Technische Universiteit Delft

Nanomechanics

Yaroslav M. Blanter

Kavli Institute of Nanoscience, Delft University of Technology

- Detection
- Shuttling
- Doubly-clamped beams
- Graphene
- Strain engineering

Persistent currents

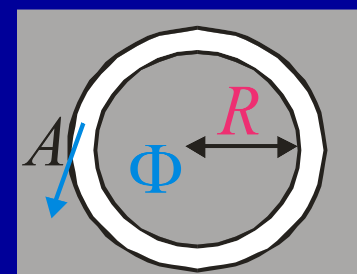
Interference is affected by Aharomov-Bohm flux

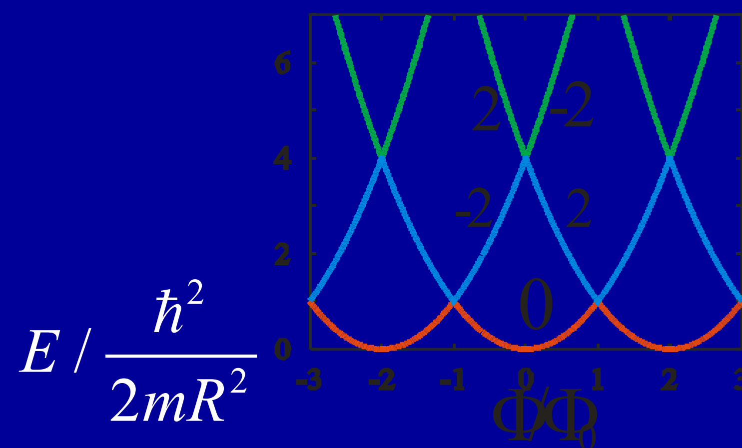
$$\hat{H} = \frac{\hbar^2}{2m}\left(\vec{\hat{p}} - \frac{e}{c}\vec{A}\right)^2 \Rightarrow$$

$$\hat{H} = \frac{\hbar^2}{2mR^2}\left(-i\frac{\partial}{\partial\phi} - \frac{\Phi}{\Phi_0}\right)^2;$$

$$\Psi(\phi) \propto e^{iN\phi} \Rightarrow$$

$$E = \frac{\hbar^2}{2mR^2}\left(N - \frac{\Phi}{\Phi_0}\right)^2$$





Energy levels vs. flux

Technische Universiteit Delft

Measurements of persistent currents

$$I = \frac{\partial E}{\partial \Phi} = \sum_{\substack{filled\\levels}} \frac{\partial E_i}{\partial \Phi}$$

A. C. Bleszynski-Jayich et al, Science **326**, 272 (2009)

Experiments to date have produced a number of confusing results in apparent contradiction with theory and even among the experiments themselves (*2*, *3*). These conflicts have remained without a clear resolution for nearly 20 years, suggesting that our understanding of how to measure and/or calculate the ground-state properties of as simple a system as an isolated metal ring may be incomplete.

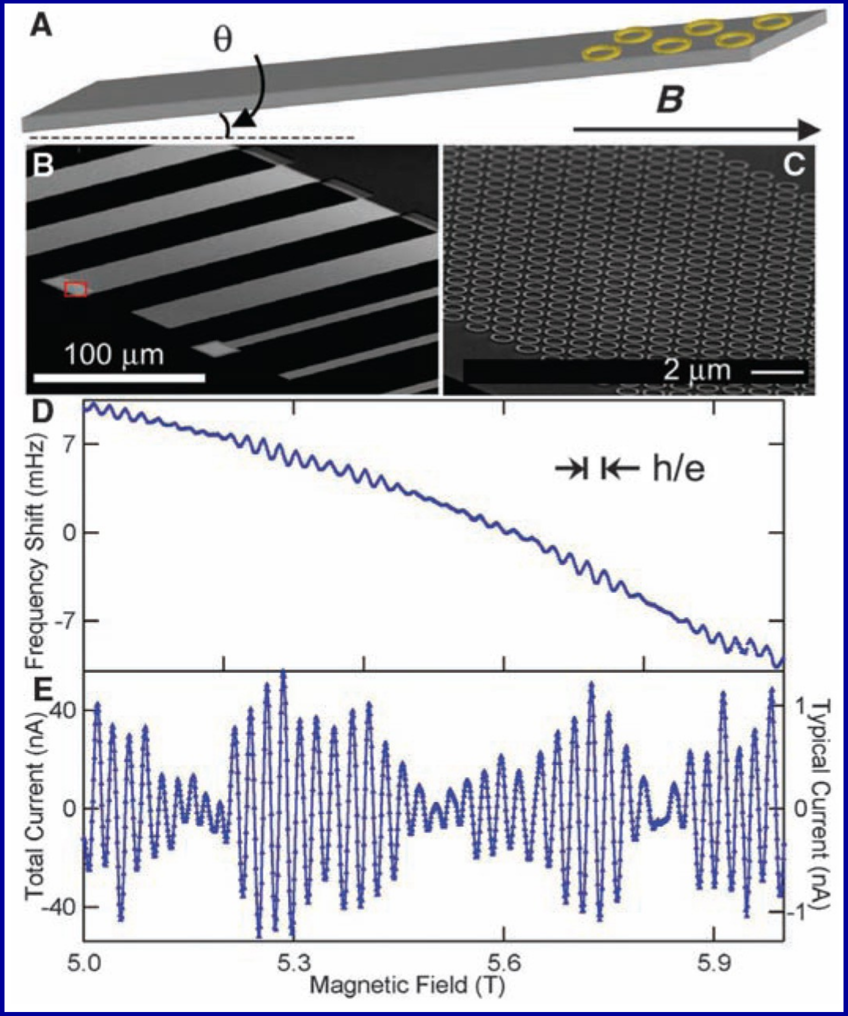
Amplitude clean, single ring: $\frac{e\hbar}{mR^2}$

Amplitude disordered:

$$I = \sum_l I_l \sin\frac{2\pi l\Phi}{\Phi_0}, I_l = -\frac{4e\delta}{\pi^2\hbar}$$

Difficult to measure!

Measurements of persistent currents



A. C. Bleszynski-Jayich et al, Science **326**, 272 (2009)

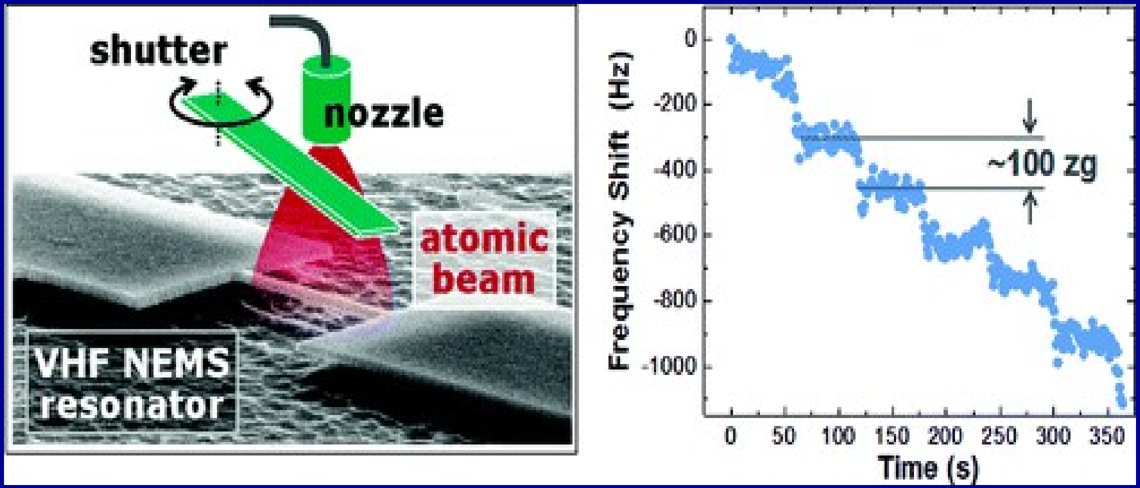
Currents produce tork and shift the cantilever frequency

$$\tau = \mu \times B$$

Good agreement with the theory predictions

Mass detection

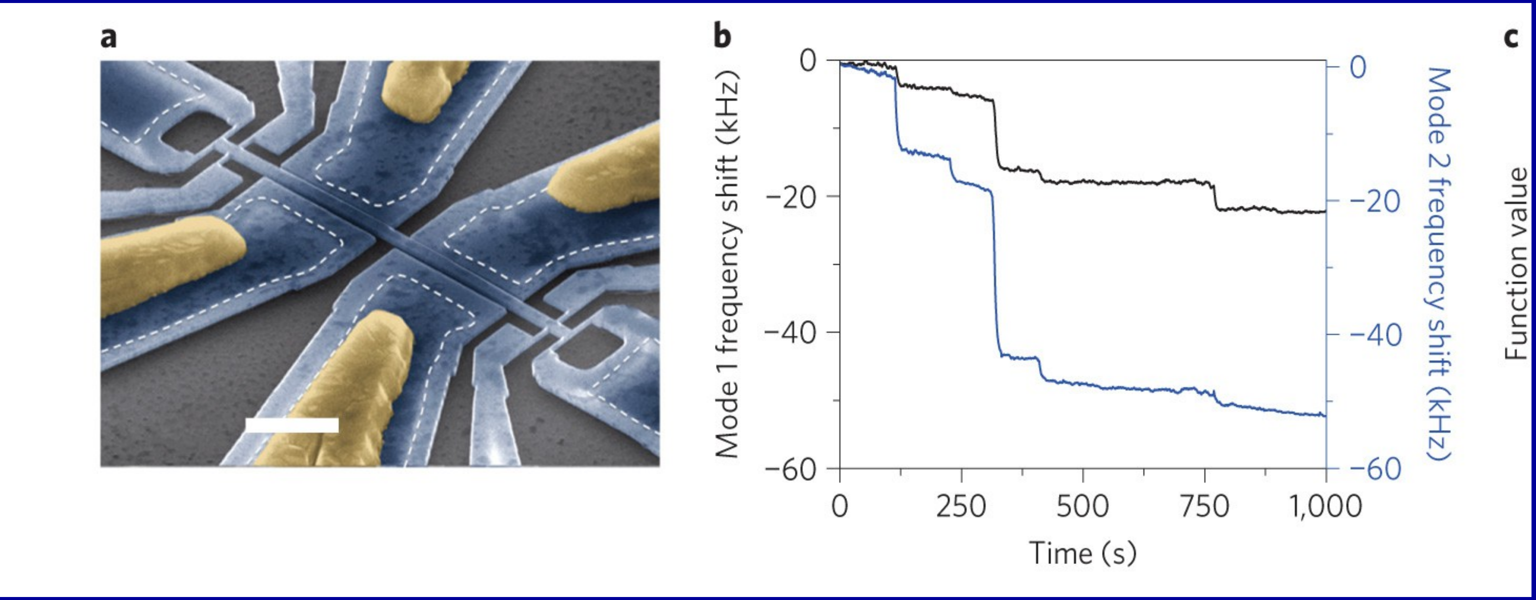
Y. T. Yang et al (Roukes group, Caltech) Nano Letters **6**, 583 (2006)



Resonant frequency: 133 MHz
Size: 2300 x 150 x 70 nm
Mass sensitivity: 100 zg

Single-molecule detection

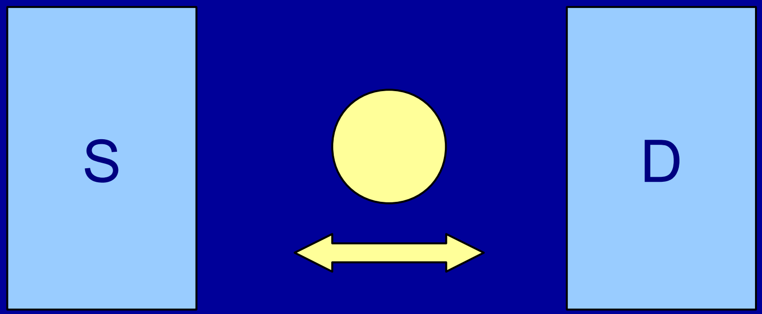
M. S. Hanay et al, Nature nanotech. **7**, 602 (2012)

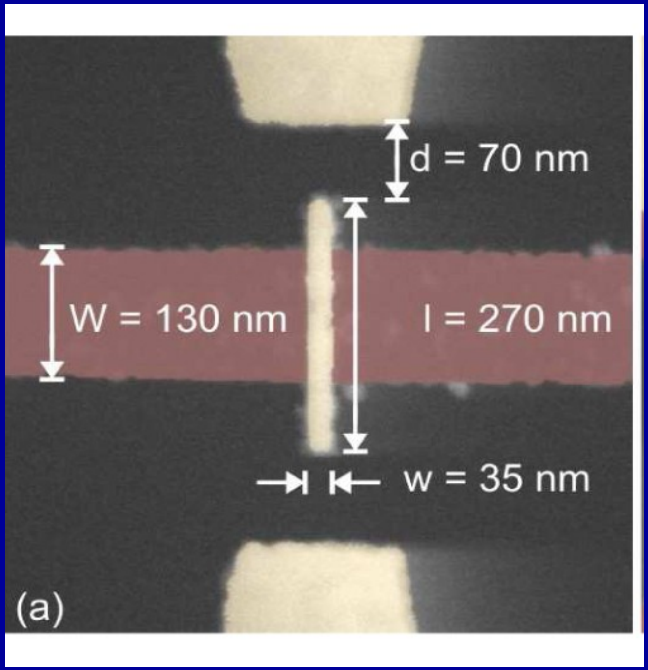


Shuttling

L. Y. Gorelik et al
PRL **80**, 4526 (1998)

D. R. König and E. M. Weig
APL **101**, 213111 (2012)



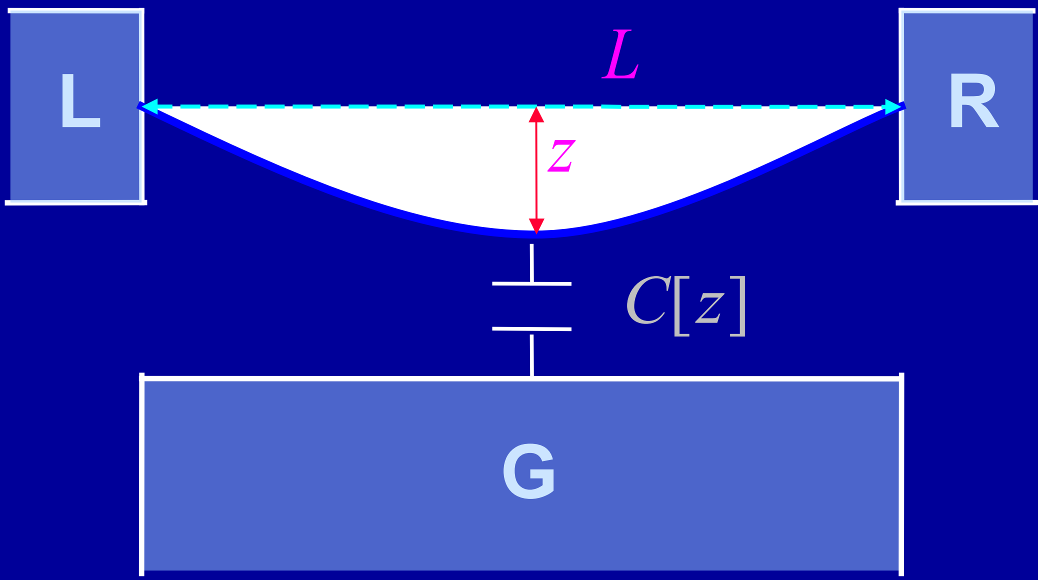


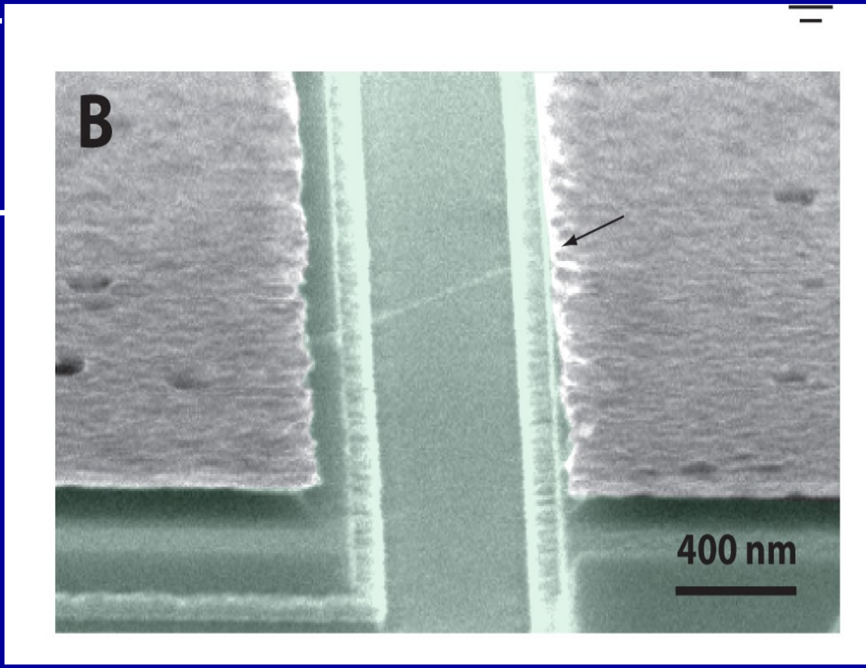
Couples phonons to charge due to the position dependence of tunnel rates and of Coulomb-induced force

Double-clamped beam

S. Sapmaz et al
PRB **67**, 235414 (2003)

G. Steele et al
Science **325**, 1103 (2009)



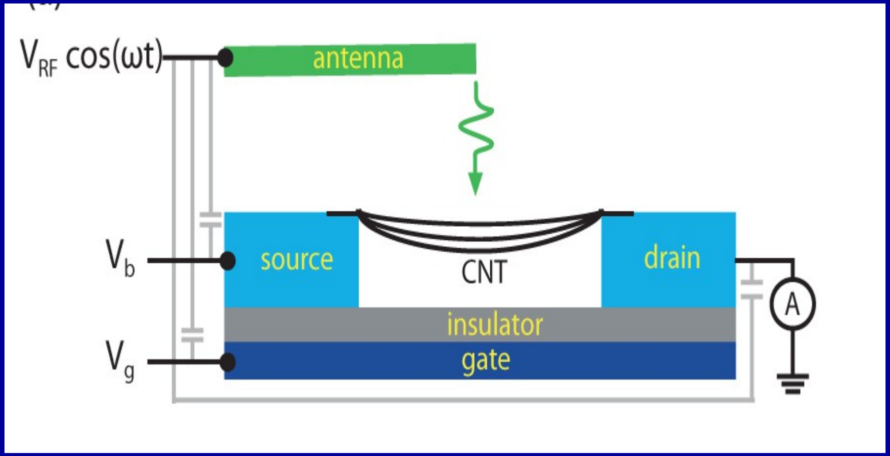


Couples phonons to charge due to the Coulomb-induced force

Size: 500 nm
Frequency: 140 MHz
Q-factor: over 10^5

Backaction in a double-clamped beam

H. B. Meerwaldt, G. Labadze, B. H. Schneider, A. Taspinar, YMB, H. S. J. van der Zant, and G. A. Steele, PRB **86**, 115454 (2012)



$$M\ddot{x} + \frac{M\omega_0}{Q}\dot{x} + M\omega_0{}^2 x = F_{RF}\cos\omega t + F[x]$$

$$F[x] = -\Delta k x - \beta x^2 - \alpha x^3$$

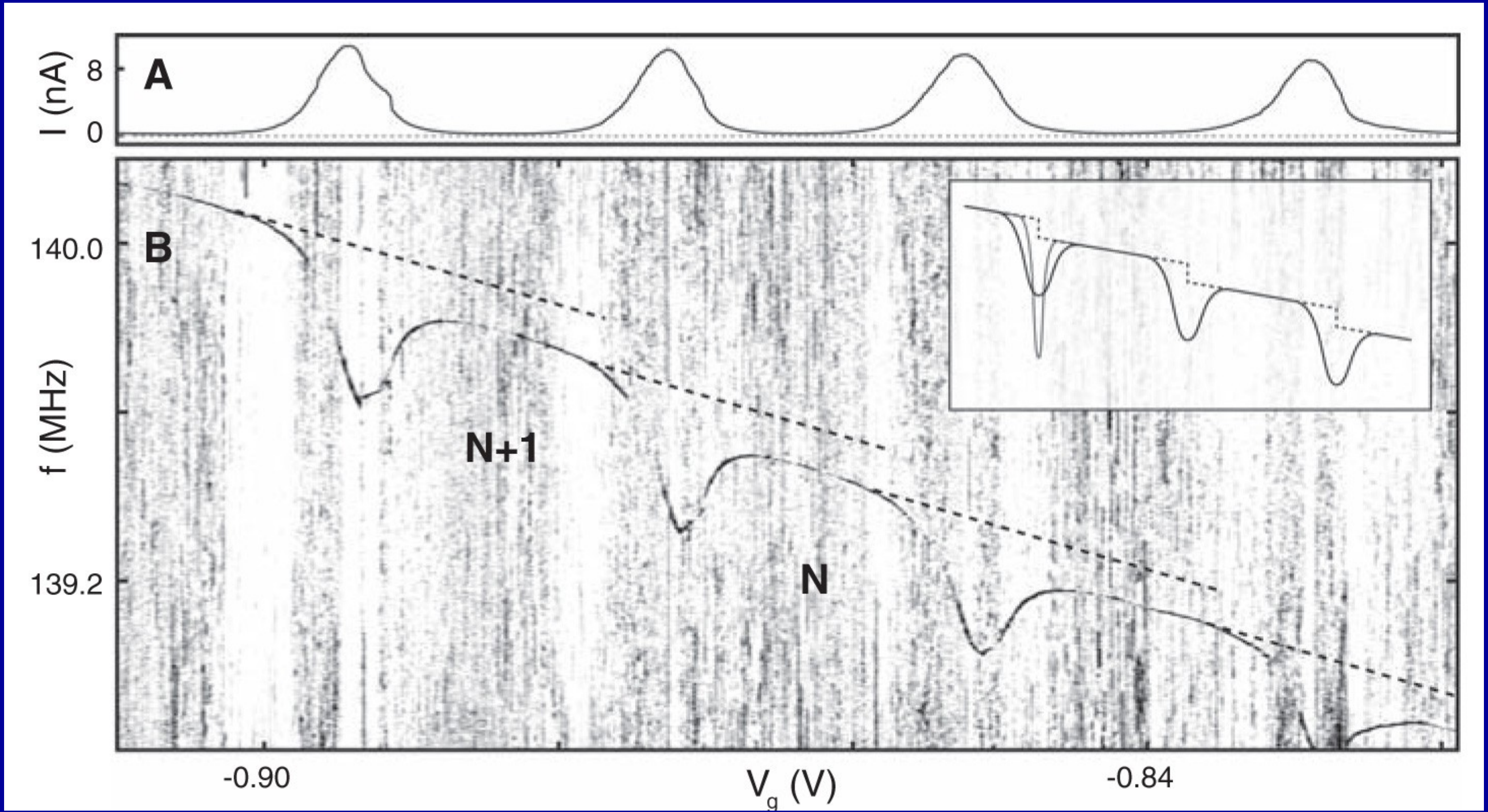
$$F = \frac{1}{2}\frac{dC_g}{dx}\left(V_g - V_{CNT}\right)^2$$

Renormalization of frequency and introducing of Duffing parameter

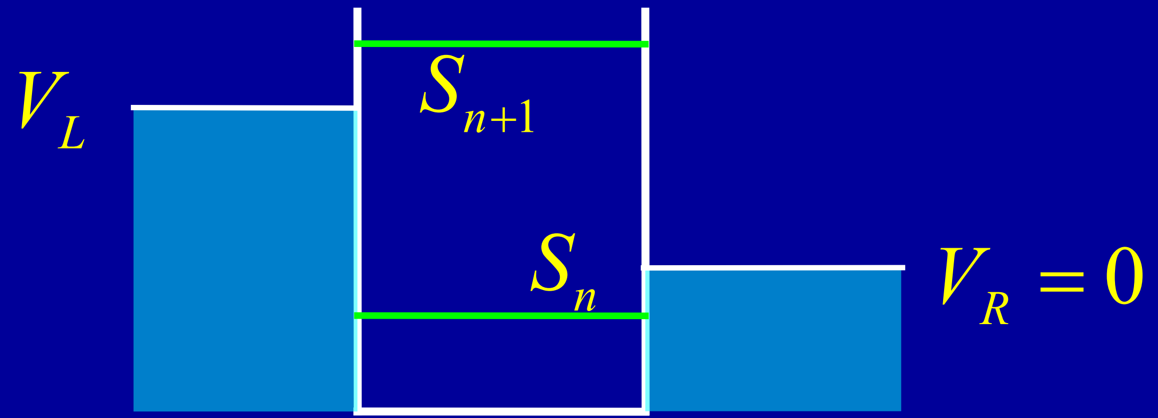
Frequency stiffening by Coulomb effects

$$\Delta\omega_0 \propto\sim 1-\frac{C_{tot}}{C_g}-\frac{e}{C_g}\frac{\partial\langle N\rangle}{\partial V_g}$$

G. Steele et al
Science **325**, 1103 (2009)



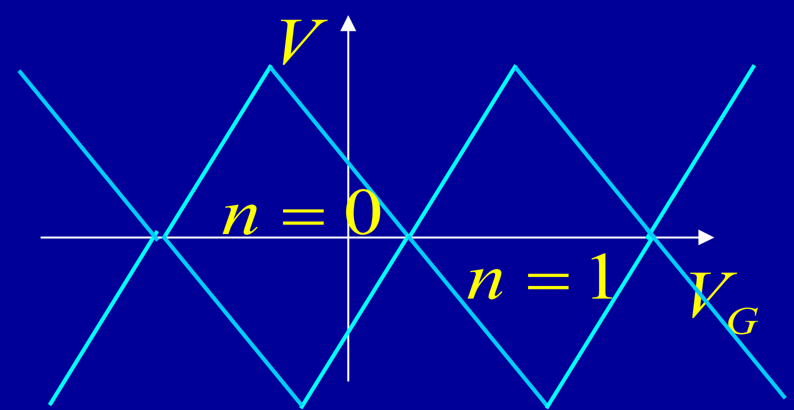
Coulomb blockade



Conditions that current is not flowing:

(a) $S_{n+1} > eV_L$ (b) $S_n < eV_L$

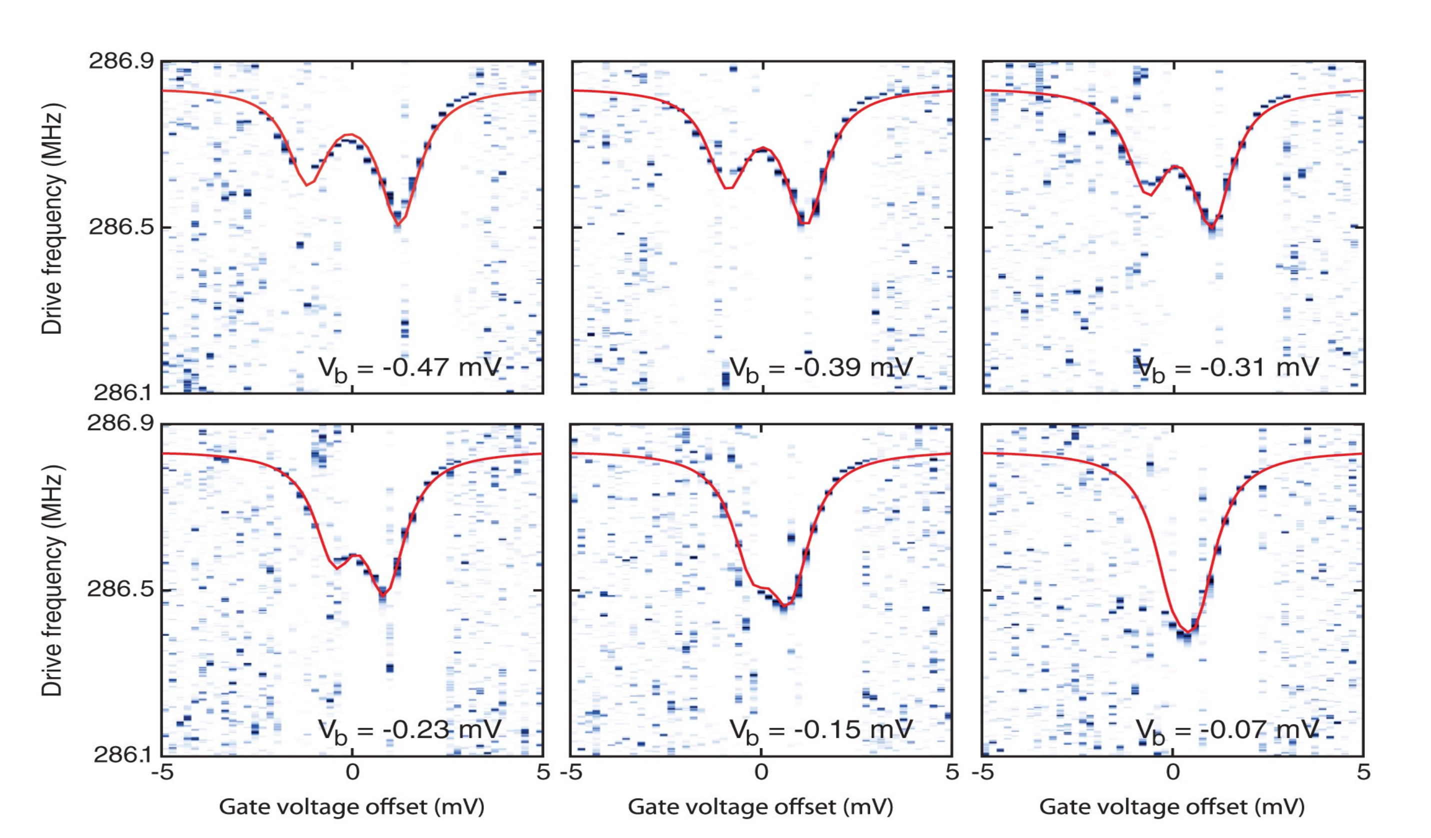
(c) $S_{n+1} > 0$ (d) $S_n < 0$



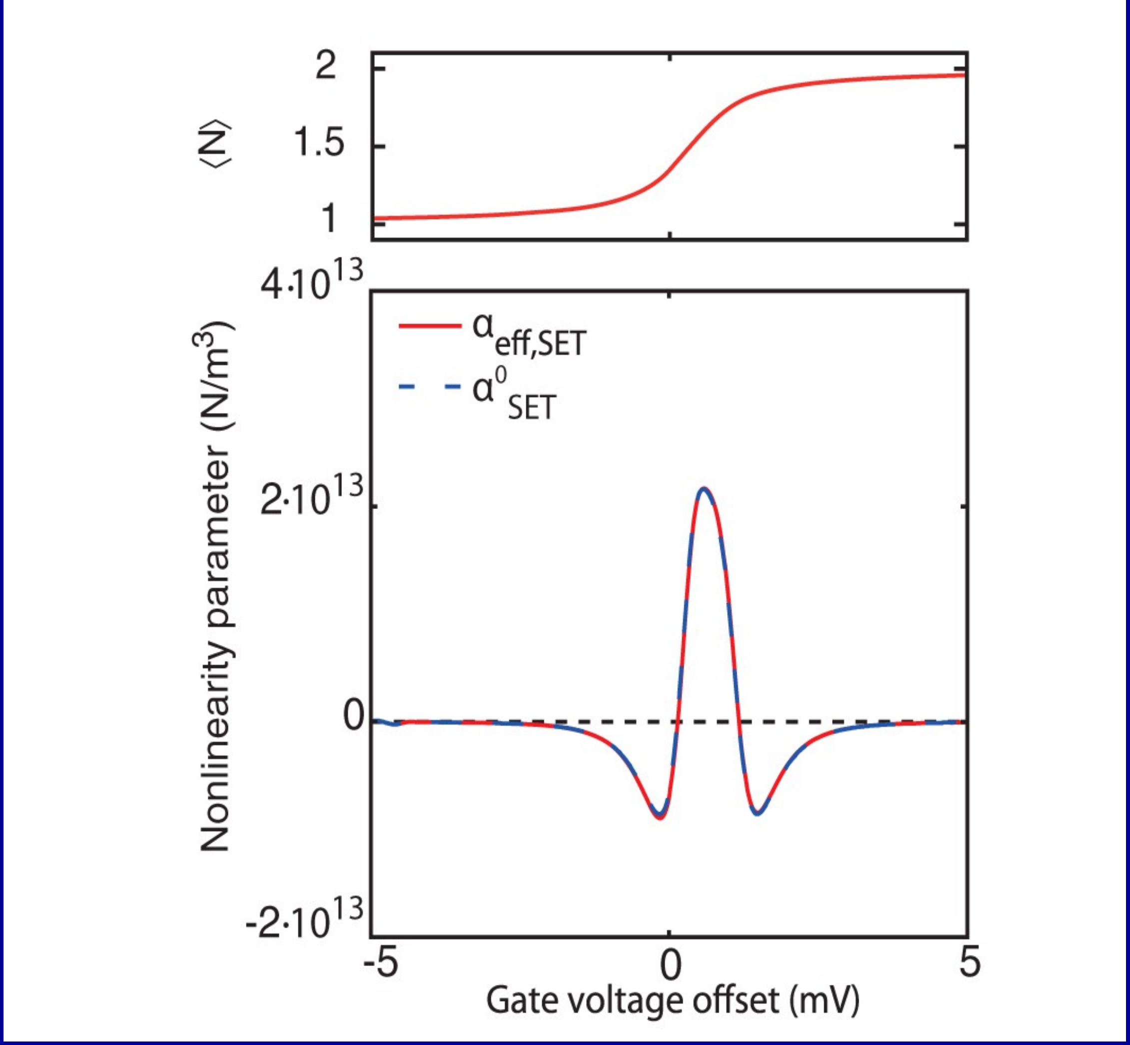
Frequency softening by Coulomb effects

H. B. Meerwaldt et al, PRB **86**, 115454 (2012)

$$\Delta\omega_0 \propto \sim 1 - \frac{C_{tot}}{C_g} - \frac{e}{C_g}\frac{\partial\langle N\rangle}{\partial V_g}$$



Coulomb-induced nonlinearity

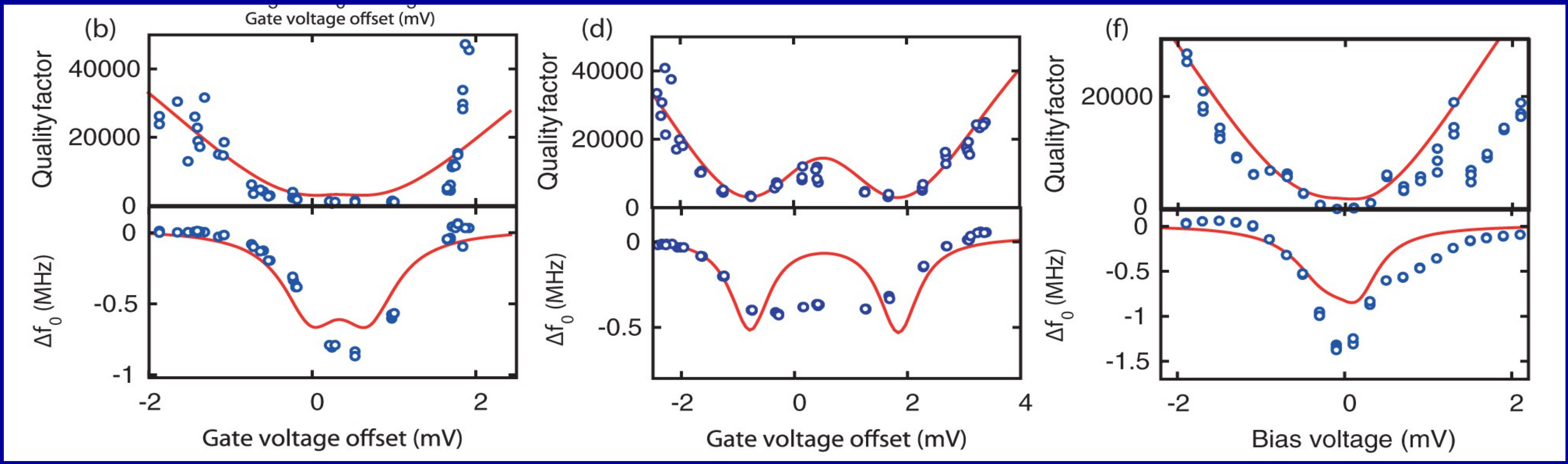


$$F[x] = -\Delta k x - \beta x^2 - \alpha x^3$$

Coulomb-induced damping

$$\frac{\omega_0}{Q} = \frac{\omega_0}{Q_0} + \frac{F_{stoch} V_g}{m C_g} \frac{1}{\Gamma_{tot}} \frac{dC_g}{dx} \frac{\partial \langle N \rangle}{\partial V_g}$$

O. Usmani, YMB, and Yu. V.Nazarov, PRB **75**, 195312 (2007)



Backaction in SET coupled to a resonator

$P_n(x,v,t)$ - obeys master equation

x – position
v - velocity

O. Usmani, YMB, and Yu. V. Nazarov, '04, '07

$$\frac{\partial P_n}{\partial t} + \left(v\frac{\partial}{\partial x} + \frac{\partial}{\partial v}\frac{F}{M} \right) P_n = St[P]$$

$$F(x,v) = -M\omega^2 x - M\gamma v + Fn$$

Adiabaticity: reduce to Fokker-Planck equation

$$\frac{\partial P}{\partial t} + v\frac{\partial P}{\partial x} - \omega^2 x \frac{\partial P}{\partial v} - \left[\frac{\omega}{Q} + \Psi(x) \right] \frac{\partial}{\partial v}(vP) = D(x)\frac{\partial^2 P}{\partial v^2}$$

Built-in dissipation

Dissipation due to tunneling

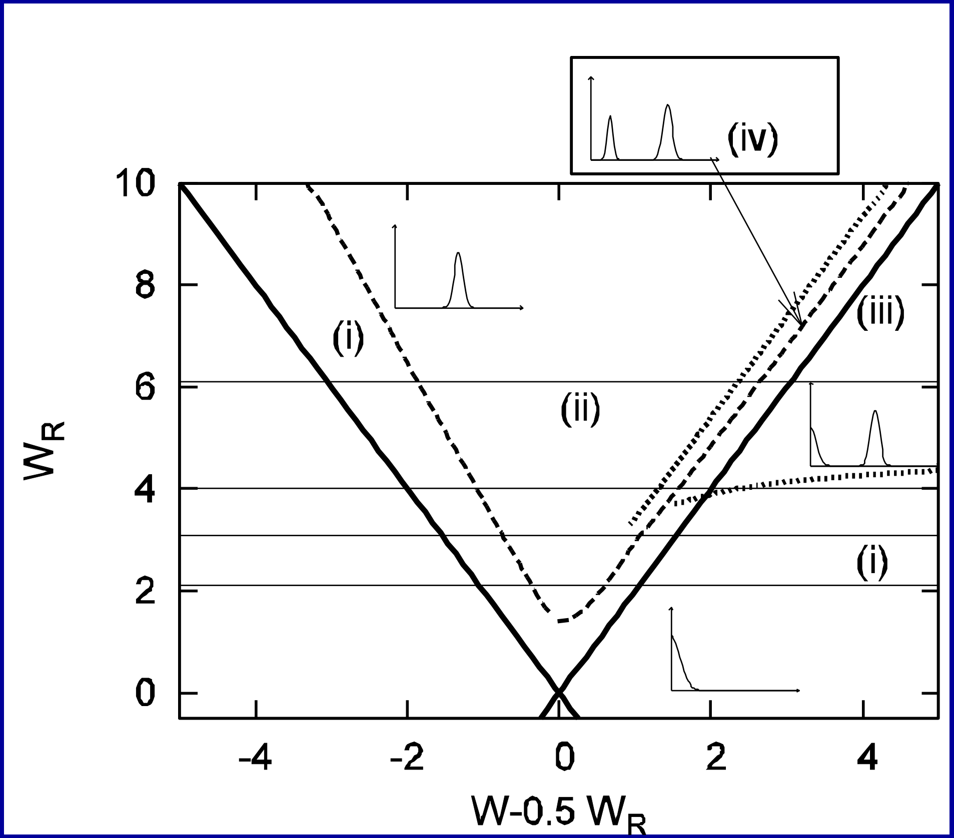
Diffusion in velocity space

$$\Psi(x) = \frac{F^2}{M^2}\frac{\Gamma^-(x)\partial_x\Gamma^+(x) - \Gamma^+(x)\partial_x\Gamma^-(x)}{\Gamma_t^3}$$

Coulomb-induced instabilities

$$\frac{\omega_0}{Q} = \frac{\omega_0}{Q_0} + \frac{F_{stoch} V_g}{m C_g} \frac{1}{\Gamma_{tot}} \frac{dC_g}{dx} \frac{\partial \langle N \rangle}{\partial V_g}$$

O. Usmani, Ya. M. Blanter, and Yu. V.Nazarov, PRB **75**, 195312 (2007)



$$\Gamma^{\pm}_{L,R} = 2e^{a_{L,R}(\Delta E_{L,R} + Fx)}$$
$$\times f_F(\pm(\Delta E_{L,R} + Fx))$$

Strain in graphene

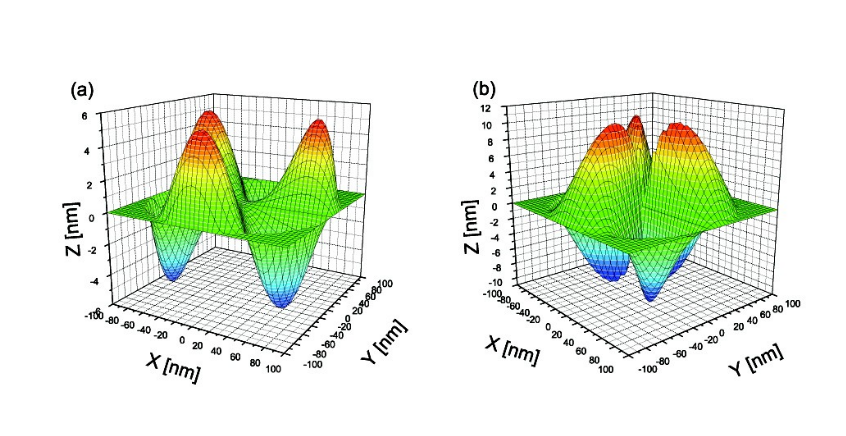
Deformation of a graphene sheet acts at electrons as pseudomagnetic field in the Dirac equation

$$A_x = t\beta(u_{xx} - u_{yy});\ A_y = -2t\beta u_{xy};\ \beta \approx 3$$

Suzuura, Ando '02
Guinea, Katsnelson, Vozmediano '08

Deformation caused by uniform load:

$$h(r) = \frac{h_0}{R^4}\left(R^2 - r^2\right)^2$$



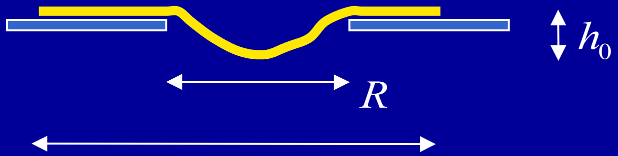
Uniform load   Local load (center)

Deformation caused by local load:

$$h(r) = \frac{h_0}{R^2}\left(\frac{1}{2}\left(R^2 - r^2\right) - r^2 \ln\frac{R}{r}\right)$$

Dirac equation: with added gauge fields

$$\vec{\sigma}(v_F\vec{p} + \vec{A})\Psi(\vec{r}) = E\Psi(\vec{r})$$

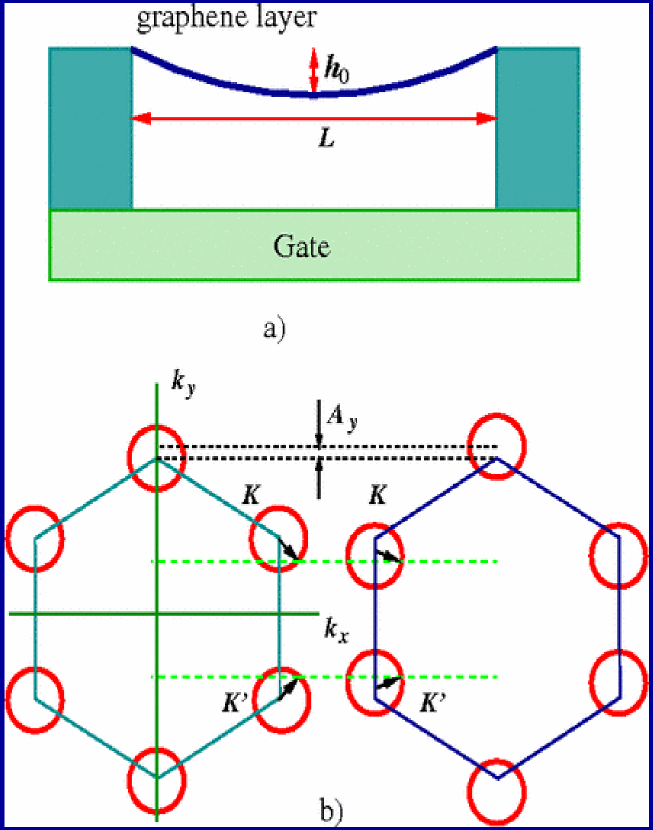


K.-J.Kim, YMB, K.-H.Ahn
Phys. Rev. B **84**, 081401 (2011)

Piezoconductivity in graphene

Deformation:

- Creates strain: pseudomagnetic gauge fields
- Creates density redistribution; the profile needs in principle to be calculated self-consistently

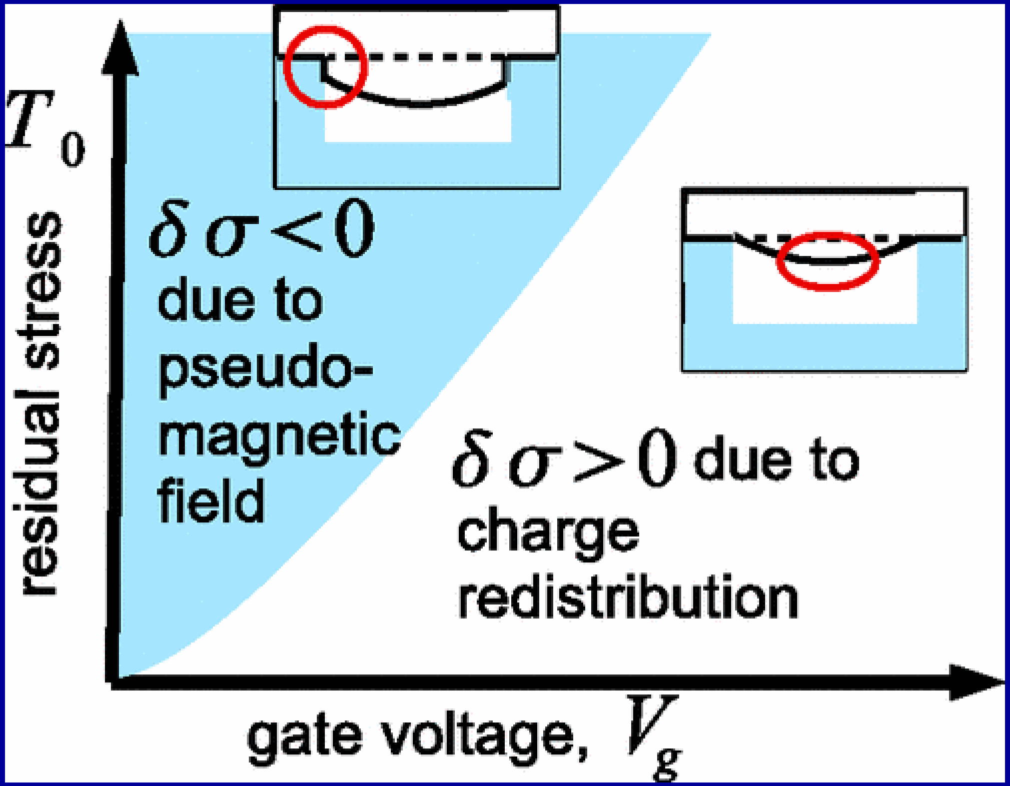


Fogler, Guinea, and Katsnelson
Phys. Rev. Lett. **101**, 226804 (2008)

Local shift of the Dirac cones:
Predicted metal-insulator transition at certain deformation

Piezoconductivity in graphene

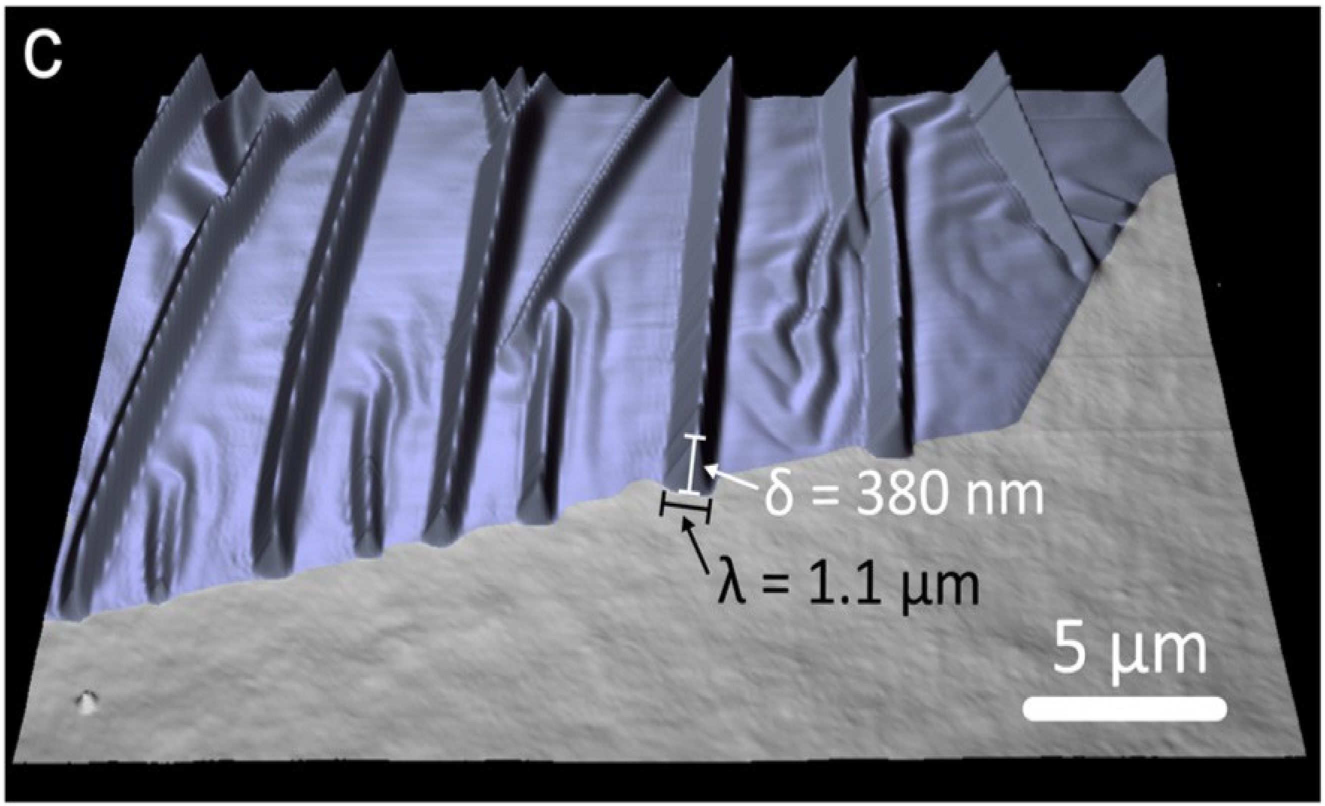
M. V. Medvedyeva and YMB
Phys. Rev. B **83**, 045426 (2011)



Strain engineering in MoS2

Wrinkles: large strain difference

A. Castellanos-Gomez et al
Nano Lett. **13**, 5361 (2013)



Strain engineering in MoS_2

Funneling of excitons

A. Castellanos-Gomez et al
Nano Lett. **13**, 5361 (2013)