Surface conduction of topological Dirac electrons in bulk insulating Bi_2Se_3

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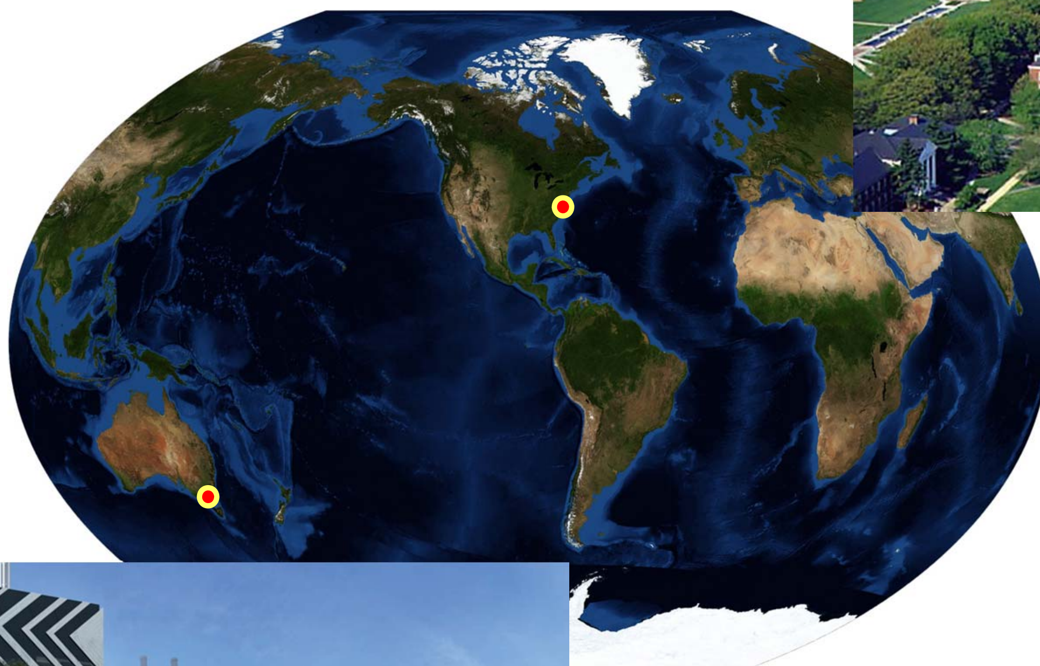
University of Maryland

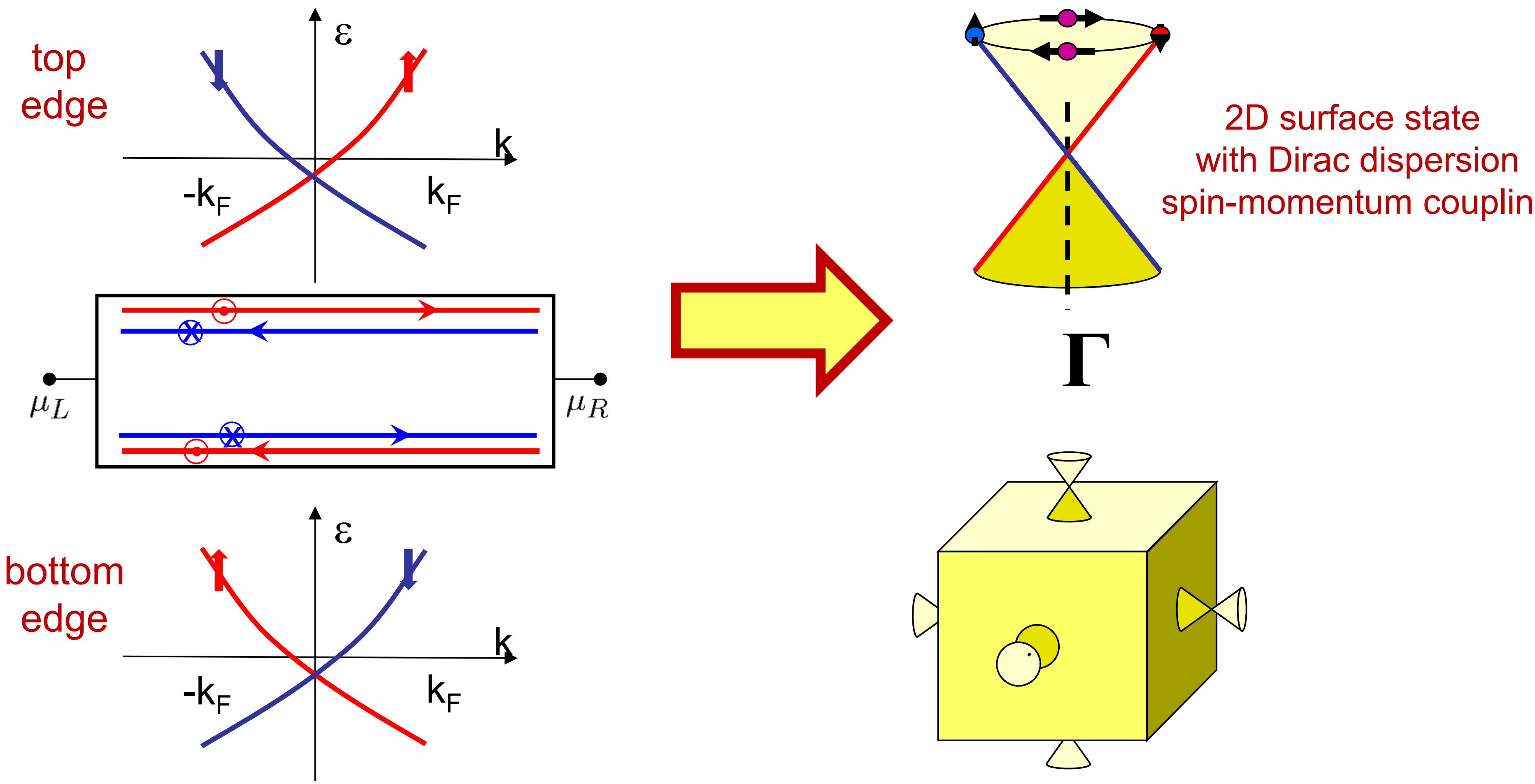


School of Physics &
New Horizons Centre
Monash University

Topological Insulators in 2D and 3D

2D – Quantum Spin Hall Effect

3D – Strong Topological Insulator



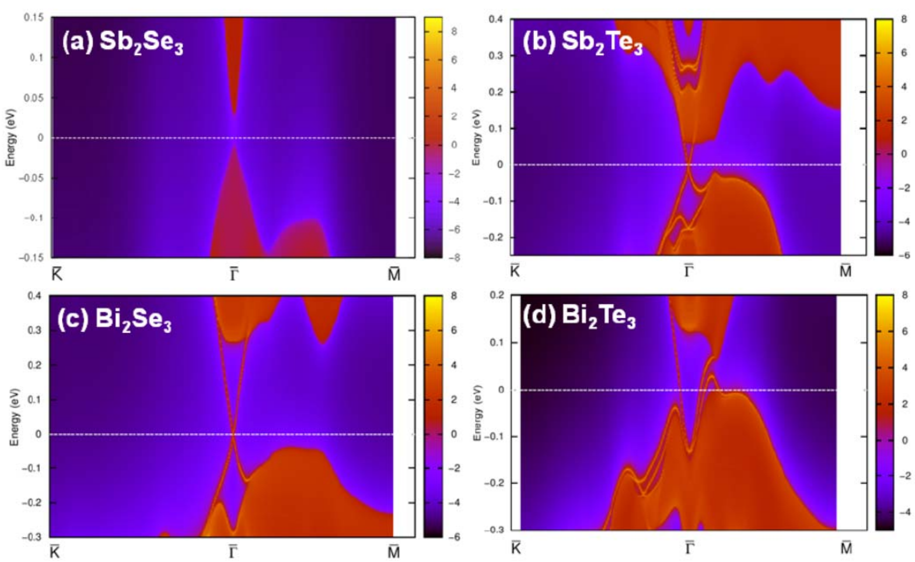
TI in 3D: $(Bi,Sb)_2(Se,Te)_3$ system

Theory

Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface

Haijun Zhang[1], Chao-Xing Liu[2], Xiao-Liang Qi[3], Xi Dai[1], Zhong Fang[1] and Shou-Cheng Zhang[3]*

DFT calculation

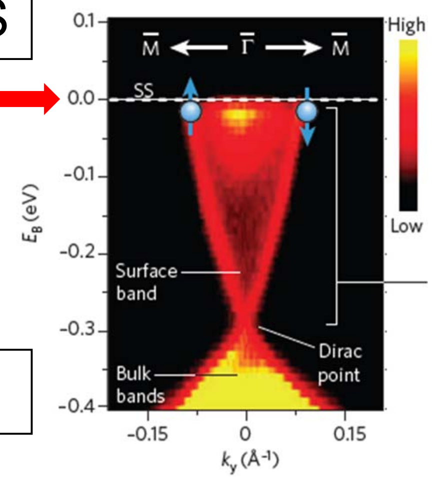


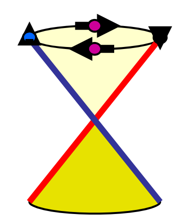
Zhang *et al.*, Nature Physics, 5, 438 (2009)

Experiment

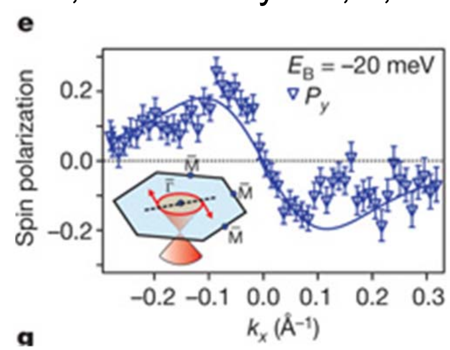
ARPES

Bi_2Se_3





Xia *et al.*, Nature Physics, 5, 398 (2009)



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

See also Bi_xSb_{1-x}: *Science* **323**, 919 (2009); *Nature* **452**, 970 (2008)

Electronic transport in a 2D Dirac band – Lessons from graphene

Charged impurity scattering

Minimum conductivity from charge inhomogeneity

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Chemical and electrochemical gating of Bi_2Se_3

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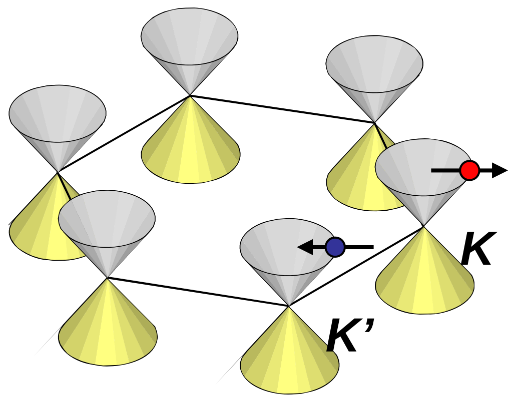
} *Nat. Phys.* **8**, 460 (2012)

Intersurface coupling

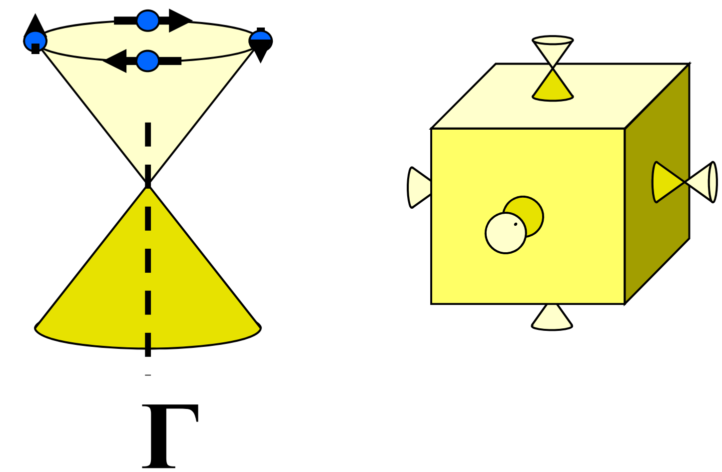
Weak anti-localization in decoupled and coupled surfaces *Nature Comm.* **4**, 2040 (2013)

Graphene ↔ Strong Topological Insulator

Graphene



Strong Topological Insulator



Pseudospin ↔ Spin

A-B sublattice symmetry ↔ Time-reversal symmetry

Long-range disorder ↔ Non-magnetic disorder

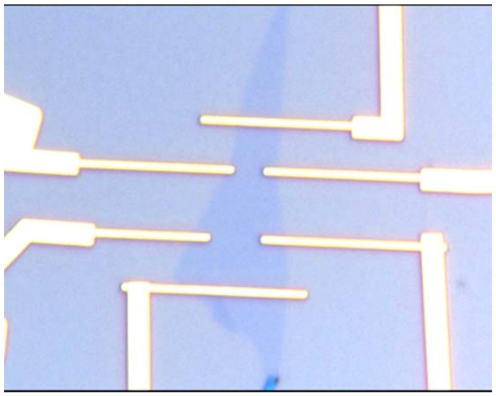
Point disorder ↔ Magnetic disorder

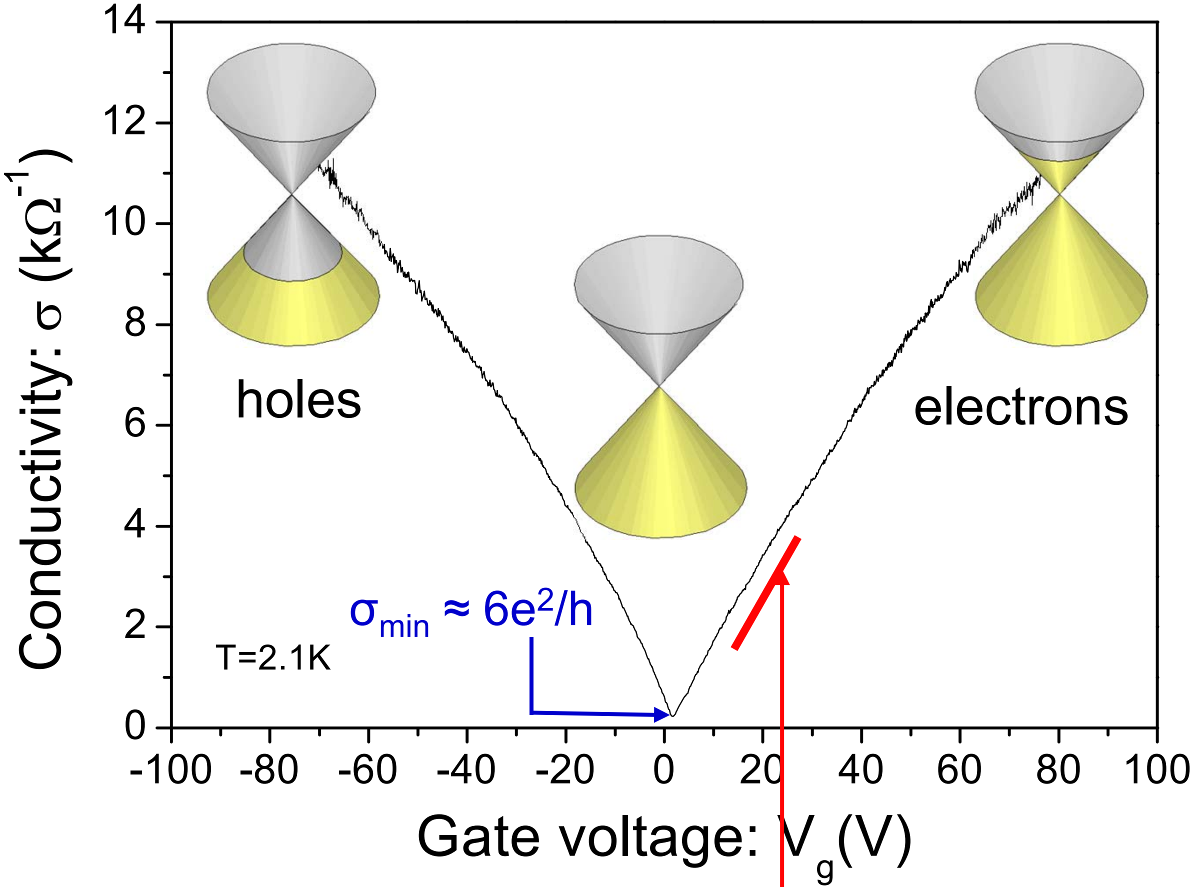
$\sigma_{xy} = 4\left(n + \frac{1}{2}\right)\frac{e^2}{h}$ ↔ $\sigma_{xy} = \left(n + \frac{1}{2}\right)\frac{e^2}{h}$ (but no edge – how to observe?)

new magnetoelectric coupling

superconductors → Majorana Fermions

Electrical Characterization of Graphene





$$\mu_{FE} = \frac{1}{e}\frac{d\sigma}{dn} = \frac{1}{c_g}\frac{d\sigma}{dV_g}$$

- Ambipolar, symmetric conduction
- Finite minimum conductivity ~ [4-10]e^2/h
- Field-effect mobility up to 20,000 cm^2/Vs

Graphene's Conductivity

$$\sigma = \frac{e^2 v_F^2}{2} D(E)\tau$$

D(E) is density of states
τ is momentum relaxation time
v_F is Fermi velocity

Fermi's Golden Rule:

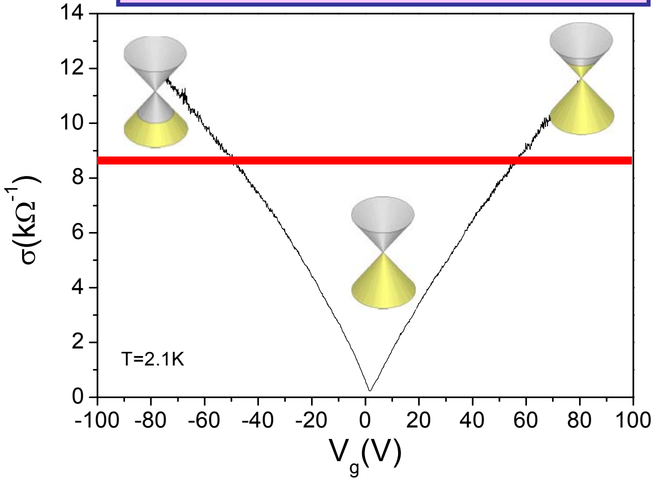
$$\frac{1}{\tau} \propto \frac{2\pi}{\hbar} \left| \langle k | V | k' \rangle \right|^2 D(E)$$

$$\Rightarrow \quad \sigma \propto \left| \langle k | V | k' \rangle \right|^{-2}$$

$$q = |\mathbf{k} - \mathbf{k}'| \sim k_F$$

"white-noise disorder": V(q) = constant

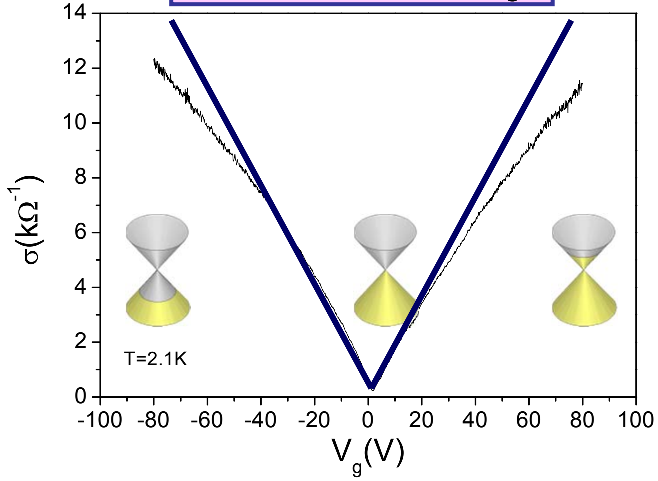
σ is independent of E_F!



True for point defects, phonons
see e.g. Pietronero (1980), T. Ando (1996)

Charged impurities: $V(q) = \frac{2\pi e^2}{\kappa q}$

$\sigma \sim k_F^2 \sim n \sim V_g$

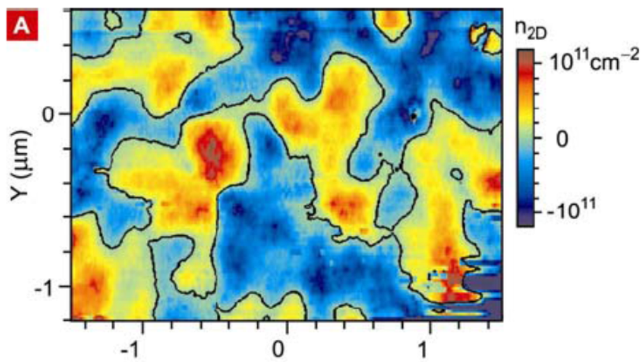


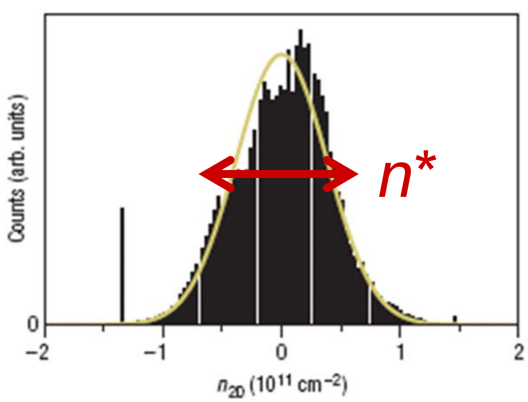
Ando (2006), Nomura & MacDonald (2007), Cheianov & Fal'ko (2006), Hwang, Adam, & Das Sarma (2007)

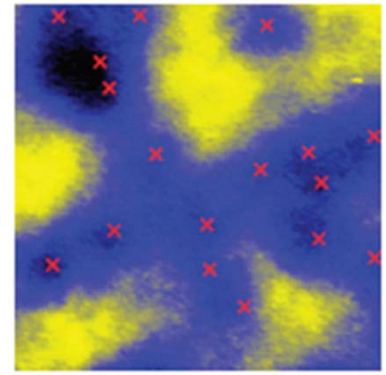
Minimum Conductivity of Graphene

At minimum conductivity point, graphene breaks into electron and hole “puddles” characterized by rms carrier density *n**

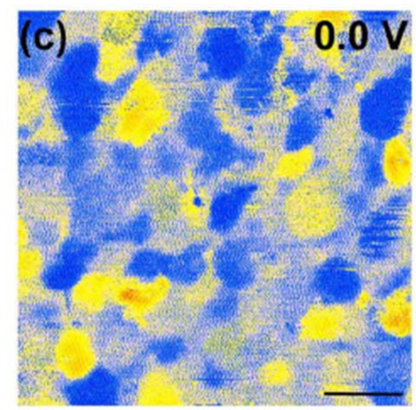
Martin et al. *Nat. Phys.* **4**, 144 (2007)
Scanning SET $n^* = 2.3 \times 10^{11}$ cm^{-2}





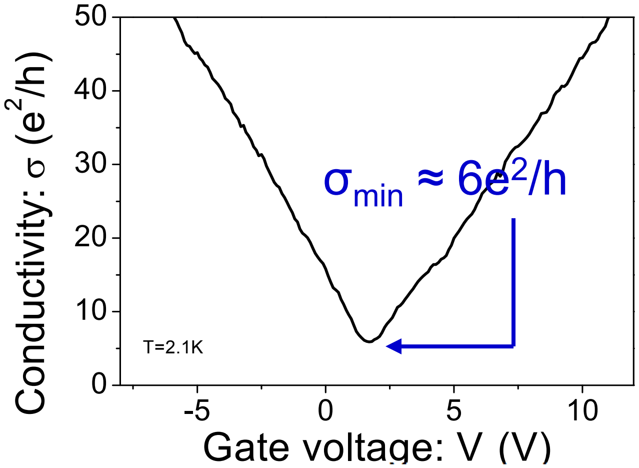


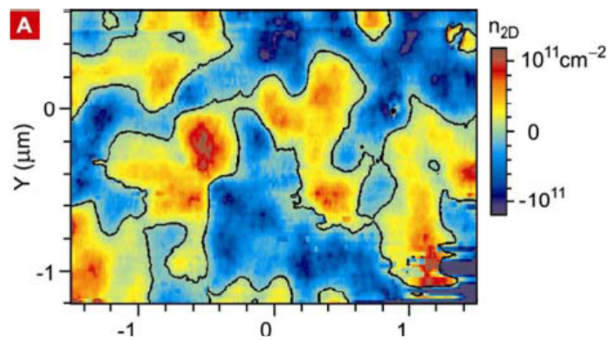
Y. Zhang *et al. Nat. Phys.* **5**, 722-726 (2009)
Scanning tunneling spectroscopy: $n^* = 4 \times 10^{11}$ cm^{-2}

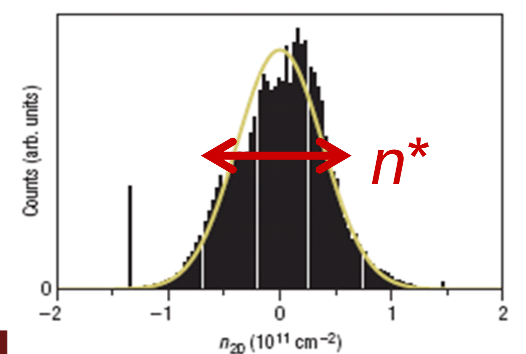


A. Deshpande *et al. PRB* **79**, 205411 (2009)
Scanning tunneling spectroscopy: $n^* = 4.3 \times 10^{11}$ cm^{-2}

Minimum Conductivity of Graphene







$$\sigma_{\min} = n^* e \mu$$

$$n^* = n_{imp}[2 r_s^2 C_0^{RPA}(r_s, 4k_F d)]$$

$$\mu = \frac{1}{n_{imp}}[20\frac{e}{h}]$$

Weak function of n_{imp}, r_s, d

σ_{min} is nearly universal ~ 4-10 e^2/h

Weakly dependent on disorder

Adam, et al., *PNAS* **104**, 18392 (2007)

Charged Impurity Scattering: Potassium Doping in UHV

J. H. Chen, et al. *Nature Physics* **4**, 377 (2008)

- Clean graphene in UHV at T = 20 K
- Potassium evaporated on graphene from getter

Upon doping with K:

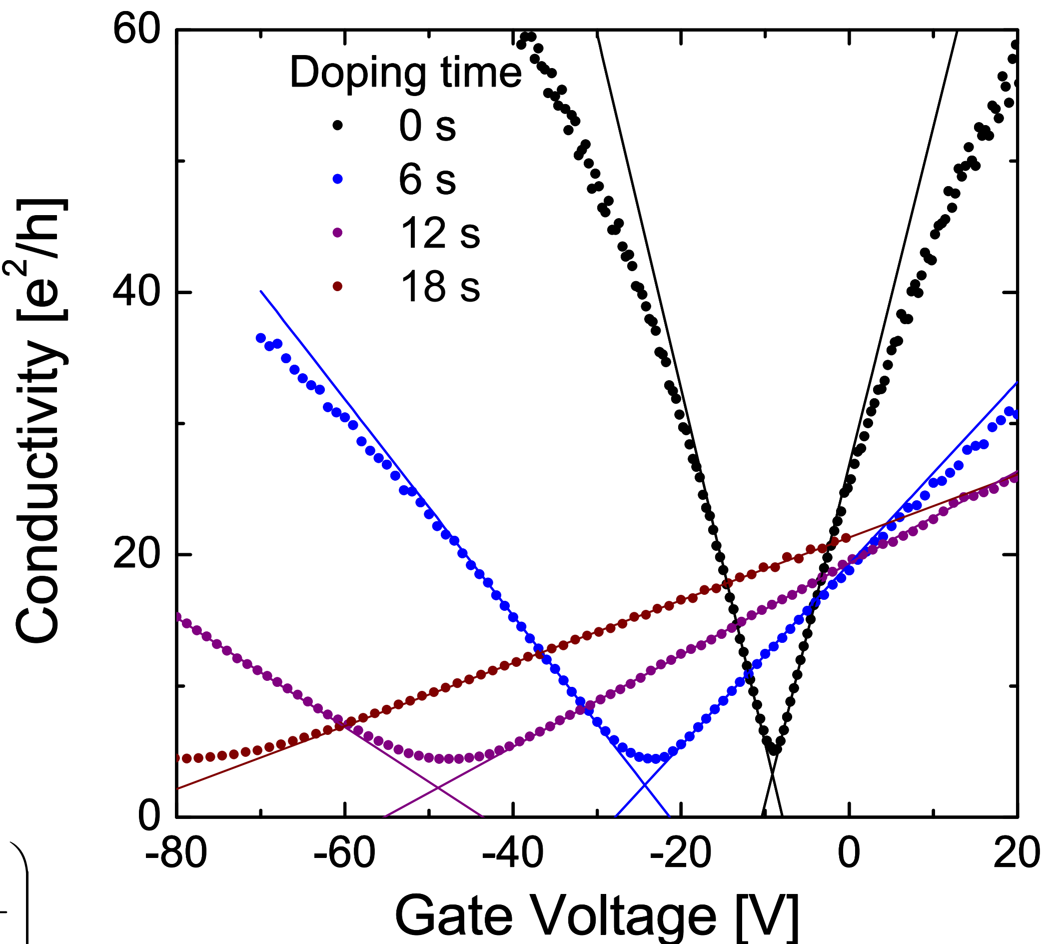
1) mobility decreases
2) σ(Vg) more linear
3) σ_{min} shifts to negative V_g
4) plateau around σ_{min} broadens
5) σ_{min} decreases (slightly)

All these feature predicted for Coulomb scattering in graphene

Adam, et al., PNAS 104, 18392 (2007)

Magnitude of scattering in quantitative agreement with theory:

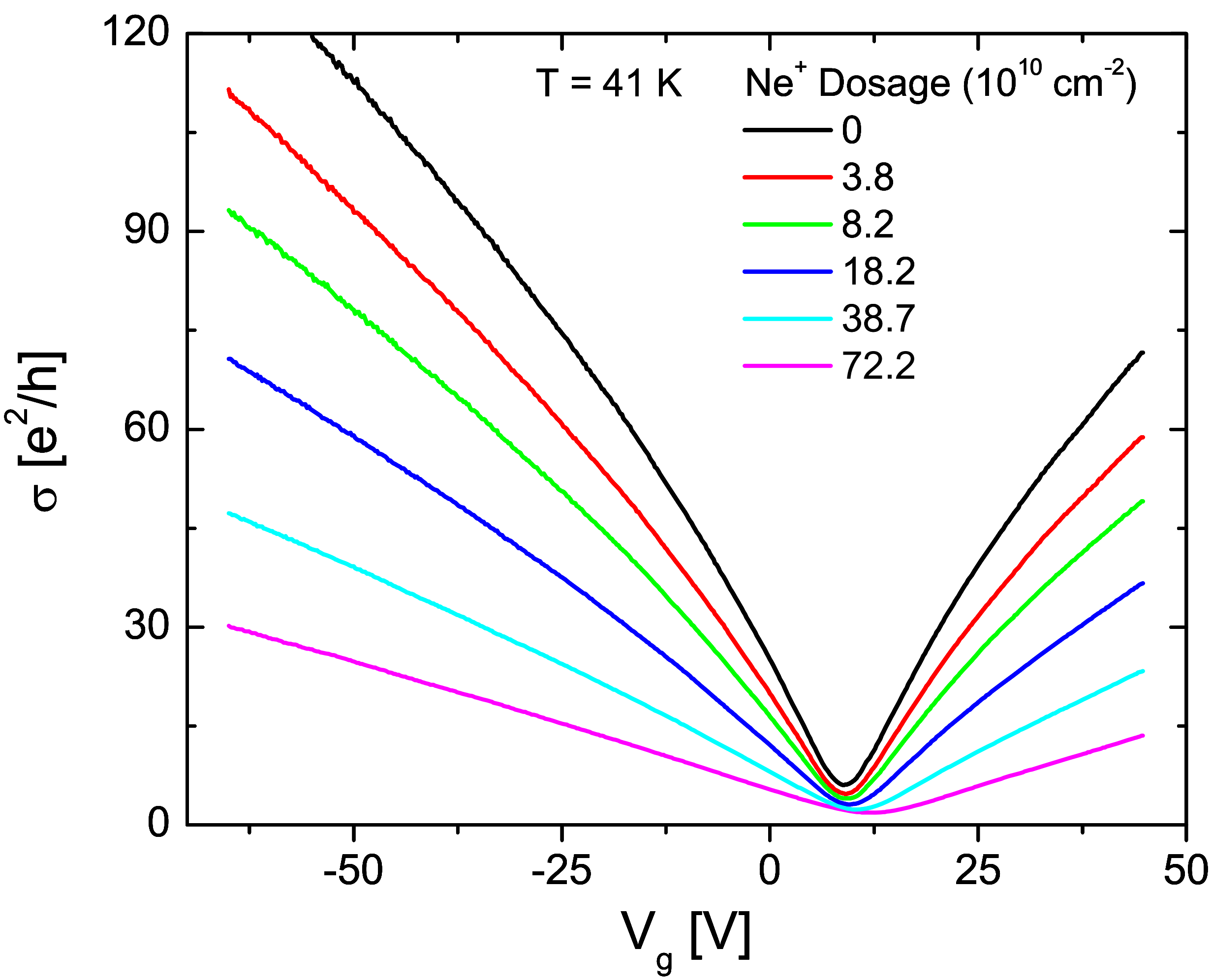
$$\sigma = \boxed{20}\frac{e^2}{h}\left(\frac{n}{n_{imp}}\right)$$



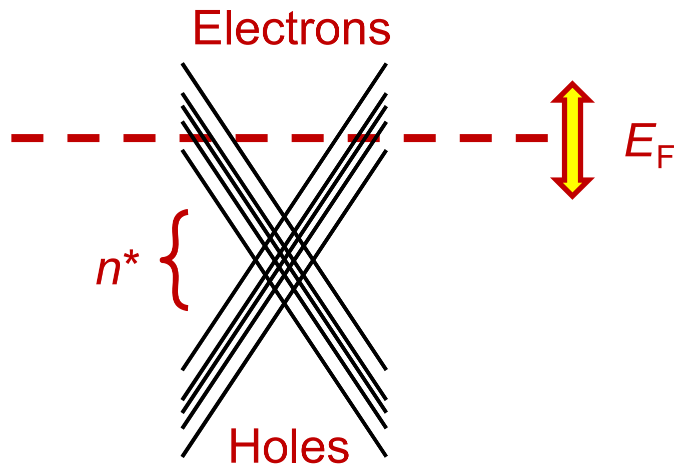
Defects in graphene

J. H. Chen, et al. *Physical Review Letters* **102**, 236805 (2009)

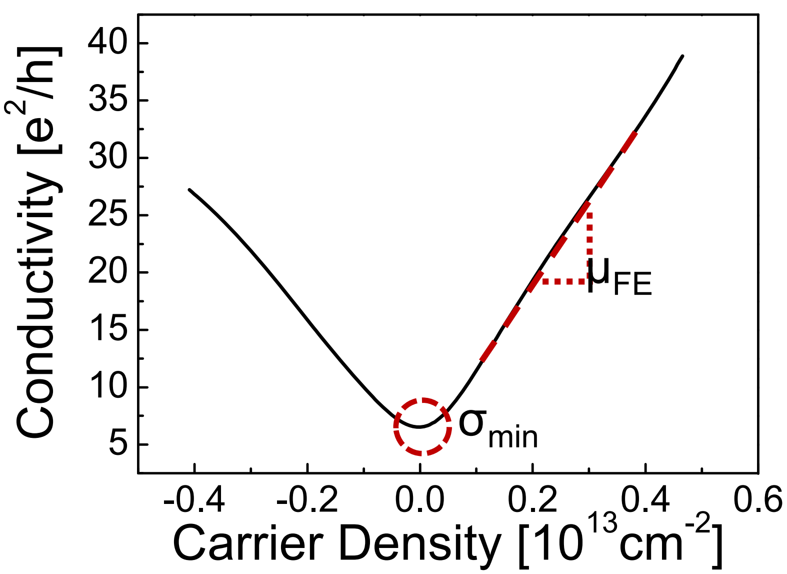
Ion irradiation with 500 eV Ne^+ → single carbon vacancies

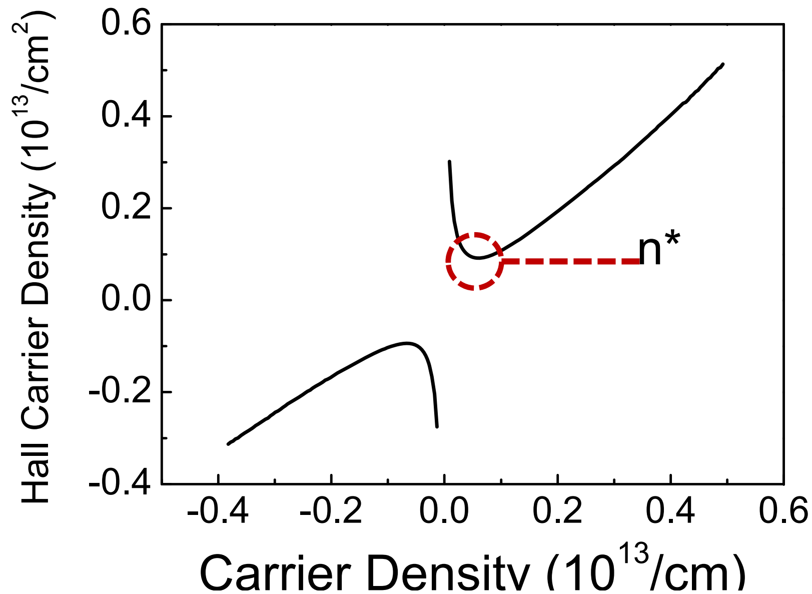


Lessons from graphene – charge impurities



- Charge disorder dominates transport near Dirac point
- Measurable quantities:
  - μ_{FE}
  - n^*
  - $\sigma_{min} = n^* e \mu_{FE}$





See Adam et al., *PNAS* **104**, 18392 (2007)

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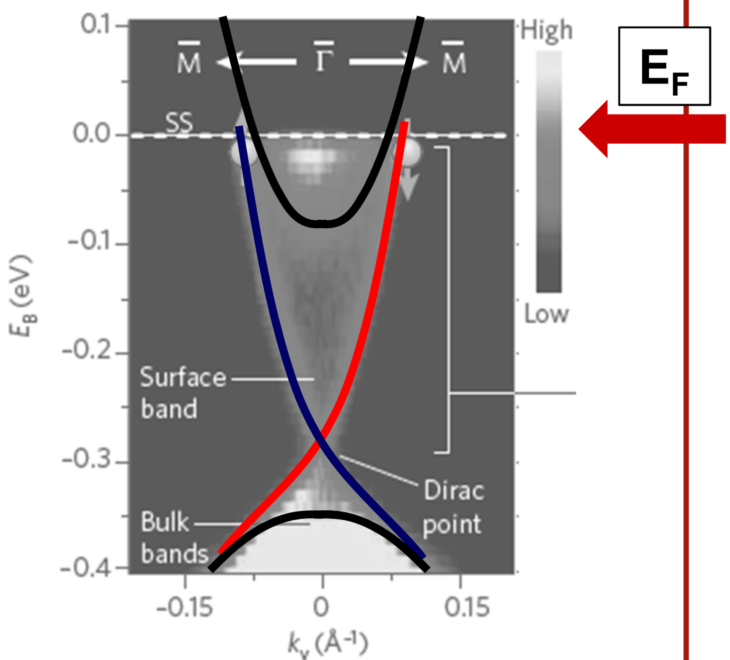
} *Nat. Phys.* **8**, 460 (2012)

Intersurface coupling

Weak anti-localization in decoupled and coupled surfaces *Nature Comm.* **4**, 2040 (2013)

3D Topological Insulators: Toward Surface Transport

ARPES Band Structure : Bi_2Se_3



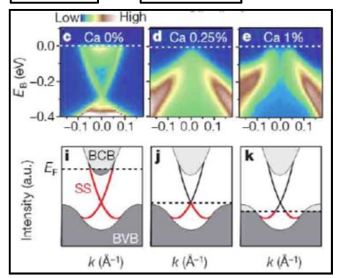
H. Zhang *et al*., *Nature Phys.*, 5, 438 (2009)

Y. Xia *et al*., *Nature Phys.*, 5, 398 (2009)

H. Hasan *et al*., *Nature*, 460, 1101 (2009)

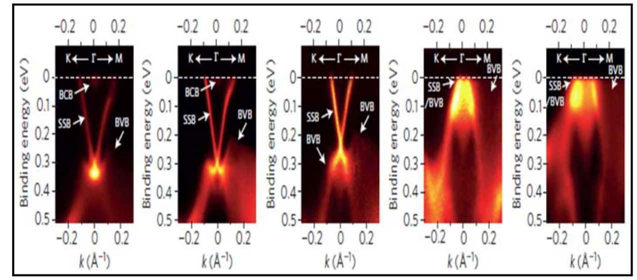
Reducing Bulk Doping : Substitution

Bi ➡ Ca



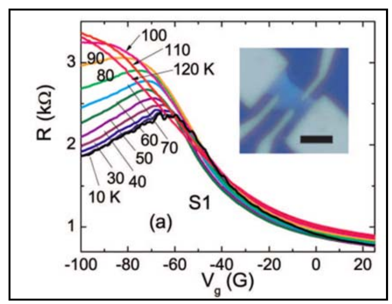
Y. Chen et al, *Science* 325, 178 (2009)

Bi ➡ Sb

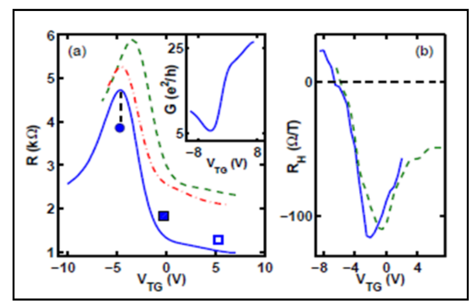


D. Kong, Y. Chen et al, *Nature Nanotech. 6, 705* (2011)

Thin Films & Gating

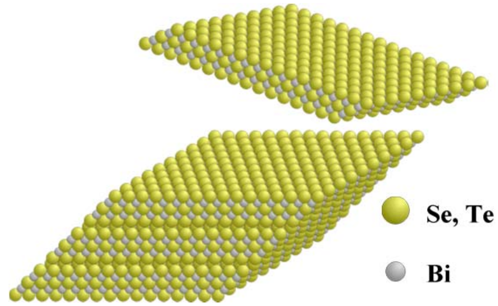


J. G. Checkelsky et al. *Rhys. Rev. Lett.* 84, 233101 (2011)



H. Steinberg et al. *Rhys. Rev. B* 84, 233101 (2011)

Exfoliated flakes of Bi_2Se_3

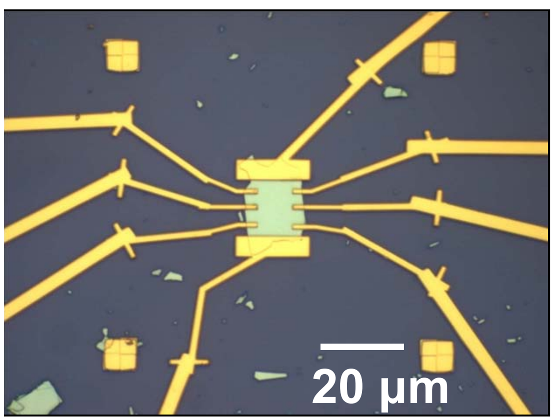


Tape exfoliation

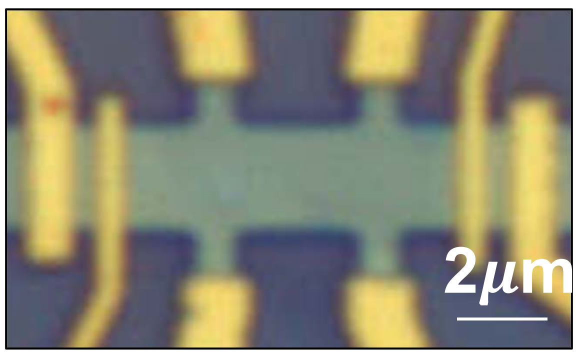
Bi_2Se_3 bulk crystal ($n \sim 10^{17} cm^{-3}$)
Paglione group, U. Maryland

N.P. Butch *et al*., *Phys. Rev. B.*, 81, 241301 (2010)

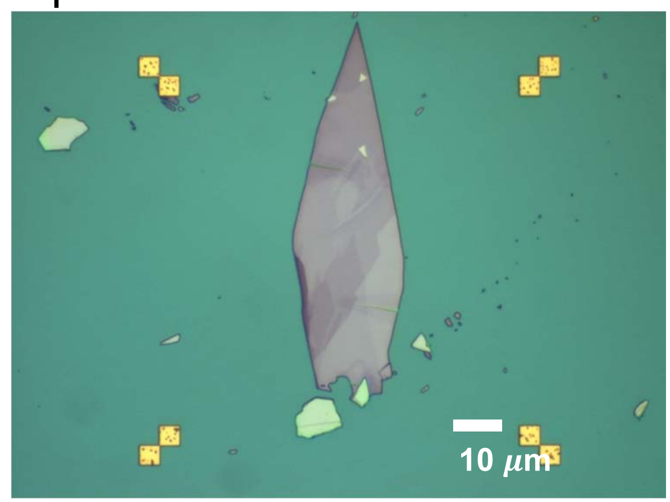
Quasi-Hall bar geometry
(as-found flakes)



Hall bar geometry
(etched by ion mill)



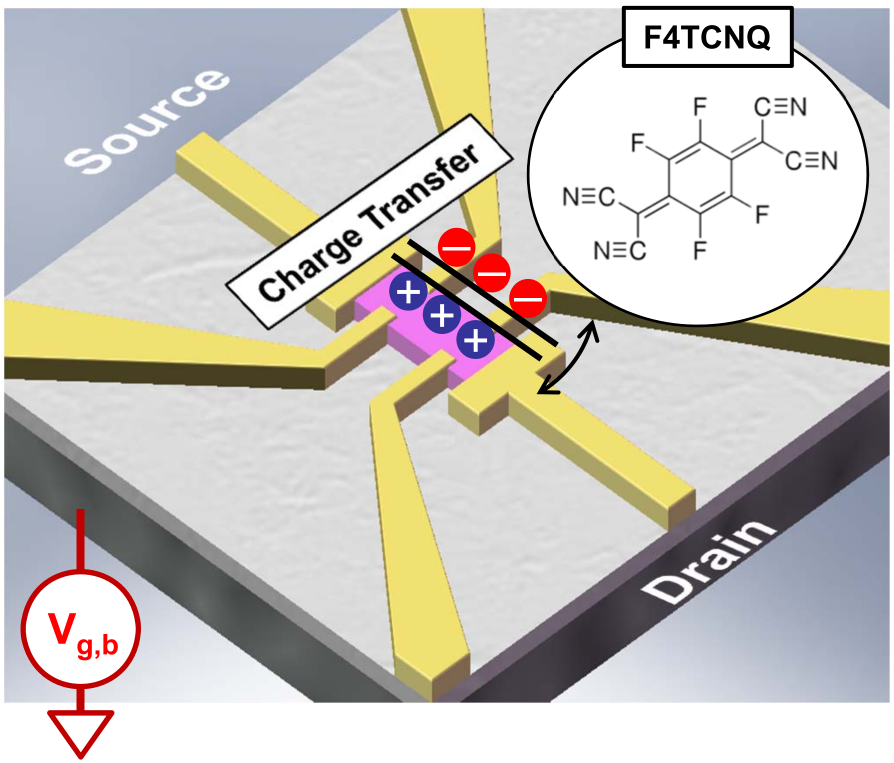
Optical and AFM identification



p-type chemical and electrochemical doping

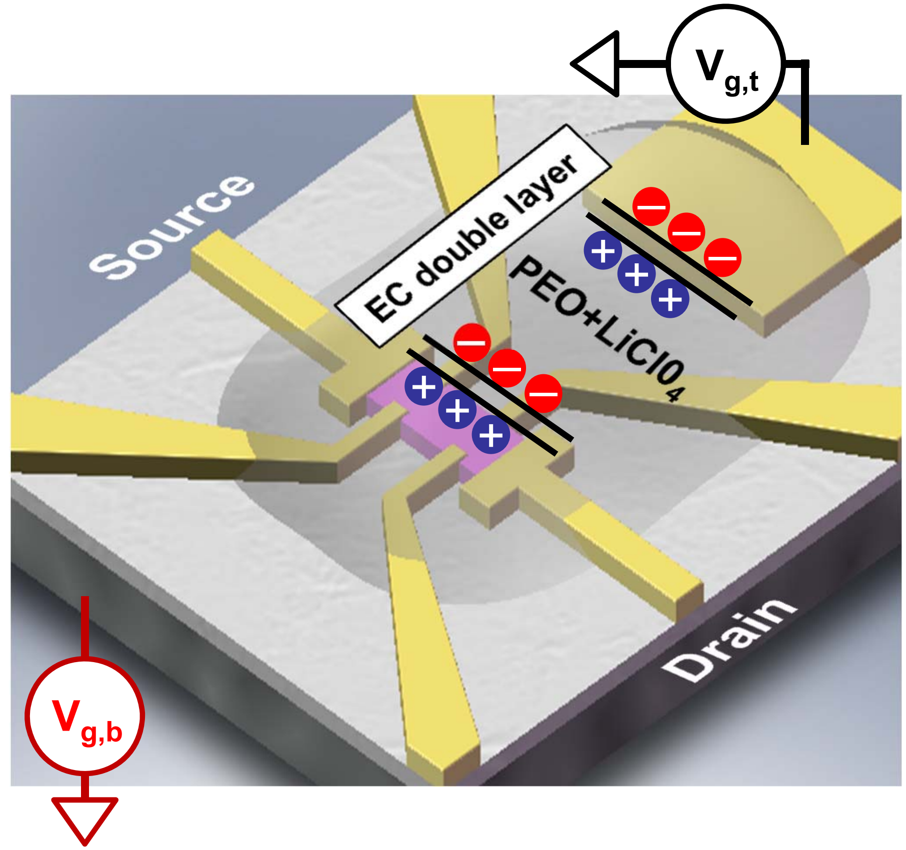
D. Kim et al., *Nature Physics* **8**, 460 (2012)

Charge Transfer Doping : F4TCNQ



Strong Electron Affinity (EA = 5. 24 eV)

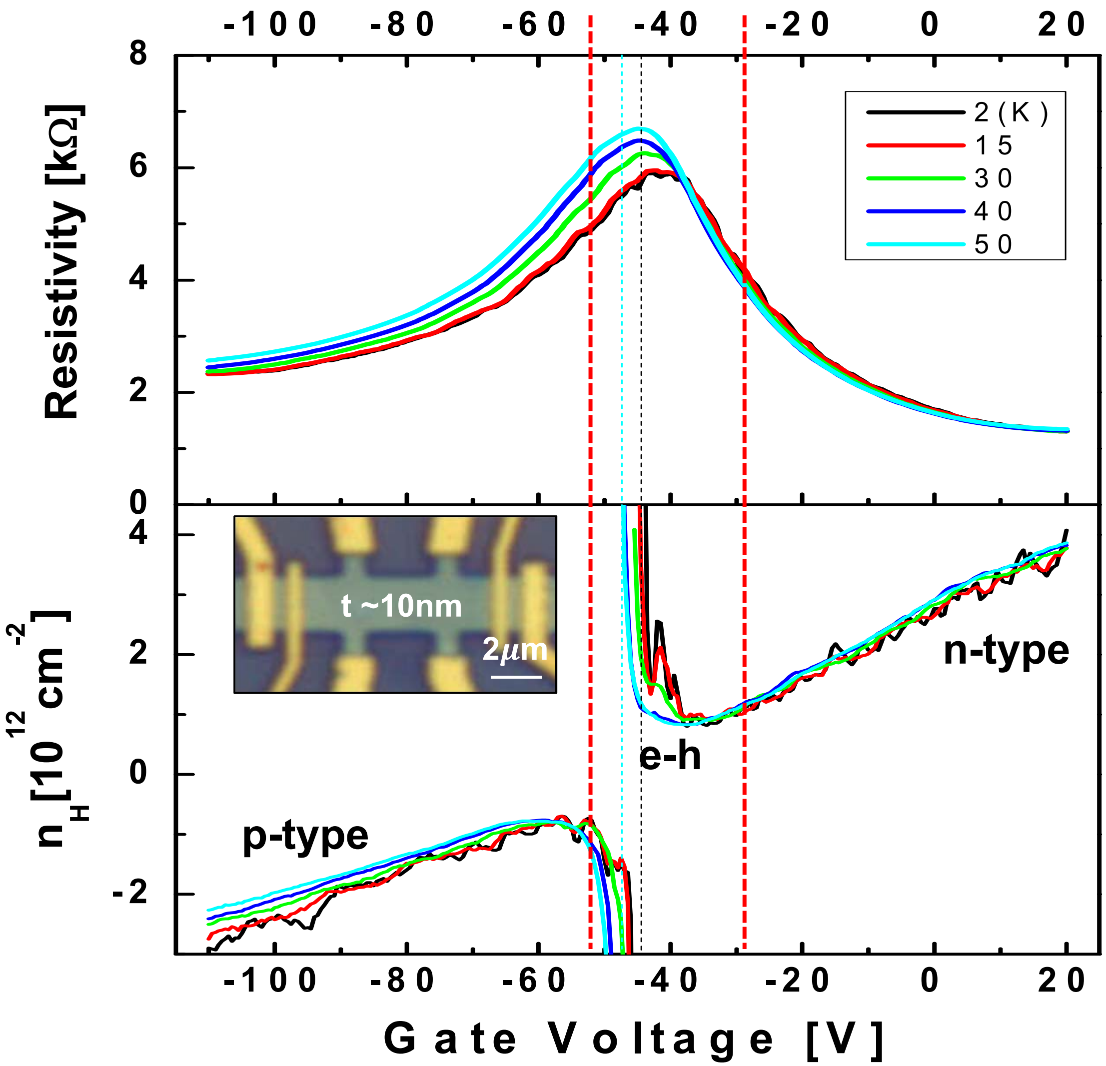
Electrolyte Gating: PEO+$LiClO_4$



Large Capacitance of ECDL (~μFcm^{-2})

Ambipolar Electric Field Effect

D. Kim et al., *Nature Physics* **8**, 460 (2012)



Key Observations

Typical *n*-doping (as fabricated):
~2 x 10^{13} cm^{-2}

After our schemes applied:
~3 x 10^{12} cm^{-2}

Clear ambipolar Conduction

Metallic *T* dependance of ρ

As expected for Gapless SS

Important Questions

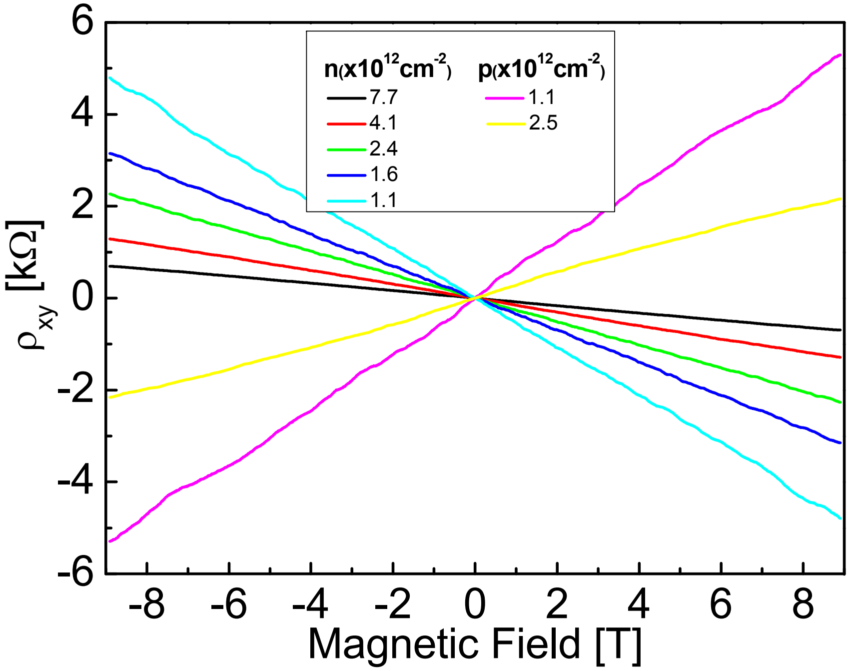
Bulk contribution to conductivity ?

Top vs. Bottom surfaces ?

Single Band Conduction in TI Regime

D. Kim et al., *Nature Physics* **8**, 460 (2012)

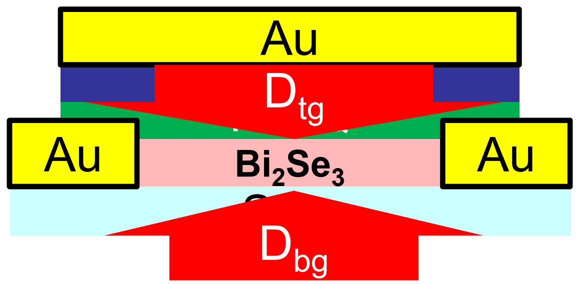
linear Hall resistivity ρ_{xy}(B)

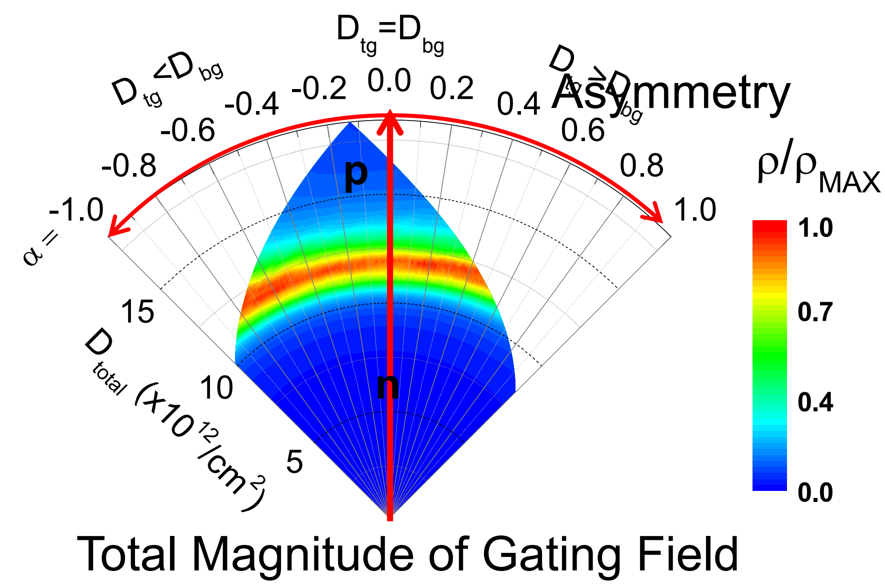


If multiple band conduction
: nonlinear ρ_{xy} (B) on the scale B~1/μ

B~1/μ~7T in the present device

Absence of Band-Bending





Resistivity depends *only on total* gating field.

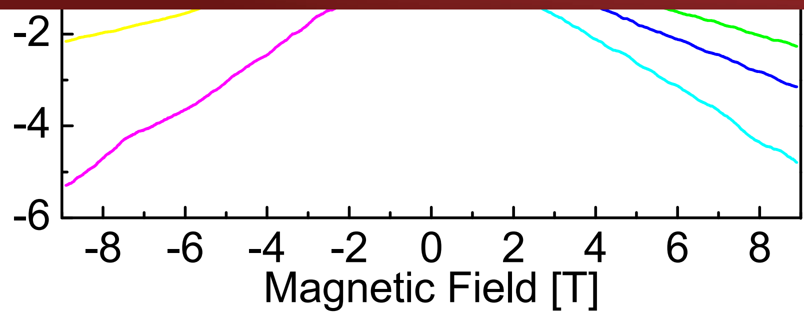
Single Band Conduction in TI Regime

D. Kim et al., *Nature Physics* **8**, 460 (2012)

linear Hall resistivity ρ_{xy}(B)

Absence of Band-Bending

We measure conductivity of simultaneously gated top/bottom surfaces without bulk contribution.



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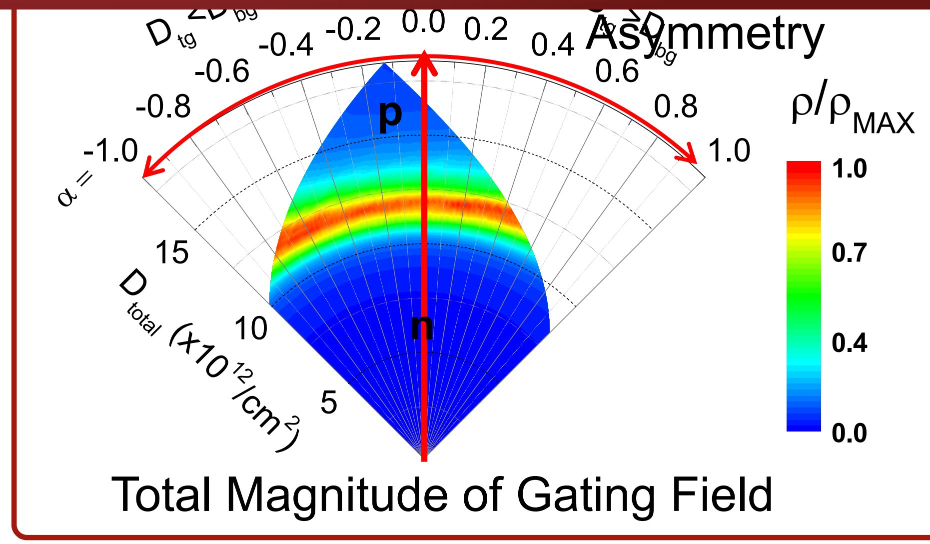

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} *Nat. Phys.* **8**, 460 (2012)

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D. Kim et al., *Nature Physics* **8**, 460 (2012)

Conductivity roughly linear in range

$$n^* < n < n_{3D}$$

where $n_{3D} \sim 5 \times 10^{12}\ cm^{-2}$

$$\sigma = C(r_s)\frac{n}{n_{imp}} \quad \textit{where} \quad r_s = \frac{e^2}{\kappa \hbar v_F}$$

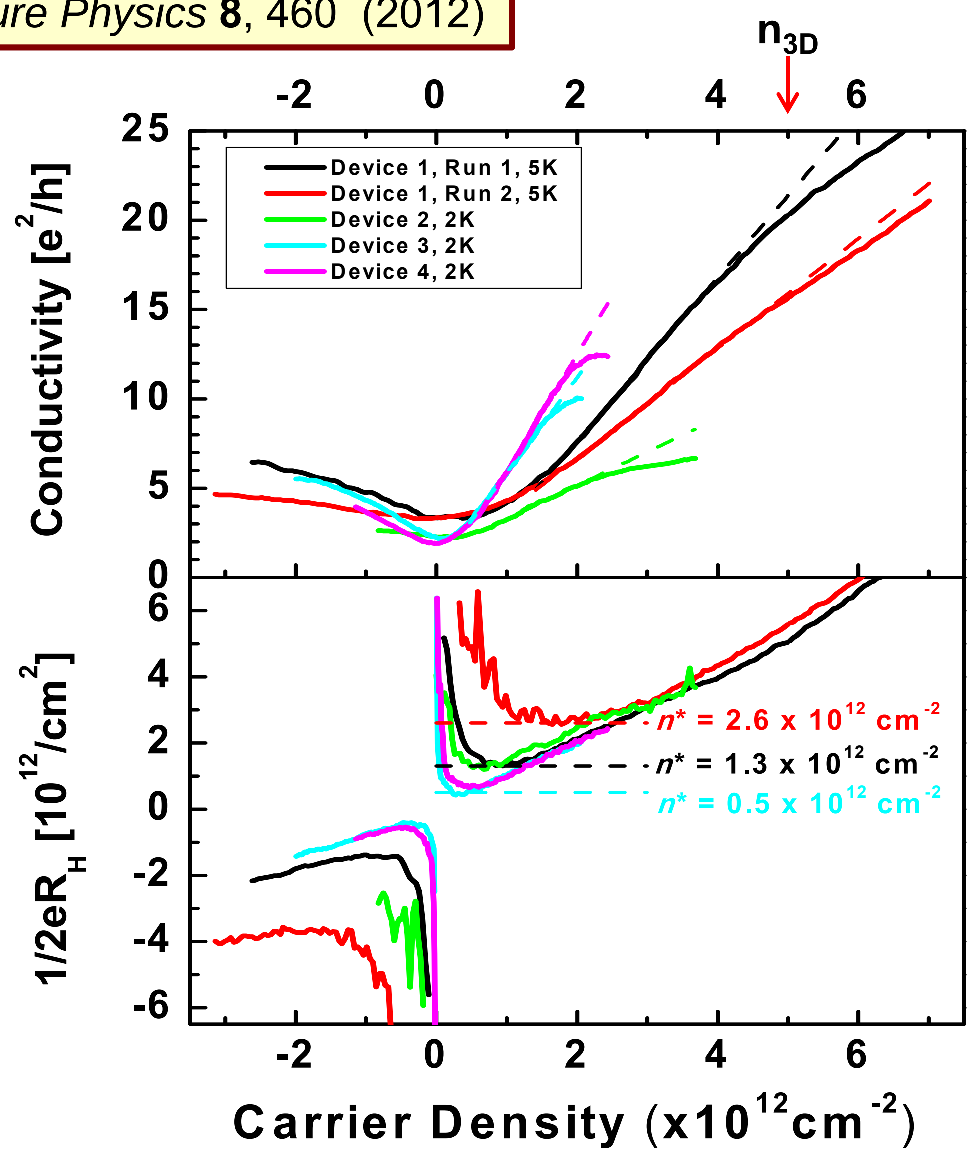
D. Culcer et al. *Phys. Rev. B* 82, 155457 (2010)

$$320 < \mu < 1500\ cm^2/Vs$$

Minimum conductivity ≡ σ_{min}

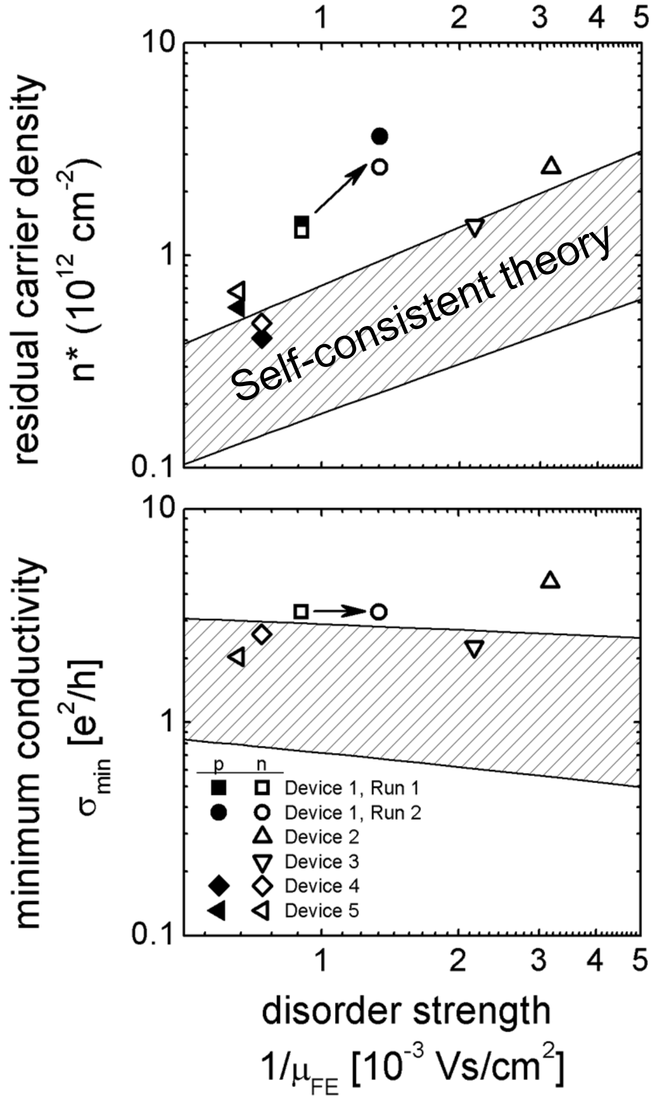
Minimum Hall carrier density ≡ n^*

(e-h puddle carrier density)



Minimum Conductivity vs. Disorder Strength

D. Kim et al., *Nature Physics* **8**, 460 (2012)



Qualitative agreement between expt. and theory - as disorder increases:

*n** increases

σ_{min} is nearly constant

Self-consistent theory:

$0.05 < r_s < 0.2$

$0.1 < d < 15$ A

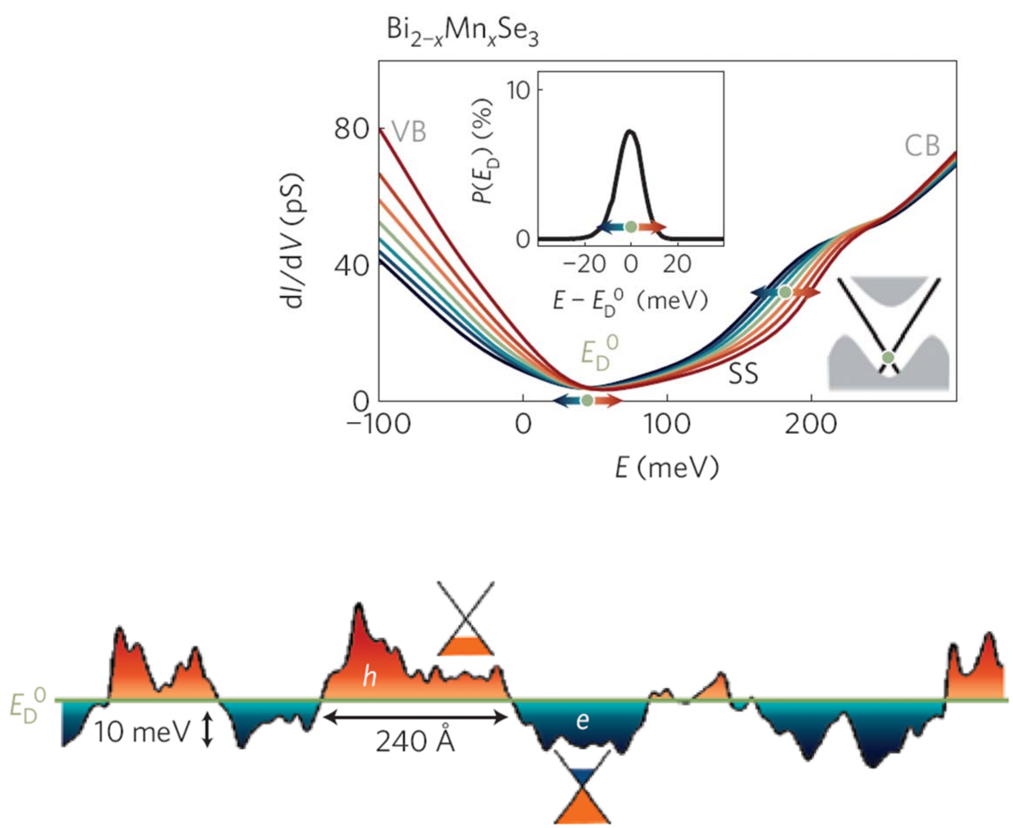
Reasonable agreement (best at large r_s, small d limit)

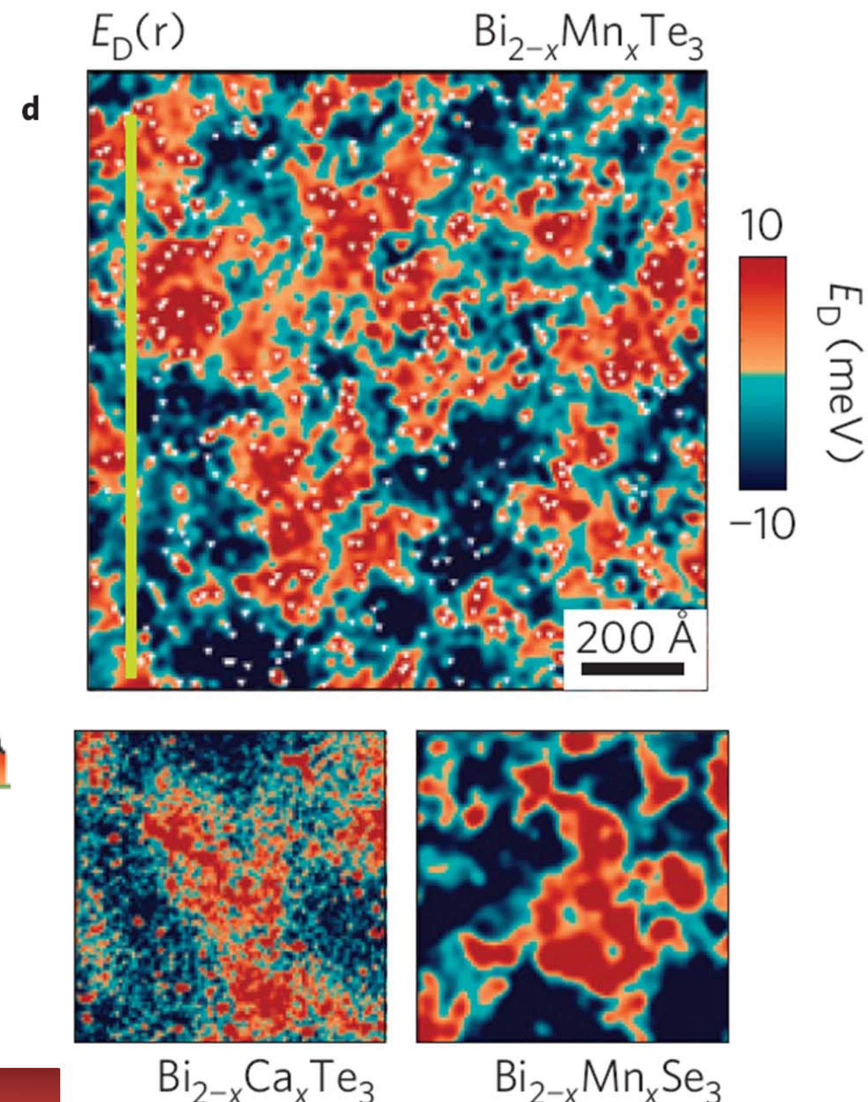
Agreement can be improved if nonlinear band structure and asymmetry taken into account

Adam, Hwang and Das Sarma, *PRB* **85**, 235413 (2012)

See also STM study of puddles in Bi_2Se_3/Bi_2Te_3

Yazdani group: H. Beidenkopf, et al. *Nat. Phys.* **7**, 939 (2011)

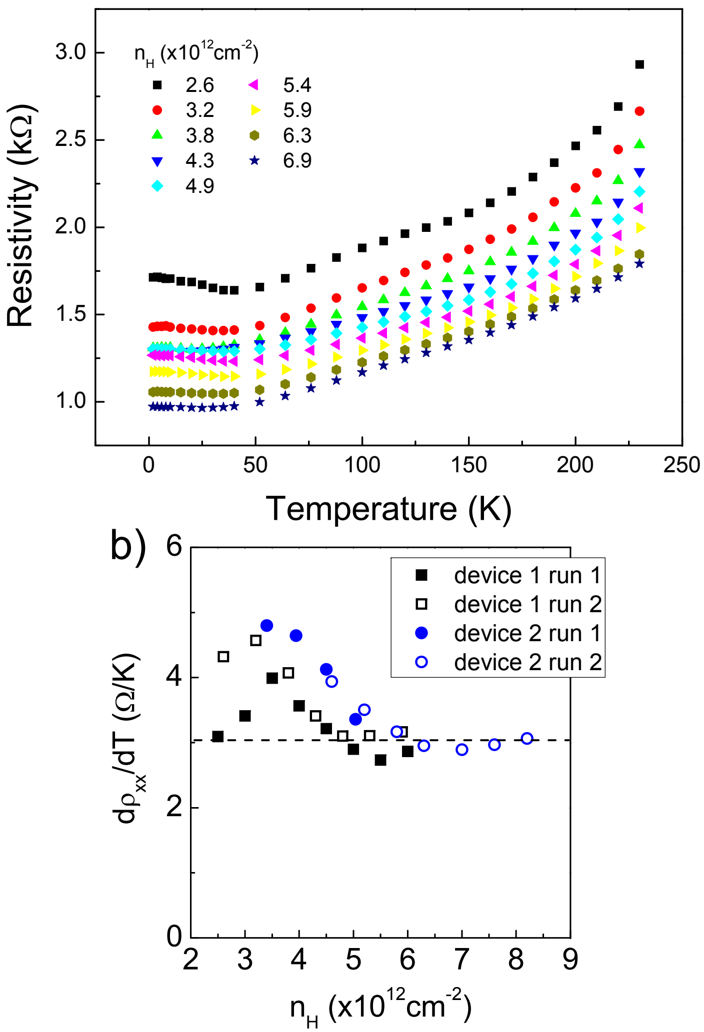




Transport in the Topological Regime in Bi_2Se_3

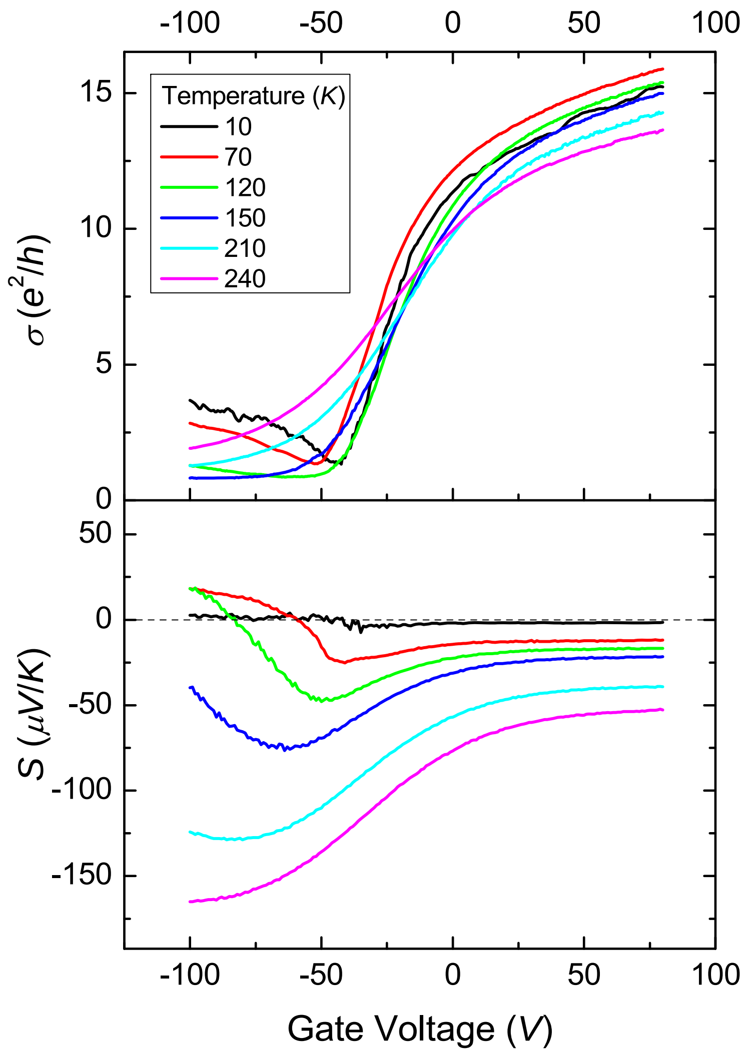
electron-acoustic phonon scattering

PRL **109**, 166801 (2012)



ambipolar thermopower

In preparation



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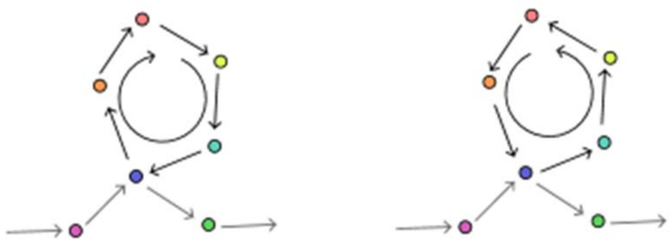
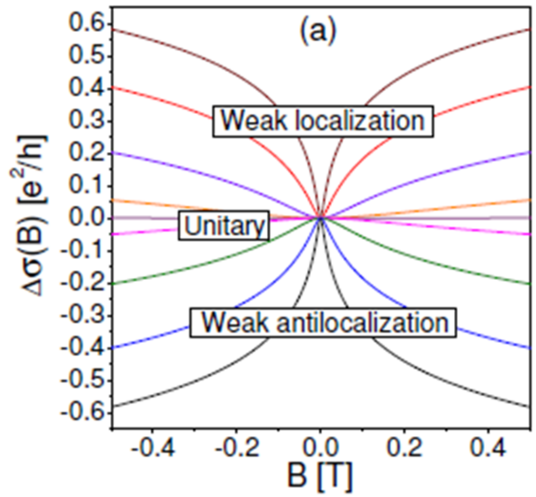
Weak (anti)-Localization

Quantum Correction to Classical Conductivity



Quantum Interference of TR paths



"HLN" formula : limit of strong SO coupling

$$\Delta\sigma_{\mathrm{HLN}}(B) = \alpha\frac{e^2}{\pi h}\left[\Psi\left(\frac{\hbar}{4eB\mathcal{L}^2}+\frac{1}{2}\right)-\ln\left(\frac{\hbar}{4eB\mathcal{L}^2}\right)\right]$$

α = 1/2 for single channel

L. Hikami et al, Prog. Theor. Phys. 63, 707-710 (1980)

Ti surface: *perfect* WAL due to Berry phase π
(always metallic)

Weak Anti-localization in TIs

Validity of HLN form in TI : Multi-channels

- Valid for Multi-channels ? Some constraints but, Yes
- α=*m*/2 probes # of channels *m*

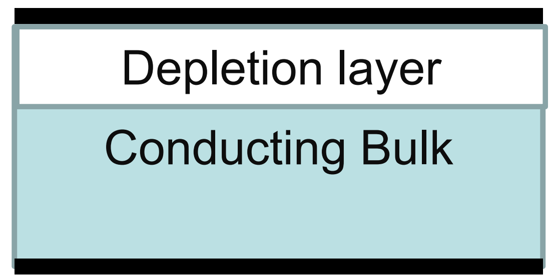
Theory: Garate and Glazman, *PRB* 86, 035422 (2012)

Ref.	sample	thickness	T (K)	α	$\mathcal{L}$ (nm)
8	Bi_2Se_3	10 nm	1.8	-0.5∼-0.38	106∼237 [a]
9	Bi_2Se_3	10∼20 nm	0.3	-0.38	
10	Bi_2Te_3	50 nm	2	-0.39	331
11	Bi_2Se_3	2∼6 QL	1.5	-0.39	75∼200
12 [b]	Bi_2Se_3	45 nm	0.5	-0.31	1100
	(Bi,Pb)Se_3			-0.35	640
14	Bi_2Se_3	5∼20 nm	0.01∼2	-1.1∼-0.4	143∼ ∞
15	Bi_2Se_3	3∼100 QL	1.5	-0.63∼-0.13	100∼1000
16	Bi_2Se_3	20 nm	0.3∼100	-1.1∼-0.7	15∼300

H. Z. Lu et al. Phys. Rev. B 84, 125138 (2011)

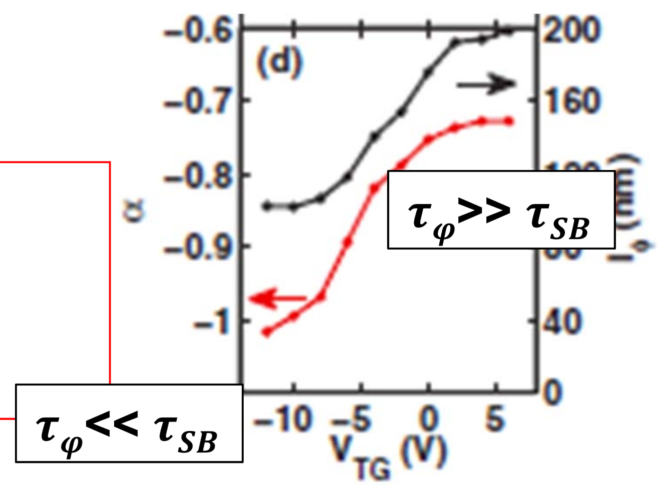
Channel 1 : Top

Channel 2 : Bulk + Bottom



Previous studies : Surface + Conducting bulk

Relevant time scales :
Phase coherence time (τ_φ)
Surface-Bulk scattering time (τ_{SB})



See also, J. Chen et al, *Phys. Rev. B* 83, 241304 (2011)

Expt.: H. Steinberg et al, *PRB* 84,233101 (2011)

WAL in TI regime ?

Phase coherent time: τ_φ

Channel 1: Top surface

Channel 2: Bottom surface

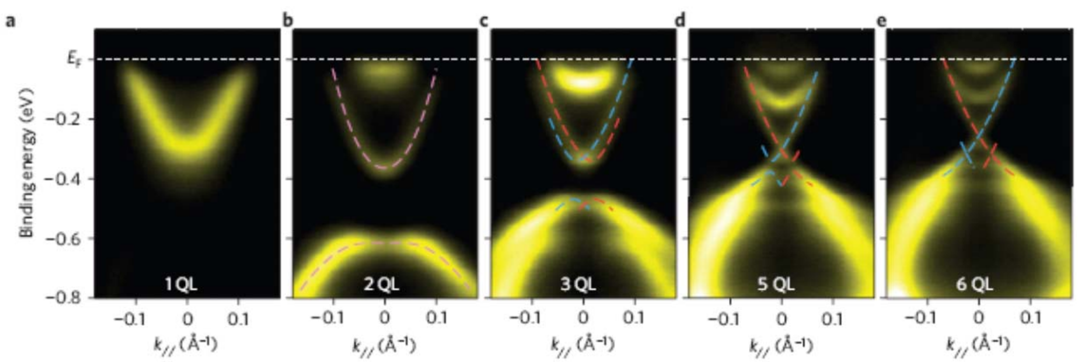
no surface/bulk scattering ($\tau_{SB} \to \infty$)

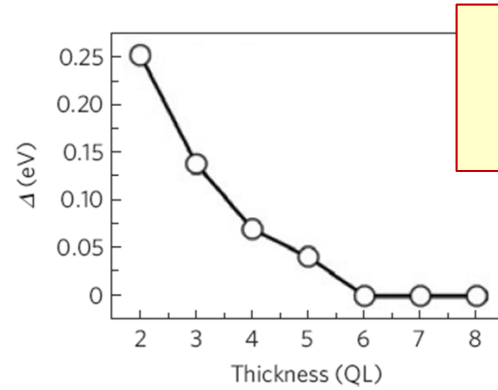
$$\alpha = \frac{1}{2} + \frac{1}{2} = 1 \ ?$$

Not necessarily.

Inter-surface tunneling time: τ_t

Use ARPES results to determine τ_t:
[Y. Zhang et al. *Nature Physics* **6**, 584 (2010)]

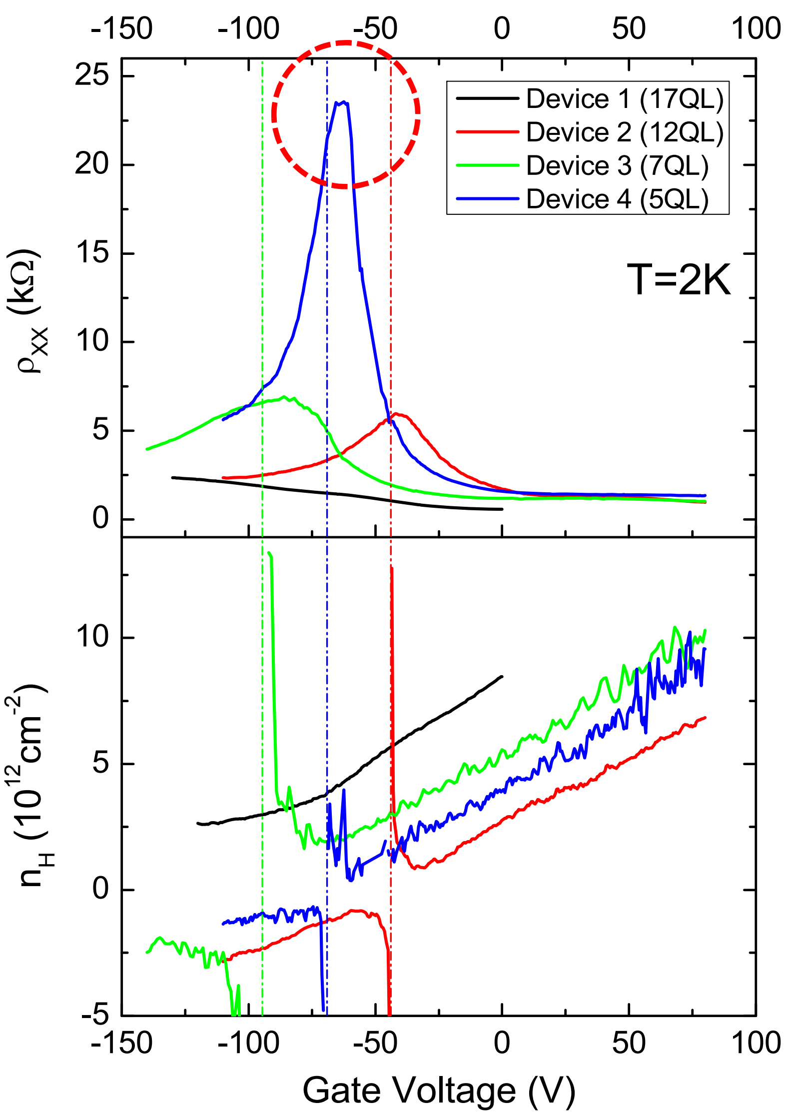




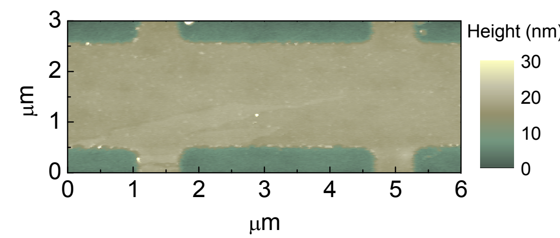
$$\tau_t = \frac{h}{2\Delta}$$

Semi-classical Transport

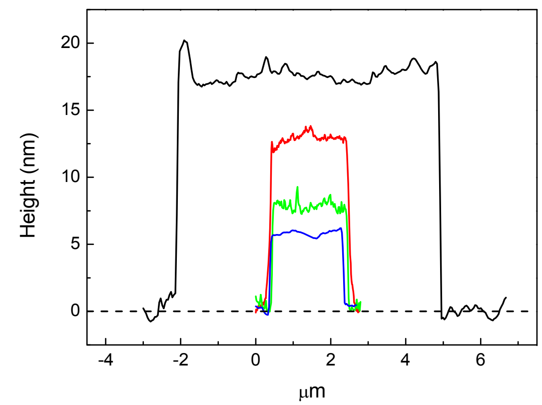
D. Kim, P. Syers, N. P. Butch, J. Paglione, M. S. Fuhrer, *Nature Comm.* **4**, 2040 (2013)



AFM scan



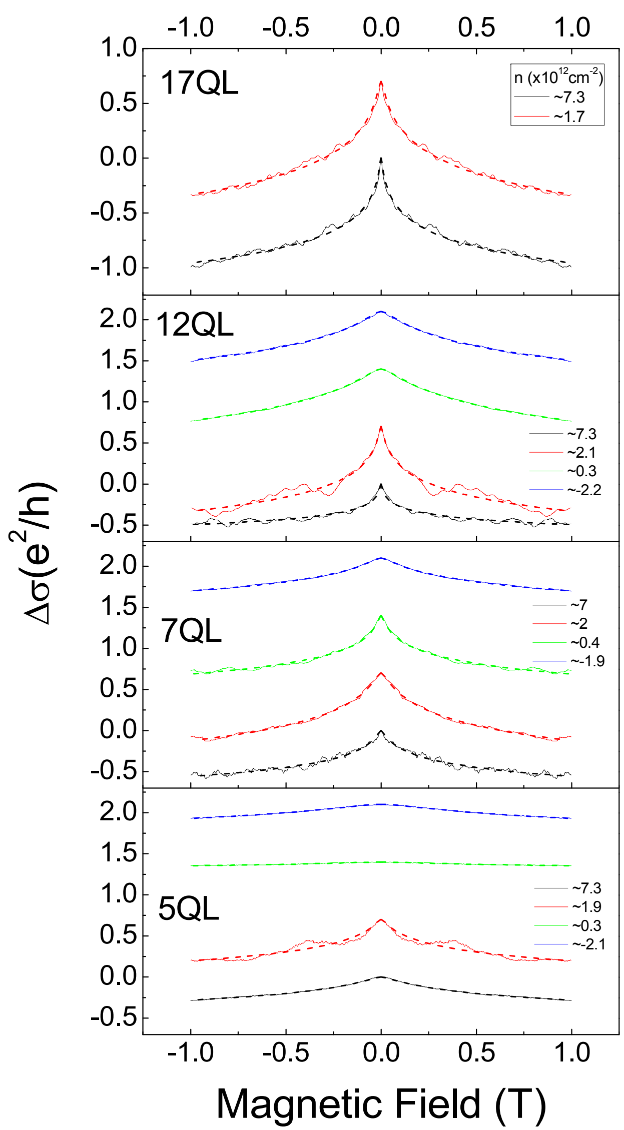
Height profiles



- highly resistive ρ_{max} in 5QL device
  sign of surface gap?

WAL fit to HLN formula

D. Kim, P. Syers, N. P. Butch, J. Paglione, M. S. Fuhrer, *Nature Comm.* **4**, 2040 (2013)



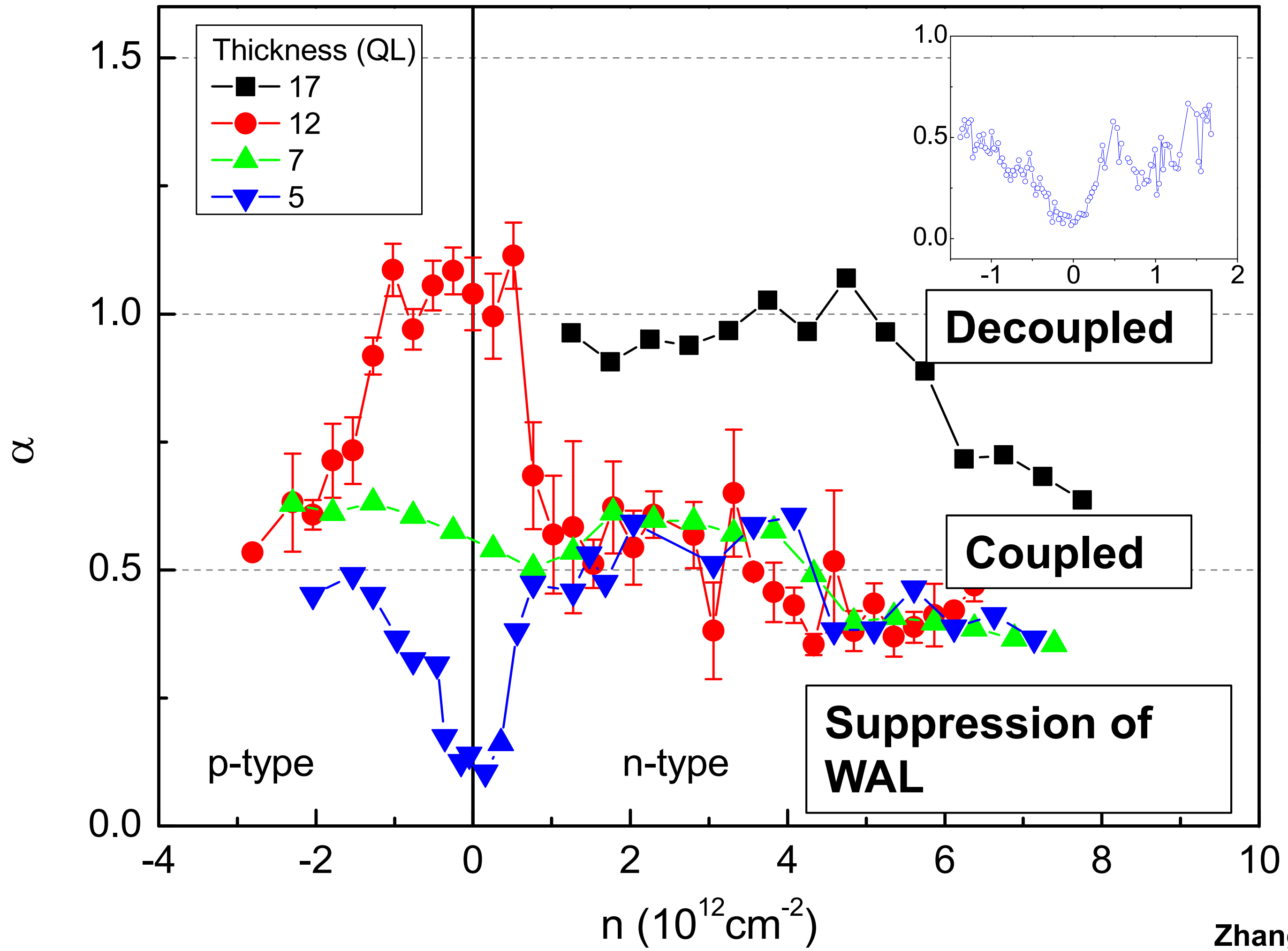
HLN formula

$$\Delta\sigma_{\mathrm{HLN}}(B) = \alpha\frac{e^2}{\pi h}\left[\Psi\left(\frac{\hbar}{4eB\mathcal{L}^2}+\frac{1}{2}\right)-\ln\left(\frac{\hbar}{4eB\mathcal{L}^2}\right)\right]$$

- **Can fit all thicknesses, carrier density**
- **Moderate contribution from UCF leads to error in α < 0.1**
- **The other fit parameter L : coherence length**
- **Can estimate τ_φ from L and Drude conductivity**

Single to Multi Channel Crossovers

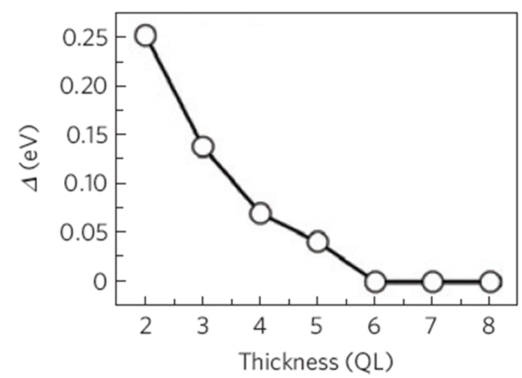
D. Kim, P. Syers, N. P. Butch, J. Paglione, M. S. Fuhrer, *Nature Comm.* **4**, 2040 (2013)



Estimation of Time Scales

1. τ_φ from WAL

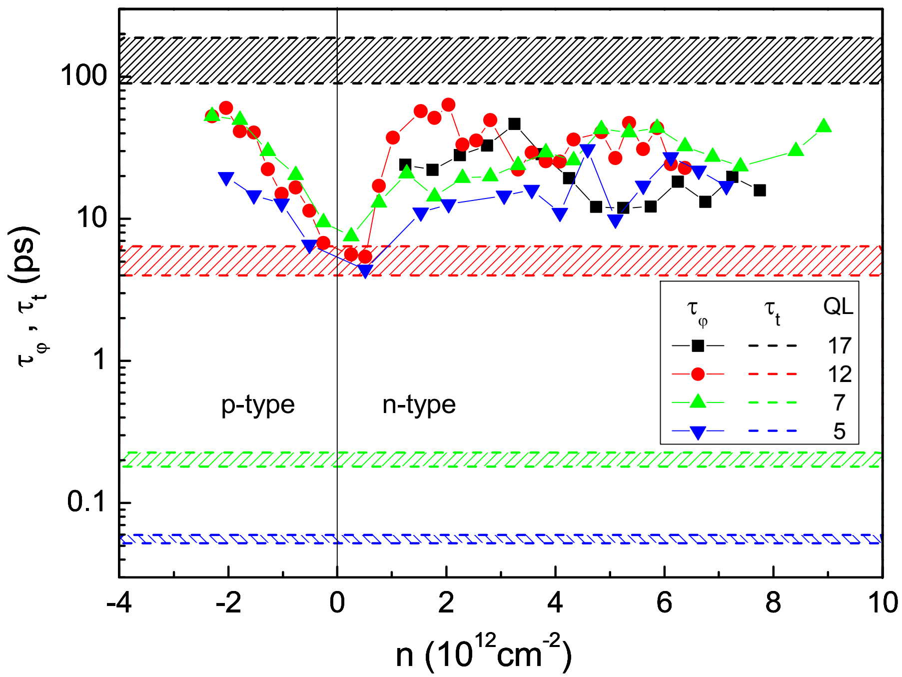
2. $\tau_t = \frac{h}{2\Delta}$ from

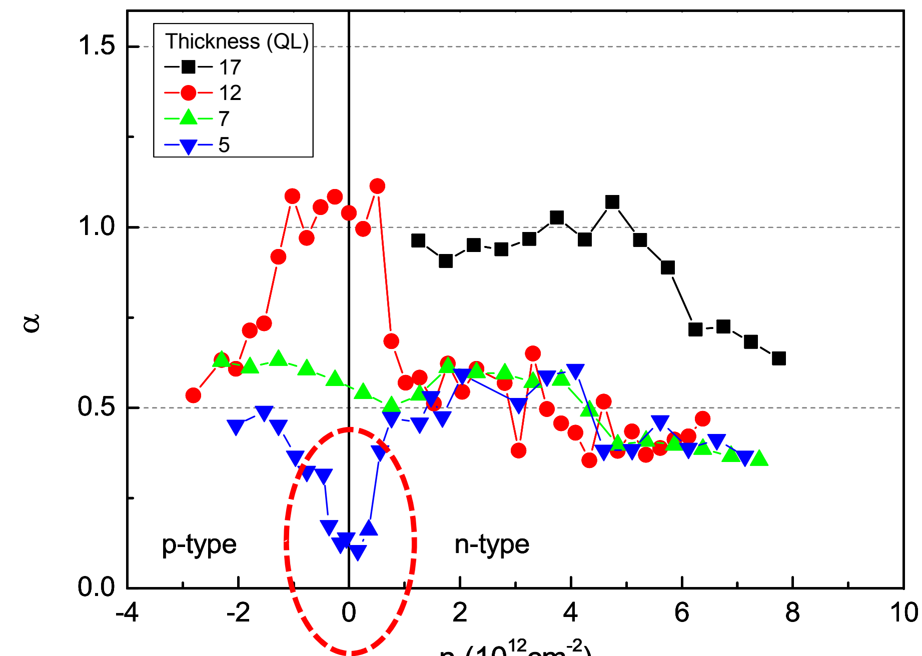


Zhang et al. Nature Phys. 6, 584 (2010)

Comparison of τ_p and τ_t

D. Kim, P. Syers, N. P. Butch, J. Paglione, M. S. Fuhrer, *Nature Comm.* **4**, 2040 (2013)





Tunneling time set by, $\tau_t = \dfrac{h}{2\Delta}$

$$\theta_B = \pi(1 - \Delta / 2E_F)$$

Strongly coupled single channel: $\tau_p >> \tau_t$, $\alpha = 1/2$

Decoupled two channels: $\tau_p << \tau_t$, $\alpha = 1$

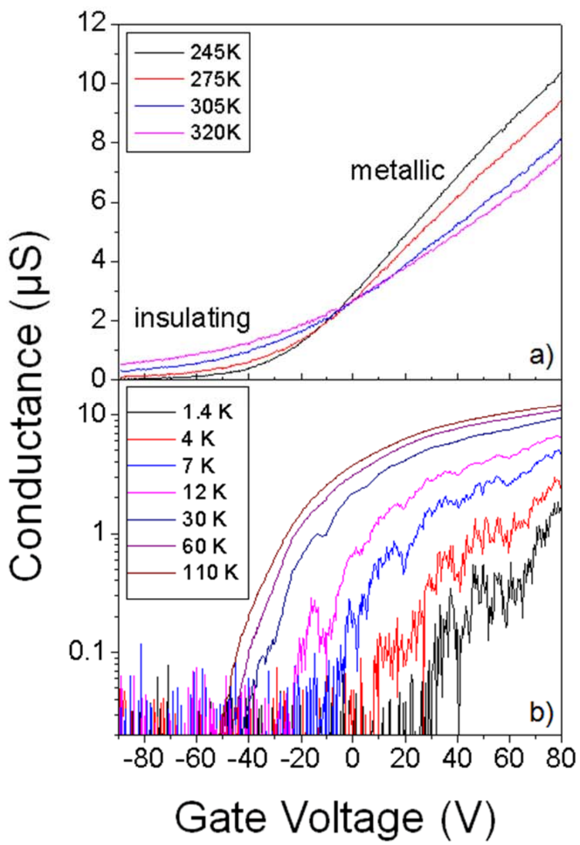
Inhomogeneous θ_B at low n
Both WL & WAL suppressed

H. Z. Lu *et al. Phys. Rev. Lett.* 107, 076801 (2011)

Thinner Bi_2Se_3 (3 QL) - Insulating

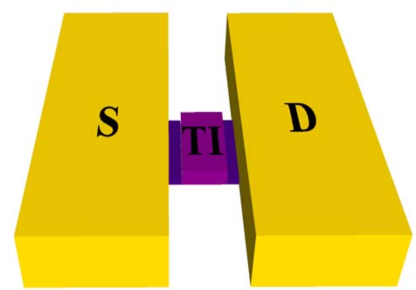
Conventional insulating behavior in 3 QL Bi_2Se_3

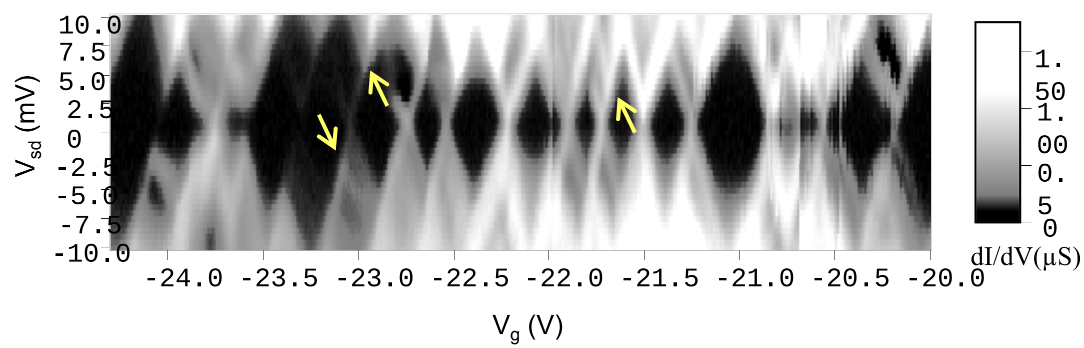
Nano Letters **11**, 1925 (2011)



Thin insulating Bi_2Se_3 as tunnel barrier: Bi_2Se_3 quantum dots

Nano Letters **12**, 469 (2012)





Thank you!

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