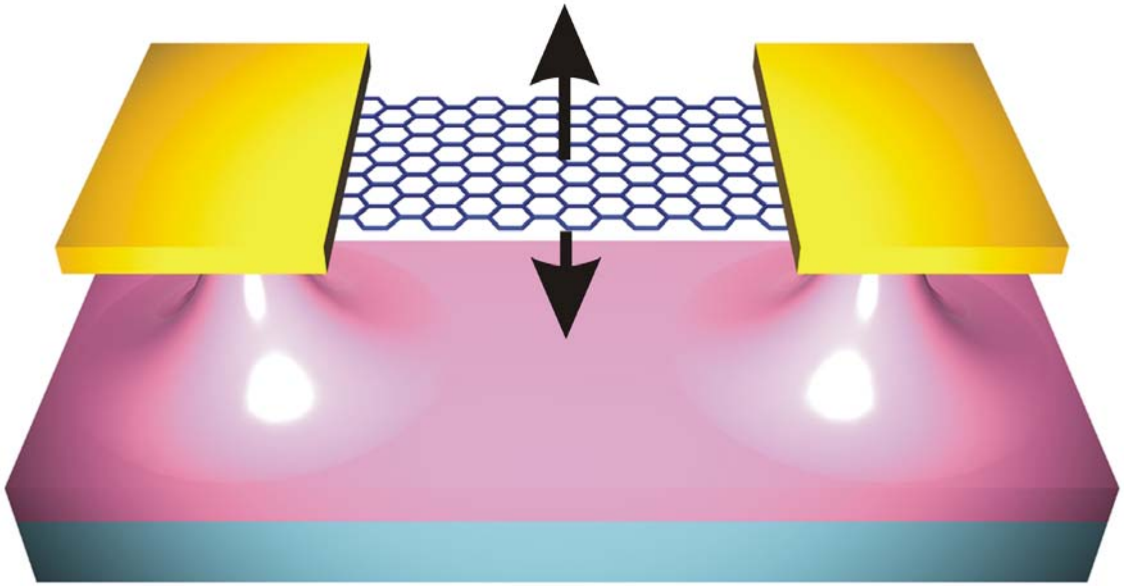
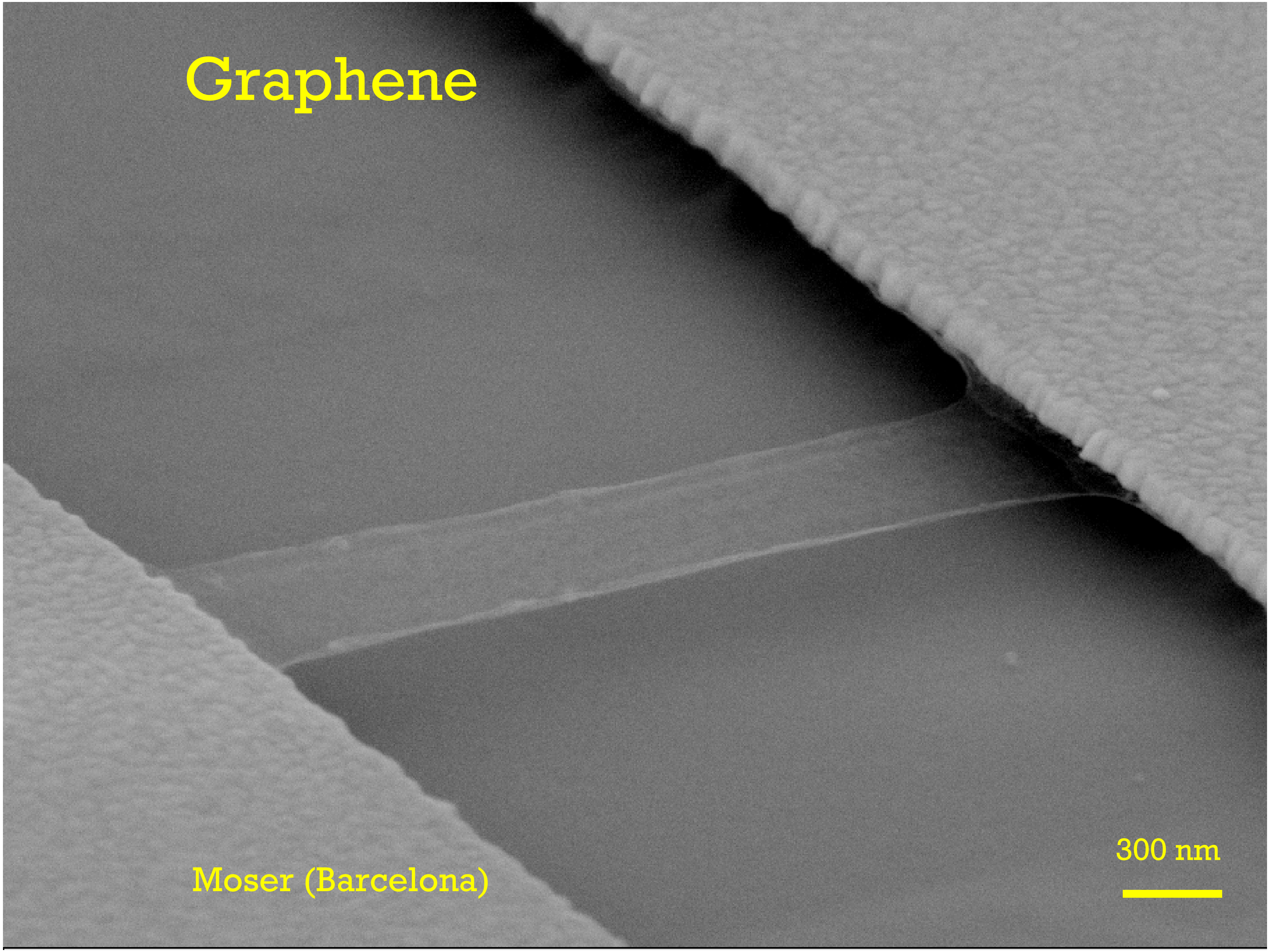
Graphene ElectroMechanical Resonators



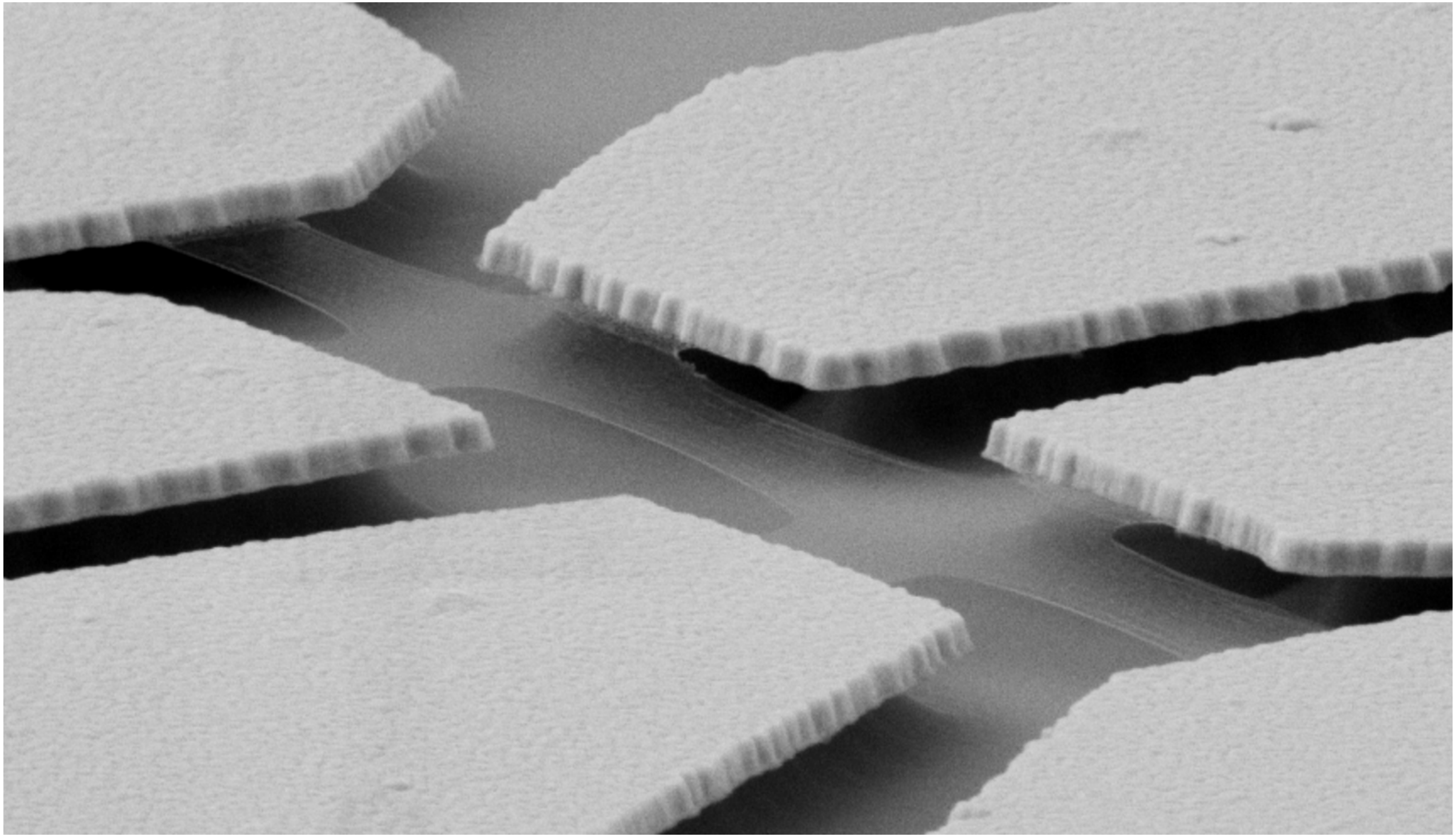
Adrian Bachtold

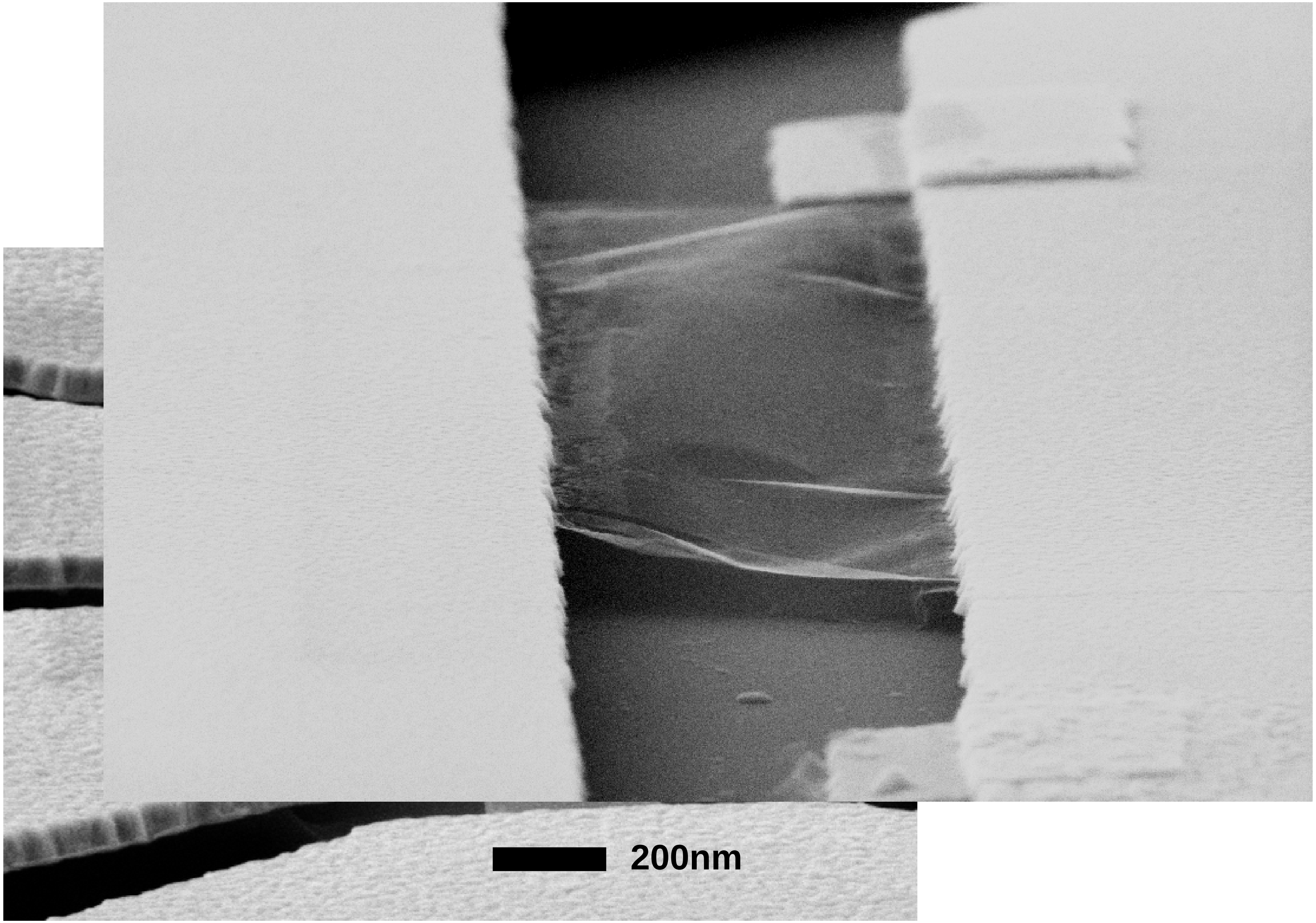
ICN, CIN2, Barcelona

Institut Català de Nanotecnologia

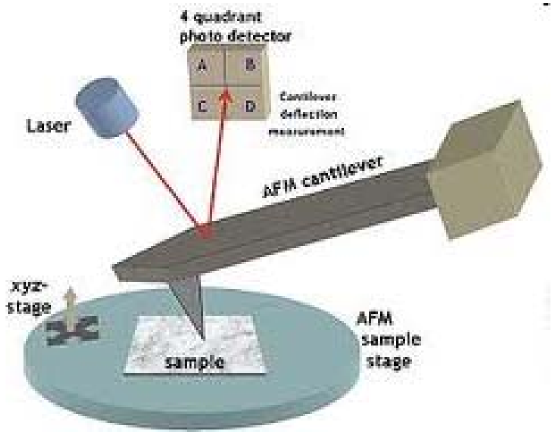

Graphene
Moser (Barcelona)
300 nm

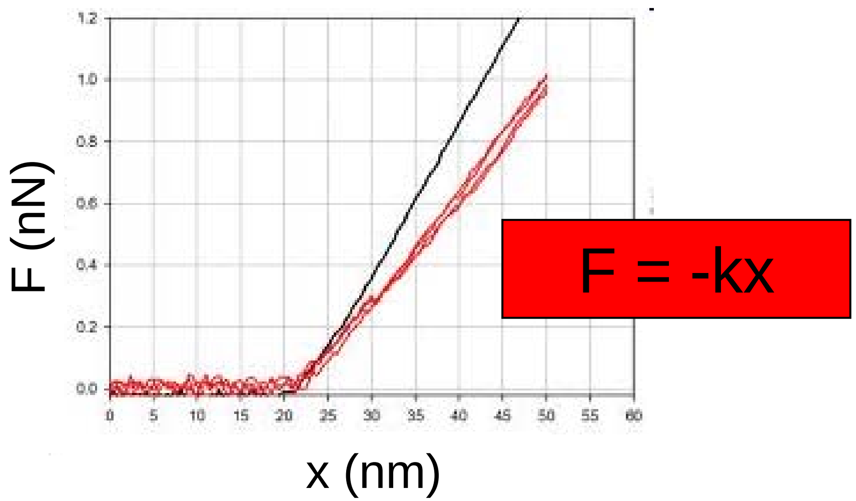
Graphene Hall Bar



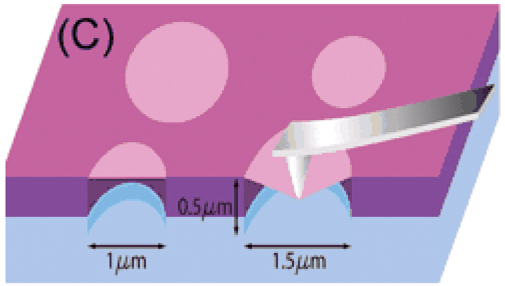

200nm

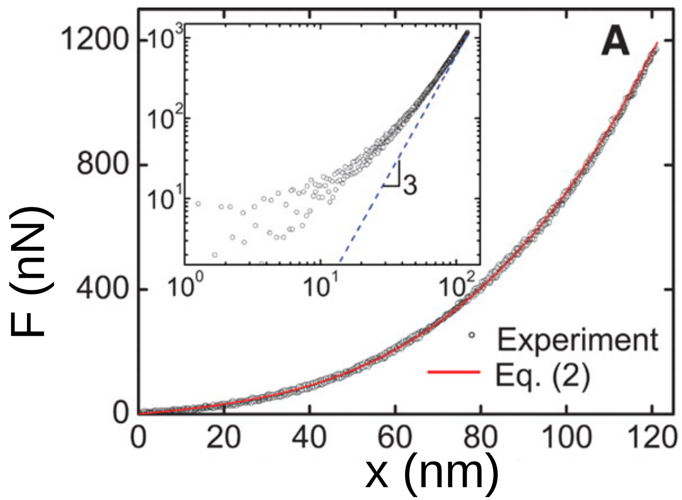
When going small





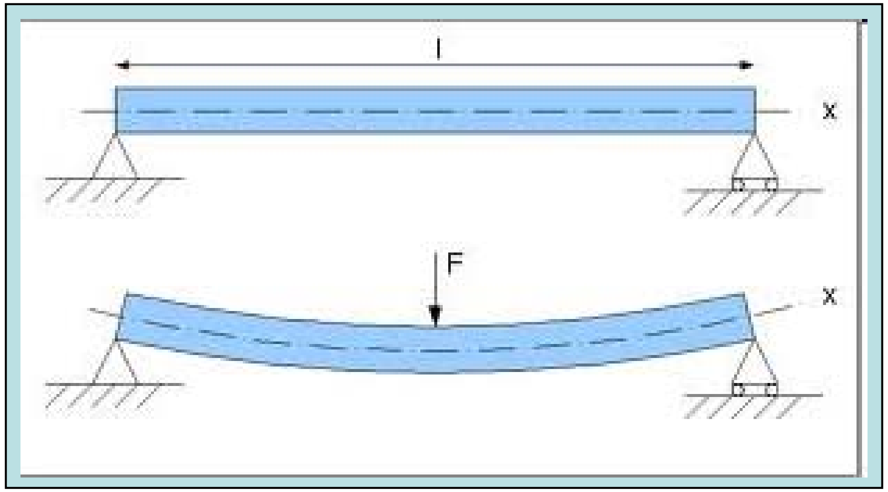
GRAPHENE



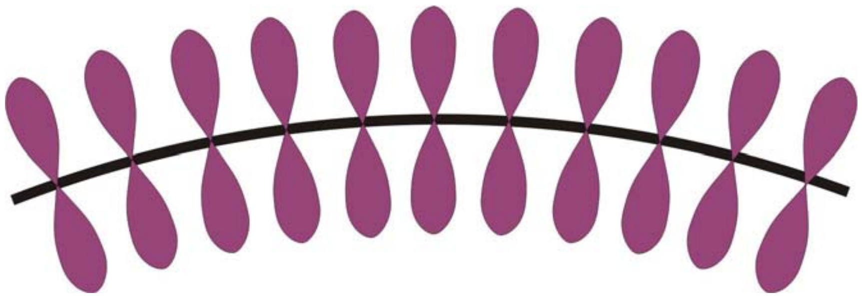


C Lee et al. Science 2008;321:385-388

bending rigidity

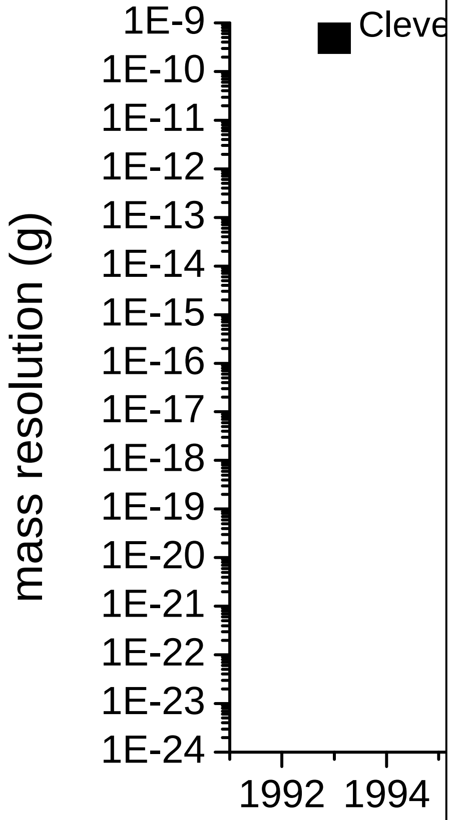


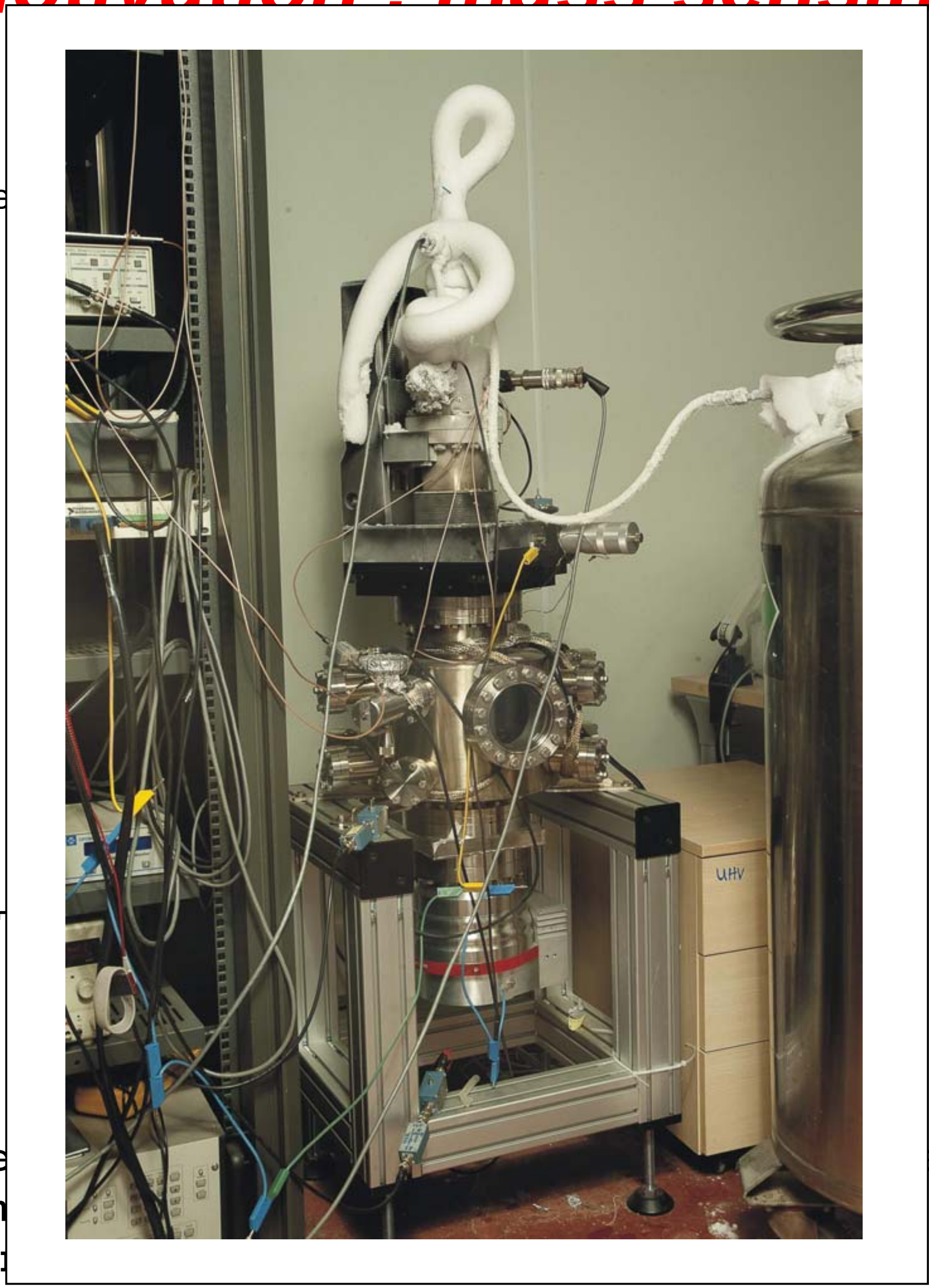
GRAPHENE

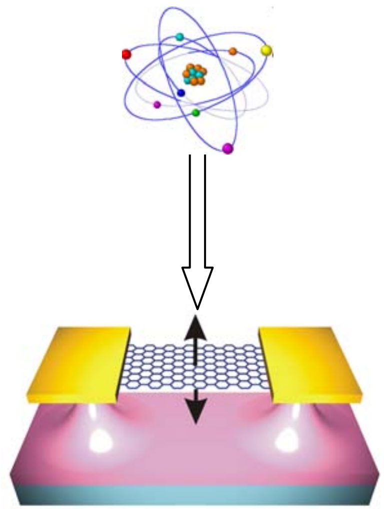


Atalaya, Isacsson and Kinaret, Nano Letters (2008)

Motivation : mass sensing





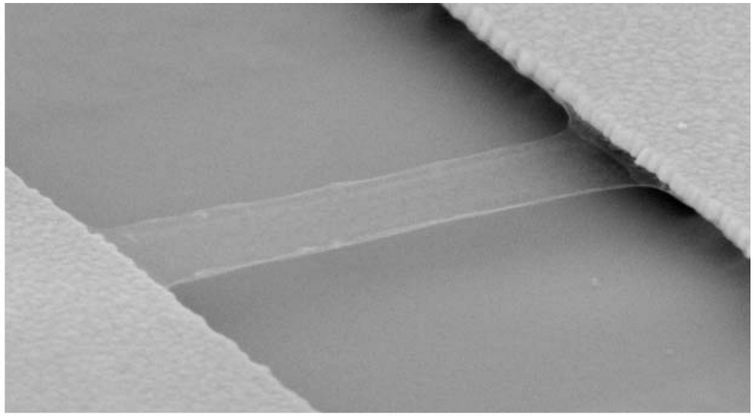


Lassagne ... ers 2008
K. Jensen
Chiu, Hu

Motivation : quantum limit

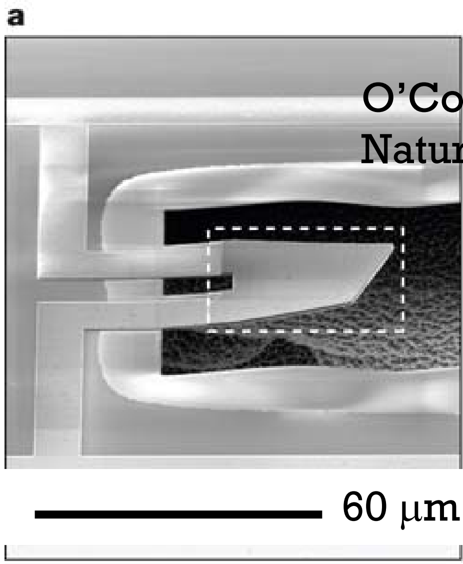
$$E = \hbar\omega(n + 1/2)$$

$$\boxed{\delta x_{QL} = \sqrt{\frac{\hbar}{m\omega}}}$$



1 μm

$\delta x_{QL} \sim 10^{-11}$ m

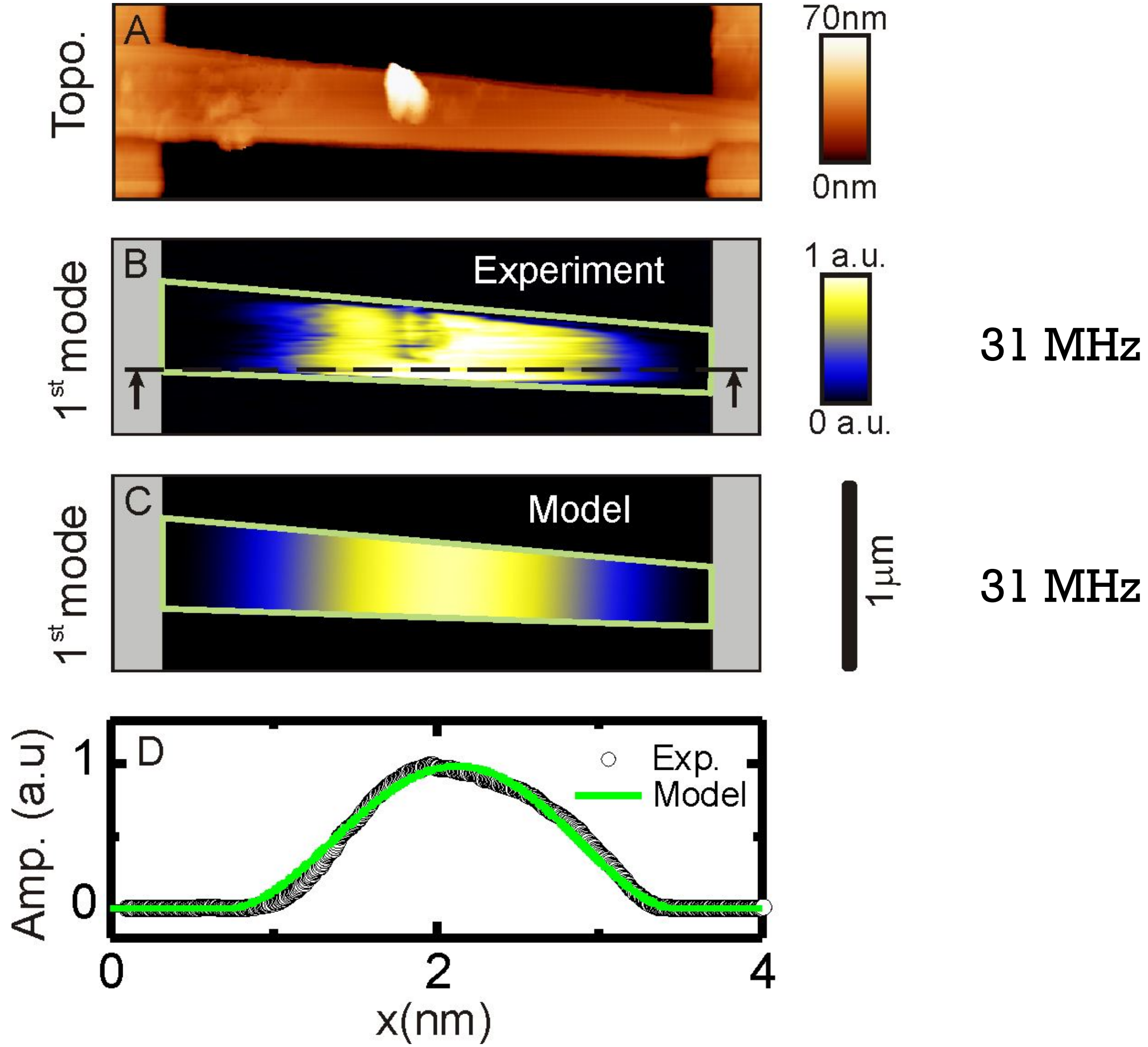


60 μm

O'Connell, et al., Nature 2010

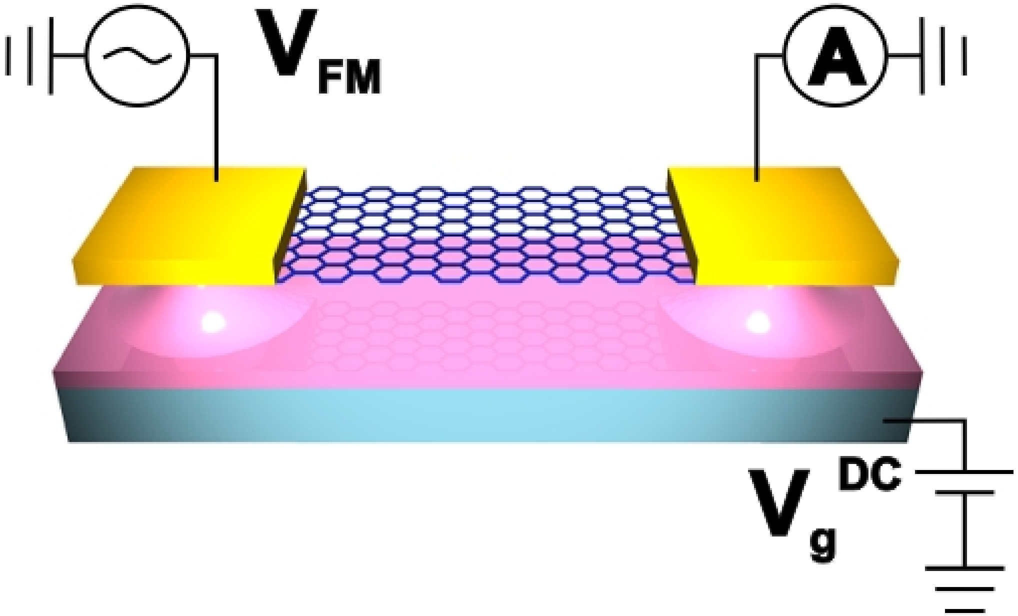
$\delta x_{QL} \sim 2 \cdot 10^{-17}$ m

seeing is believing



Garcia-Sanchez, van der Zande, San Paulo, Lassagne, McEuen, Bachtold
Nano Letters 8, 1399 (2008)

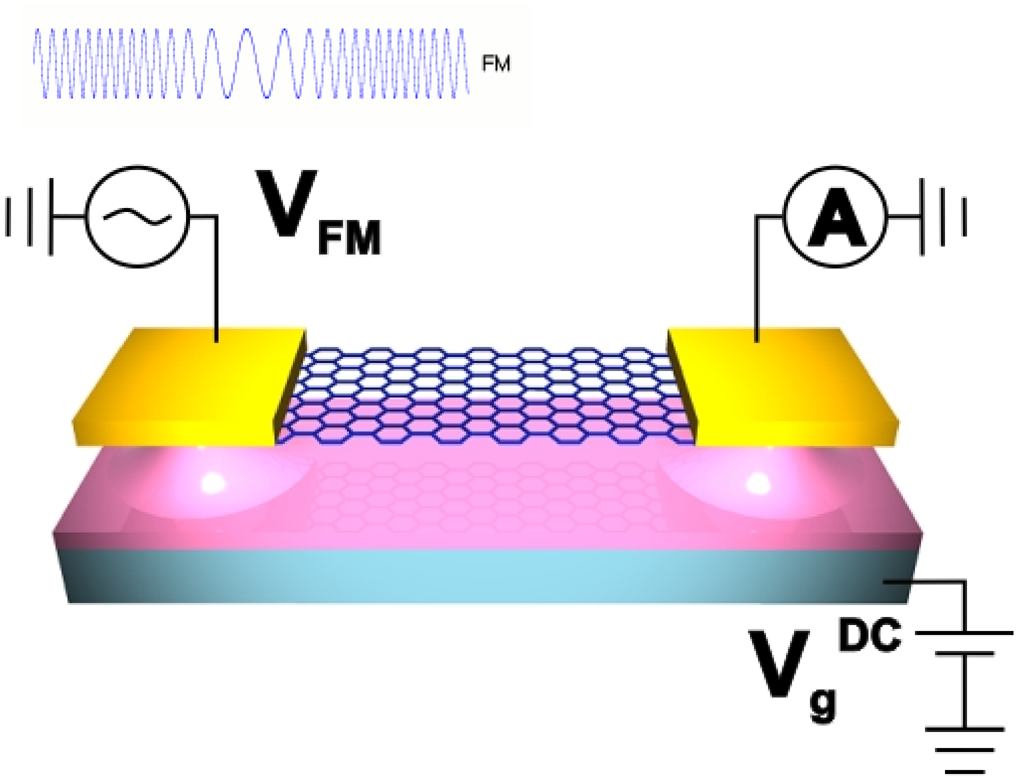
mixing technique – frequency modulation



V. Gouttenoire *et al.*, Small **6**, 1060 (2010)

adapted from V. Sazonova *et al.*, Nature **431**, 284 (2004)

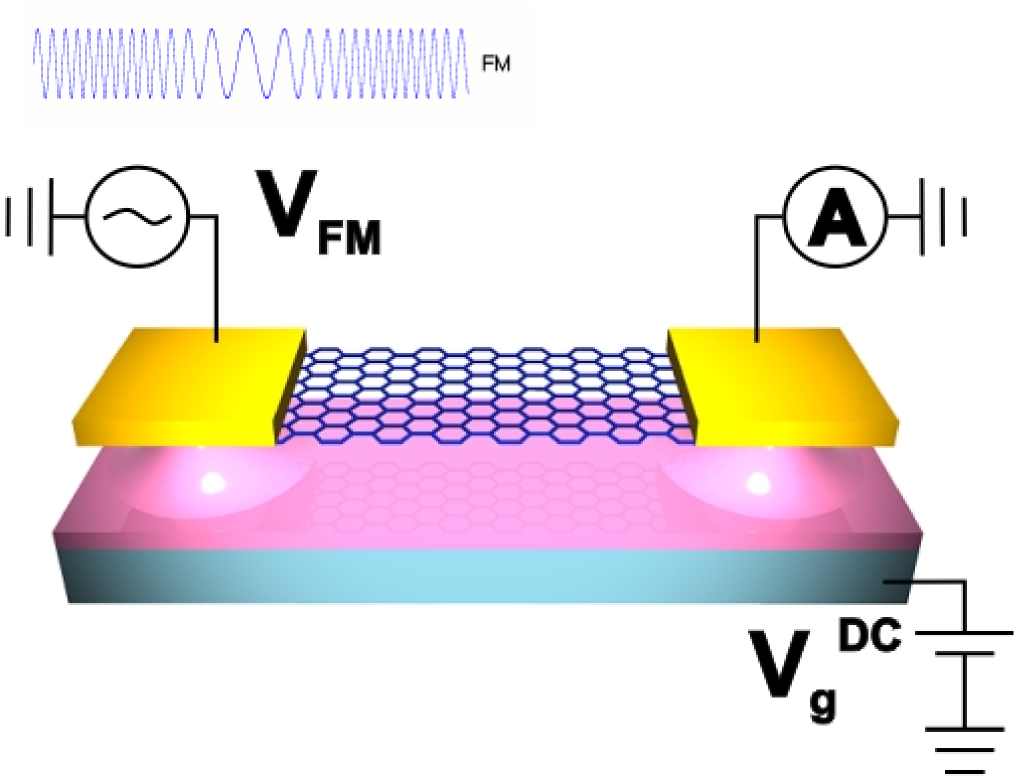
mixing technique – frequency modulation

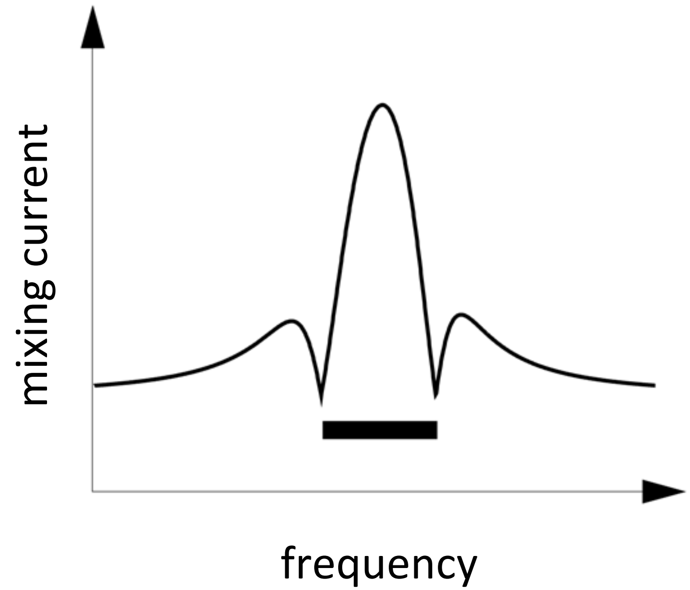


V. Gouttenoire *et al.*, Small **6**, 1060 (2010)

adapted from V. Sazonova *et al.*, Nature **431**, 284 (2004)

mixing technique – frequency modulation

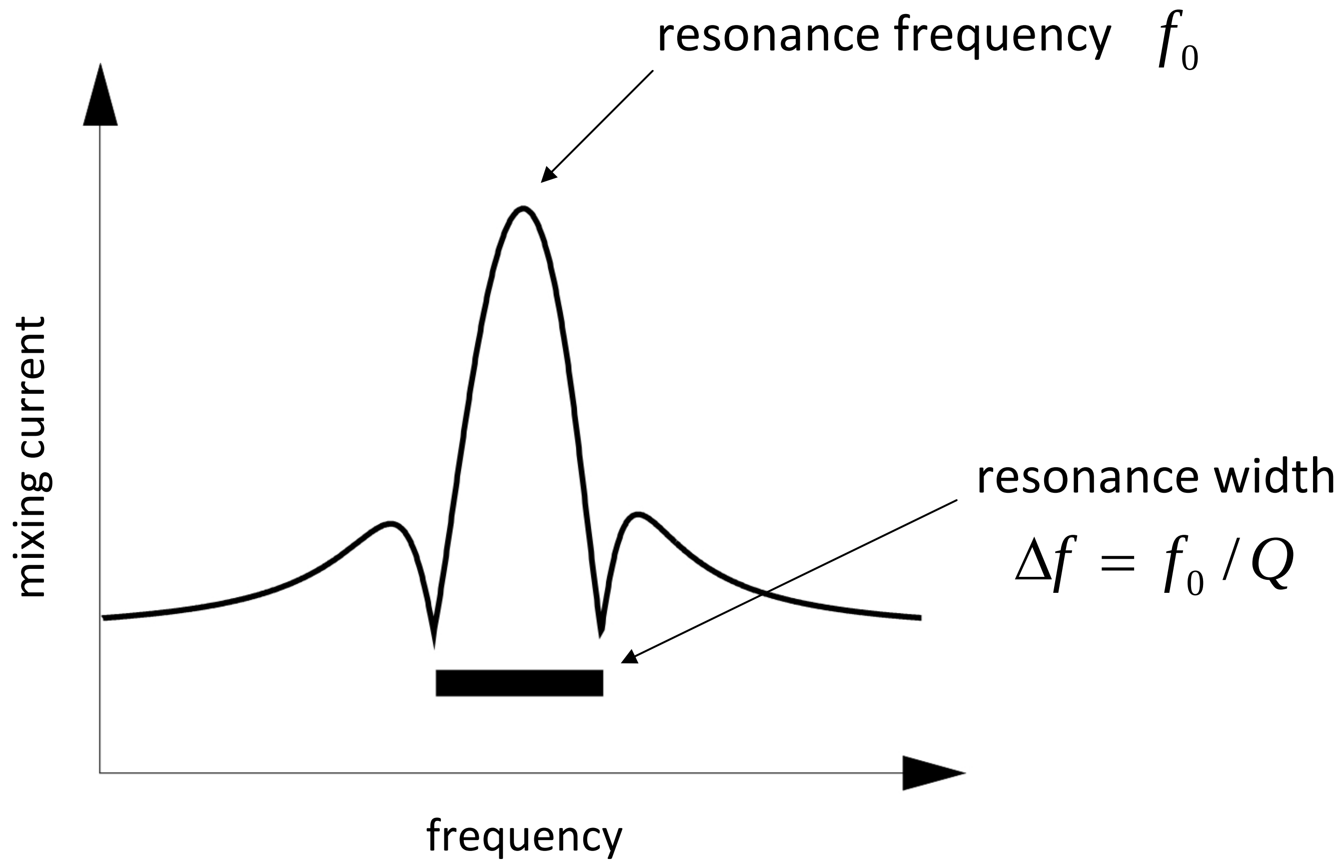




$$I_{mix} \propto \left| \partial / \partial f \; \mathrm{Re}(x) \right|$$

V. Gouttenoire *et al.*, Small **6**, 1060 (2010)

adapted from V. Sazonova *et al.*, Nature **431**, 284 (2004)

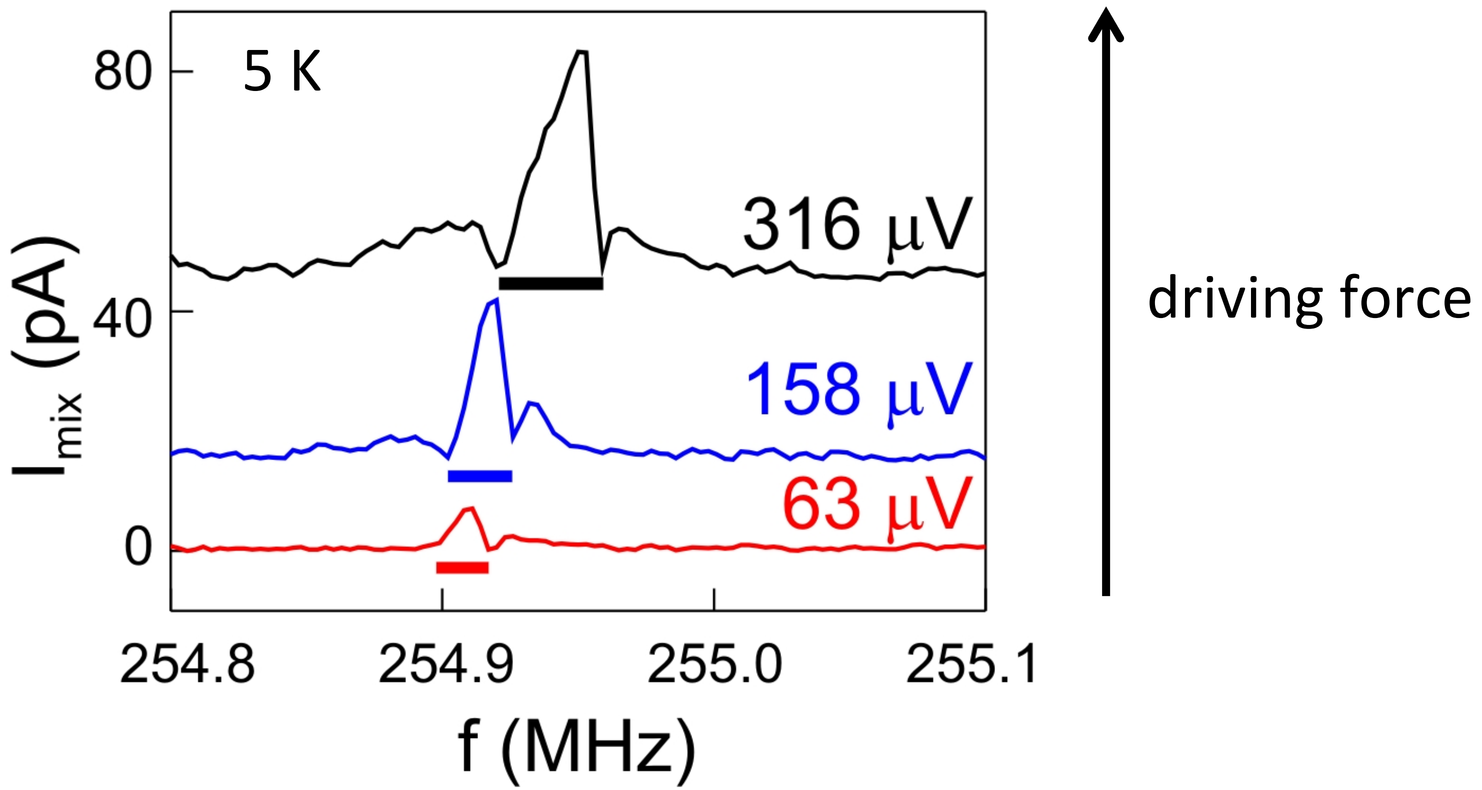


$$m\frac{\partial^2 x}{\partial t^2} + \gamma \frac{\partial x}{\partial t} + kx = F_0 \cos(2\pi f t)$$

$$f_0 = \frac{1}{2\pi}\sqrt{k/m}$$

$$Q = \frac{2\pi m f_0}{\gamma}$$

What a surprise !

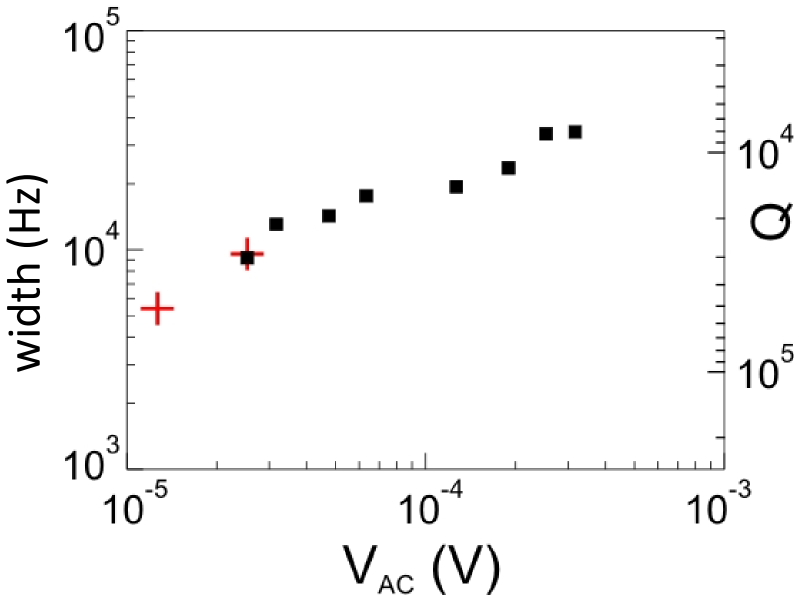


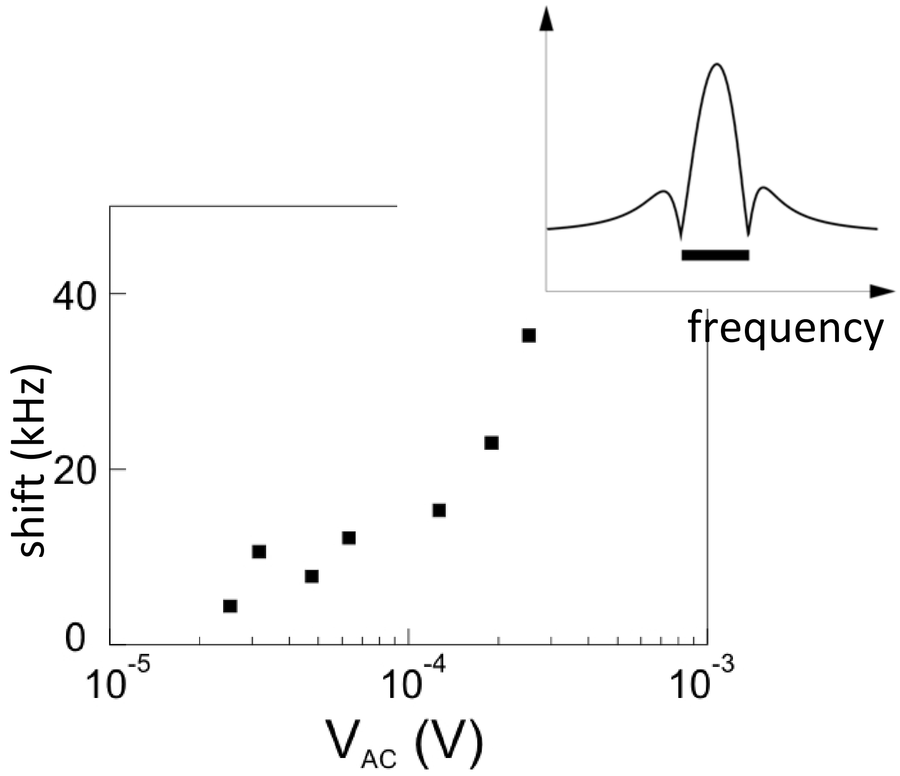
$$m\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}+kx=F_0\cos(2\pi f t)$$

$$f_0=\frac{1}{2\pi}\sqrt{k/m}$$

$$Q=\frac{2\pi m f_0}{\gamma}$$

strong deviation



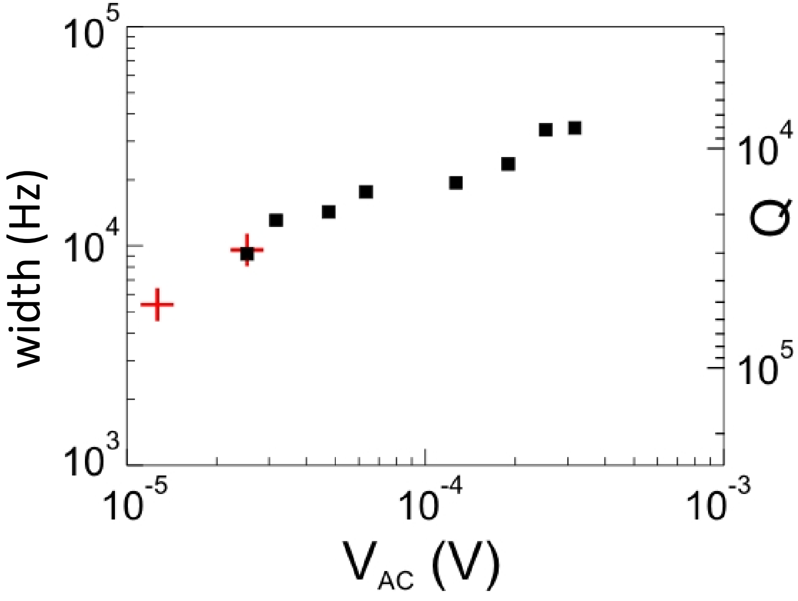


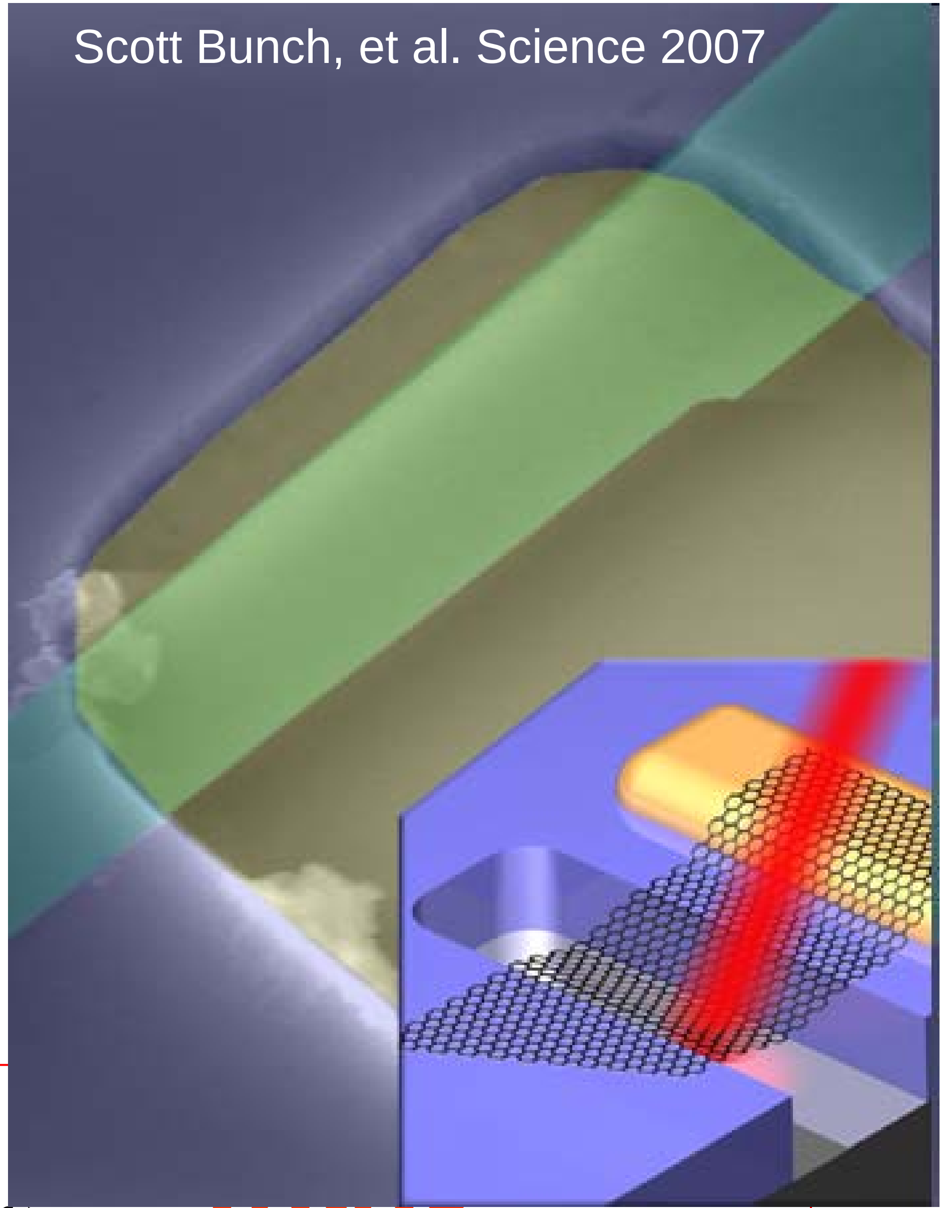
$$m\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}+kx=F_0\cos(2\pi ft)$$

$$f_0=\frac{1}{2\pi}\sqrt{k/m}$$

$$Q=\frac{2\pi m f_0}{\gamma}$$

strong deviation

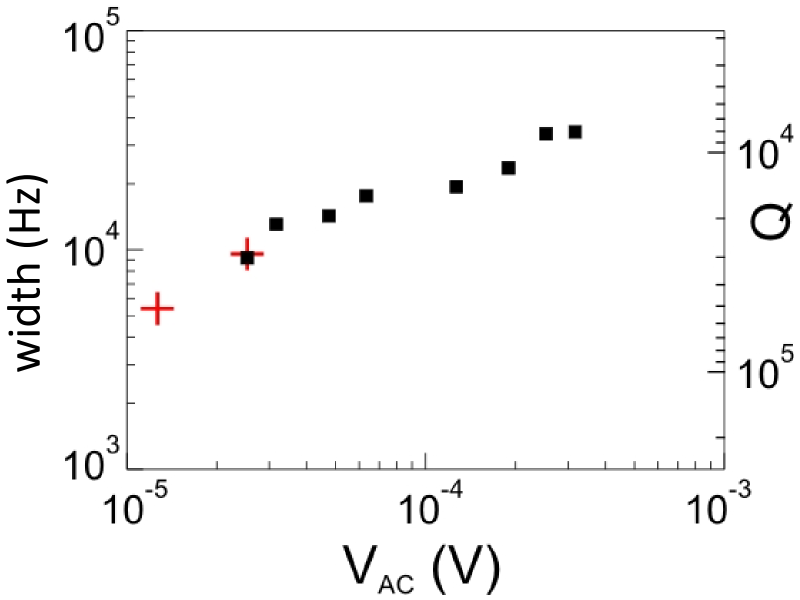


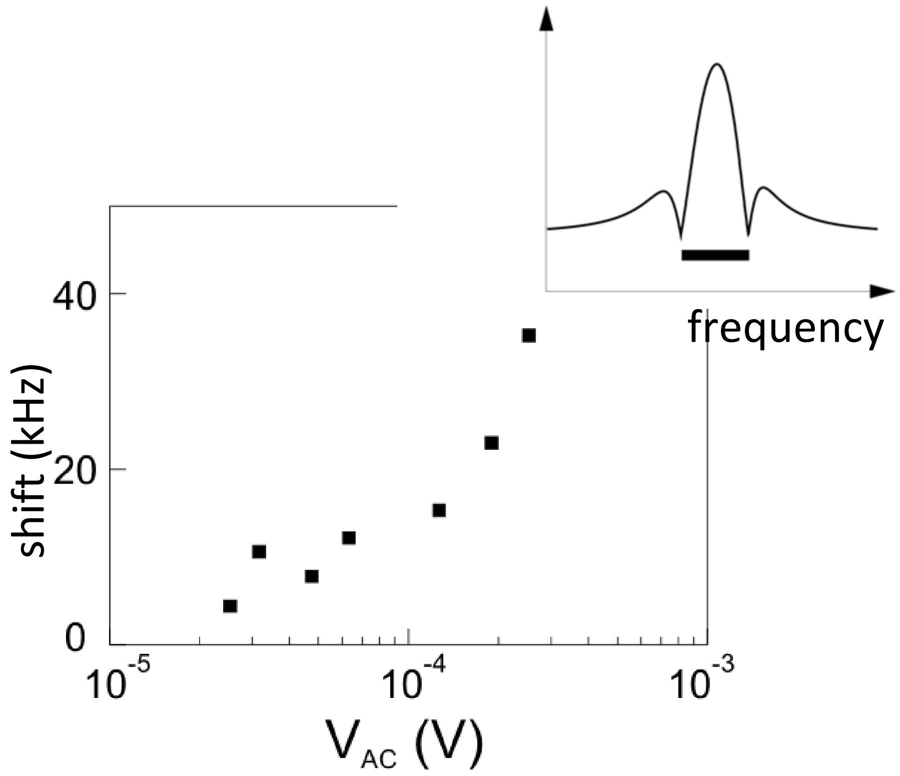


$$m\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}+kx=F_0\cos(2\pi f t)$$

strong devi

$$Q=\frac{2\pi m f_0}{\gamma}$$





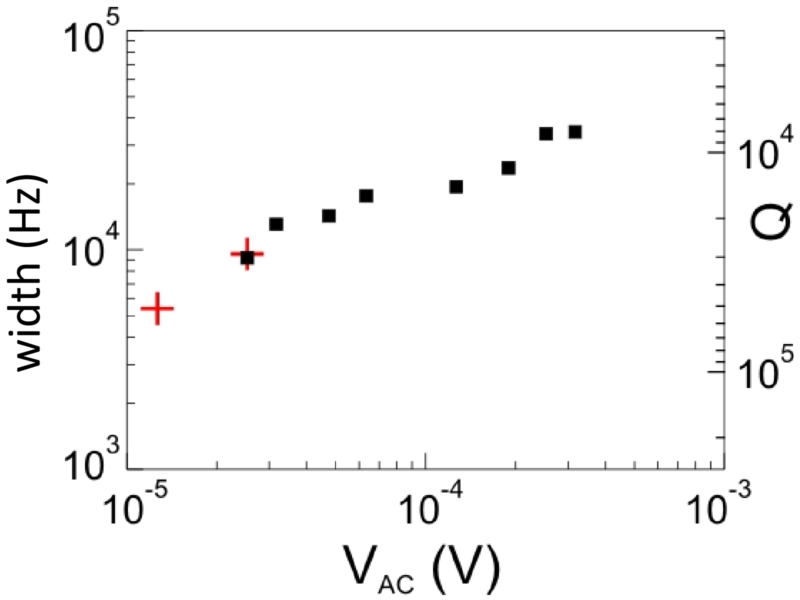
$$m\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}+kx=F_0\cos(2\pi f t)$$

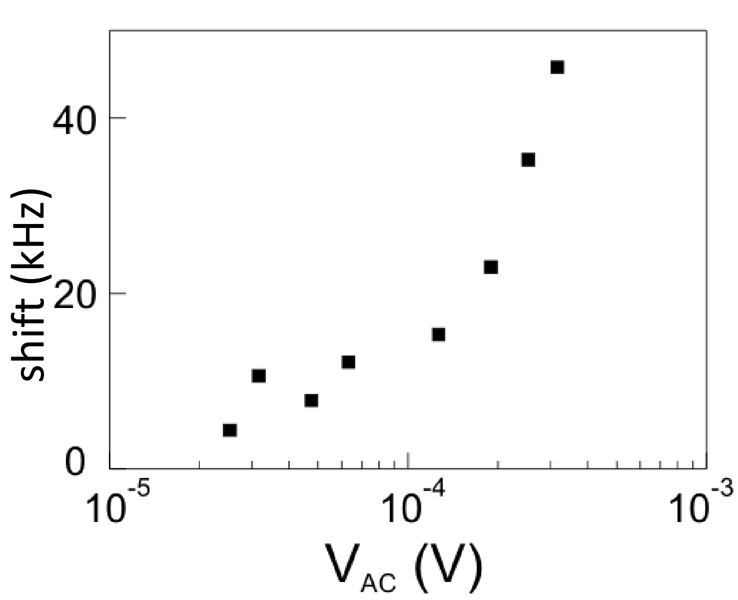
$$f_0=\frac{1}{2\pi}\sqrt{k/m}$$

$$Q=\frac{2\pi m f_0}{\gamma}$$

strong deviation

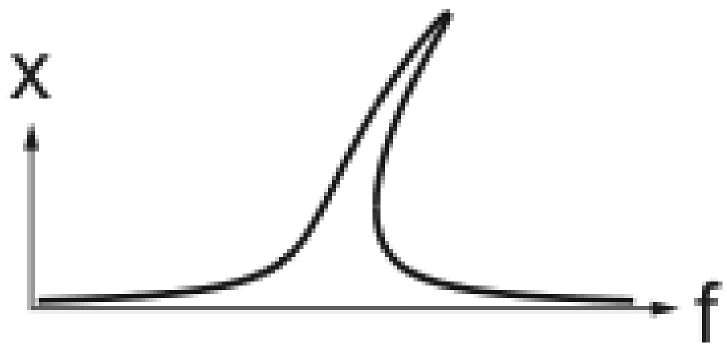
higher order terms



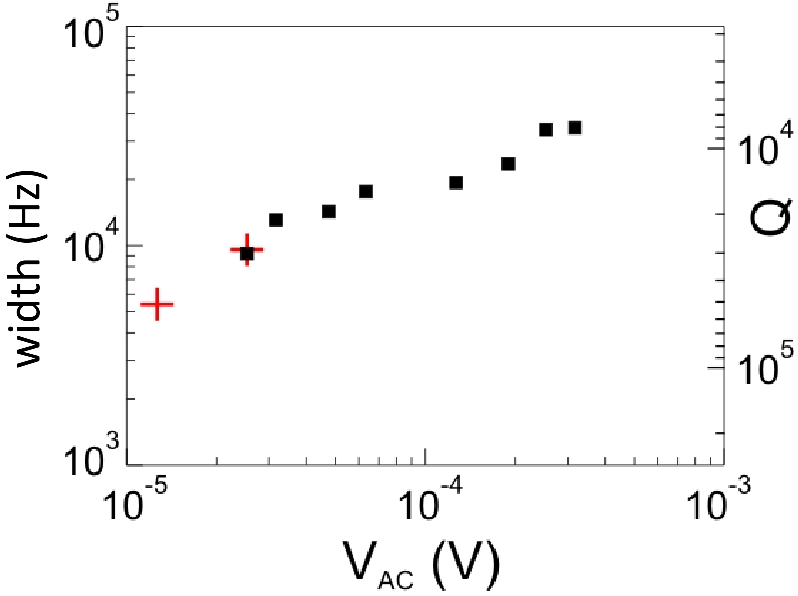


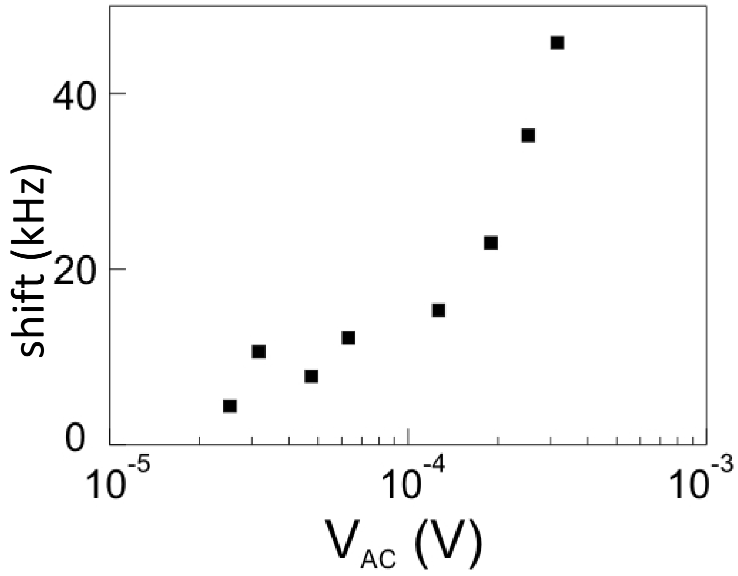
$$m\ddot{x} = -kx - \gamma\dot{x} - \alpha x^3$$

Duffing force



higher order terms

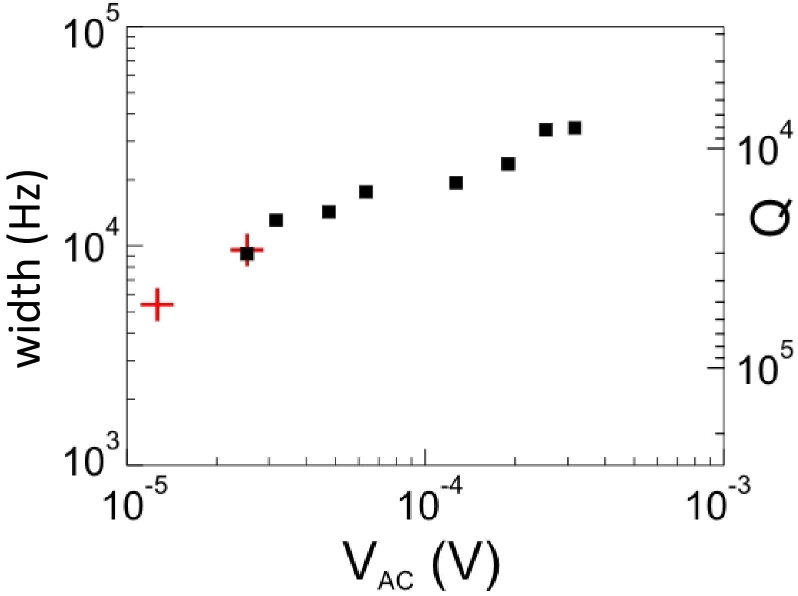


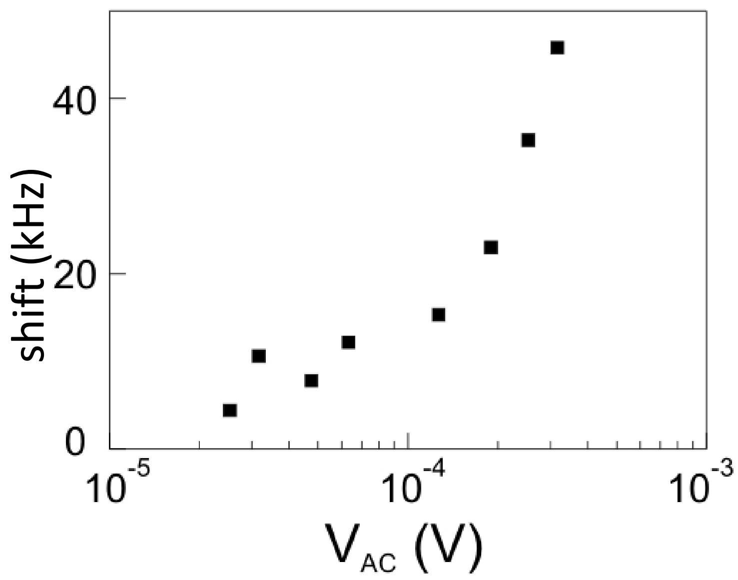


$$m\ddot{x} = -kx - \gamma\dot{x} - \alpha x^3$$

$$- ax^2 - bx\dot{x} - cx\dot{x}^2 - dx^2\dot{x} - e\dot{x}^3$$

higher order terms



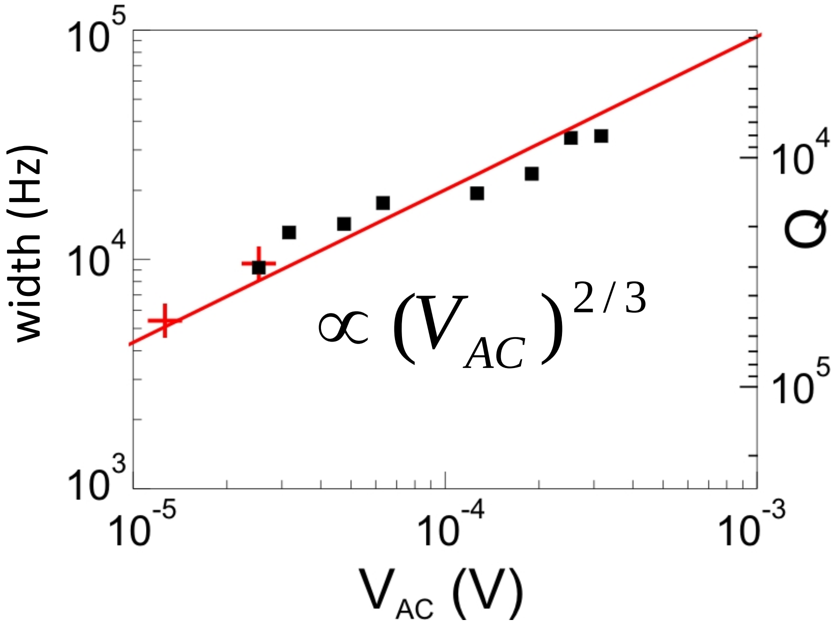


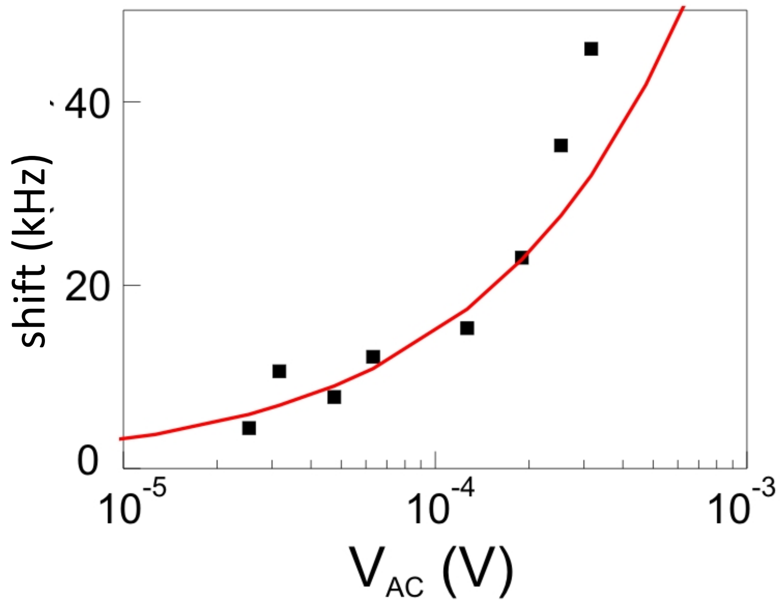
$$m\ddot{x} = -kx - \gamma\dot{x} - \alpha x^3 - \eta x^2 \dot{x}$$

nonlinear damping

Ron Lifshitz and M.C. Cross. *Review of Nonlinear Dynamics and Complexity* **1** (2008) 1-52.
S. Zaitsev, O. Shtempluck, E. Buks, O. Gottlieb, arXiv:0911.0833

NONLINEAR DAMPING

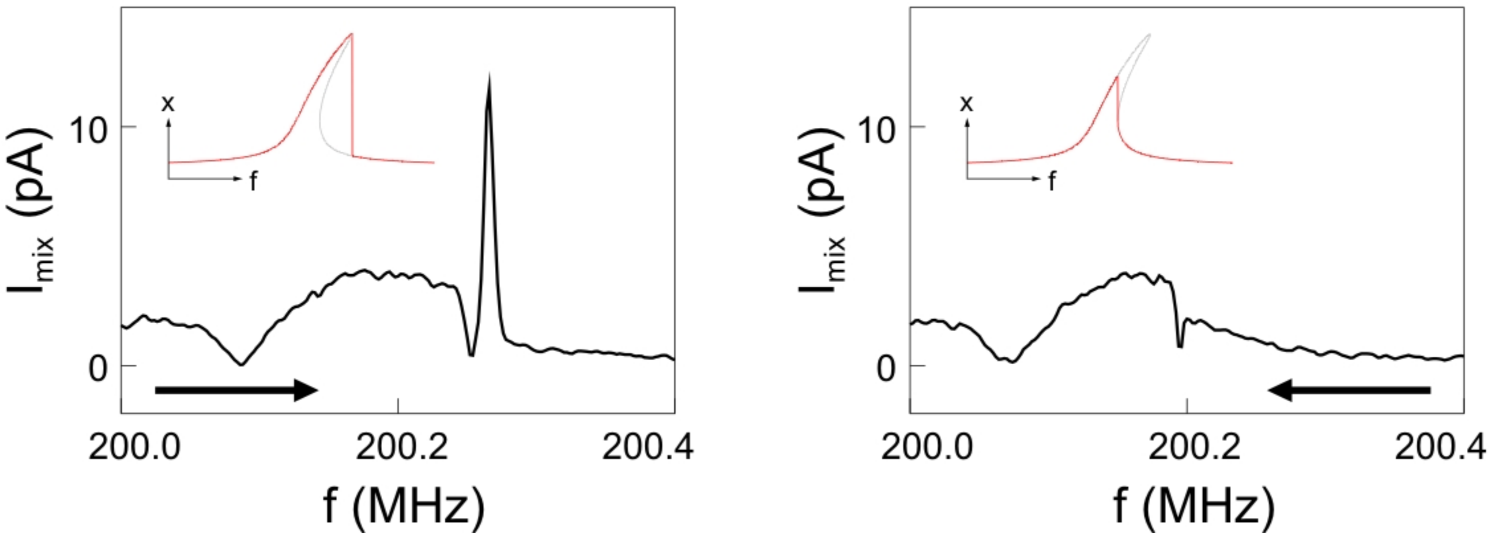




$$m\ddot{x} = -kx - \cancel{\gamma\dot{x}} - \alpha x^3 - \eta x^2 \dot{x}$$

A. Eichler, J. Moser, J. Chaste, M. Zdrojek, I. Wilson-Rae, A. Bachtold, arXiv:1103.1788

hysteresis and nonlinear damping

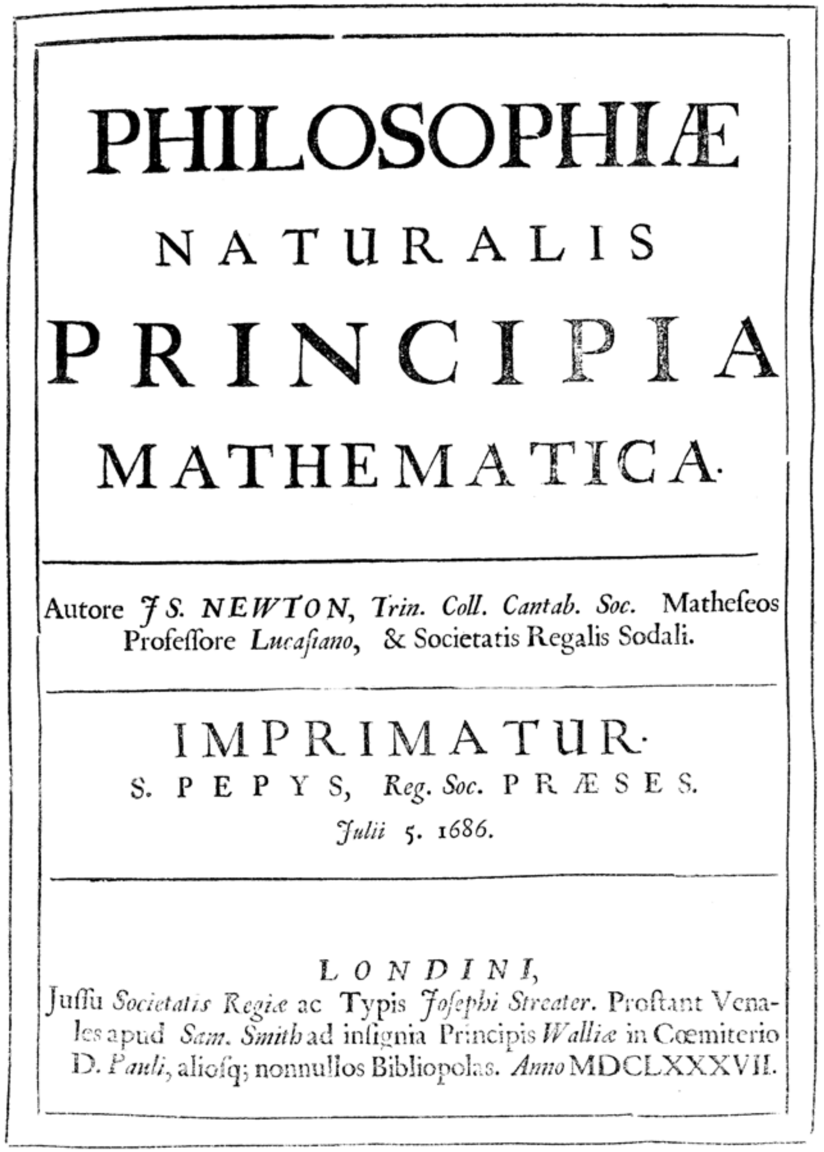


$$m\ddot{x} = -kx - \gamma\dot{x} - \alpha x^3 - \eta x^2 \dot{x}$$

$\eta / \alpha > \sqrt{3} / 2\pi f_0$ ⇨ NO hysterisis

$\eta / \alpha < \sqrt{3} / 2\pi f_0$ ⇨ hysterisis

DAMPING



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S.* NEWTON, *Trin. Coll. Cantab. Soc.* Mathefeos Profeffore *Lucafiano*, & Societatis Regalis Sodali.

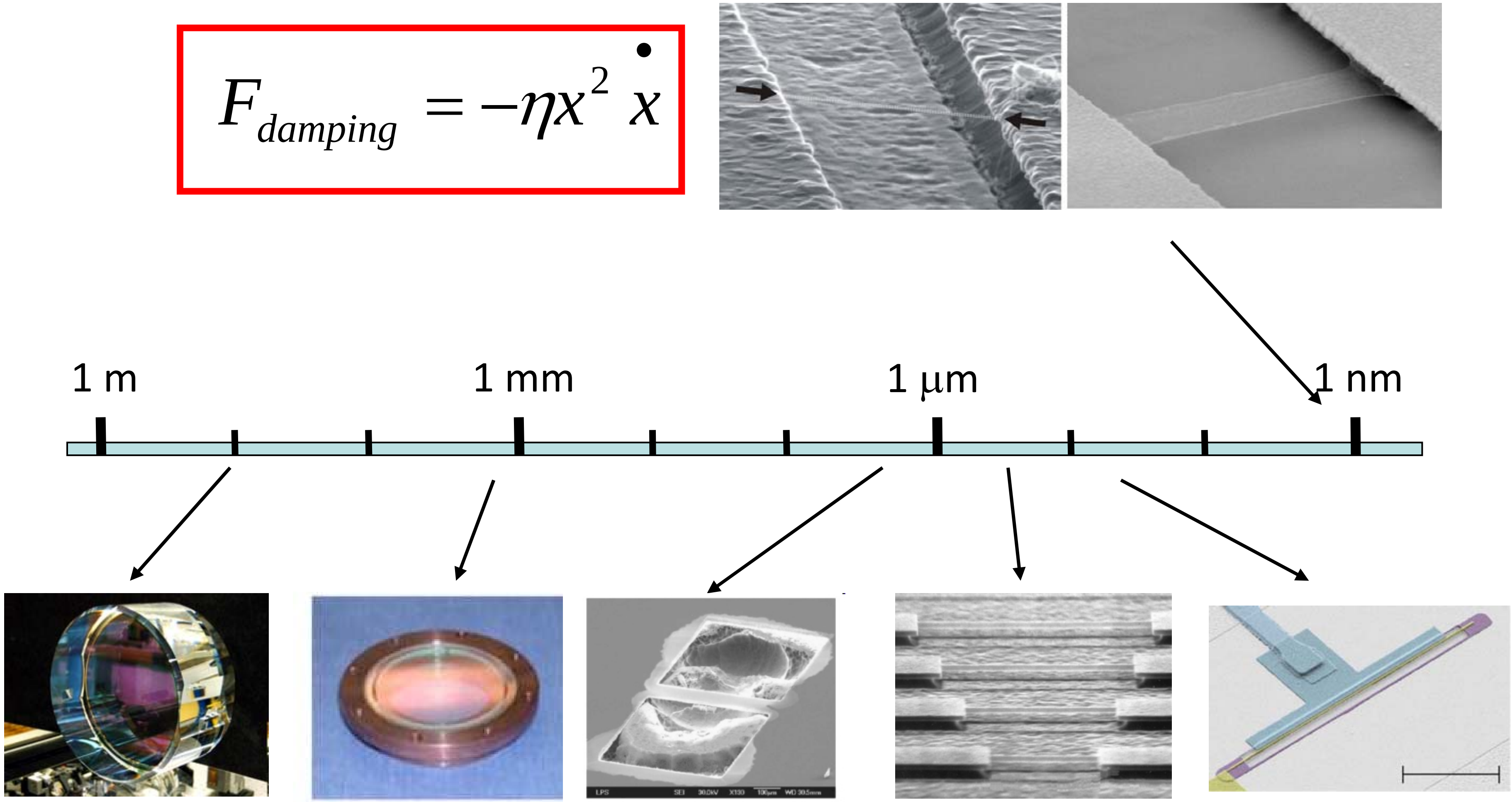
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juffu *Societatis Regiæ* ac Typis *Jofephi Streater*. Proftant Venales apud *Sam. Smith* ad infignia Principis *Walliæ* in Cœmiterio D. *Pauli*, aliofq; nonnullos Bibliopolas. *Anno* MDCLXXXVII.

$$\boxed{F_{damping} = \gamma \dot{x}}$$

for mechanical resonators

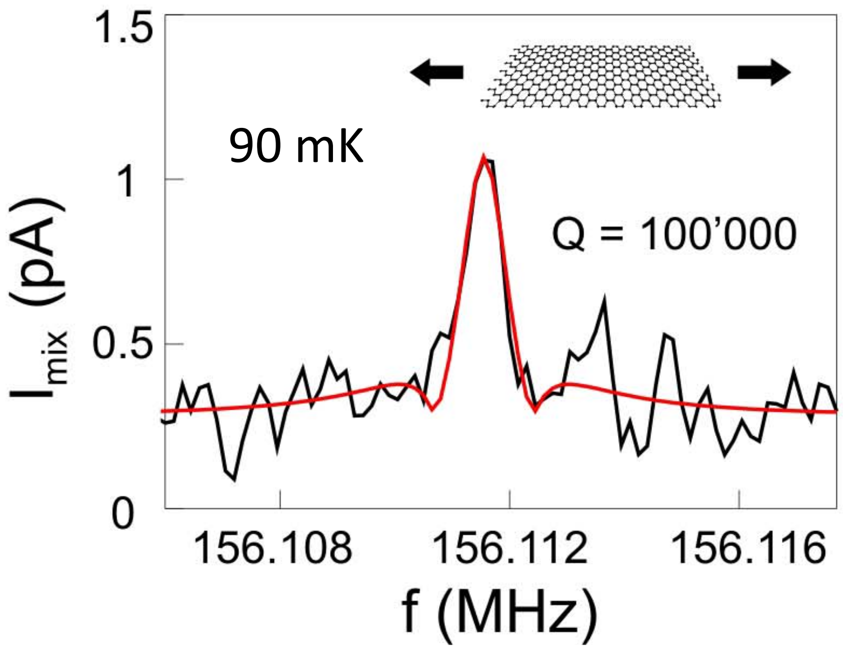
$$\boxed{F_{damping} = -\eta x^2 \dot{x}}$$



Ligo Paris Vienna Caltech Caltech

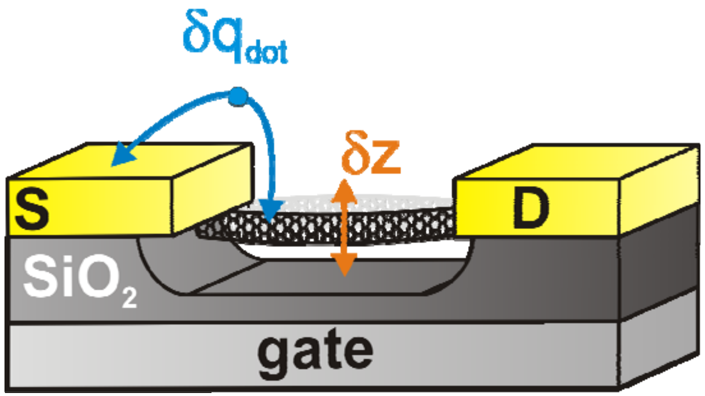
$$\boxed{F_{damping} = -\gamma \dot{x}}$$

high quality factor



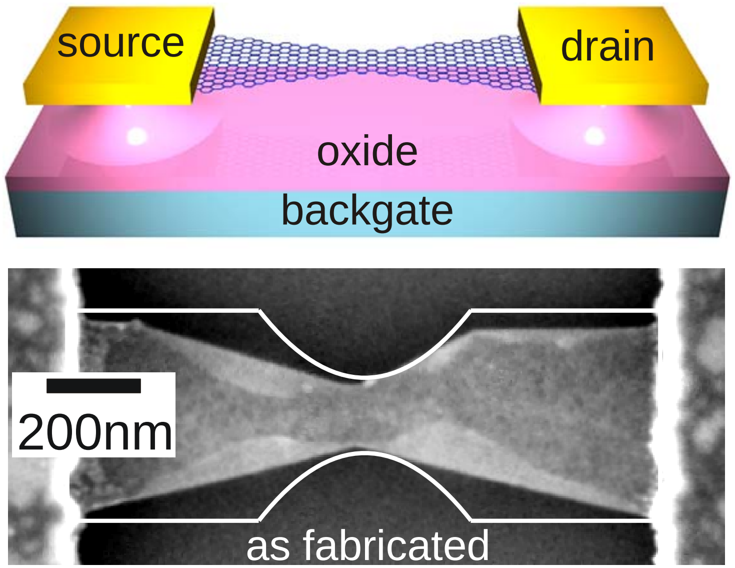
Can we tune:

$$m\ddot{x} = -kx - \gamma\dot{x} - \alpha x^3 - \eta x^2\dot{x} \quad ?$$

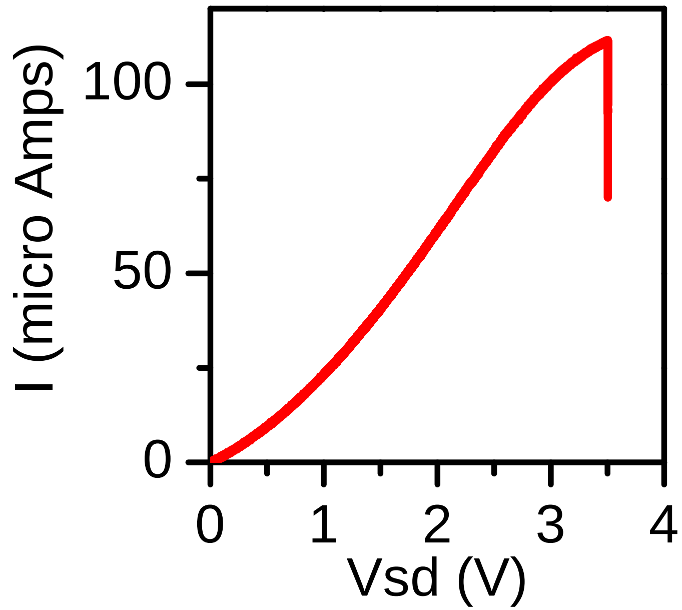


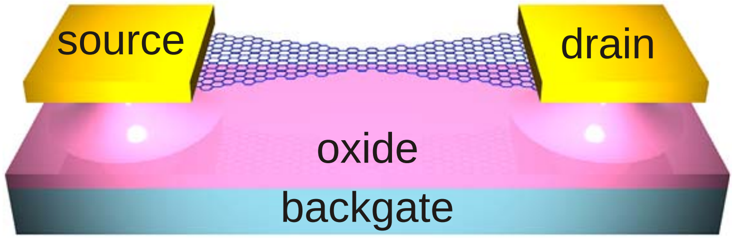
quantum dot $\Rightarrow$ $F_{electro} = -k_{electro}x - \gamma_{electro}\dot{x}$

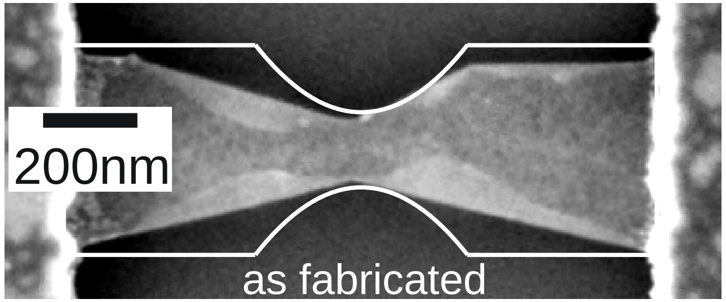
Lassagne, Tarakanov, Kinaret, Garcia-Sanchez, Bachtold, Science (2009)
see also: Steele, Hüttel, Witkamp, Poot, Meerwaldt, Kouwenhoven, van der Zant, Science (2009)

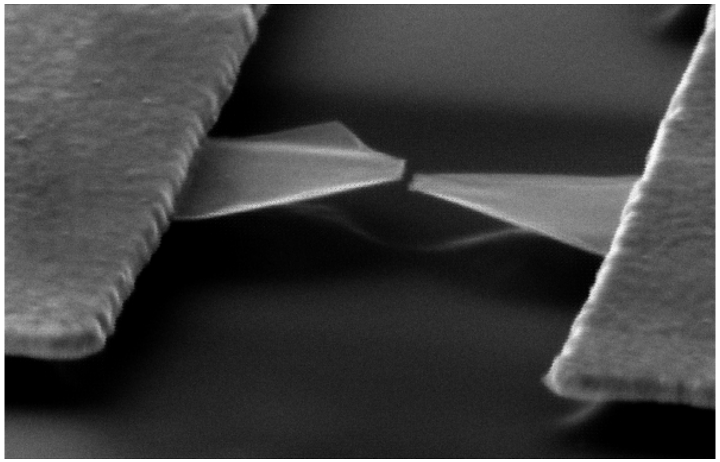


Saturation current ~1microAmps per nm

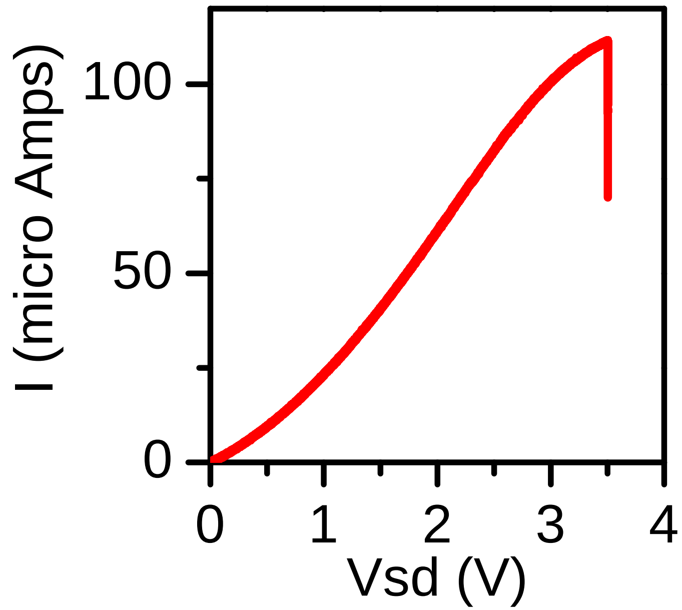


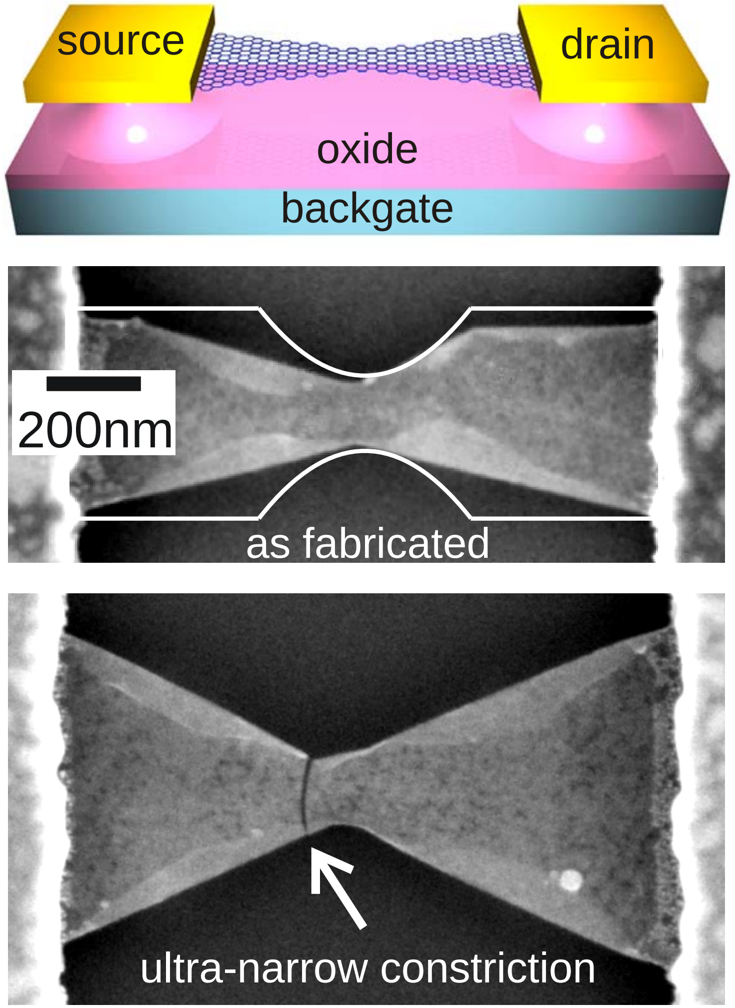




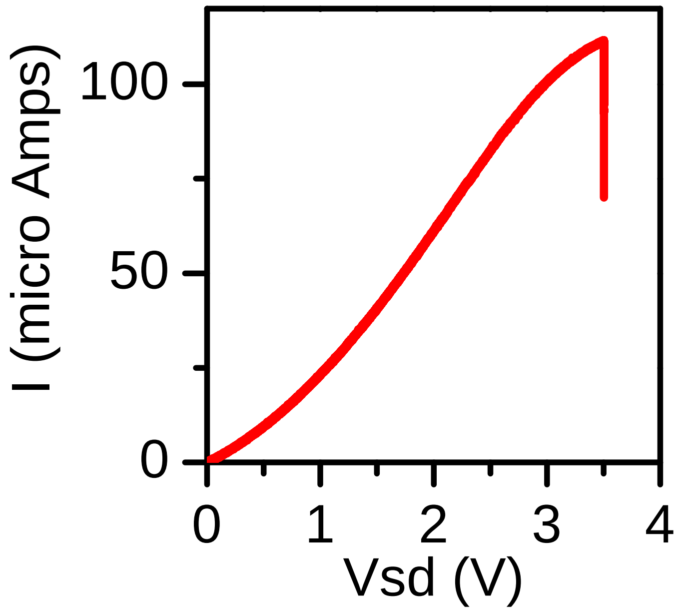


Saturation current ~1microAmps per nm

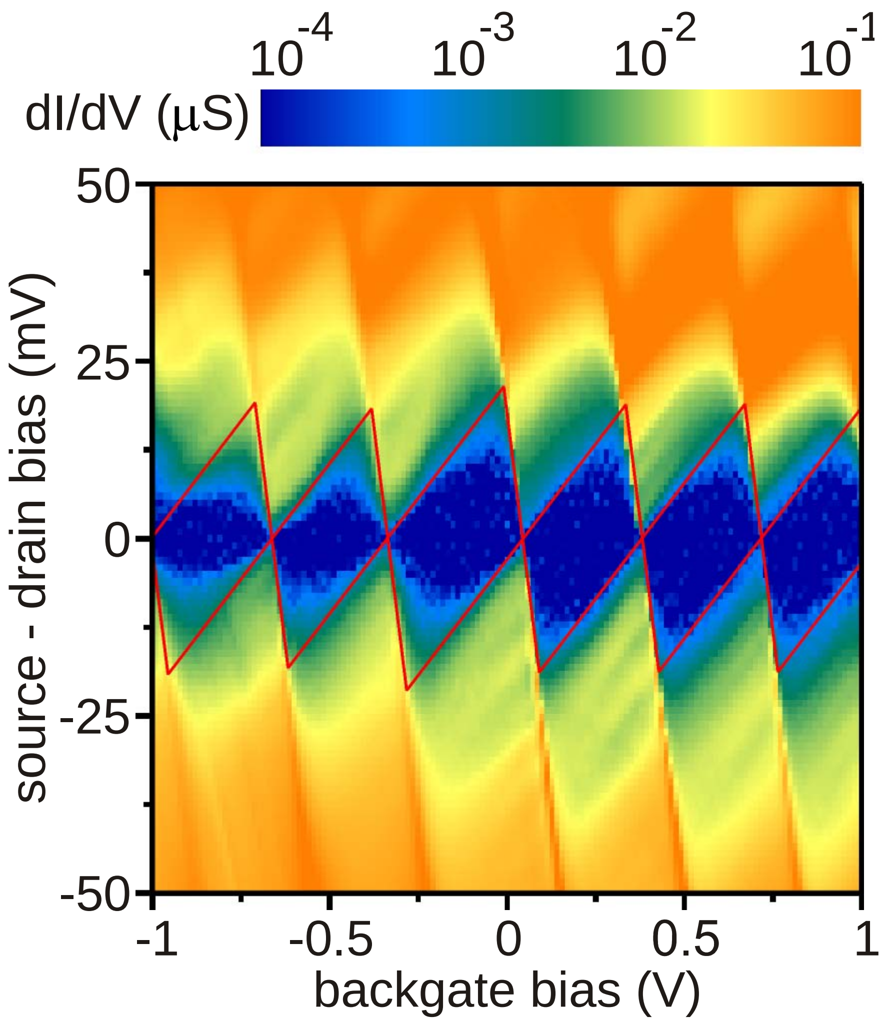




Saturation current ~1microAmps per nm

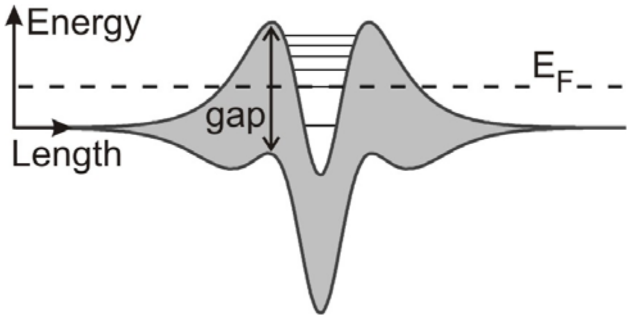


Stability diagrams



J. Moser and A. Bachtold, Appl. Phys. Lett. **95**, 173506 (2009)

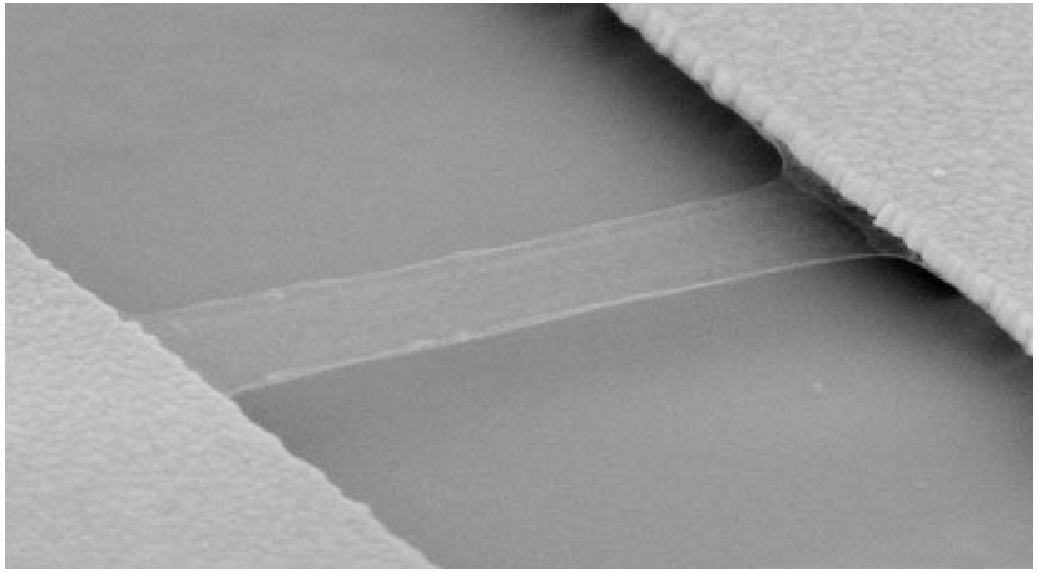
Models for quantum dots in constrictions



Gap between valence and conductance bands

- K. Todd, H.-T. Chou, S. Amasha, and D. Goldhaber-Gordon
  Nano. Lett. **9**, 416 (2009)
- C. Stampfer, J. Güttinger, S. Hellmüller, F. Molitor, K. Ensslin, and T. Ihn
  Phys. Rev. Lett. **102**, 056403 (2009)
- Xinglan Liu, J.B. Oostinga, A.F. Morpurgo, and L.M.K. Vandersypen
  Physical Review B **80**, 121407 (2009)
- M.Y. Han, B. Oezyilmaz, Y. Zhang, and P. Kim
  Phys. Rev. Lett. **98**, 206805 (2007)

conclusion



$$m\ddot{x} = -kx - \cancel{\gamma\dot{x}} - \alpha x^3 - \eta x^2\dot{x}$$

quantum dot → $F_{electro} = -k_{electro}x - \gamma_{electro}\dot{x}$

Quantum NanoElectronics group ICN

MJ Esplandiu
J Chaste
A Eichler
B Lassagne
J Moser
M Zdrojek

A Barreiro
D Garcia
M Slezinska
A Gruneis
A Afshar
I Tsioutsios

EURYI, NMP RODIN, Spanish ministry

Barcelona
R Rurali
E Hernandez
A San Paulo
F Perez
S Zippilli
G Morigi
F Alzina
C Sotomayor
S Roche

Chalmers
Y Tarakanov
J Kinaret

Munich
I Wilson-Rae

Cornell
A van der Zande
P McEuen

MIT
P Jarillo-Herrero

Paris
M. Lazzeri
F. Mauri

Santa Barbara
B Thibeault