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ICTP Conference Graphene Week 2008

25 - 29 August 2008

Electric and Thermoelectric Transport in Graphene

P. Kim
Columbia University, New York, U.S.A.

Electric and Thermoelectric Transport in Graphene

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Columbia University and the National Science Foundation
Center for Electron Transport in Molecular Nanostructures

Outlines

I. Electron transport in suspended graphene samples

K. I. Bolotin et. al., Solid State Comm. 146, 351-355 (2008);
K. I. Bolotin, et. al., arXiv:0805.1830.

II. Quantum oscillations in graphene pnp junctions

A. F. Young and P. Kim, arXiv:0808.0855;
will also be presented in the poster session by Andrea Young

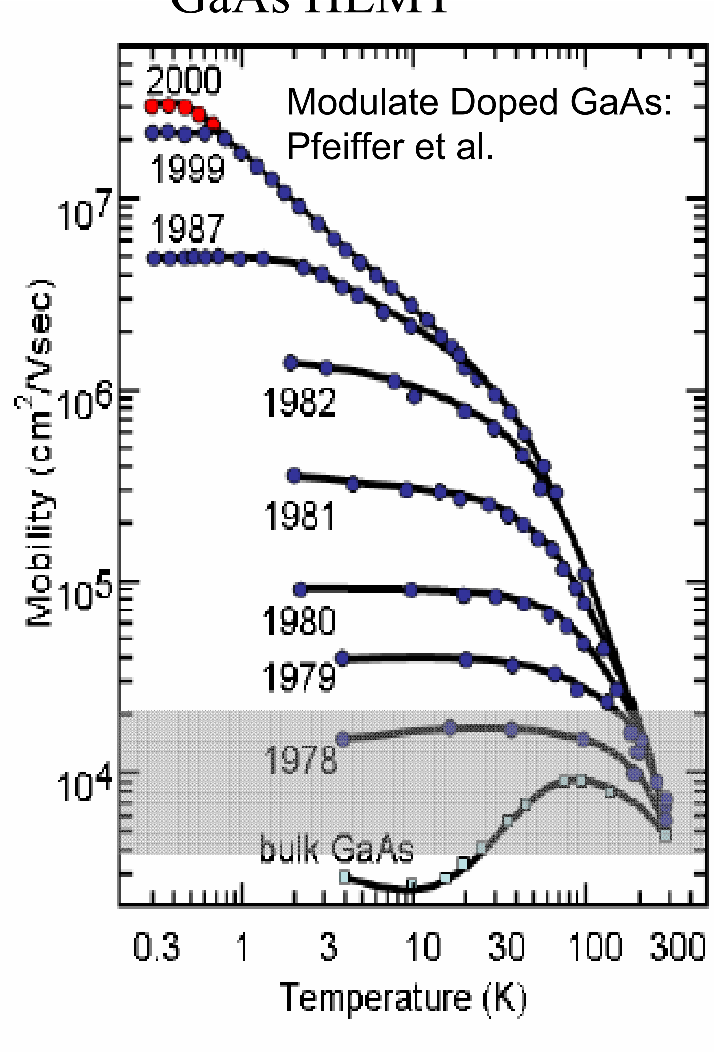
III. Thermoelectric power in graphene

Y. Zuev, W. Chang, and P. Kim, in preparation

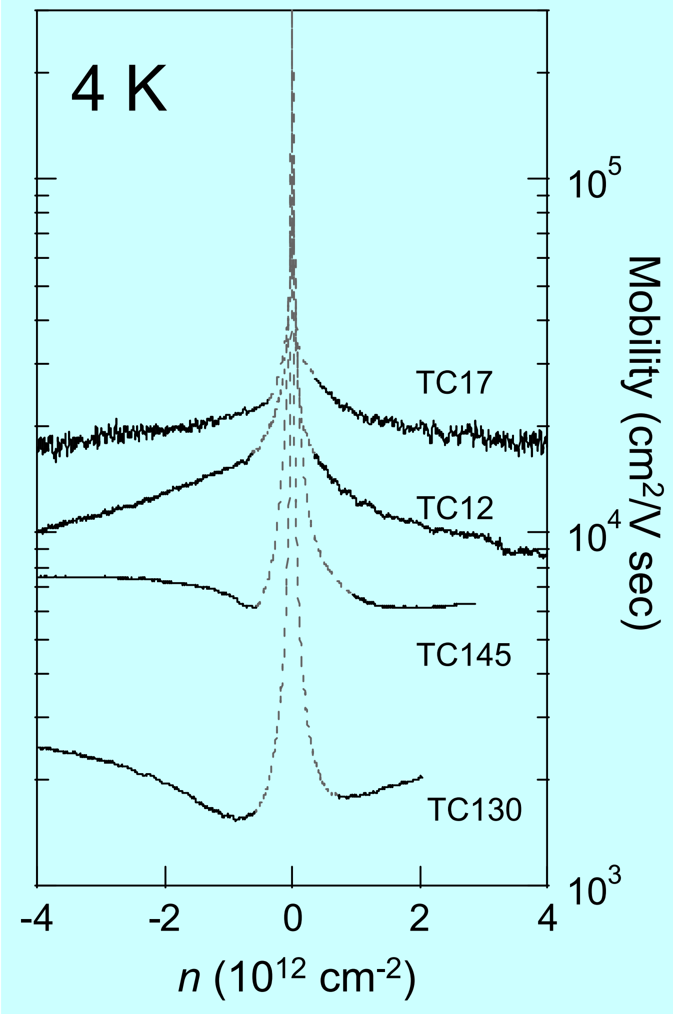
Graphene Mobility

$\sigma = en\mu$

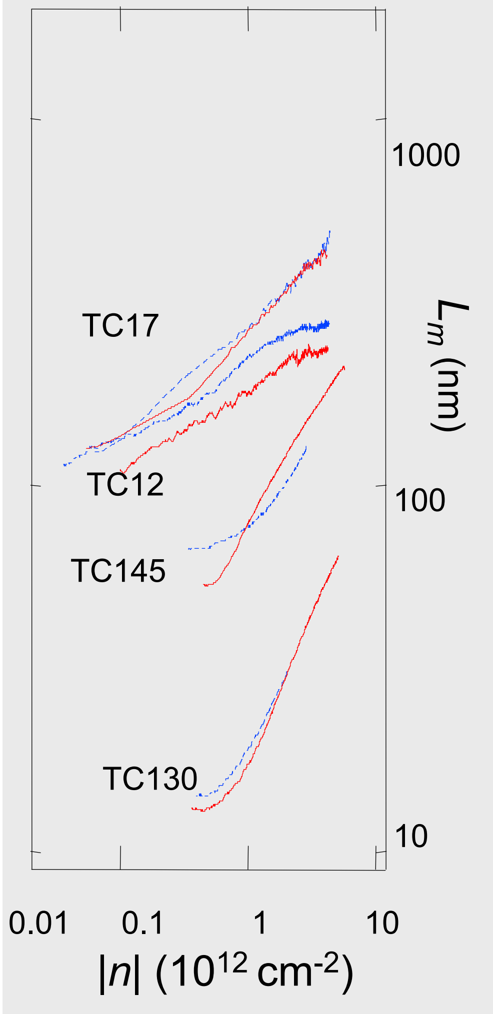
GaAs HEMT



Graphene Mobility



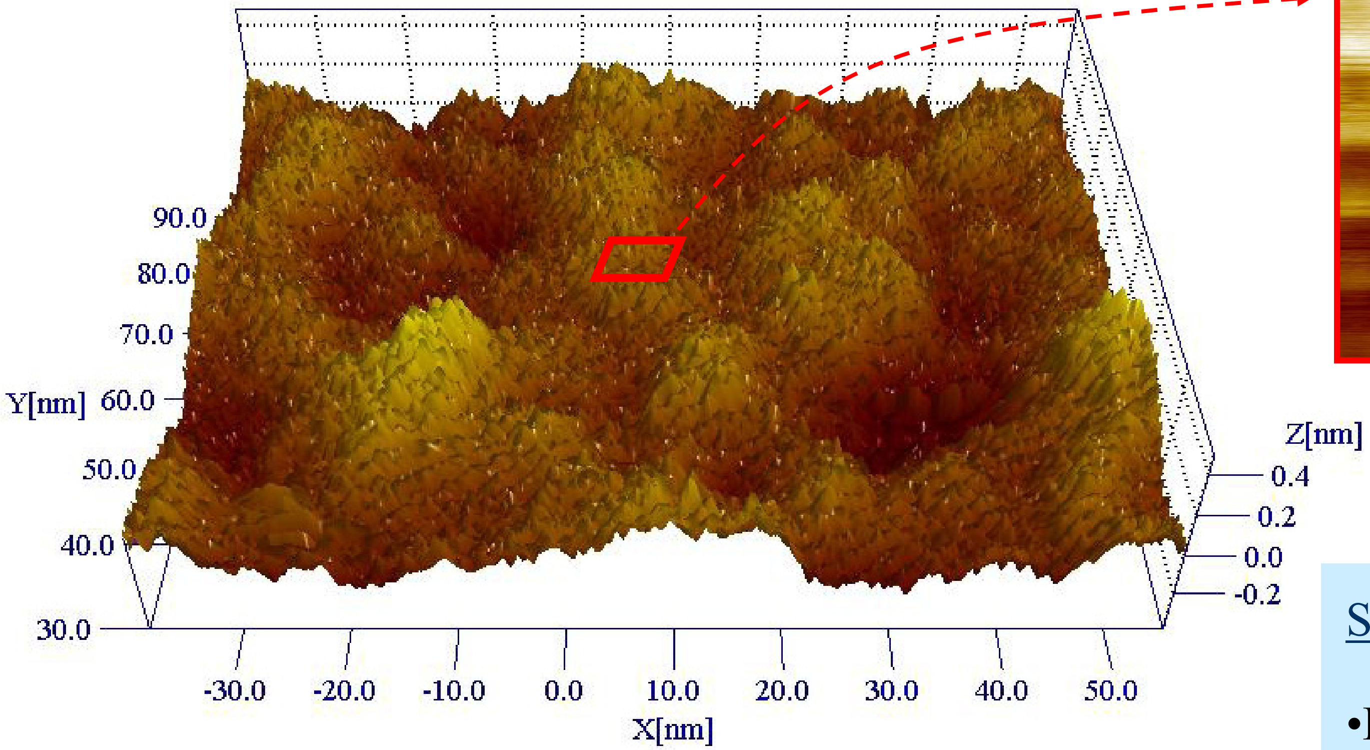
Mean free path



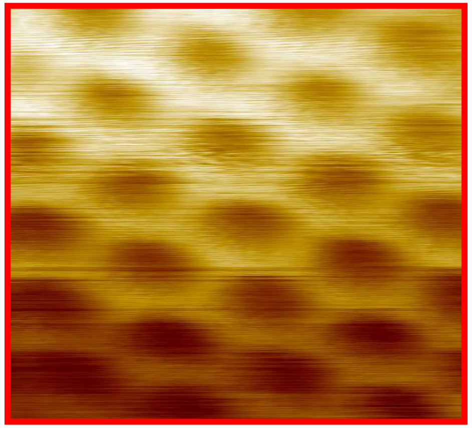
Tan et al. PLR (2007)

STM on Graphene

Ripples of graphene on a SiO_2 substrate



Atomic resolution



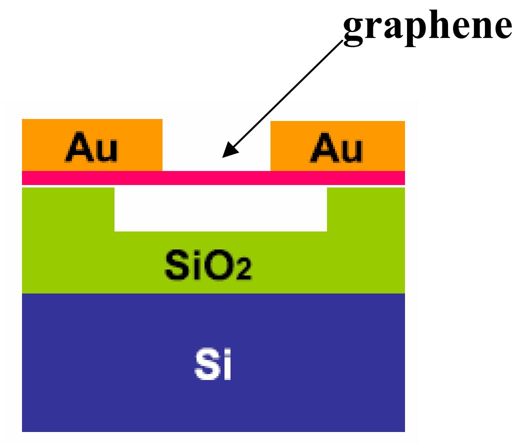
Elena Polyakova et al (Columbia Groups), PNAS (2007)

See also Meyer et al, Nature (2007) and Ishigami et al, Nano Letters (2007)

Scattering Mechanism?

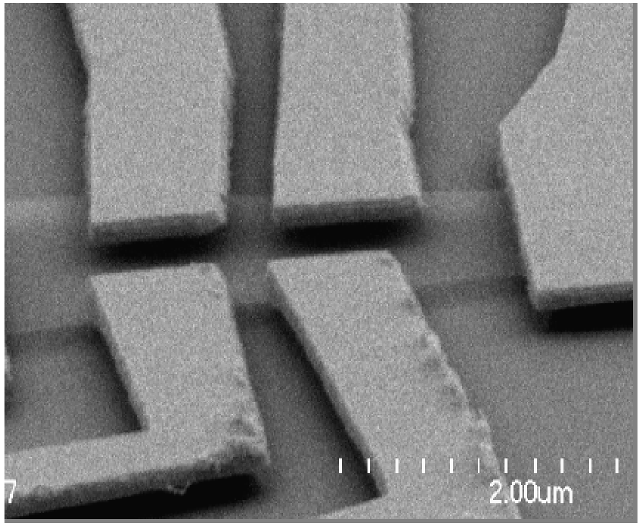
- Ripples
- Substrate (charge trap)
- Absorption
- Structural defects

Toward High Mobility: Suspending Samples



HF etching
-> critical pointing drying

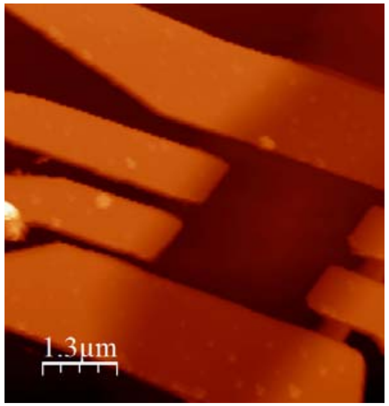
SEM image of suspended graphene

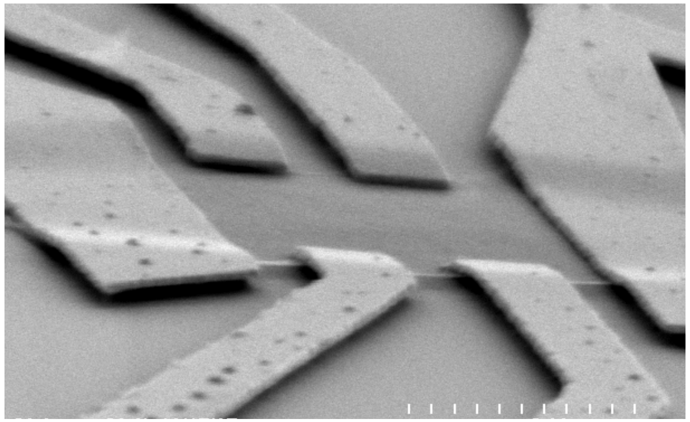


AFM image of suspended graphene

You should not apply to high gate voltage, otherwise…

Collapsed graphene devices…





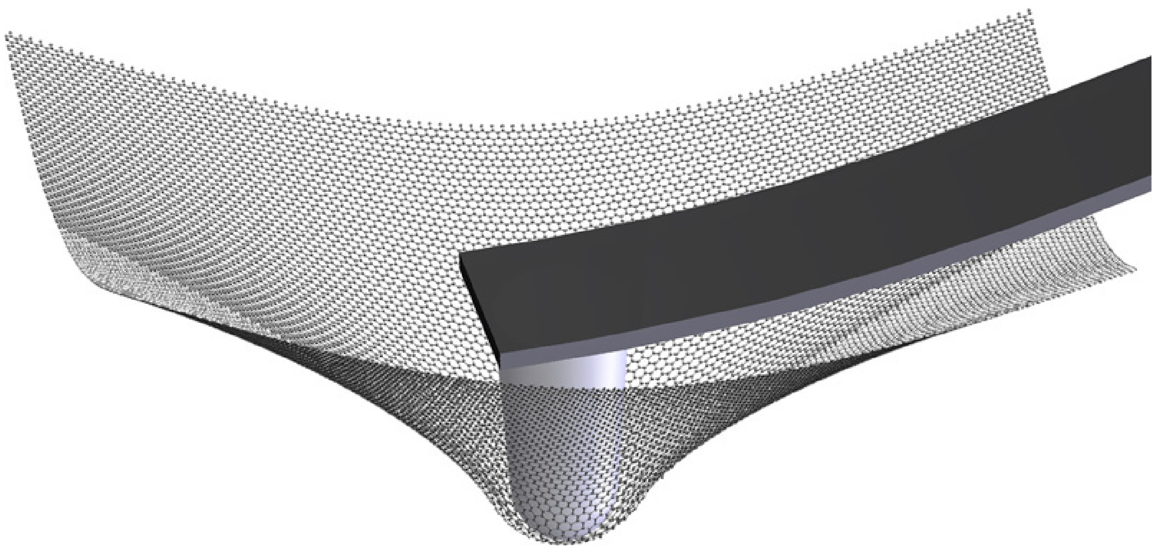
K. Bolotin et al., SSC (2008); similarly Du et al., Nat. Nanotech (2008)

www.sciencemag.org SCIENCE VOL 321 18 JULY 2008

Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene

Changgu Lee,[1,2] Xiaoding Wei,[1] Jeffrey W. Kysar,[1,3] James Hone[1,2,4]*

We measured the elastic properties and intrinsic breaking strength of free-standing monolayer graphene membranes by nanoindentation in an atomic force microscope. The force-displacement behavior is interpreted within a framework of nonlinear elastic stress-strain response, and yields second- and third-order elastic stiffnesses of 340 newtons per meter (N m^{-1}) and −690 N m^{-1}, respectively. The breaking strength is 42 N m^{-1} and represents the intrinsic strength of a defect-free sheet. These quantities correspond to a Young's modulus of E = 1.0 terapascals, third-order elastic stiffness of D = −2.0 terapascals, and intrinsic strength of σ_{int} = 130 gigapascals for bulk graphite. These experiments establish graphene as the strongest material ever measured, and show that atomically perfect nanoscale materials can be mechanically tested to deformations well beyond the linear regime.



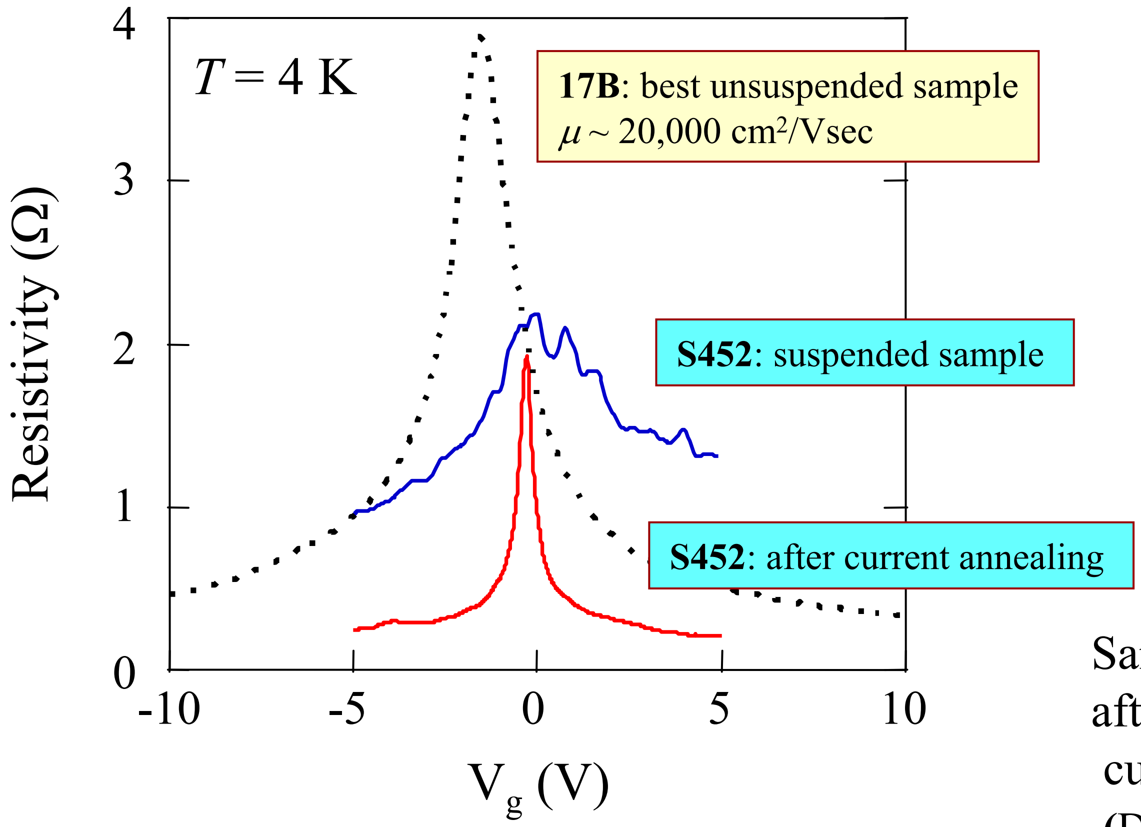
Young's modulus

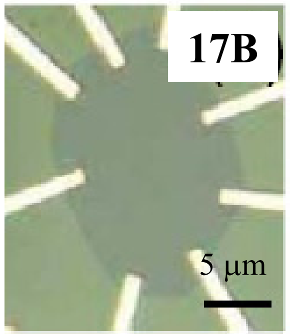
~ 1 TPa

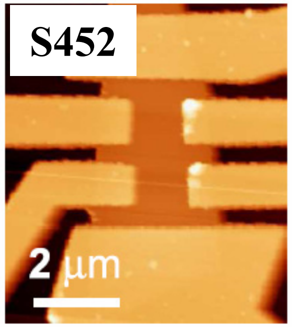
Critical Strain

~ 25 %

Cleaning Graphene Surfaces: Annealing







Sample quality can be improved after self-heating annealing:
current density ~ 10^8 A/cm^2
(Developed by Bachtold et al, APL (2007))

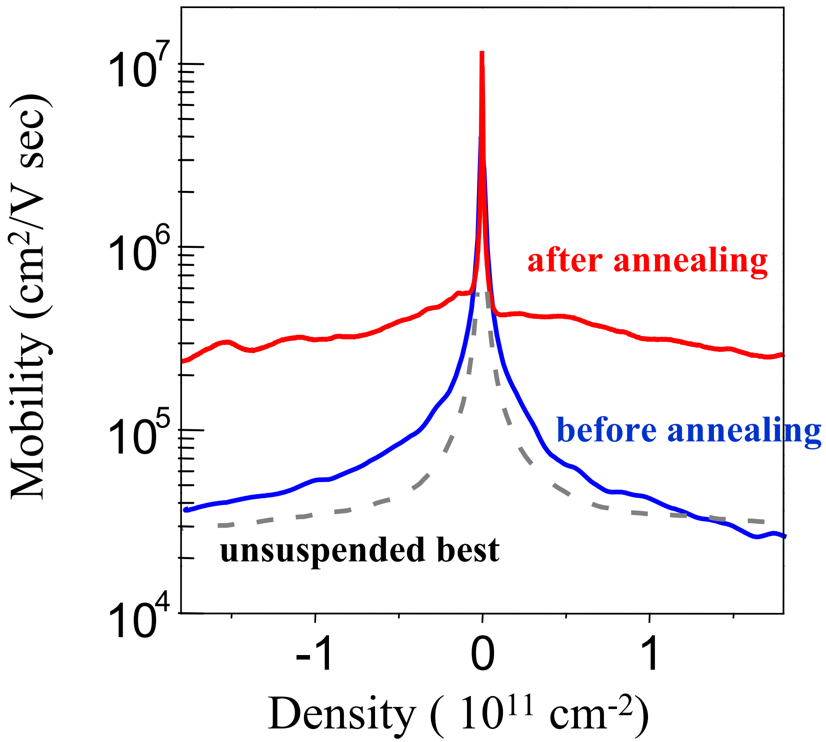
Unsuspended (300 nm SiO_2): $C_g = 115$ aF/μm^2

Suspended (~150 nm SiO_2): $C_g \sim 50$ aF/μm^2

Characteristics of Suspended Samples: Mobility

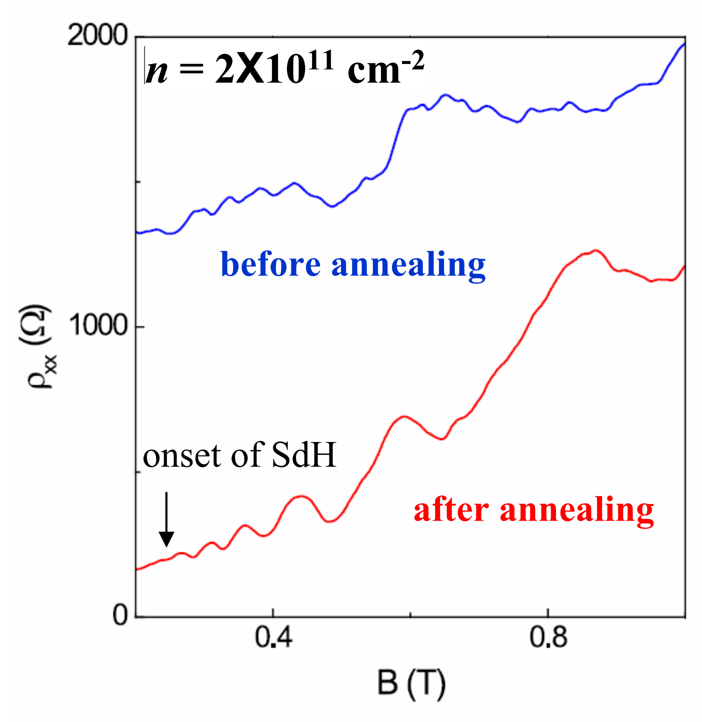
$\mu = \sigma / en$

Drude Mobility



$\mu \sim 250{,}000$ cm^2/Vs
@ 2.5X10^{11} cm^{-2}

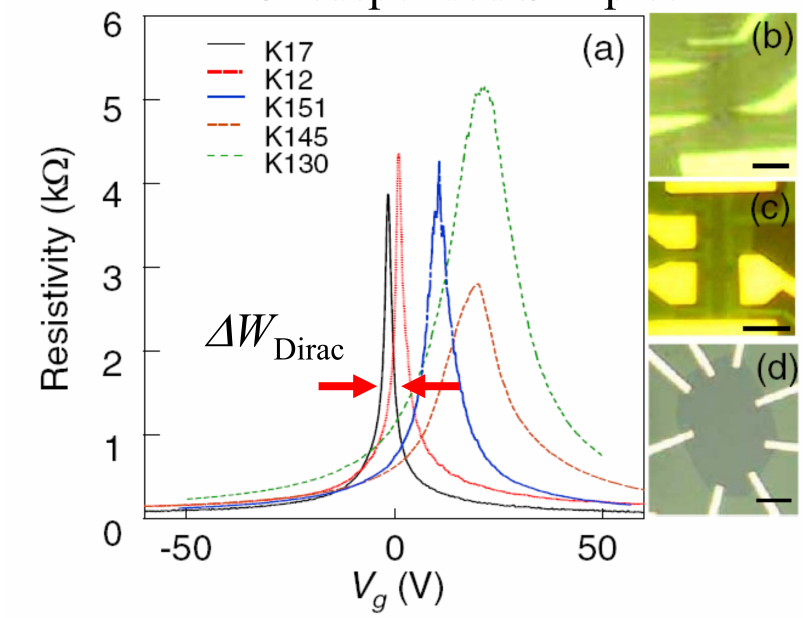
SdH Oscillations



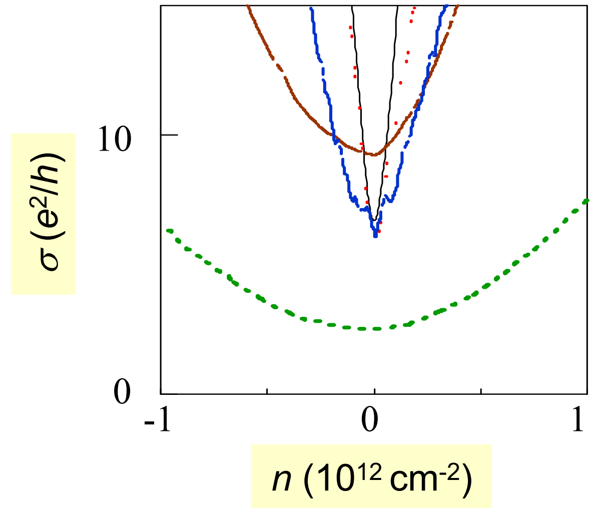
$\mu > 1/B_{SdH} \sim 100{,}000$ cm^2/Vs

Charge Inhomogeneity near the Charge Neutrality Point: Unsuspended samples

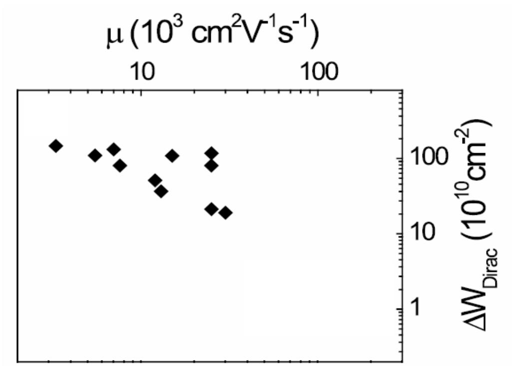
Unsuspended Samples



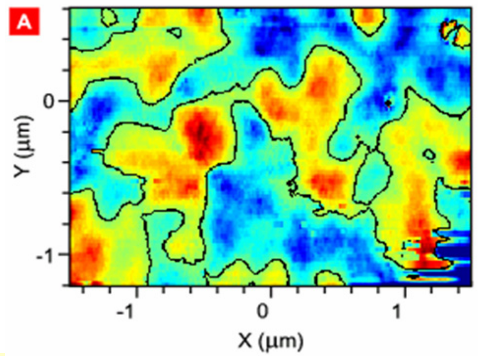
Conductivity near zero density



Mobility
Versus
Inhomogeneirty
(unsuspended)



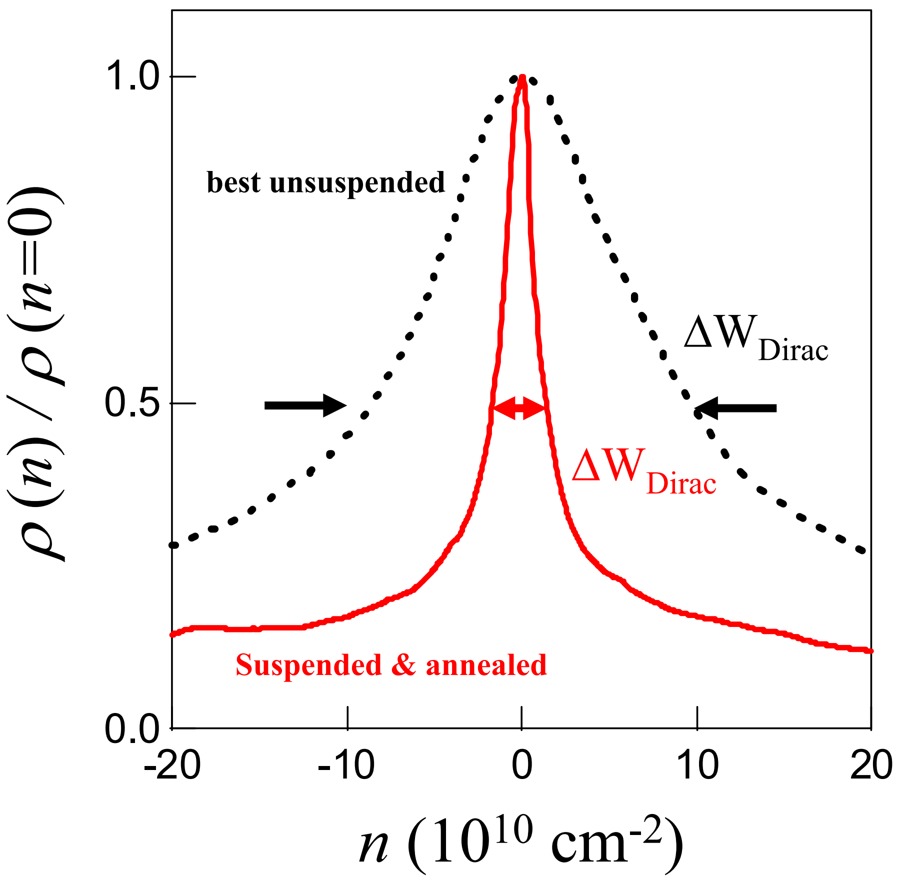
Charge inhomogeneity near zero density



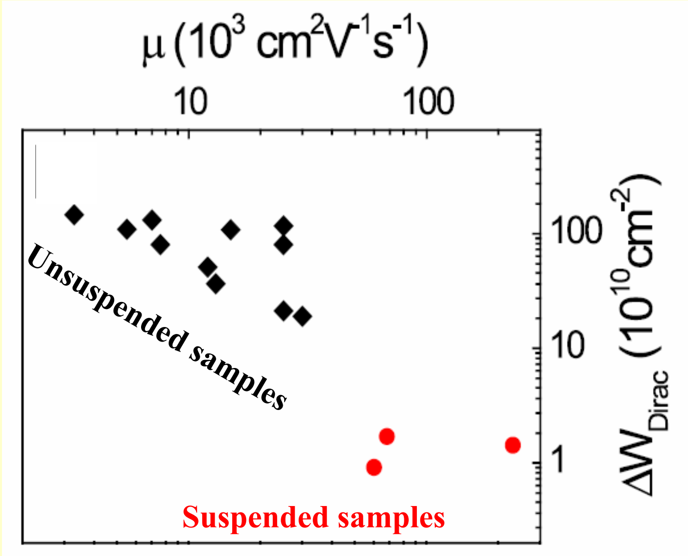
Martin *et al.* Nature Phys. (2008)

Toward High Mobility Samples

Normalized Resistivity

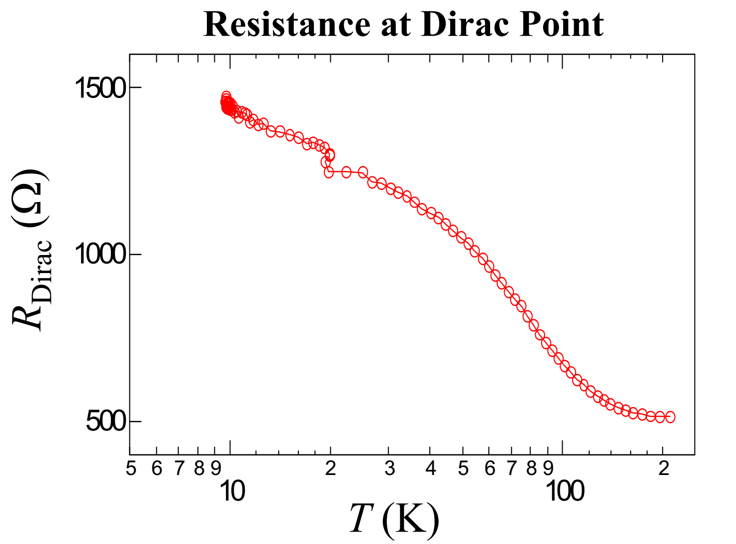


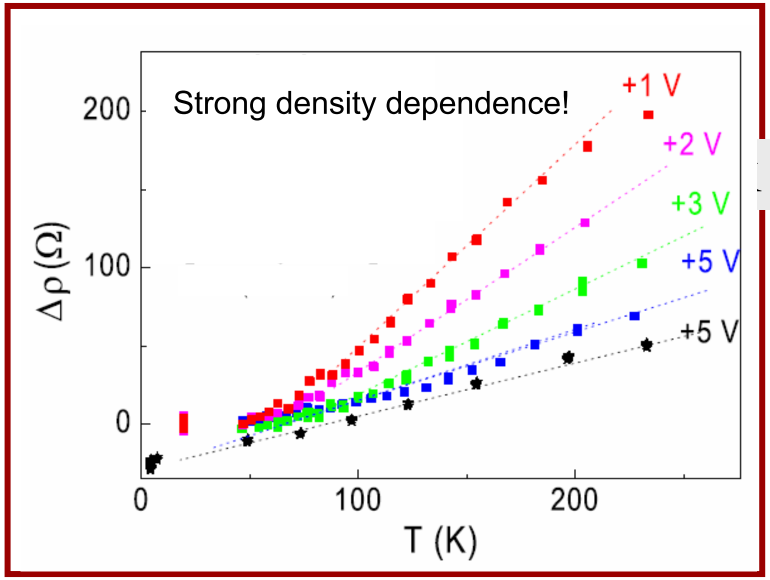
Mobility VS. Inhomogeneirty



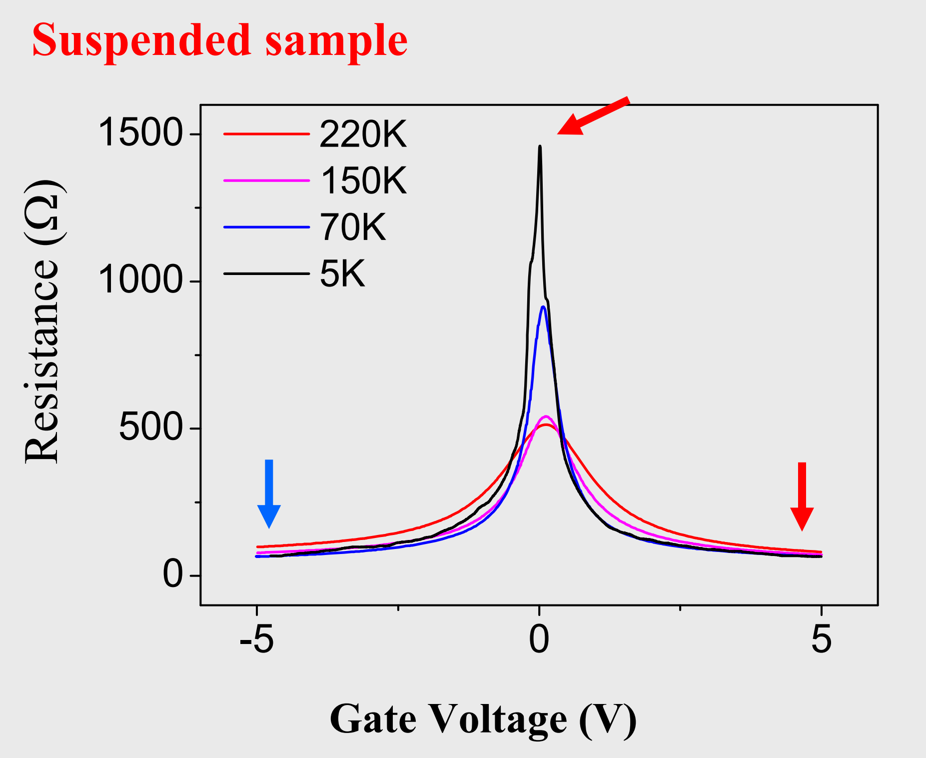
Density Inhomogeneity < 10^{10} cm^{-2} is possible!

Strong Temperature Dependence in Suspended Samples





K. Bolotin, K. Sikes, J. Hone, H. Stormer and P. Kim, PRL in press

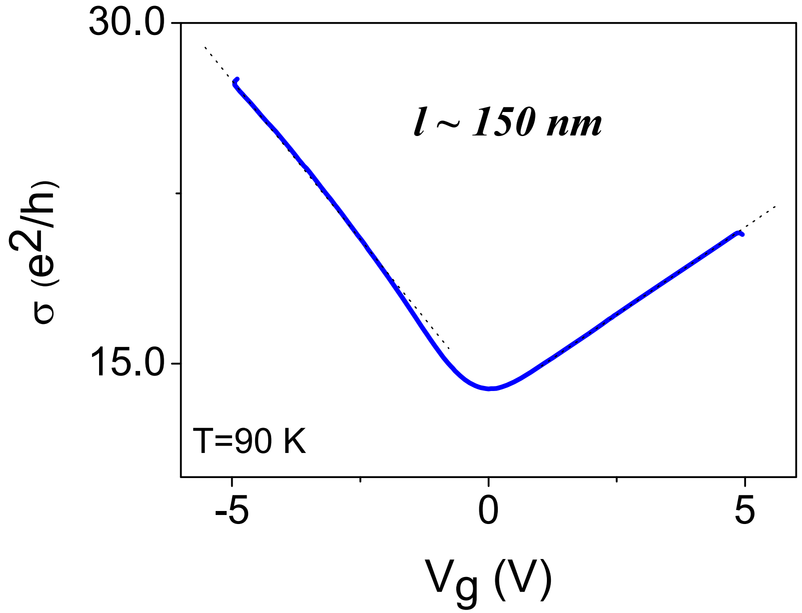


Theory estimates dR/dT ~ 0.4 Ω/K,
assuming acoustic phonons and electrons
Vasko & Ryzhii PRB (2007)

Room Temperature mobility > 100,000 $cm^2/Vsec$

Ballistic Transport in Suspended Samples

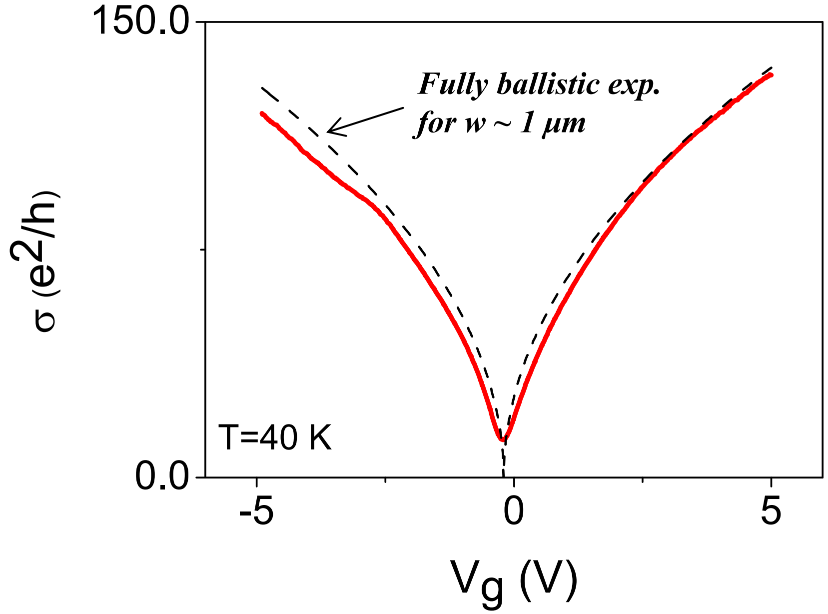
before current annealing



- Mean free path < sample size
- $\sigma(n) \sim n$, Coulomb scatterers dominated diffusive transport

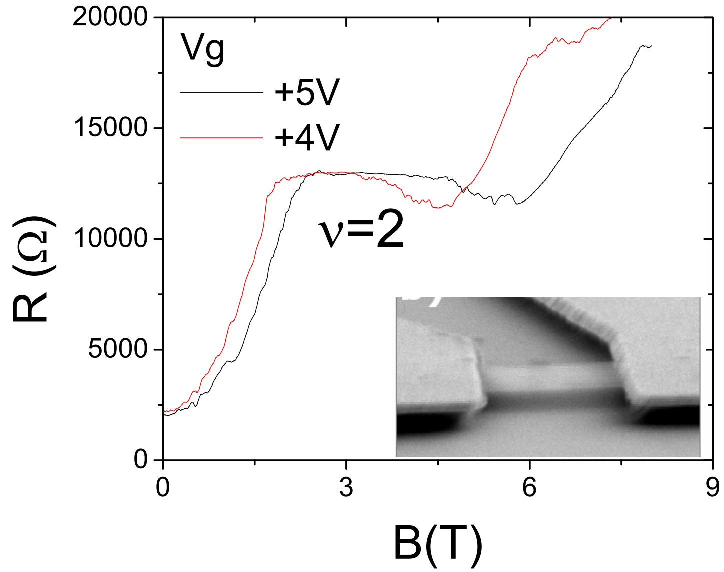
Similar results reported Du *et al*., Nat. Nanotech (2008)

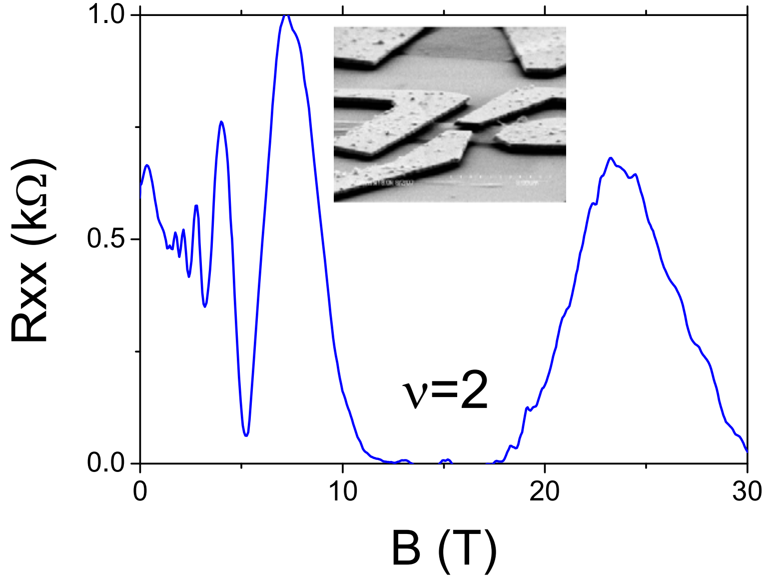
after current annealing



- Mean free path ~ sample size
- Conductance ~ $4e^2/h \times$ *(number of modes)*
- $\sigma(n) \sim \sqrt{n}$, as expected for ballistic conductor
- Near ballistic transport at high density

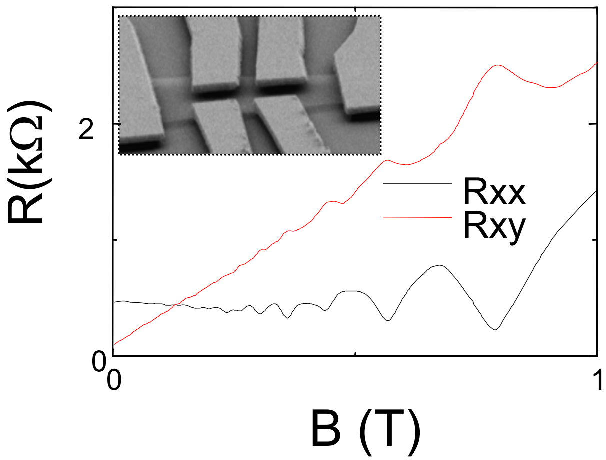
QHE in suspended sample

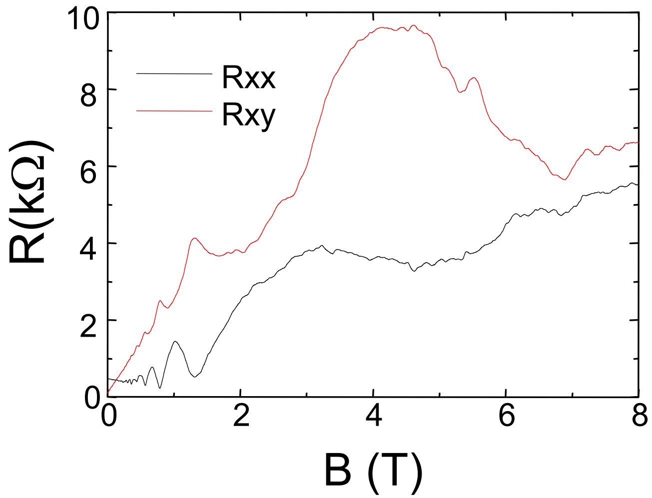




Typical samples:

Low Field



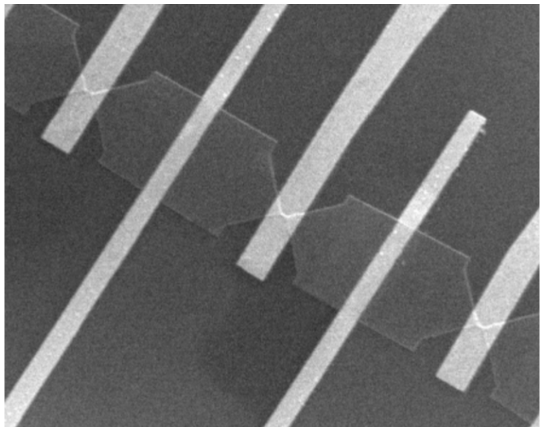


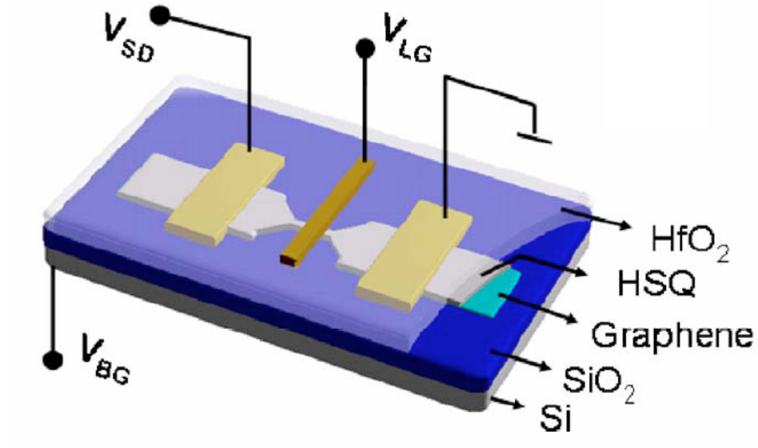
Graphene Device Fabrication

- Developing Graphene Nanostructure Fabrication Process

Contacts:	Graphene patterning:	Graphene etching:	Local gates:
PMMA	HSQ	Oxygen plasma	ALD HfO_2
EBL	EBL		EBL
Evaporation	Development		Evaporation

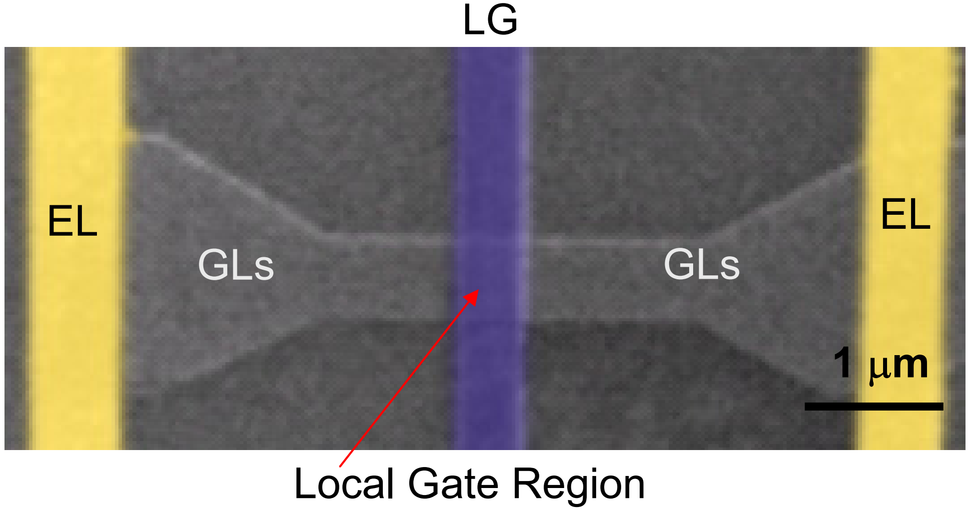
- Graphene device structure with local gate control

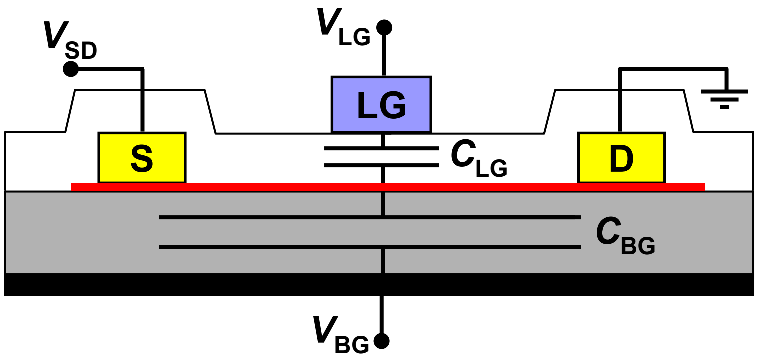


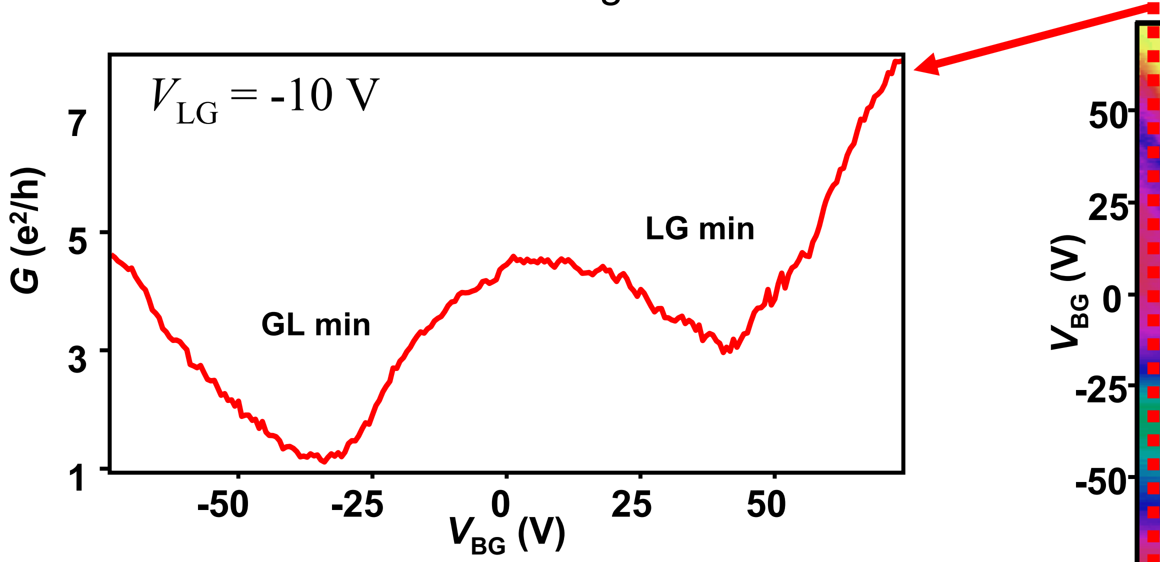


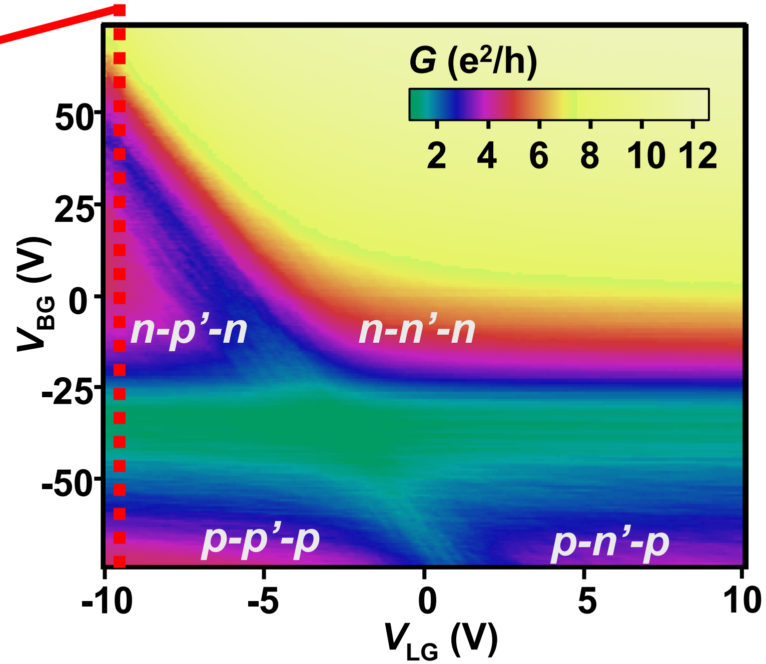
Oezyilmaz, Jarrilo-Herrero and Kim APL (2007)

Graphene *bipolar hetero*junctions



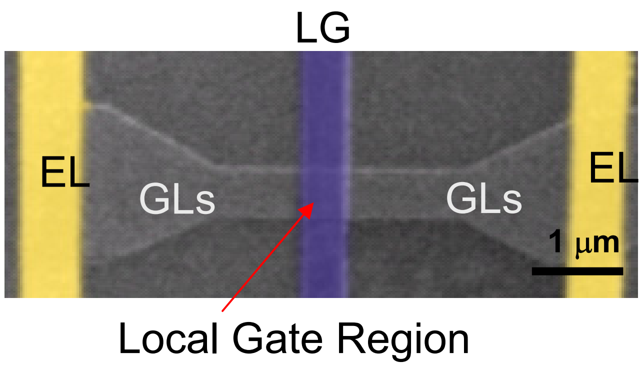


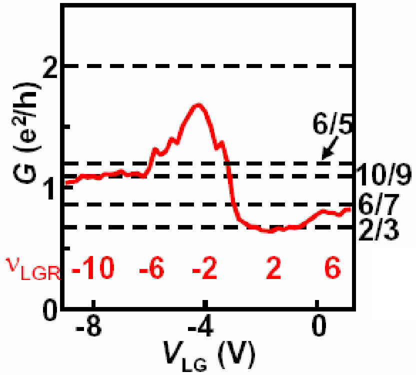


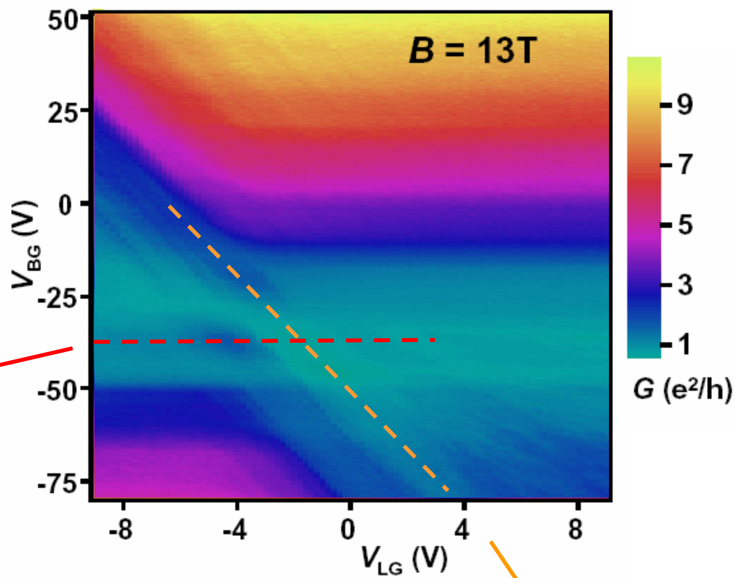


Oezyilmaz, Jarrilo-Herrero and Kim PRL (2007)
Related work by Huard *et al.* PRL (2007)

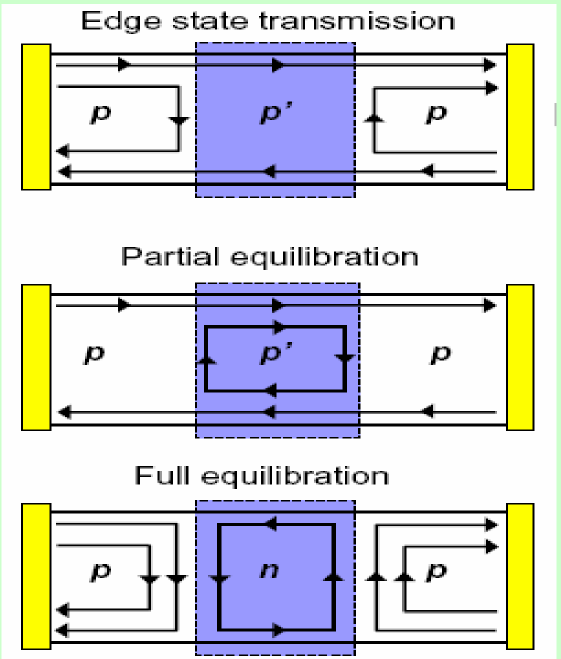
Graphene Quantum Hall Edge State Conduction

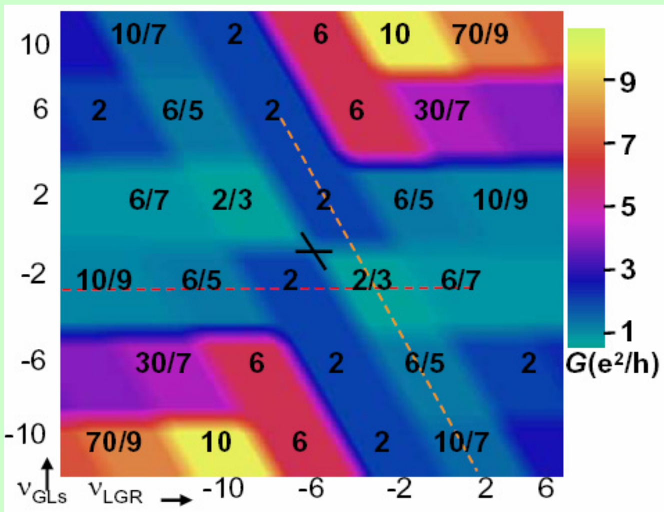


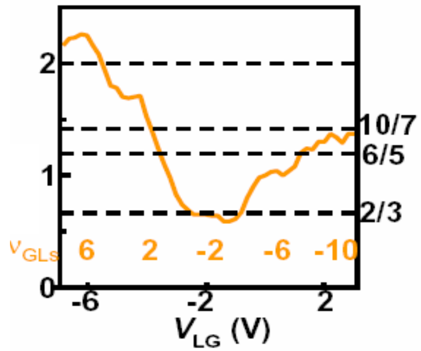




simple model (following Haug *et al*)





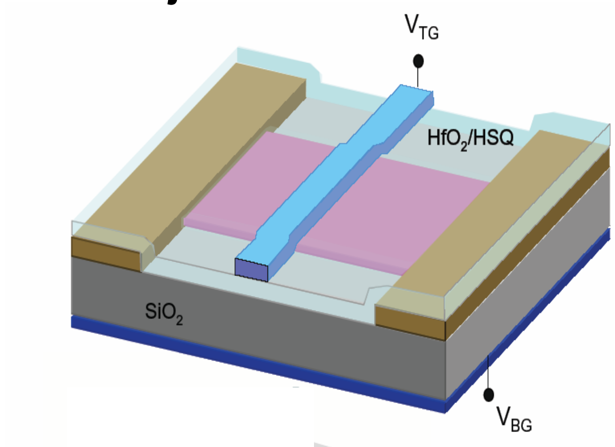


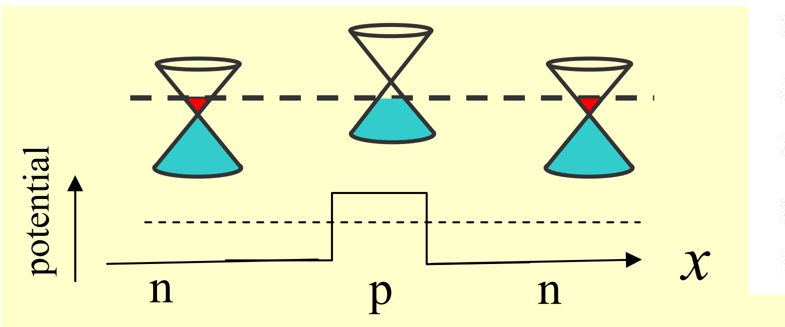
Oezyilmaz, et al., PRL (2007) See also Related work by Williams *et al.* Science (2007)

Ballistic Quantum Transport in Graphene Heterojunction

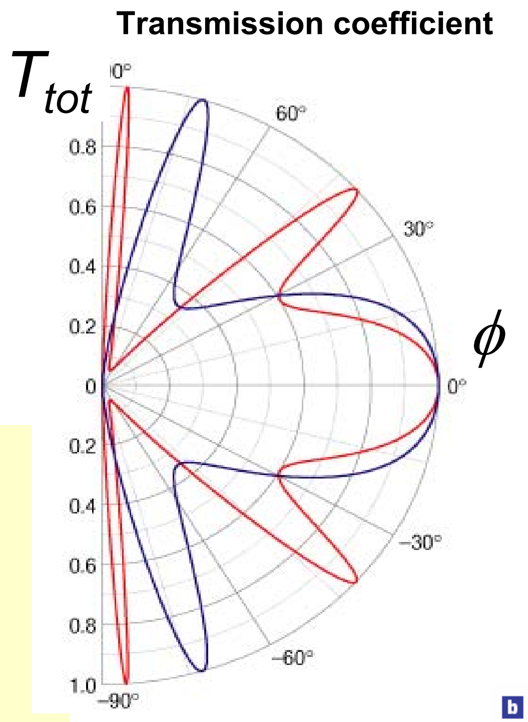
Novoselov et al, Nat. Phys (2006)

Graphene NPN junctions





Klein Tunneling



n_p=1x10^{12} cm^2

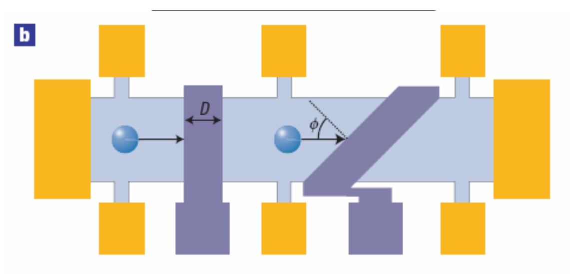
n_p=3x10^{12} cm^2

n_n=0.5x10^{12} cm^2

Collimation:
(resonance)

$k_{2x} = \pi n/L$

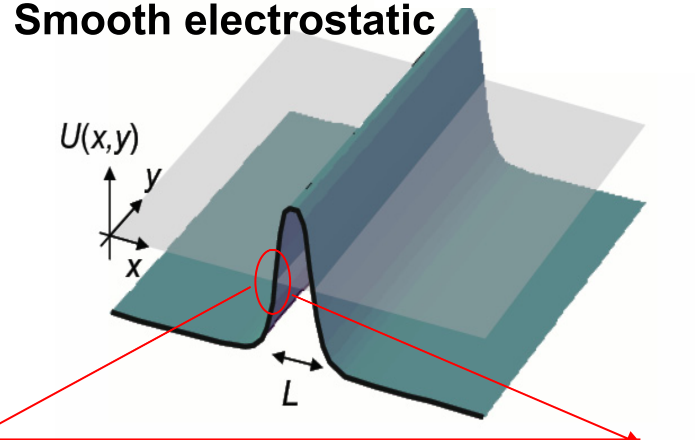
Perfect transmission



Realistic Graphene Heterojunction

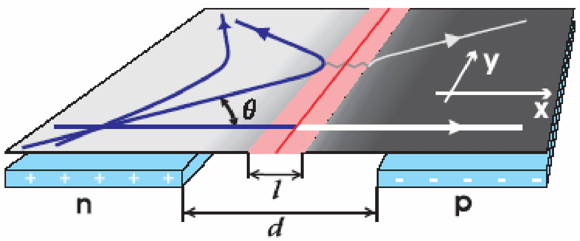
Mean free path < 100 nm

Smooth electrostatic



$n \sim 10^{12}\ cm^{-2}$
$\lambda_F \sim 30$ nm
$d_{dielectric} \sim 20$ nm
$L \sim 100$ nm

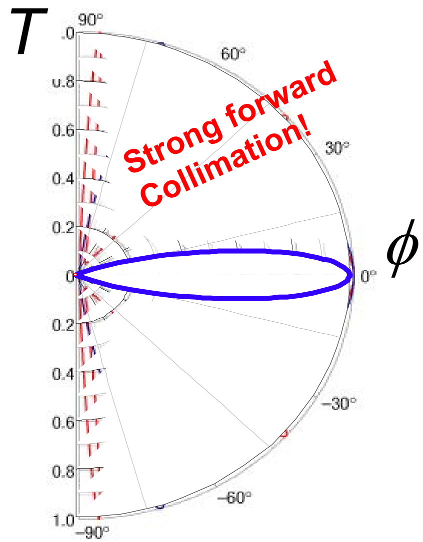
Tunneling through smooth pn junction



Cheianov and Fal'ko (2006)

Zhang and Fogler (2008)

transmission



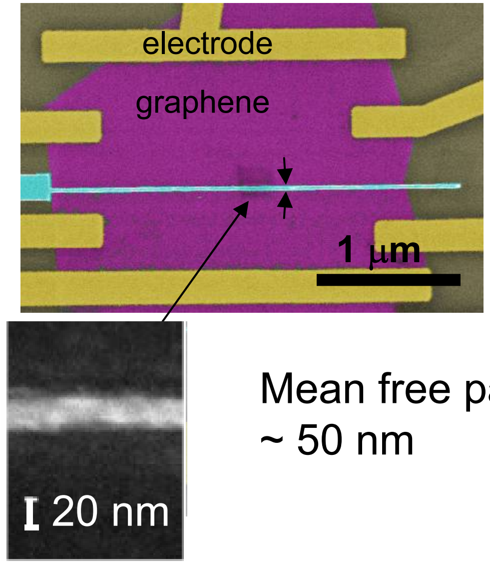
Tunneling through Classically Forbidden regime

$$T(\theta) = e^{-\pi (k_F d)\sin^2\theta}$$

Requirements for Ballistic pn junctions

- **Long Mean free path -> Ballistic conduction**
- **Large electric field -> Small *d* -> promote resonance**

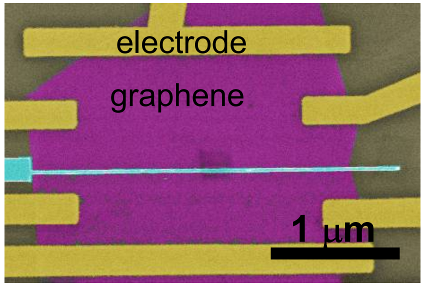
SEM image of device



Mean free path ~ 50 nm

Transport Ballistic Graphene Heterojunction

Young and Kim (2008)



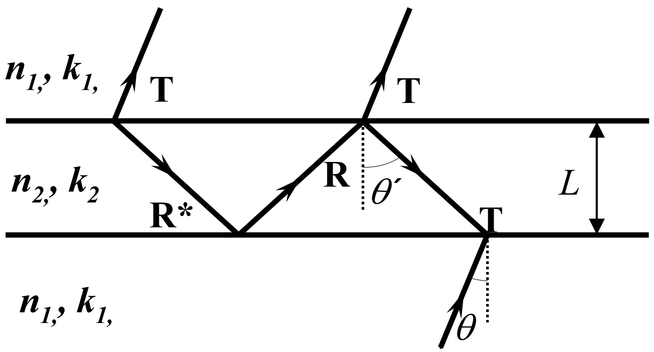
PN junction resistance

$$R = (\pi/2)(h/e^2)\sqrt{\hbar v \,/\, e|F_{pn}|}$$

Cheianov and Fal'ko (2006)

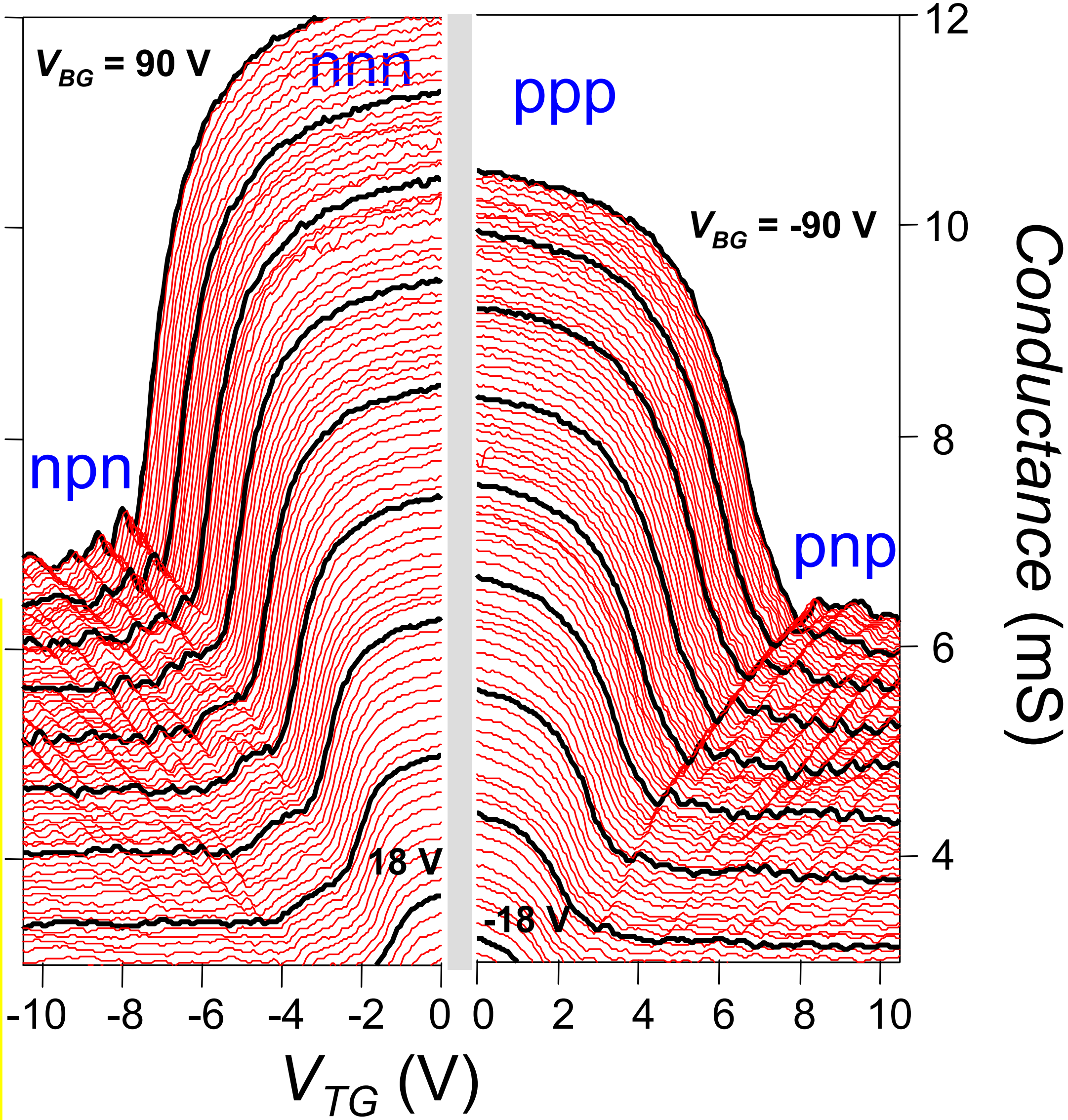
See also Shavchenko et al and Goldhaber-Gordon's recent preprint

Conductance Oscillation: Fabry-Perot



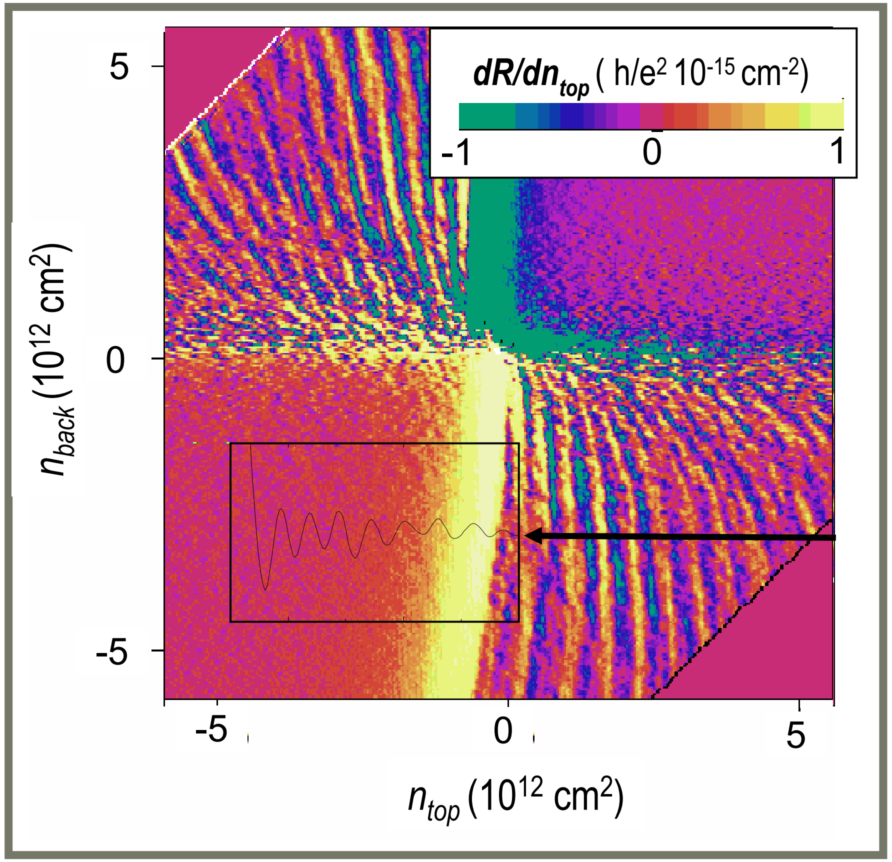
$k_1/k_2 = \sin\theta' / \sin\theta$

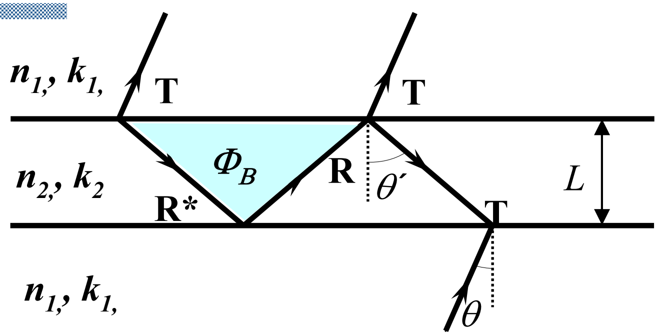
$\Delta\phi = 2L/\cos\theta'$



Quantum Oscillations in Ballistic Graphene Heterojunction

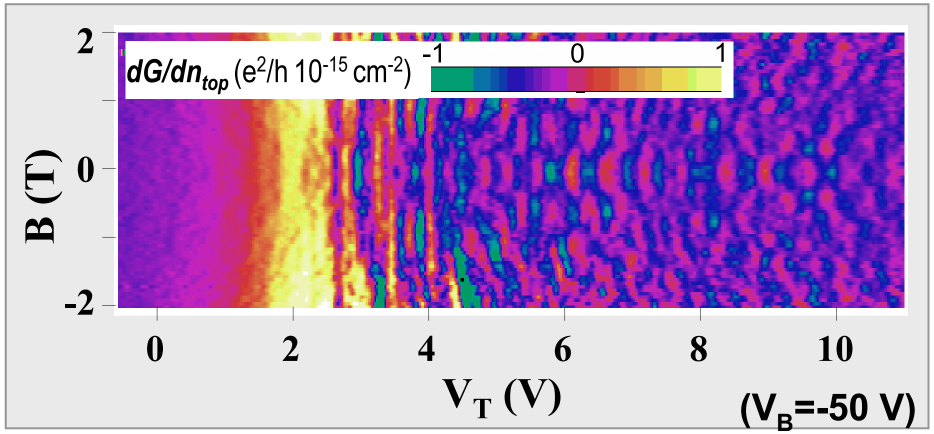
Resistance Oscillations





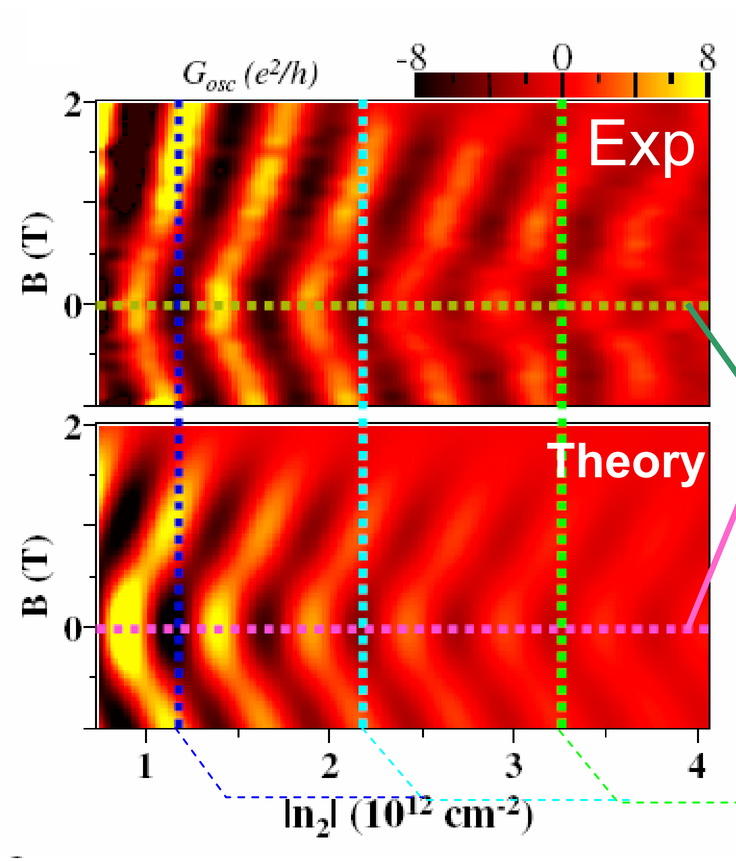
Magnetoresistance Oscillations (B≠0)

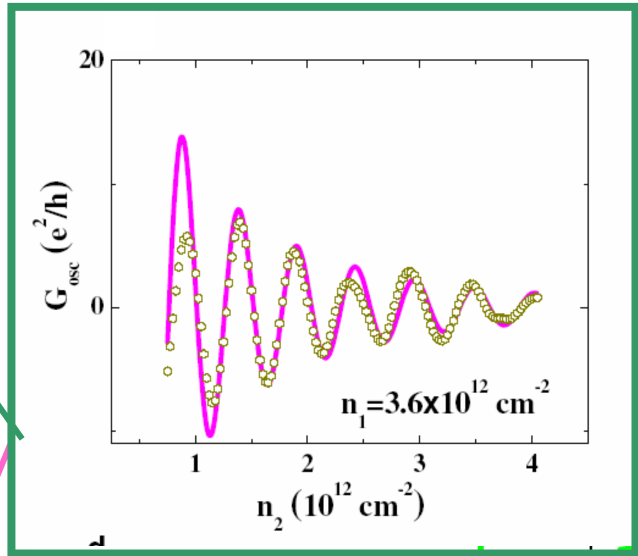
Aharonov-Bohm phase: $\Phi_B = B\,L^2 \sin\theta' / \cos\theta'$



$$G_{osc} = e^{-2L/l_{LGR}} \frac{8e^2 W k_1}{h} \int \frac{d\theta}{2\pi} \left|T(\theta)\right|^2 \left|R(\theta)\right|^2 \cos\left(2Lk_2(1+\theta^2/2)\right)$$

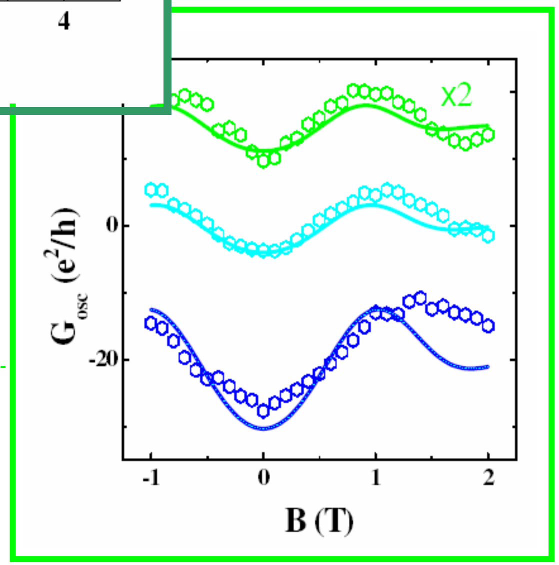
Resonant Magneto-Oscillations in Graphene Heterojunctions





- **Ballistic pn junction**
- **Collimation**

See also Shytoy et al., arXiv:0808.0488

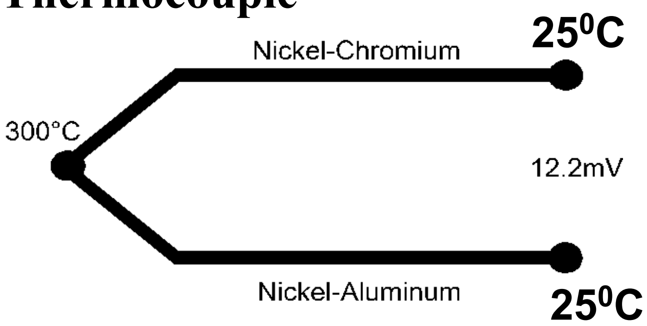


Two fitting parameters: l_{LGR} = 27 nm; l_{GL}= 50 nm

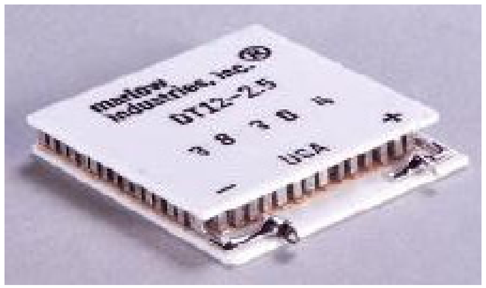
$$G_{osc} = e^{-2L/l_{LGR}} \frac{8e^2 W k_1}{h} \int \frac{d\theta}{2\pi} \left|T(\theta)\right|^2 \left|R(\theta)\right|^2 \cos\left(2Lk_2(1+\theta^2/2) + \frac{eBL(L+l_{GL})}{\hbar}\theta\right)$$

Thermo Electricity

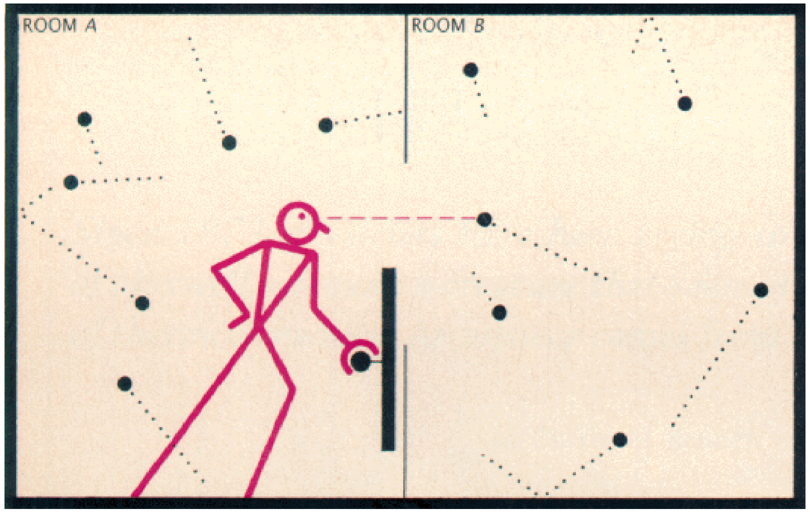
Thermocouple



- **Thermoelectric (Peltier) cooler:**



Entropy Flow with Charge



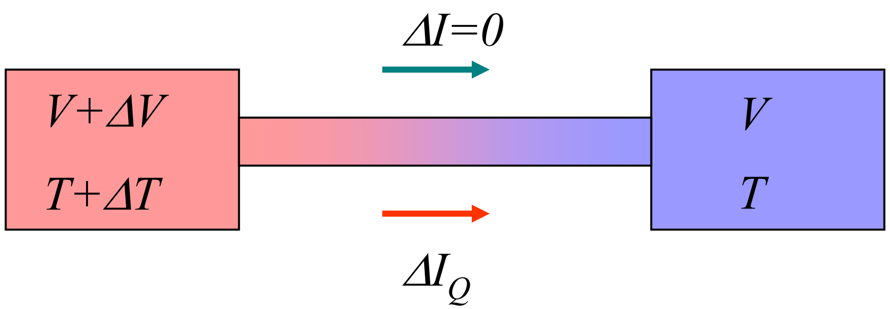
Maxwell's demon

Thermopower and Mott Formula

Thermoelectric Power (TEP)

= Thermopower

= Seebeck Coefficient



$$S = -\left(\frac{\Delta V}{\Delta T}\right)_{\Delta I=0}$$

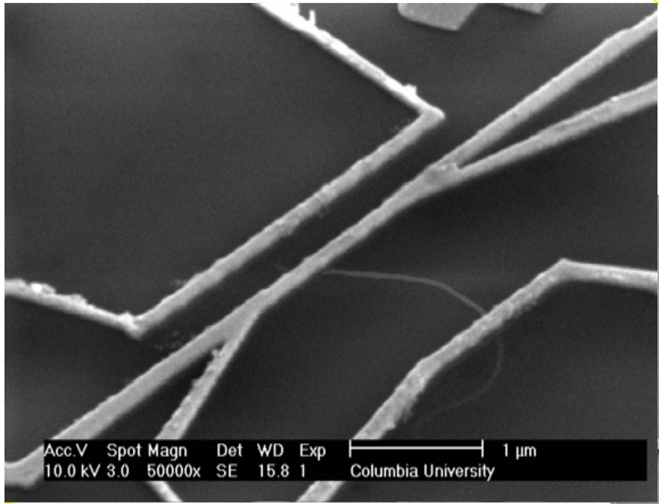
Microscopic theory (Boltzman transport theory, and etc.)

Mott's formula $$S_d = \frac{-\pi^2 k_B{}^2 T}{3|e|}\frac{1}{\sigma}\frac{d\sigma}{dE}\bigg|_{E_f}$$

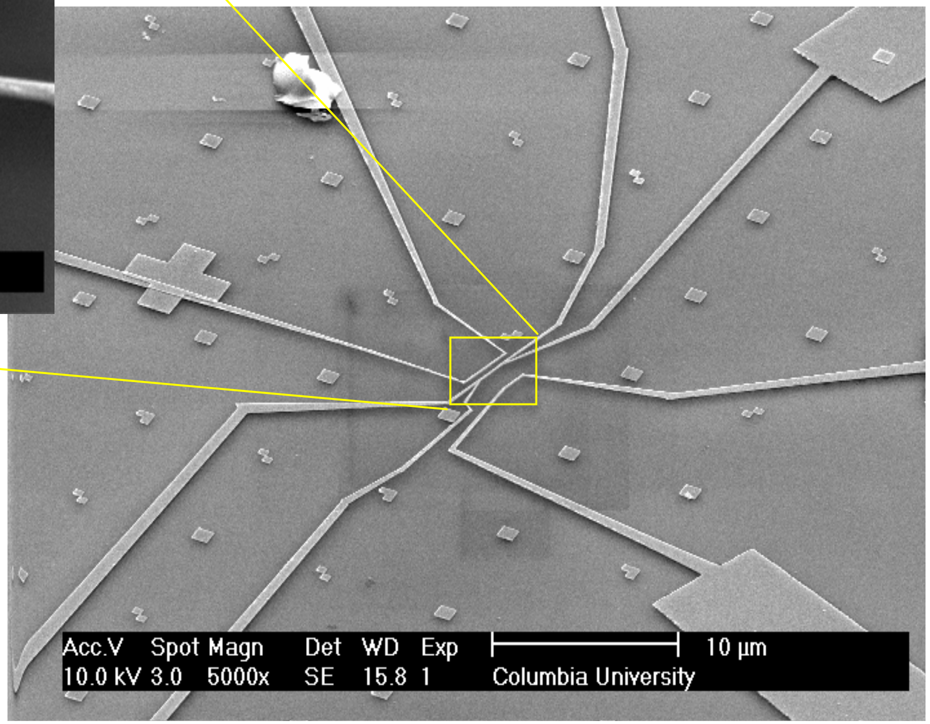
σ: electric conductance

Mesoscopic Thermopower measurement of Nanotube

Microfabricated devices for electric and thermal transport

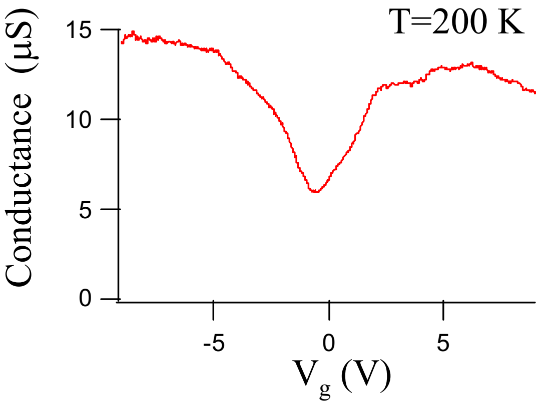


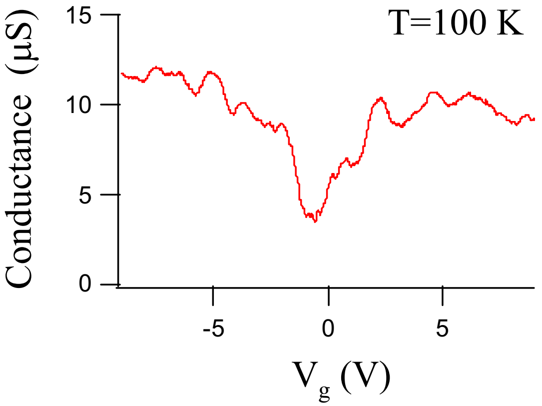
A device with CVD grown SWNT



J. P. Small, K. Peretz, and P. Kim, PRL (2003)

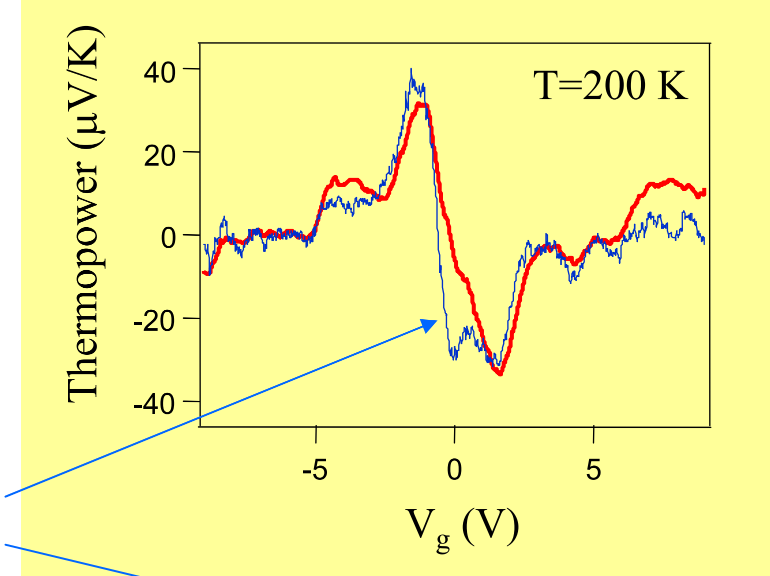
Metallic Nanotube: Mott Formula

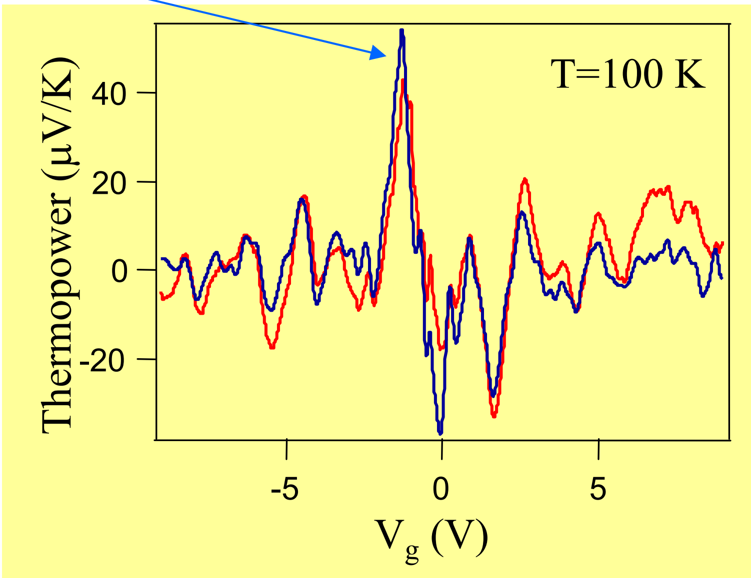


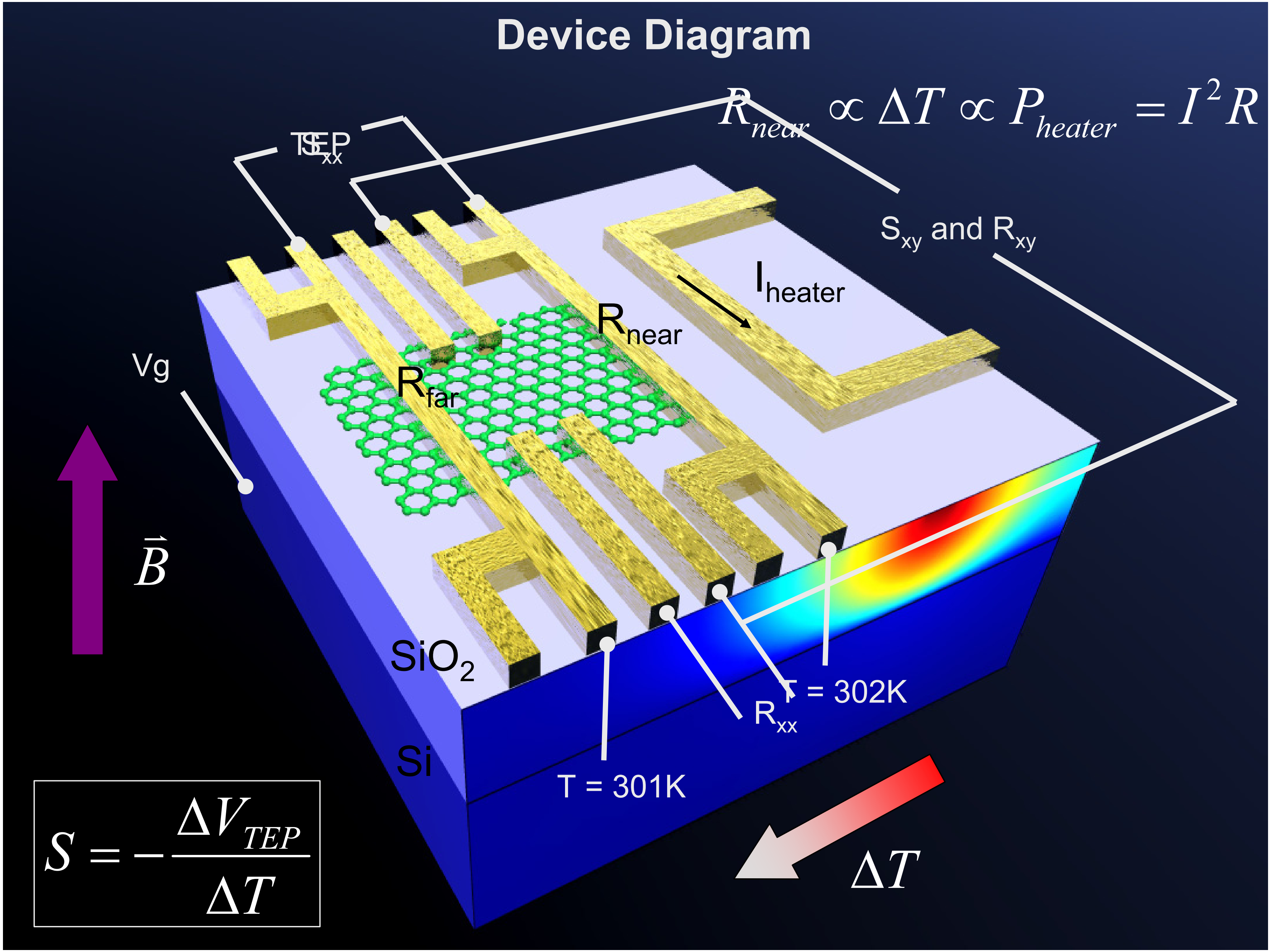


$$S_{Mott} = \frac{-\pi^2 k_B{}^2 T}{3|e|} \frac{1}{G} \left.\frac{dG}{dE}\right|_{E_f}$$

$$\Delta E_F = \frac{C_g}{DOS(E)} V_g$$

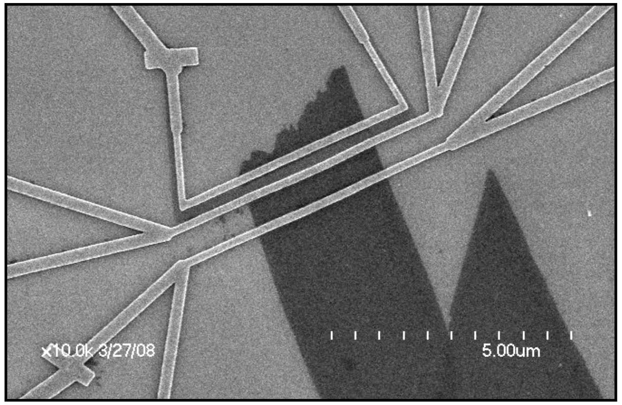




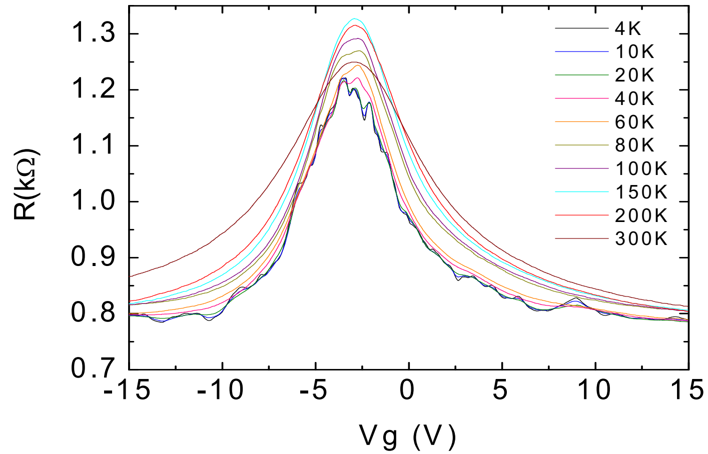

Device Diagram
$R_{near} \propto \Delta T \propto P_{heater} = I^2 R$
TEP
S_{xx}
S_{xy} and R_{xy}
I_{heater}
R_{near}
R_{far}
Vg
$\vec{B}$
SiO_2
Si
T = 301K
R_{xx}
T = 302K
ΔT
$S = -\frac{\Delta V_{TEP}}{\Delta T}$

Conductance and TEP (ThermoElectric power) in Graphene

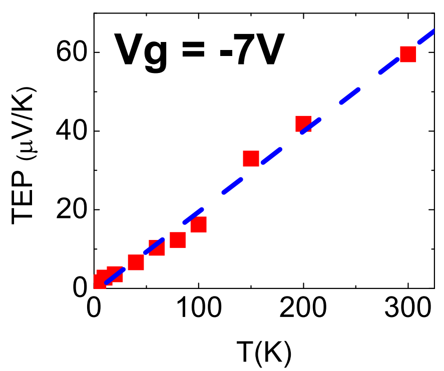
Graphene TEP device (SEM image)



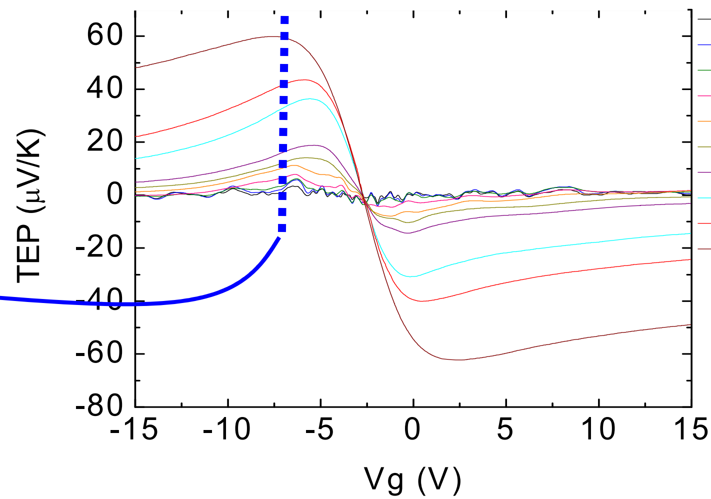
Temperature dependence of Resistance



Linear
T-dependence



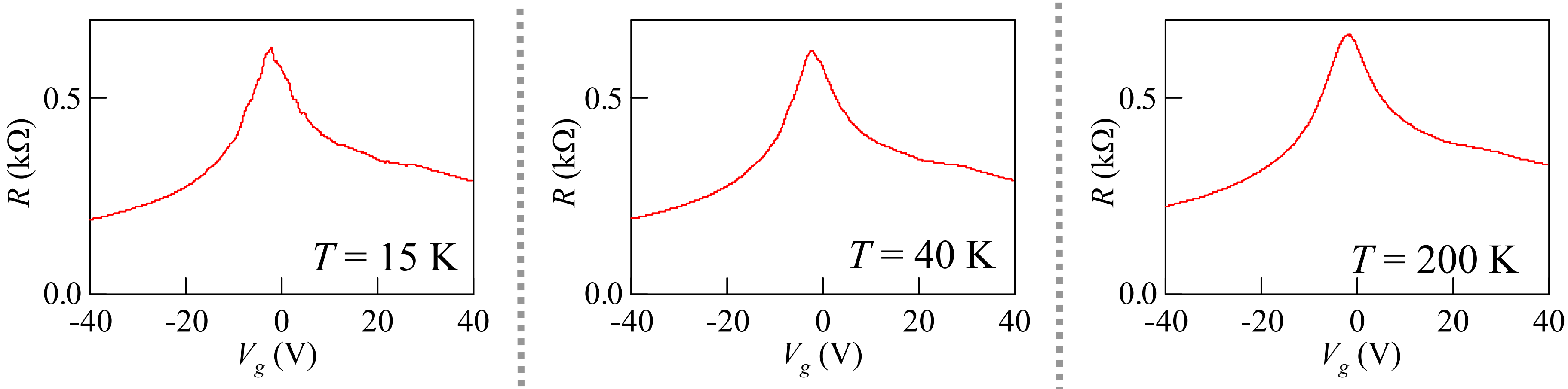
Temperature dependence of TEP



<u>Mott relation</u> :

$$S_{Mott} = \frac{\pi^2 k_B^2 T}{3|e|} \frac{d \ln R}{dE}\bigg|_{E_f}$$

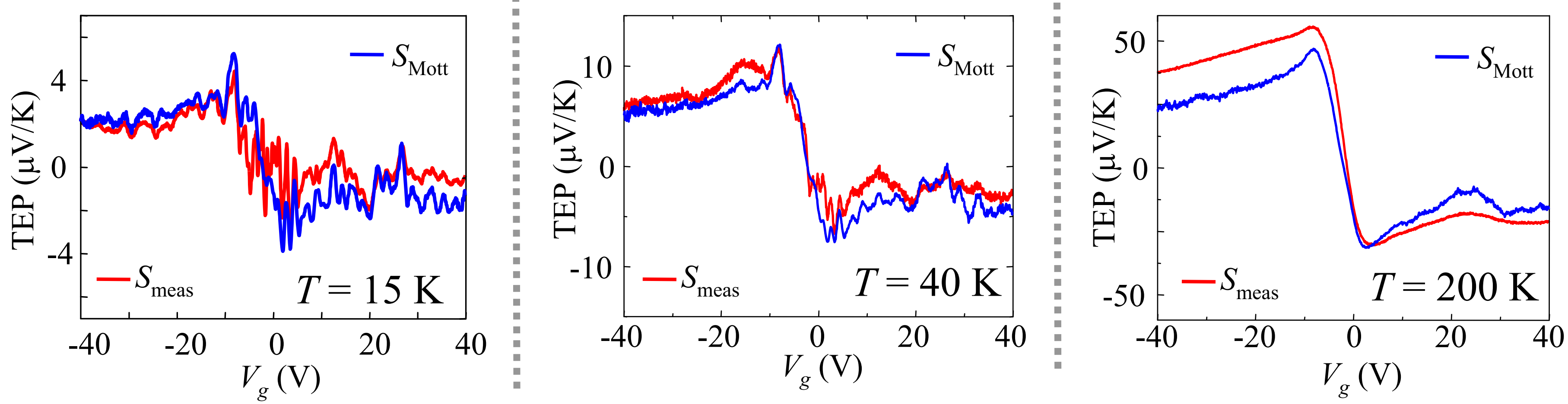
Quantitative Comparison with the Mott Formula



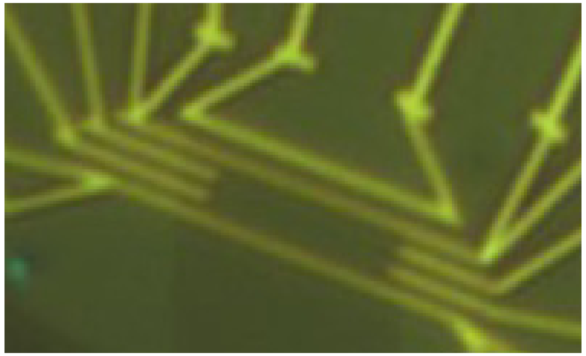
$$S_{Mott} = \frac{\pi^2 k_B{}^2 T}{3|e|} \frac{d \ln R}{dE}\bigg|_{E_f}$$

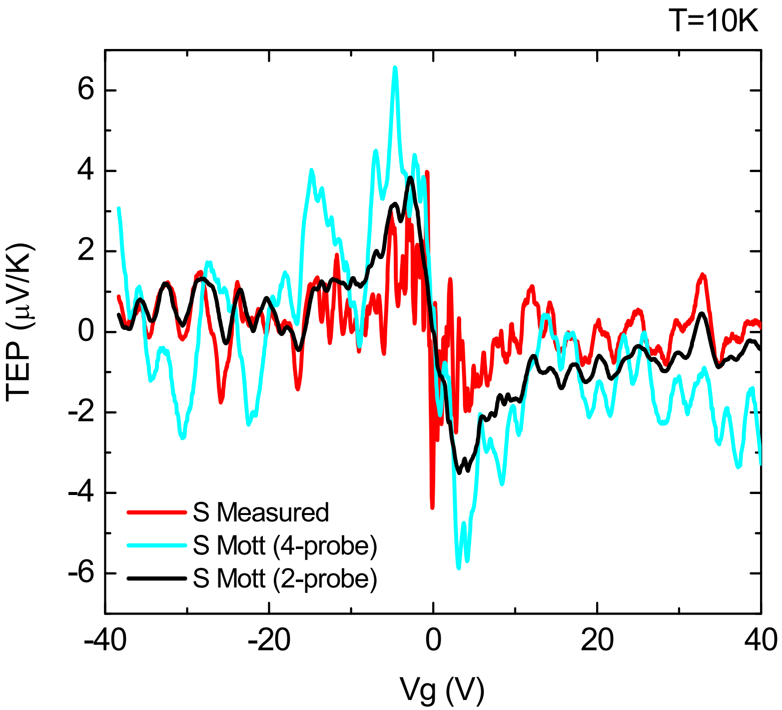
$$E_F = \hbar v_F \sqrt{\pi C_g \Delta V_g}$$

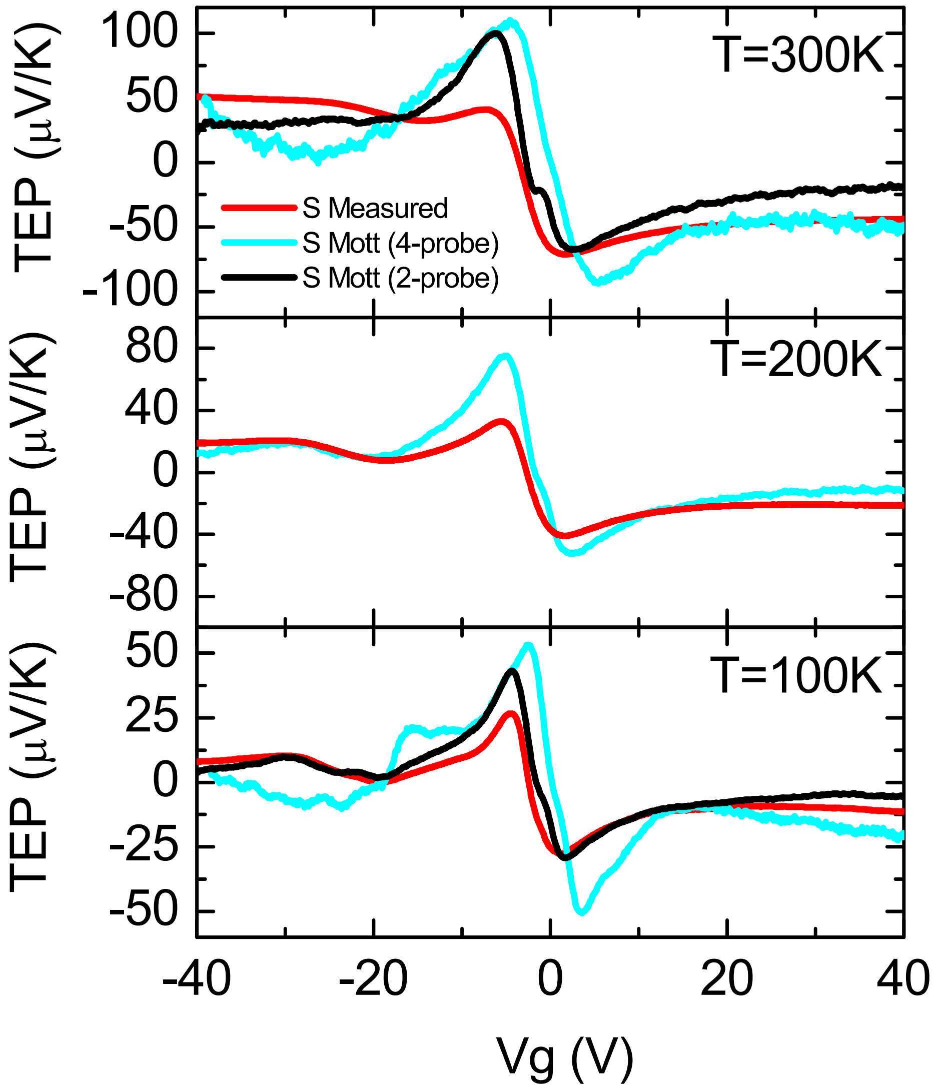
Mott relation holds!



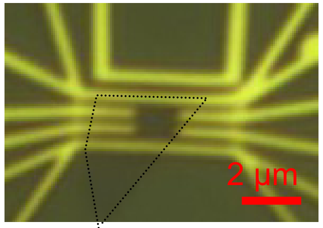
Two-Terminal Versus 4-Terminal Measurement







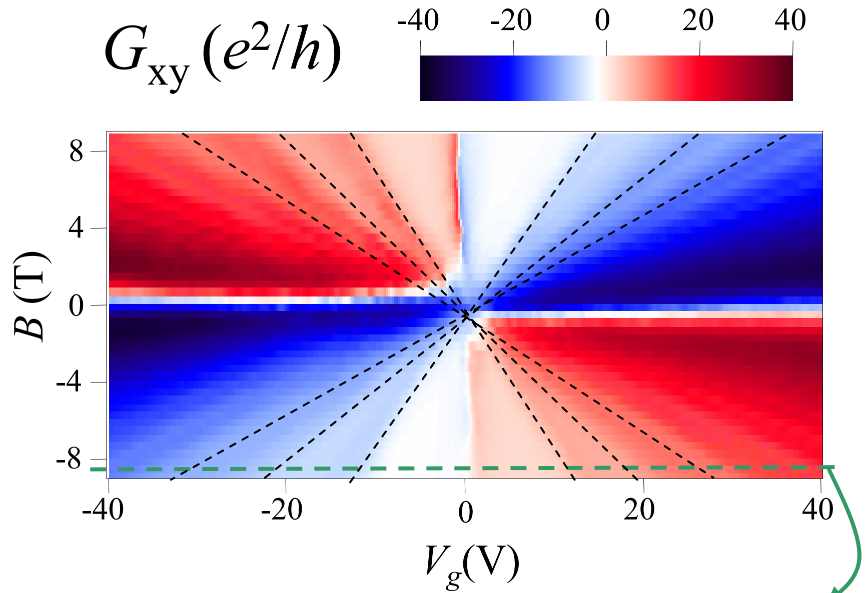
Magneto-Thermoelectric Measurement in Graphene

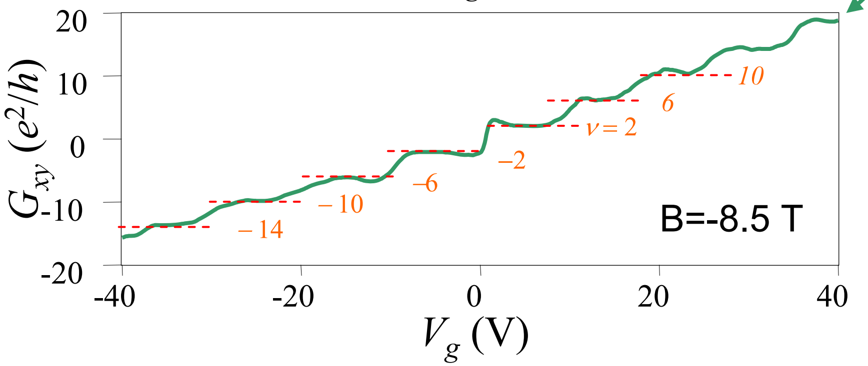


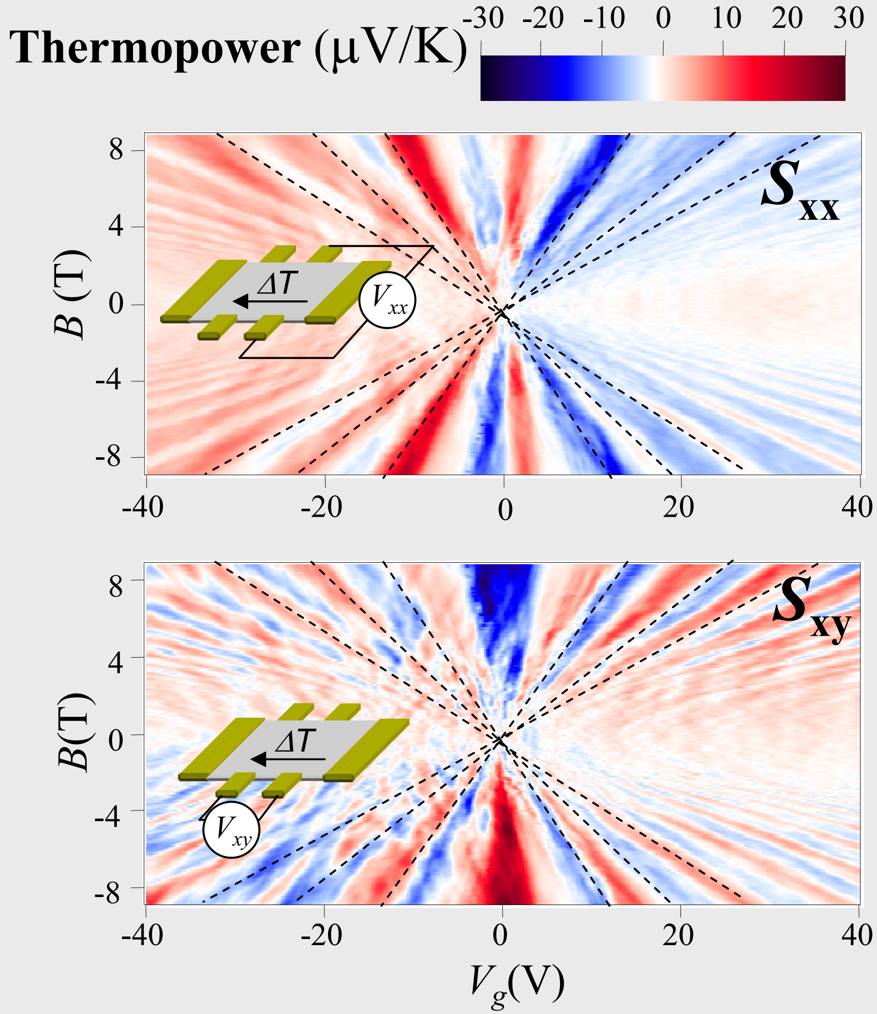
Multiterminal device
Mobility ~ 3000 cm^2/Vsec
Measure R_{xx} and R_{xy}

T = 10 K

magnetoconductance

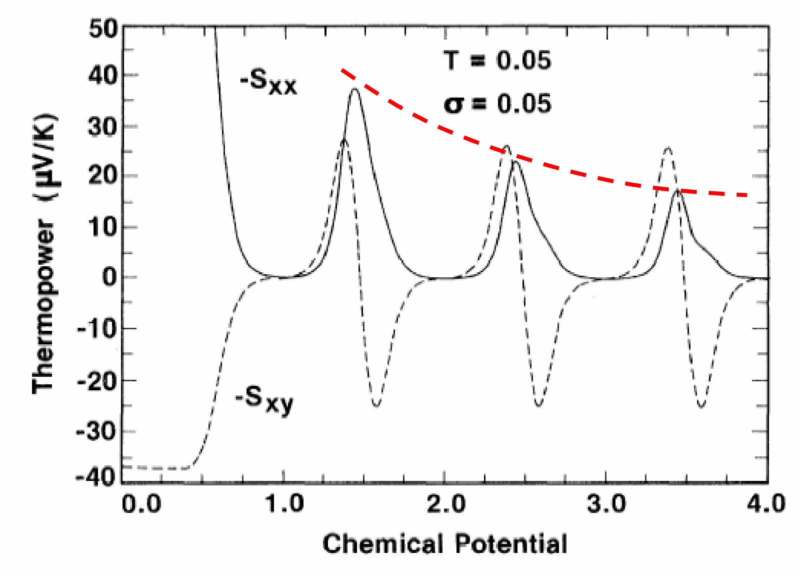






Thermopower in QH Regime in 2DEG

Jonhson and Girvin 1984:



$$S_{ij} = -\frac{\pi^2}{3}\frac{k_B^2 T}{e}\sum_k \left(\sigma^{-1}\right)_{ik}\left(\frac{\partial \sigma}{\partial \mu}\right)_{kj}$$

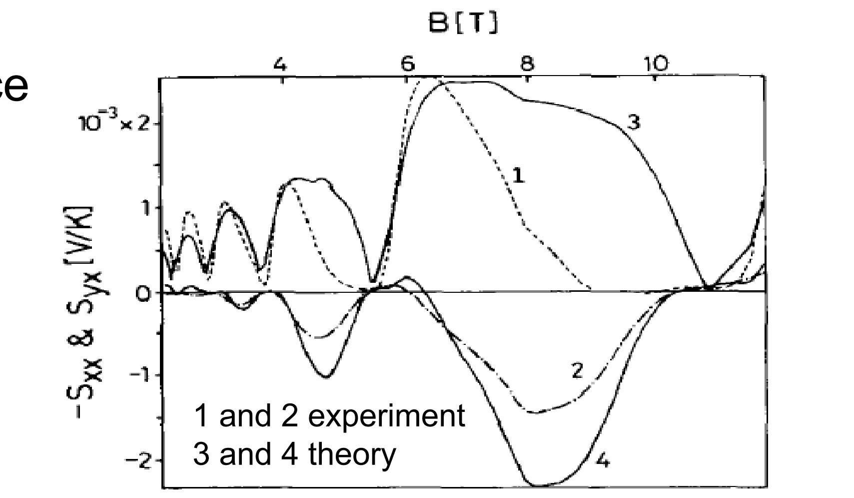
$$S_{xx}^{peak} = \frac{-\ln(2)k_B/e}{(N+1/2)}$$

where N is number of 1D channels

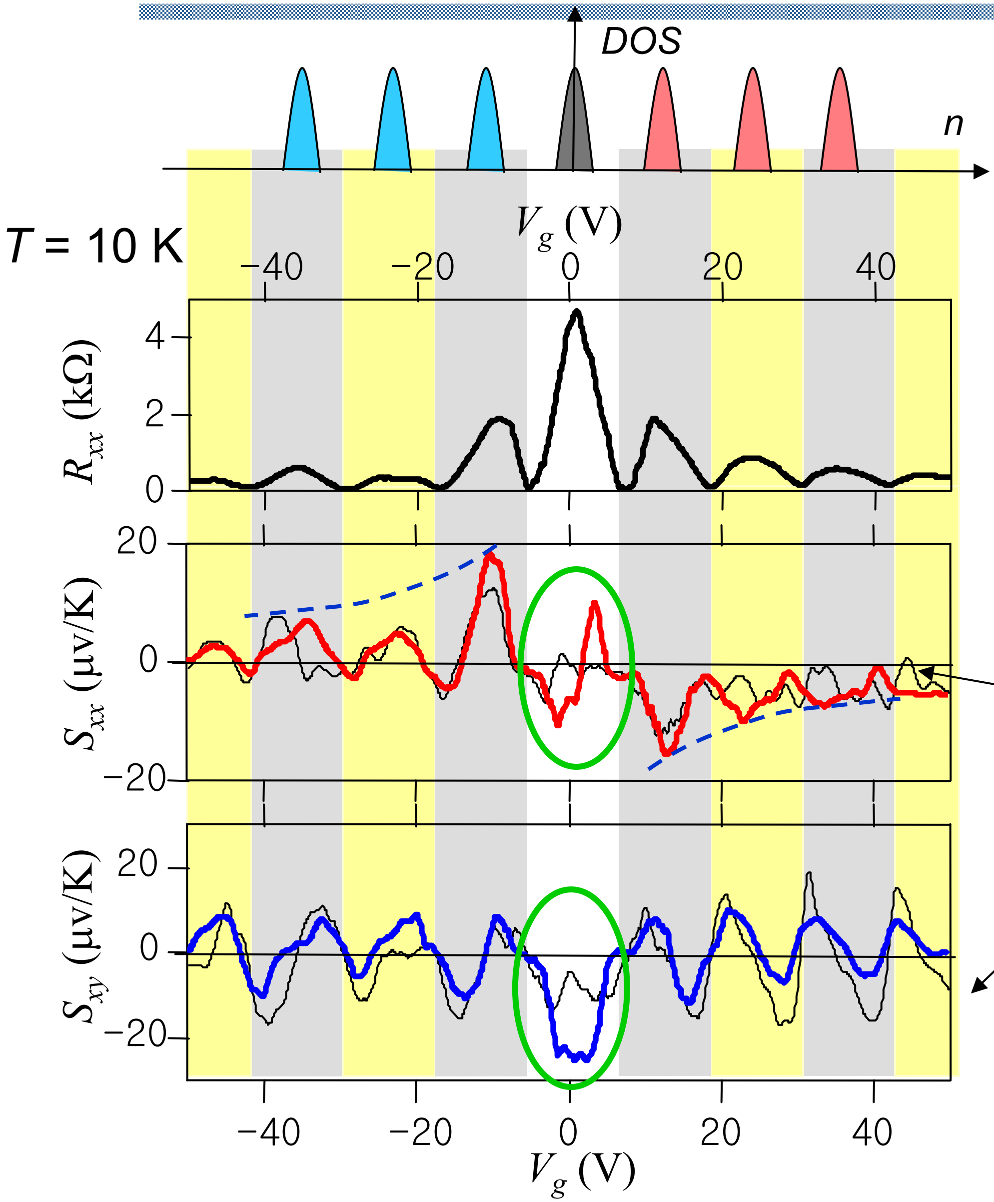
Obloh H. and Von Klizting, 1984 Surface Science

Fromhold TM et al., 1992 Surface Science

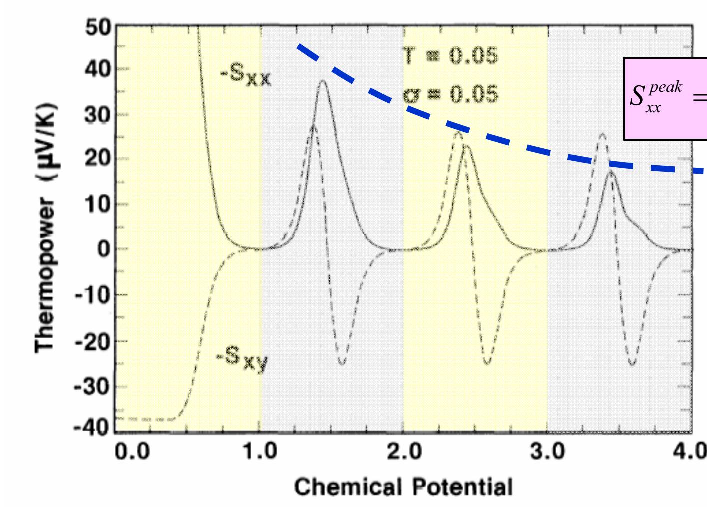
$$S = S_{diffusive} + S_{phonon\ drag}$$



QHE in magneto-TEP in graphene



Jonhson and Girvin PRB (1984):



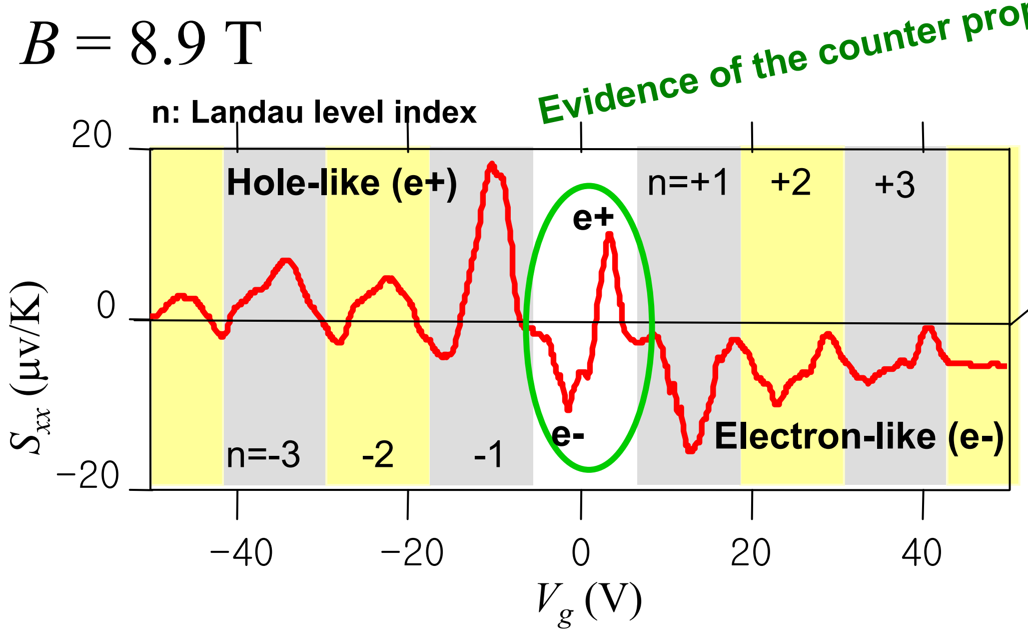
$$S_{xx}^{peak} = \frac{-\ln(2)k_B/e}{(N+1/2)}$$

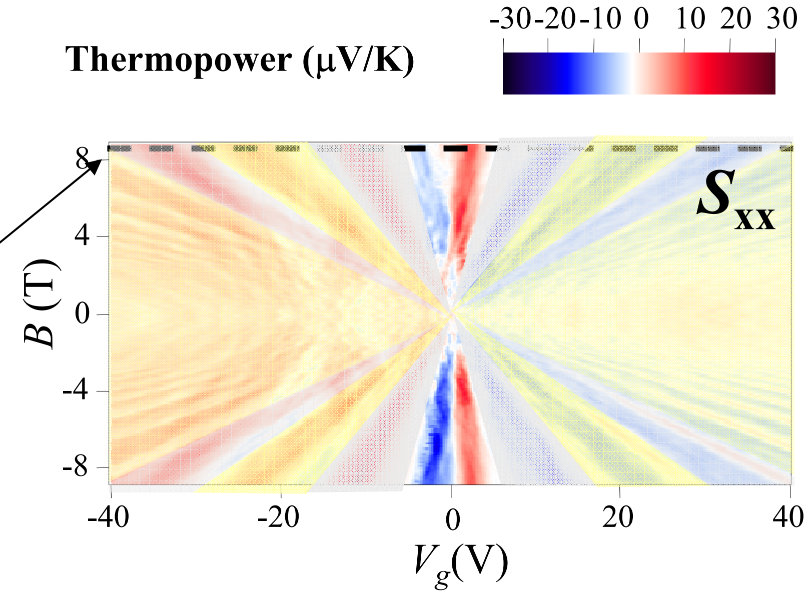
Generalized Mott Formula

$$S_{ij} = -\frac{\pi^2}{3}\frac{k_B^2 T}{e}\sum_k \left(\sigma^{-1}\right)_{ik}\left(\frac{\partial\sigma}{\partial\mu}\right)_{kj}$$

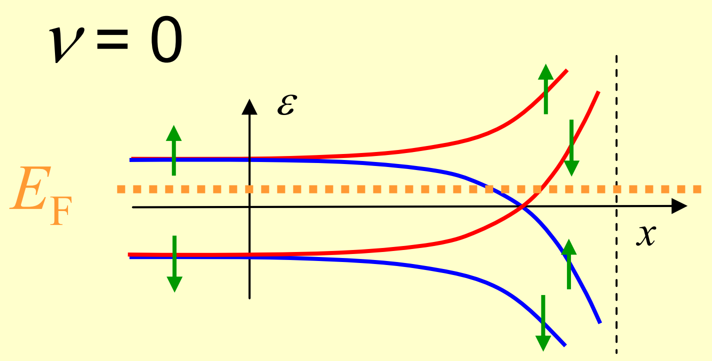
TEP at the Dirac point is unusual !!

Magneto-Thermopower at the Dirac Point

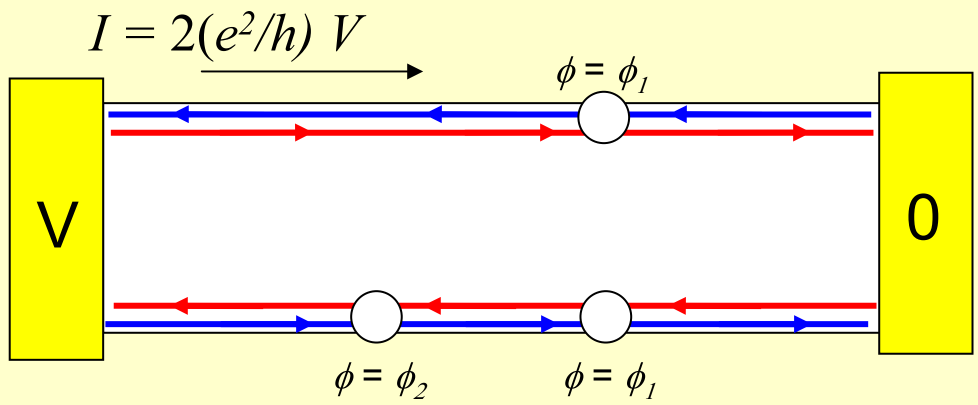




Counter propagating QH edge state at ν=0



Abanin, et al., Phys. Rev. Lett. 98, 196806 (2007)



Conclusions

•Mobility of graphene can be greatly improved by suspending and subsequent annealing of samples.

•Quantum Oscillations in graphene heterojunction devices were observed and they indicate the collimated ballistic transport of the chiral particles across the p-n junctions.

• Thermoelectric power graphene agrees with generalized Mott Formula except near the Dirac point.

(Unspoken: variable range hopping in graphene nanoribbons, possible manybody effect in cyclotron resonance in graphene)

Challenges: Controlled Growth & Edge Control