NPSMP2015 Symposium
2015/6/11

Valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene

Yuya Shimazaki[1], Michihisa Yamamoto[1,2], Ivan V. Borzenets[1], Kenji Watanabe[3], Takashi Taniguchi[3], and Seigo Tarucha[1,4]

[1]Department of Applied Physics, University of Tokyo

[2]PRESTO, JST

[3]Advanced Material Laboratory, National Institute for Materials Science

[4]Center for Emergent Matter Science, RIKEN

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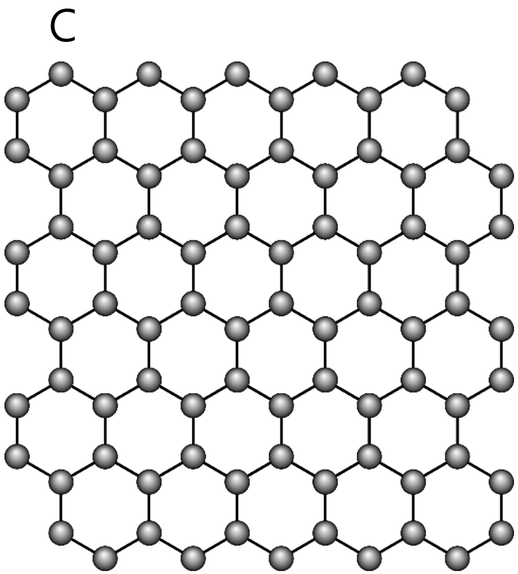
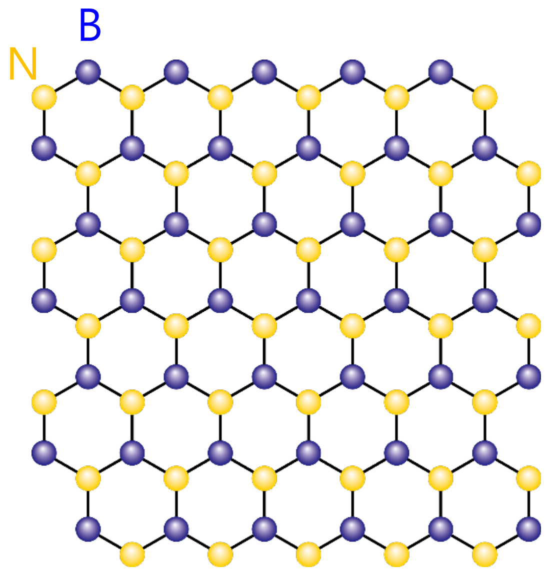
Honeycomb lattice systems

Graphene



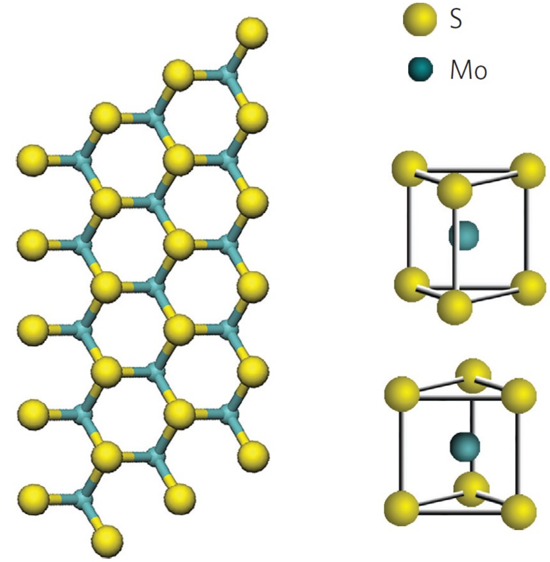
Metal

h-BN



Insulator

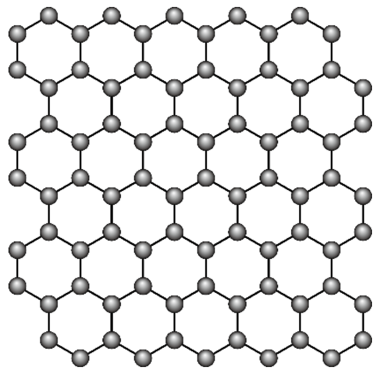
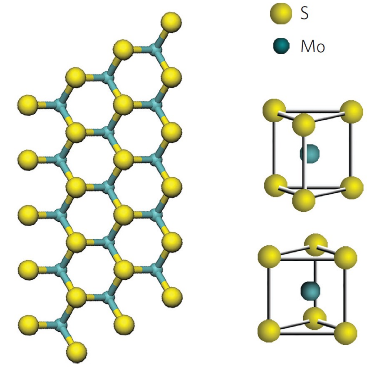
Transitional Metal
Dichalcogenides (TMDC)



Semiconductor: MoS_2, WSe_2, …

H. Zeng *et al.*,
Nature Nanotechnol. **7**, 490 (2012)

Valley degree of freedom

<table>
<tr><th></th><th>Graphene</th><th>TMDC</th></tr>
<tr><td>Lattice</td><td></td><td>
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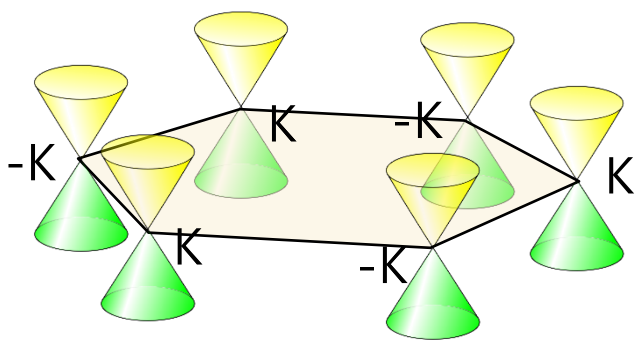
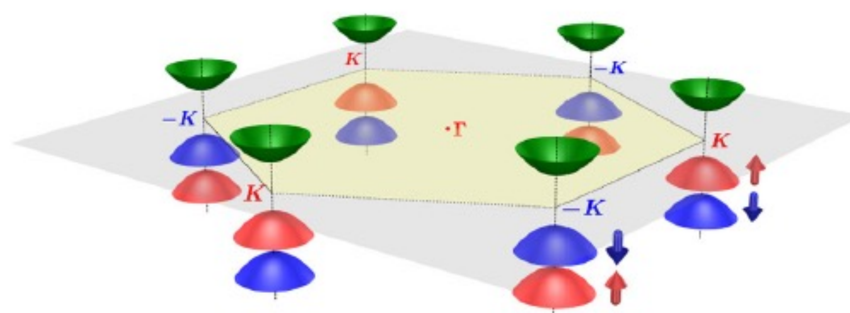
<tr><td>Band structure</td><td>
</td><td>

D. Xiao et al., Phys. Rev. Lett. 108, 196802 (2012)</td></tr>
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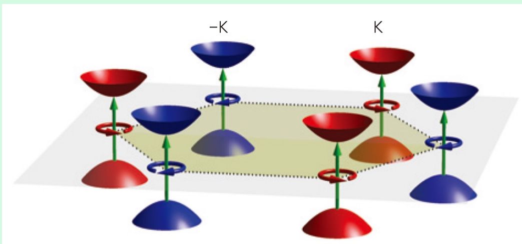
Valley degree of freedom : K or -K → Valleytronics

The rise of Valleytronics

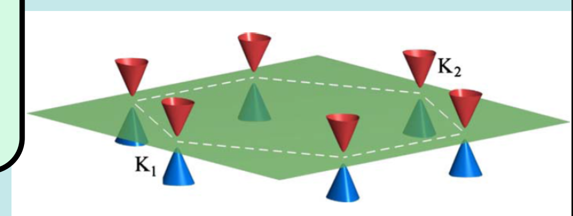
Light



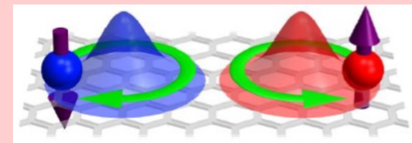
Valley ⇔ Circularly polarized light

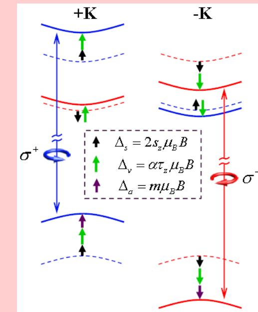
T. Cao *et al.*, *Nature Commun.* **3**, 887 (2012)
K. F. Mak *et al.*, *Nature Nanotechnol.* **7**, 490 (2012)
H. Zeng *et al.*, *Nature Nanotechnol.* **7**, 494 (2012)
Y. J. Zhang *et al.*, *Science* **344**, 725 (2014)

Valley



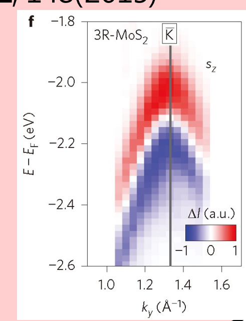
Magnetic field/Spin





Valley Zeeman effect

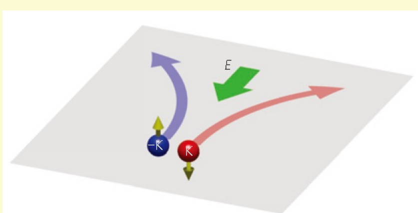
Y. Li *et al.*, *Phys. Rev. Lett.* **113**, 266804 (2014)
D. MacNeill *et al.*, *Phys. Rev. Lett.* **114**, 037401(2015)
A. Srivastava *et al.*, *Nature Phys.* **11**, 141(2015)
G. Aivazian *et al.*, *Nature Phys.* **11**, 148(2015)



Valley-spin coupling

R. Suzuki M. Sakano *et al.*,
Nature Nanotechnol. **9**, 611 (2014)

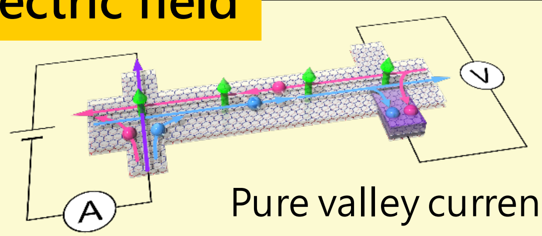
Electric field



Valley Hall effect

TMDC (MoS_2)

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



Pure valley current

Graphene

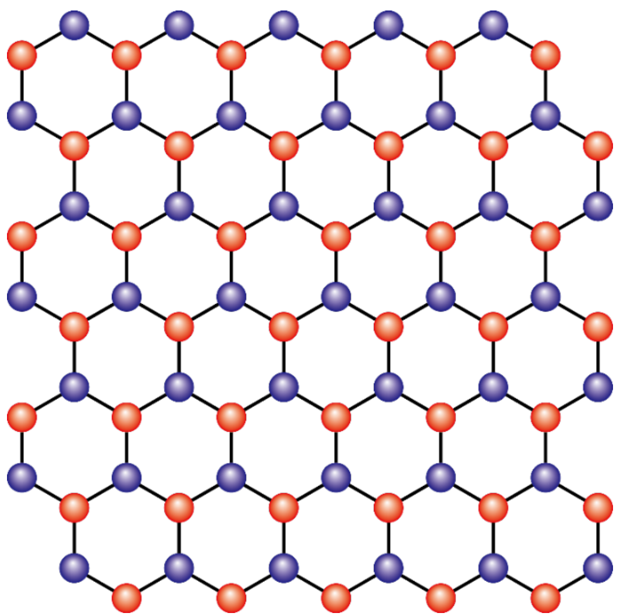
R. V. Gorbachev *et al.*, *Science* **346**, 448 (2014)
M. Sui *et al*, arXiv:1501.04685 (2015)
Y. Shimazaki *et al*, arXiv:1501.04776 (2015)

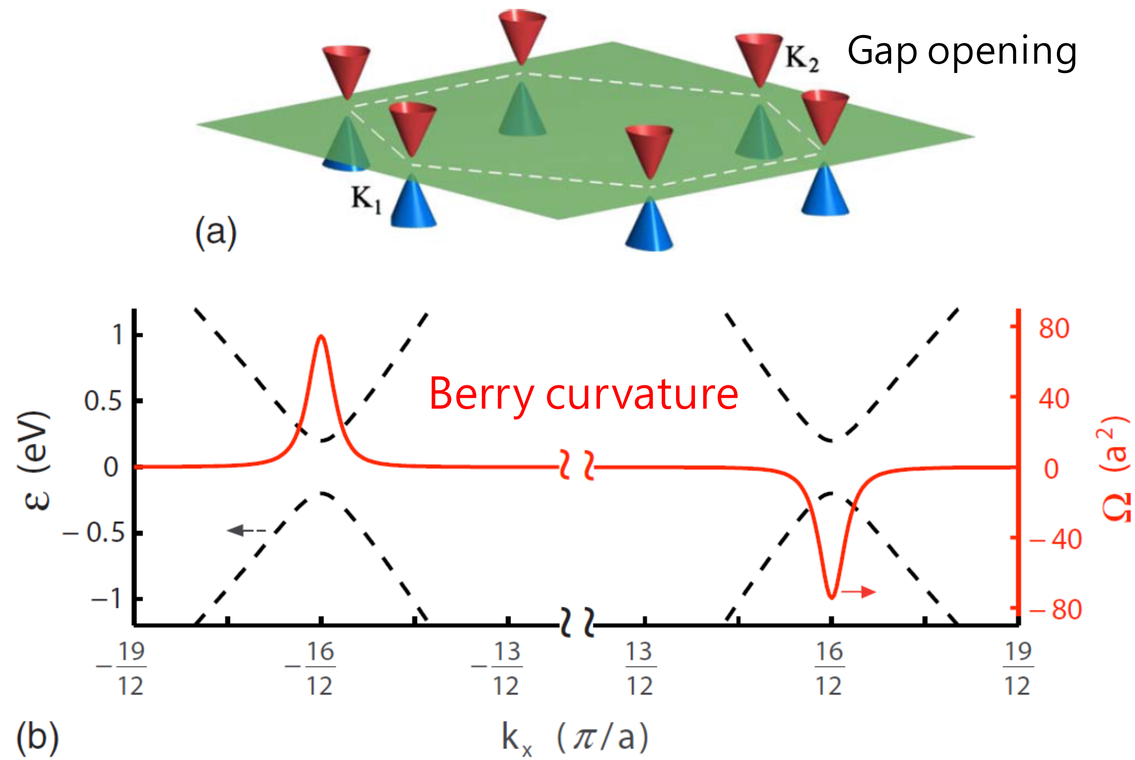
D. Xiao *et al.*,
Rev. Mod. Phys. **82**, 1959 (2010)

X. Xu *et al.*,
Nature Phys. **10**, 343 (2014)

Inversion symmetry broken honeycomb lattice

Inversion symmetry broken
honeycomb lattice





D. Xiao *et al., Rev. Mod. Phys.* **82**, 1959 (2010)

Valley Hall effect

Berry curvature:
"Magnetic field in momentum space"

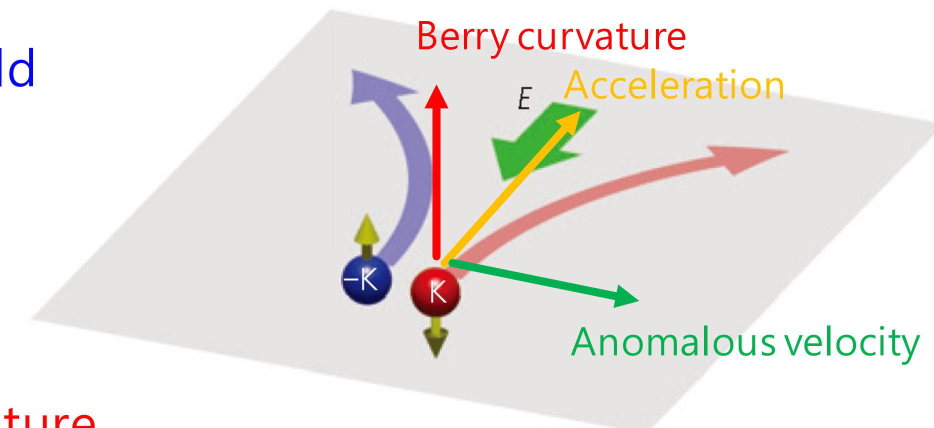
Lorentz force (Acceleration, Magnetic field, Velocity)

$$\dot{\boldsymbol{k}} = -\frac{e}{\hbar}\dot{\boldsymbol{r}}\times\boldsymbol{B}$$

Anomalous velocity (Velocity, Berry curvature, Acceleration)

$$\dot{\boldsymbol{r}} = -\dot{\boldsymbol{k}}\times\boldsymbol{\Omega}$$

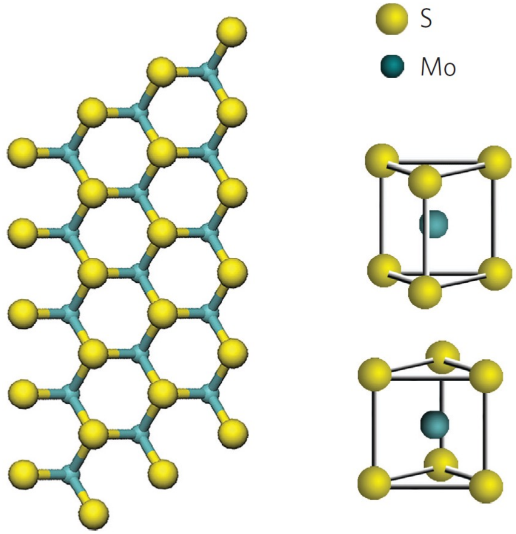
Valley Hall effect



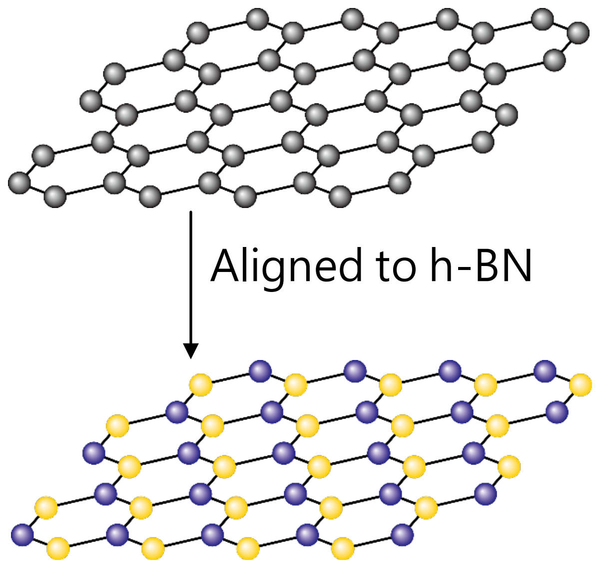
D. Xiao *et al, Phys. Rev. Lett.* **99**, 236809 (2007)

How to break inversion symmetry?

MoS_2



Monolayer graphene



Initially symmetry broken

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

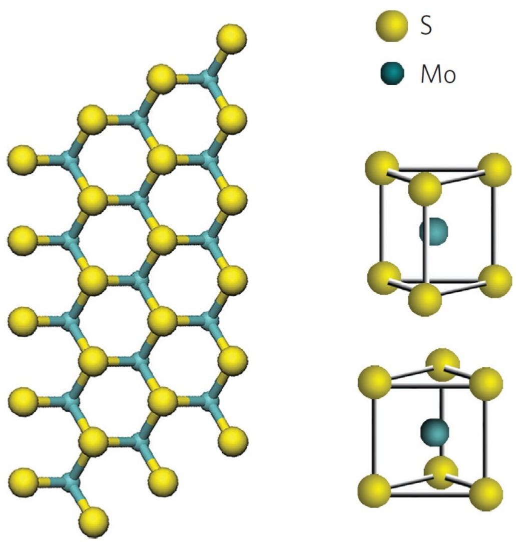
R. V. Gorbachev *et al.*,
Science **346**, 448 (2014)

Structurally inversion symmetry broken system

→Valley Hall effect has been reported

How to break inversion symmetry?

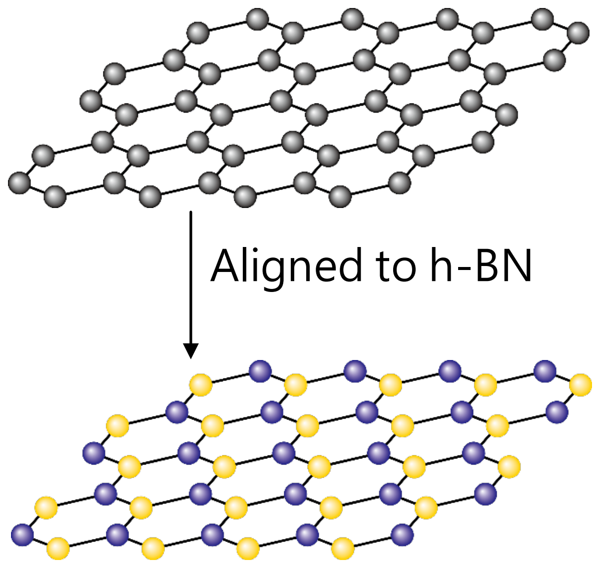
MoS$_2$



Initially symmetry broken

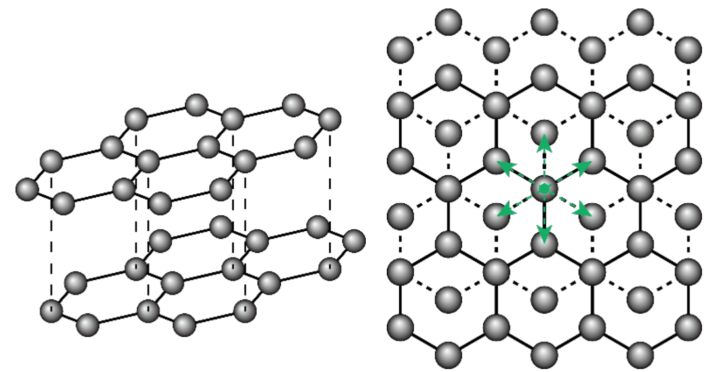
K. F. Mak *et al.*,
Science **344**, 1489 (2014)

Monolayer graphene



R. V. Gorbachev *et al.*,
Science **346**, 448 (2014)

Bilayer graphene

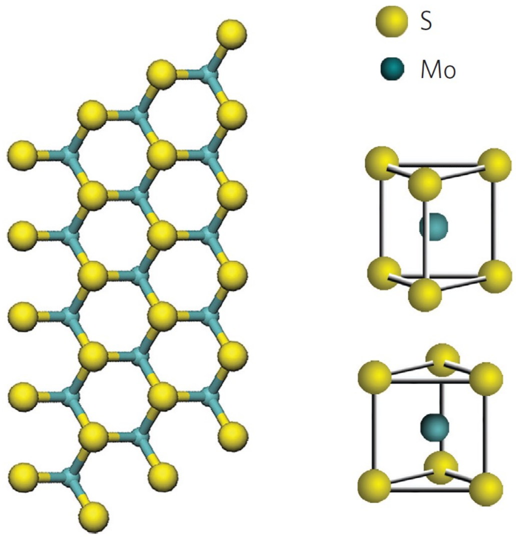


Structurally inversion symmetry broken system

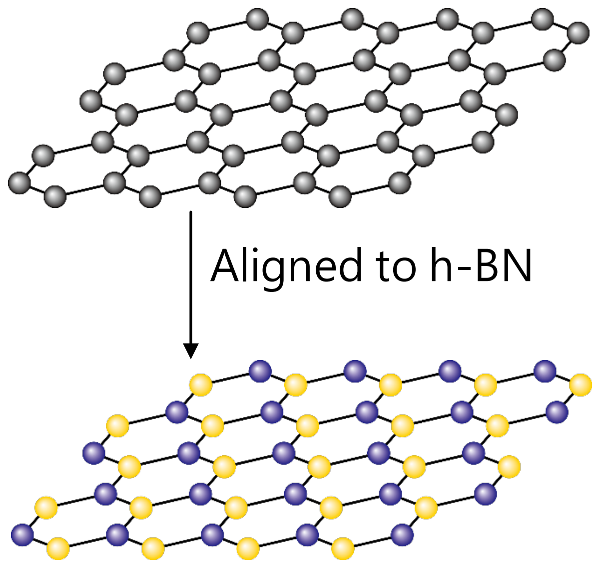
→Valley Hall effect has been reported

How to break inversion symmetry?

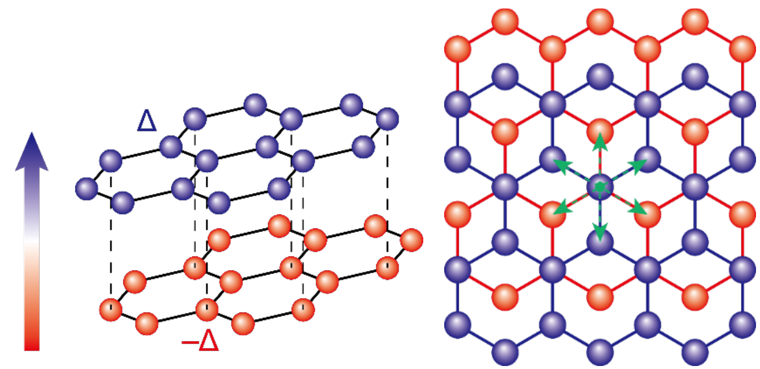
MoS_2



Monolayer graphene



Bilayer graphene



Top view

Initially symmetry broken

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

R. V. Gorbachev *et al.*,
Science **346**, 448 (2014)

Structurally inversion symmetry broken system

→Valley Hall effect has been reported

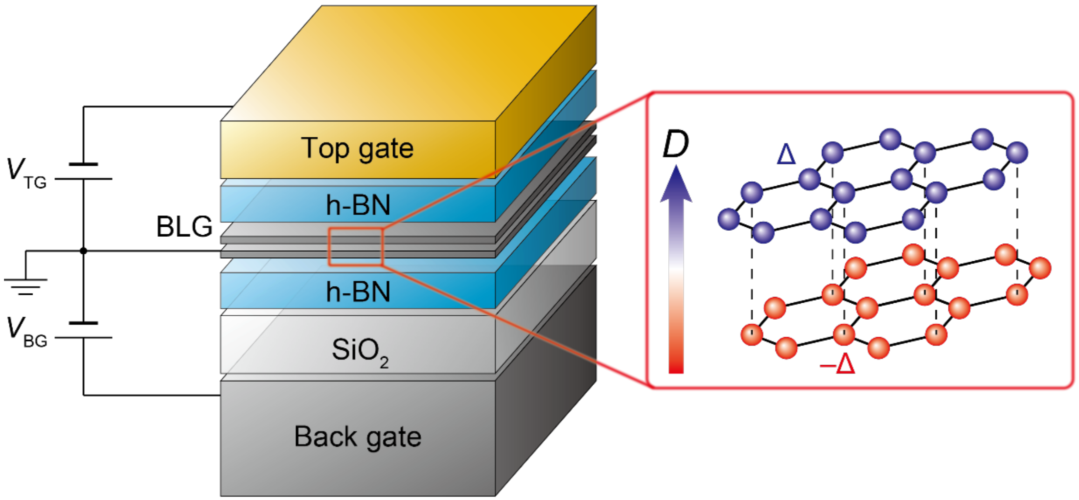
Perpendicular electric field

Electrically inversion symmetry broken system

Further controllability

Dual gate structure

Dual gate structure



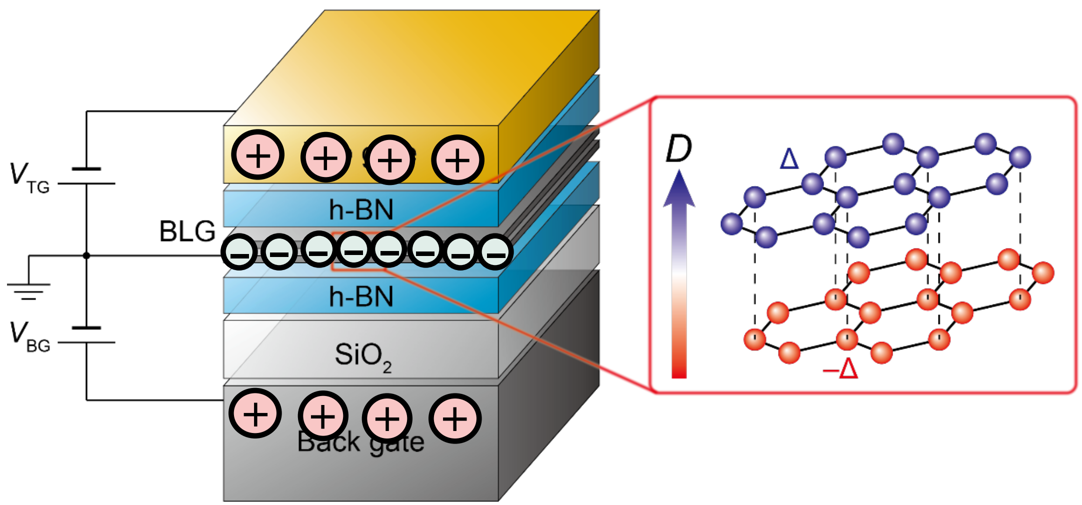
Independent control of

- Perpendicular electric field(D)
- Carrier density

J. B. Oostinga *et al*, *Nature Materials* **7**, 151 (2008)

Dual gate structure

Dual gate structure



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J. B. Oostinga *et al, Nature Materials* **7**, 151 (2008)

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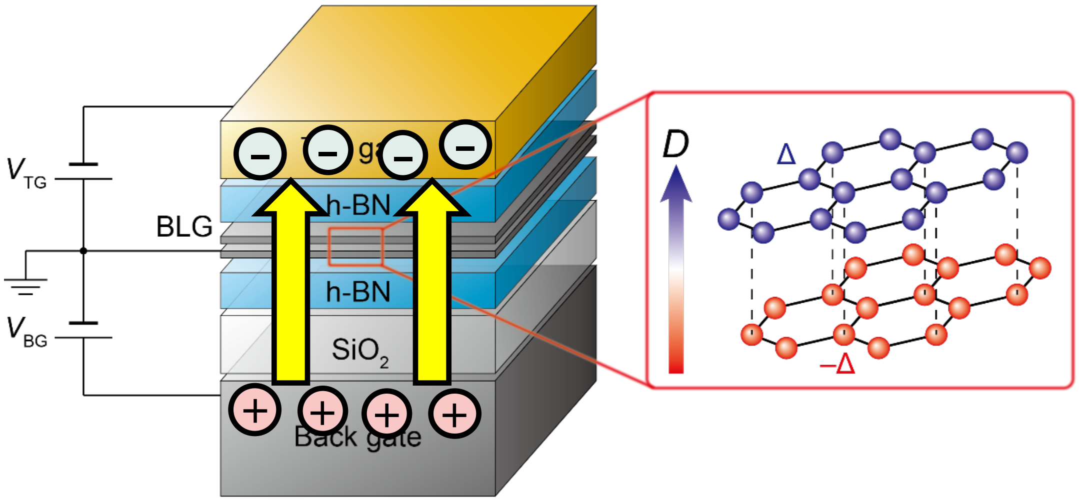
Dual gate structure



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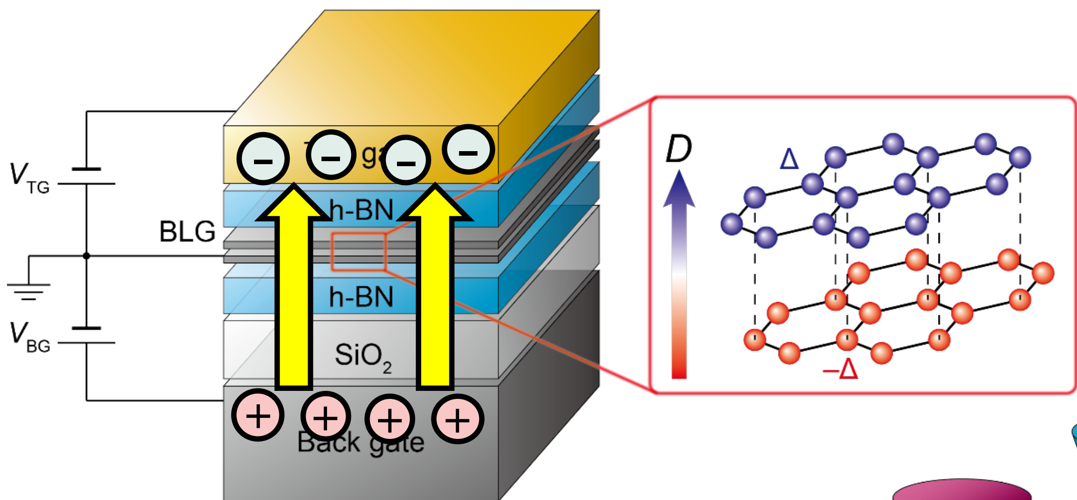
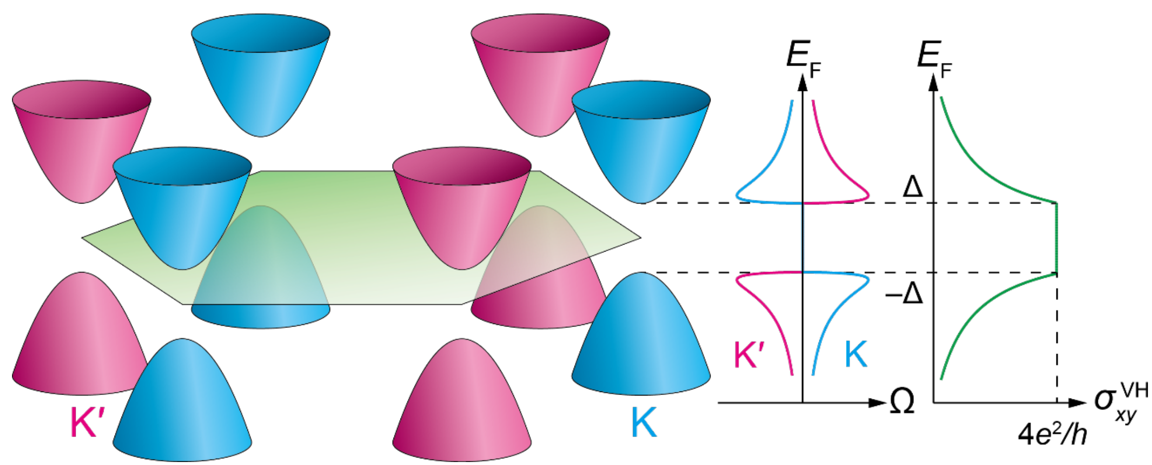


Electrical induction of Berry curvature



Independent control of

- Perpendicular electric field (D)
- Carrier density

J. B. Oostinga *et al, Nature Materials* **7**, 151 (2008)

Valley Hall effect

Valley current mediated nonlocal transport

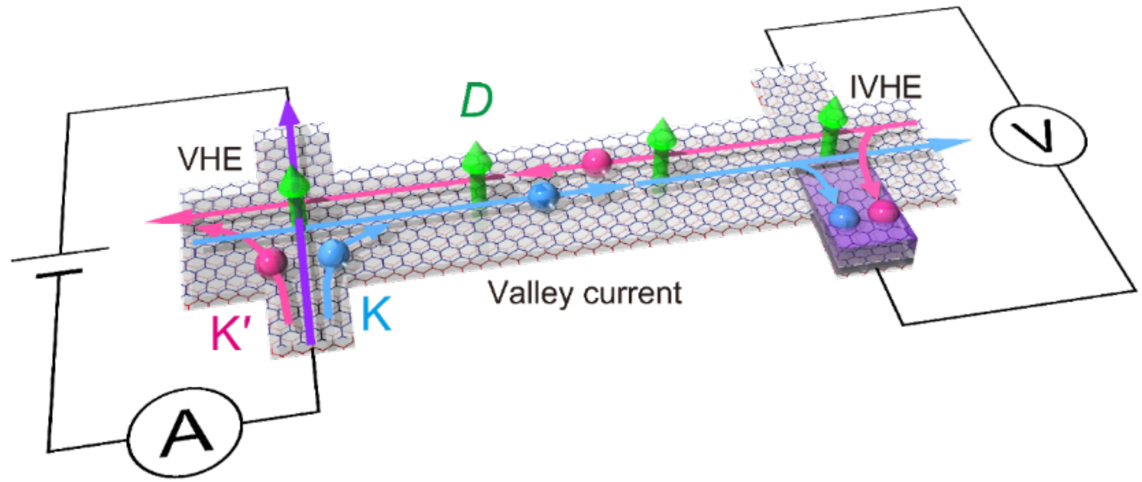
Nonlocal transport measurement in spintronics field

Spin current detection by ISHE

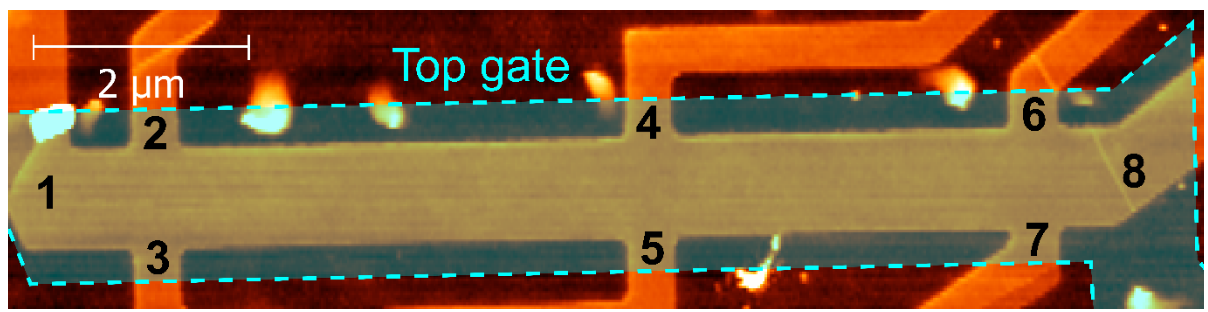
S. O. Valenzuela *et al.*, *Nature* **442**, 176 (2006)

Spin current generation by SHE

T. Kimura *et al.*, *Phys. Rev. Lett.* **98**, 156601 (2007)



AFM image before top h-BN deposition

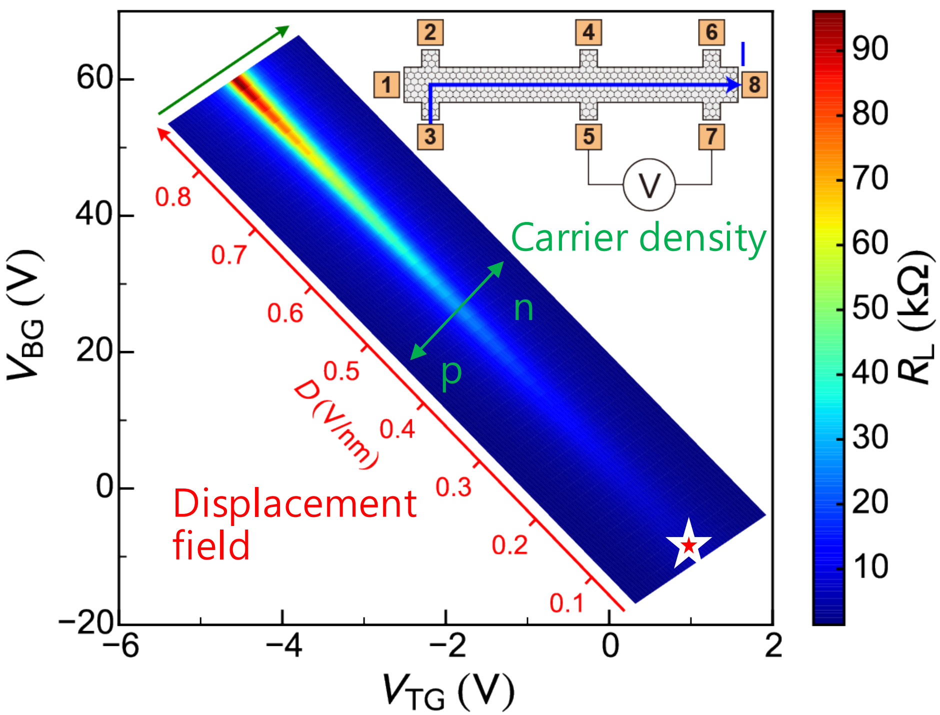


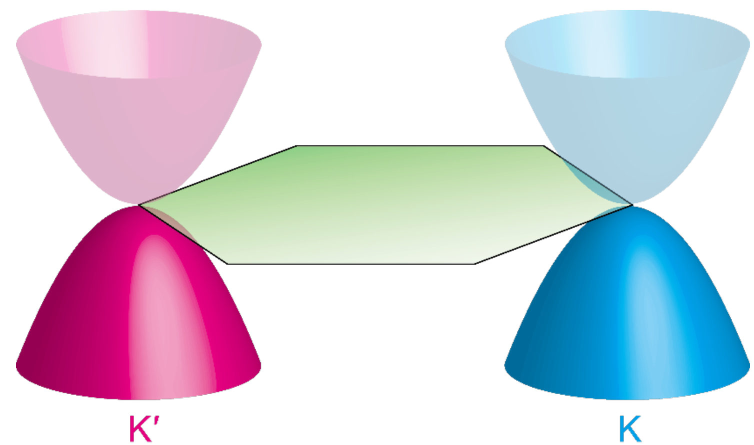
Mobility～15,000cm^2/Vs

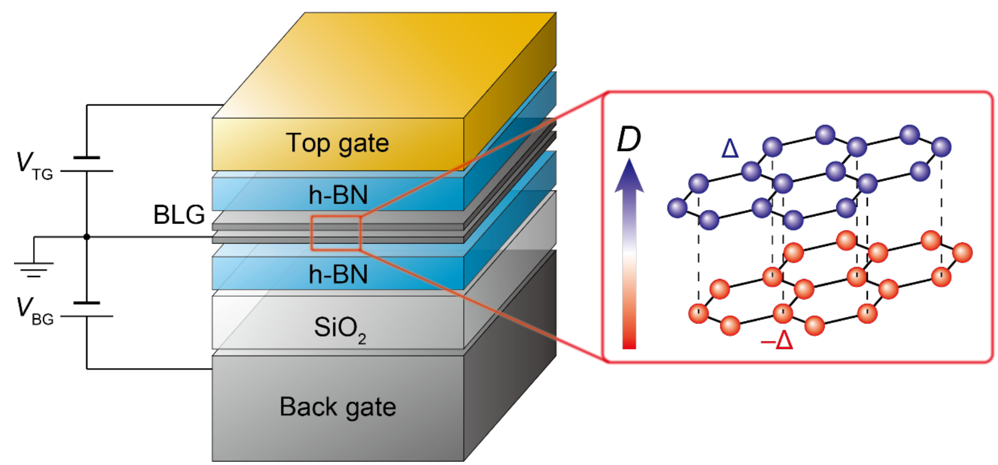
Local and Nonlocal resistance

$T = 70\text{K}$

Local resistance





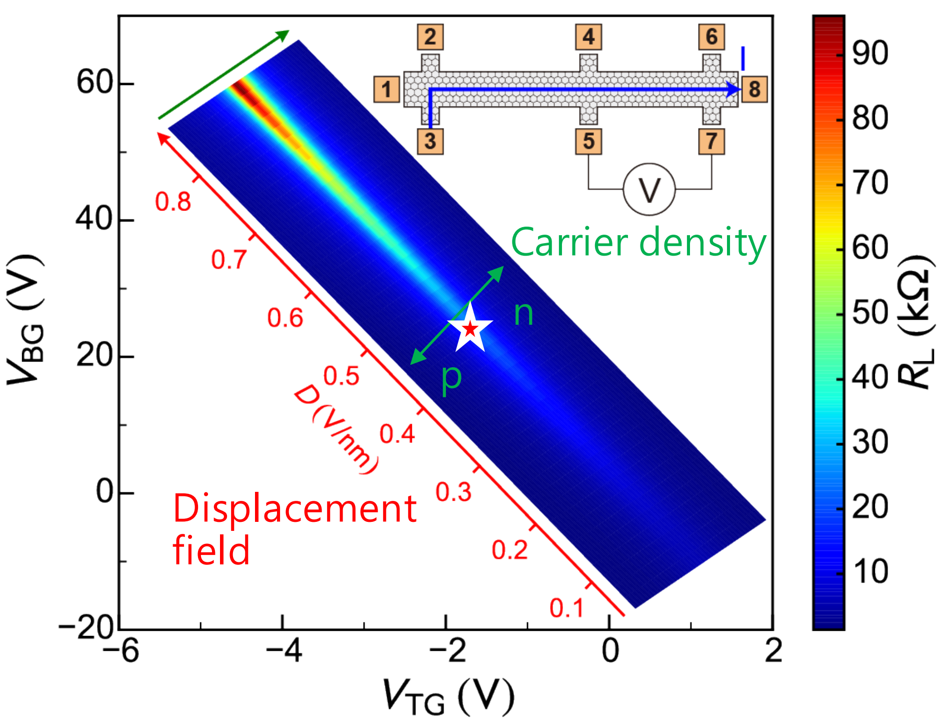


$$D = \frac{D_{BG} + D_{TG}}{2} \qquad D_{BG} = \varepsilon_{BG}(V_{BG} - V_{BG}^{CNP})$$

Local and Nonlocal resistance

$T = 70\mathrm{K}$

Local resistance



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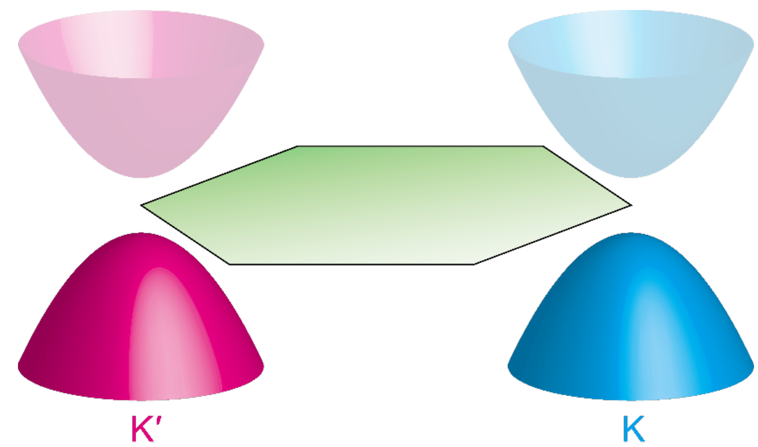

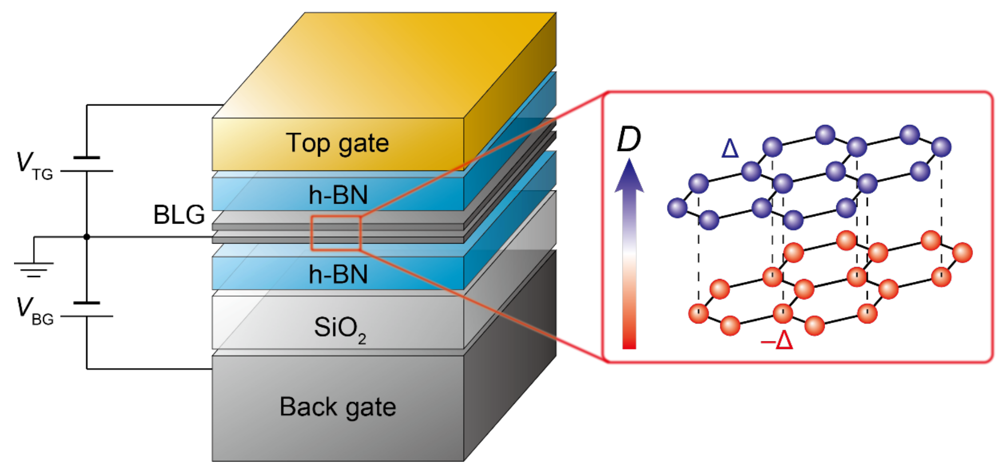

Local and Nonlocal resistance

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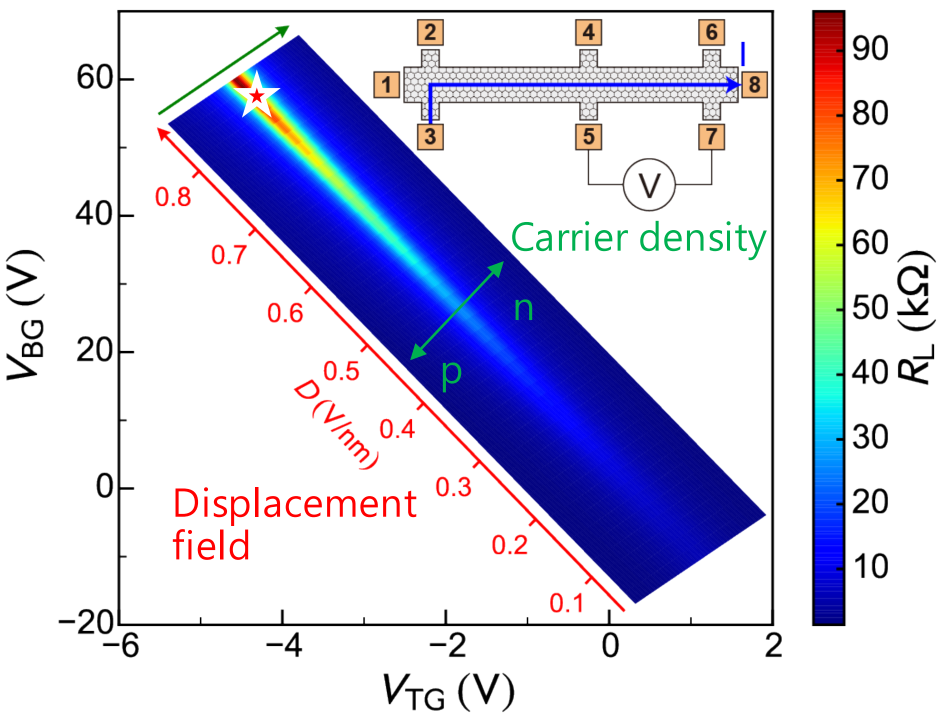
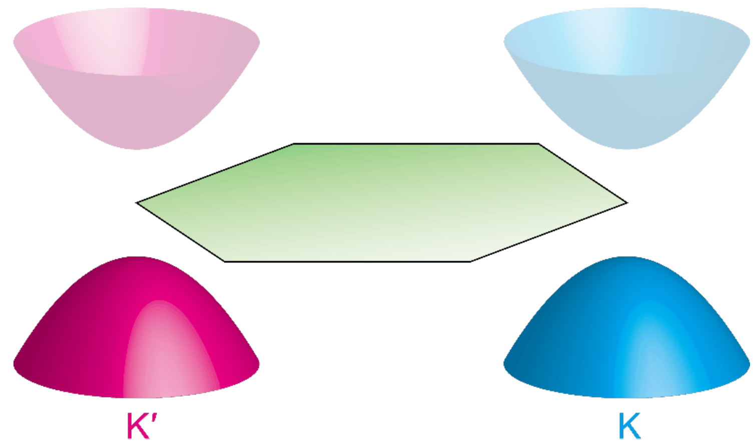
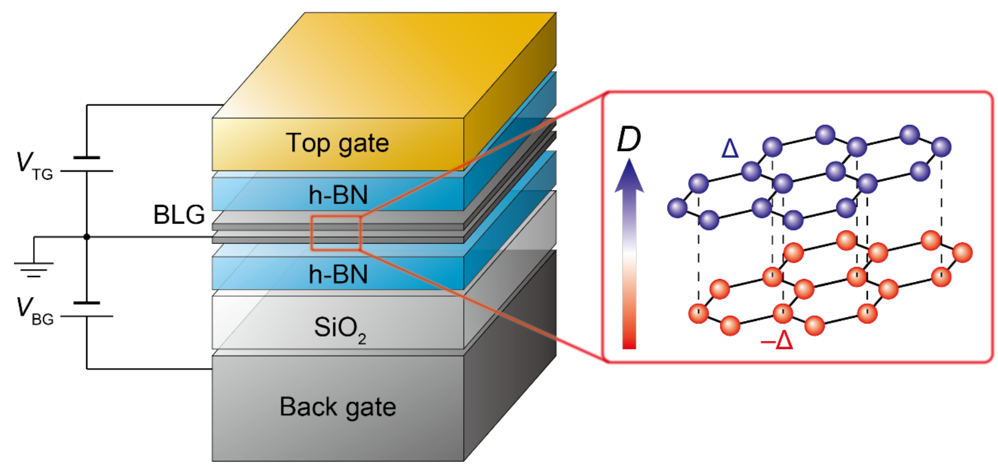
Local resistance







$$D = \frac{D_{BG} + D_{TG}}{2} \qquad D_{BG} = \varepsilon_{BG}(V_{BG} - V_{BG}^{CNP})$$

Local and Nonlocal resistance

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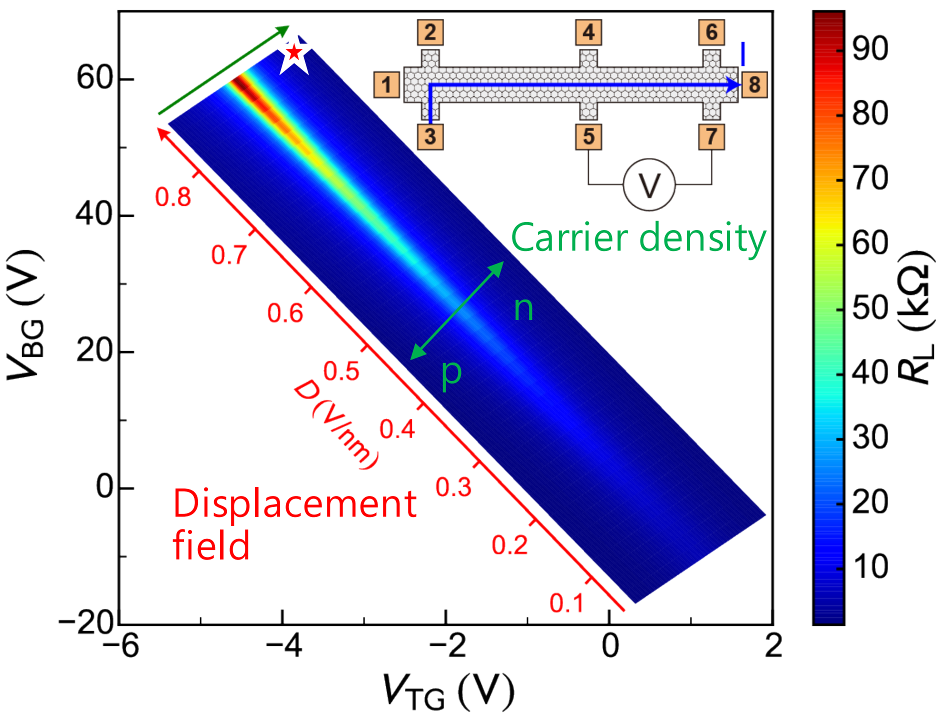
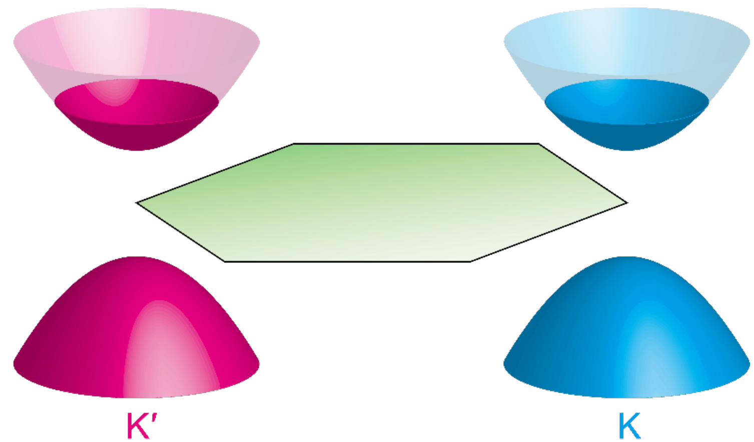
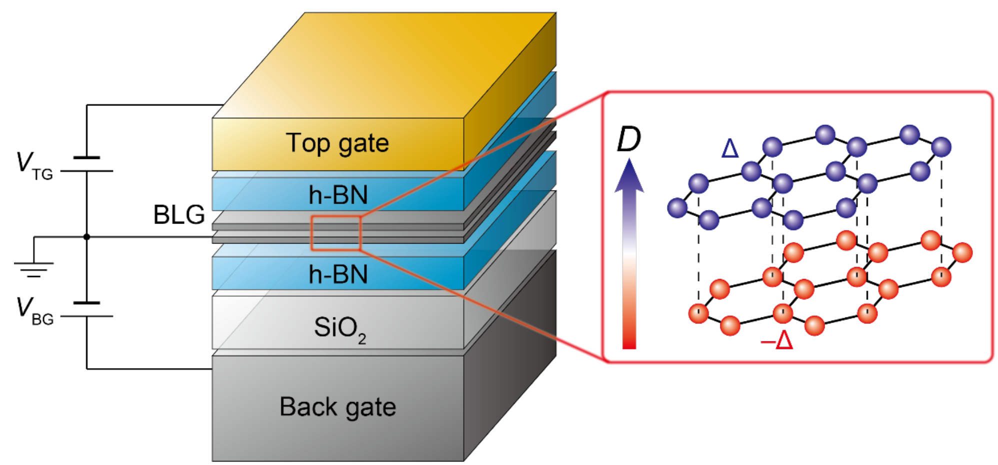
Local resistance





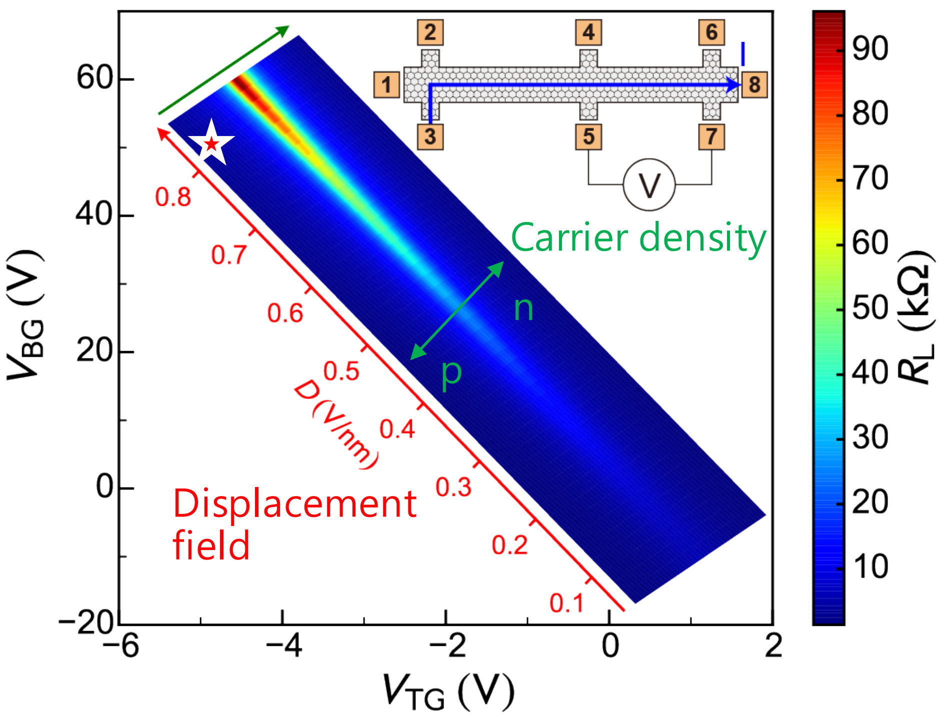


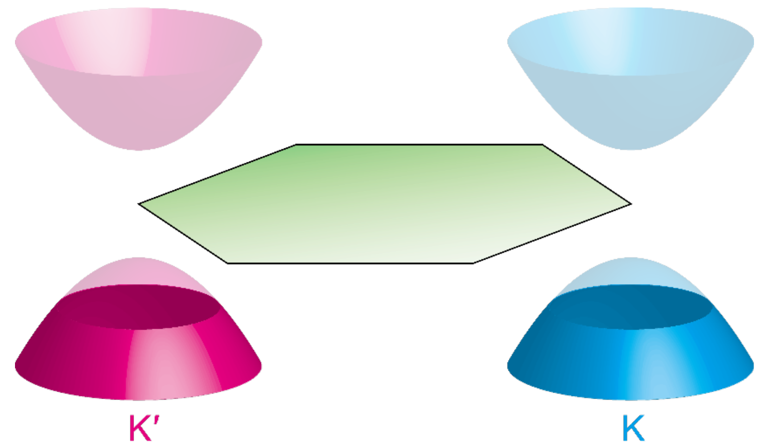
$$D = \frac{D_{BG} + D_{TG}}{2} \qquad D_{\mathrm{BG}} = \varepsilon_{\mathrm{BG}}(V_{\mathrm{BG}} - V_{\mathrm{BG}}^{\mathrm{CNP}})$$

Local and Nonlocal resistance

$T = 70\text{K}$

Local resistance





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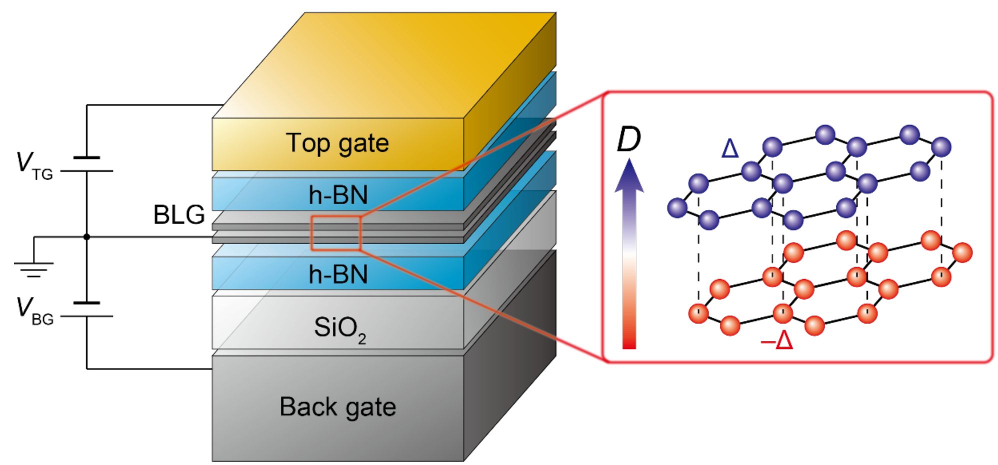
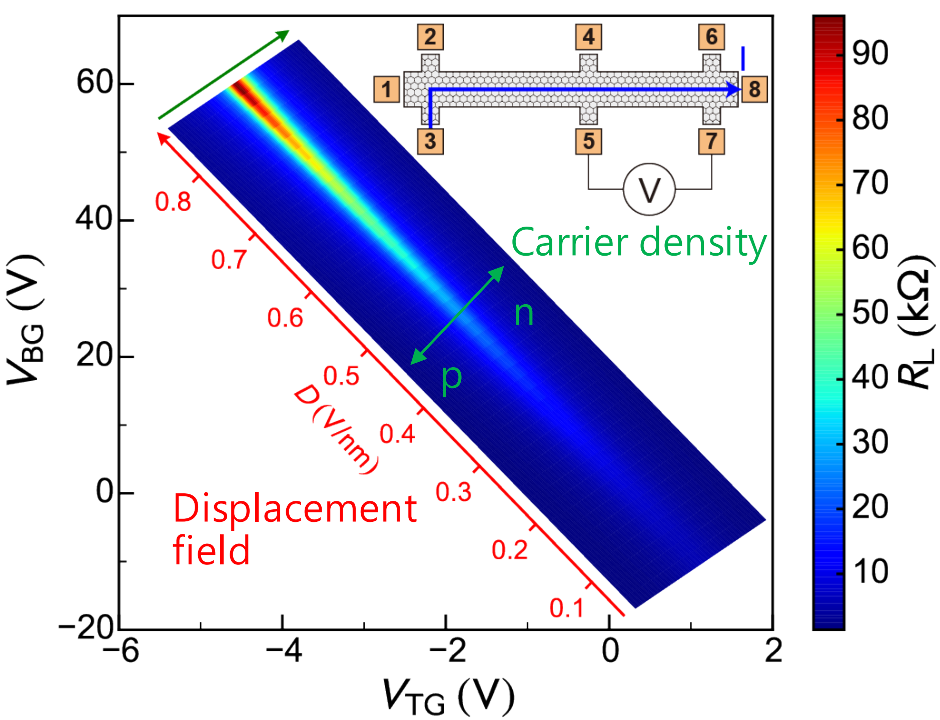


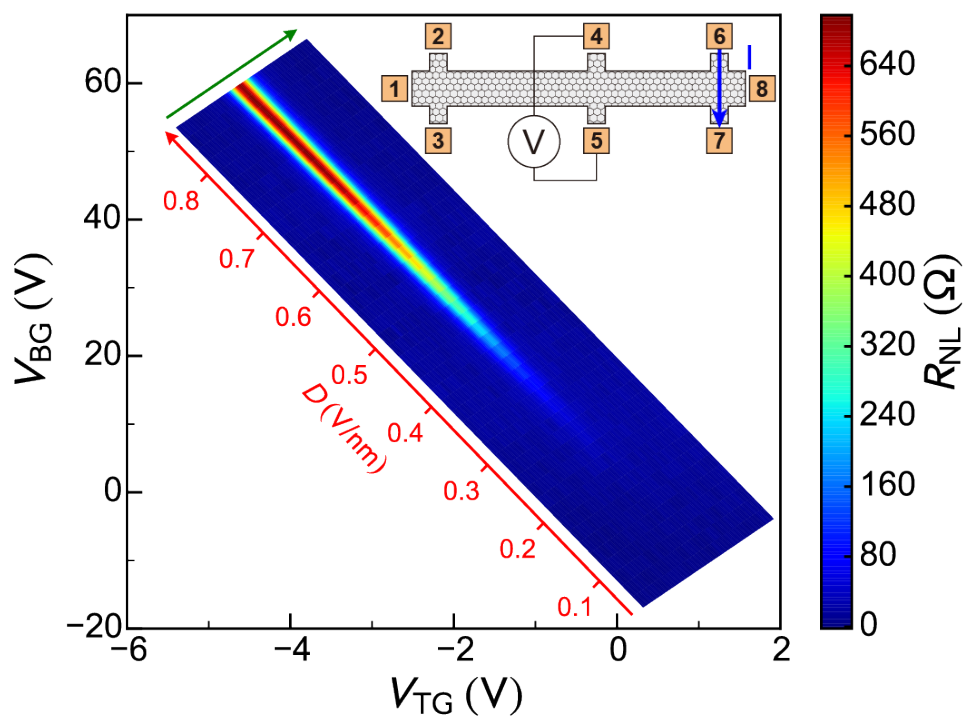
Local and Nonlocal resistance

$T = 70\mathrm{K}$

Local resistance



Nonlocal resistance

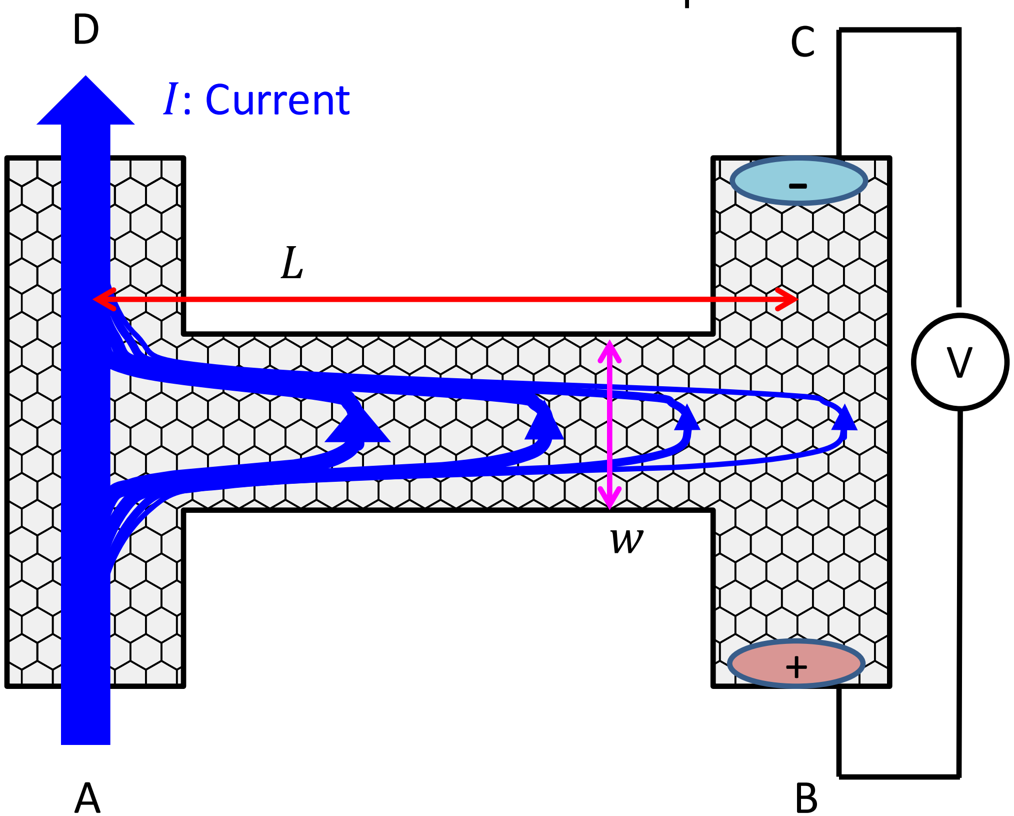


$$D = \frac{D_{BG} + D_{TG}}{2} \qquad D_{\mathrm{BG}} = \varepsilon_{\mathrm{BG}}(V_{\mathrm{BG}} - V_{\mathrm{BG}}^{\mathrm{CNP}})$$

By increasing displacement field D, non-local resistance appeared around Charge Neutrality Point (CNP)

Trivial nonlocal transport : Ohmic contribution

Classical diffusive transport



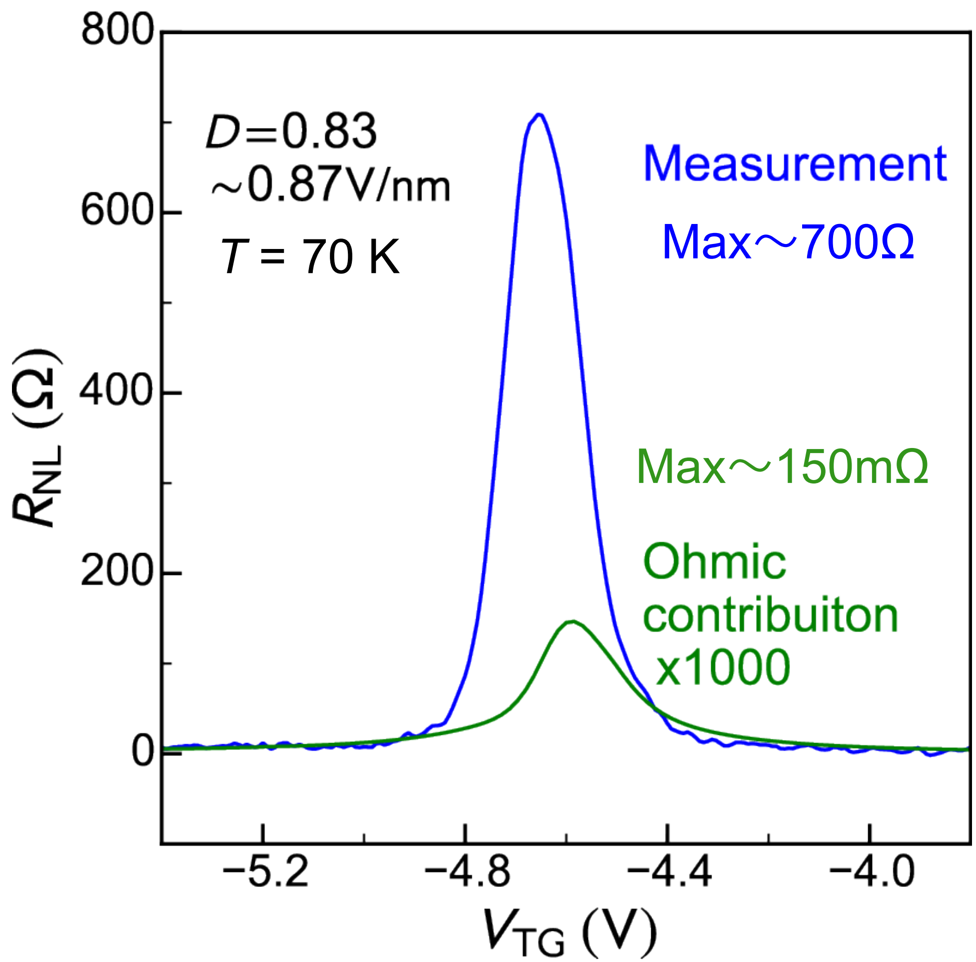
From van der Pauw formula

$L \gg w$

$$R_{NL}^{\mathrm{Ohm}} = \frac{\rho}{\pi} \exp\left(-\pi \frac{L}{w}\right)$$

$$R_{NL}^{\mathrm{Ohm}} \propto \rho$$

Measurement result vs Ohmic contribution



Calculated Ohmic contribution from

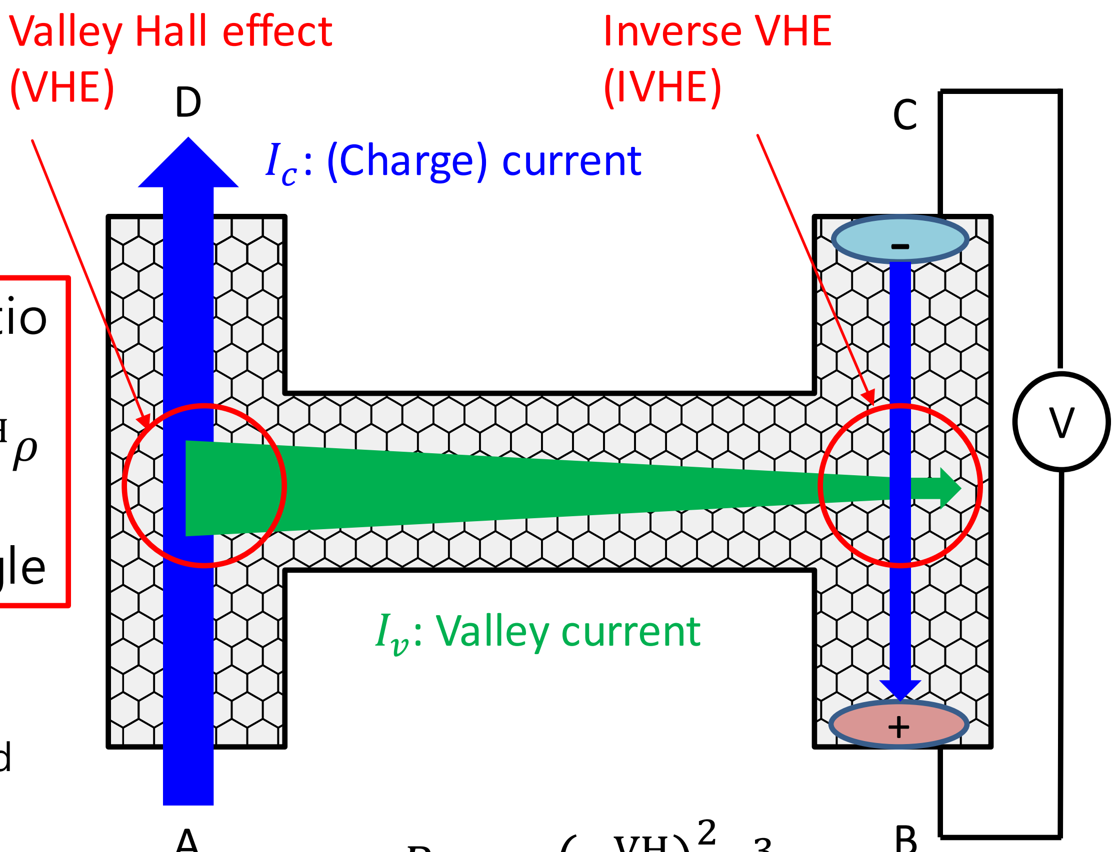
$$R_{NL}^{\mathrm{Ohm}} = \frac{\rho}{\pi} \exp\left(-\pi \frac{L}{w}\right)$$

Observed nonlocal resistance is much larger (5,000 times) than Ohmic contribuion

Quantitatively not Ohmic contribution

Scaling relation between R_{NL} and ρ

Sequential conversion picture



Conversion ratio

$$\alpha = \frac{\sigma_{xy}^{\mathrm{VH}}}{\sigma_{xx}} \sim \sigma_{xy}^{\mathrm{VH}} \rho$$

Valley Hall angle

Conversion ratio

$$\alpha = \frac{\sigma_{xy}^{\mathrm{VH}}}{\sigma_{xx}} \sim \sigma_{xy}^{\mathrm{VH}} \rho$$

Current to voltage

ρ

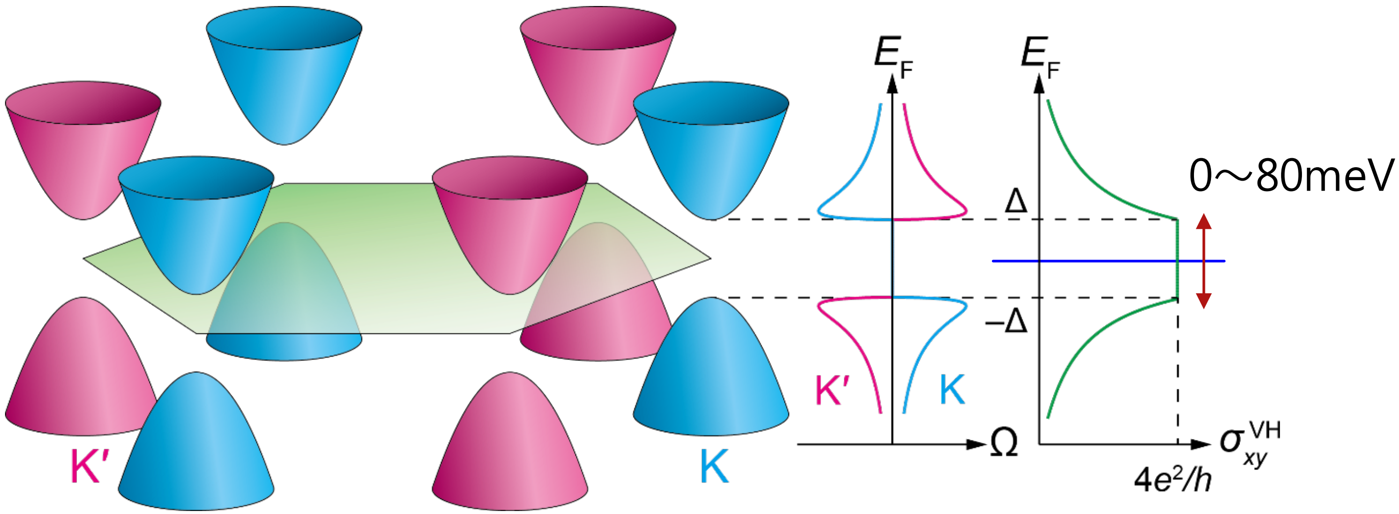
SHE and ISHE mediated nonlocal transport

D. A. Abanin *et al.*, *Phys. Rev. B* **79**, 035304 (2009)

$$R_{\mathrm{NL}} \propto \left(\sigma_{xy}^{\mathrm{VH}}\right)^2 \rho^3$$

Valid for small valley Hall angle ($\alpha \ll 1$)

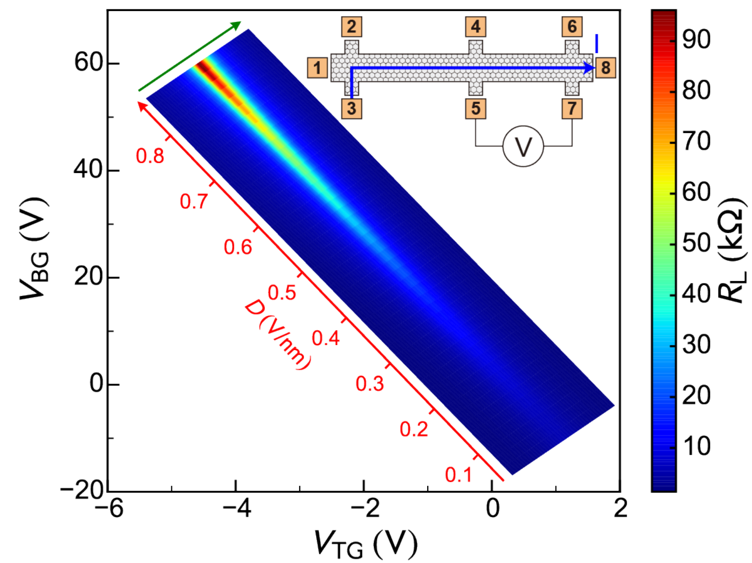
Scaling relation between R_{NL} and ρ



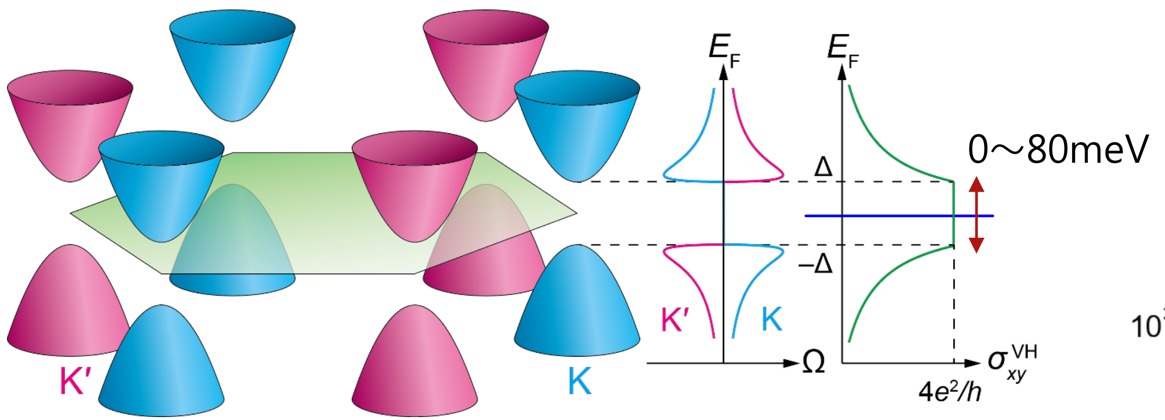
At charge neutrality point,
changed perpendicular electric field
→ Bandgap size changes

- Resistivity ρ changes
- Valley Hall conductivity $\sigma_{xy}^{\mathrm{VH}}$ is constant

$$R_{\mathrm{NL}} \propto \left(\sigma_{xy}^{\mathrm{VH}}\right)^2 \rho^3 \propto \rho^3$$



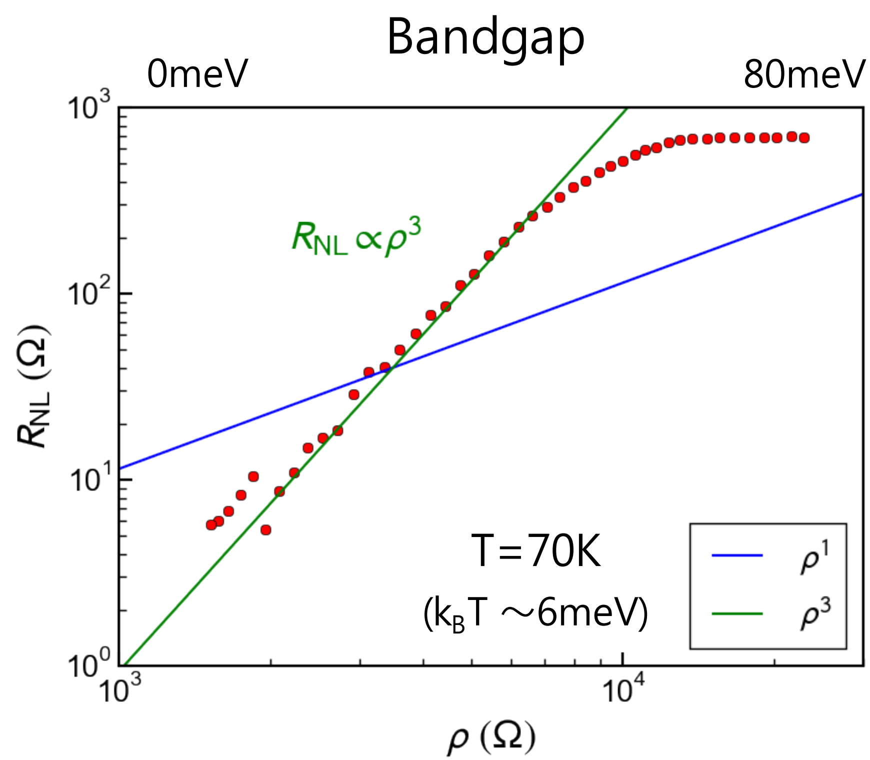
Scaling relation between R_{NL} and ρ



$$R_{\mathrm{NL}} \propto \left(\sigma_{xy}^{\mathrm{VH}}\right)^2 \rho^3 \propto \rho^3$$

Cubic scaling

→Transport mediated by pure valley current



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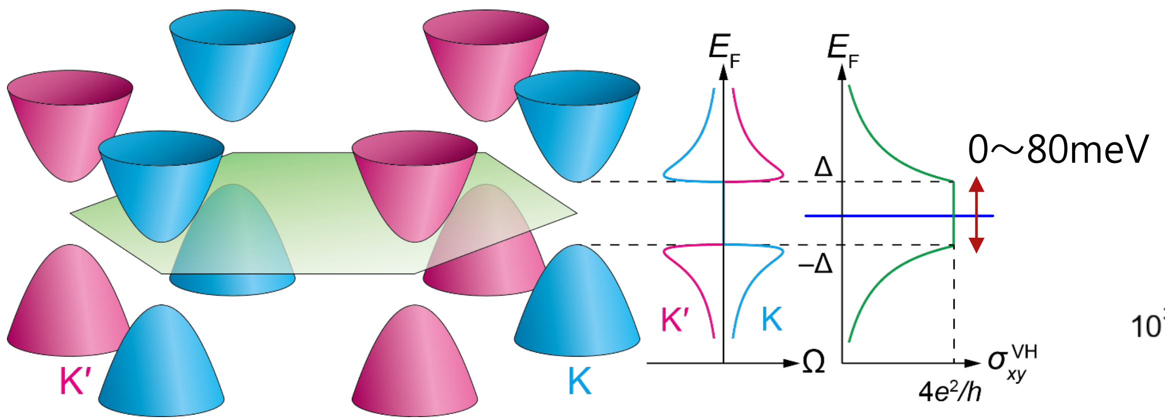
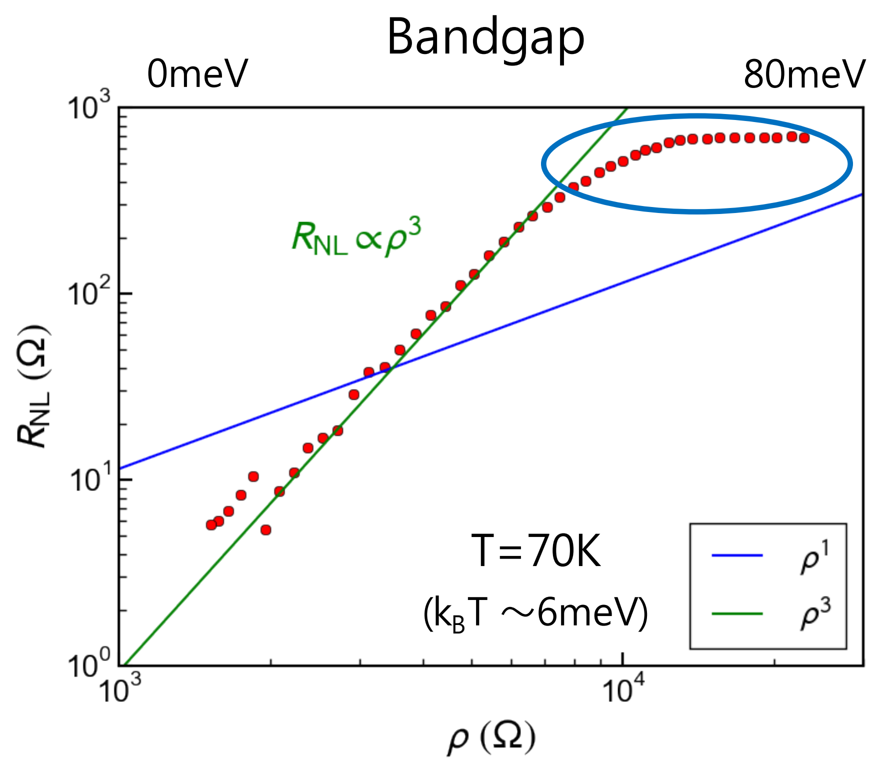


Crossover behavior at high displacement field

1. Valley Hall angle α
$\alpha \ll 1 \rightarrow \alpha \sim 1$ or $\alpha \gg 1$

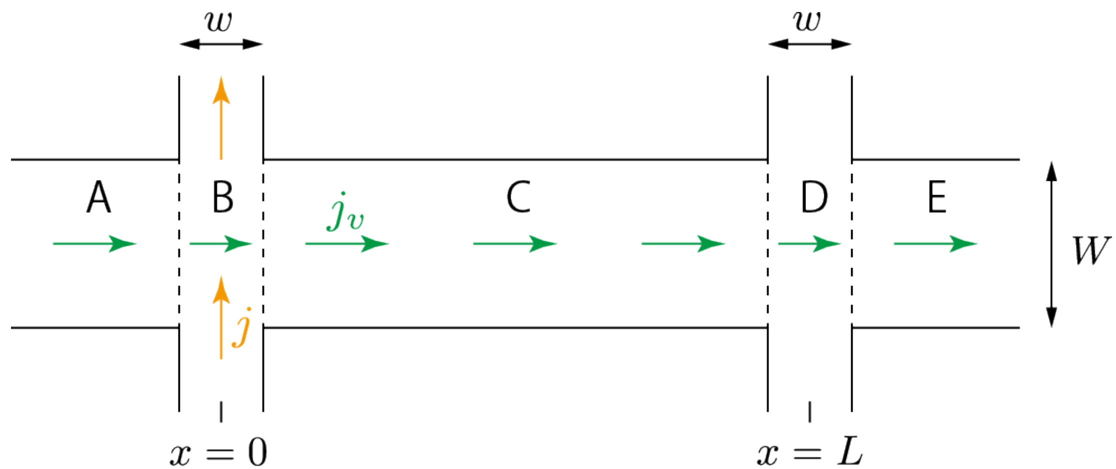
2. Transport mechanism
Band conduction → Hopping conduction

Open question



Valley Hall angle dependence of nonlocal resistance

$_v^{A}(x \quad) \quad 0$



$_v^{E}(x \quad) \quad 0$

$_v$, j_v : Continuous at the interface

$v \quad K \quad K$

Equations

Diffusion eq. $\frac{}{^2 x} \quad {}_v^i \quad \frac{1}{^2_i} \quad {}_v^i$

Conductance matrix $\begin{matrix} j_c^i \\ j_v^i \end{matrix} \quad \begin{matrix} {}_{xx} & {}_{xy}^{VH} \\ {}_{xy}^{VH} & {}_{xx} \end{matrix} \quad \begin{matrix} E^i \\ \frac{1}{2e}\frac{}{x} \quad {}_v^i \end{matrix}$

$w \quad 0$

$R_{NL} \quad \frac{W}{2} \frac{^2}{_{xx} \quad 1 \quad ^2} \exp \quad \frac{L}{}$

Valley Hall angle: ${}_{xy}^{VH} / {}_{xx}$

Inter-valley scattering length: λ

Valley Hall angle dependence of nonlocal resistance

$$R_{\mathrm{NL}} \quad \frac{W}{2} \frac{\quad^{2}}{_{xx} \; 1 \quad^{2}} \exp \quad \frac{L}{\quad}$$

Valley Hall angle: $\quad ^{\mathrm{VH}}_{xy} / \quad _{xx}$

For small valley Hall angle: $= 1$

For large valley Hall angle: ? 1

$$R_{\mathrm{NL}} \quad \frac{W}{2} \frac{\left(^{\mathrm{VH}}_{xy}\right)^{2}}{^{3}_{xx}} \exp \quad \frac{L}{\quad}$$

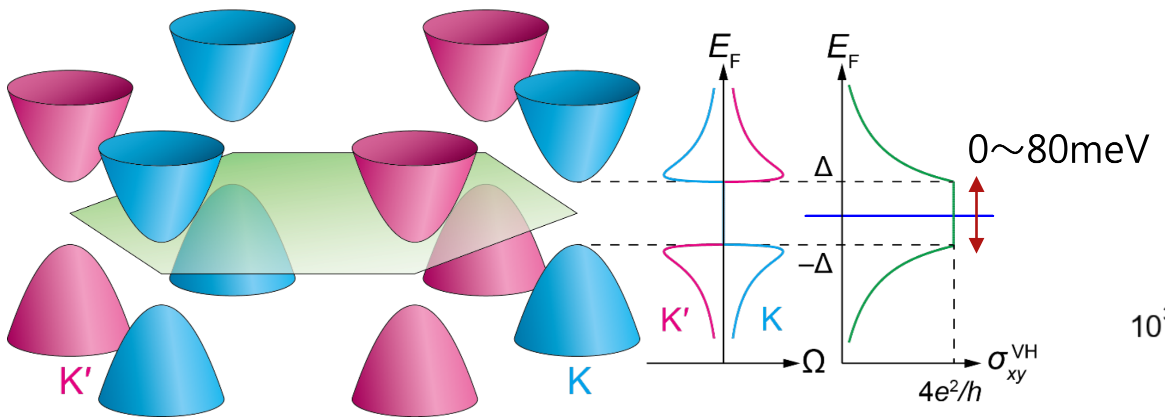
$$R_{\mathrm{NL}} \quad \frac{W}{2} \frac{1}{_{xx}} \exp \quad \frac{L}{\quad}$$

Reproduces

D. A. Abanin *et al.*, *Phys. Rev. B* **79**, 035304 (2009)

$R_{\mathrm{NL}} \quad ^{3}$ Cubic scaling → Crossover → R_{NL} Linear scaling

Scaling relation between R_{NL} and ρ



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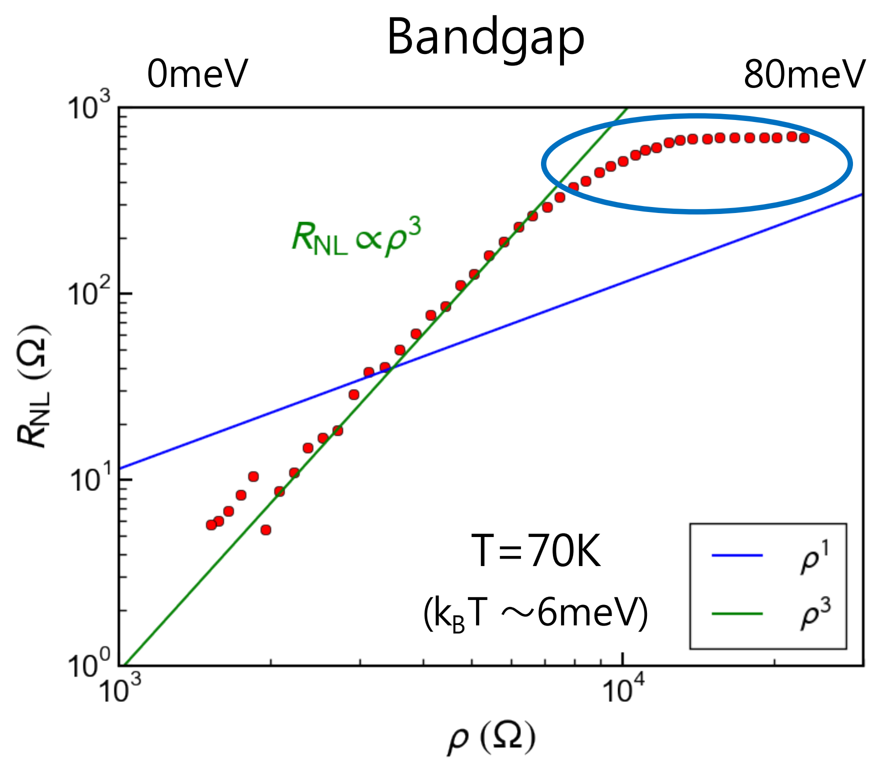
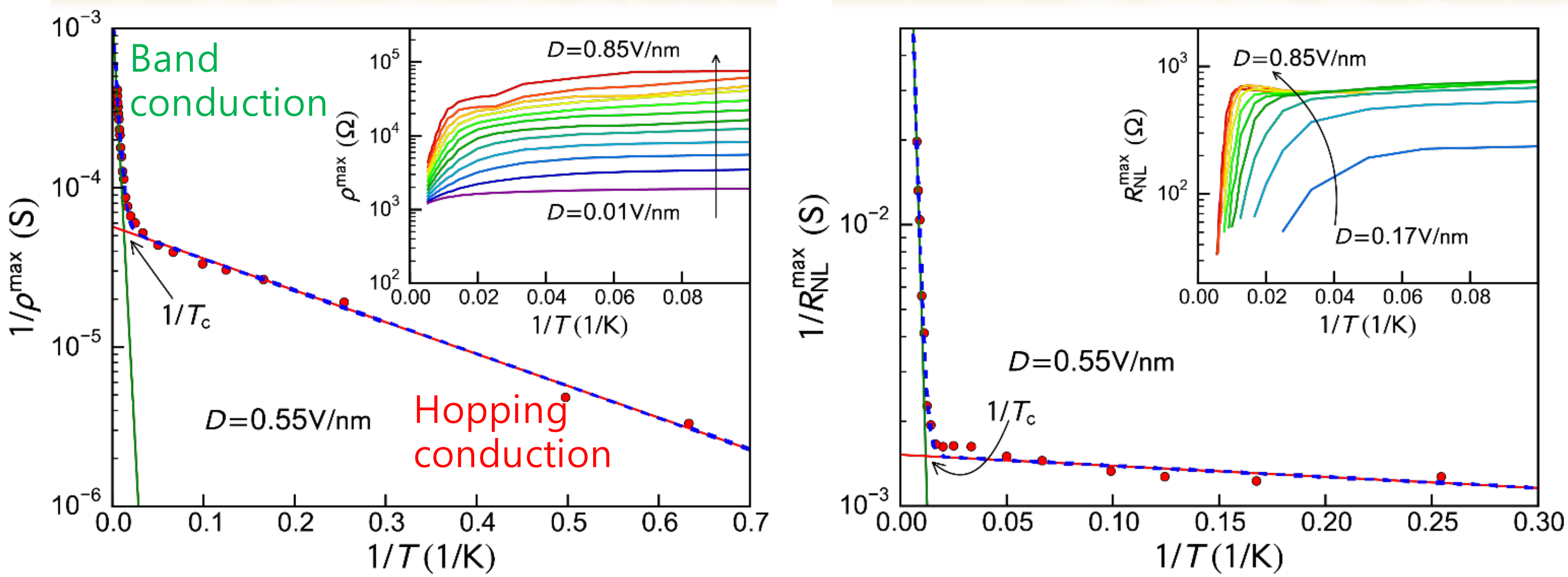


Temperature dependence



- Insulating behavior due to gap opening
- Crossover behavior for both $\rho^{\max}$ and $R_{\rm NL}^{\max}$ between high T and low T region

Fitting function

$$\frac{1}{\rho^{\max}} = \frac{1}{\rho_1}\exp\left(-\frac{E_1^{\rm L}}{k_{\rm B}T}\right) + \frac{1}{\rho_2}\exp\left(-\frac{E_2^{\rm L}}{k_{\rm B}T}\right)$$

Band conduction (Thermal activation across bandgap) — Hopping conduction (Nearest neighbor hopping)

Fitting function

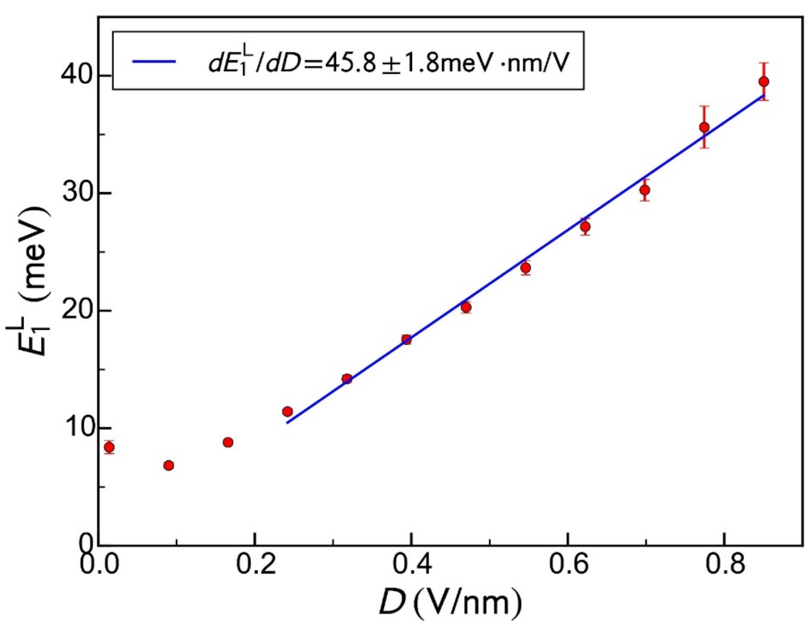
$$\frac{1}{R_{\rm NL}^{\max}} = \frac{1}{R_1}\exp\left(-\frac{E_1^{\rm NL}}{k_{\rm B}T}\right) + \frac{1}{R_2}\exp\left(-\frac{E_2^{\rm NL}}{k_{\rm B}T}\right)$$

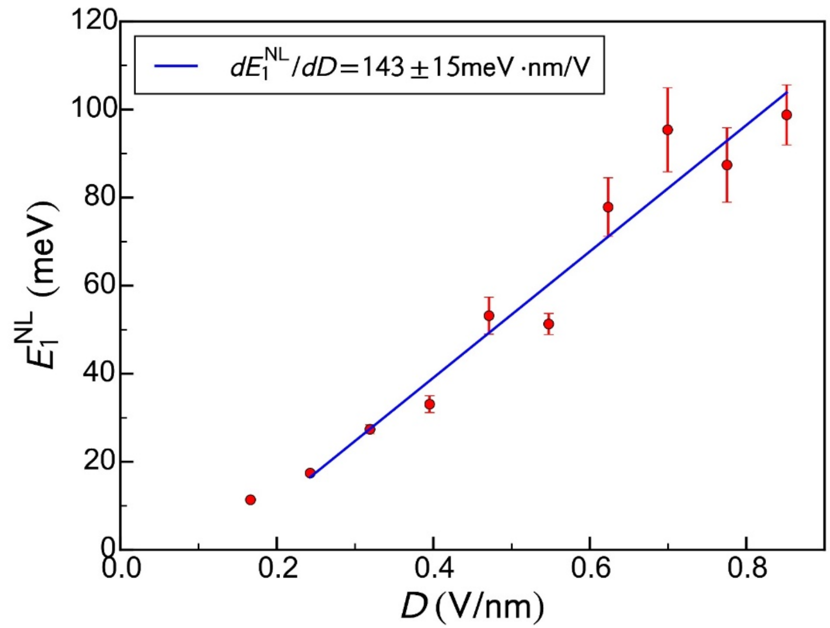
High T — Low T

K. Zou *et al.*, *Phys. Rev. B* **82**, 081407 (2010)

Activation energy

From $R_{\mathrm{NL}} \propto \rho^3$, $E_1^{\mathrm{NL}} = 3E_1^{\mathrm{L}}$ is expected



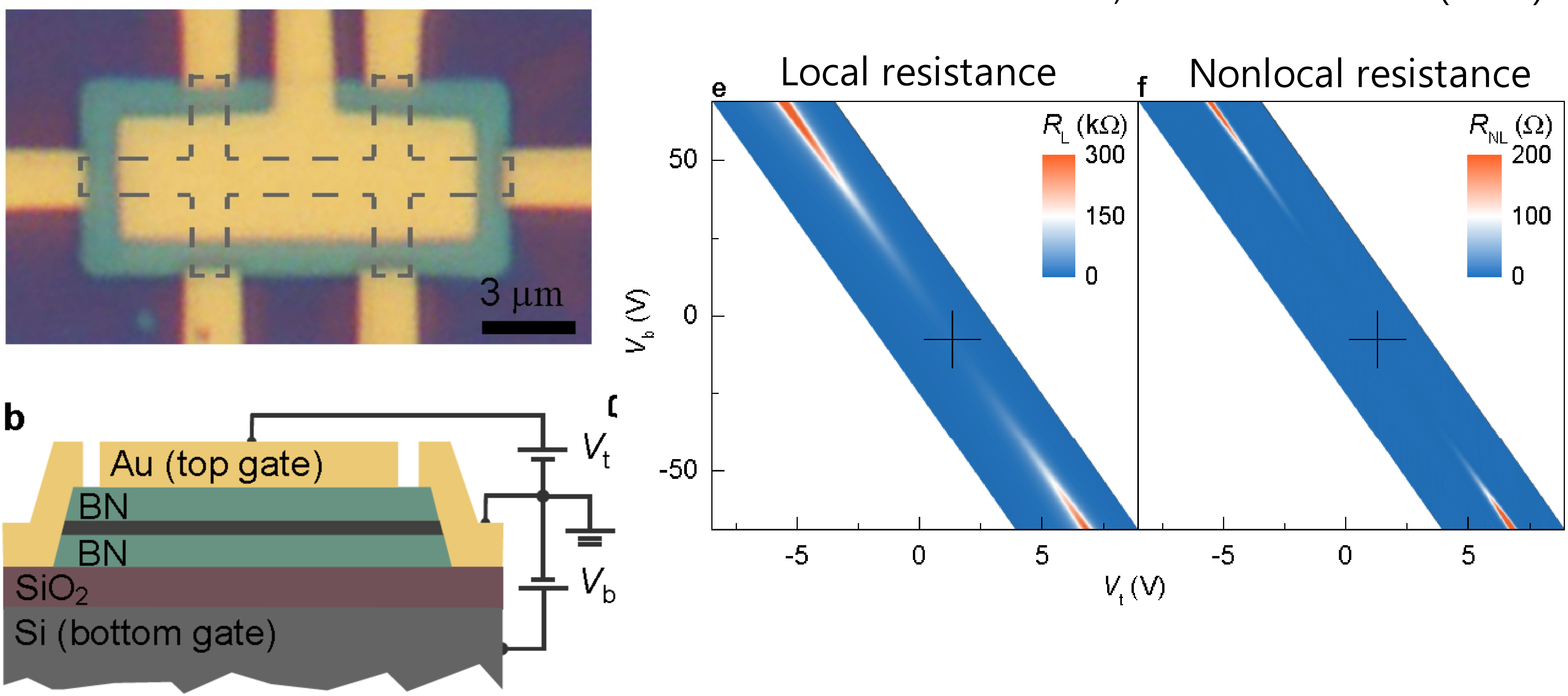


$$\frac{dE_1^{\mathrm{NL}}}{dD} = (3.13 \pm 0.36)\frac{dE_1^{\mathrm{L}}}{dD}$$

Experiment by Fudan group

Gate-tunable Topological Valley Transport in Bilayer Graphene

M. Sui *et al.*, arXiv:1501.04685 (2015)

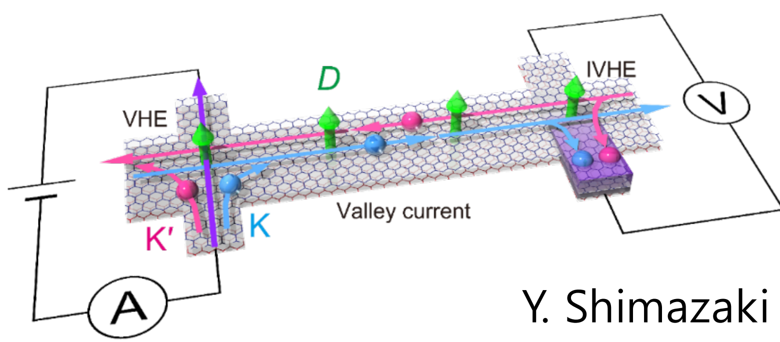


Summary

- In electrically spatial inversion symmetry broken bilayer graphene, we observed the signature of valley Hall effect and pure valley current which is cubic scaling relation:

$$R_{\mathrm{NL}} \propto \rho^3$$

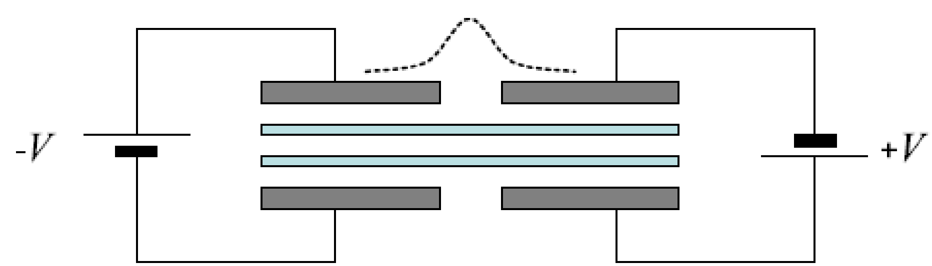
- We observed the crossover behavior in scaling relation for higher displacement field region, which is still open question
- Nonlocal transport was detected even in insulating regime, indicates pure valley current can flow in insulating regime
- Our highly controllable system provides further possibility for the investigation of topological current in insulator and application to valleytronics



Y. Shimazaki *et al.*, arXiv:1501.04776 (2015)

Graphene valleytronics

- Appropriate system to study valley current transport
  - Graphene has long inter-valley scattering length
- Appropriate system for mesoscopic experiment
  - Super high mobility (>1,000,000cm^2/Vs) graphene device has been reported
- Topological property is gate controllable
  - Tunable Berry curvature
  - Switchable valley Chern number



I. Martin *et al., Phys. Rev. Lett.* **100**, 036804 (2008)

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