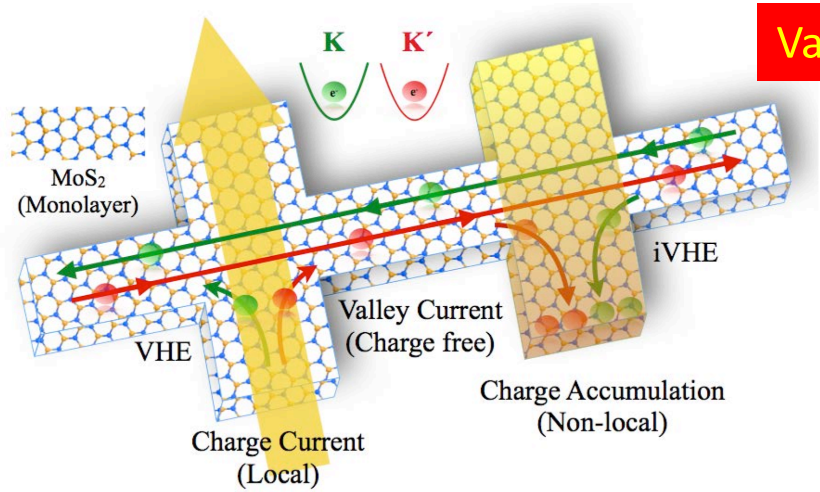
Tunable P-type Doping

Air Stable

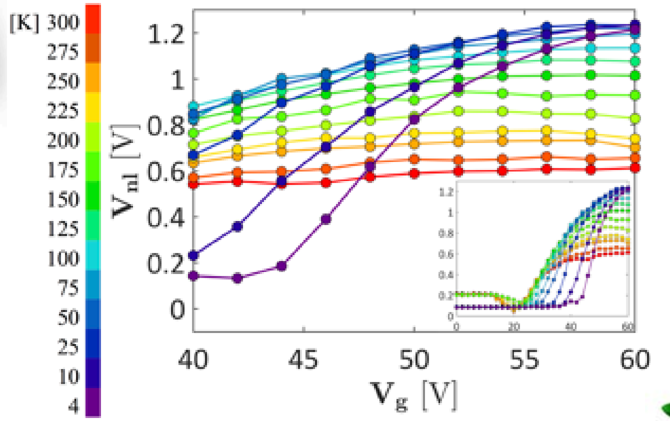


T. Hung, C.-S. Pang, et. al., submitted (2019)

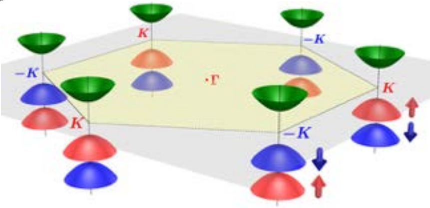
Electrical Detection of Valley Coupled Spin Currents in WSe_2

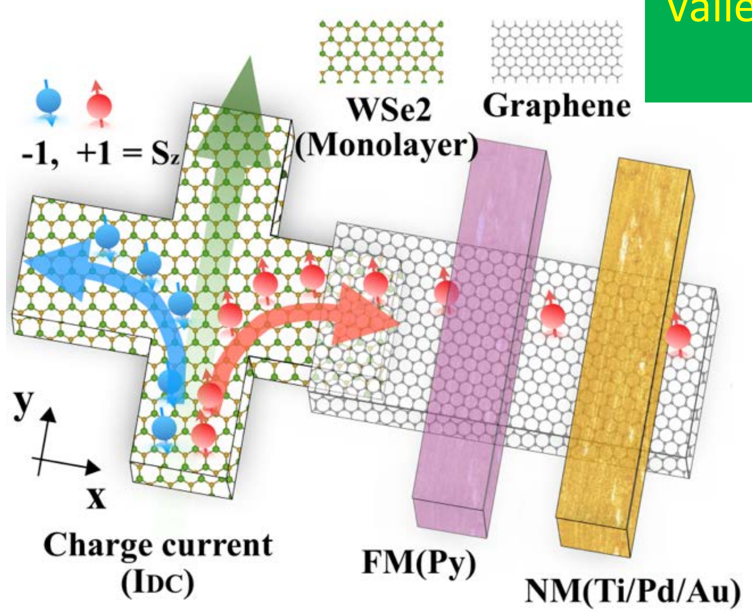


Valley Current Detection Only in MoS_2



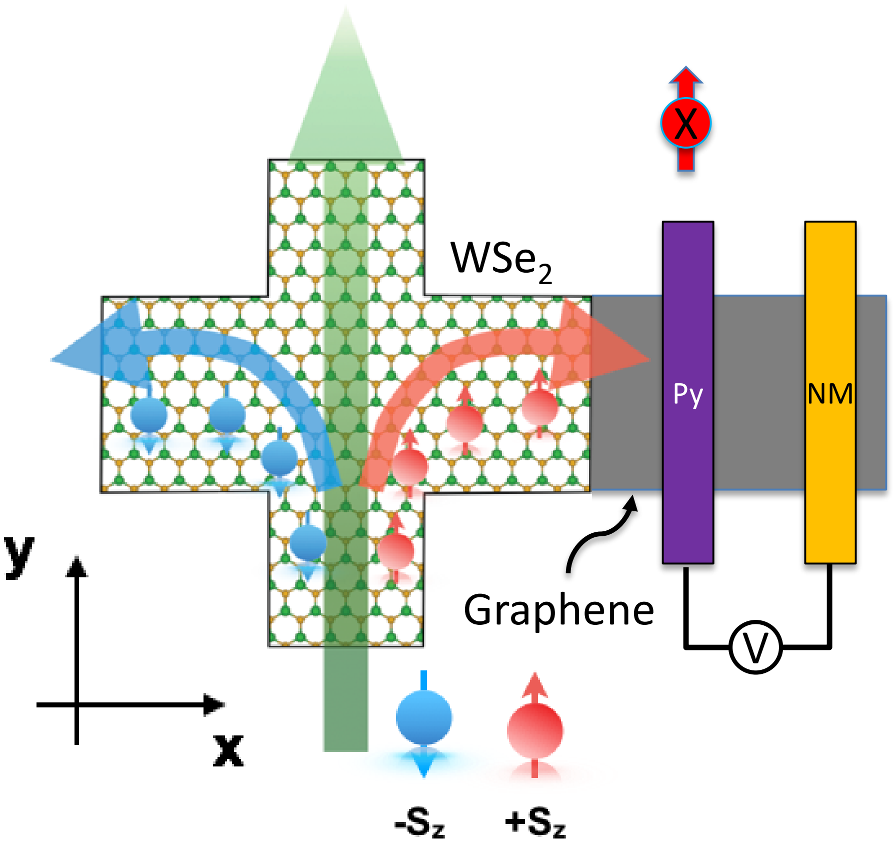
Valley Coupled Spin Current Detection in WSe_2





- Ferromagnetic (FM) contact for spin detection
- Graphene channel for spin diffusion
- Nonlocal spin valve device configuration
- Magnetic field scanning to align FM from in-plane to out-of-plane magnetization

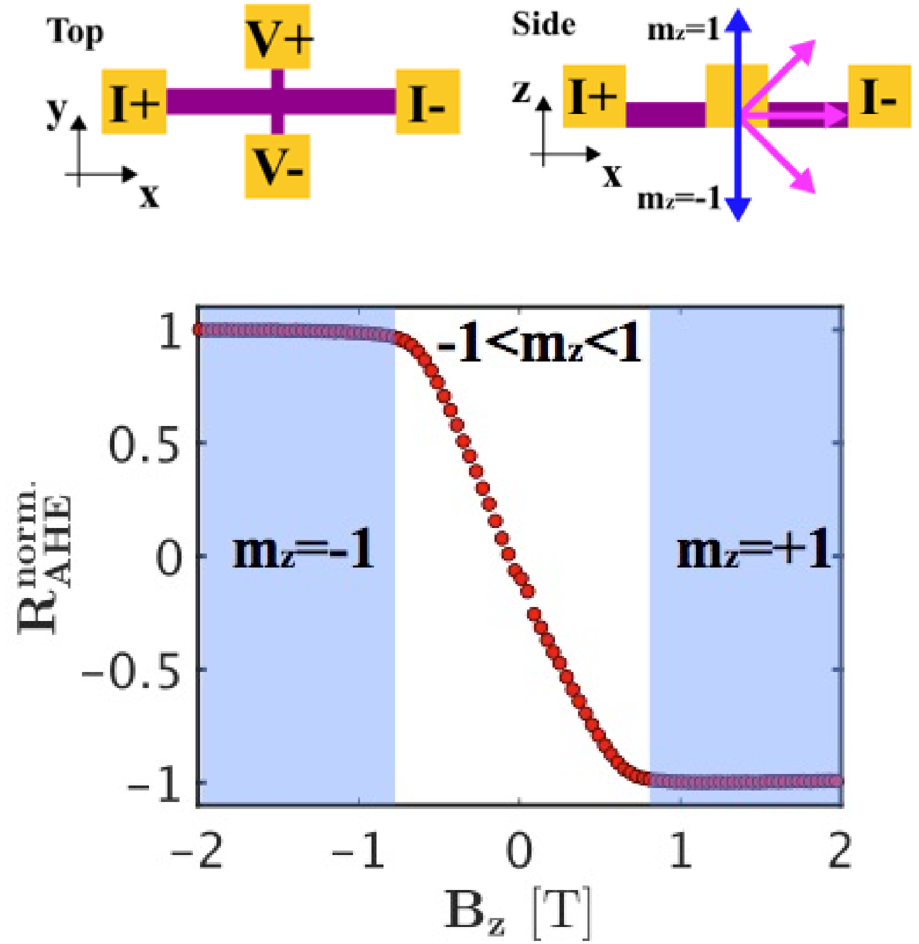
Nonlocal Spin Valve Measurements for Out-of-Plane Spins



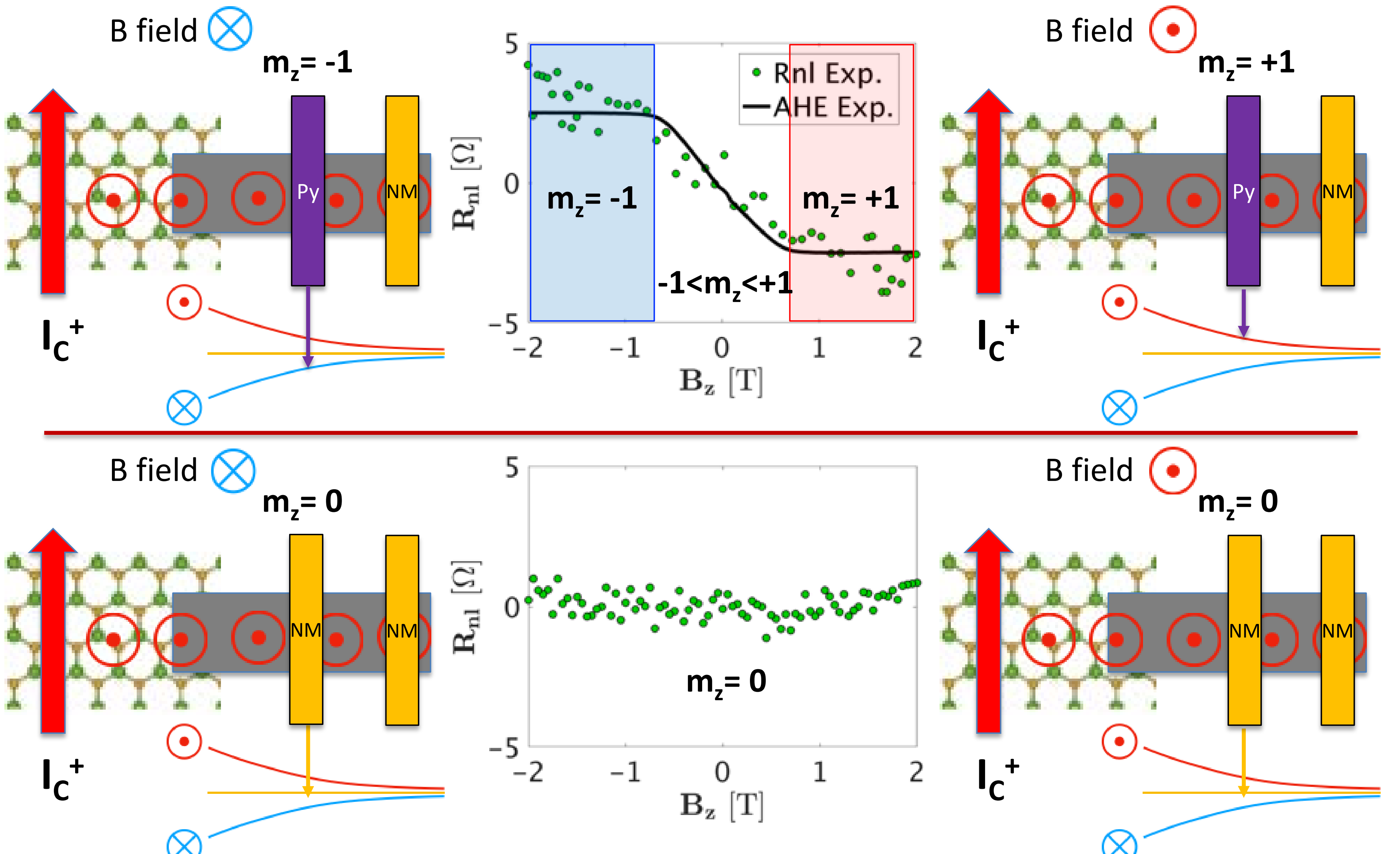
Spin Generation

Spin Detection

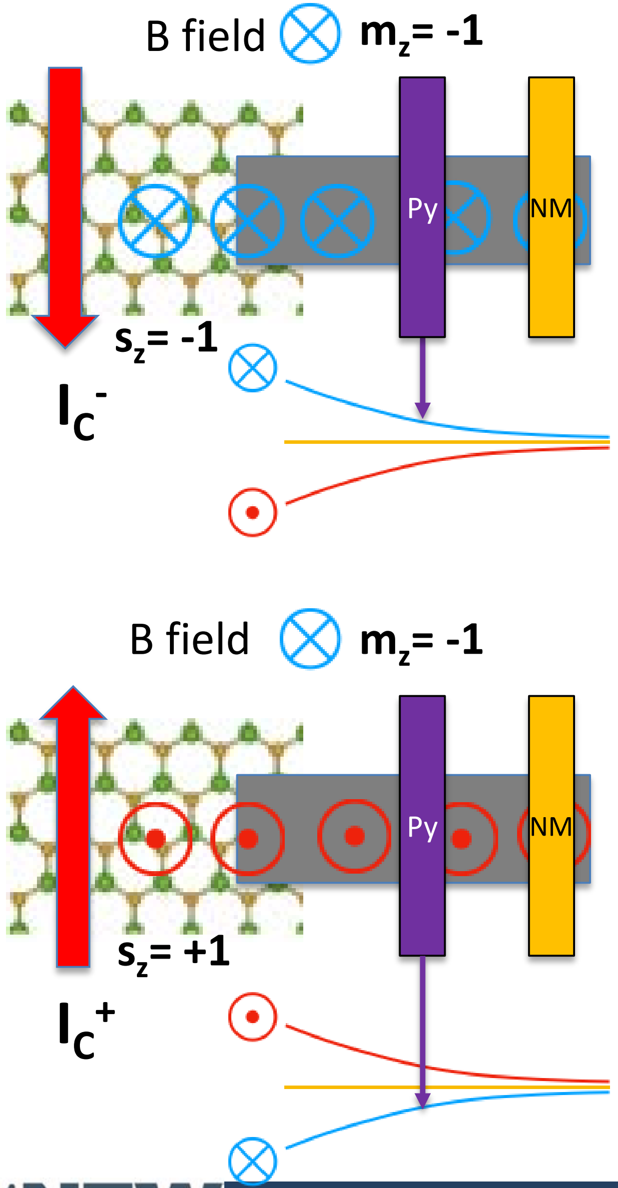
In-plane FM - Py's Anomalous Hall Effect

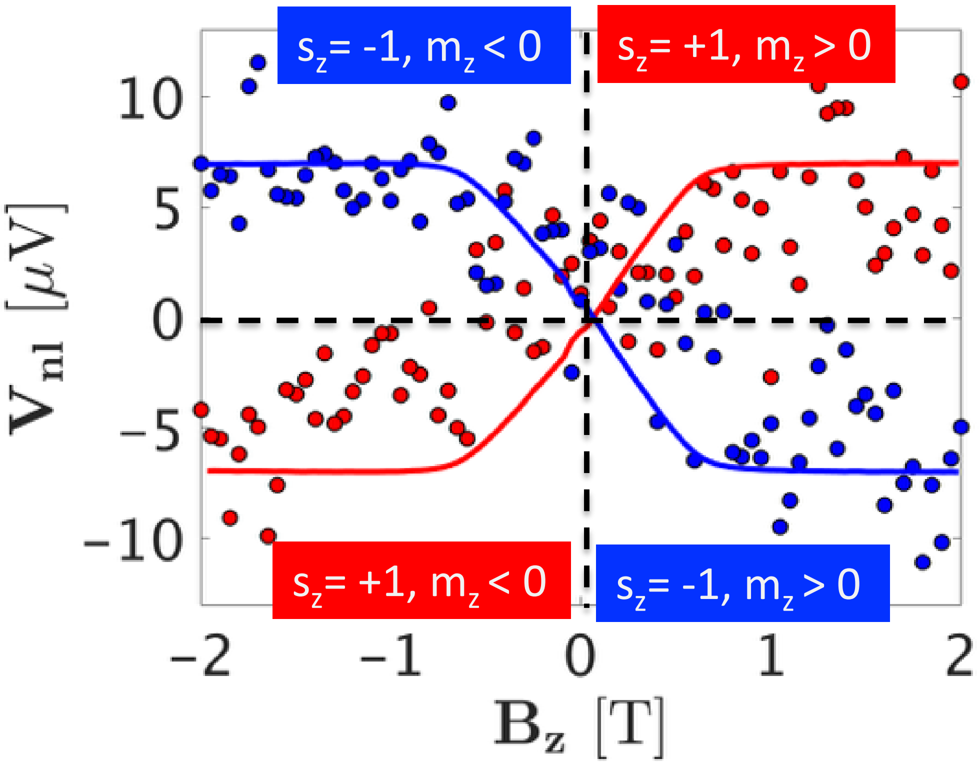


Nonlocal Spin Valve Measurements for Out-of-Plane Spins



Nonlocal Spin Valve Measurements for Out-of-Plane Spins





Collaborators:

Prof. Moon Kim's group (UT Dallas)

Prof. Robert Wallace's group (UT Dallas)

http://www.purdue.edu/discoverypark/newlimits/index.php

Thank you!