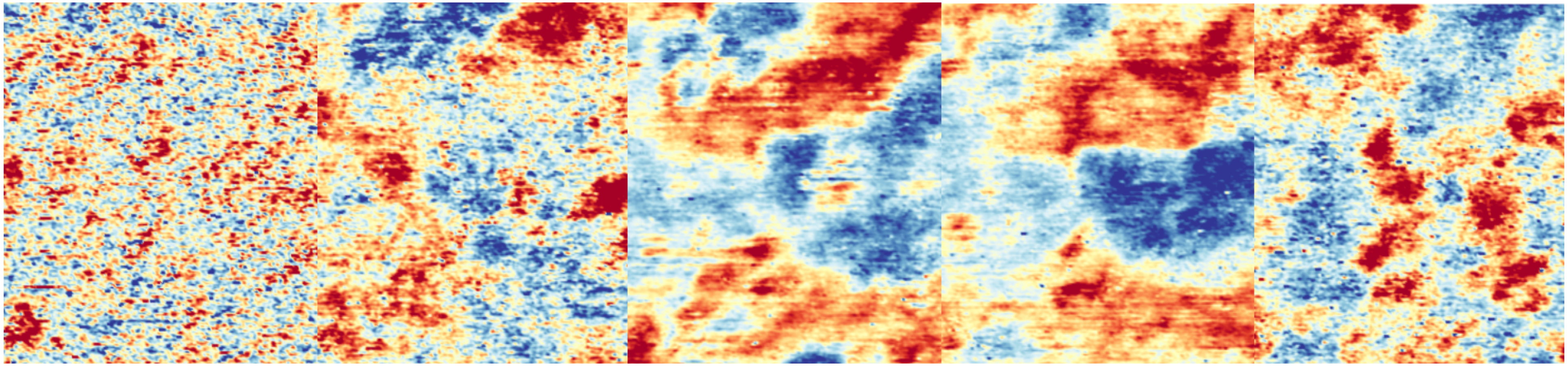
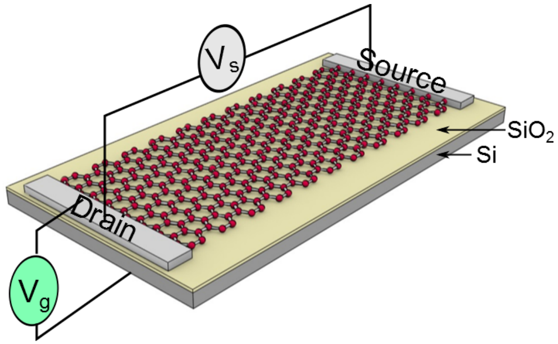
Graphene at the local scale: charge disorder, screening and work function

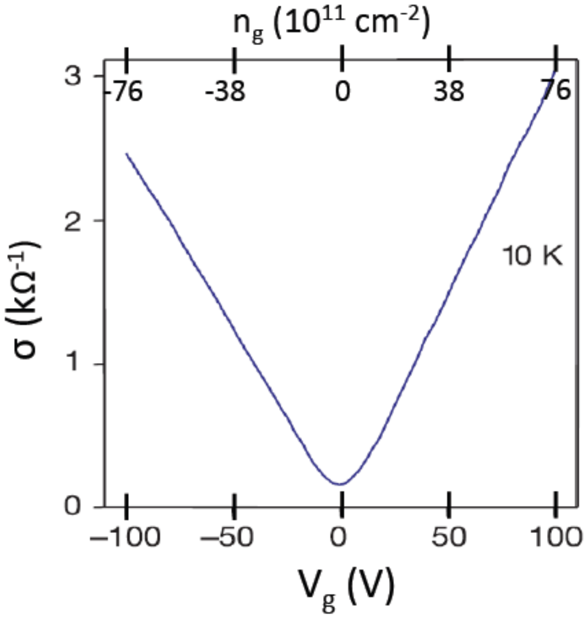


Clemens Winkelmann
QNES, Institut Néel

GDR Physique quantique mésoscopique
Aussois, 8 December 2016

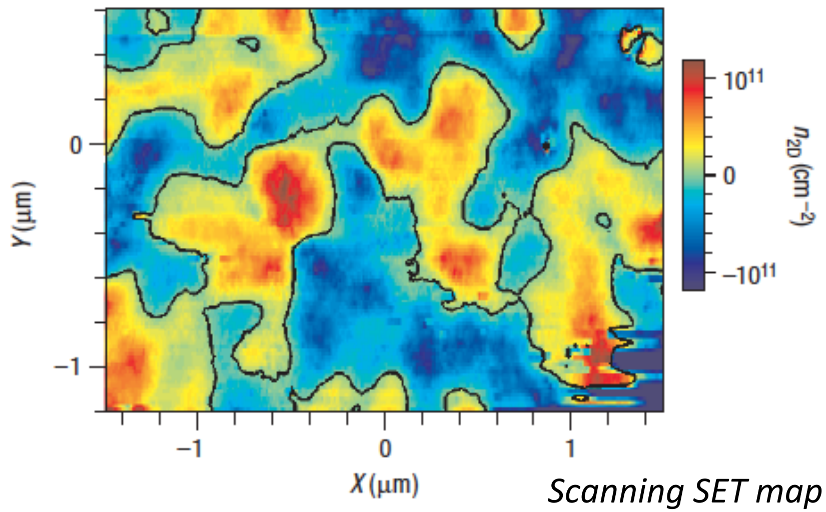
Charge disorder in graphene on SiO_2





Novoselov *et al.*, Science (2004)
Chen *et al.*, Nat. Phys. (2008)

Charge density inhomogeneities (puddles)

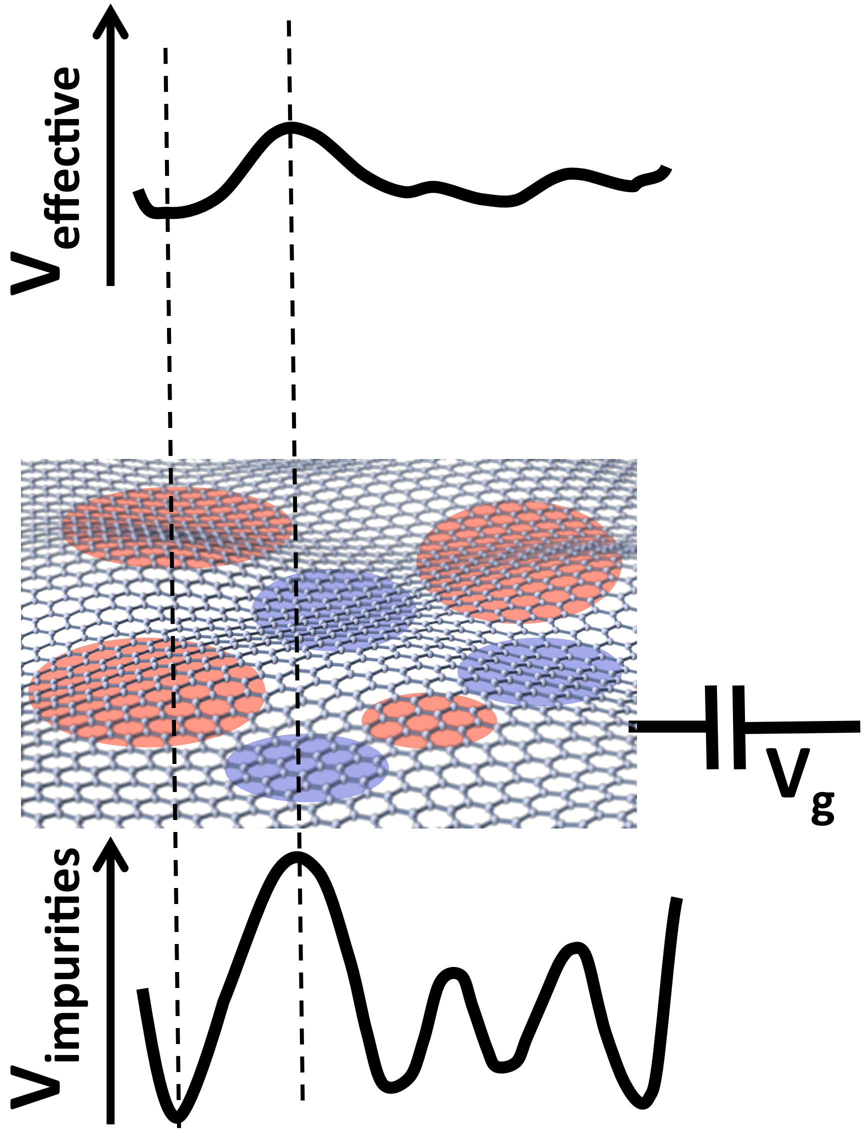


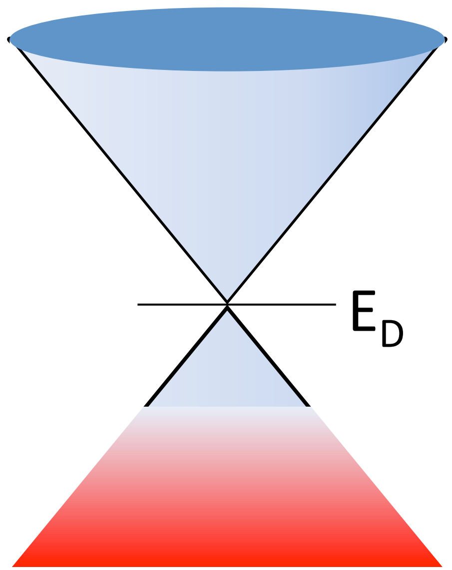
Scanning SET map

J. Martin *et al.*, Nat. Phys. (2008)
Y. Zhang *et al.*, Nat. Phys. (2009)

- Overall charge neutrality cannot be reached in Gr/ SiO_2.
- Graphene response to disorder itself carries the signature of Dirac fermions

Charge disorder in graphene





Gate-tunable carrier density

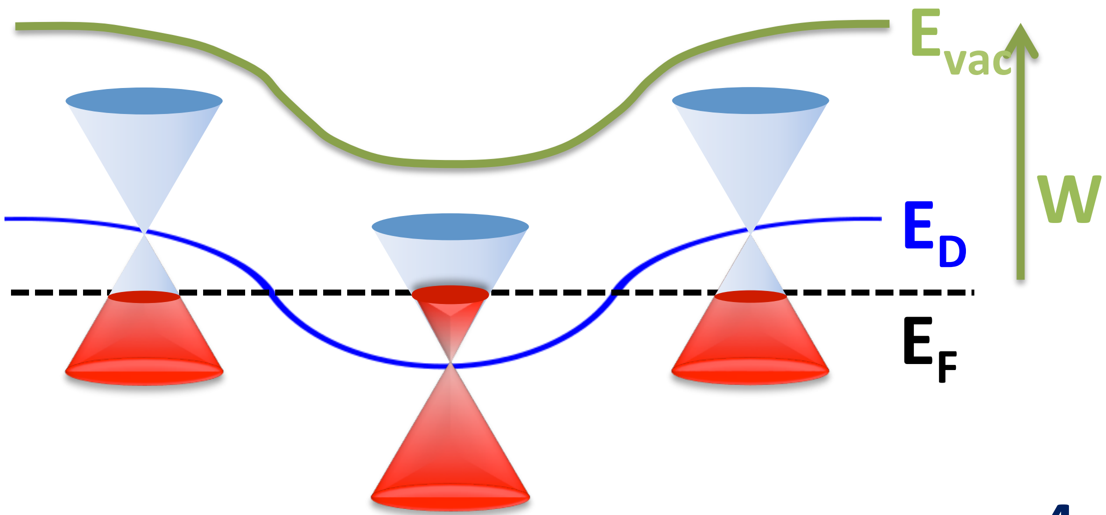
$$E_F - E_D \propto \sqrt{n} \propto \sqrt{V_g - V_g^0}$$

Thomas-Fermi screening (2D)

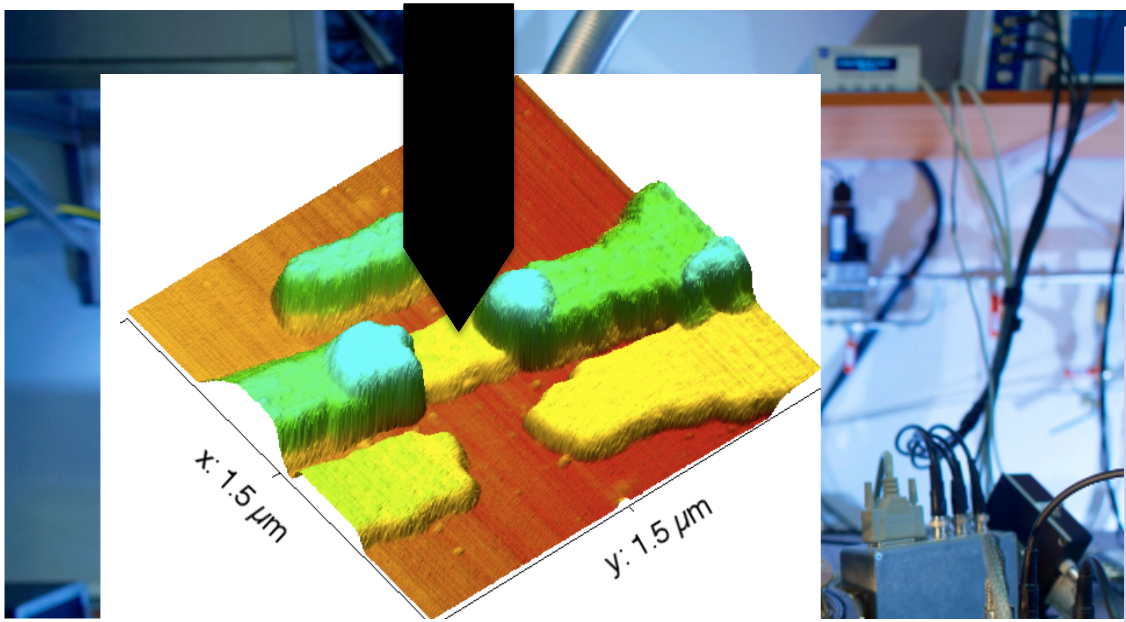
$$q_{TF} \propto DOS \quad \left(\propto \sqrt{n}\right)$$

Outline

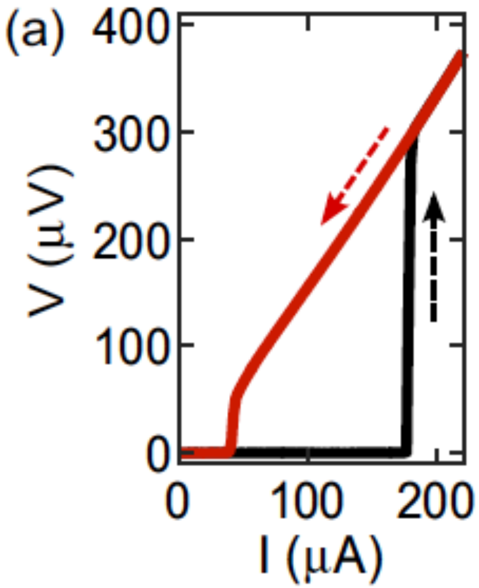
- Nanoscale mapping of charge puddles in graphene
- Doping disorder in decoupled graphene on a metallic substrate
- Doping disorder in a graphene device
- Doping versus work function in graphene

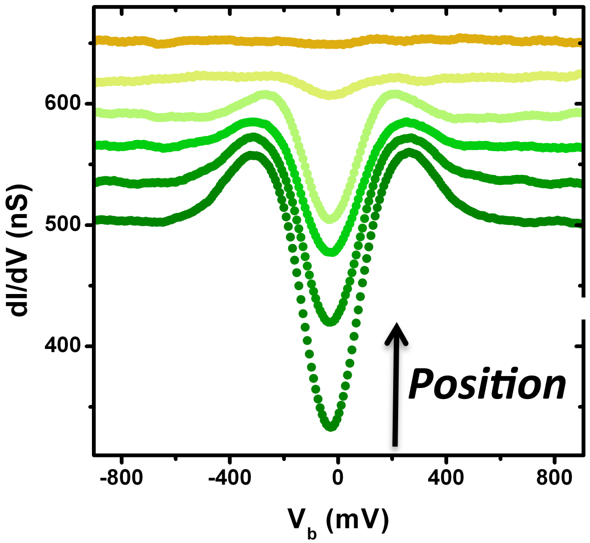


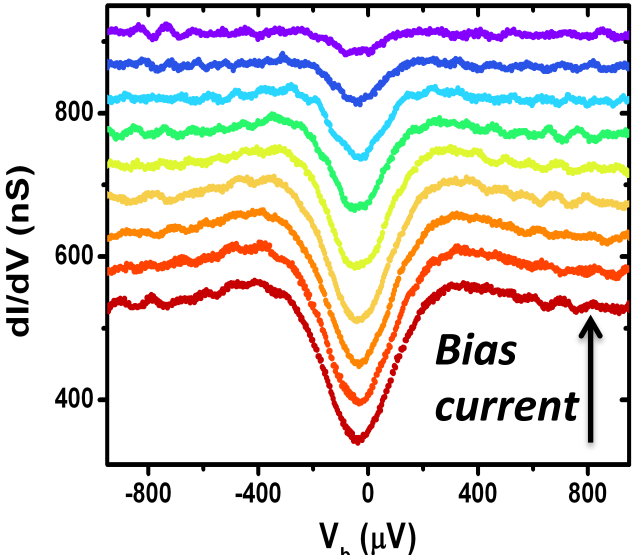
Hybrid cryogenic scanning probe microscope



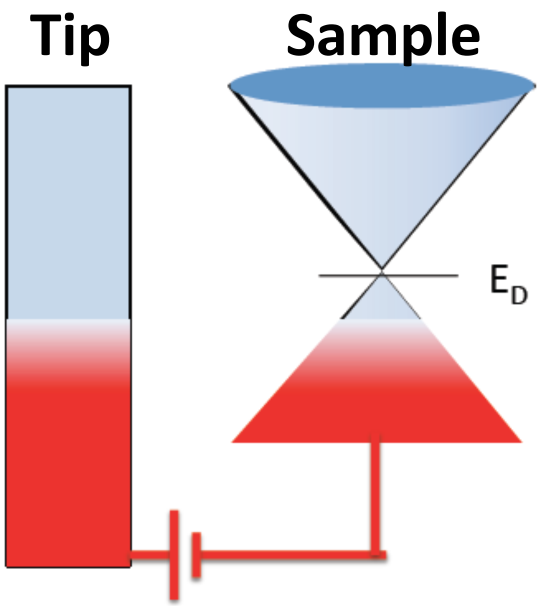
- AFM
- STM
- Transport
- Coarse sample displacement
- T = 100 mK
- B = 2 T
- *No prep chamber…*

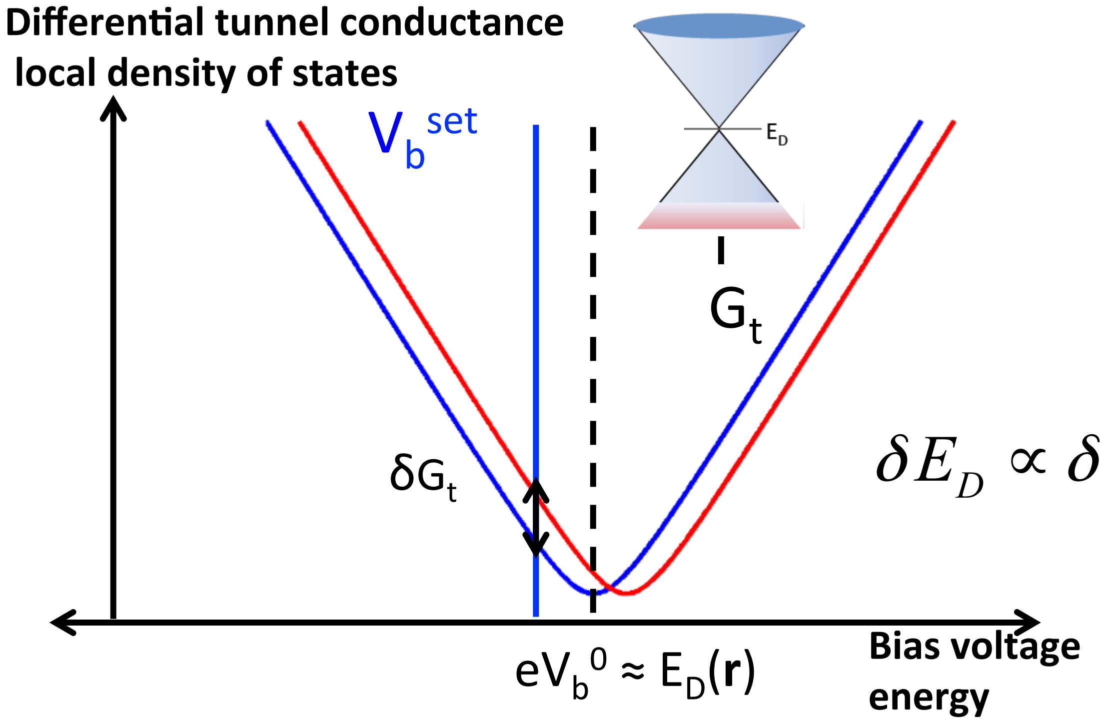






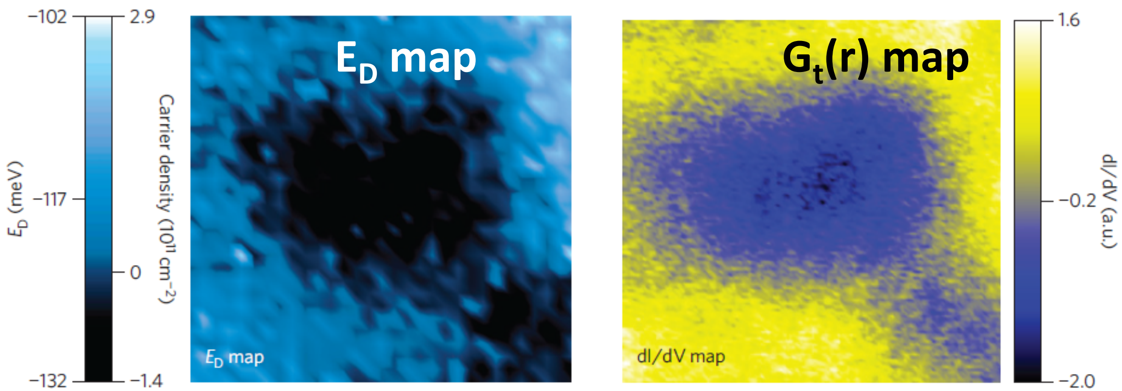
Puddles mapping



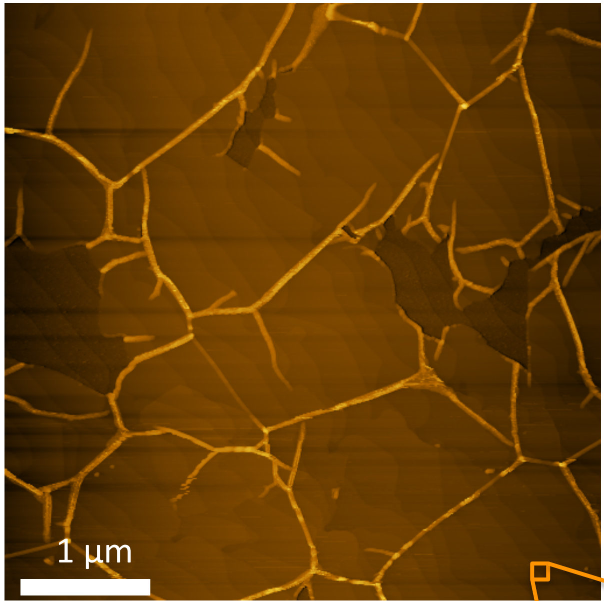


$$\delta E_D \propto \delta G_t$$

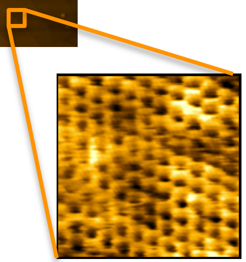
Zhang et al., *Nat. Phys.* (2009)

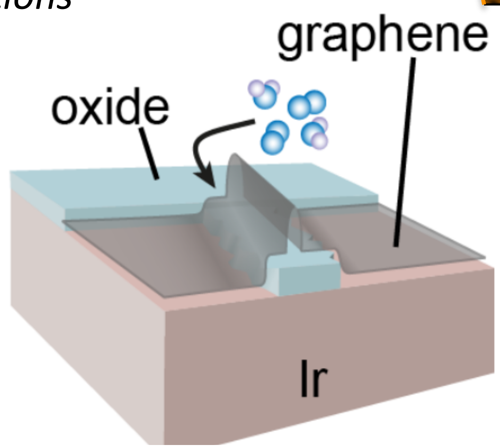


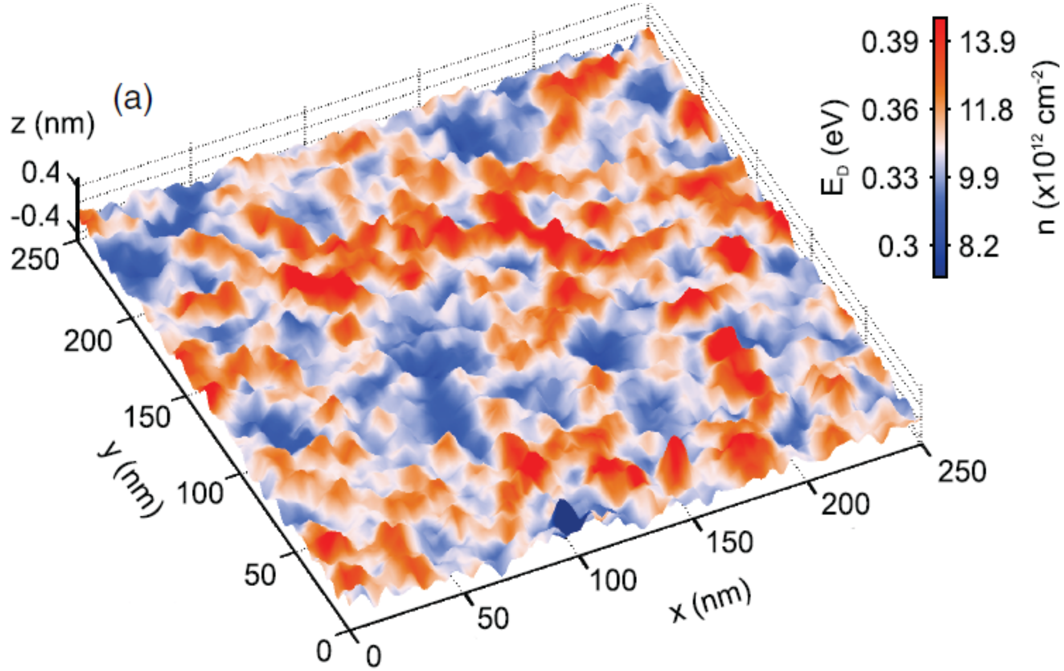
Decoupled graphene on a metallic substrate



- *CVD-grown single layer graphene on Ir(111)*
- *Exposed to ambient conditions*



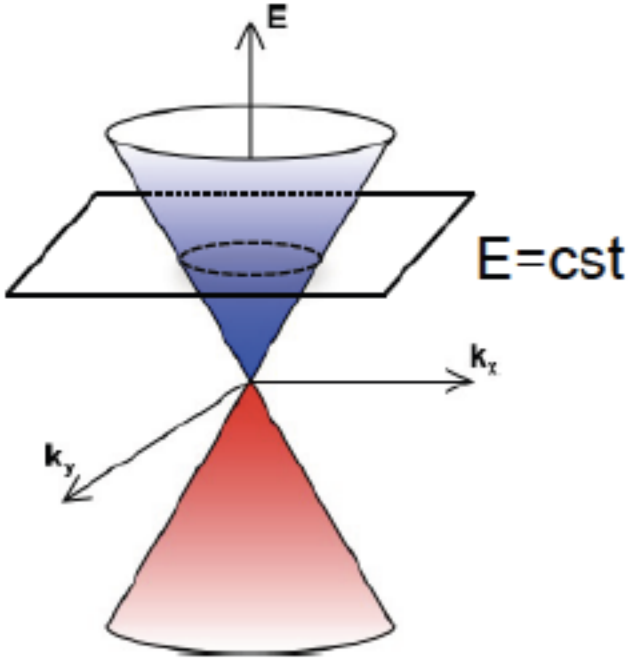


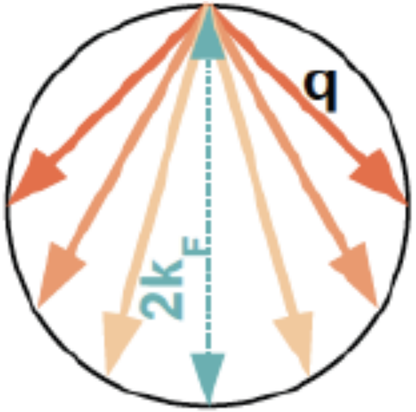


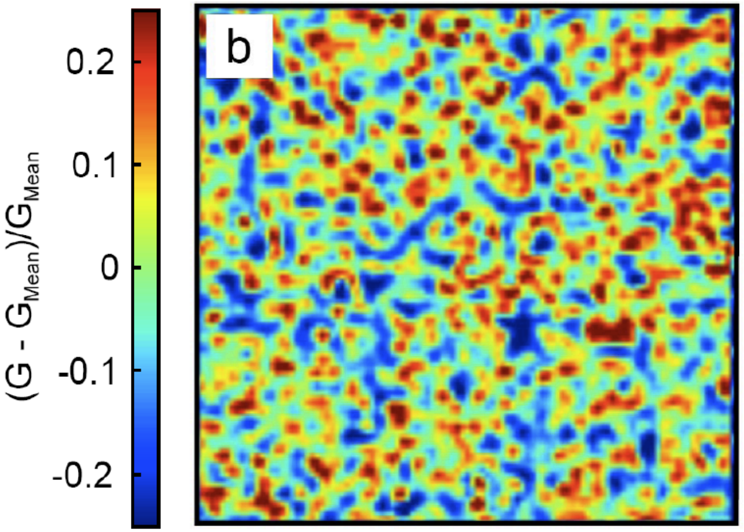
- Strong *p*-doping
- Diffusion of oxygen along graphene wrinkles: Intercalation
- Positive E_D vs. z correlations

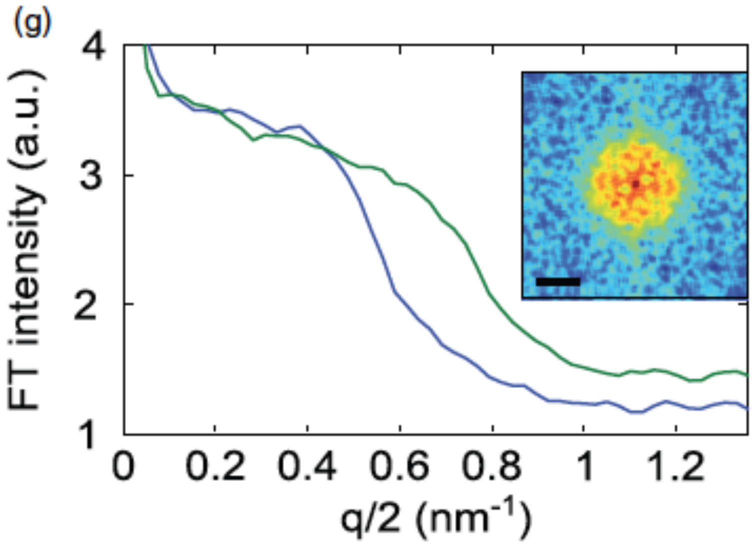
Kimouche *et al.*, Carbon (2014)
Martin *et al.*, Phys. Rev. B (2015)

Fourier Transform STS



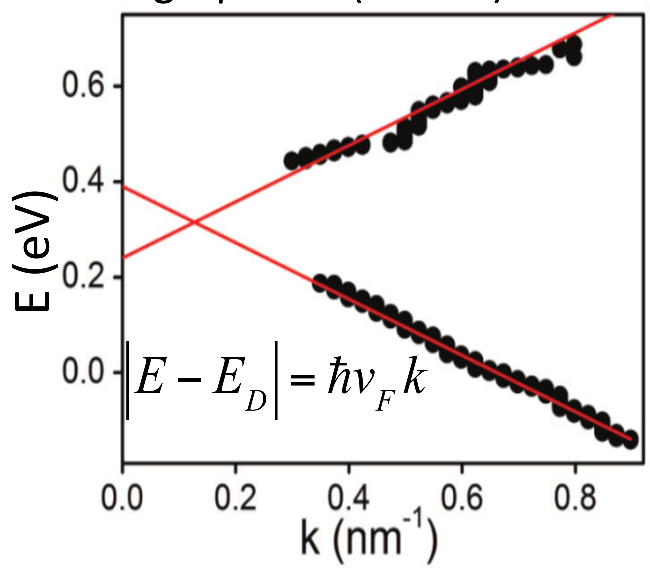




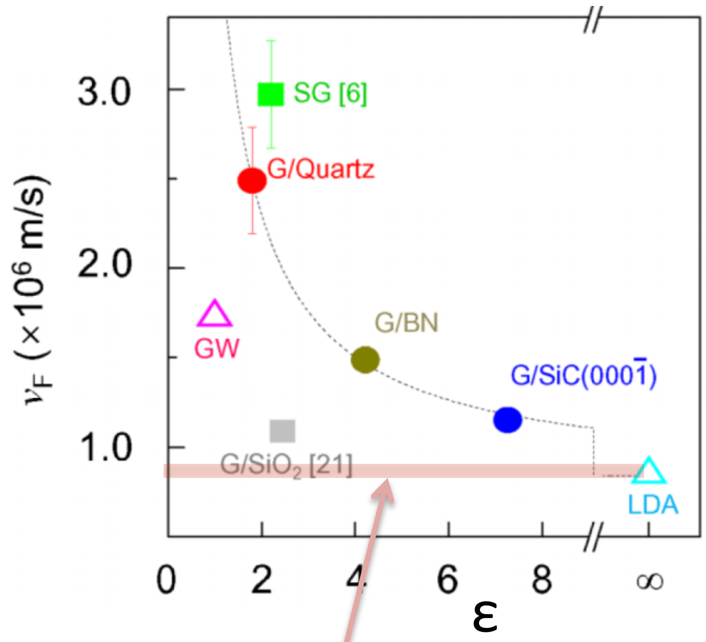


Fermi velocity renormalization: signature of strong screening

Dispersion relation of graphene (FT-STS)



Hwang *et al.*, Sci. Rep. (2012)



decoupled graphene on iridium

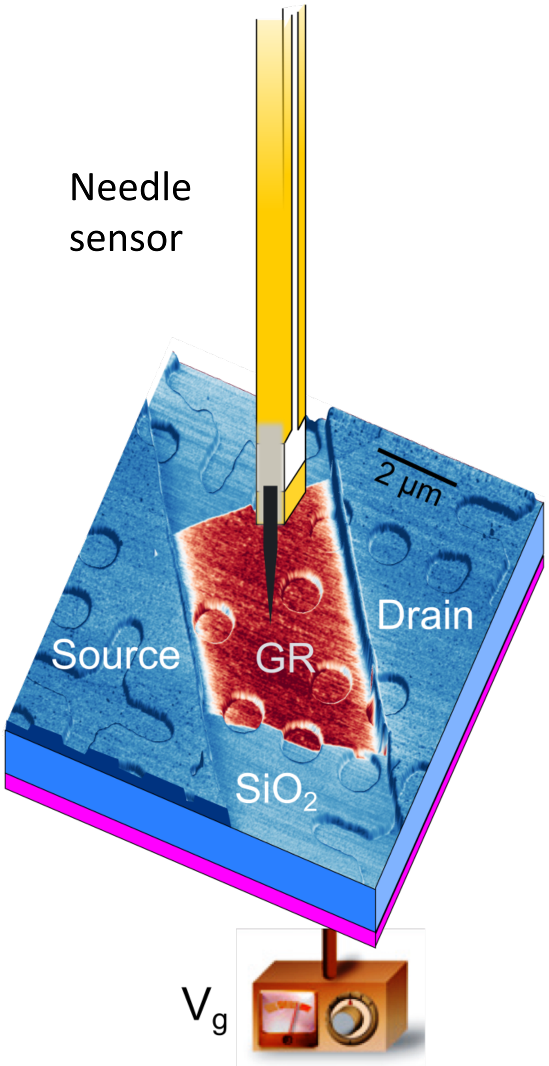
- Fermi velocity:

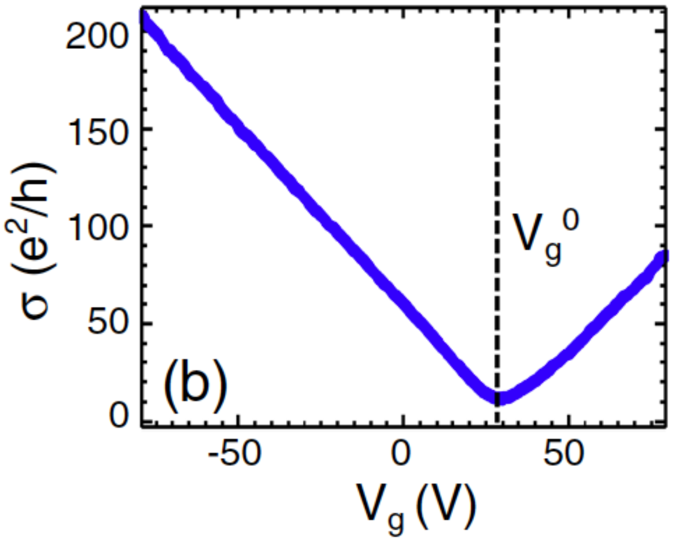
v_F = 0.9 ± 0.04 x 10^6 m.s^{-1}

- Strong screening environment: metallic substrate about 1 nm below

Martin *et al.*, Phys. Rev. B (2015)

Charge disorder in a graphene device: transport properties





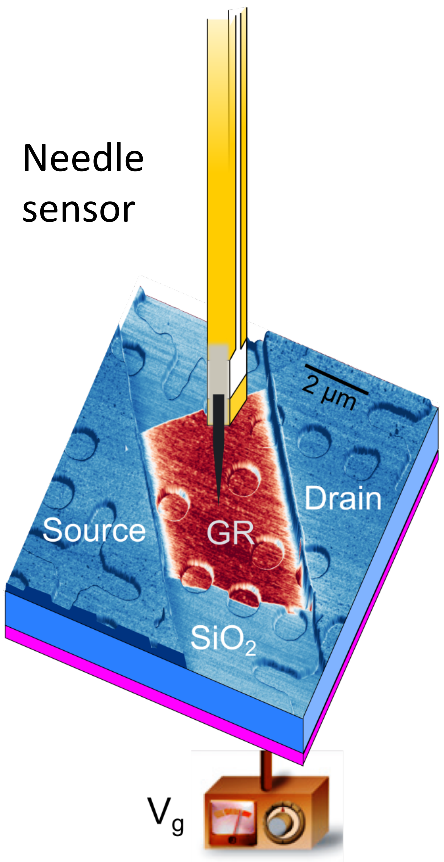
- Resist-free microfabrication
- Transport properties

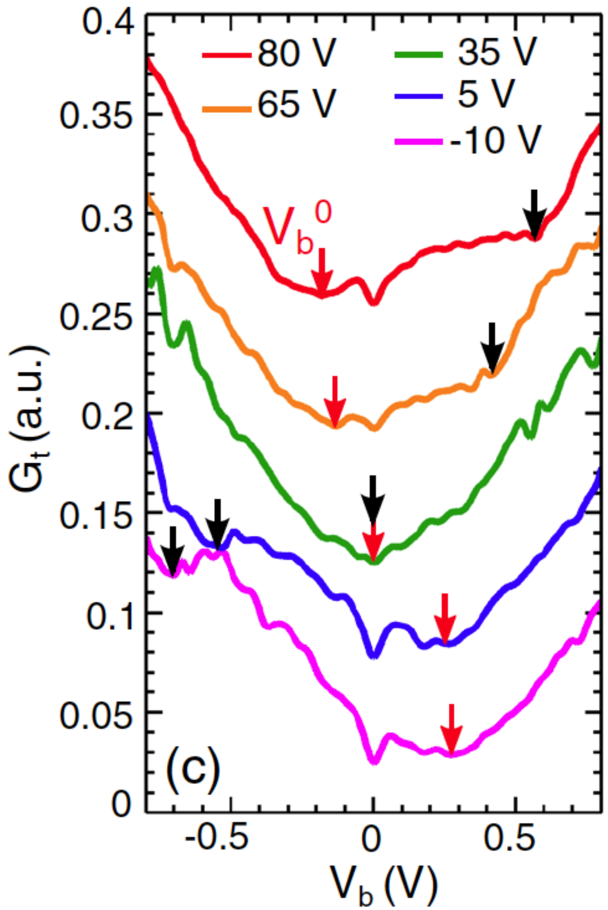
mobility:	$\mu = 6000\ cm^2V^{-1}s^{-1}$
substrate charge impurity density:	$n_i = 8.10^{11}\ cm^{-2}$
residual charge carrier density:	$n^* = 5.10^{11}\ cm^{-2}$
graphene-impurity distance:	$d \approx 0.5$ nm

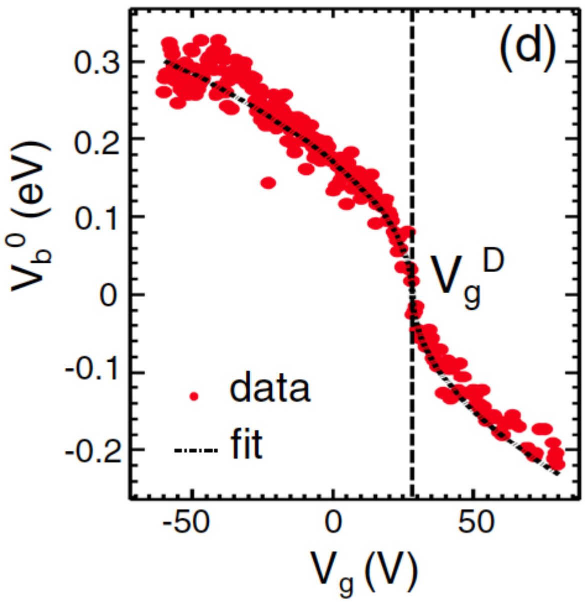
Theory: RPA – Boltzmann formalism

Adam *et al.,* PNAS (2007), Das Sarma *et al.*, Rev. Mod. Phys. (2011)

Gate dependence of the local Dirac point

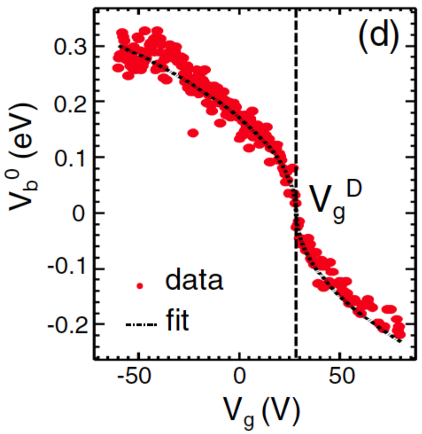




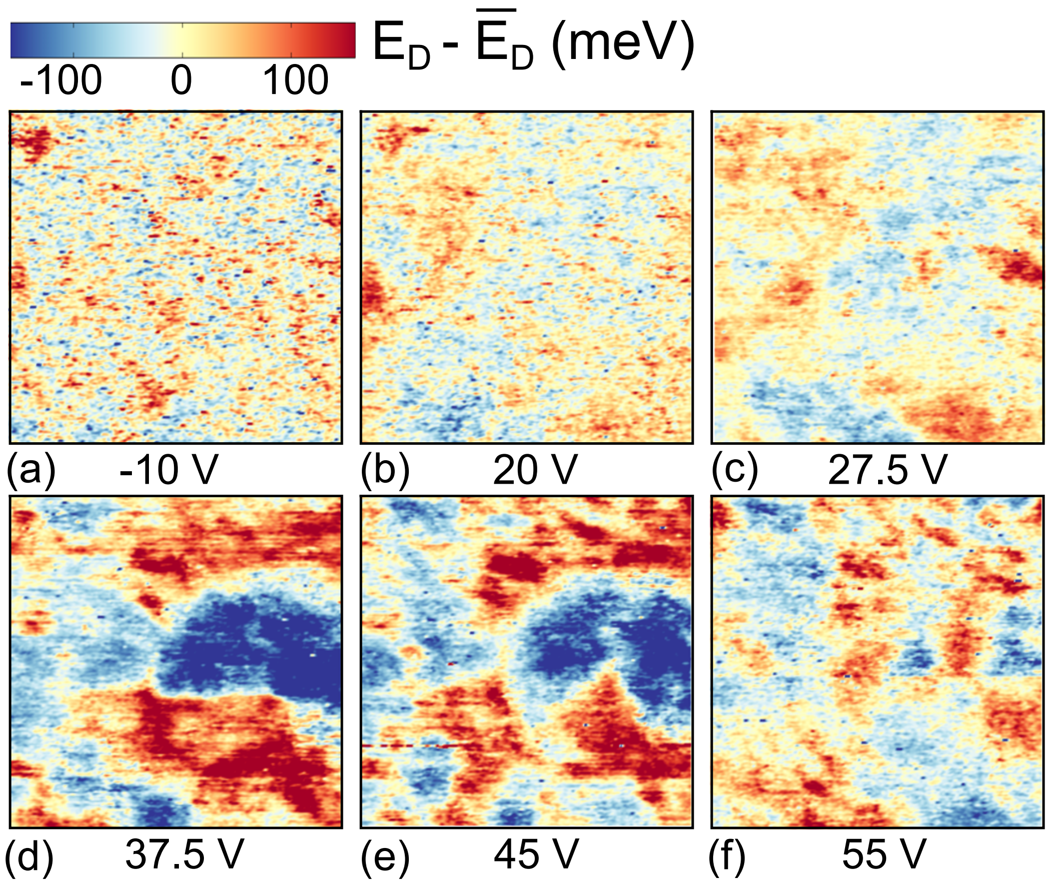


Tunneling spectroscopy: Gate-dependent local Dirac point

Puddle maps at variable charge carrier density

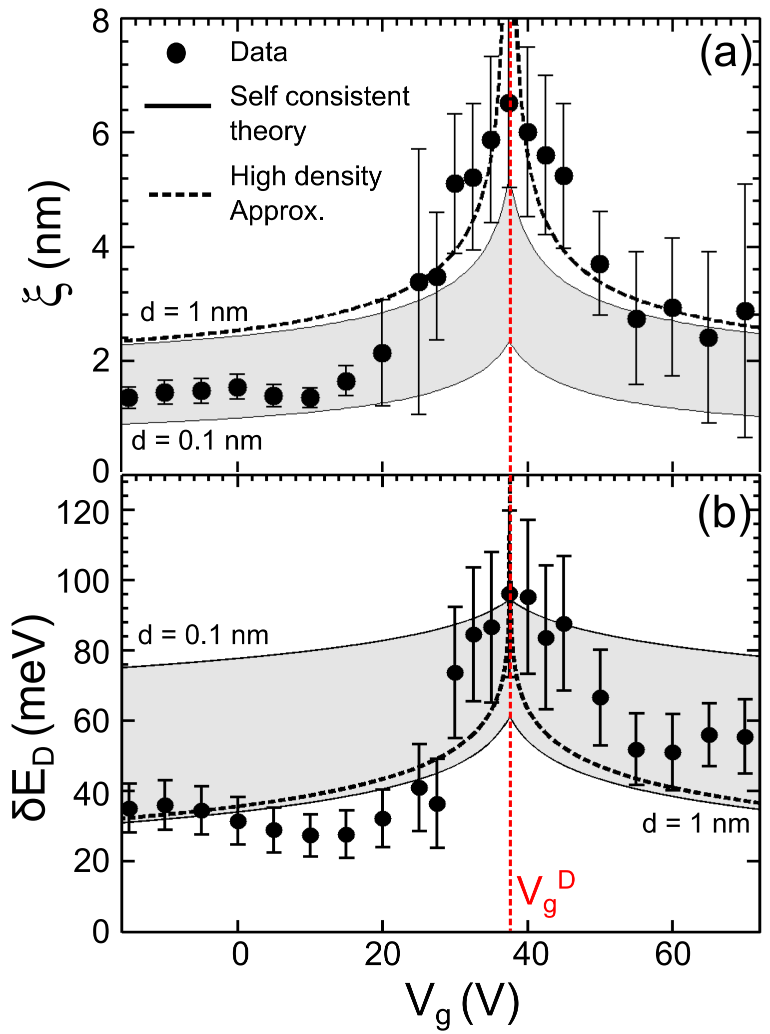


- Puddle maps as a function of V_g
- Marked maximum of puddles' size and amplitude.
- Overall charge neutrality at V_g = 38 V ≠ V_g^0 = 29 V
  → gating by the tip.



100 x 100 nm²

Charge puddles near the Dirac point



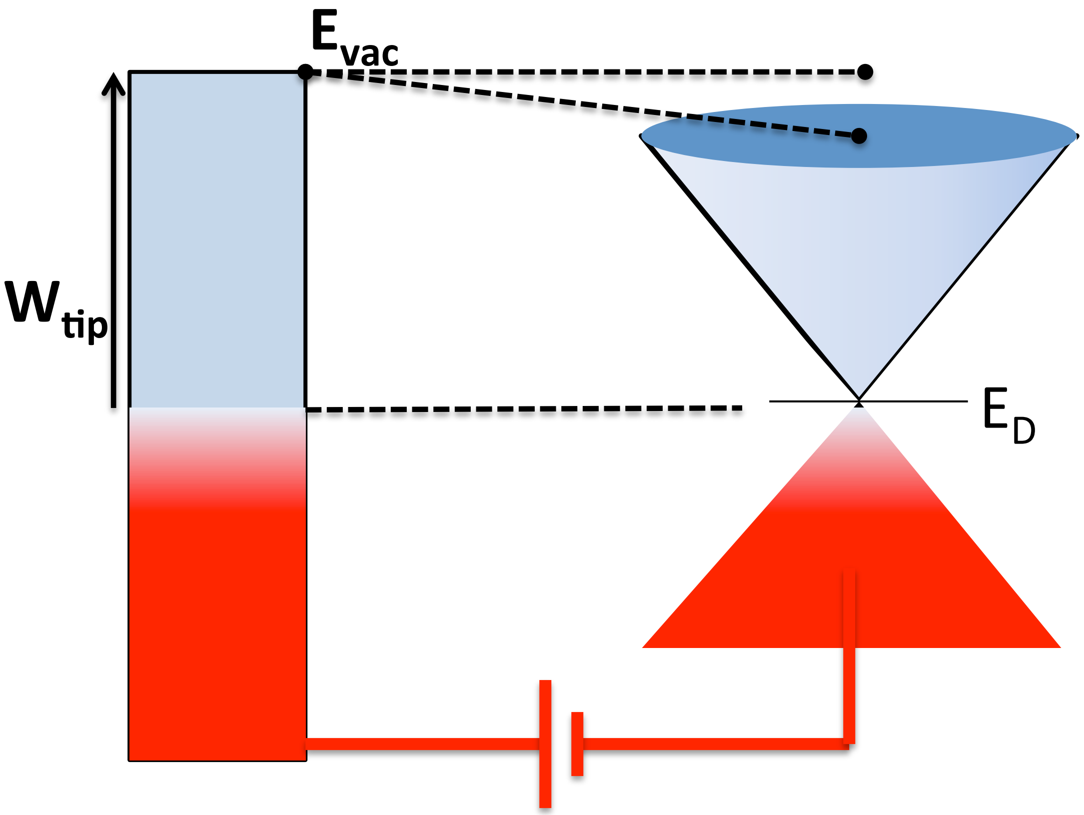
- Strong increase of puddles' **size** and **amplitude** near Dirac point.

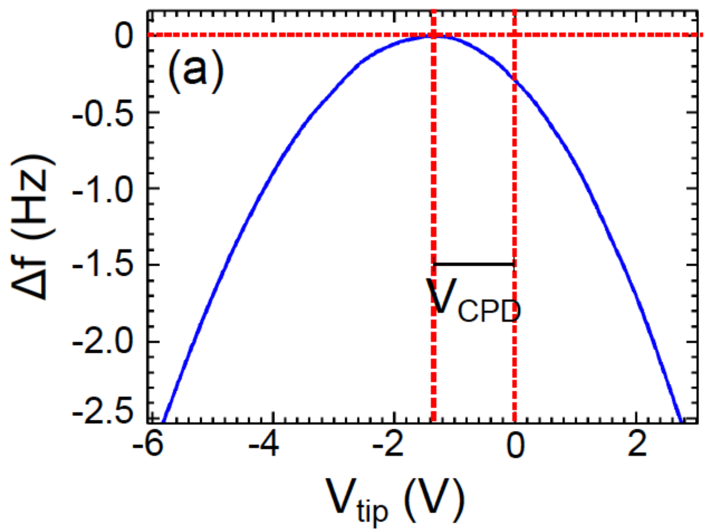
$$\xi \propto q_{TF}^{-1} \propto n^{-1/2}$$

- Good agreement with self-consistent screening theory (µscopic parameters from transport measurements).
- At finite charge disorder there is screening even at the Dirac point.

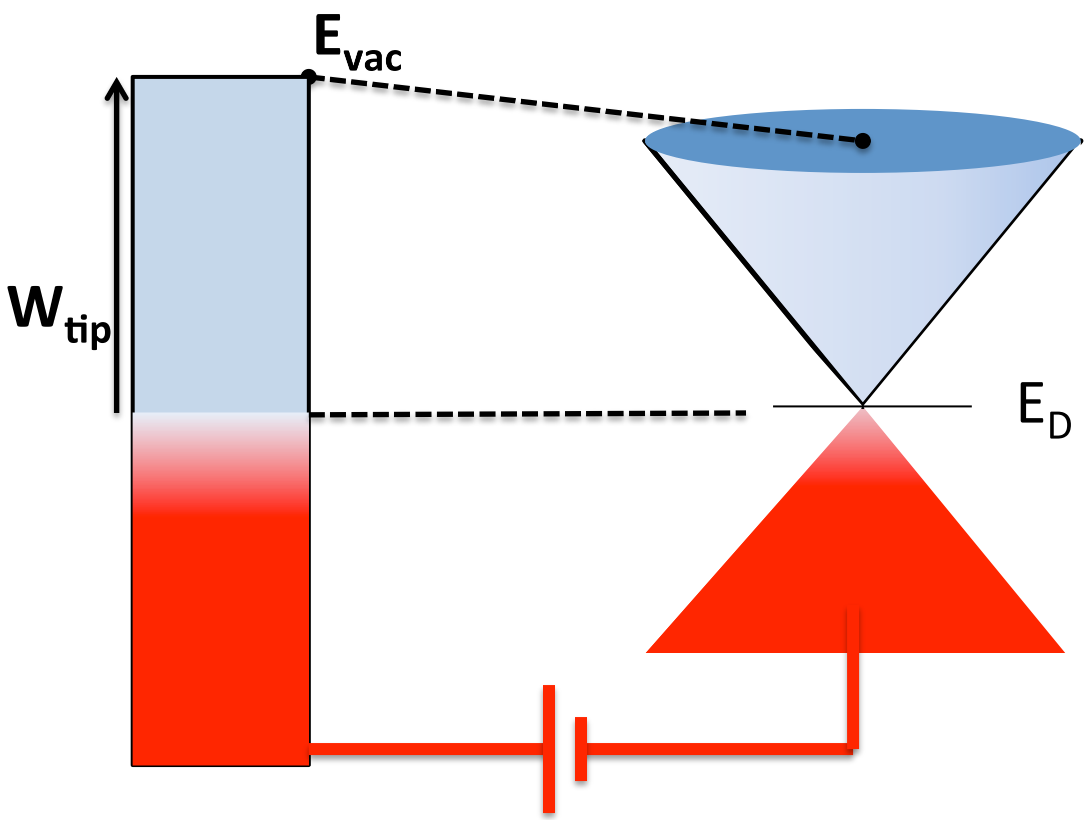
S. Samaddar *et al.*, Phys. Rev. Lett. (2016).

Work function vs. Fermi level

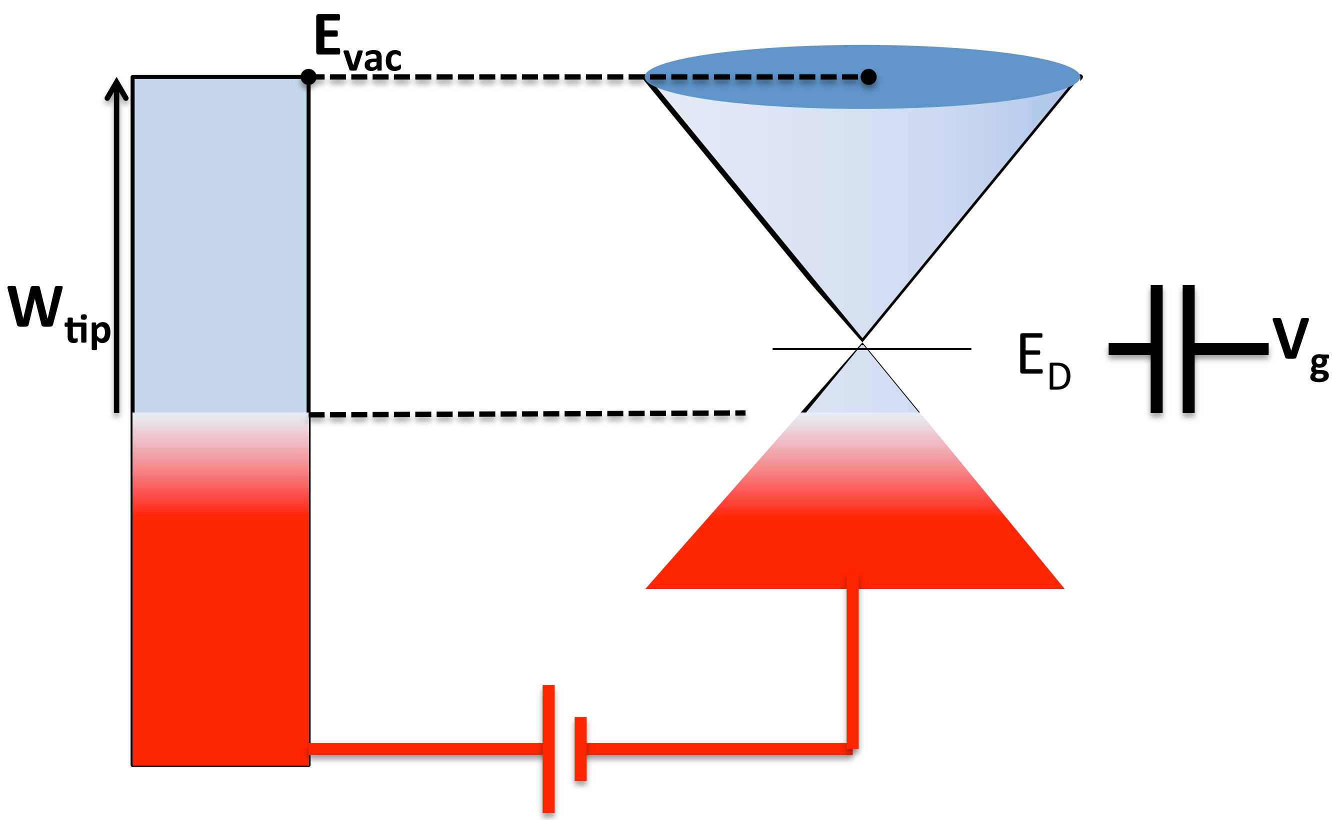




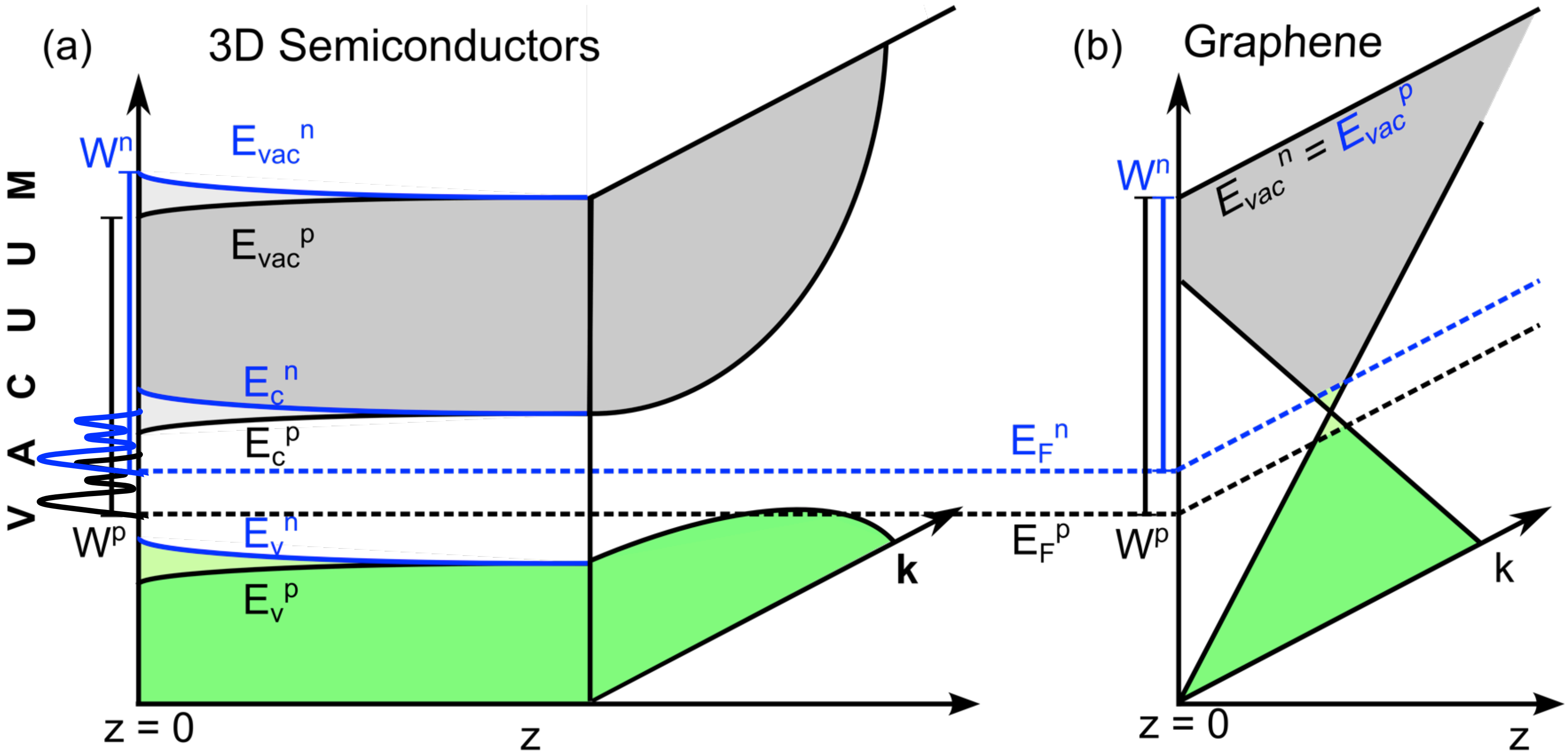
Work function vs. Fermi level



Work function vs. Fermi level



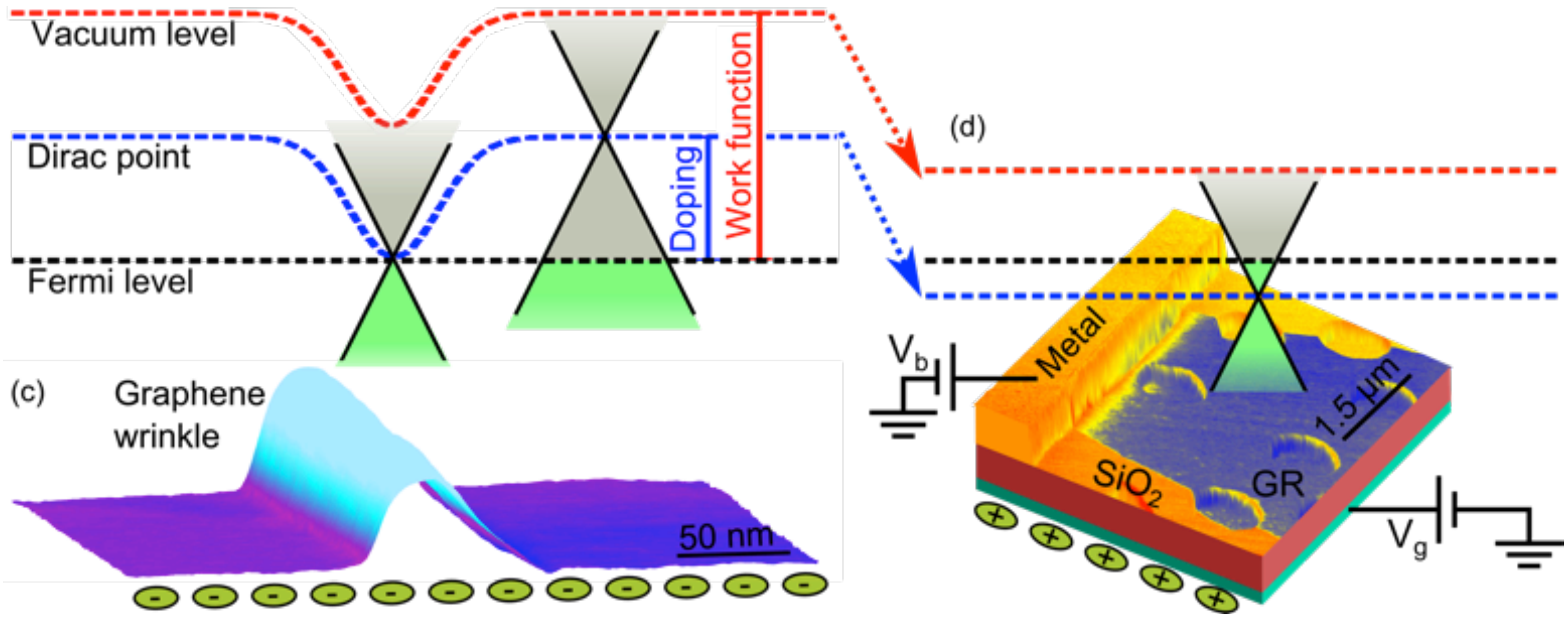
Work function: semiconductor vs. graphene



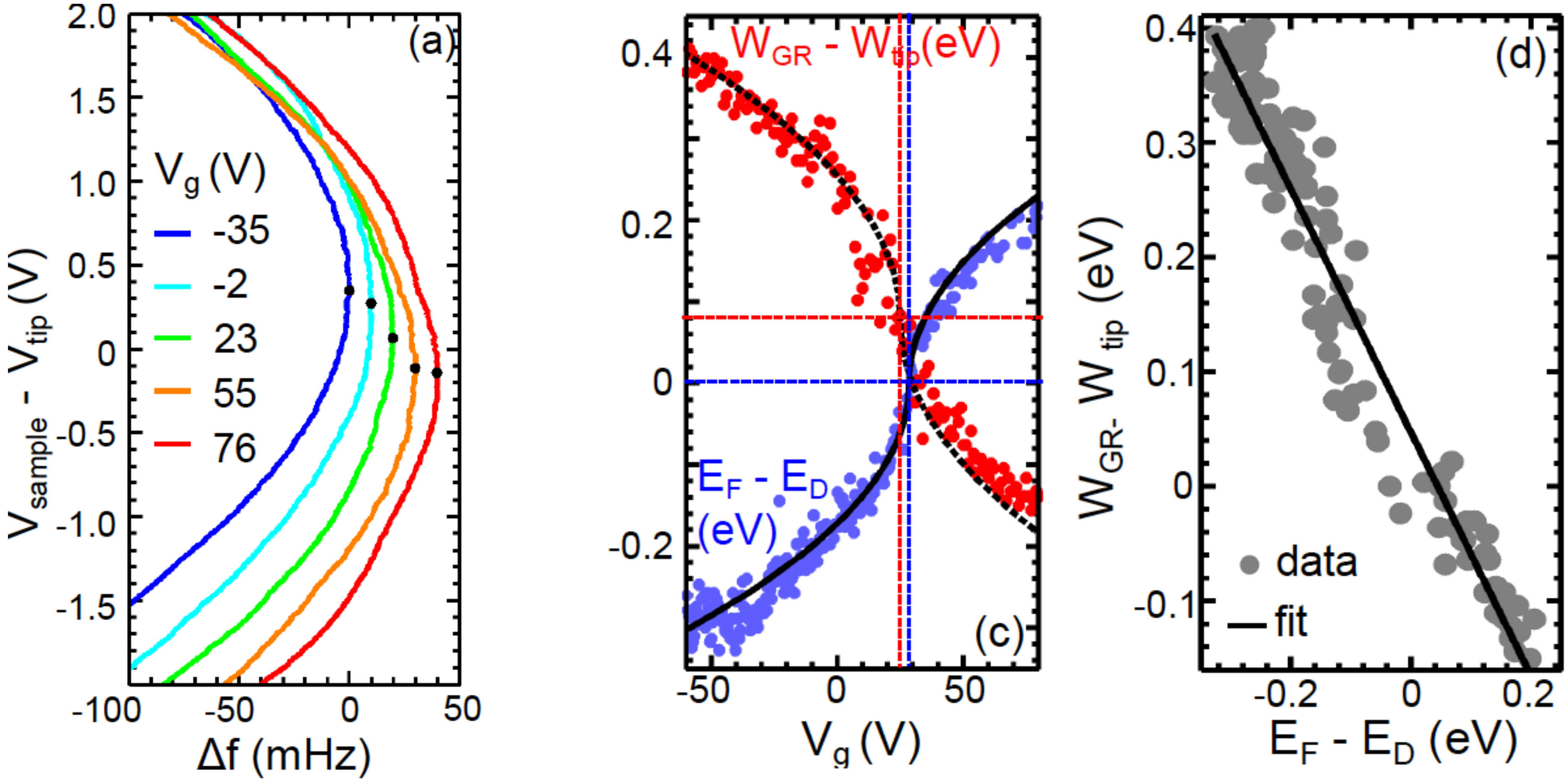
At surface: $$\frac{\partial W_{semicon}}{\partial (E_0 - E_F)} << 1$$ $$\frac{\partial W_{graphene}}{\partial (E_D - E_F)} = 1$$

Mönch, *Semiconductor surfaces and interfaces* (1987)

Work function: semiconductor vs. graphene



Work function vs. doping level in gated graphene



See also:
Yu et al., Nanolett. (2010).

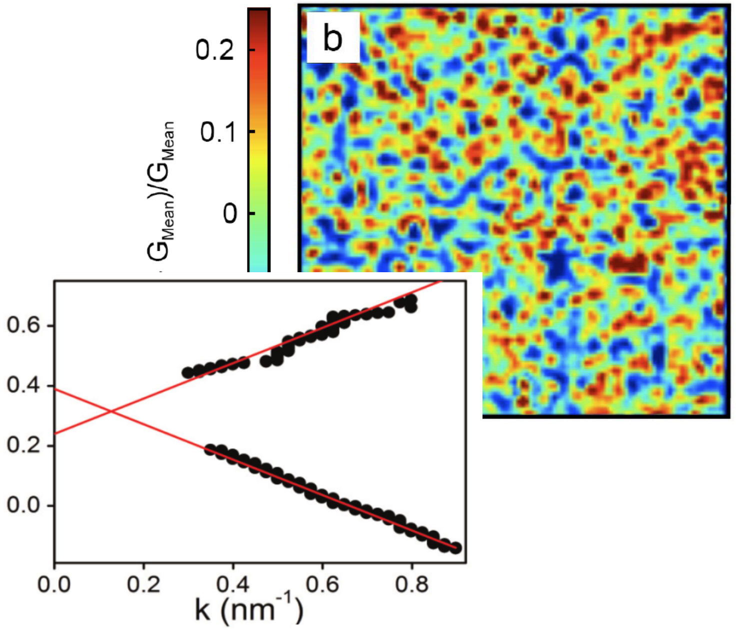
$$\frac{\partial W_{graphene}}{\partial (E_D - E_F)} = 1$$

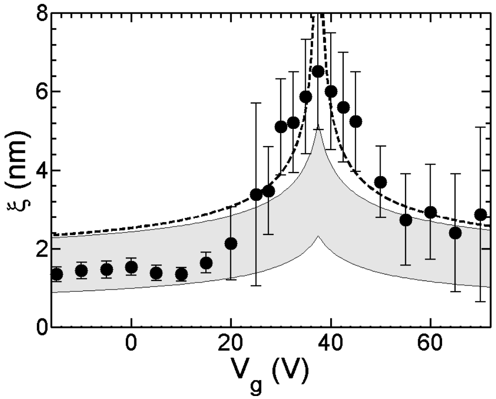
Summary

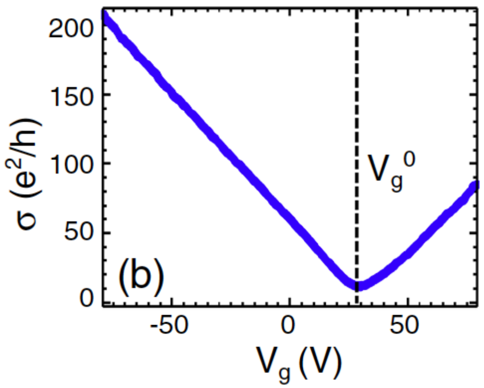
- Local and global properties

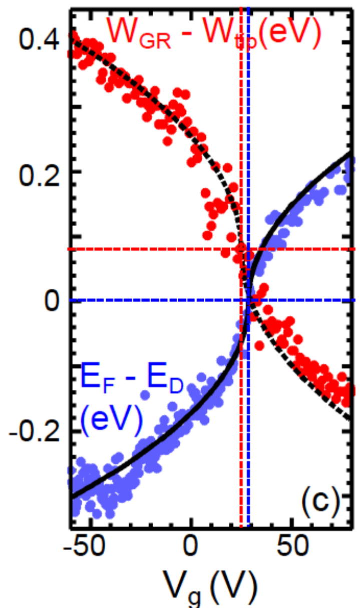
  in situ probing of *microscopic* device properties

- Graphene response to charge disorder:
  - probe of e-e interactions
  - strong growth of doping inhomogeneities near charge neutrality









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D. Lepoittevin	Electronics
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