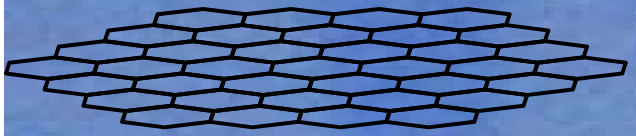
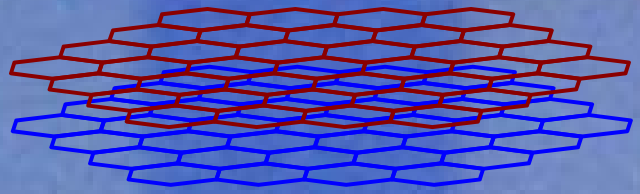
Diffusive Charge Transport in Graphene





Michael S. Fuhrer
Department of Physics and
Center for Nanophysics and Advanced Materials
University of Maryland

Outline

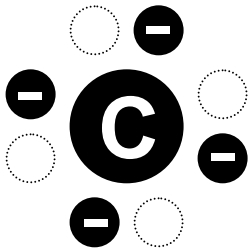
I. Introduction to Graphene
- "Massless" electrons
- Pseudospin and Berry's phase

II. Fabrication and Characterization of Graphene on SiO_2
- Micro-Raman spectroscopy
- Cleaning graphene

III. Diffusive Transport in Graphene
- Boltzmann Transport
  - Charged impurities
  - Charged impurities – minimum conductivity
  - Phonons
  - Dielectric Environment – Tuning Fine Structure Constant
  - Corrugations
  - Lattice defects

Carbon and Graphene

Carbon



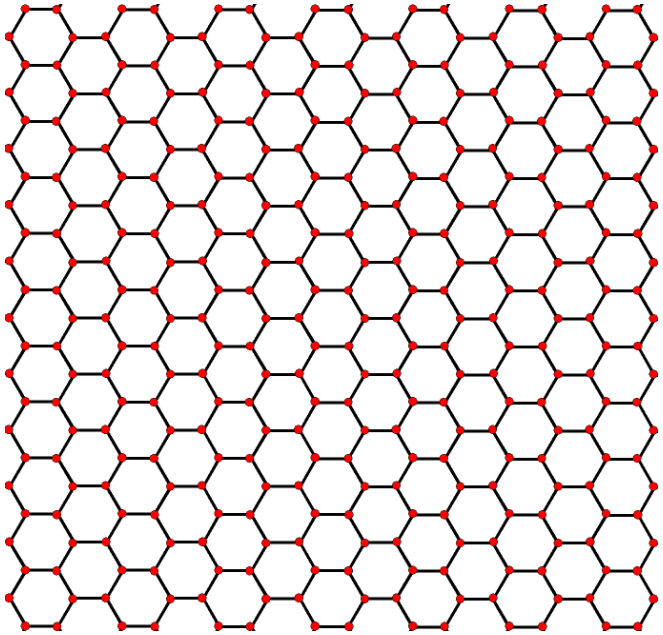
4 valence electrons

1 p_z orbital

3 sp^2 orbitals

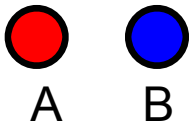
Graphene

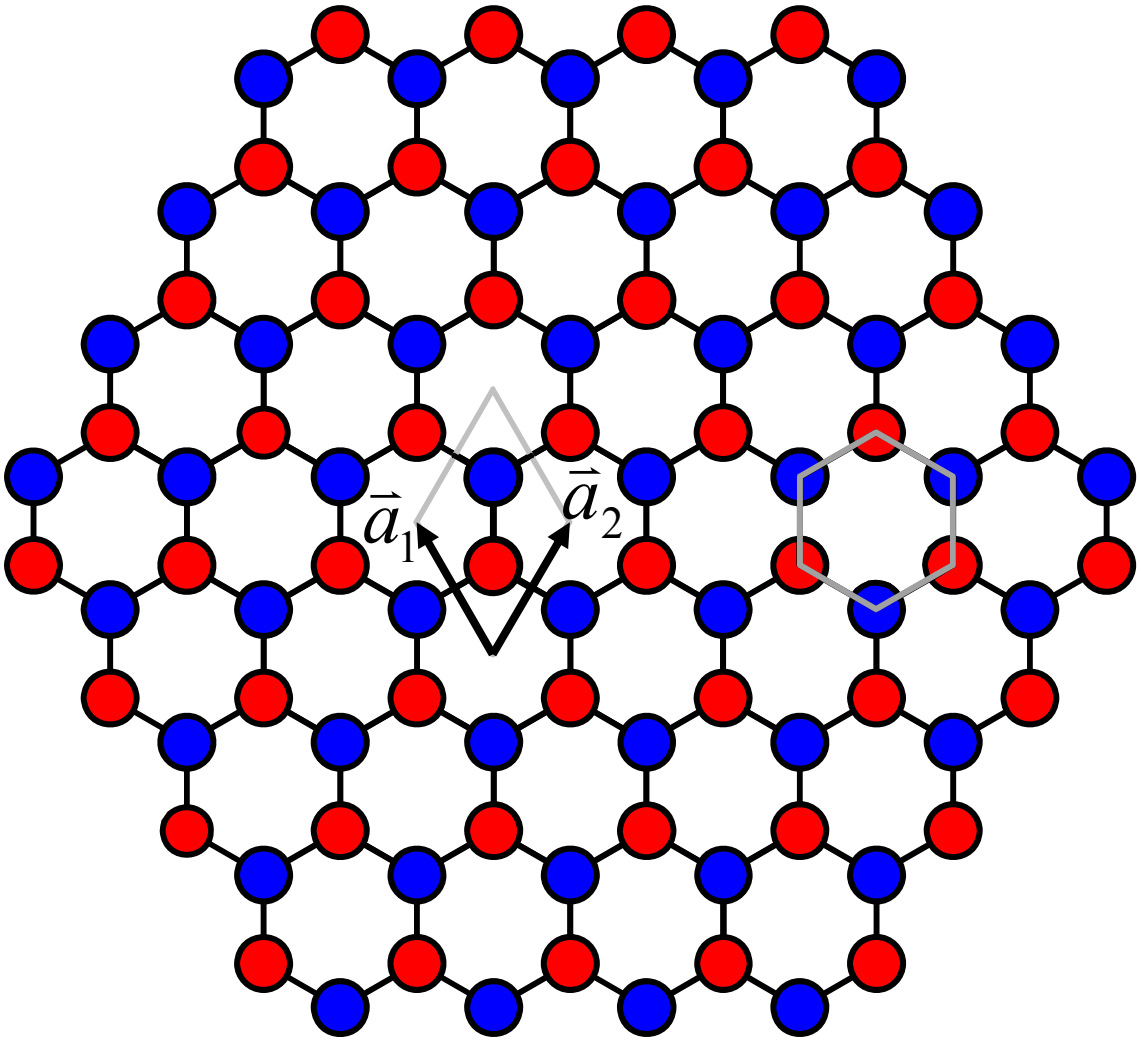
Hexagonal lattice;
1 p_z orbital at each site



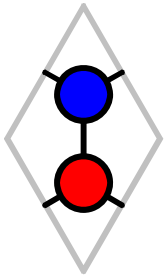
Graphene Unit Cell

Two *identical* atoms in unit cell:

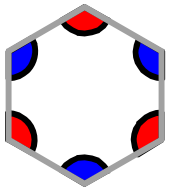




Two representations of unit cell:



Two atoms

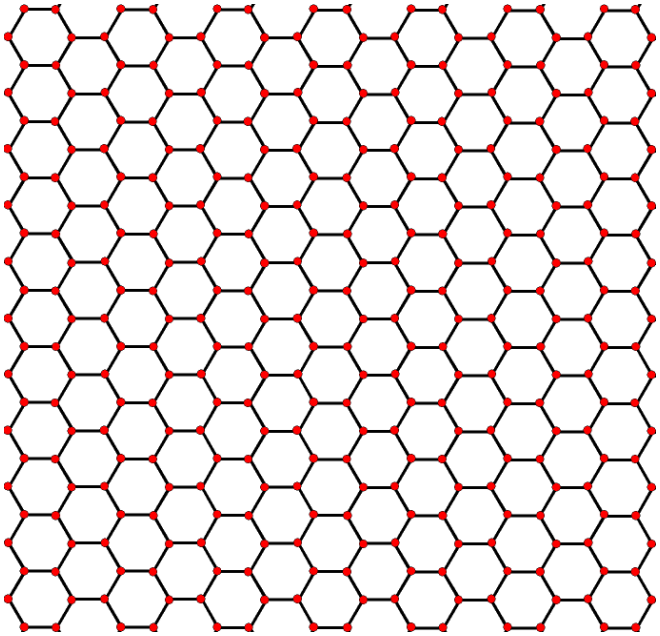


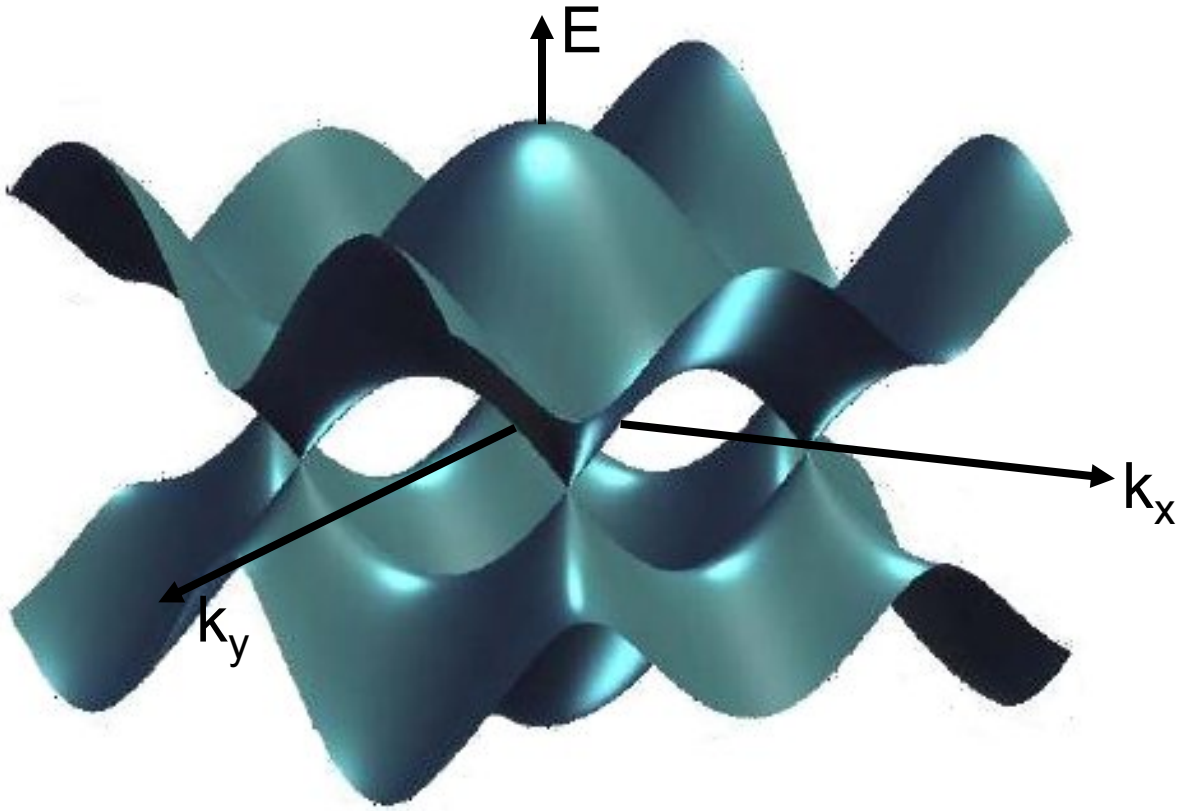
1/3 each of 6 atoms = 2 atoms

Band Structure of Graphene

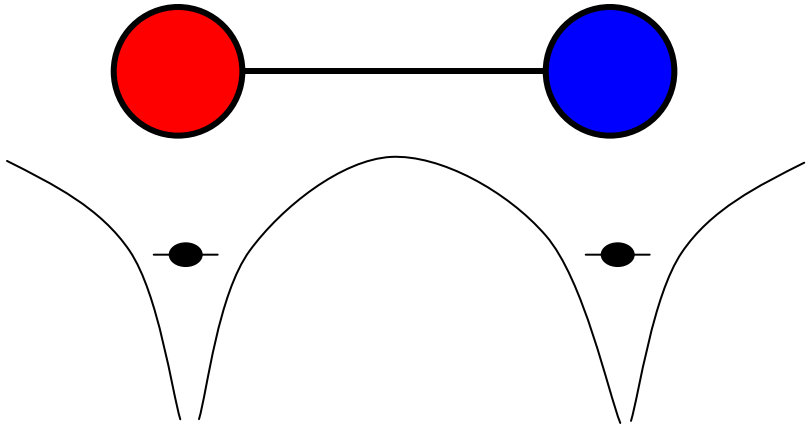
Tight-binding model: P. R. Wallace, (1947)
(nearest neighbor overlap = γ_0)

$$E(\boldsymbol{k}) = E_F \pm \gamma_0 \sqrt{1 + 4\cos\left(\frac{\sqrt{3}k_x a}{2}\right)\cos\left(\frac{k_y a}{2}\right) + 4\cos^2\left(\frac{k_y a}{2}\right)}$$



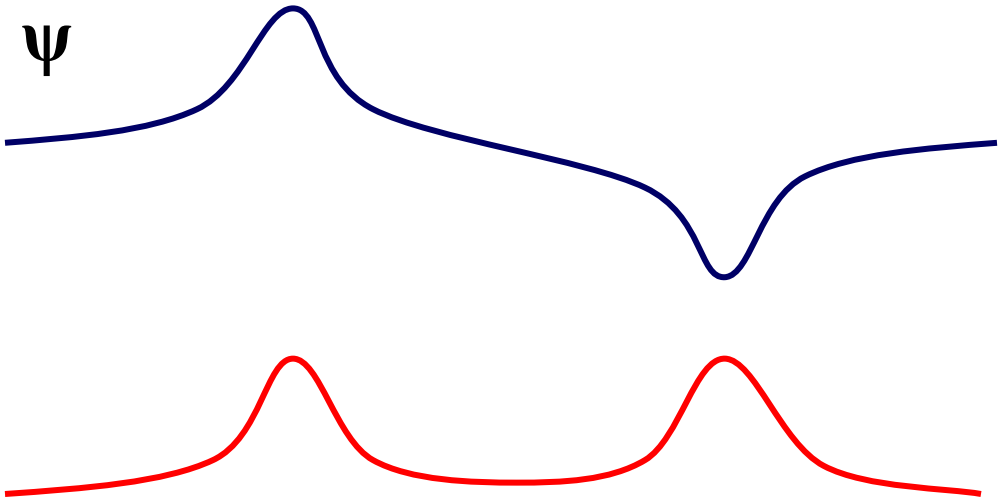


Bonding vs. Anti-bonding



$$H = \begin{bmatrix} 0 & -\gamma_0 \\ -\gamma_0 & 0 \end{bmatrix} \qquad E = \pm\gamma_0$$

γ_0 is energy gained per pi-bond



"anti-bonding"
anti-symmetric wavefunction

$$\psi_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix} \qquad E_1 = +\gamma_0$$

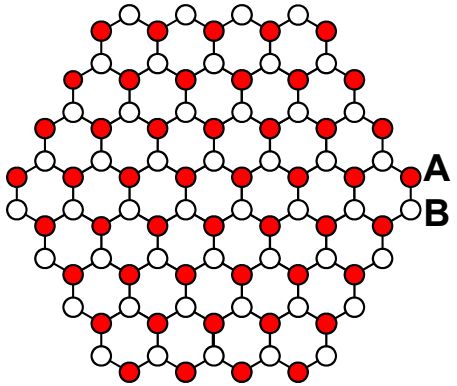
"bonding"
symmetric wavefunction

$$\psi_2 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad E_2 = -\gamma_0$$

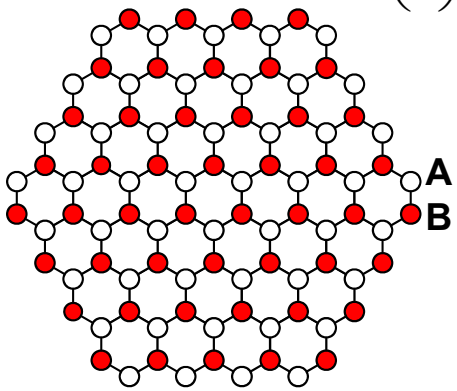
Band Structure of Graphene – Γ point (k = 0)

Bloch states:

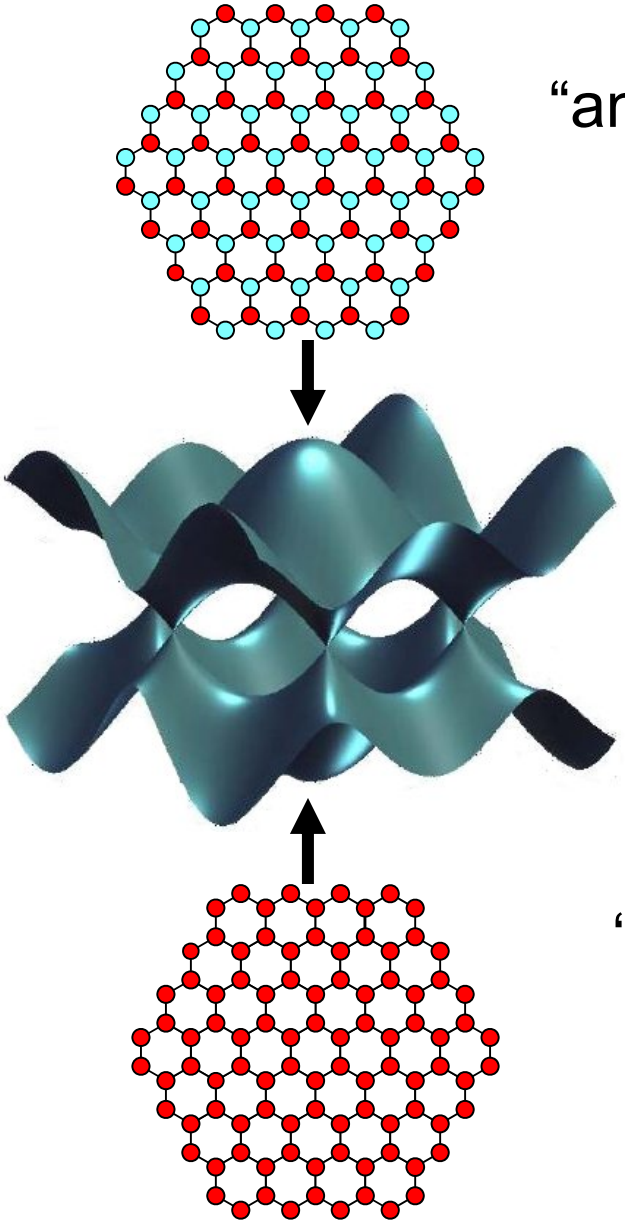
$F_A(r)$, or $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$



$F_B(r)$, or $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$



Γ point:
k = 0



"anti-bonding"

$E = +3\gamma_0$

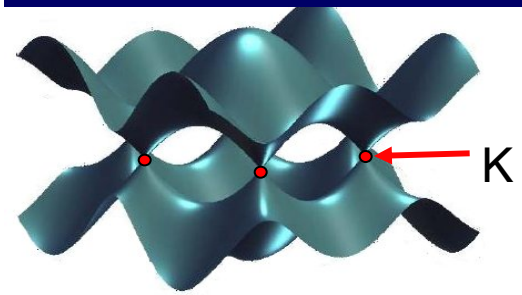
$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$

"bonding"

$E = -3\gamma_0$

$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$

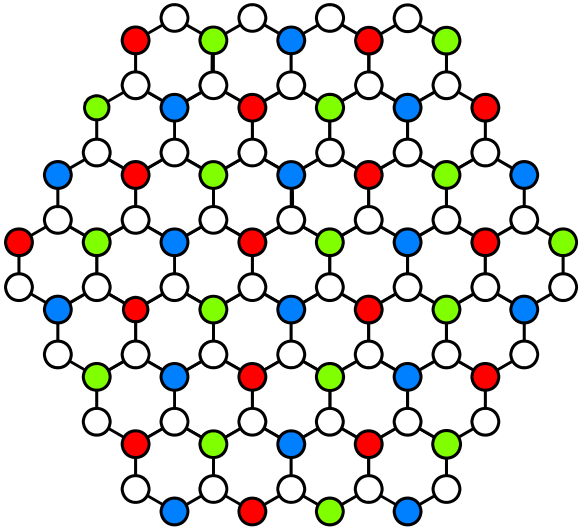
Band Structure of Graphene – K point

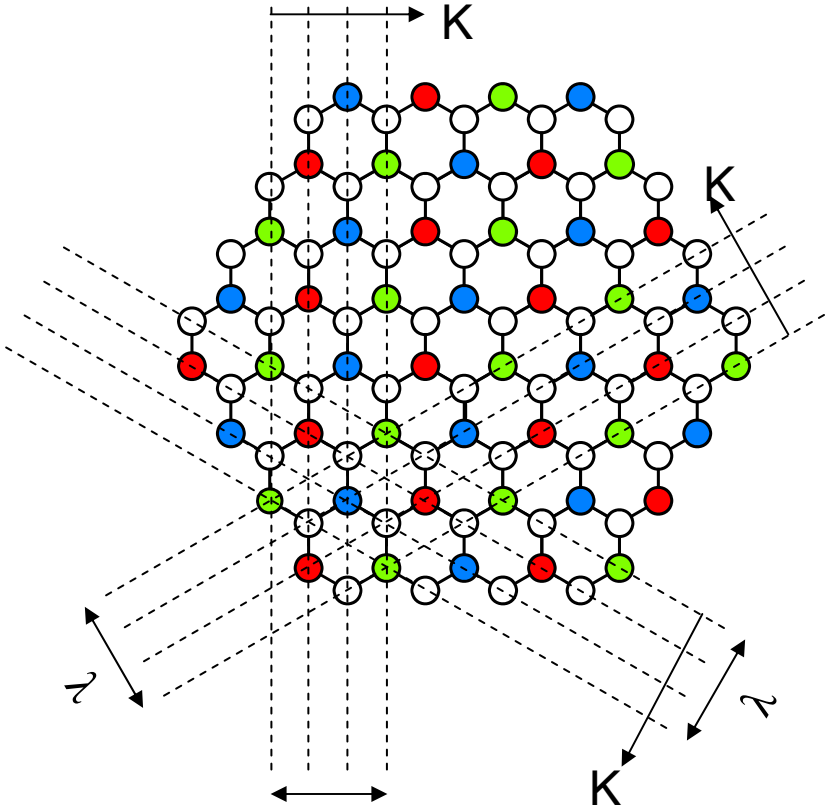


$$|\boldsymbol{K}| = \frac{4\pi}{3a} \Rightarrow \lambda = \frac{3a}{2}$$

$F_A(r)$, or $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$F_B(r)$, or $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$





Phase:

1

$e^{i\frac{2\pi}{3}}$

$e^{i\frac{4\pi}{3}}$

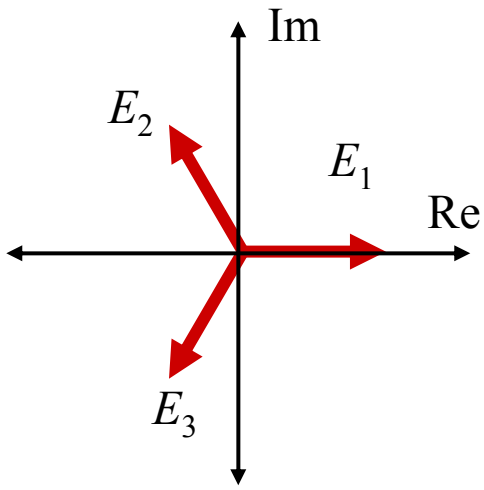
Bonding is Frustrated at K point

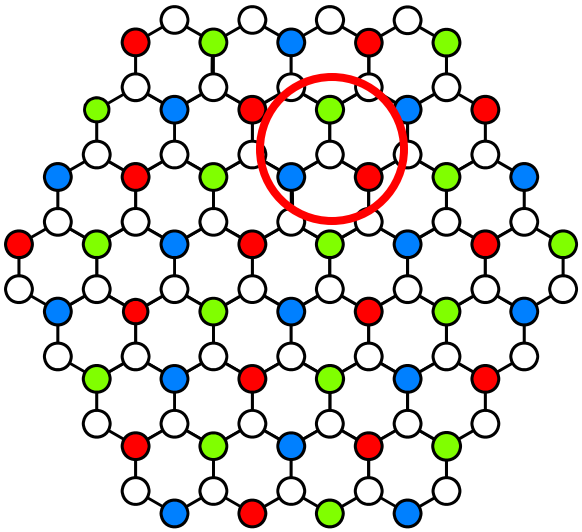
Phase:

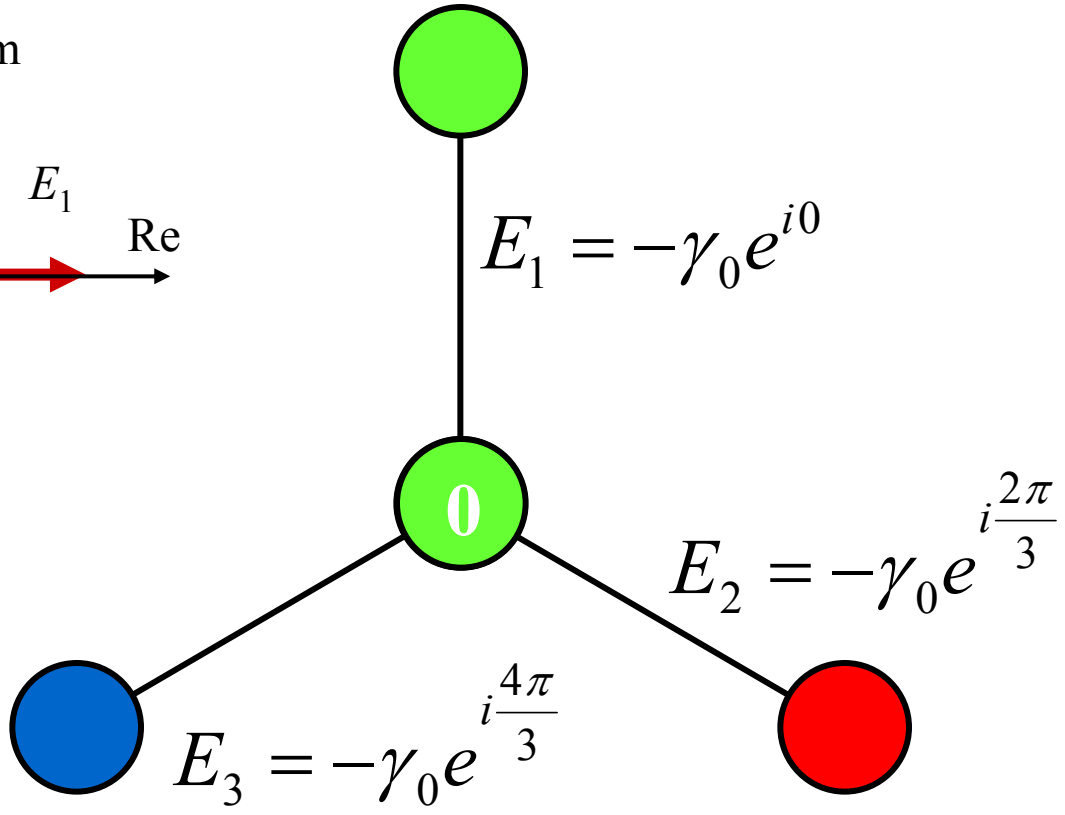
$e^{i0} = 1$

$e^{i\frac{2\pi}{3}}$

$e^{i\frac{4\pi}{3}}$







$$E = -\gamma_0 \left(e^{i0} + e^{i\frac{2\pi}{3}} + e^{i\frac{4\pi}{3}} \right) = 0$$

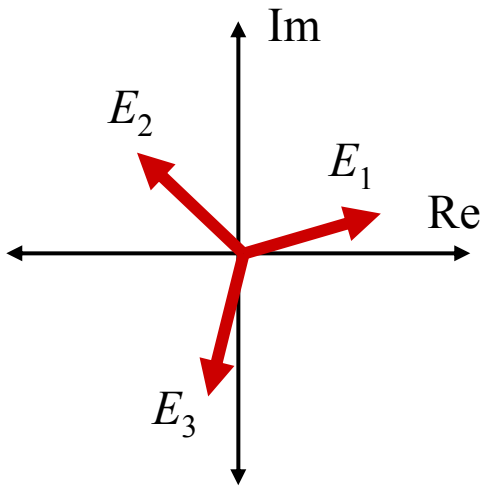
Bonding is Frustrated at K point

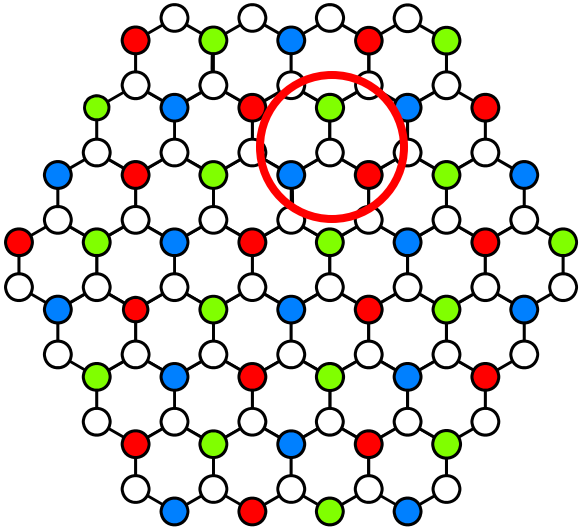
Phase:

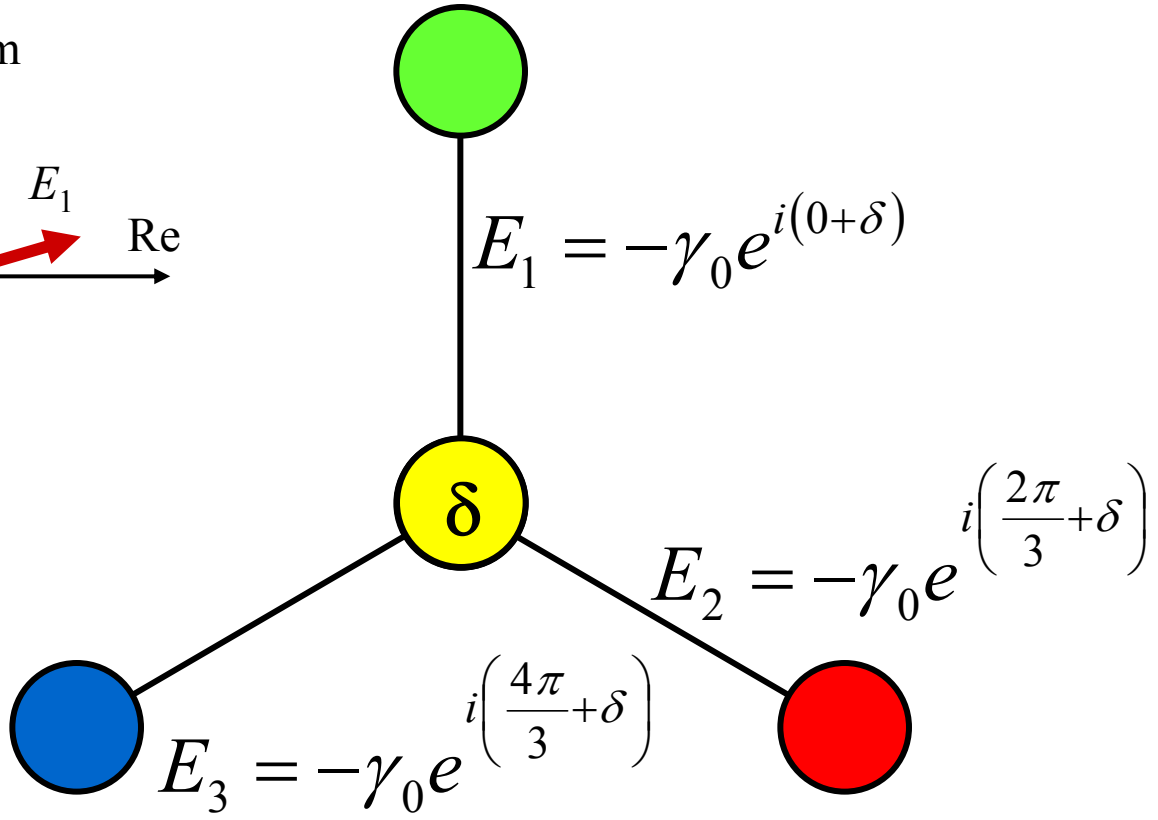
$e^{i0} = 1$

$e^{i\frac{2\pi}{3}}$

$e^{i\frac{4\pi}{3}}$







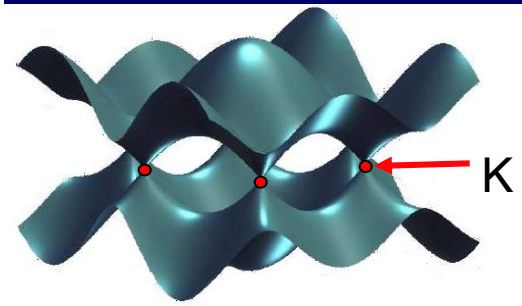
$$E_1 = -\gamma_0 e^{i(0+\delta)}$$

$$E_2 = -\gamma_0 e^{i\left(\frac{2\pi}{3}+\delta\right)}$$

$$E_3 = -\gamma_0 e^{i\left(\frac{4\pi}{3}+\delta\right)}$$

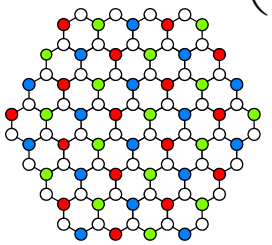
$$E = -\gamma_0 \left(e^{i(0+\delta)} + e^{i\left(\frac{2\pi}{3}+\delta\right)} + e^{i\left(\frac{4\pi}{3}+\delta\right)} \right) = 0e^{i\delta} = 0$$

Bonding is Frustrated at K point

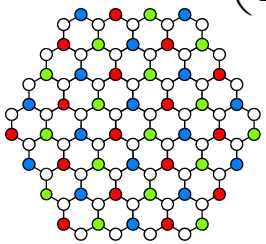


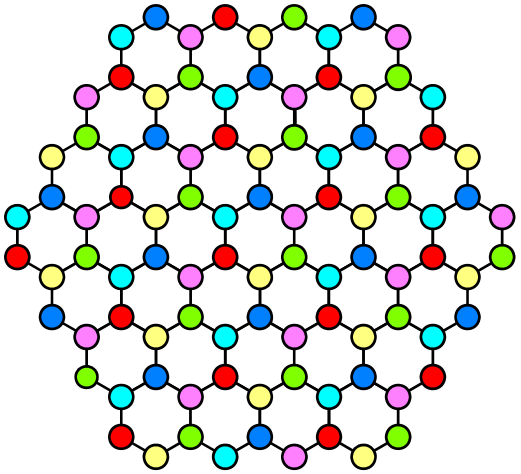
$$|\boldsymbol{K}| = \frac{4\pi}{3a} \Rightarrow \lambda = \frac{3a}{2}$$

$F_A(r)$, or $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$



$F_B(r)$, or $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

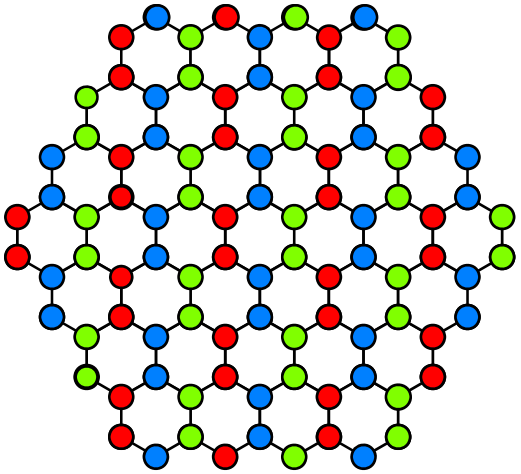




"anti-bonding"

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

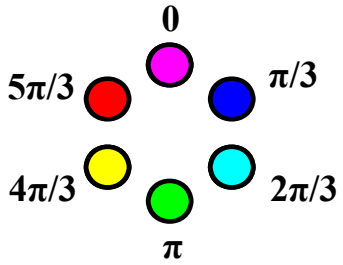
$E = 0!$



"bonding"

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$E = 0!$



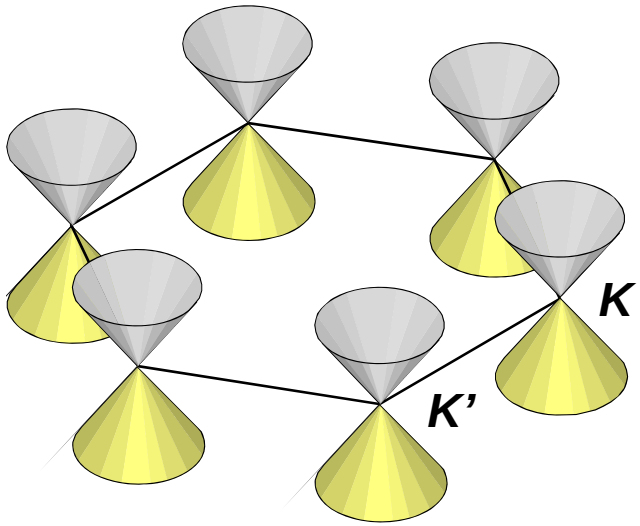
K point:
Bonding and anti-bonding are degenerate!

Band Structure of Graphene: k·p approximation

Hamiltonian:

$$\hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} \begin{pmatrix} F_A(r) \\ F_B(r) \end{pmatrix} = \varepsilon \begin{pmatrix} F_A(r) \\ F_B(r) \end{pmatrix}$$

$$\hbar v_F (\boldsymbol{\sigma} \cdot \boldsymbol{k}) \boldsymbol{F}(r) = \varepsilon \boldsymbol{F}(r)$$



Eigenvectors:

$$|k\rangle = \frac{1}{\sqrt{2}} e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \begin{pmatrix} -ibe^{-i\theta_k/2} \\ e^{i\theta_k/2} \end{pmatrix};$$

θ_k is angle **k** makes with y-axis
b = 1 for electrons, -1 for holes

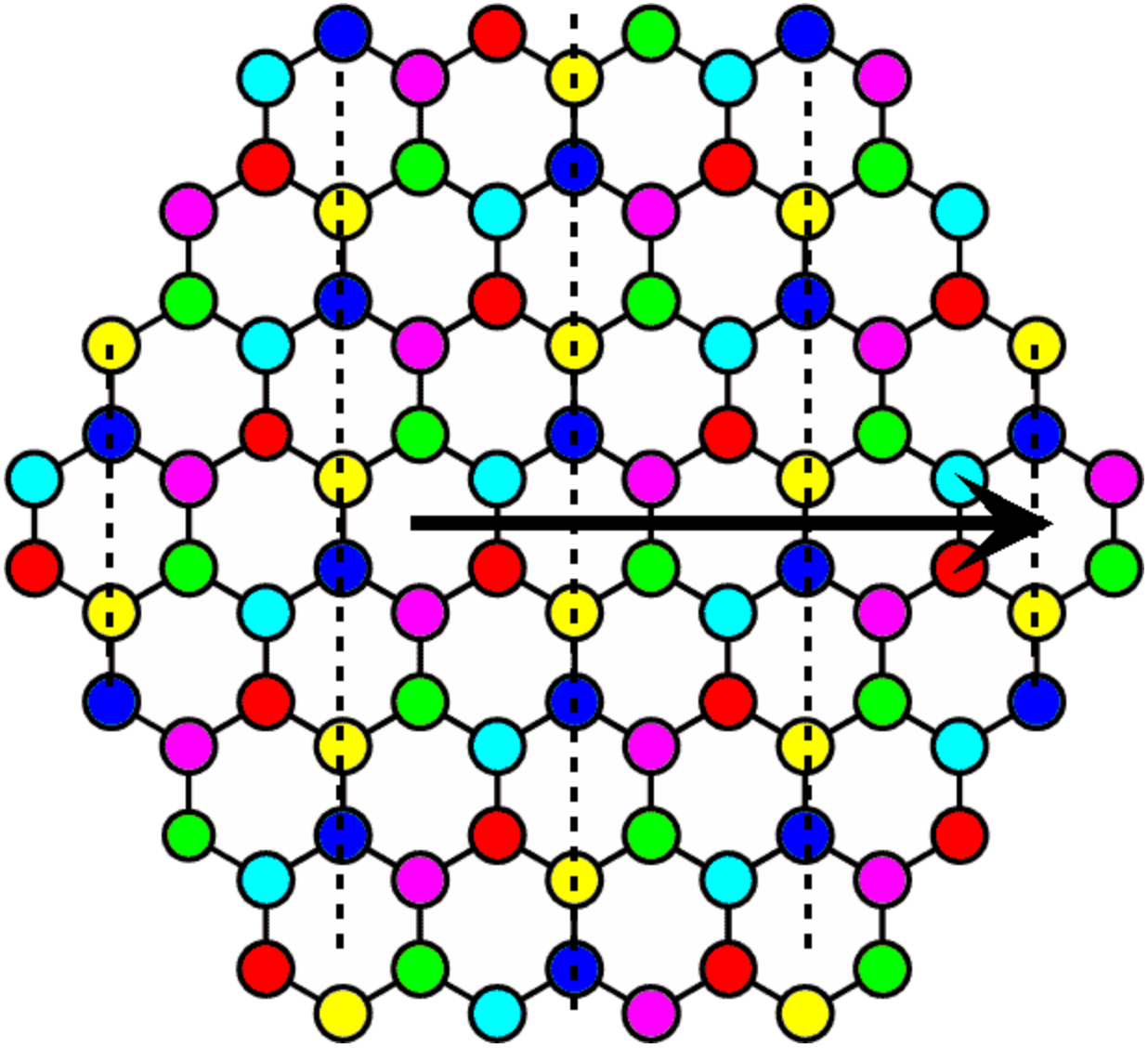
electron has "pseudospin"
points parallel (anti-parallel) to momentum

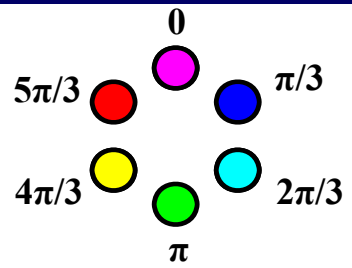
Energy:

$$\varepsilon = b\hbar v_F |k|$$

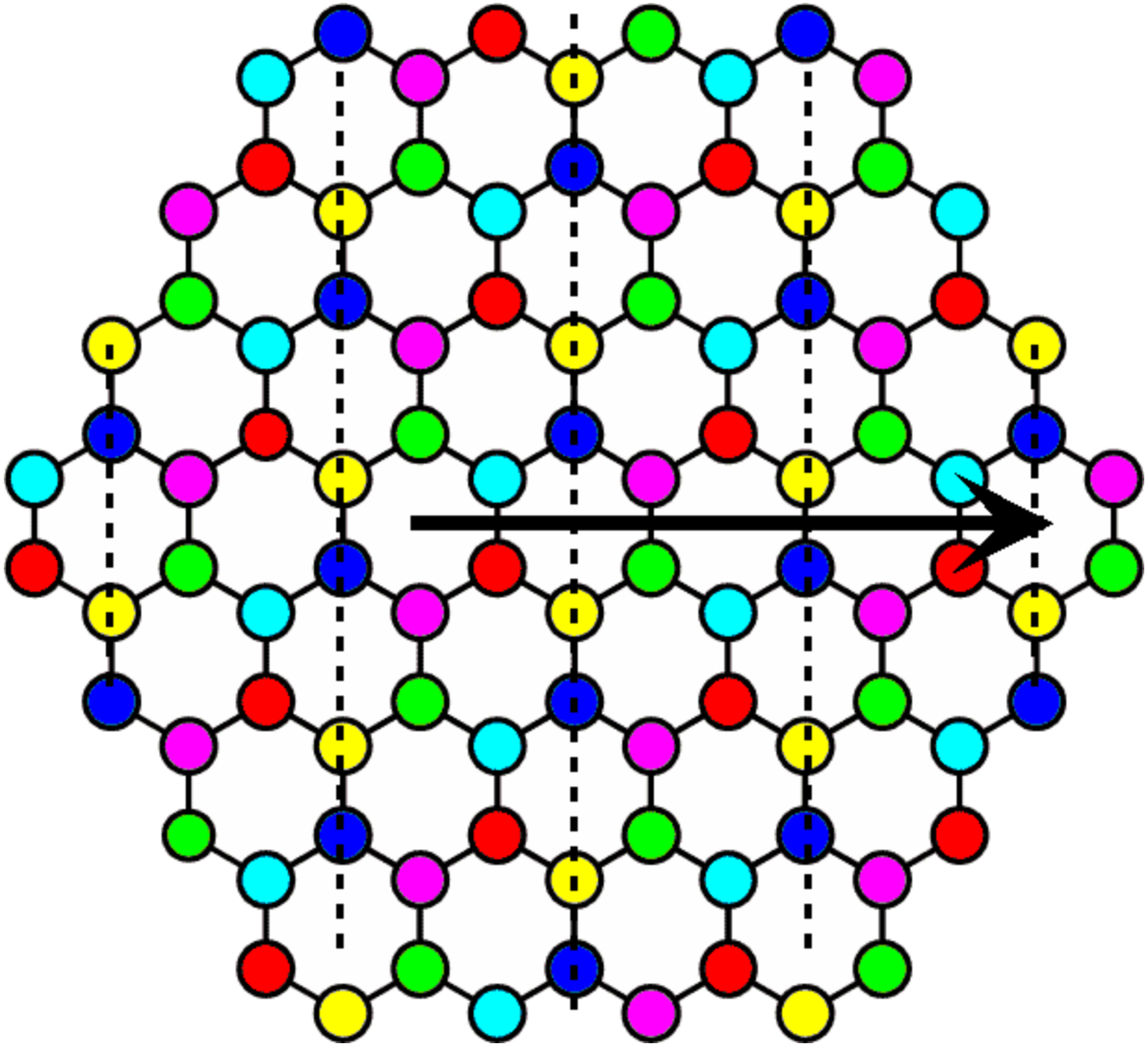
linear dispersion relation
"massless" electrons

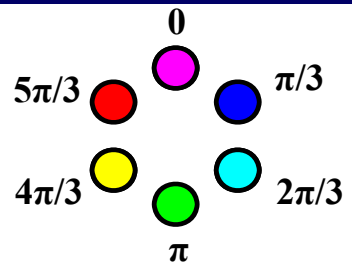
Visualizing the Pseudospin



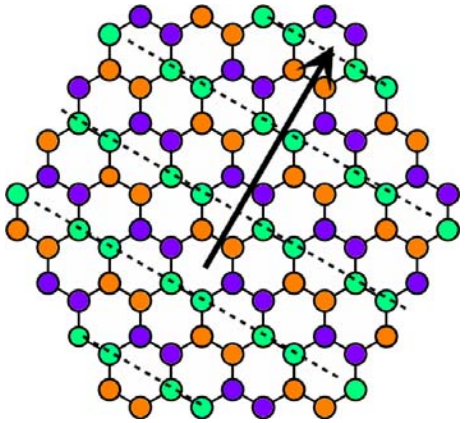


Visualizing the Pseudospin

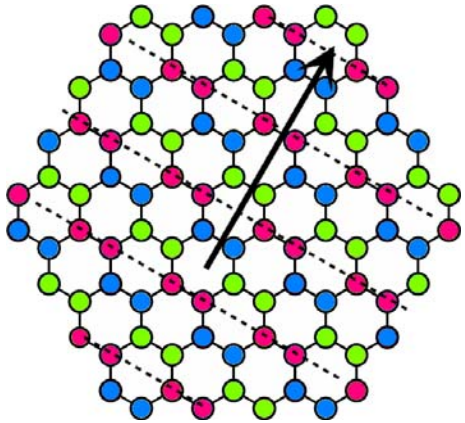




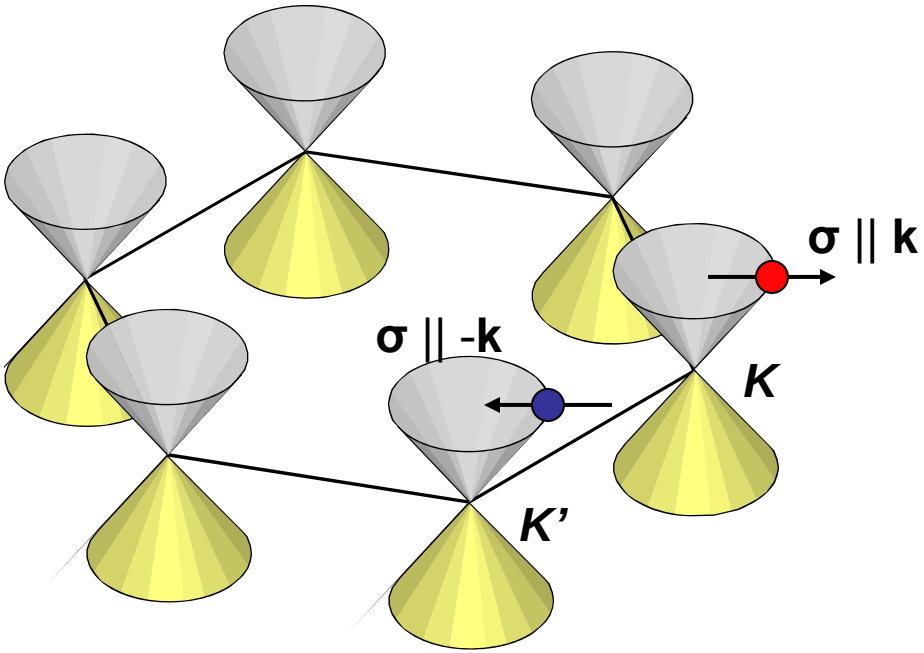
30 degrees



390 degrees



Pseudospin



$$H_K = \hbar v_F \vec{\sigma} \cdot \vec{k} = \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

$$H_{K'} = \hbar v_F \vec{\sigma}^t \cdot \vec{k}$$

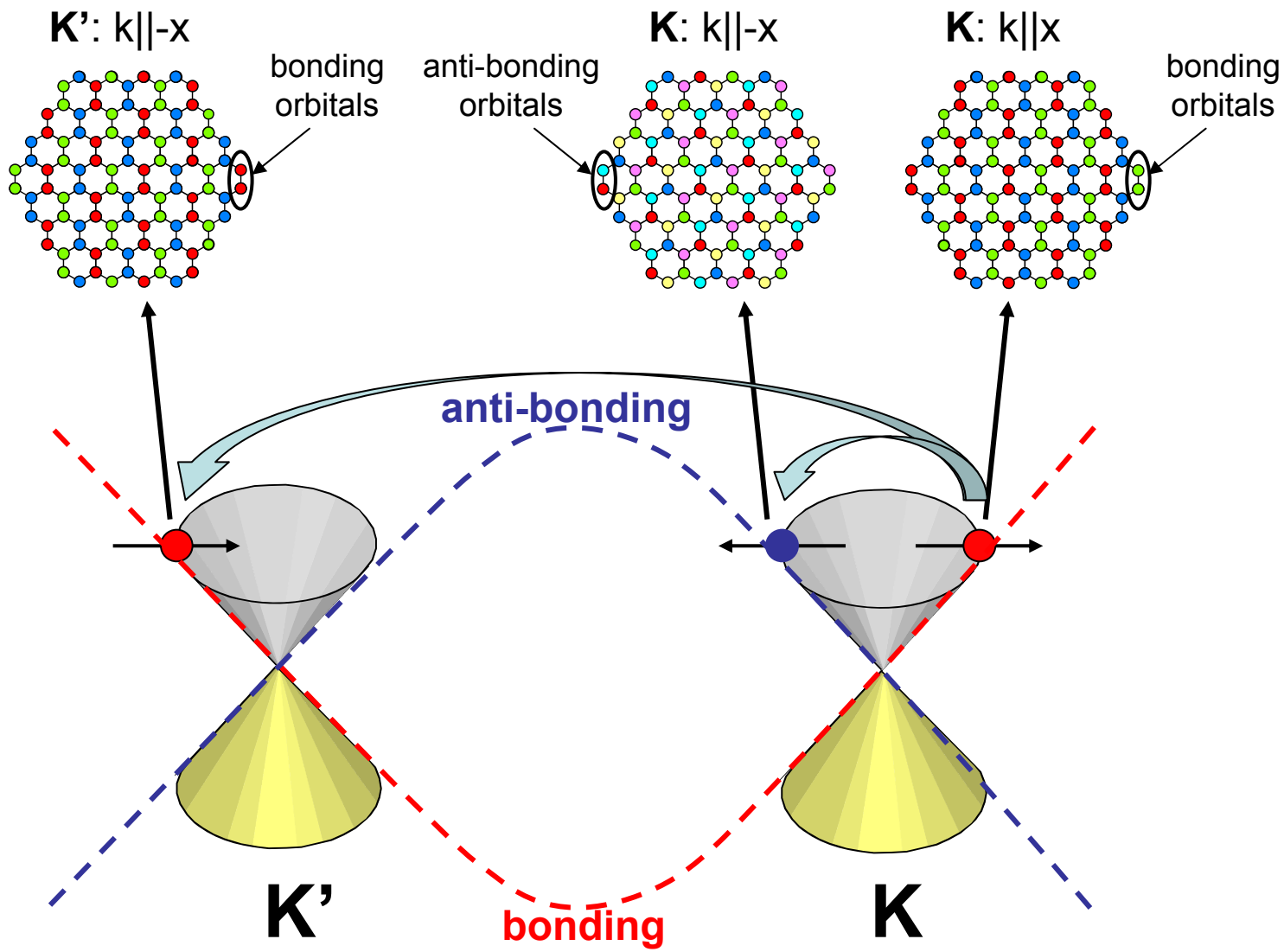
- Hamiltonian corresponds to spin-1/2 "pseudospin"
  Parallel to momentum (K) or anti-parallel to momentum (K')

- Orbits in k-space have Berry's phase of π

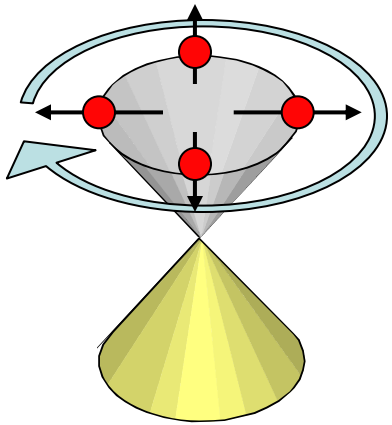
Pseudospin: Absence of Backscattering

real-space wavefunctions (color denotes phase)

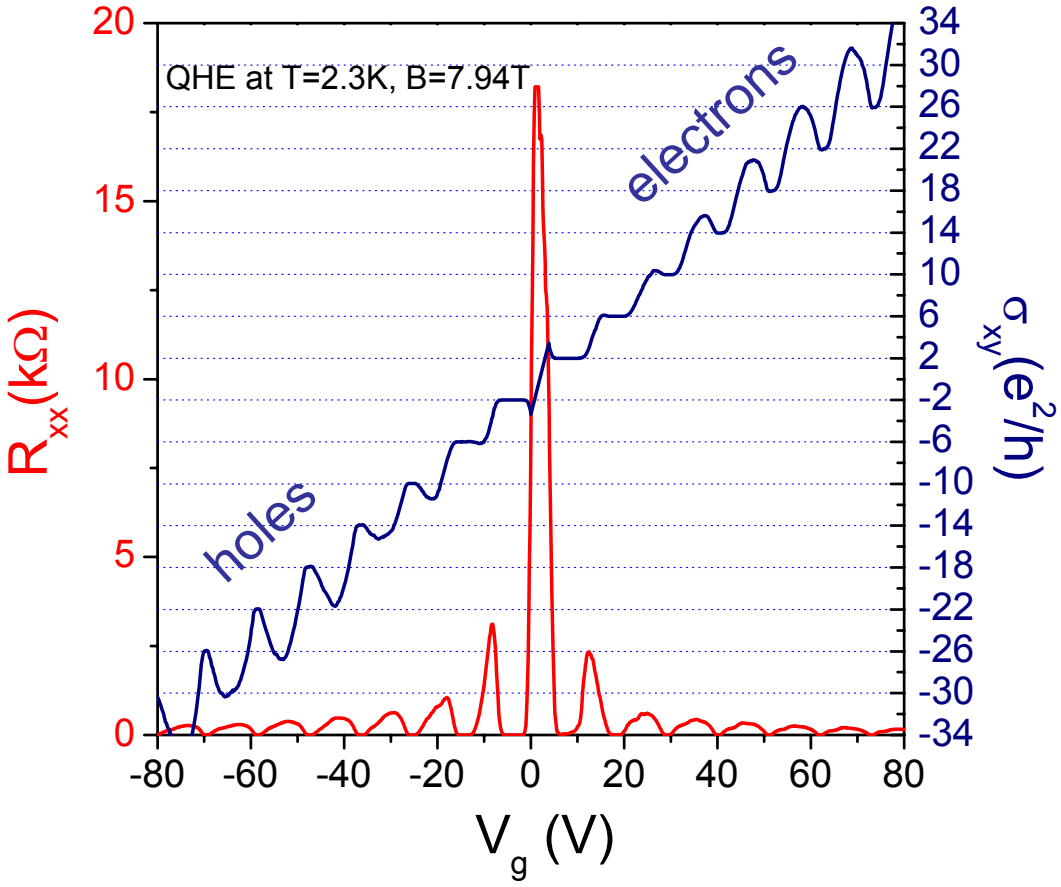
k-space representation



“Pseudospin”: Berry’s Phase in IQHE



π Berry’s phase for electron orbits results in ½-integer quantized Hall effect



$$\sigma_{xy} = \nu \frac{e^2}{h} \qquad \nu = 4\left(n + \frac{1}{2}\right)$$

$$g_s g_v = 2 \times 2 = 4$$

Berry’s phase = π

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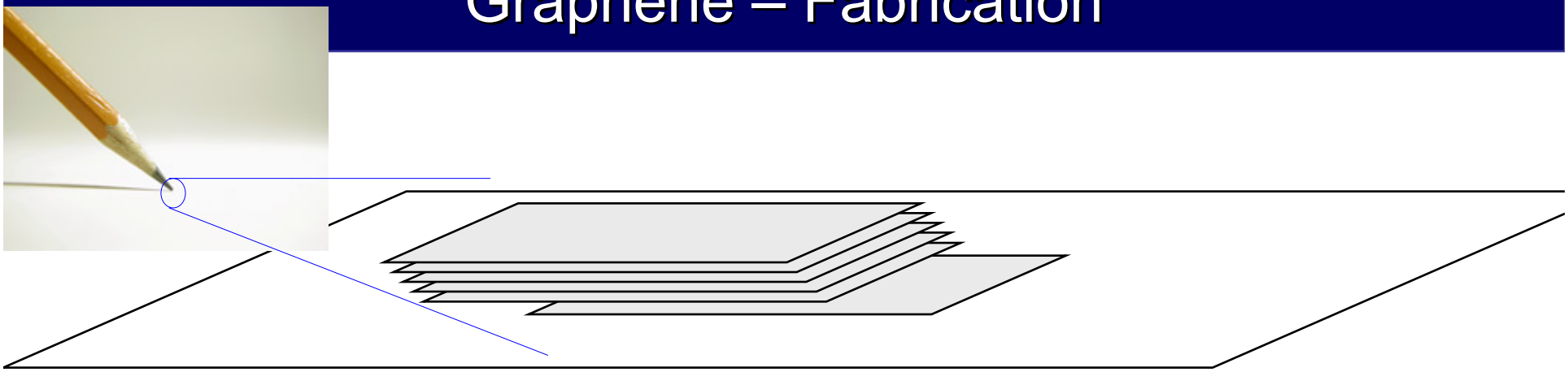
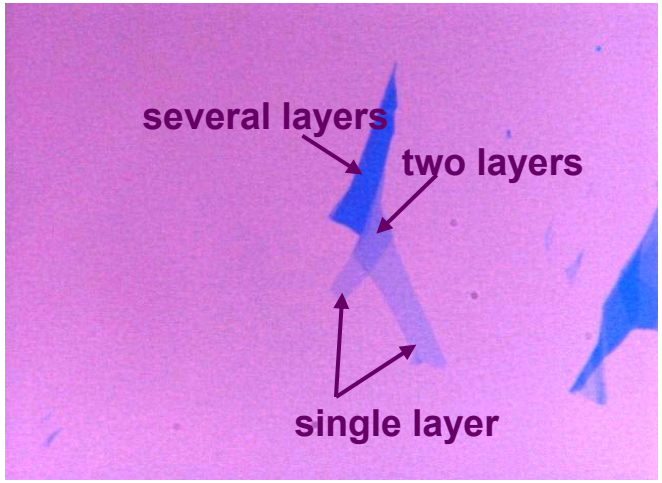
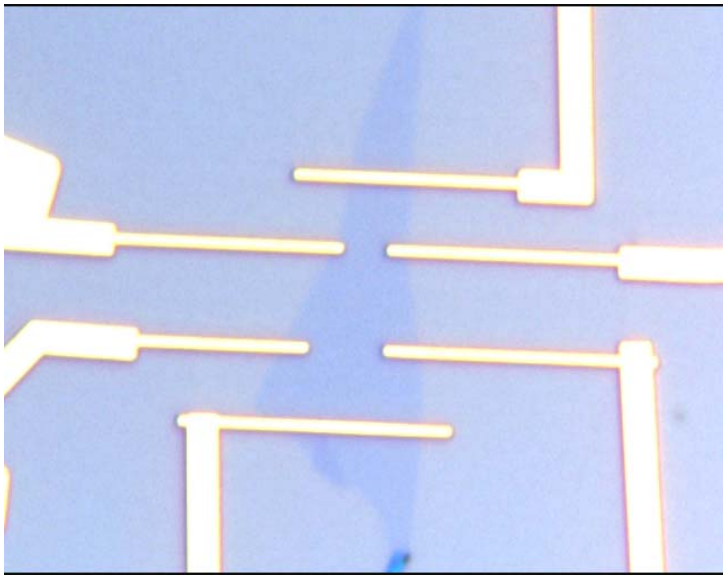
Graphene – Fabrication





Optical micrograph (layer thickness verified by AFM)

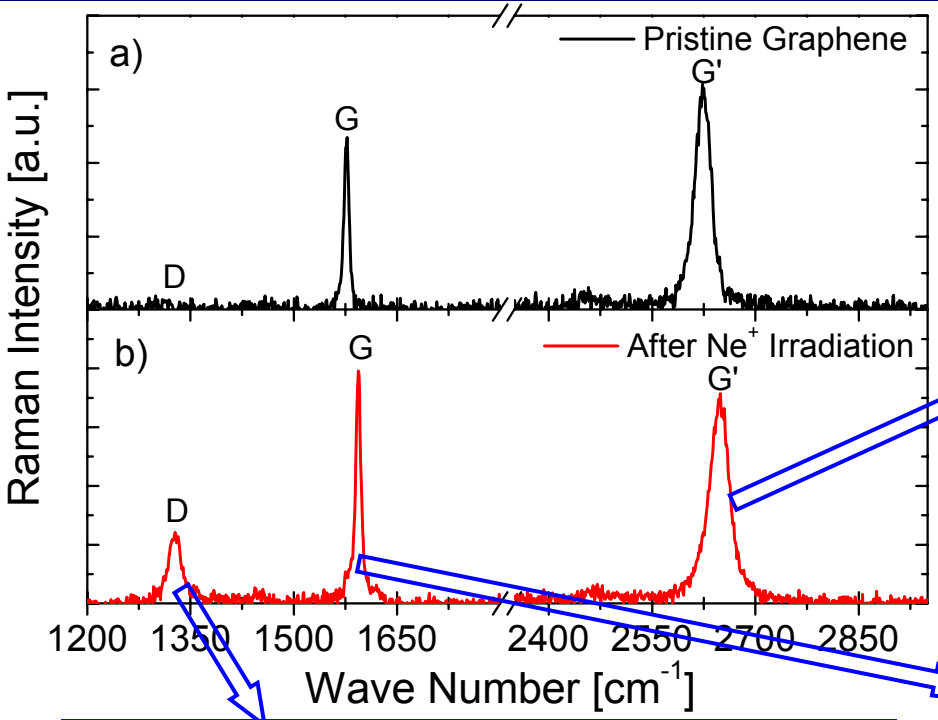


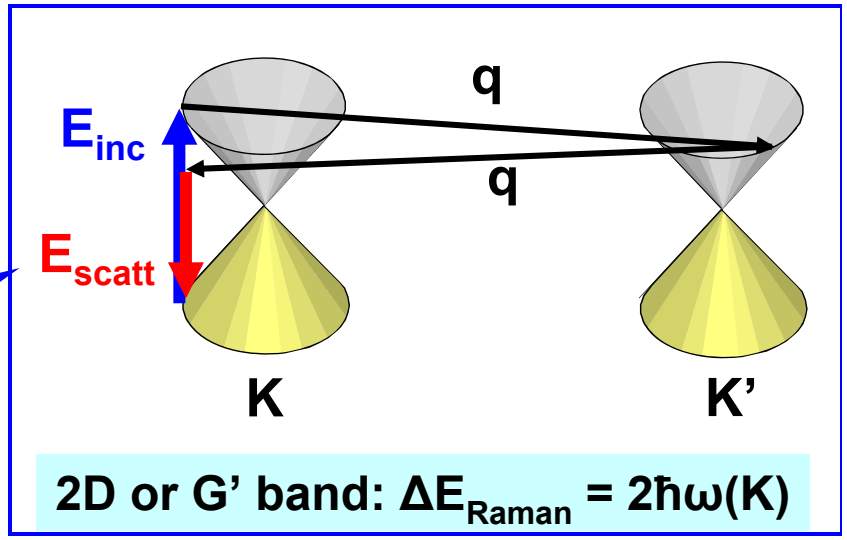
Single layer device after e-beam lithography

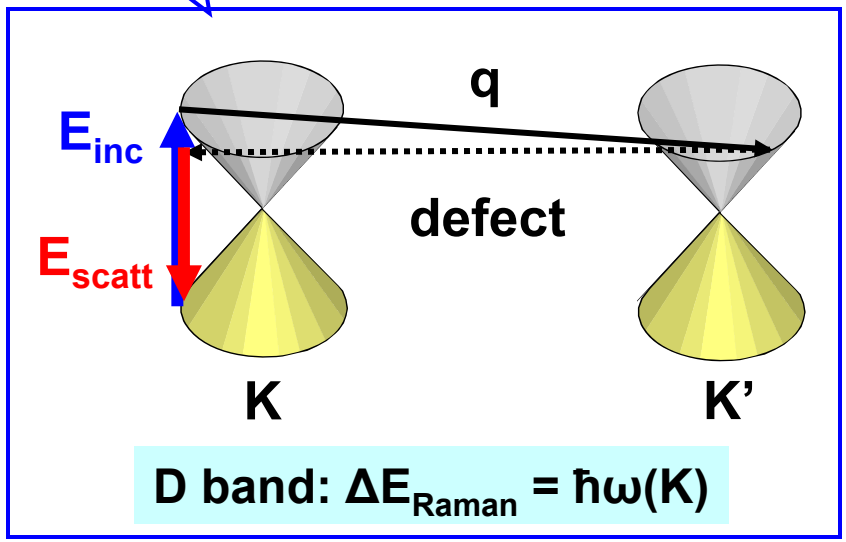
- Starting material is single-crystal Kish graphite
- Mechanically exfoliate on 300 nm SiO_2/Si chips

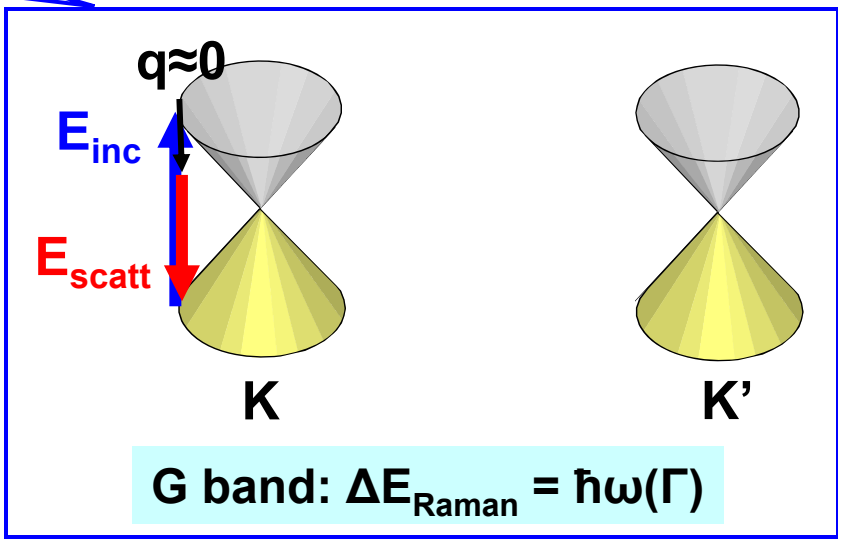
Method adapted from Novoselov, et al. *PNAS* **102** 10341 (2005)

Raman spectroscopy of graphene



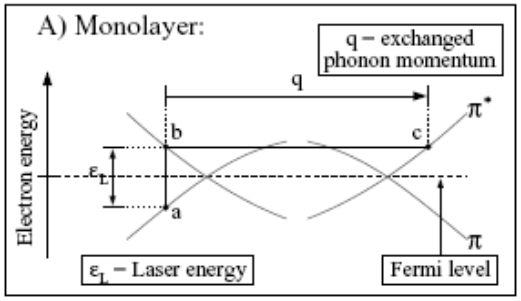


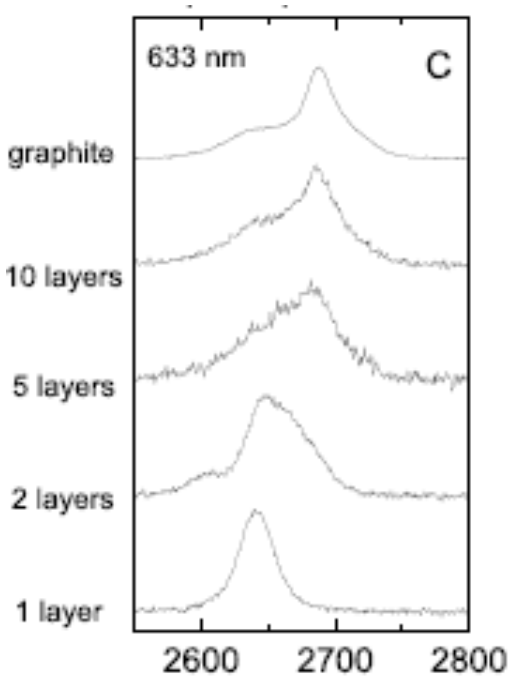




Graphene fingerprint in Micro-Raman

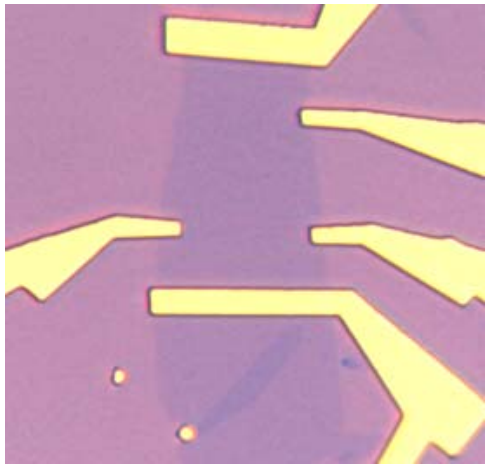
- Raman G' band is two-photon/two-phonon resonant excitation; sensitive to electronic structure of graphene

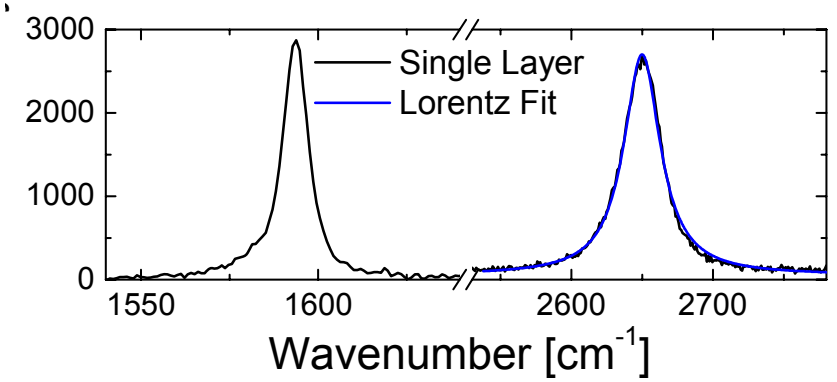




Ferrari, et al., *PRL* **97**, 187401 (2006)

Fuhrer group sample

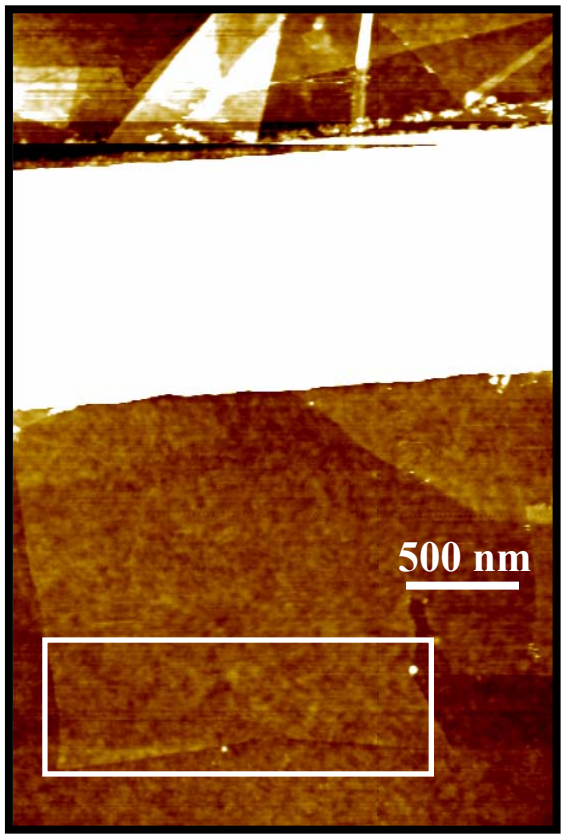




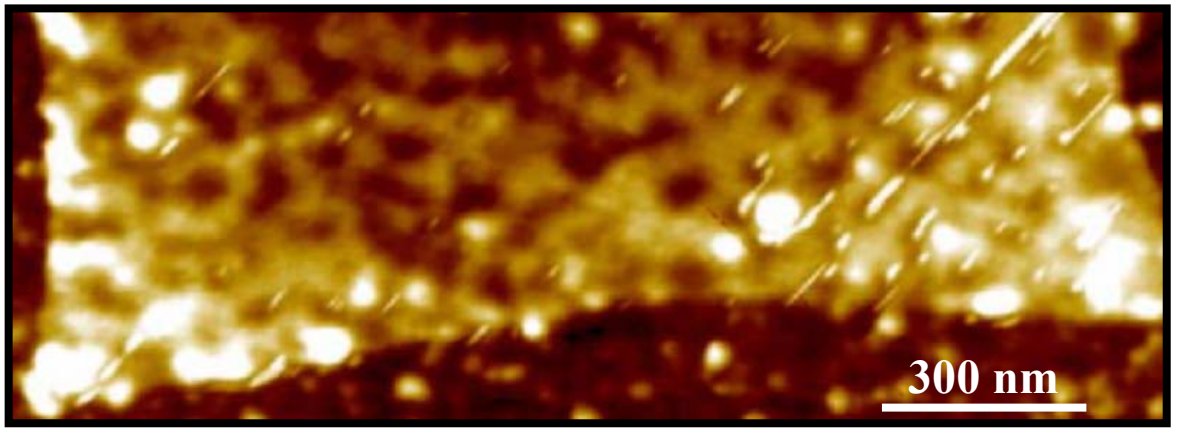
single Lorentzian G' peak indicates single-layer graphene

Removing Photoresist Residue from Graphene

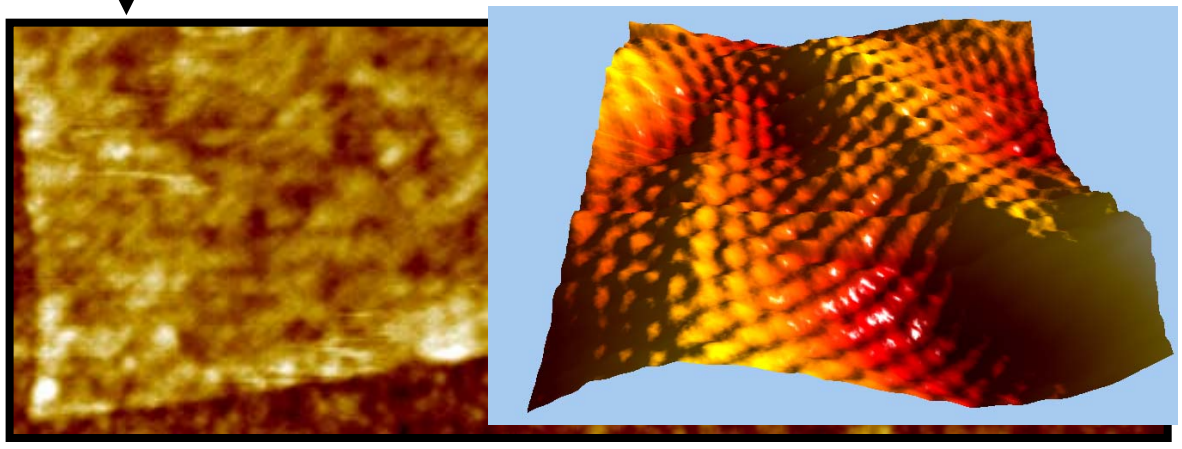
Ishigami, et al., *Nano Letters* **7**, 1643 (2007)



Residues from PMMA/MMA photoresist



Novel photoresist residue removal process
Anneal in flowing H_2 at 400°C



Complete removal of photoresist residues

Atomically clean STM images

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  - Charged impurities — minimum conductivity
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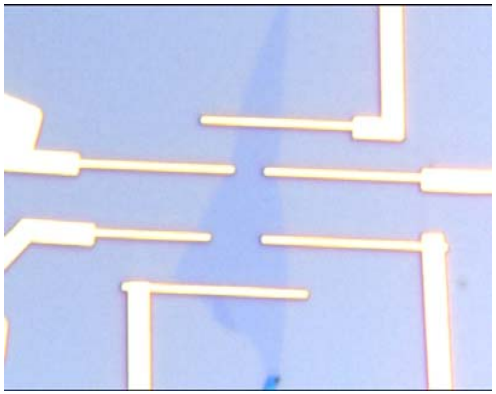
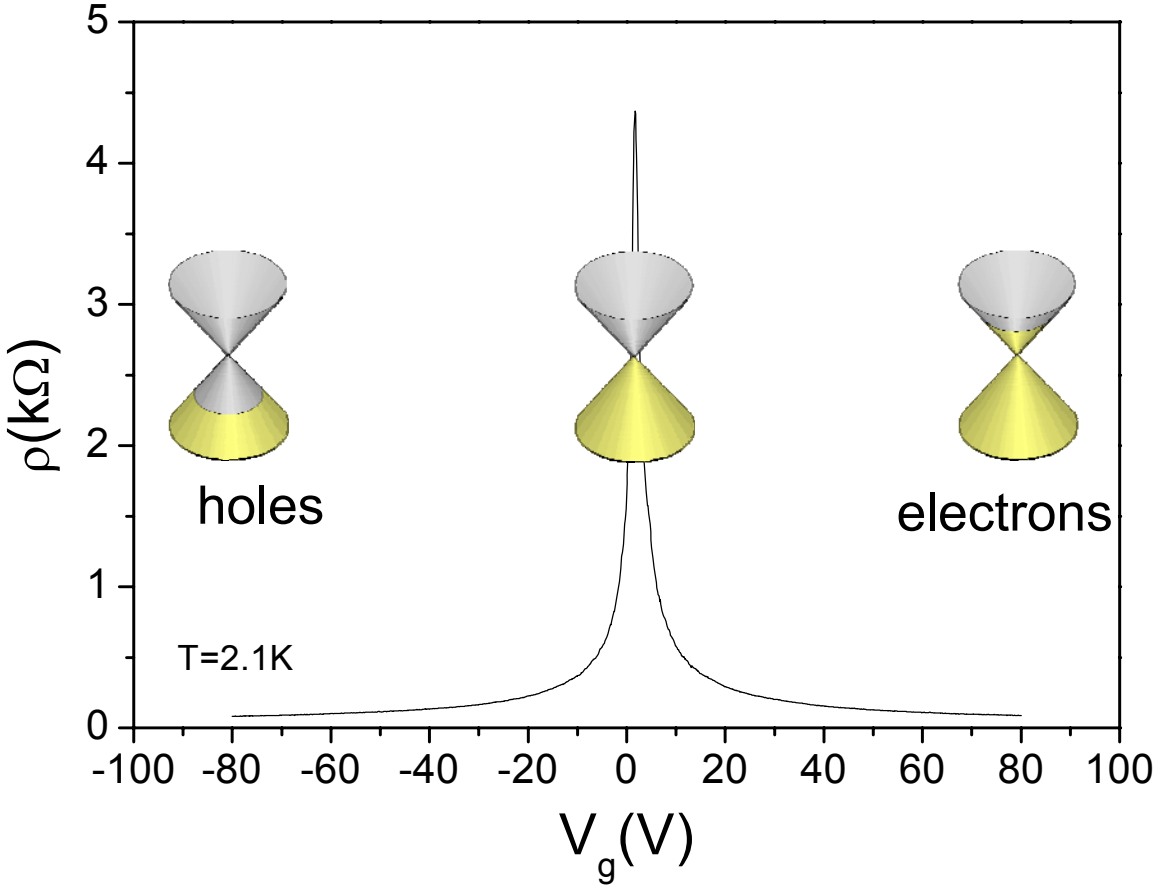
  - Corrugations
  - Lattice defects

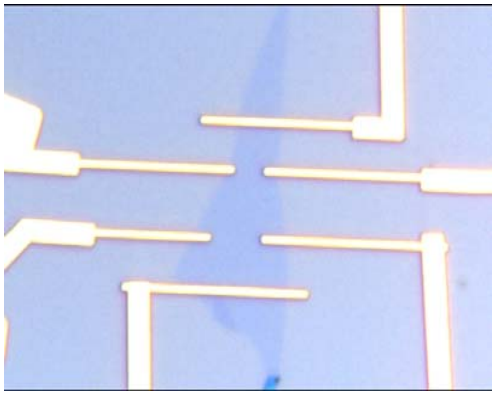
Electrical Characterization of Graphene

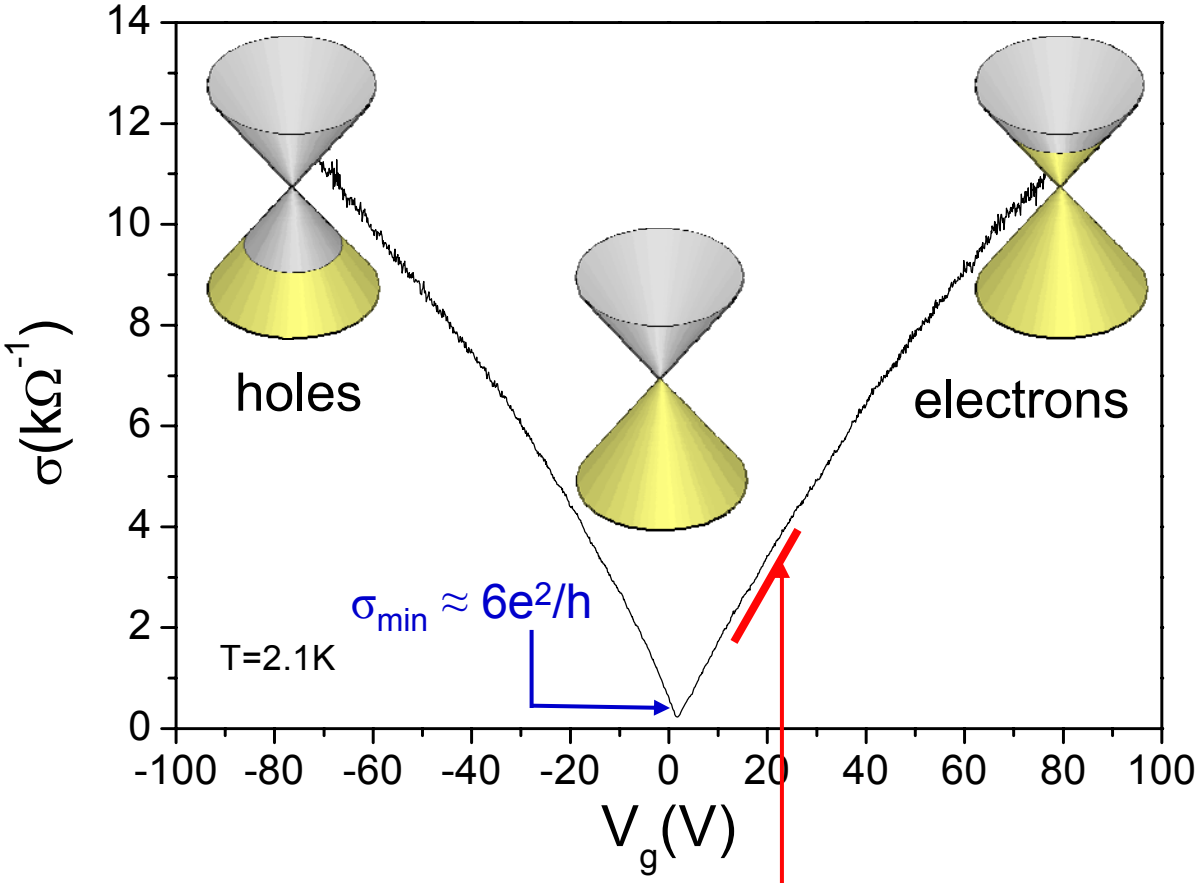




- Ambipolar, symmetric conduction
- Finite minimum conductivity ~ [4-10]e^2/h
- Field-effect mobility up to 20,000 cm^2/Vs

Electrical Characterization of Graphene





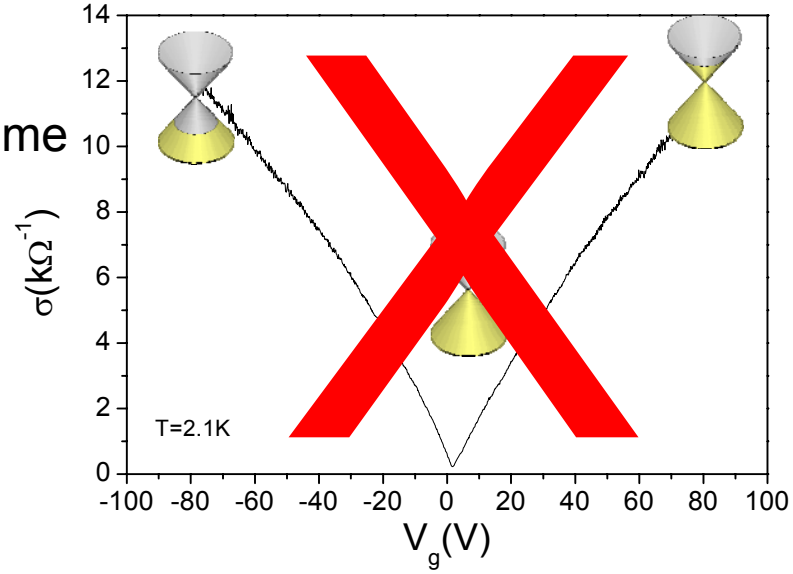
- Ambipolar, symmetric conduction
- Finite minimum conductivity ~ [4-10]e²/h
- Field-effect mobility up to 20,000 cm²/Vs

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

Boltzmann Transport

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

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

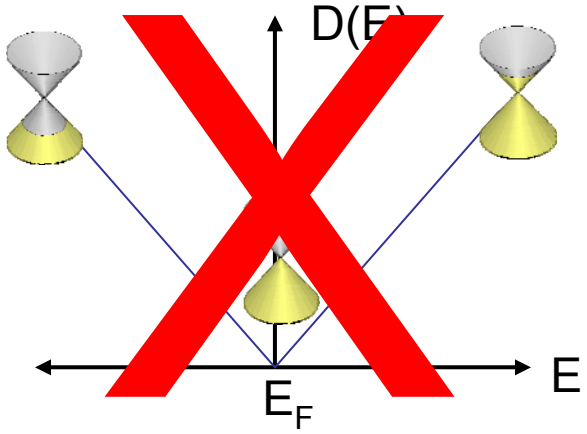


Graphene: $D(E) = \frac{2E_F}{\pi\hbar^2 v_F^2}$

But: Fermi's Golden Rule:

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

$$\therefore D(E)\tau \propto \text{constant!}$$

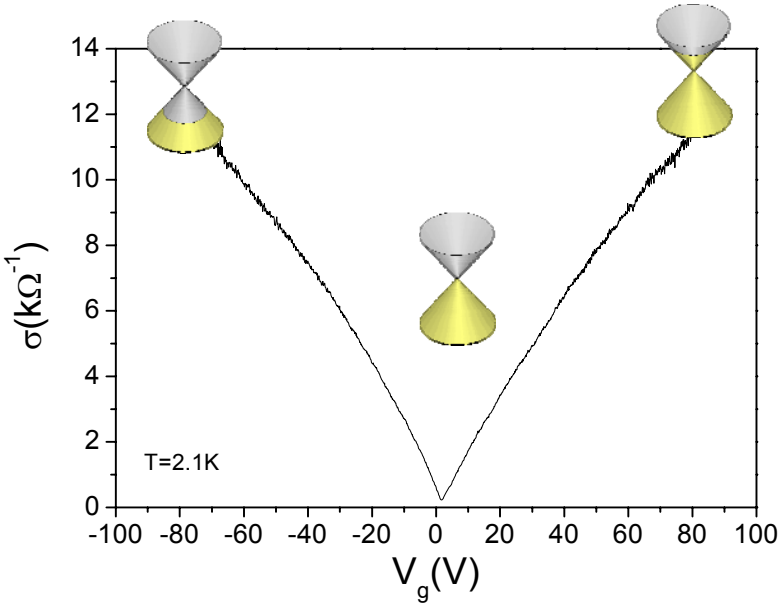


⇒ σ is independent of E_F!

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

How to explain linear $\sigma(V_g)$?

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



Interaction must be *q*-dependent

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

Coulomb interaction: $V_{Coulomb} = \frac{2\pi e^2}{\kappa q}$

N.B. In graphene, *screened* Coulomb interaction remains ~1/k_F

$\Rightarrow$ $\sigma \sim E_F^{1/2} \sim n \sim V_g$

See:
Ando, *J. Phys. Soc. Jpn.* **75**, 074716 (2006)
Nomura & MacDonald *PRL* **98**, 076602 (2007)
Cheianov & Fal'ko *PRL* **97**, 226801 (2006)
Hwang, Adam, & Das Sarma, *PRL* **98**, 186806 (2007)

Minimum Conductivity of Graphene

- At minimum conductivity point, graphene breaks into electron and hole "puddles"
- Minimum conductivity *decreases* with increasing impurity concentration

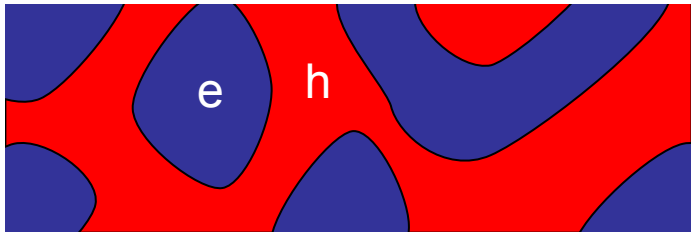
$$\sigma_{\min} = n^* e\mu$$

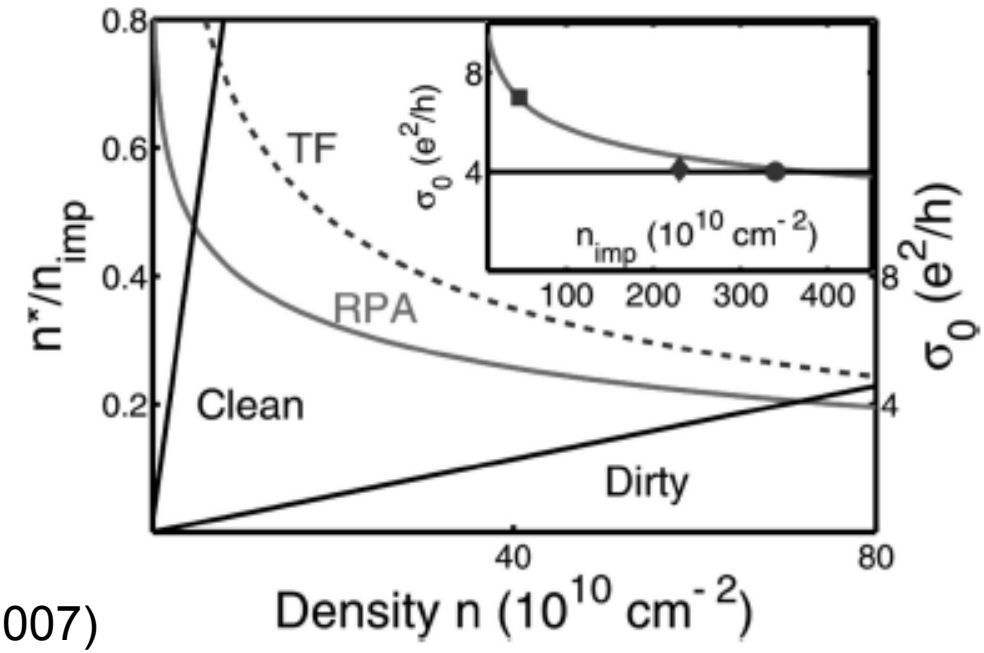
Residual density in puddles

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

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

Weak function of n_{imp}, r_s, d





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

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Charged Impurity Scattering: Potassium Doping in UHV

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

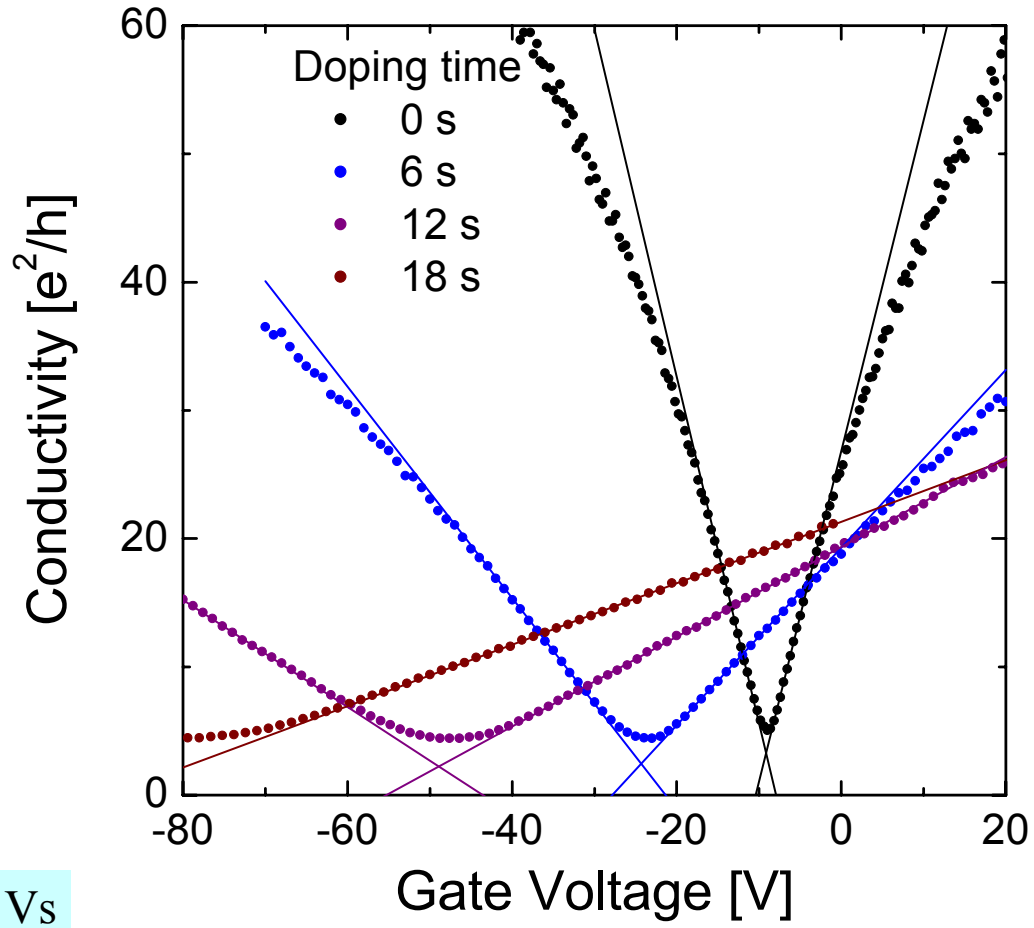
- Clean graphene in UHV at T = 20 K
- Potassium evaporated on graphene from getter

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:

$$\mu = \frac{5\text{x}10^{11}\,\text{Vs}}{n_{imp}}$$

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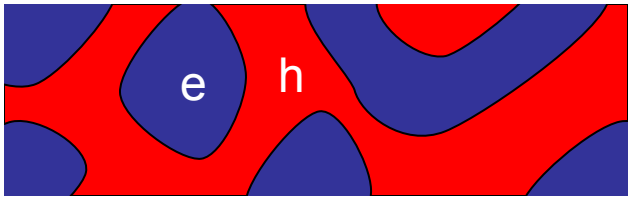
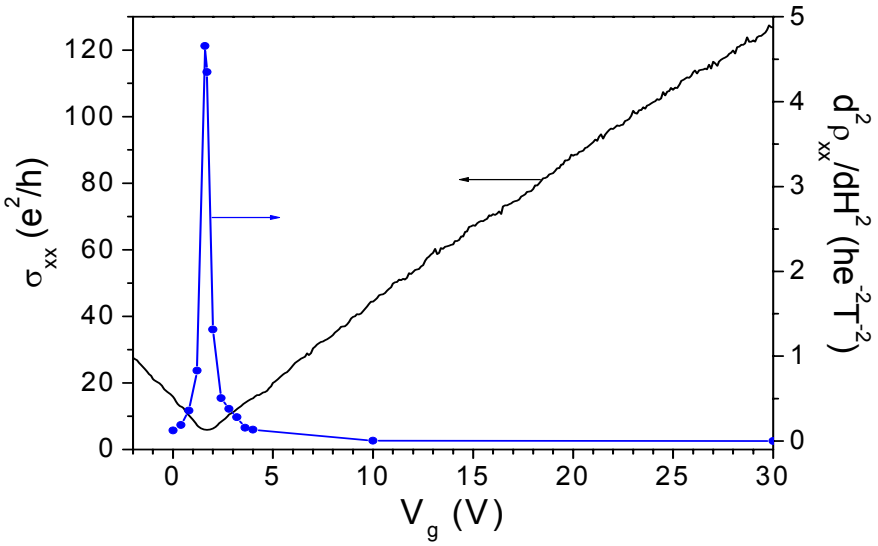
Magnetoresistance at Minimum Conductivity Point

S. Cho and M. S. Fuhrer, *PRB* **77**, 084102(R) (2008)

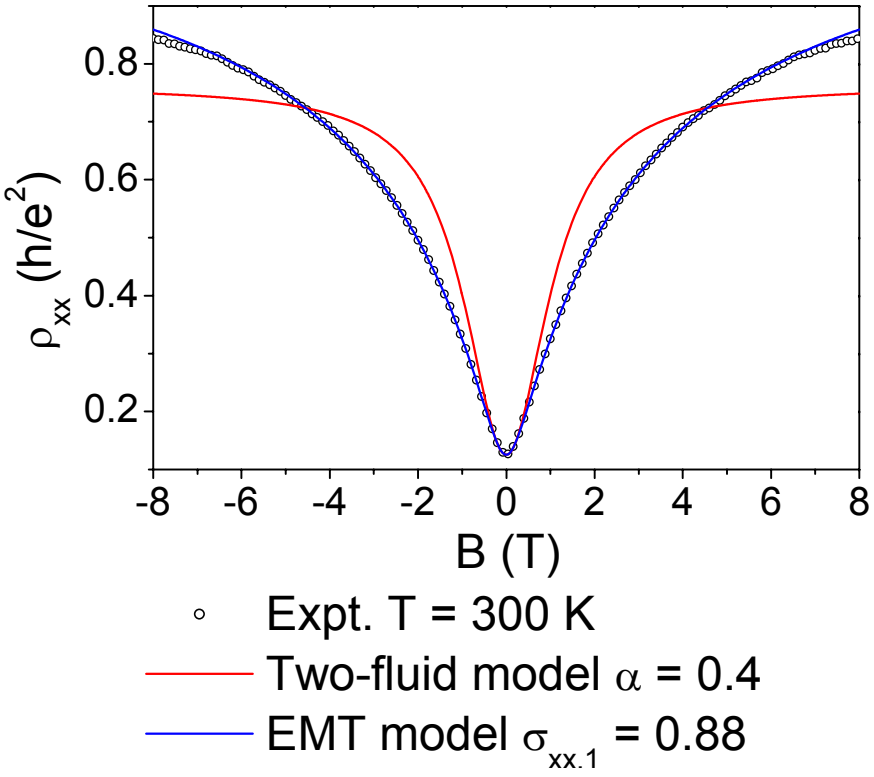
- At minimum conductivity point, graphene breaks into electron and hole "puddles"

  Hwang, et al., *PRL* **98,** 186806 (2007); Adam, et al., *PNAS* **104**, 18392 (2007)





Large spike in magnetoresistance at Dirac point



Functional form of ρ(B):

effective medium theory for inhomogeneous e/h regions

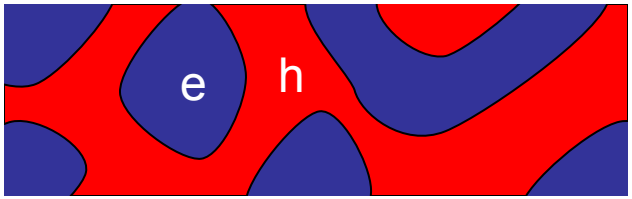
[Guttal and Stroud, *PRB* **71** 201304 (2005)]

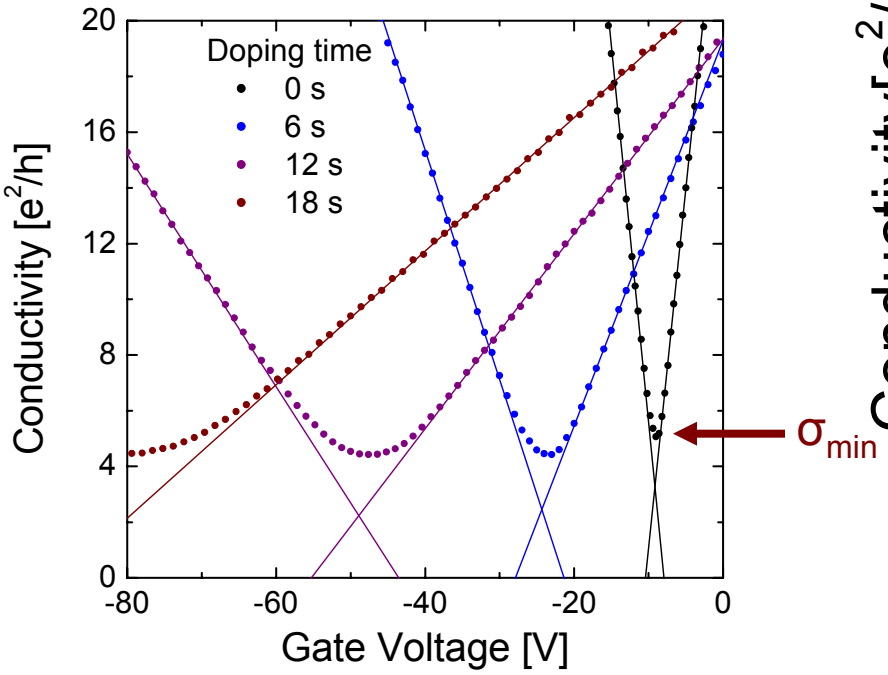
Charged Impurity Scattering: Minimum Conductivity

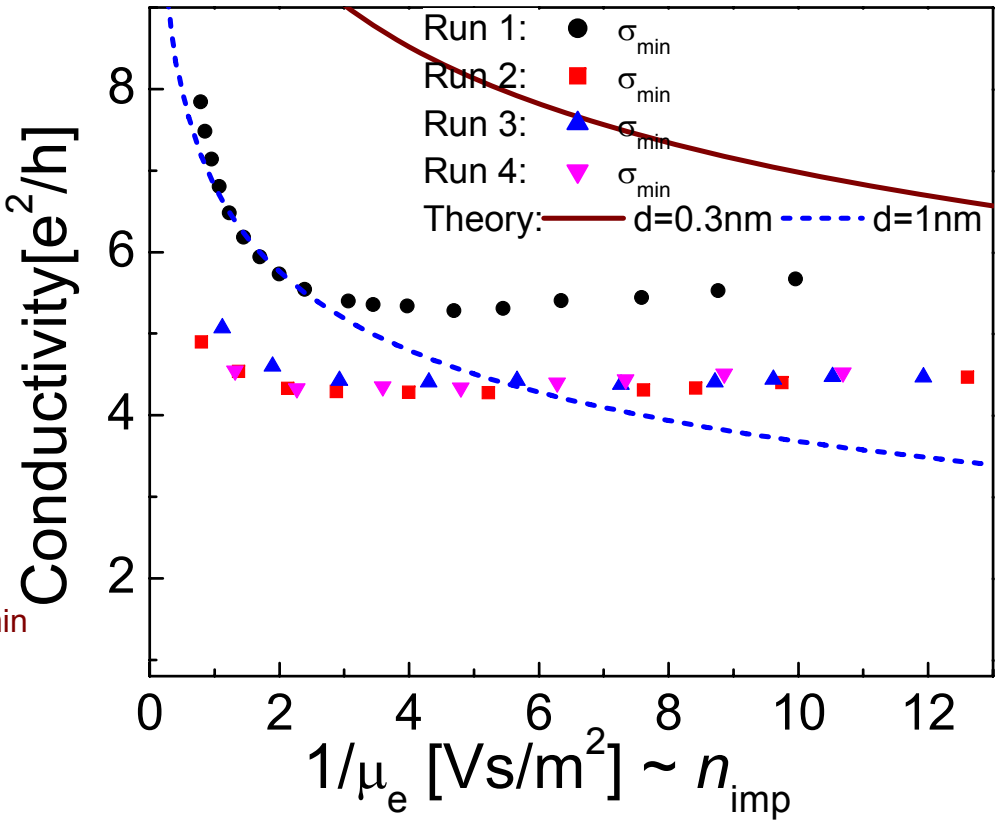
J. H. Chen, et al. *Nature Physics* **4**, 377 (2008)

- At minimum conductivity point, graphene breaks into electron and hole "puddles"
- Minimum conductivity *decreases* with increasing impurity concentration

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







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Electron-Phonon Scattering

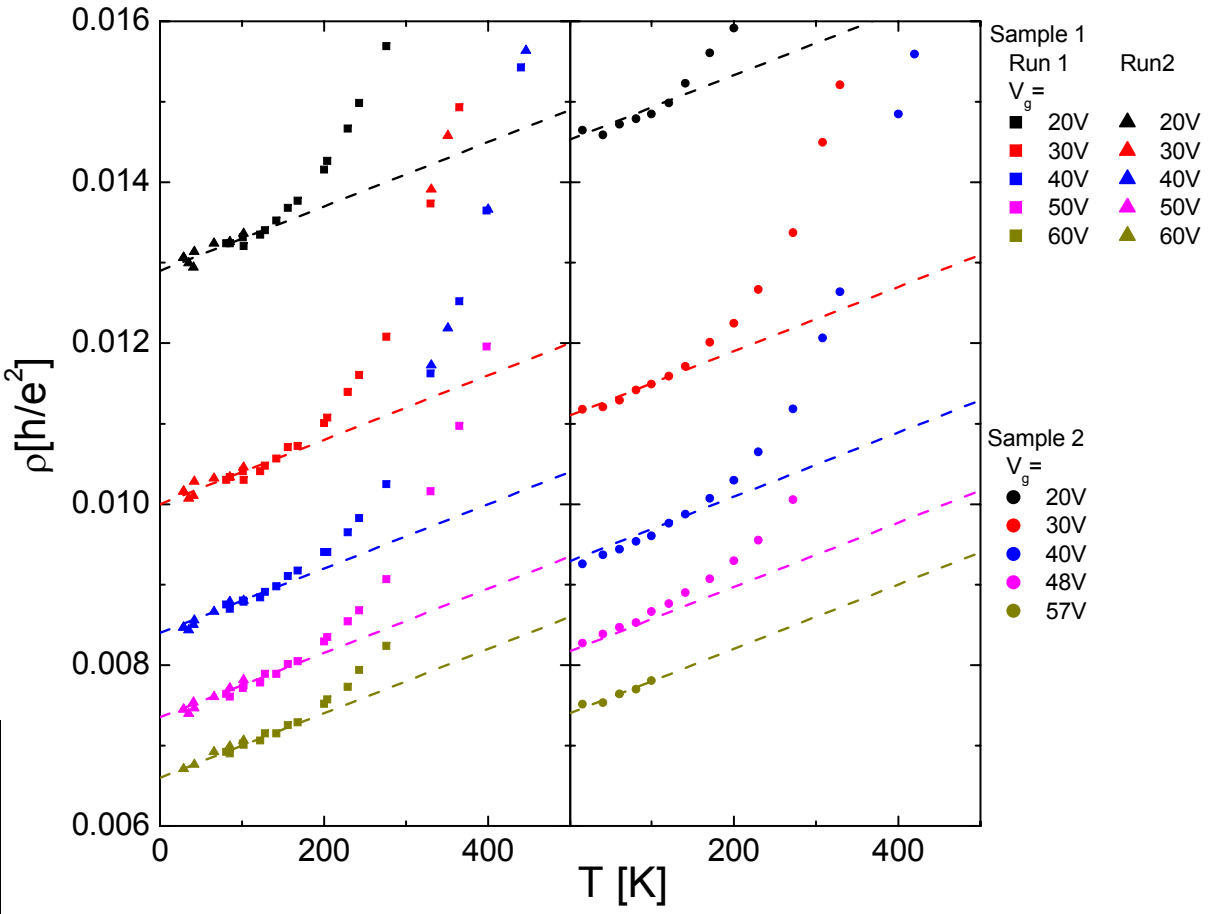
J. H. Chen, et al. *Nature Nanotechnology* **3**, 206 (2008)

Linear *T*-dependence at low *T*

Longitudinal acoustic phonons in graphene

$\rho = \rho_0 + AT$
$A = 0.1\ \Omega/K$

A is independent of charge carrier density, as predicted



$$\rho_A(T) = \left(\frac{h}{e^2}\right)\frac{D_A^2 k_B T}{16 e^2 \hbar^2 \rho_s v_s^2 v_F^{\ 2}}$$

→ **D_A = 18 ± 1 eV**

(good agreement w/CNT, graphite)

Electron-Phonon Scattering

J. H. Chen, et al. *Nature Nanotechnology* **3**, 206 (2008)

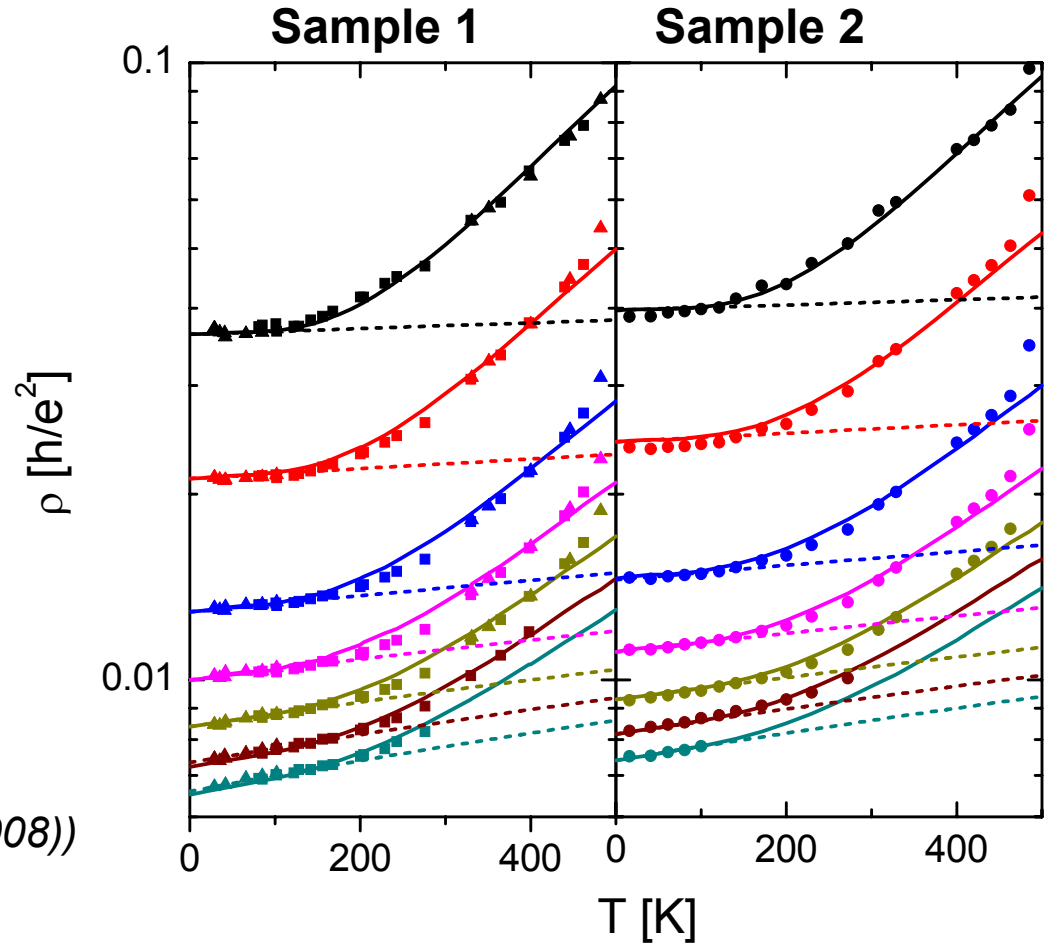
Activated *T*-dependence at high *T*

Consistent with:

LA phonons in graphene

$$\rho(n,T) = \rho_0 + AT + Bn^{-\alpha}\left(\frac{1}{e^{(59meV)/k_BT}-1} + \frac{6.5}{e^{(155meV)/k_BT}-1}\right)$$

polar optical surface phonons in SiO_2
*(see Fratini and Guinea, PRB **77**, 195415 (2008))*



(3 global fit parameters for all curves)

Potential due to polar optical phonons is long-ranged; leads to density-dependent resistivity

Mobility Limits in Graphene

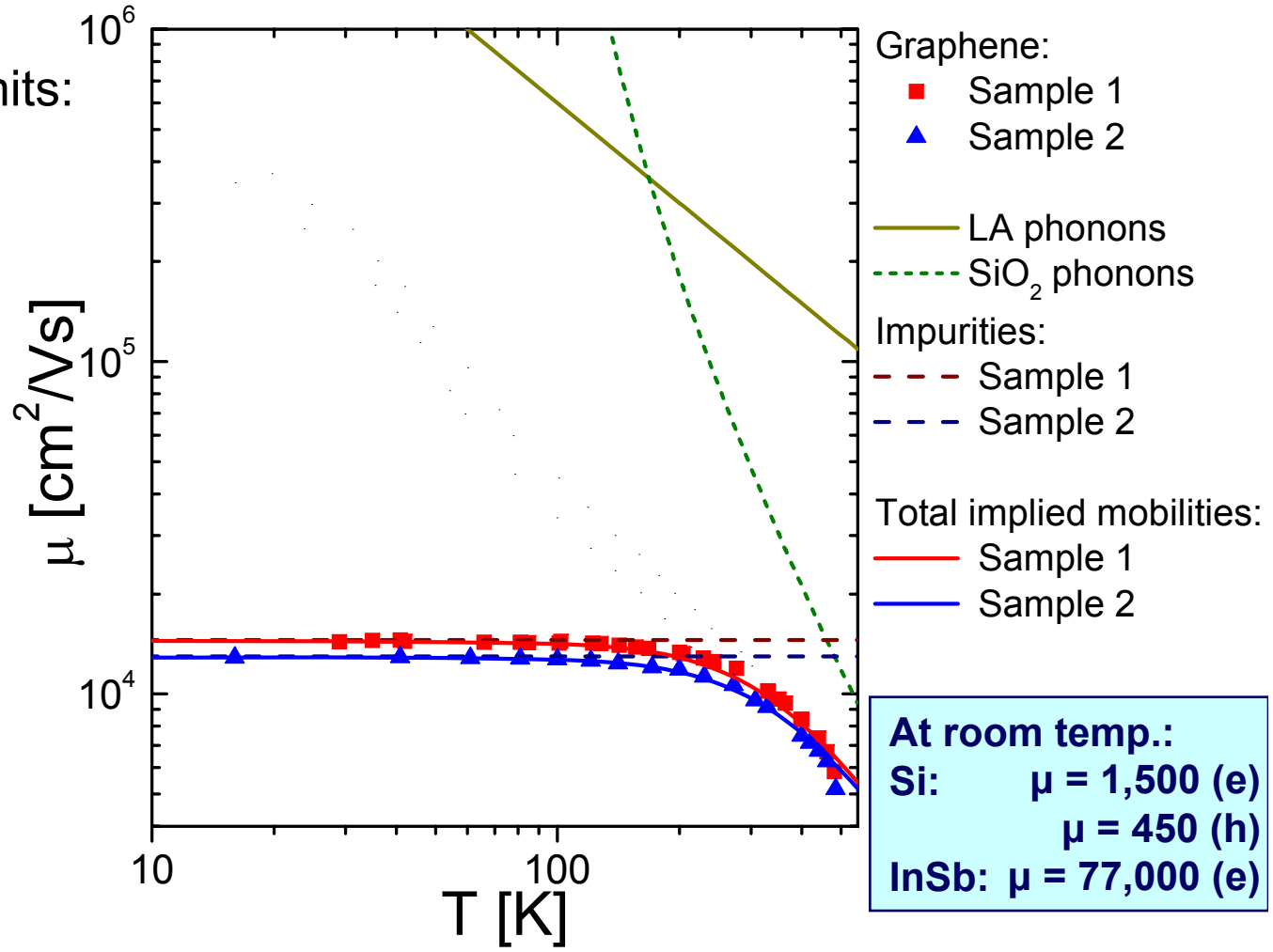
J. H. Chen, et al. *Nature Nanotechnology* **3**, 206 (2008)

Room Temperature Limits:

Currently:
μ_{RT} ~ 10,000 cm²/Vs
(charged impurities)

Substrate-limited:
SiO_2 surface phonons:
μ_{RT} ~ 40,000 cm²/Vs

Intrinsic:
acoustic phonons:
μ_{RT} ~ 200,000 cm²/Vs
@ n = 10^{12} cm^{-2}



Room temperature mobility of **200,000 cm²/Vs** possible!

Ballistic transport over >2 microns

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r_s in graphene?

$$r_s = \frac{a}{a_b} = \frac{m^* e^2}{4\pi^{3/2}\varepsilon\hbar^2 n^{1/2}}$$

Problem: what is mass?
(no characteristic length a_b for massless particles)

There still exists a unitless quantity:

$$r_s = \frac{U}{K}$$

U = potential energy of two electrons at distance a

K = kinetic energy of electron with wavelength $\lambda = 2\pi a$

Massive particles:

$$r_s = \frac{U}{K} = \frac{a}{a_b}$$

$$U = \frac{e^2}{4\pi\varepsilon a}$$

$$K = \hbar v_F k = \frac{\hbar v_F}{a}$$

$$r_s = \frac{e^2}{4\pi\varepsilon\hbar v_F}$$

Independent of density!

Graphene's Fine Structure Constant?

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137.036}$$

α is fine structure constant
"coupling constant" – describes relative strength of Coulomb interaction

For graphene, define:

$$\alpha \equiv r_s = \frac{e^2}{4\pi\varepsilon\hbar v_F}$$

Fine structure constant, with
$c \rightarrow v_F$
$\varepsilon_0 \rightarrow \varepsilon$
describes strength of Coulomb interaction

For:
$v_F = 10^8$ m/s = $c/300$
$\varepsilon = 2.5\varepsilon_0$

$$\alpha \approx 1$$

Graphene is:
weakly interacting for condensed matter,
strongly interacting for relativistic Fermions

Interesting opportunities:
Atomic collapse of hypercritical nuclei: $Z_c = 1/\alpha = 137$ (difficult to achieve in nuclear physics),
Possible in graphene where $Z_c \approx 1$

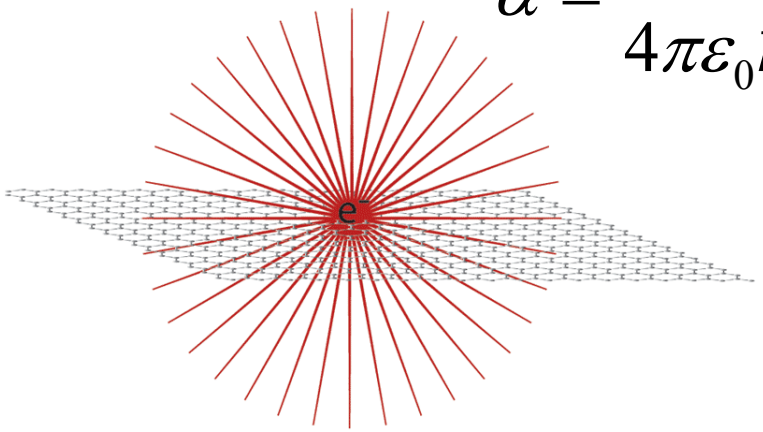
Tuning the "Fine Structure Constant"

C. Jang, et al. *Physical Review Letters* **101**, 146805 (2008)

Conventional 2D electron system:

$$r_s = \frac{m^* e^2}{4\pi^{3/2}\varepsilon\hbar^2 n^{1/2}}$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar v_F}$$

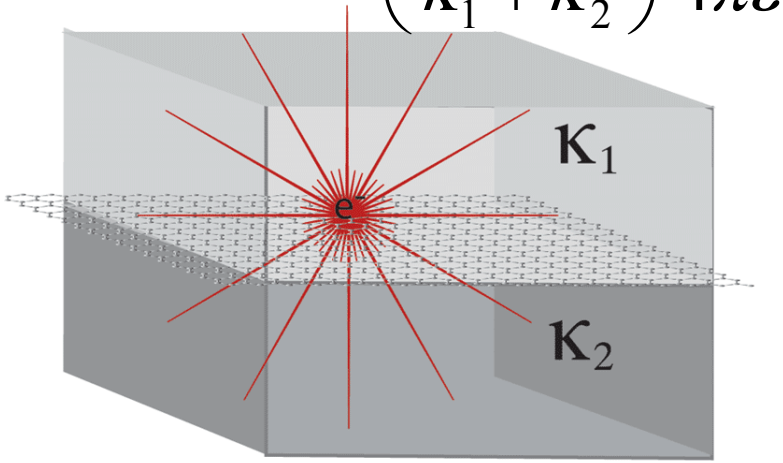


Tune r_s thru density n

Graphene:

$$\alpha = \frac{e^2}{4\pi\varepsilon\hbar v_F} = \frac{e^2}{4\pi\kappa\varepsilon_0\hbar v_F}$$

$$\alpha = \left(\frac{2}{\kappa_1 + \kappa_2}\right)\frac{e^2}{4\pi\varepsilon_0\hbar v_F}$$



Graphene's "Fine Structure Constant"
α independent of n

But, can tune κ!

Two Effects of Dielectric Screening

C. Jang, et al. *Physical Review Letters* **101**, 146805 (2008)

Reducing α:

- Reduces interaction of carriers with charged impurities
  - Dominant effect for charged-impurity scattering
- Reduces screening by carriers
  - Dominant effect for short-range scattering

Within RPA:

$$\sigma_L = \frac{2e^2}{h}\frac{n}{n_{imp}}\frac{1}{F_L(\alpha)}; \qquad F_L(\alpha) = \pi\alpha^2 + \ldots$$

Coulomb scattering reduced:
Mobility μ_L *increases*

$$\sigma_S = \frac{\sigma_0}{F_S(\alpha)}; \qquad F_S(\alpha) = \frac{\pi}{2} - \frac{32\alpha}{3} + \ldots$$

Short-range scattering increased:
Conductivity σ_S *decreases*

$$\sigma_{\min} = n^* e\mu_L; \quad n^* \sim \alpha^2; \quad \mu_L \sim \frac{1}{\alpha^2}$$

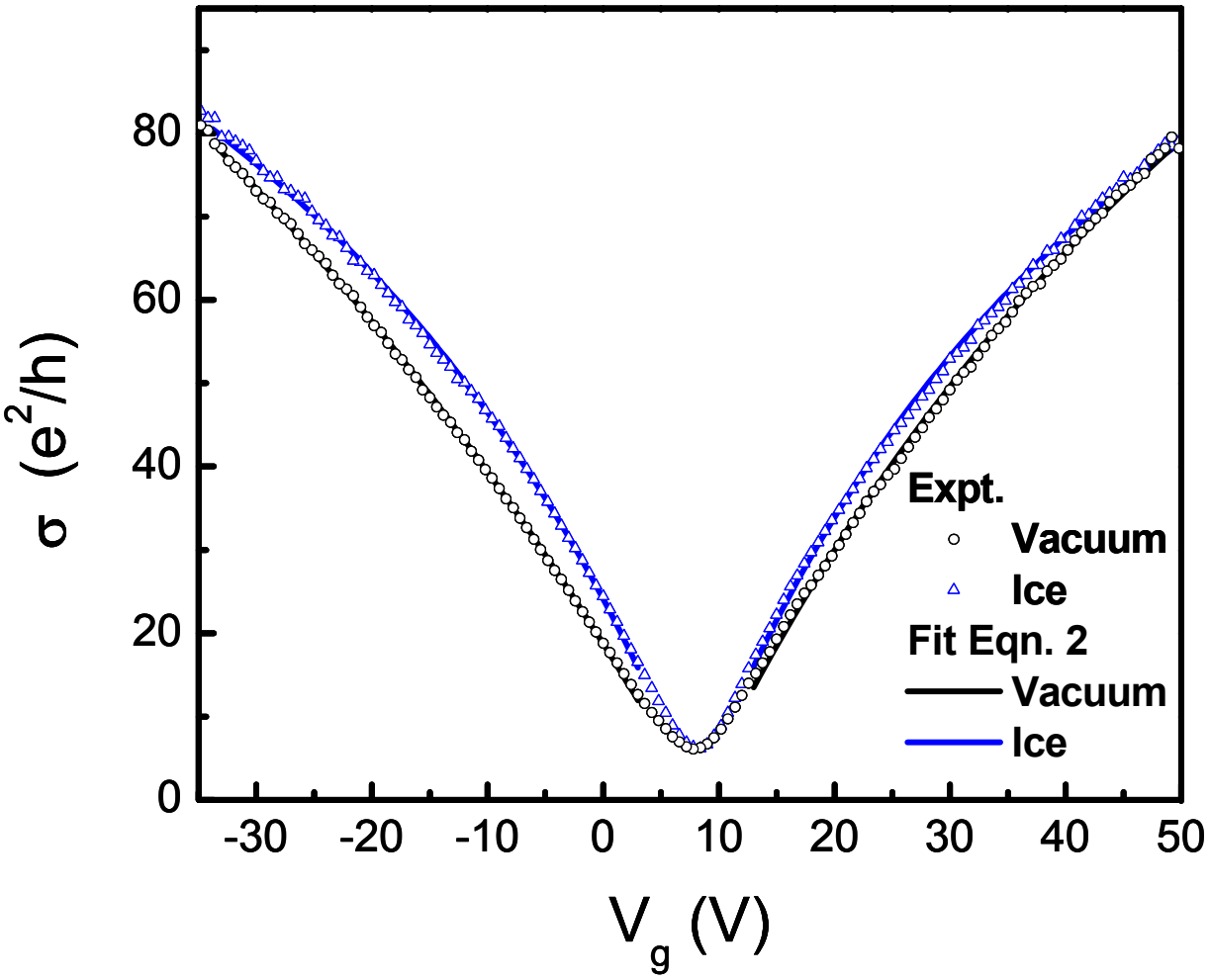
e-h puddle density decreased, mobility increased:
Min. conductivity σ_{min} *constant*

Effects of Dielectric Screening

C. Jang, et al. *Physical Review Letters* **101**, 146805 (2008)

Add ice to clean graphene in UHV:

α (SiO_2/vacuum) = 0.81 α (SiO_2/ice) = 0.56



Fit:

$$\sigma^{-1} = (ne\mu_L)^{-1} + \sigma_S^{-1}$$

Coulomb (long-range) scattering

Short-range scattering

(slight asymmetry in Coulomb scattering; take symmetric component of each)

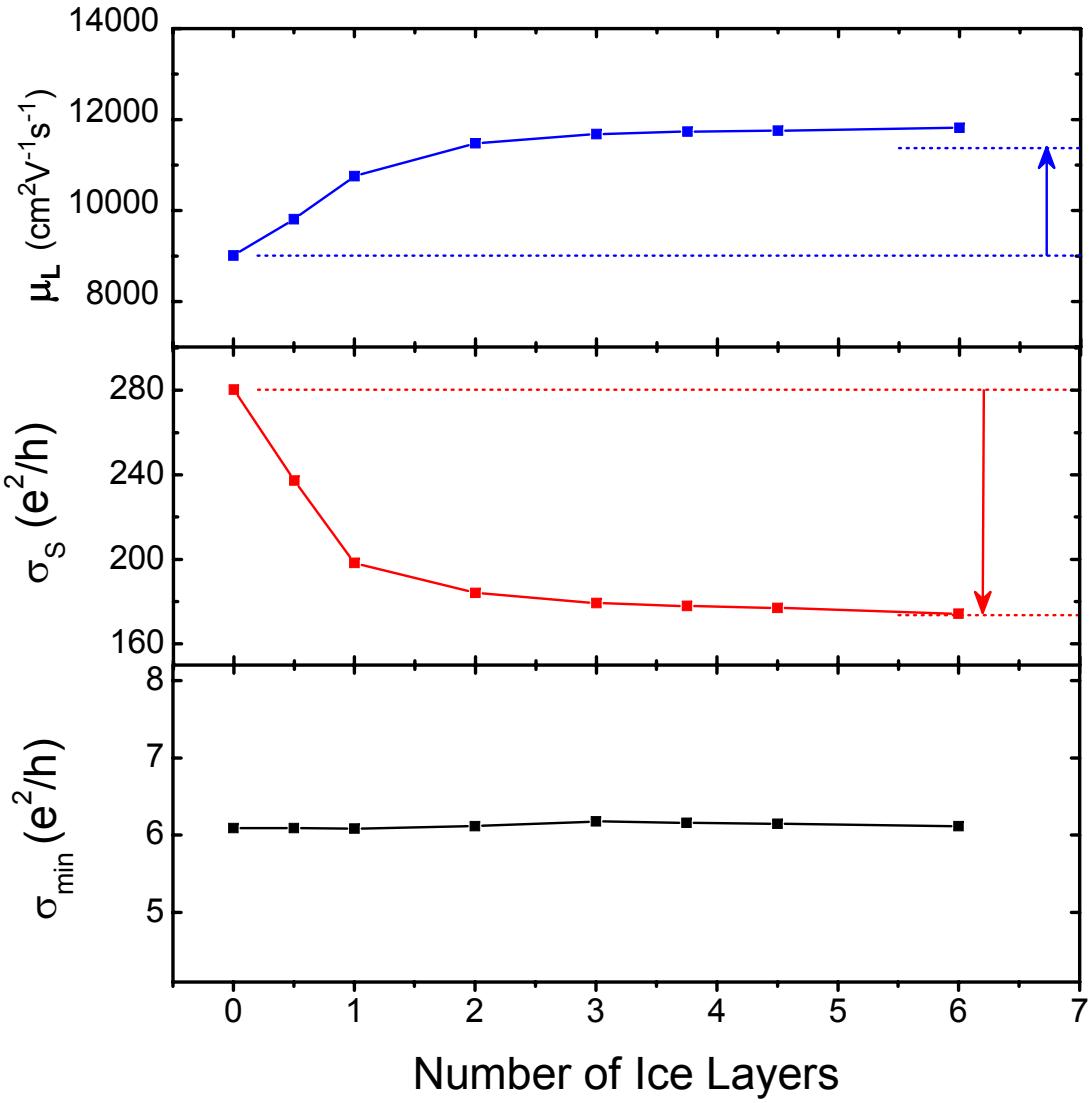
Dielectric Screening: Theory and Expt.

C. Jang, et al. *Physical Review Letters* **101**, 146805 (2008)

Coulomb scattering reduced:
Mobility μ_L *increases*

Short-range scattering increased:
Conductivity σ_S *decreases*

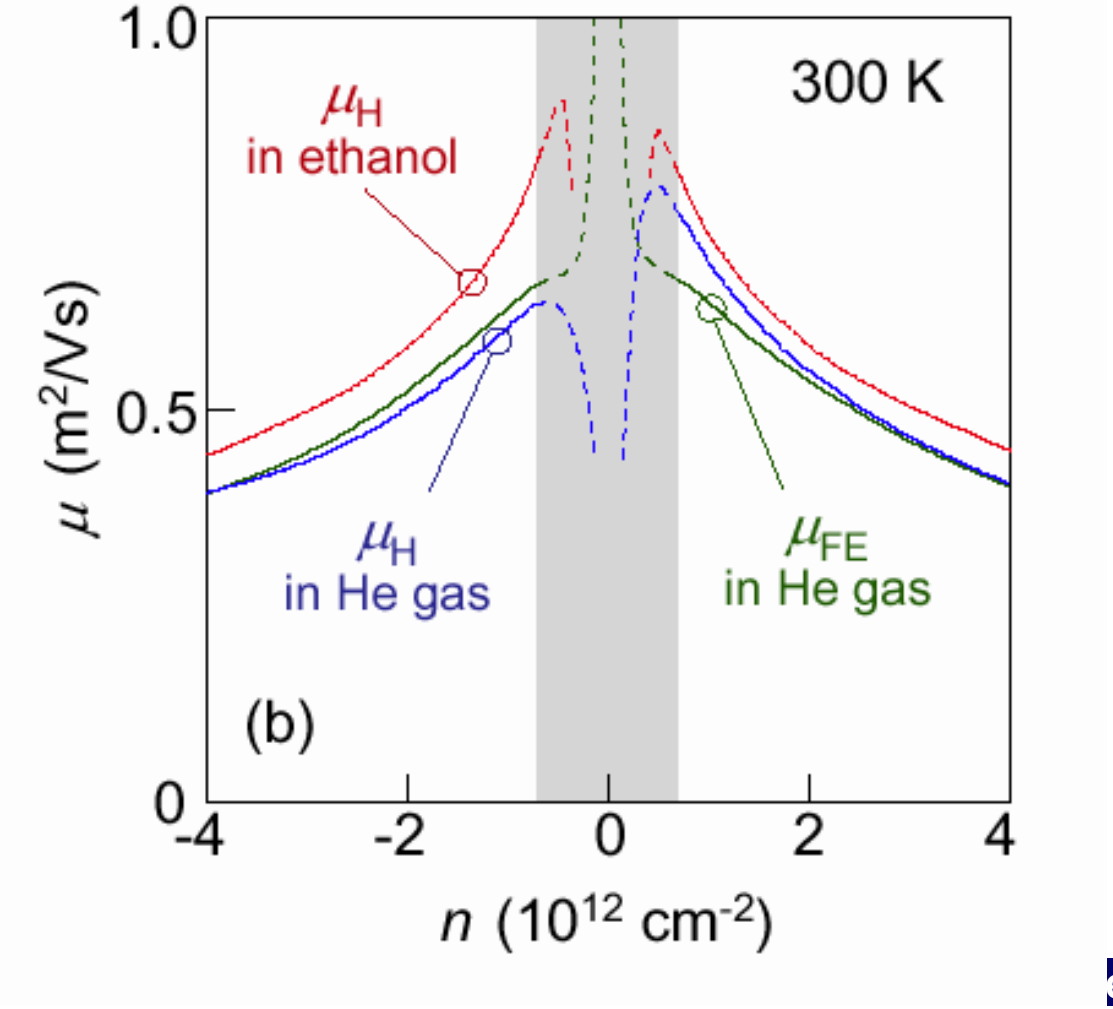
e-h puddle density decreased, mobility increased:
Min. conductivity σ_{min} *constant*



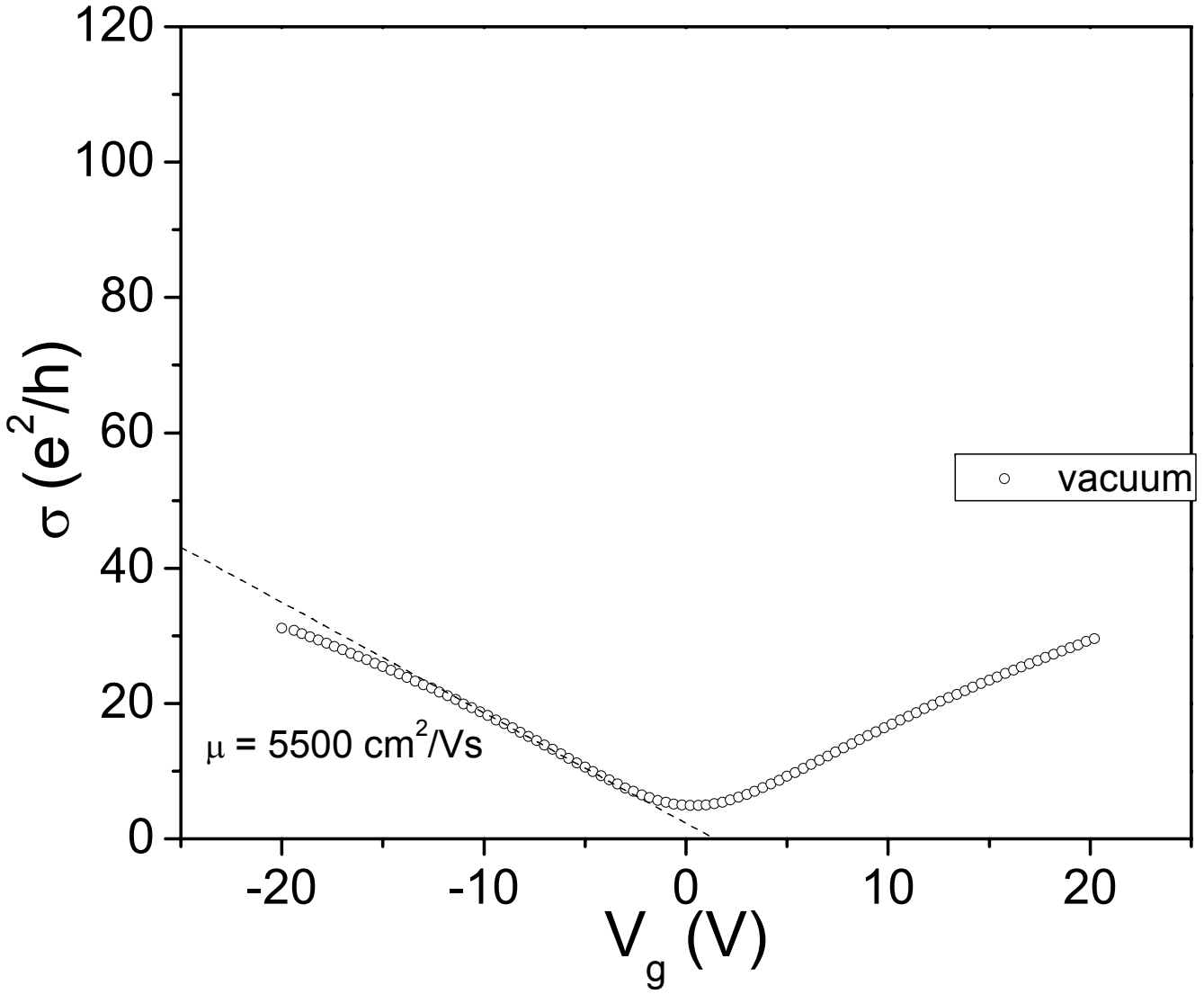
Graphene in high-K liquids – a mystery?

T. M. Mohiuddin et al. Arxiv:0809.1162 (Manchester group)

- Mobility increases <50% in ethanol (κ = 25) and liquid water (κ = 80)
- Concluded that charged impurities NOT dominant scatterers in graphene

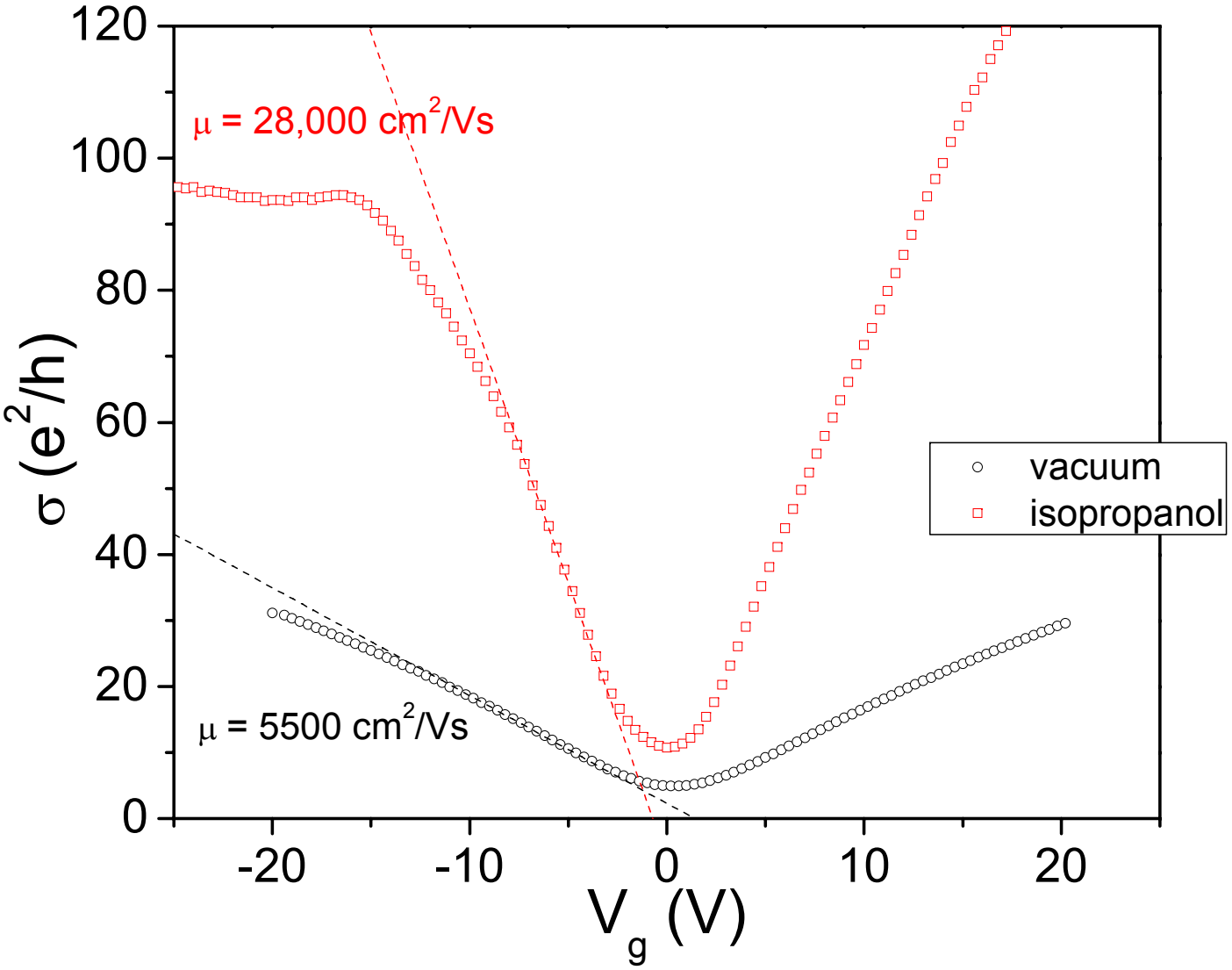


Graphene in high-K liquids – our group



Graphene in high-K liquids – our group

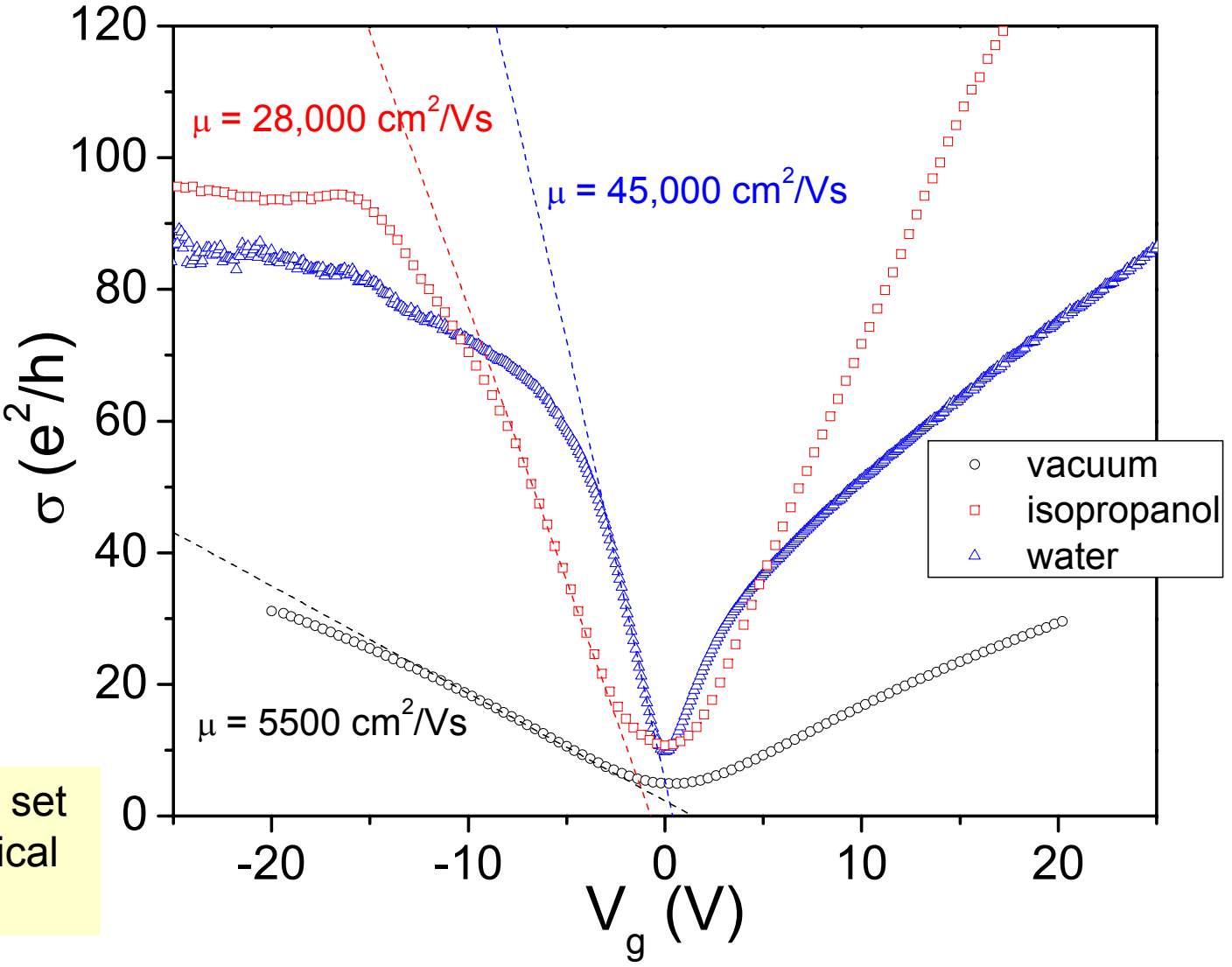
Isopropanol
κ = 19.9
α = 0.167
Mobility up 510%



Graphene in high-K liquids – our group

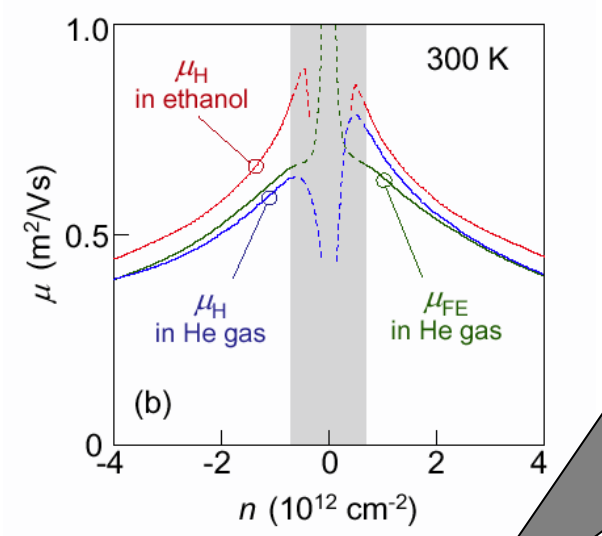
Isopropanol
κ = 19.9
α = 0.167
Mobility up 510%

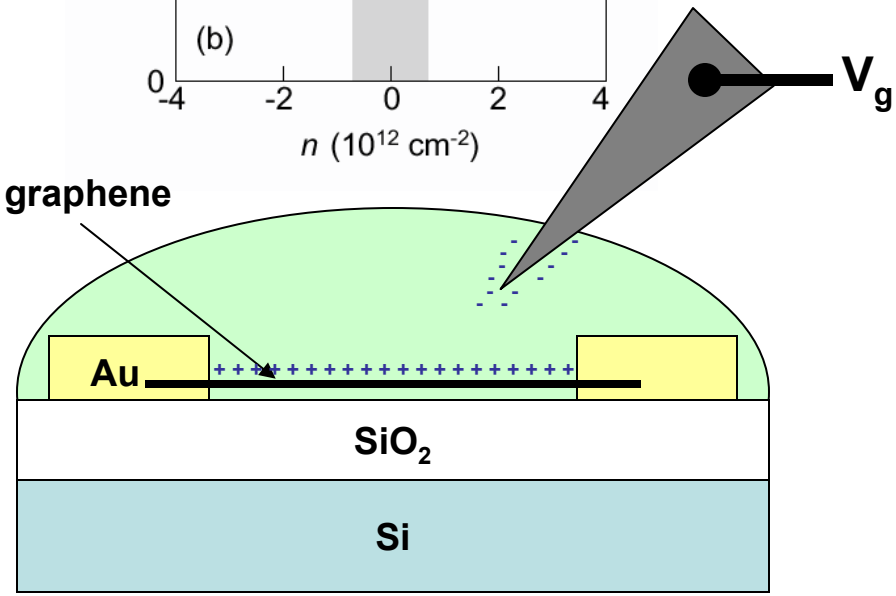
DI Water
κ = 80
α = 0.047
Mobility up 820%

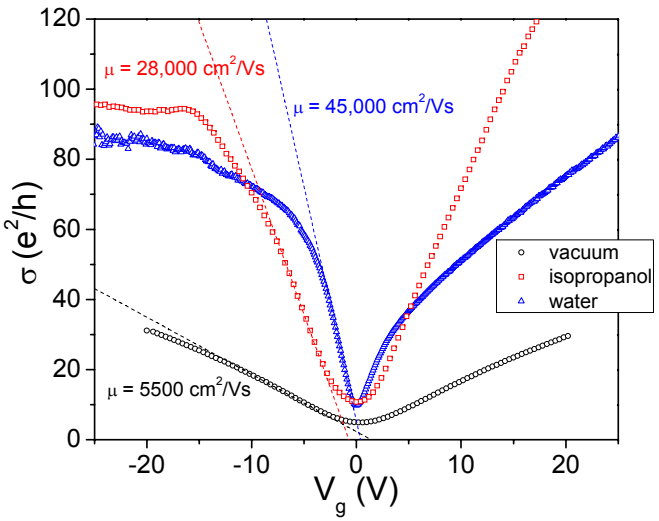


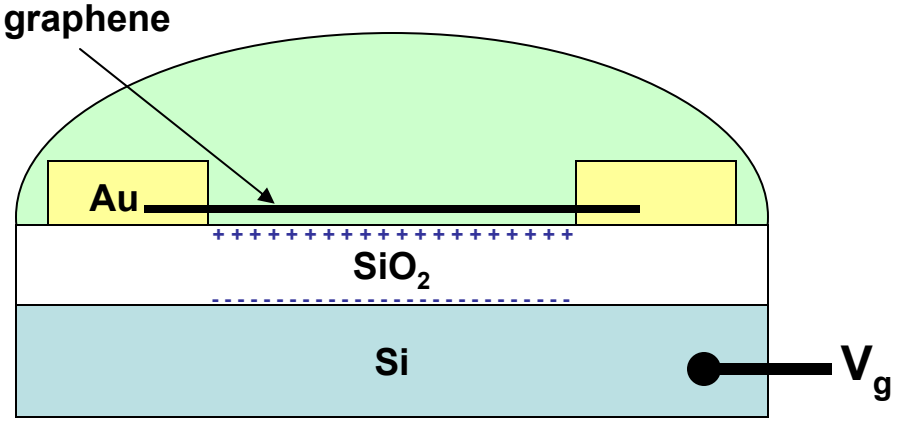
Possibly reaching limit set by substrate polar optical phonons

What is the difference?









Mohiuddin et al. :
- Used electrolyte as gate
- Gate charges are ions → scatterers!

Our work :
- Used SiO_2 back-gate
- No add'l scatterers

Outline

I. Introduction to Graphene
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- Pseudospin and Berry's phase

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Graphene Corrugation - Scattering

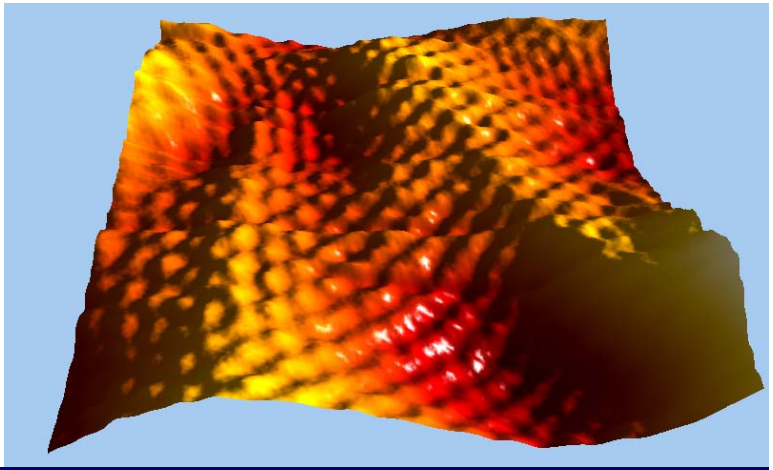
$$\sigma = \frac{2e^2}{h} E_F \tau \qquad \frac{1}{\tau} \propto \frac{2\pi}{\hbar} \left| \langle k | V | k' \rangle \right|^2 D(E)$$

q-dependent interaction
→ carrier-density dependent σ(n)

1) Coulomb interaction: $q = |\boldsymbol{k} - \boldsymbol{k}'| \sim k_F \Longrightarrow \sigma \sim n$

2) Corrugated graphene†: $\underbrace{\langle [h(r) - h(0)]^2 \rangle}_{\text{height-height correlation function}} \propto r^{2H} \Longrightarrow \sigma \sim n^{2H-1}$

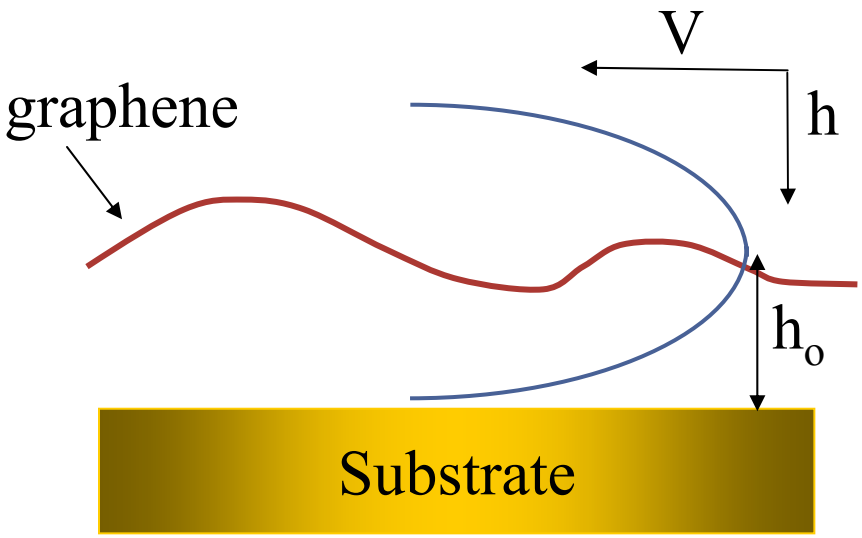
†Katsnelson & Geim, *Phil. Trans. R. Soc. A* **366**, 195-204 (2008)



What is exponent 2H?

Graphene Corrugation

Model 1:
Intrinsic graphene bending constrained via interface confining potential

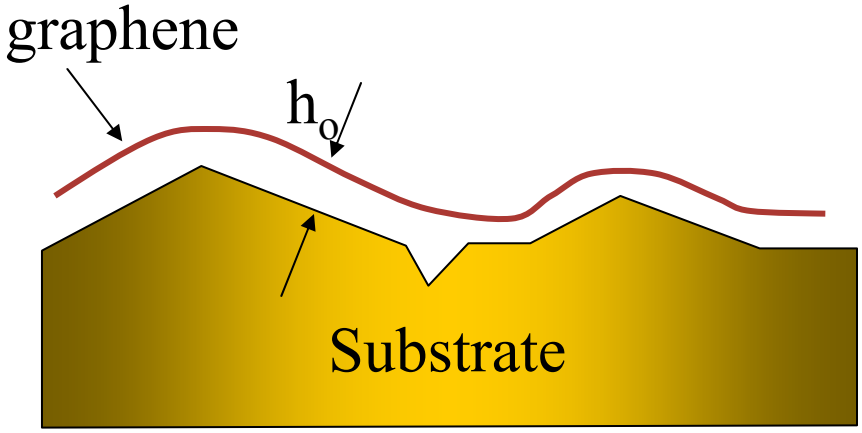


$$F = \frac{1}{2}\kappa\left[\nabla^2 h(x,y)\right]^2 + \frac{1}{2}Vh^2(x,y)$$

$$\left\langle \left(h(r)-h(0)\right)^2 \right\rangle \sim r^2$$

σ(*n*) ~ *n*
(mimics Coulomb scatting)

Model 2:
Corrugations determined by strong direct interaction governed by height variations of the substrate



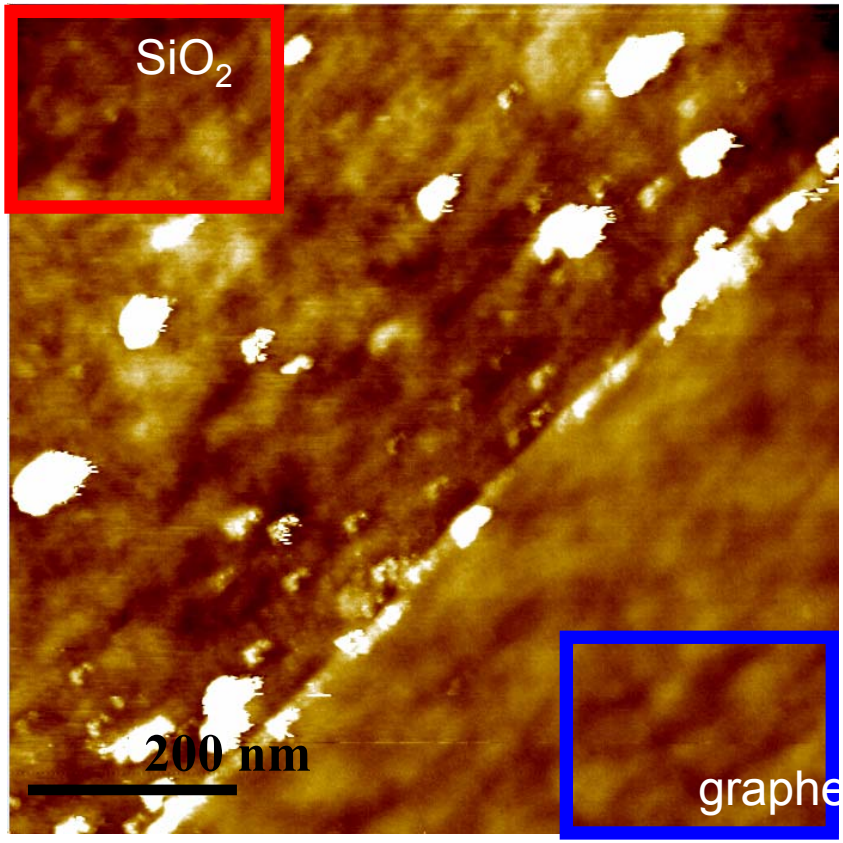
Height-height correlations will match those of the substrate.

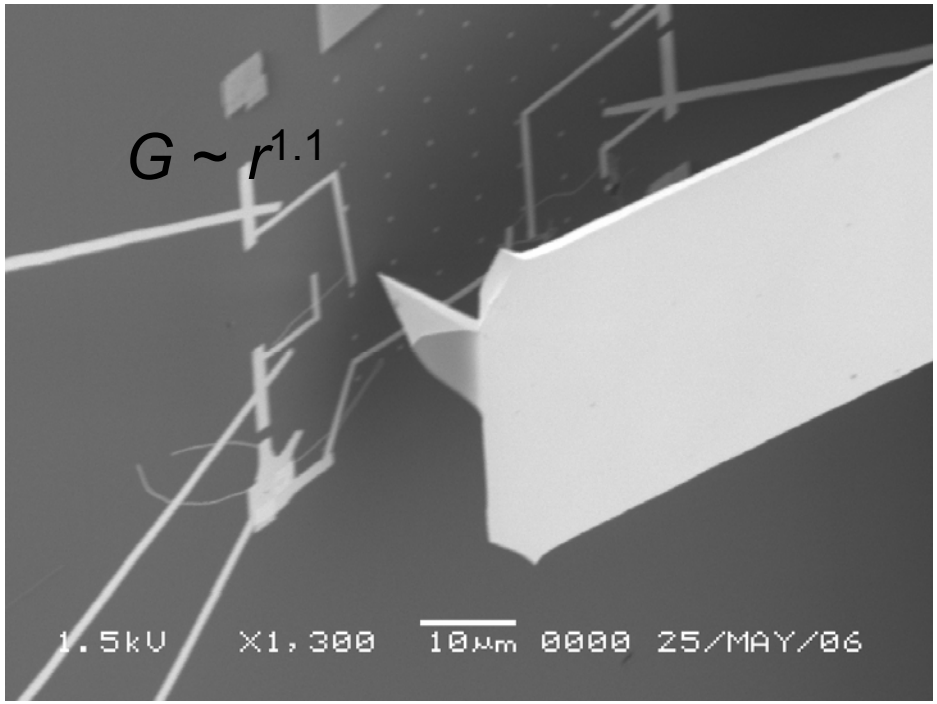
Typical non-equilibrium surfaces show: $\left\langle \left(h(r)-h(0)\right)^2 \right\rangle \sim r^{2H}$ with 2H ≈ 1.

σ(*n*) ~ *constant*
(mimics short range scattering)

Graphene Corrugations on SiO_2

Non-contact AFM image in UHV



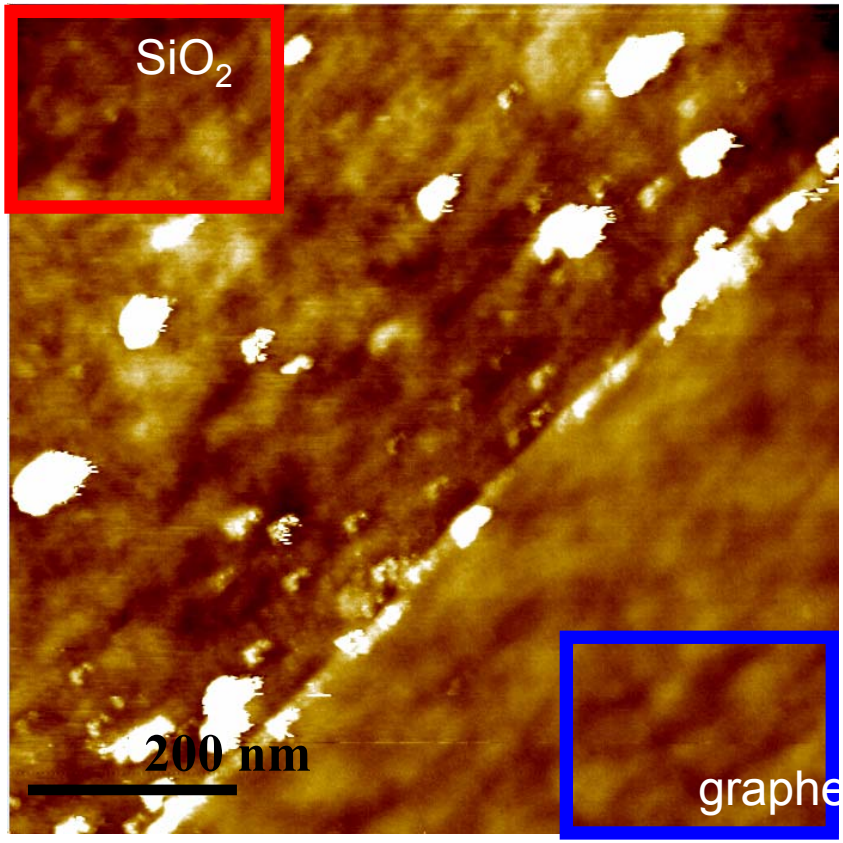


Height [nm]

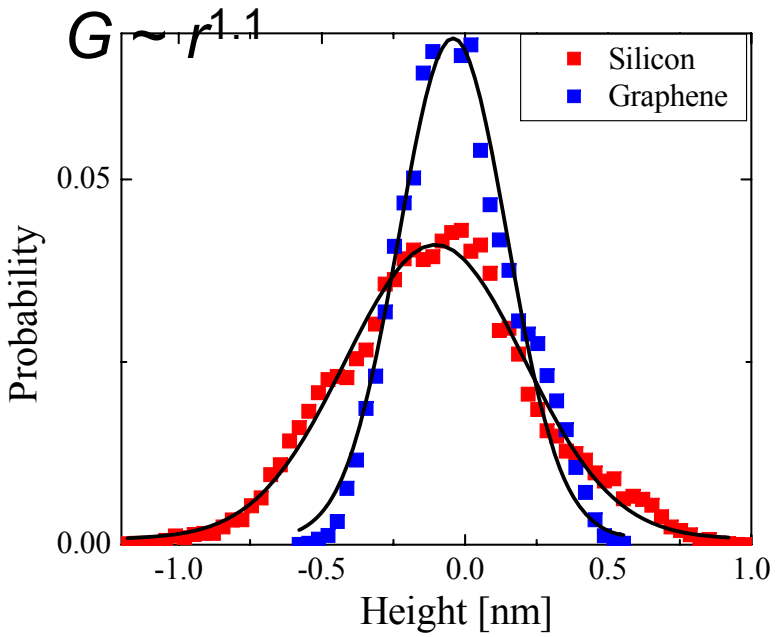
M. Ishigami et al., *Nano Letters* 7, 1643 (2007)

Graphene Corrugations on SiO_2

Non-contact AFM image in UHV



Oxide-graphene boundary

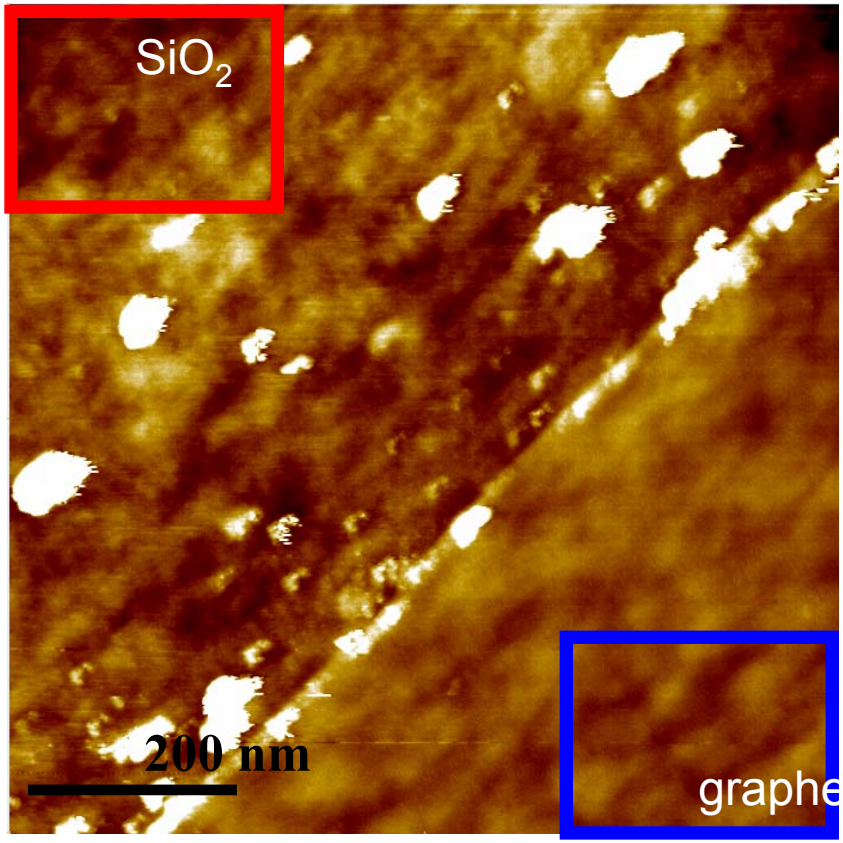


- σ_{oxide} = 3.1 Å and $\sigma_{graphene}$ = 1.9 Å
- Graphene 60% smoother than SiO_2

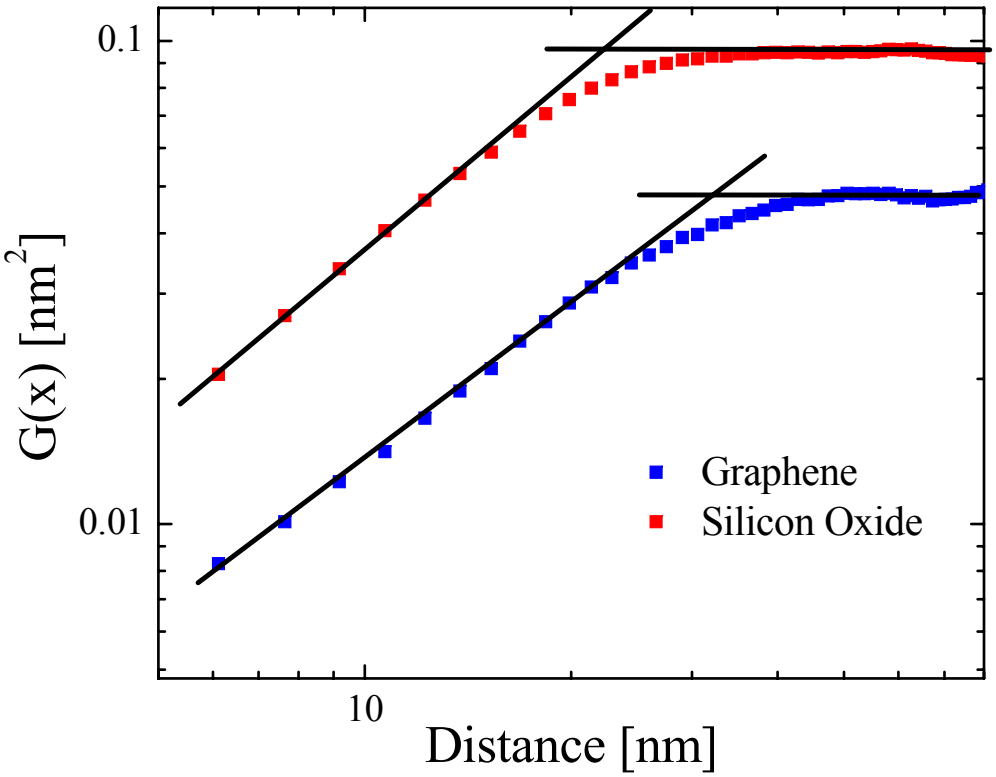
M. Ishigami et al., *Nano Letters* 7, 1643 (2007)

Graphene Corrugations on SiO_2

Non-contact AFM image in UHV



Oxide-graphene boundary



Height-height correlations function

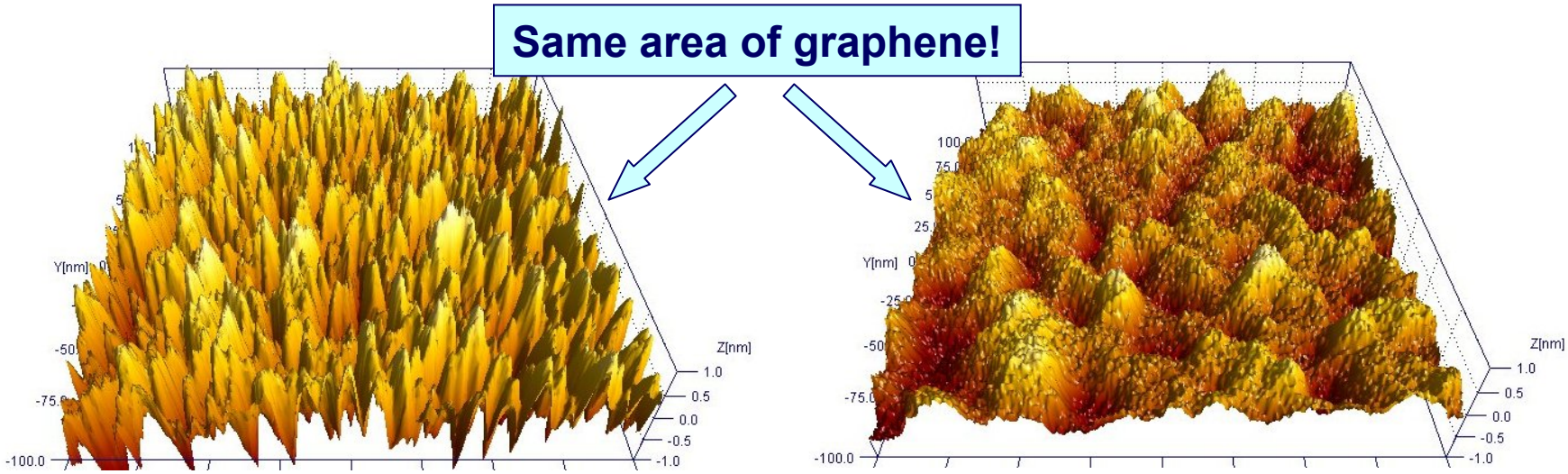
$$\left\langle \left(h(r)-h(0)\right)^2 \right\rangle \sim r^{2H}$$

with 2H ≈ 1

σ(*n*) ~ *constant*
(mimics short range scattering)

M. Ishigami et al., *Nano Letters* 7, 1643 (2007)

STM vs. NC-AFM topography



STM: 1V, ~50 pA

Similar to Morgenstern group (preprint)

NC-AFM: 4.6 Hz Δf

Reproduces our earlier work
Ishigami, et al. Nano Letters 7, 1643 (2007)

- **Both images acquired from same area, on 1-layer graphene device.**
- **Why does STM measure topography so differently?**
- **STM more strongly interacting – electro-mechanical effect**

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  - Charged impurities – minimum conductivity
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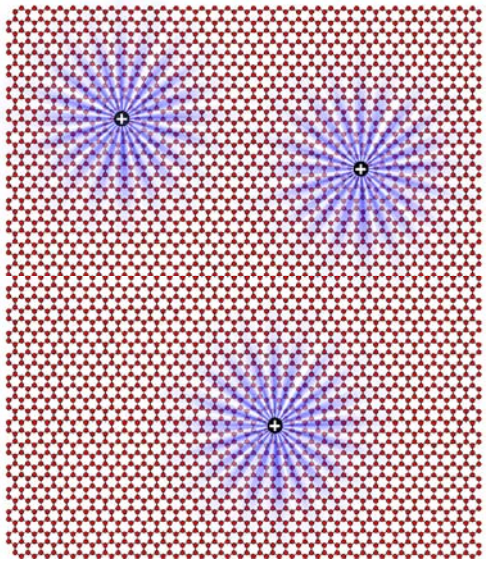
  - Dielectric Environment – Tuning Fine Structure Constant
  - Corrugations
  - Lattice defects

Lattice defect scattering in graphene

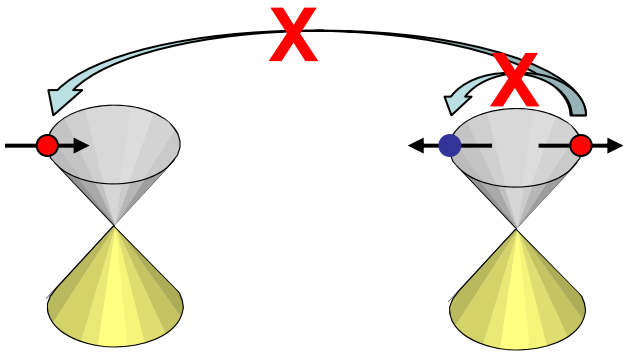


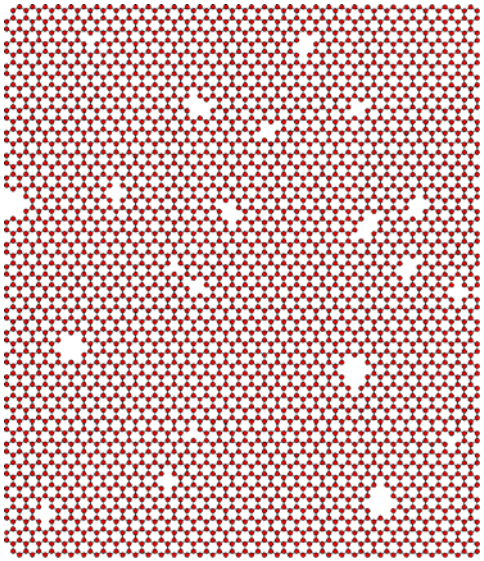
Charged-impurity scattering:

Linear σ(V_g)

*Intra*valley scattering
No backscattering
weak *anti*-localization

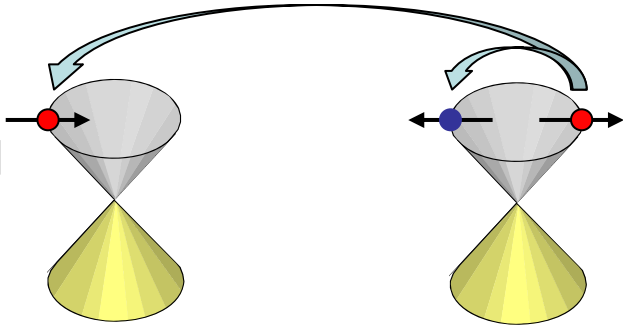
Metallic





Defect scattering:

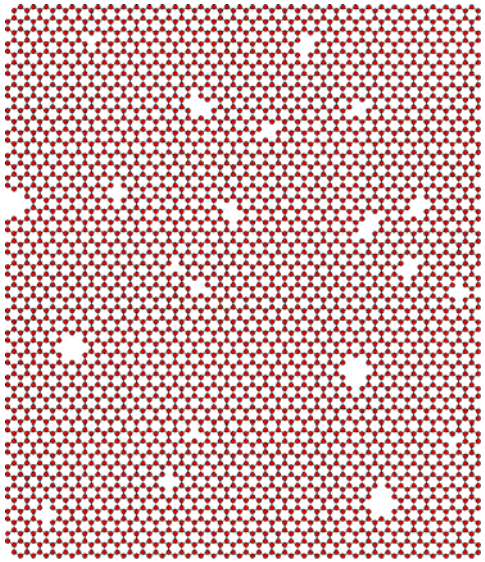
Constant σ(V_g)? [Shon, & Ando, (1998)]
Linear σ(V_g)? [Hentschel (2007); Stauber (2007)]



Expect *intra*valley and *inter*valley scattering
Backscattering allowed
weak anti-localization or weak localization?

Metallic or insulating?

Inducing lattice defects in graphene



- Sample is cleaned in H_2/Ar at 300 °C
  [Ishigami, *Nano Letters* **7**, 1643 (2007)]
- Sample baked in UHV at 220 °C overnight

- Ne^+ or He^+ ion irradiation at 500 eV via sputter gun
- Dose given by current collected by Faraday cup

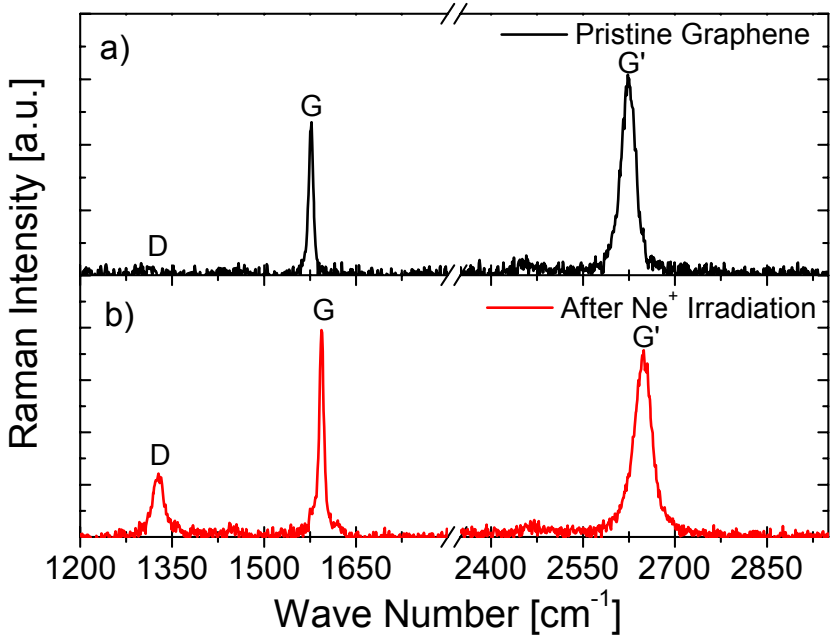
- Sample annealed at 220 °C overnight between ion irradiation runs; mobility partially recovers on annealing

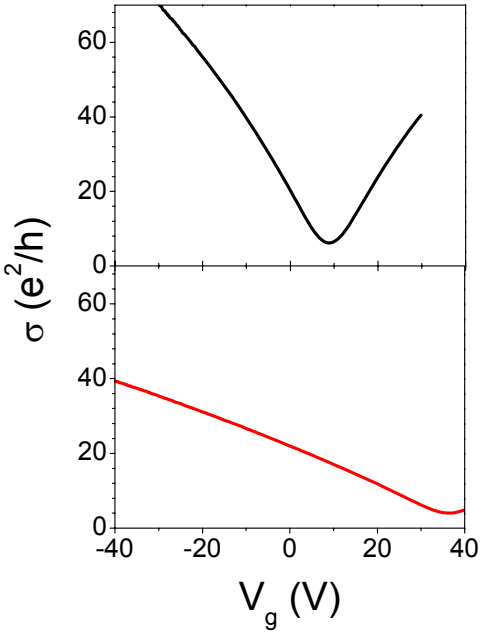
Expect:

- **One ion → one defect consisting of multi-atom vacancy**

  See e.g. G. M. Shedd and P. E. Russell, *JVSTA* **9**, 1261 (1991)
  J. R. Hahn, et al., *PRB* **53**, R1725 (1996)

Raman D peak - intervalley scattering





Mobility

μ = 8600 cm²/Vs

μ = 1300 cm²/Vs

Graphitic particles of grain size L_a: $L_a = \left[2.4\text{x}10^{-10}\ \text{nm}^{-3}\right]\lambda^4\left(\frac{I_D}{I_G}\right)^{-1}$

Cancado, et al., *APL* **88**, 163106 (2006).

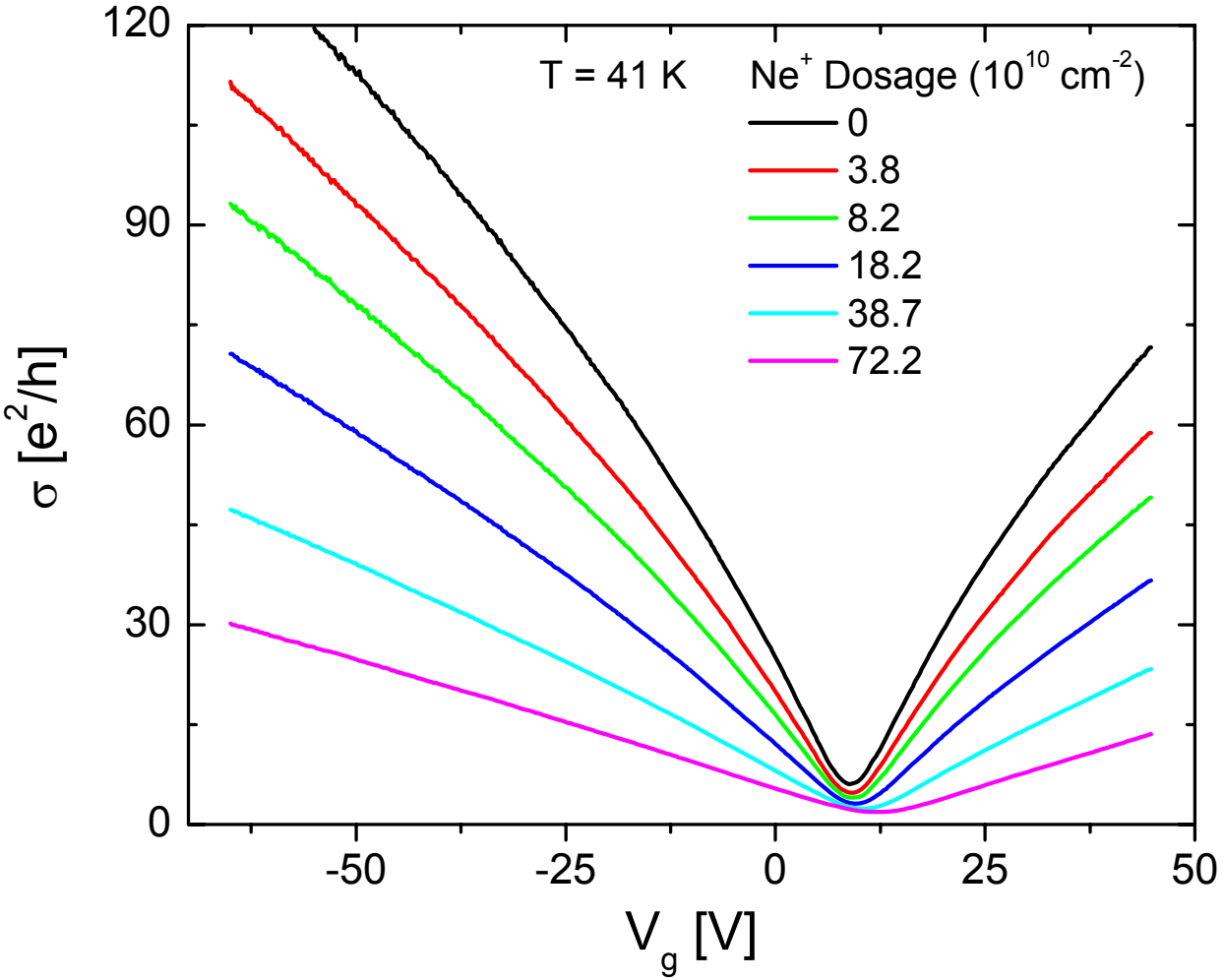
Point defects: identify L_a with defect scattering length.

Our samples: L_a = 70 nm

μ = 1300 cm²/Vs; $n \approx 10^{13}$ cm^{-2} (in ambient) → $l_{mfp} \approx 50$ nm

Defect scattering lengths from Raman and transport agree

Defects in graphene



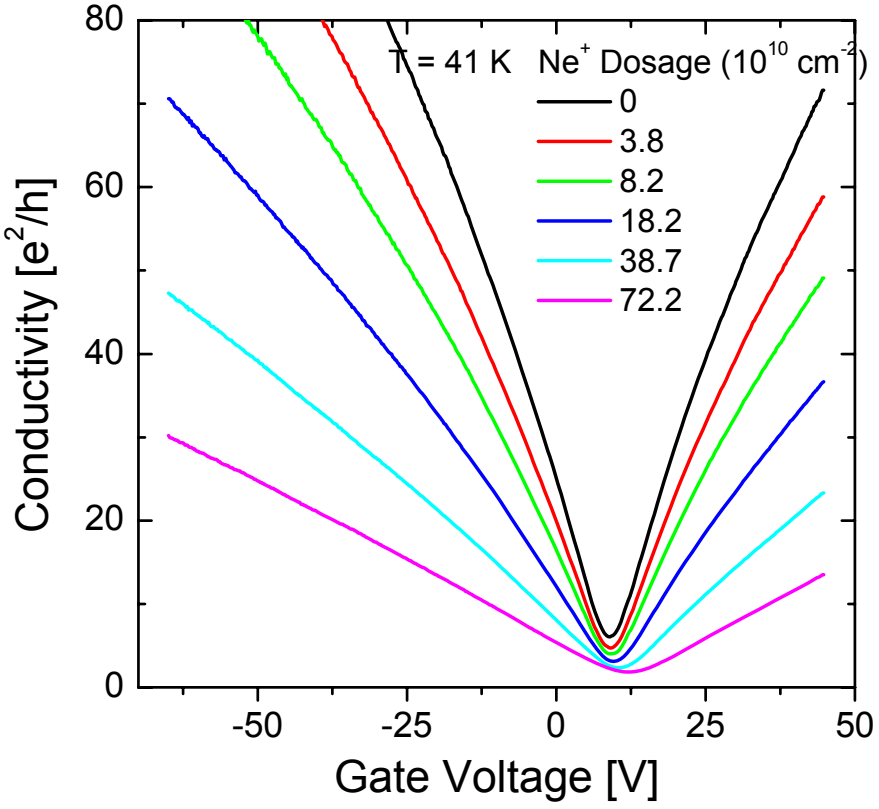
Fit each curve to: $\sigma^{-1} = (ne\mu)^{-1} + \rho_S$

"Long-range scattering"
Constant mobility

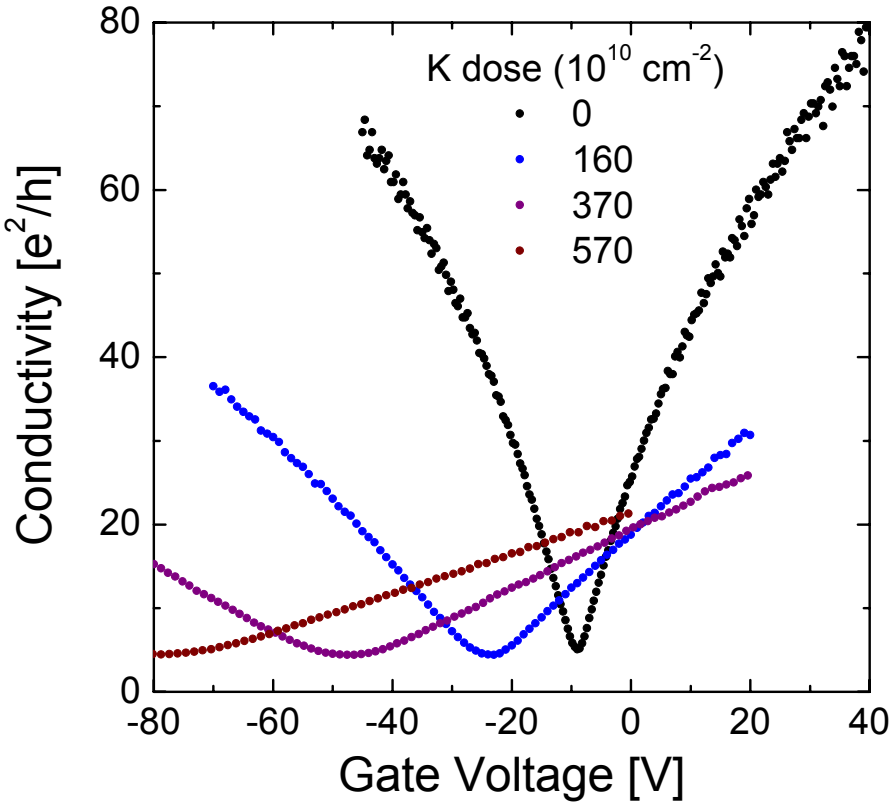
"Short-range scattering"
Constant resistivity

Defects in graphene

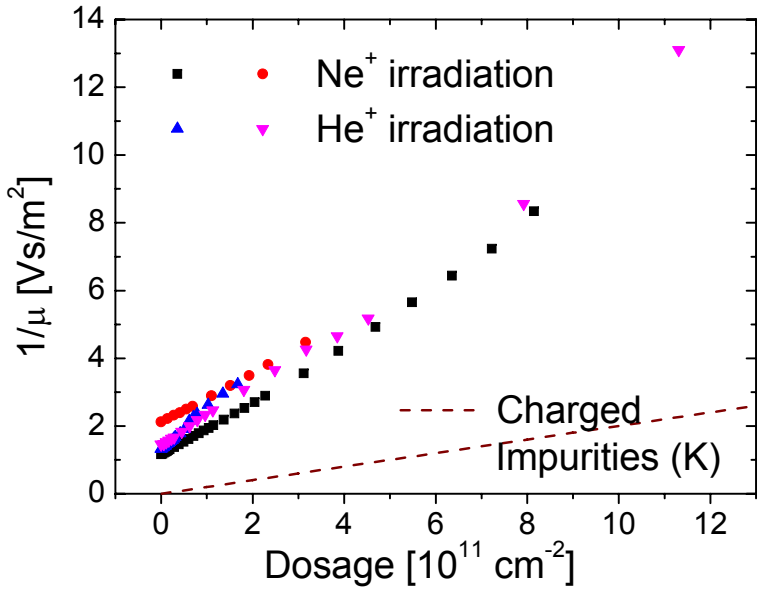
Ne^+ irradiation (lattice defects)



K doping (charged impurities)



Defects in graphene

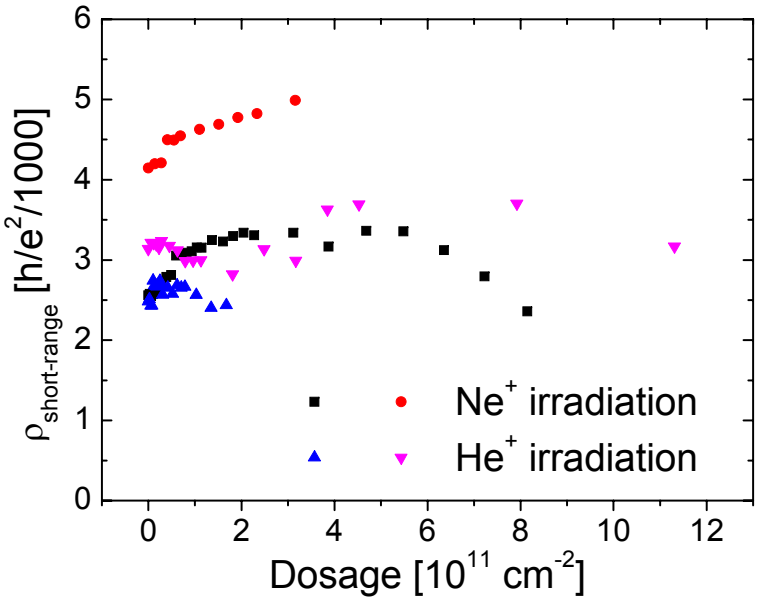


Defects:

• Defects change the *linear* term in $\sigma(V_g)$

Like charged impurities!

• Linear $\sigma(V_g)$ scattering 4x stronger than for same concentration of charged impurities



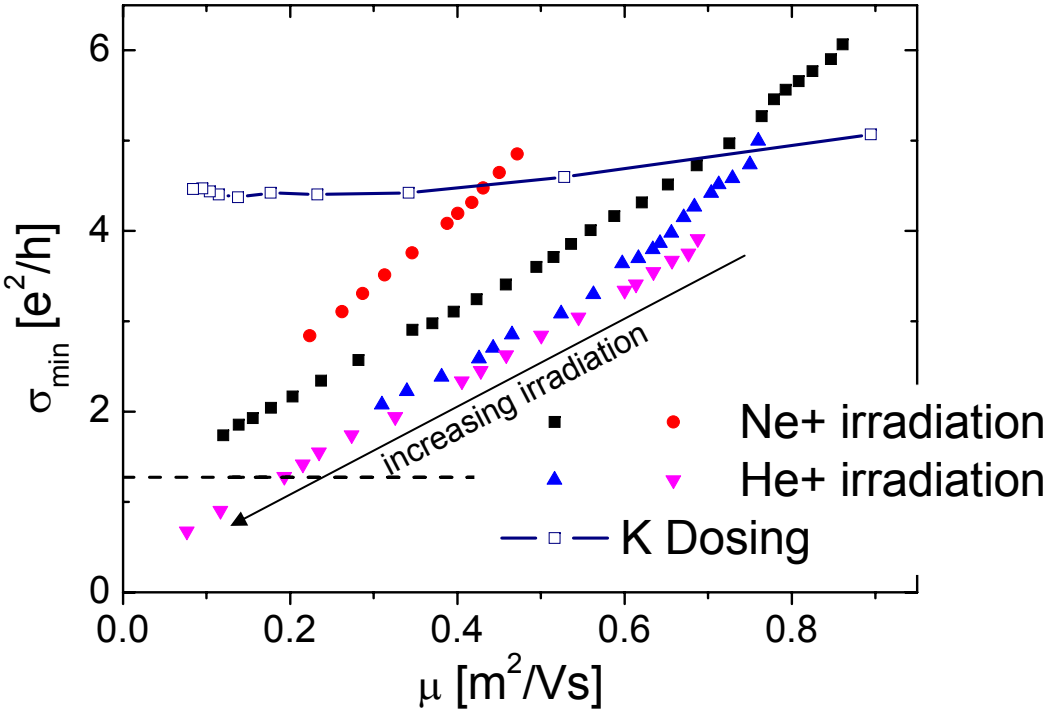
Defects:

• Carrier-density-independent ρ_s scattering does *not* change

• ρ_s corresponds to l_{mfp} ~2 microns

→ ρ_s *cannot* be the scattering seen in Raman D band

Defects in graphene – Minimum conductivity



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

*n** is carrier density in "puddles"
*n** is function of charged impurity density

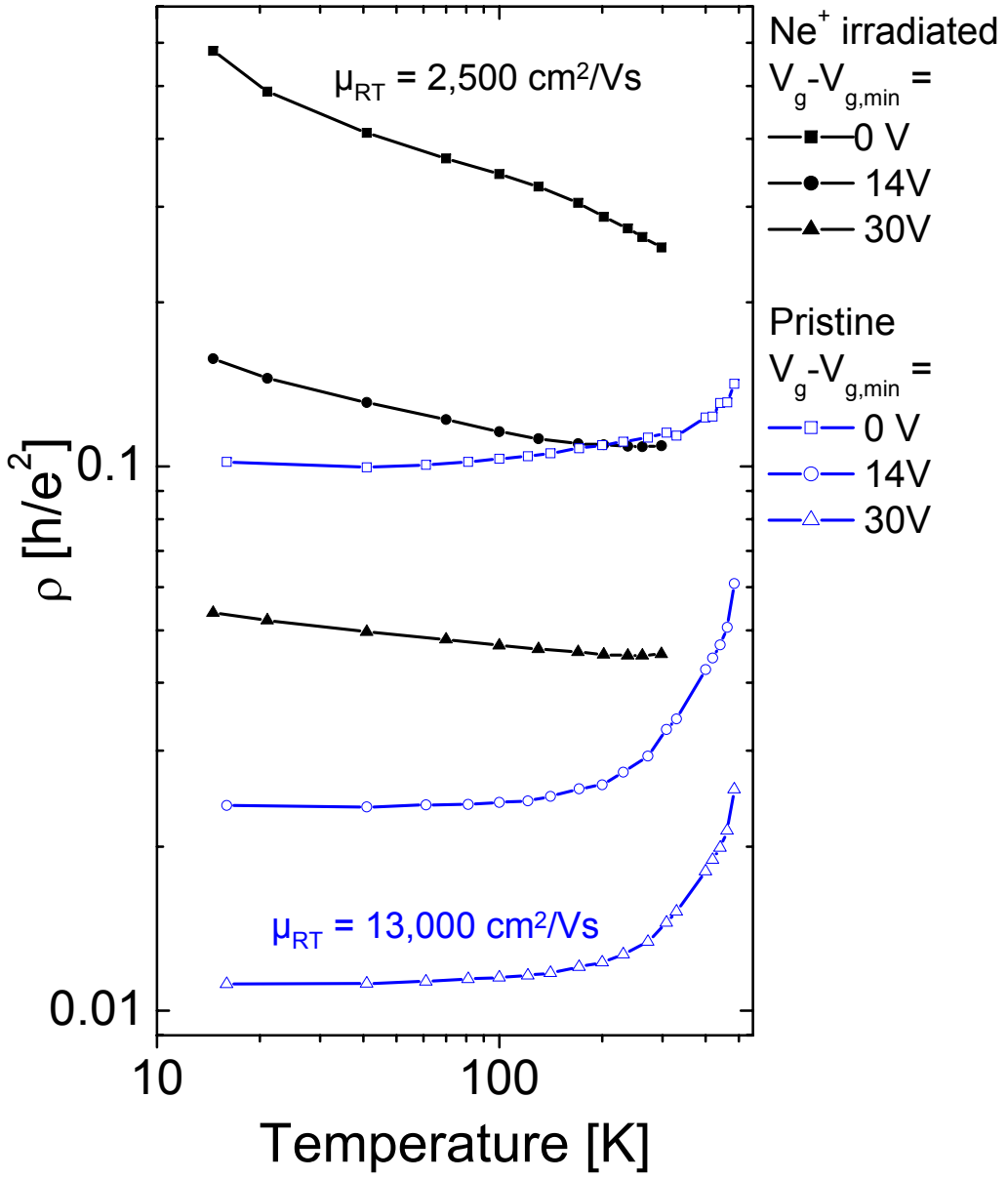
Charged impurities:
n_{imp} increases: μ decreases, *n** increases
→ σ_{min} changes very weakly

$$\sigma_{\min} = n^* e\mu \qquad n^* \uparrow \quad \mu \downarrow$$

Defects:
n_{defect} increases: μ decreases, *n** constant
→ σ_{min} proportional to μ

$$\sigma_{\min} = n^* e\mu \qquad n^* \text{ const.} \quad \mu \downarrow$$

Defects in graphene – Metal or Insulator?



Theory:

Graphene with only *intra*valley scattering is metallic (weak anti-localization)

Graphene with *inter*valley scattering is insulator (weak localization)
[Bardarson, et al. *PRL* **99**, 106801 (2007)]

Experiment:

Graphene with charged impurities shows metallic ρ(*T*) at low *T*
[Novoselov, *Nature* **438**, 197 (2005)]
[Chen, *Nature Nano* **3**, 206 (2008)]

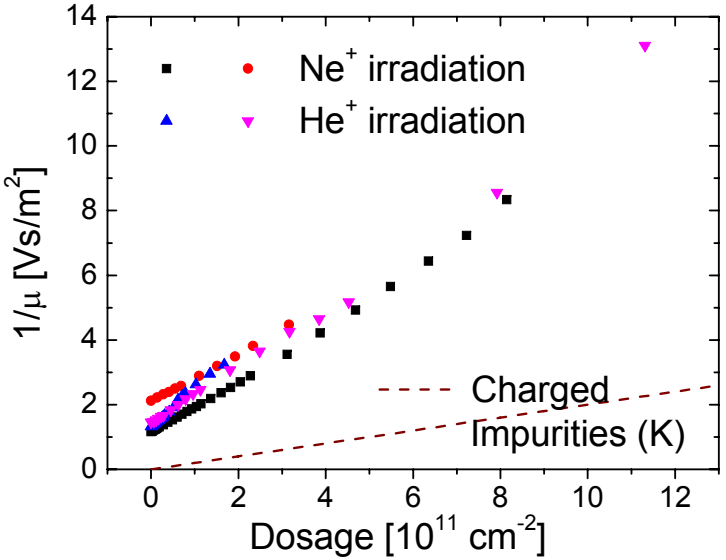
Graphene with defects shows diverging ρ(*T*) at low *T* even for modest mobilities (~2,000 cm²/Vs)!

Midgap states - Theory

[Hentschel & Guinea, *PRB* **76**, 115407 (2007); Stauber, Peres, & Guinea, *PRB* **76**, 205423 (2007)]

- Defect potential modeled as circular well of radius R, depth ε_0, intervalley scattering Δ.
- Spectrum inside the potential well is gapped by Δ; has bound midgap states.
- Conductivity is:

$$\sigma_d = ne\mu_d = \frac{2e^2}{h}\frac{n}{n_d}\ln^2\left(k_F R\right)$$



Experimentally, $\mu_d \approx [1.2 \times 10^{15}\ \mathrm{V^{-1}s^{-1}}]/n_d$

For $n = 2\times10^{12}\ \mathrm{cm^{-2}} \rightarrow R \sim 8$ Å

Reasonable value for 500 eV irradiation (multiple-atom vacancies)

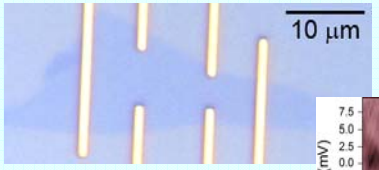
$\ln^2(k_F R)$ dependence *not* observed, but k_F only varies by factor of ~3 outside puddle regime ($n > n^*$)

Conclusions

- **Mobility of graphene on SiO_2 limited by charged impurities**
  - Charged impurities give linear $\sigma(V_g)$
  - Minimum conductivity determined by density in *e*-*h* puddles
  - Addition of dielectric layer increases mobility
- **Room temperature intrinsic mobility ~200,000 cm^2/Vs**
  - Remote interfacial phonon scattering from SiO_2 limits to ~40,000 cm^2/Vs
- **Corrugations**
  - Graphene corrugations follow SiO_2 substrate roughness
- **Graphene with lattice defects**
  - Linear $\sigma(V_g)$ with 4x lower mobiltiy compared to charged impurities
  - Consistent with midgap states, R = 2-3 Å
  - Depressed σ_{min}~ μ; can be less than $4e^2/\pi h$
  - Intervalley scattering gives insulating ρ(T); Raman D band

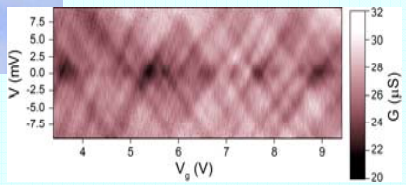
Prof. Michael S. Fuhrer's Group

Sungjae Cho
Chaun Jang
Shudong Xiao
Alexandra Curtin

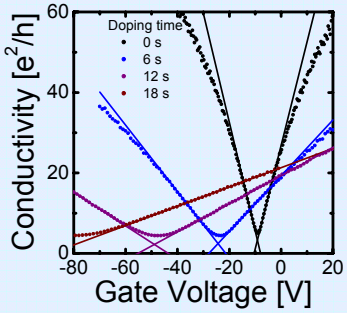


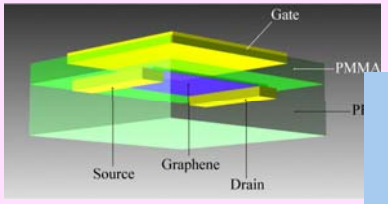
MR in graphene

graphene Fabry-Pérot



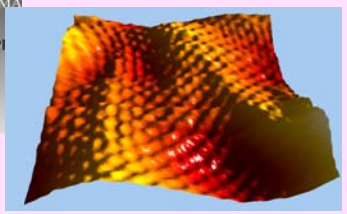
UHV doping, dielectric expts.





transfer-printing

STM



Prof. Ellen D. Williams' Group:

Dr. William Cullen
Prof. Masa Ishigami (now @ UCF)
Daniel Hines
Jianhao Chen

Prof. Sankar Das Sarma's Group

Dr. Shaffique Adam Dr. Euyheon Hwang
Dr. Enrico Rossi Wang-Kong Tse

Theory

More Info:

Fuhrer group: **www.physics.umd.edu/mfuhrer**
Williams group: **www.physics.umd.edu/spg**
Das Sarma group: **www.physics.umd.edu/cmtc**

Funding: