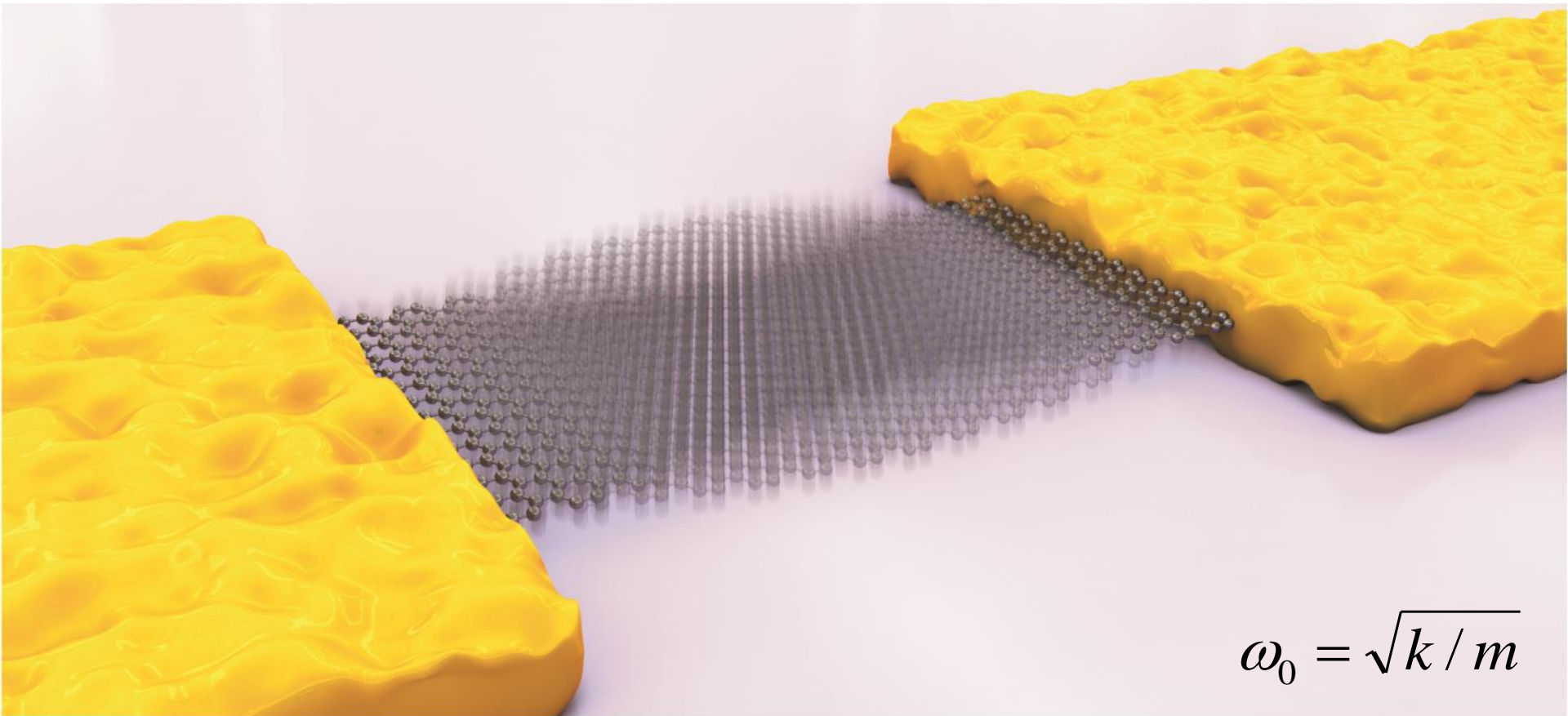


Graphene nanoelectromechanics



$$\omega_0 = \sqrt{k / m}$$

Julien Chaste



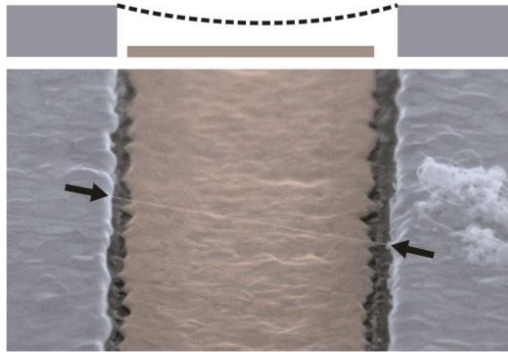
(A. Cresti and M. Mouis)



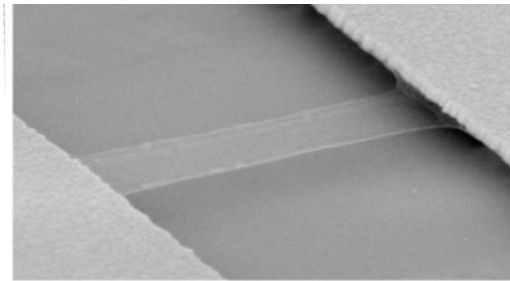
LABORATOIRE
DE PHOTONIQUE
ET DE
NANOSTRUCTURES



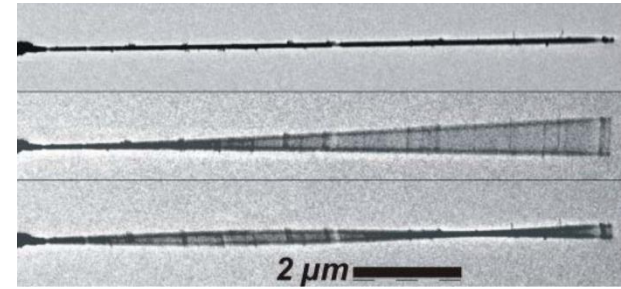
Why is nanomechanics interesting?



nanotube



graphene



nanowire

$$\omega_0 = \sqrt{k/m}$$

$$\omega_0 = 10\text{MHz to } 100\text{GHz}$$



Quantum vibrations



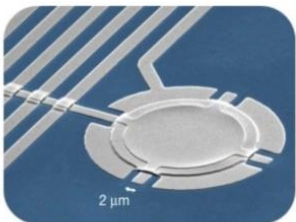
Mass detector



Strong coupling to localized charges or spins

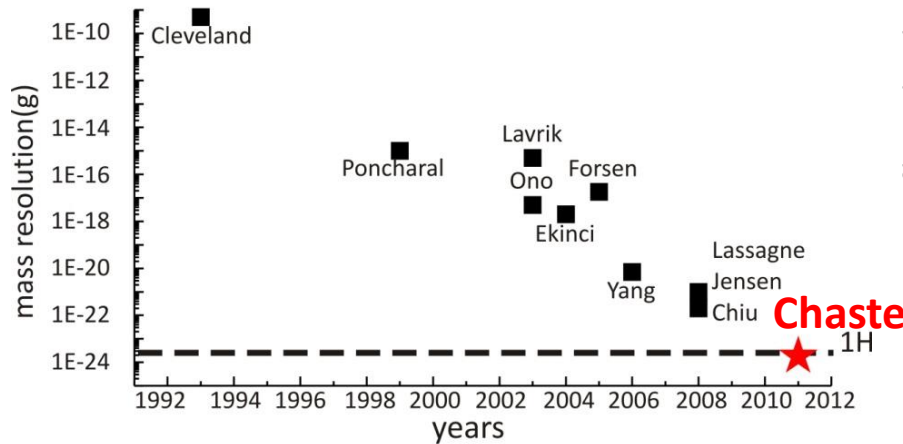
$$\delta x_{QL} = \sqrt{\frac{\hbar}{m\omega}}$$

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

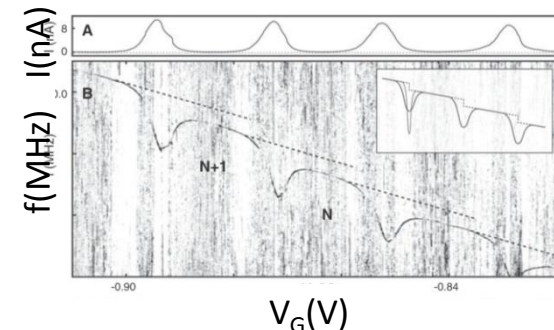


Teufel et al., Nature 2011
Boudler USA

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

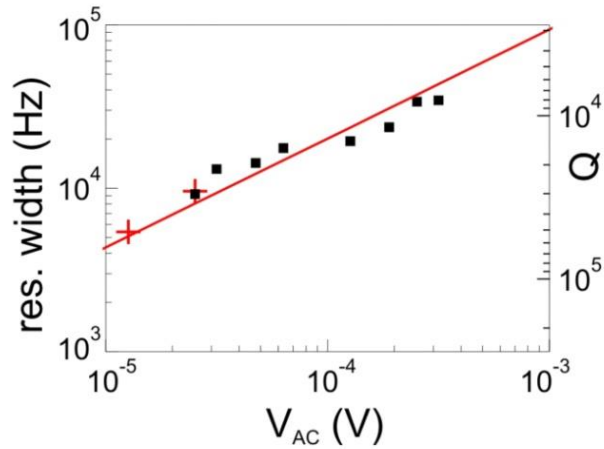


J. Chaste et al., Nature nano 7, 301 (2012)



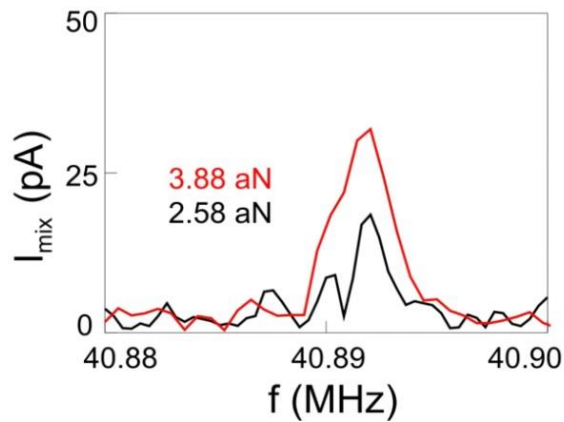
B. Lassagne et al., Science (2009)
G. A Steele et al., Science (2009)

Non-linear damping

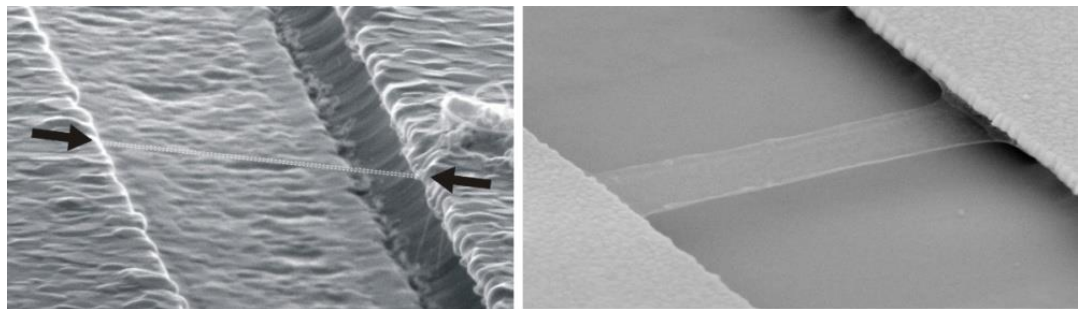


Strong deviation

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



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



Epitaxial graphene NEMS

Quantum conductor= **Low dimension** = low mass resonator

Balistic transport= **Pristin cristal** = low dissipation

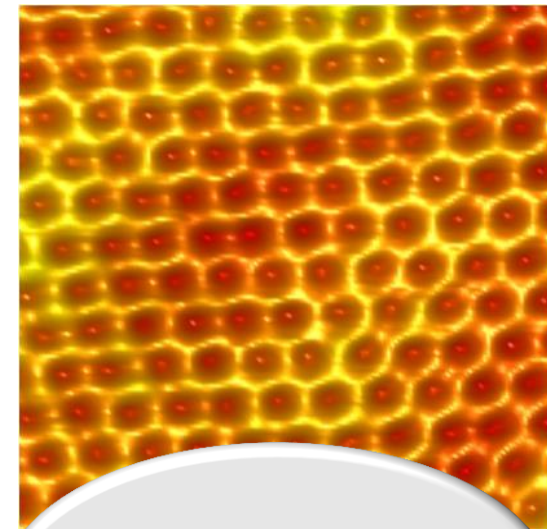
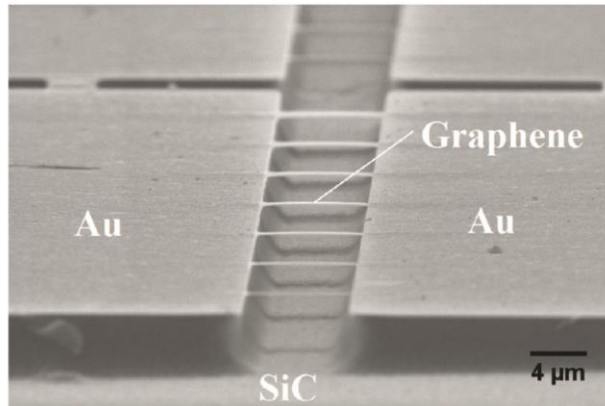
High fermi velocity= **Carbon** = high binding energy

S. Shivaraman et al., *Nanoletters* 9, 3100 (2009)

A. Ouerghi + 5 persons

Done with KOH etching

$Q \sim 1000$ at 300K



High electrostatic coupling

Geometry on demand

Huge number of sample

High mobility
(at LPN $\rightarrow >10\,000\text{ cm}^2/\text{Vs}$)



LABORATOIRE
DE PHOTONIQUE
ET DE
NANOSTRUCTURES

Carbon NEMS in France

Experiments on N&N nems

Magnetic molecules detection :
Benjamin Lassagne (LPCNO)
Wolfgang Wernsdorfer (Néel)

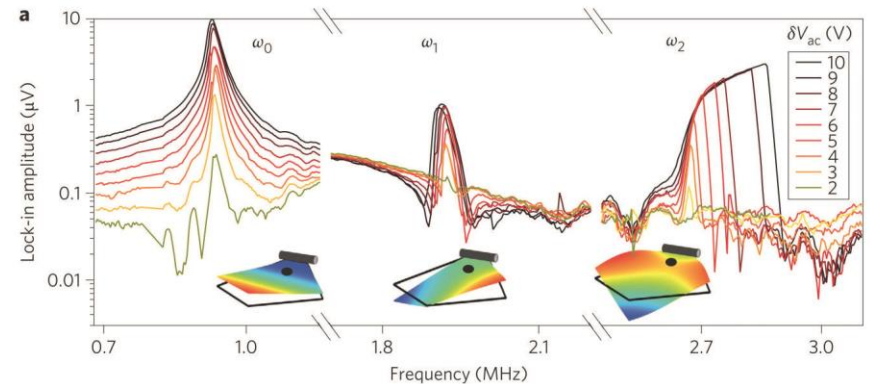
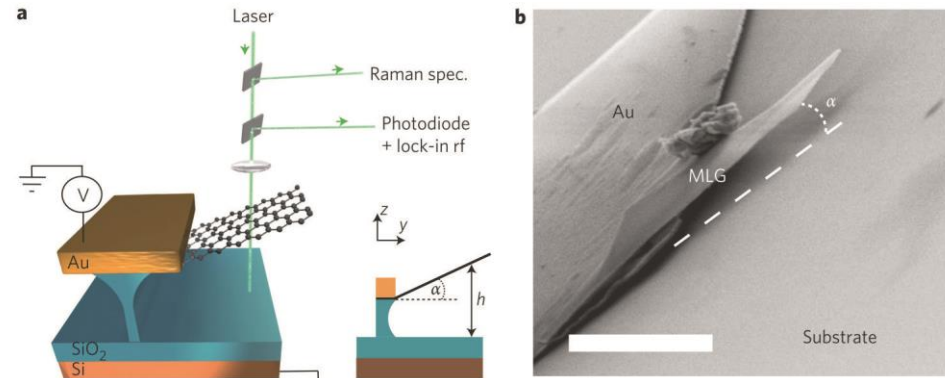
Nanotube AFM-tip:
Bernard Legrand (IEMN)

Field emission:
Steven Purcell (LPMCN)

+Hélène Bouchiat (LPS)

Theory on nanotube nems
Fabio Pistolesi (LOMA)

Experiments on graphite nems



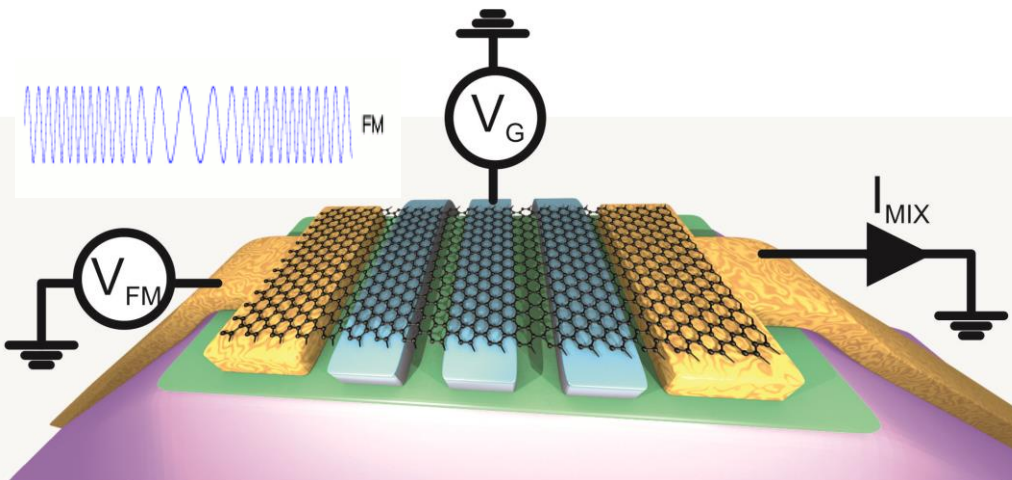
A. Reserbat-Plantey et al., *Nature nano* 7, 151 (2012)

Graphene NEMS in France

(to my knowledge)



Vibration detection improvement



Now in publications,
it is pA range resolution!!!

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

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

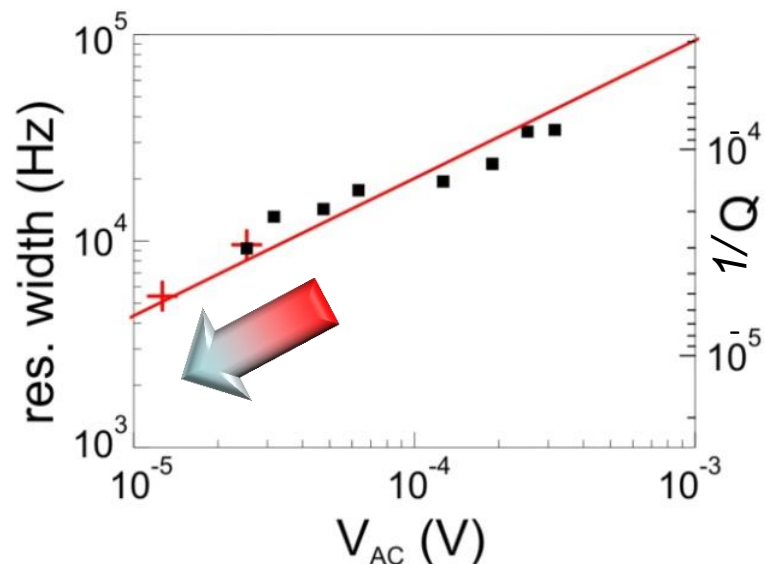
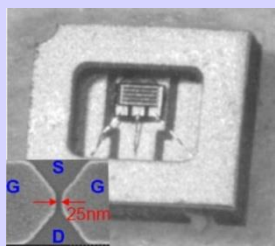
LPN 4K amplifier (Yong Jin)

with $\sim 0.2 \text{ nV/Hz}^{0.5}$

for graphene resistance

$\sim 1\text{-}10 \text{ fA/Hz}^{0.5}$

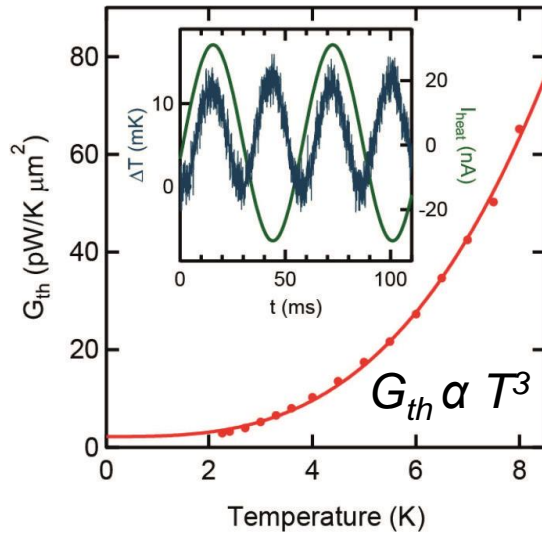
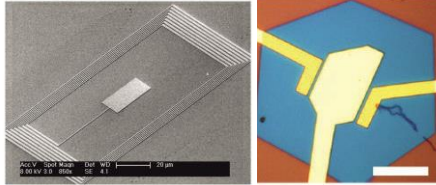
$\sim 1\text{-}10 \text{ mK/Hz}^{0.5}$



Another solution in parallel:
to reach the ultra low temperature
(Yuri Mouskarsky, SPEC)

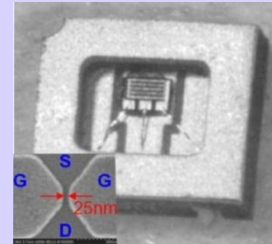
Thermal measurements (electron-phonons)

Superconducting LC tank



K. C. Fong et al., *PRX.* **2**, 031006(2012)

Sensitivity $2\text{mK/Hz}^{0.5}$



LPN 4K amplifier
 $\sim 1\text{-}10 \text{ mK/Hz}^{0.5}$

Same resolution
+ simple to use
+ B field
+ very high input impedance (2pF)
+ suspended graphene

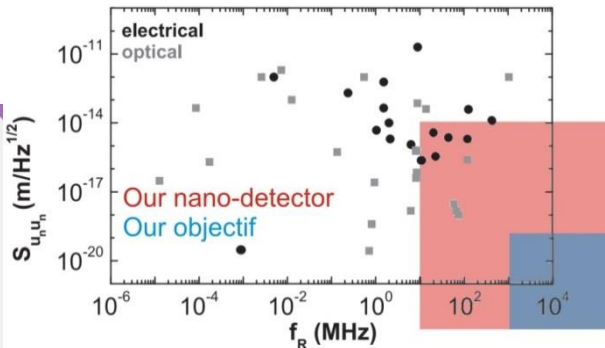


Allows small mechanical resonators
 $\hbar\omega \geq k_B T$

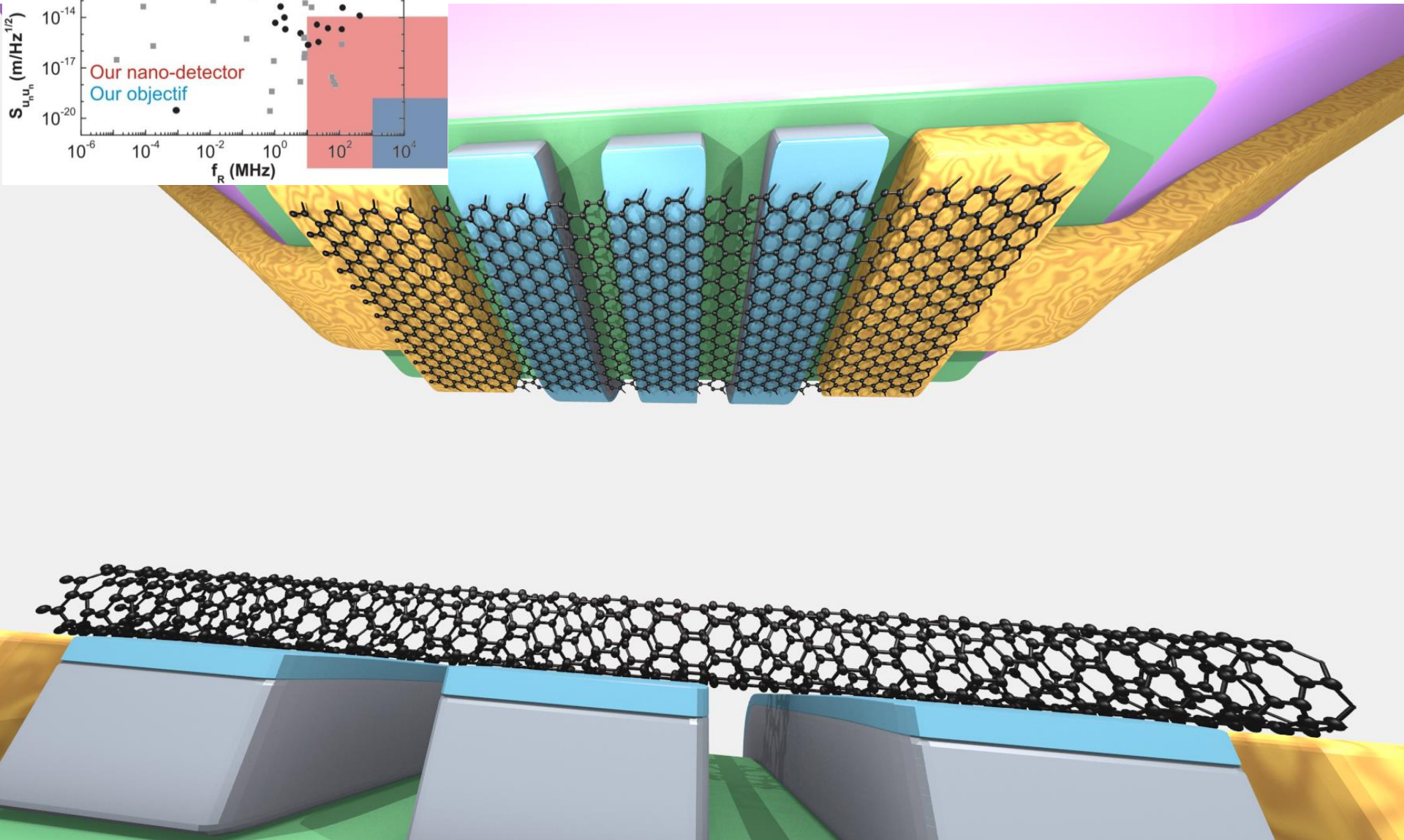
$\omega_0 = 10\text{MHz to } 100\text{GHz}$

An ultrasensitive detector of graphene vibrations

M. Poot, and H. S. J. van der Zant,
Physics Reports-Review **511**, 273 (2012).



Strong or ultrastrong electrostatic coupling



Etude des propriétés électromécaniques du graphène

Alessandro Cresti
et Mireille Mouis
à Minatec Grenoble

Labex MINOS

Objectif fondamental: Corréler propriétés de transport et déformation (statique ou quasi statique) pour du graphène (non idéal)

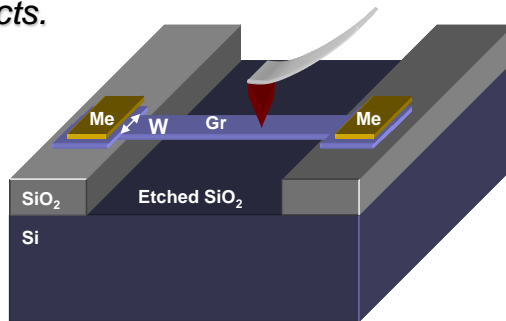
*Objectifs applicatif: Capteurs (pression, flux, force, ...)
Composants sur substrat flexible*

■ Graphène suspendu

Graphène suspendu et contacté.

Mis en contrainte et mesure de déflexion par AFM (force contrôlée).

Mesure simultanée du courant aux contacts.

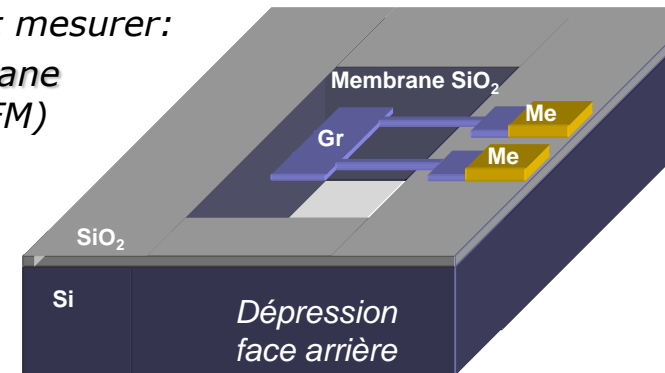


■ Graphène sur membrane

Graphène mis en déformation par une membrane SiO₂ flexible, elle-même déformée par pression hydrostatique.

A pression donnée, on peut mesurer:

- la topologie de la membrane (interférométrie laser, AFM)
- le spectre Raman du graphène
- les $I(V)$ aux contacts



Corrélation force/flux-déformation-courant

Etude des propriétés électromécaniques du graphène

Fabrication des structures de test

- Développement technologique (thèse I. Aydin)
- Etapes de fabrication maîtrisées: patterning graphène, contacts, membranes
- En cours: suspension du graphène dans un procédé complet incluant la réalisation des contacts

Modélisation

Distribution de la contrainte

FEM pour grandes dimensions

Description non-linéaire possible

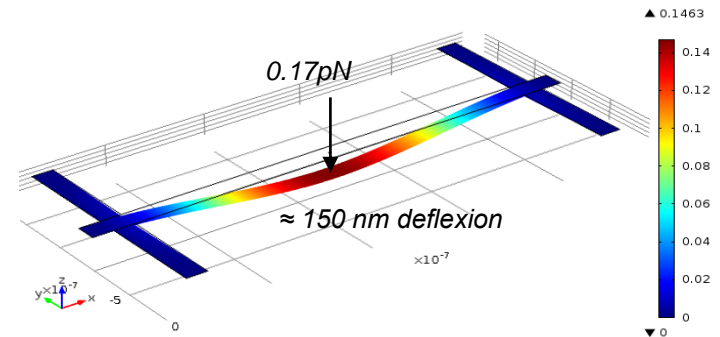
Dimensionnement des structures, référence théorique pour la relation contrainte/déformation

Structure électronique et transport quantique dans le graphène contraint

Strain map: FEM ou expérimentale

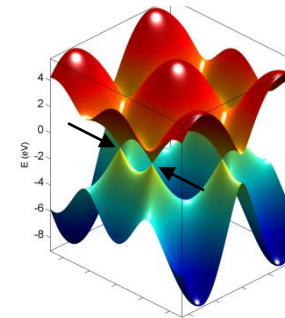
Simulation: fonctions de Green + tight-binding (home-made, incluant short-range et long-range defects)

Dimensionnement des structures, référence théorique pour la relation déformation/courant...

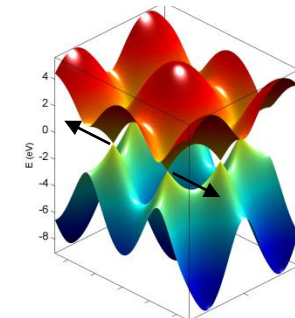


Exemple: simulation d'une structure de graphène déformée par une pointe AFM. Déformation.

Armchair, $\sigma=10\%$, 0°



Zig-zag, $\sigma=10\%$, $\pi/2$



A. Cresti,
2012

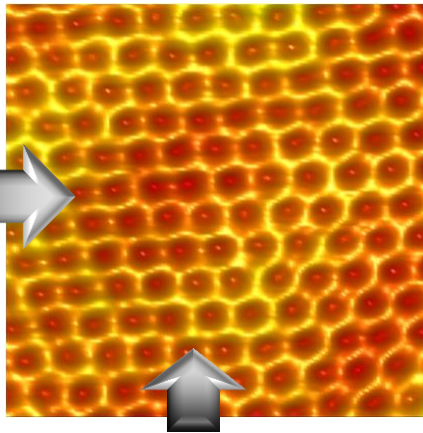
Graphene at LPN

Oven dedicated for
epitaxial graphene
on SiC

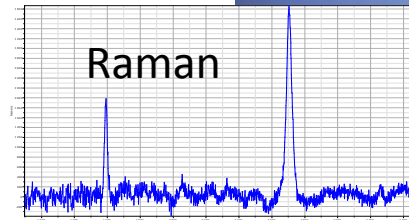
+ transport
($>10\,000\text{ cm}^2/\text{Vs}$)

+ cyclotron

A. Ouerghi + 5 persons

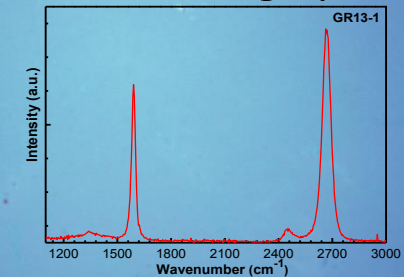


STM on graphene at LPN
J.-C. Girard and G. Rodary



As grown
graphene

Transferred graphene



200 μm

CVD graphene (soon with a new PECVD oven)

A. Madouri + 5 persons

National and international relations



- ICFO (Barcelona): A. Bachtold, J. Moser
- LPA (Paris): B. Placais
- ICN (Barcelona): G. Ceballos, S. Roche
- Aalto University (Helsinki): P. Hakonen
- Warsaw university: M. Zdrojek
- IEMN (Lille): H. Happy, G. Dambrine
- LPCNO (Toulouse): B. Lassagne
- LOMA (Bordeaux): F. Pistolesi
- SPEC (Saclay): Y. Moukharski

...



- LETI: A. Zenasni, A. Delamoreanu, C. Rabot (croissance et transfert), F. Triozon (théorie)
- LTM: G. Cunge (procédé de fabrication), C. Vallée (croissance et transfert)
- LITEN: J. Dijon (croissance et transfert, conductivité du graphène)
- LNCMI Toulouse: B. Raquet (magnéto-transport)
- Trinity College: G. Duesberg, T. HallamStanford Univ.: P. Wong, T. Howes, Daesung Lee
- ICN: S. Roche (simulation)
- UCL: J.-C. Charlier (calculs ab-initio)
- Univ. Pisa: M. Maccucci (théorie et simulation)

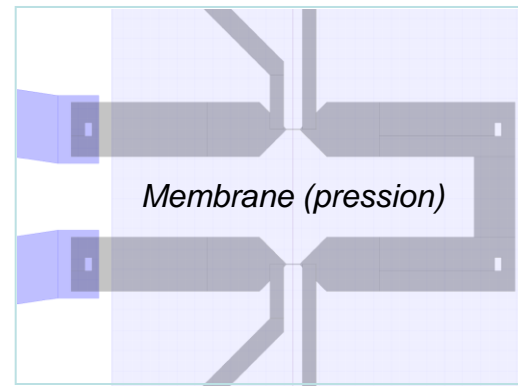
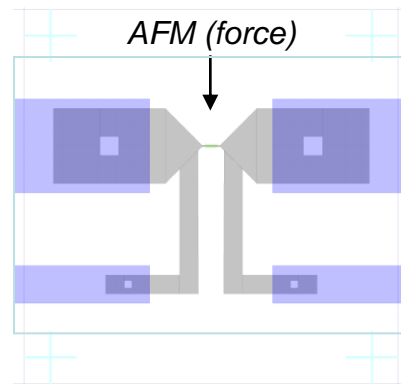
Fin

Etude des propriétés électromécaniques du graphène

- **Objectif fondamental:** Corréler propriétés de transport et déformation (statique ou quasi statique) pour du graphène (non idéal)
- **Objectifs applicatif:** Capteurs (pression, flux, force...)
Composants sur substrat flexible

■ Configurations étudiées

Graphène libéré ou sur membrane SiO_2 flexible
Mise en contrainte par AFM ou par pression hydrostatique



■ Fabrication des structures de test

- Graphène utilisé: graphène CVD/métal reporté sur Si/SiO_2 (collaborations)
- Etapes de fabrication maîtrisées: patterning graphène, contacts, membranes
- En cours: libération ou formation de cavités dans un procédé complet

Thèse
Işil Ömür Aydın

Etude des propriétés électromécaniques du graphène

• Caractérisation

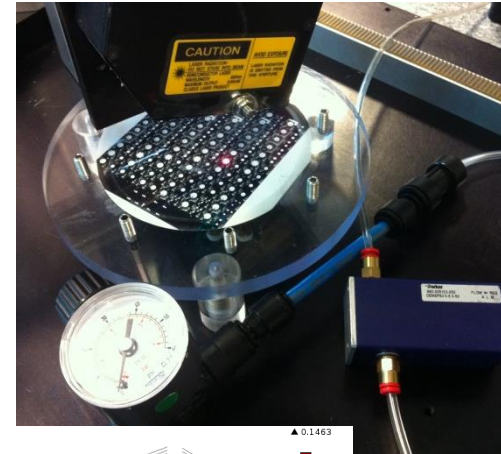
- **En l'absence de contrainte:** Transport, bruit BF (pièges et défauts)
- **Graphène sur membrane:** Déformation (réflexion, interférométrie, AFM), contrainte (Raman) et conduction, sous pression contrôlée
- **Graphène suspendu:** $I(V)$ couplé à déformation, sous force contrôlée (AFM en mode force)

X. Xu, Nanotechnology 2011

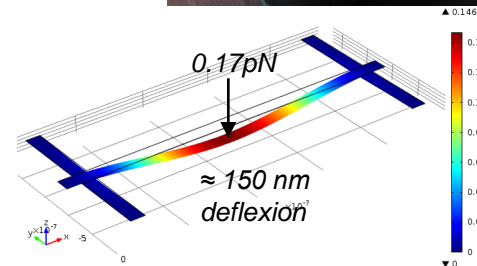
Corrélation force/flux-déformation-courant

■ Modélisation

- **Distribution de la contrainte**
FEM pour grandes dimensions, non linéarité
- **Structure de bande et transport quantique dans le graphène contraint**
Contraintes: FEM ou expérimentales
Simulation: fonctions de Green + tight-binding et ab-initio



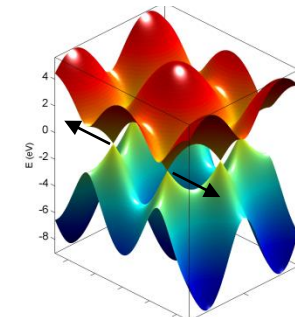
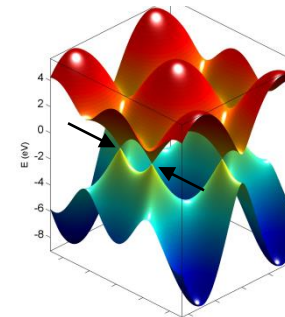
Exemple: mesure laser de la déformée d'une membrane sous pression contrôlée (ici, capot ôté)



Simulation multi-physique: dimensionnement, référence théorique

Armchair, $\sigma=10\%$, 0°

Zig-zag, $\sigma=10\%$, $\pi/2$



A. Cresti, 2012

• Personnes impliquées

FMNT
Labex MINOS

- A. Cresti: simulation quantique, crestial@minatec.inpg.fr
- M. Mouis: modélisation, contraintes, caractérisation électrique, mouis@minatec.inpg.fr
- I. Aydin*: fabrication, développement des procédés de fabrication des composants graphène à la PTA, caractérisation
- L. Montès: fabrication, caractérisations électromécaniques
- G. Ghibaudo: caractérisation électrique et en bruit
- G. Ardila: modélisation multi-physique et caractérisation AFM
- O. Chaix (LMGP): Raman

■ Collaborations nationales et internationales

Labex MINOS

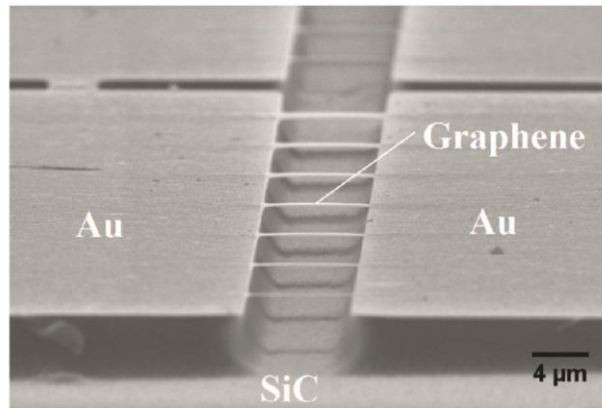
FMNT
Labex MINOS

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- LITEN: J. Dijon (croissance et transfert, conductivité du graphène)
- LNCMI Toulouse: B. Raquet (magnéto-transport)
- Trinity College: G. Duesberg, T. Hallam* (growth and transfer)
- Stanford Univ.: P. Wong, D. Lee* (graphene nanorelays)
- ICN: S. Roche (simulation)
- UCL: J-C. Charlier (calculs ab-initio)
- Univ. Pisa: M. Maccucci (théorie et simulation)

*Doctorants ou post-doctorants

graphene on SiC

Done with KOH etching



S. Shivaraman et al., *Nanoletters* **9**, 3100 (2009)

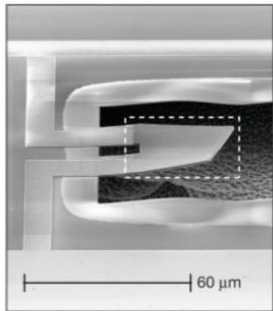
colossal number of samples → $Q \sim 1000$ at 300K

Mechanical resonator?

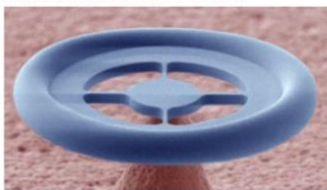
$$\omega_0 = \sqrt{k / m}$$



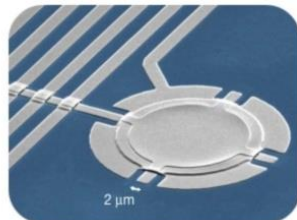
Macroscopic quantum vibrations



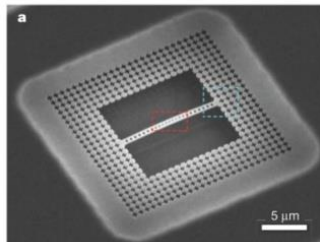
O'Connell et al, nature 2010
Santa Barbara USA



Verhagen et al, Nature 2012
Lausanne Suisse



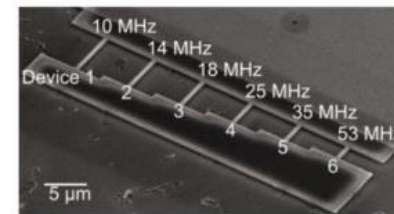
Teufel et al, nature 2011
Boulder USA



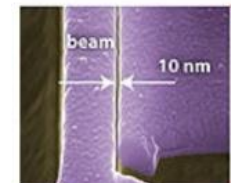
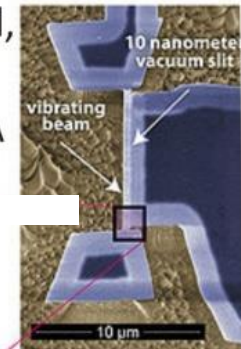
Chan et al, nature 2011
Pasadena USA



Oscillators, low noise amplifier, non-linear system, ...

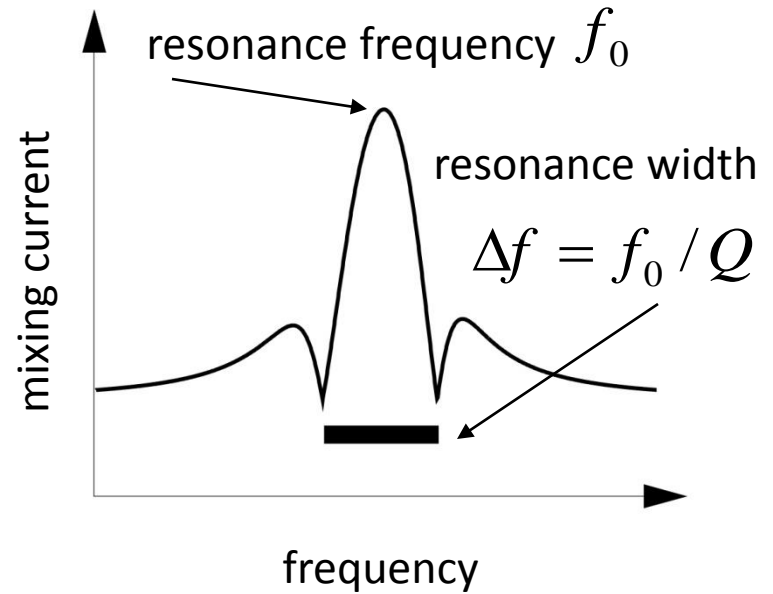
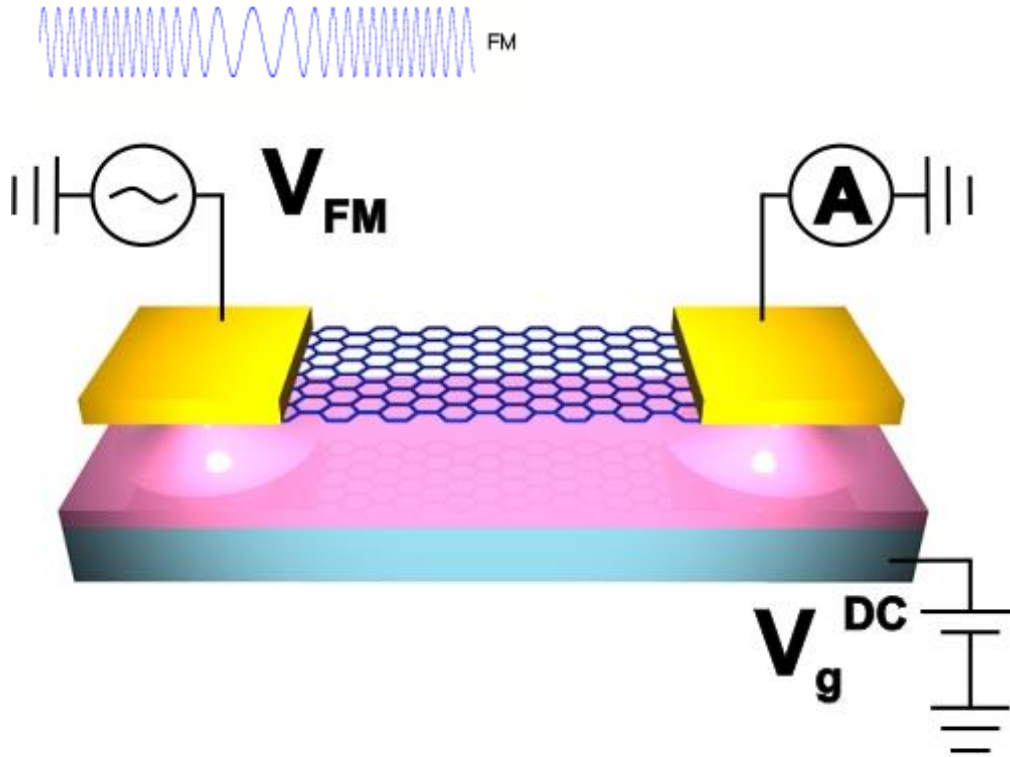


Karabalin et al,
APL 2010
Pasadena USA



Massel et al, nature 2011
Aalto Finland

mixing technique – frequency modulation

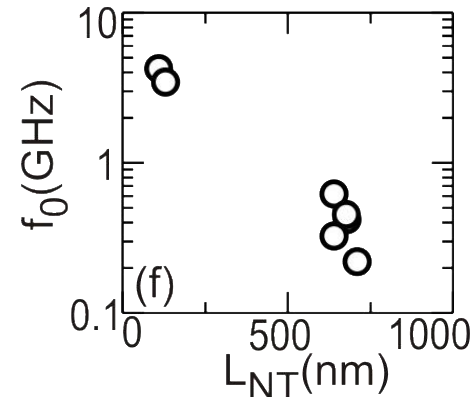
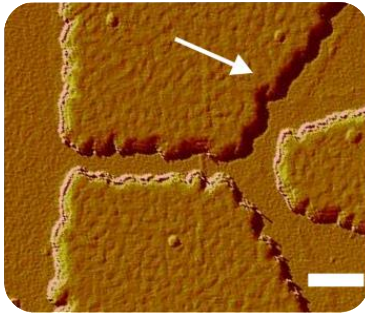


V. Gouttenoire et al., *Small* **6**, 1060 (2010)

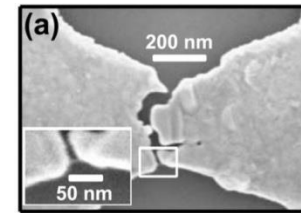
adapted from V. Sazonova et al., *Nature* **431**, 284 (2004)

$$I_{mix} \propto \left| \frac{\partial}{\partial f} \text{Re}(x) \right|$$

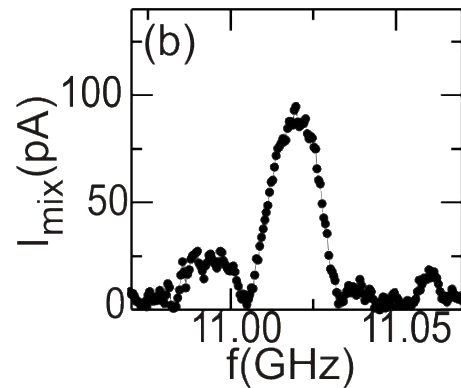
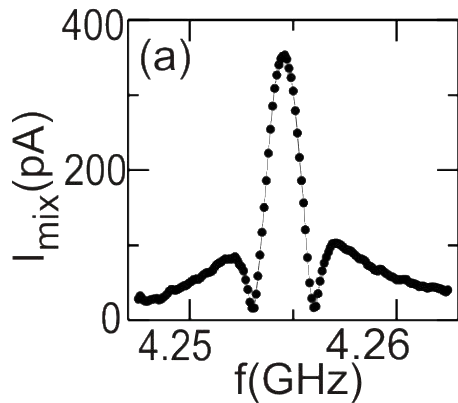
High frequency resonators under tension



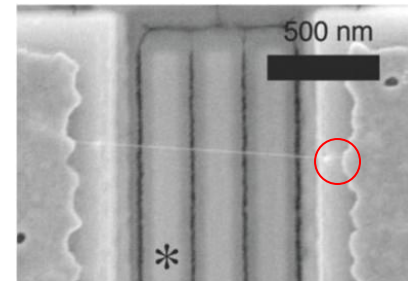
Island J. O. et al., *Nano letters* **12**, 4564 (2012)



At ~70-240GHz

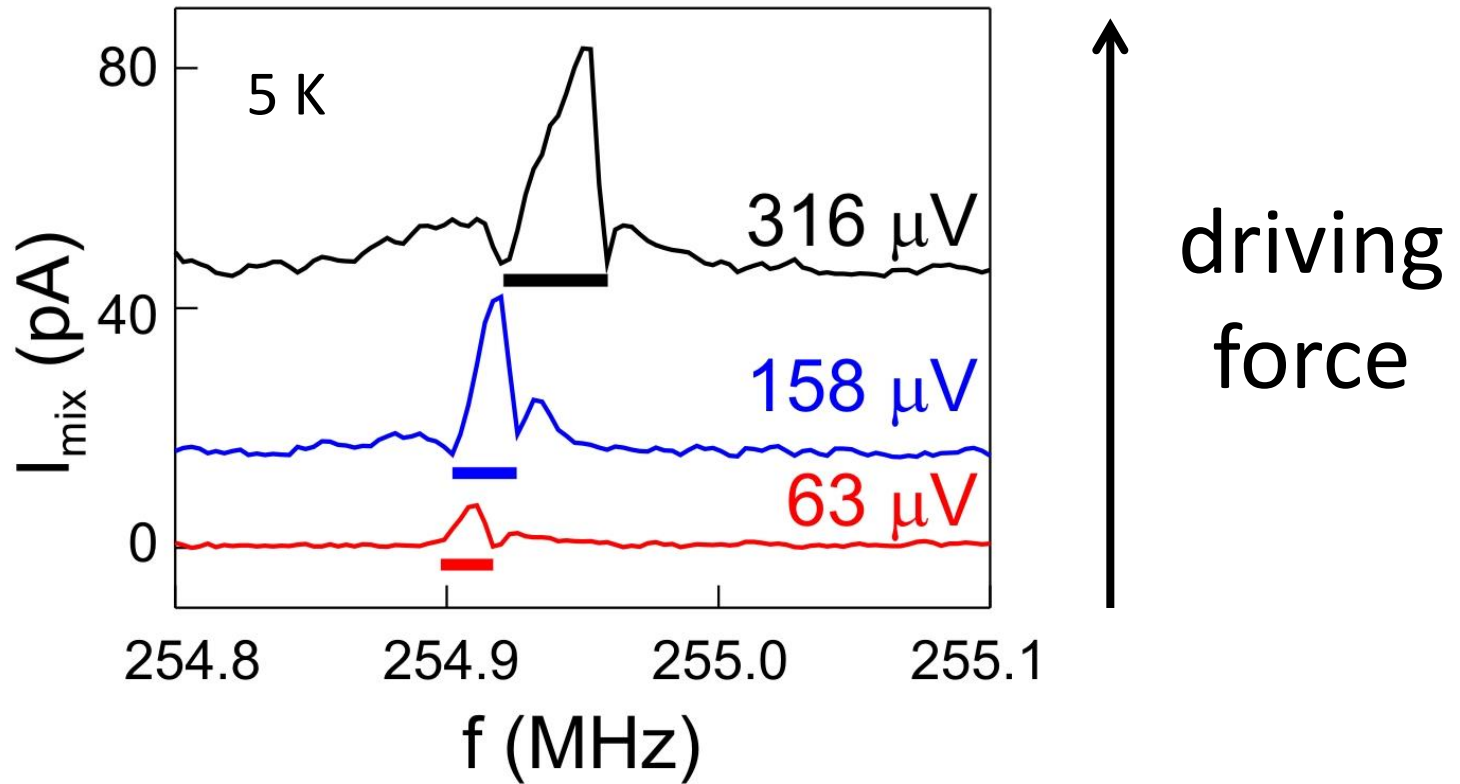


E. A. Laird et al., *Nano letters* **12**, 193 (2012)



At 40GHz!

J. Chaste, M. Sledzinska, M. Zdrojek, J. Moser, and A. Bachtold, *APL* **99**, 213502 (2011)



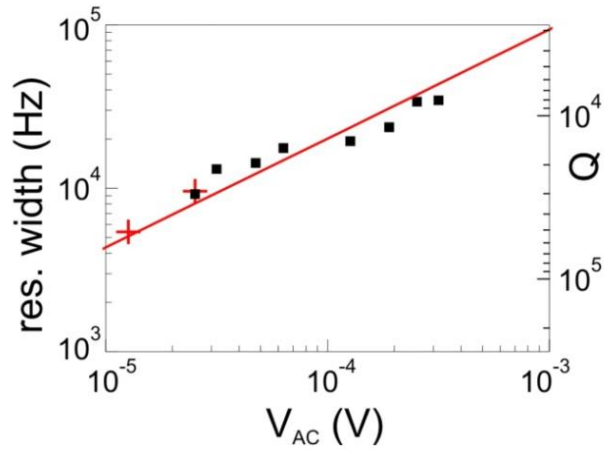
$$m \frac{\partial^2 x}{\partial t^2} + \gamma \frac{\partial x}{\partial t} + kx = F_0 \cos(2\pi f t)$$

strong deviation

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

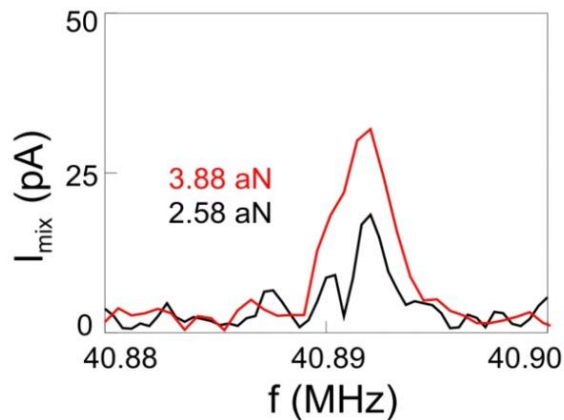
$$Q = \frac{2\pi m f_0}{\gamma}$$

Non-linear damping

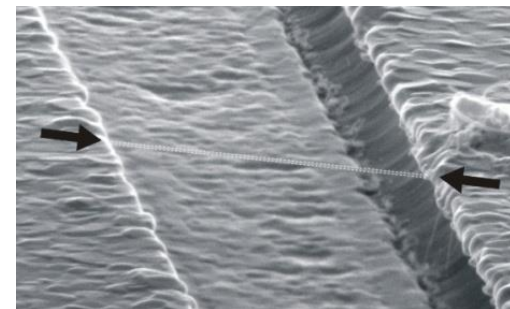


Strong deviation

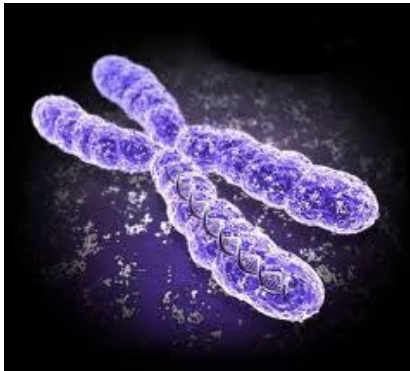
$$F_{damping} = -\gamma \dot{x}$$



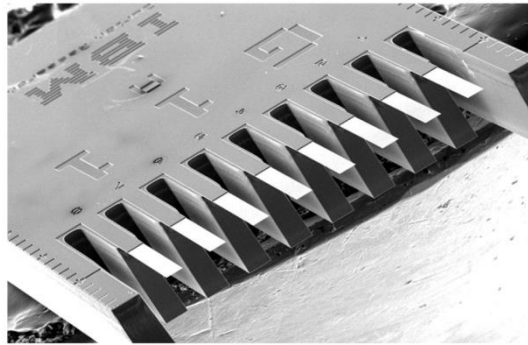
$$F_{damping} = -\eta x^2 \dot{x}$$



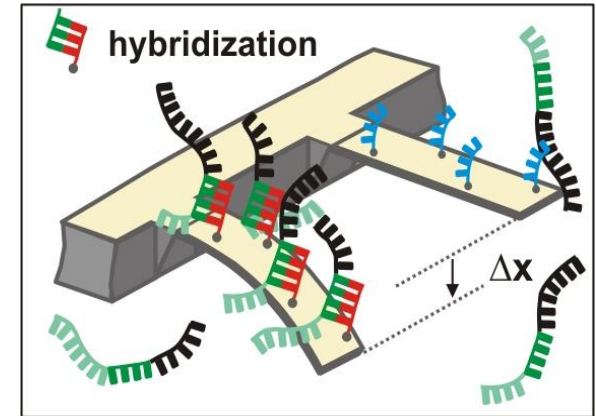
Talk of Christoph Gerber (Basel)



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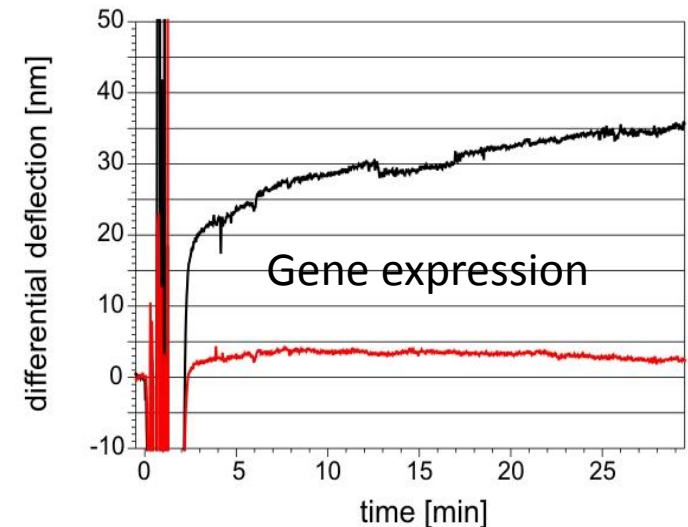
Gene fishing and human genome with nems

J. Zhang et al., Nature Nano. 1, 214-220 (2006)

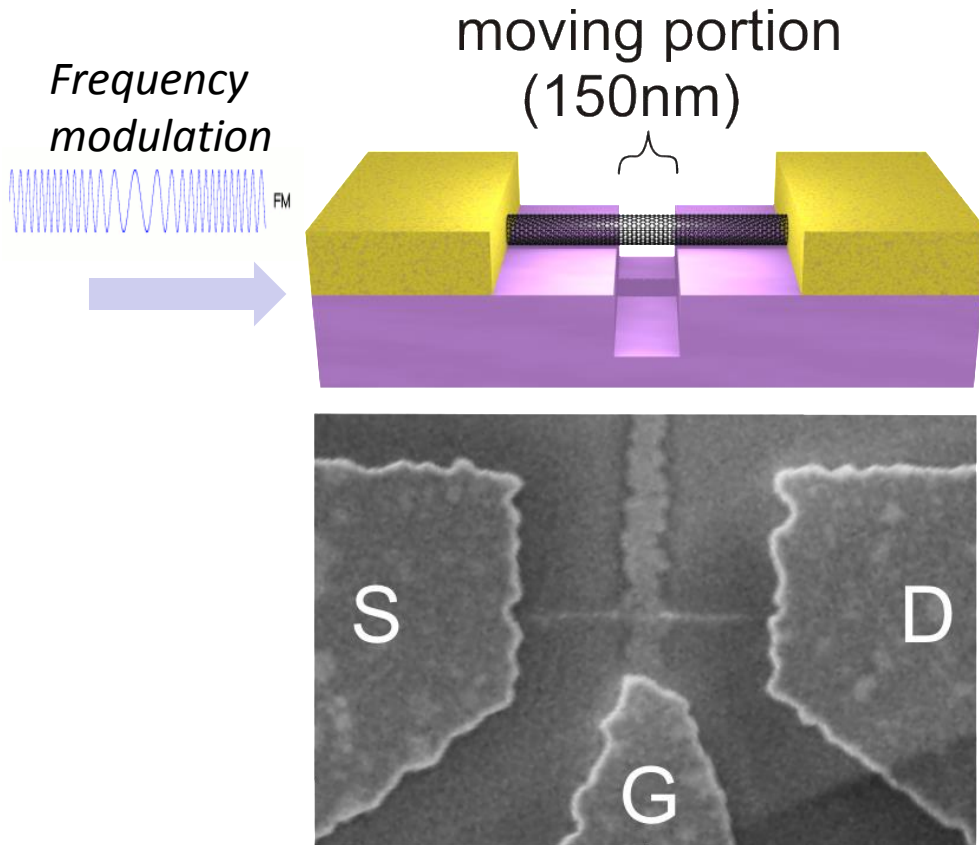
50% of melanoma patients carry the BRAF V600 mutation: RG7204 shows a significant survival benefit in melanoma

Huber F. et al., Biosens. Bioelectr., 8,21 (2006),

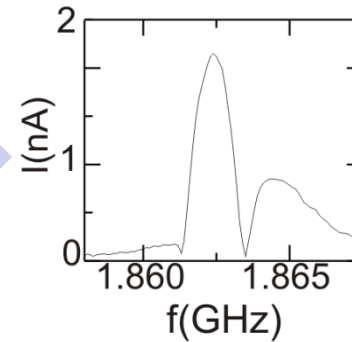
Braun T. et al., Nature Nano., 3,4 (2009),



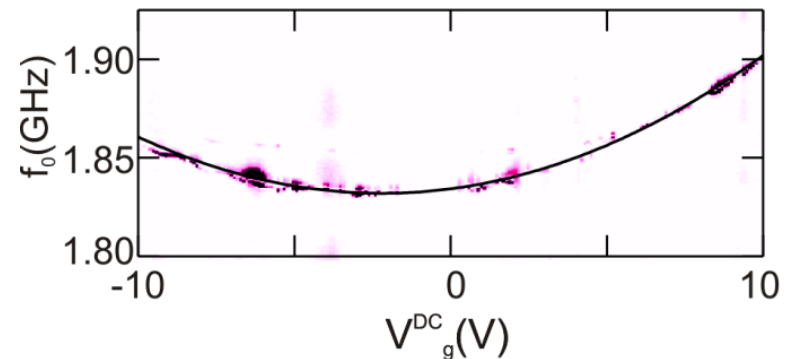
High frequency resonators



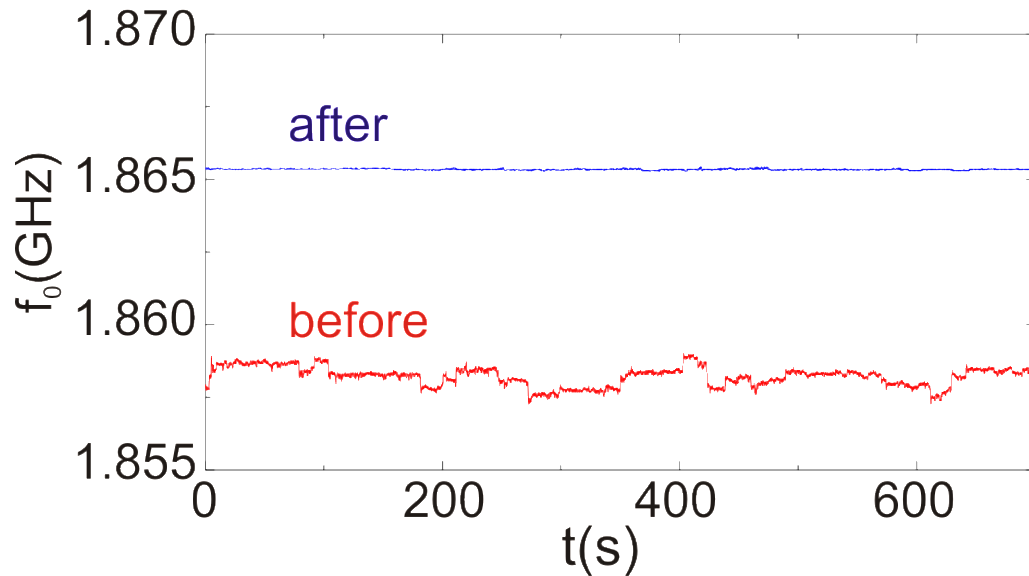
at 4K and $P=5 \cdot 10^{-11}$ mbar



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



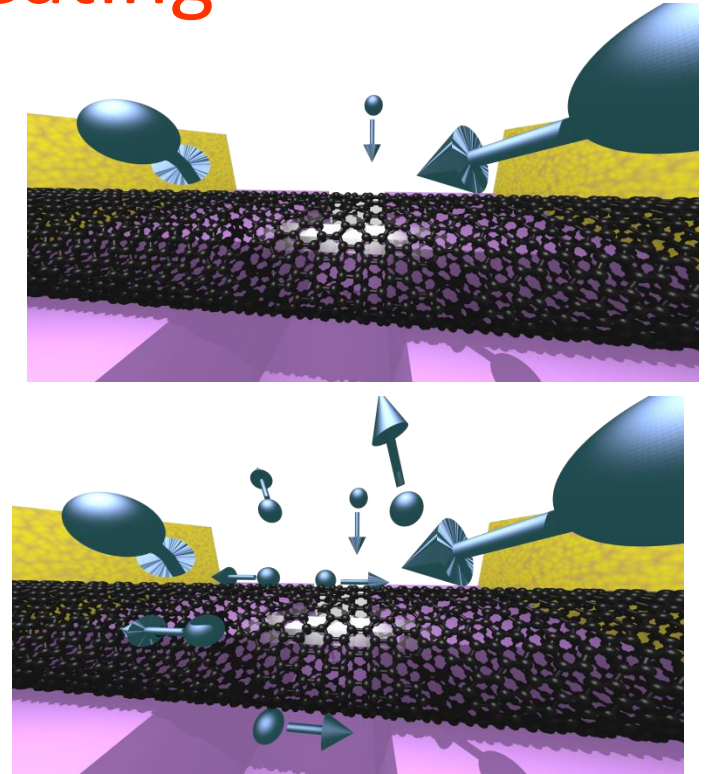
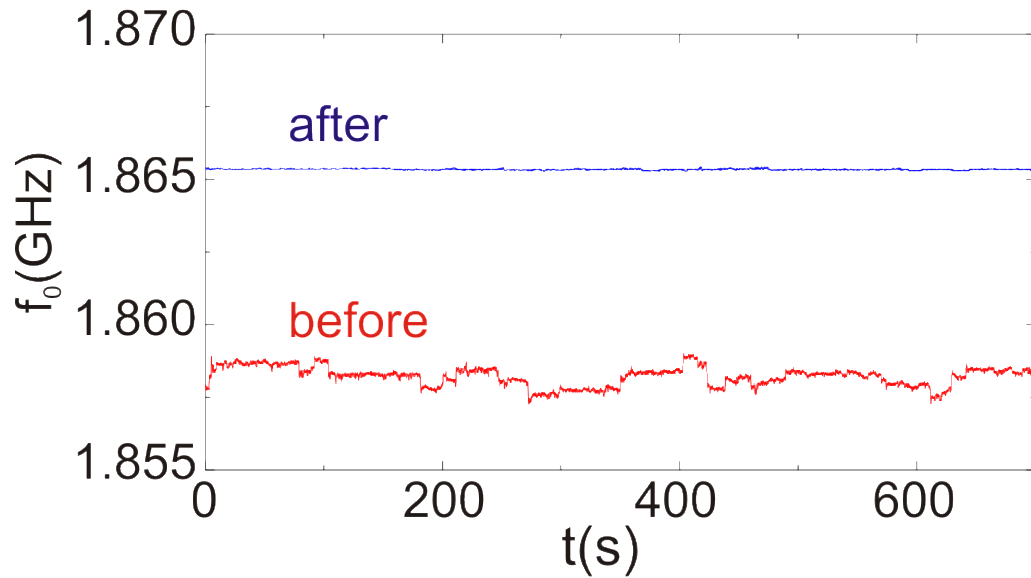
Cleaning of carbon resonator with current heating



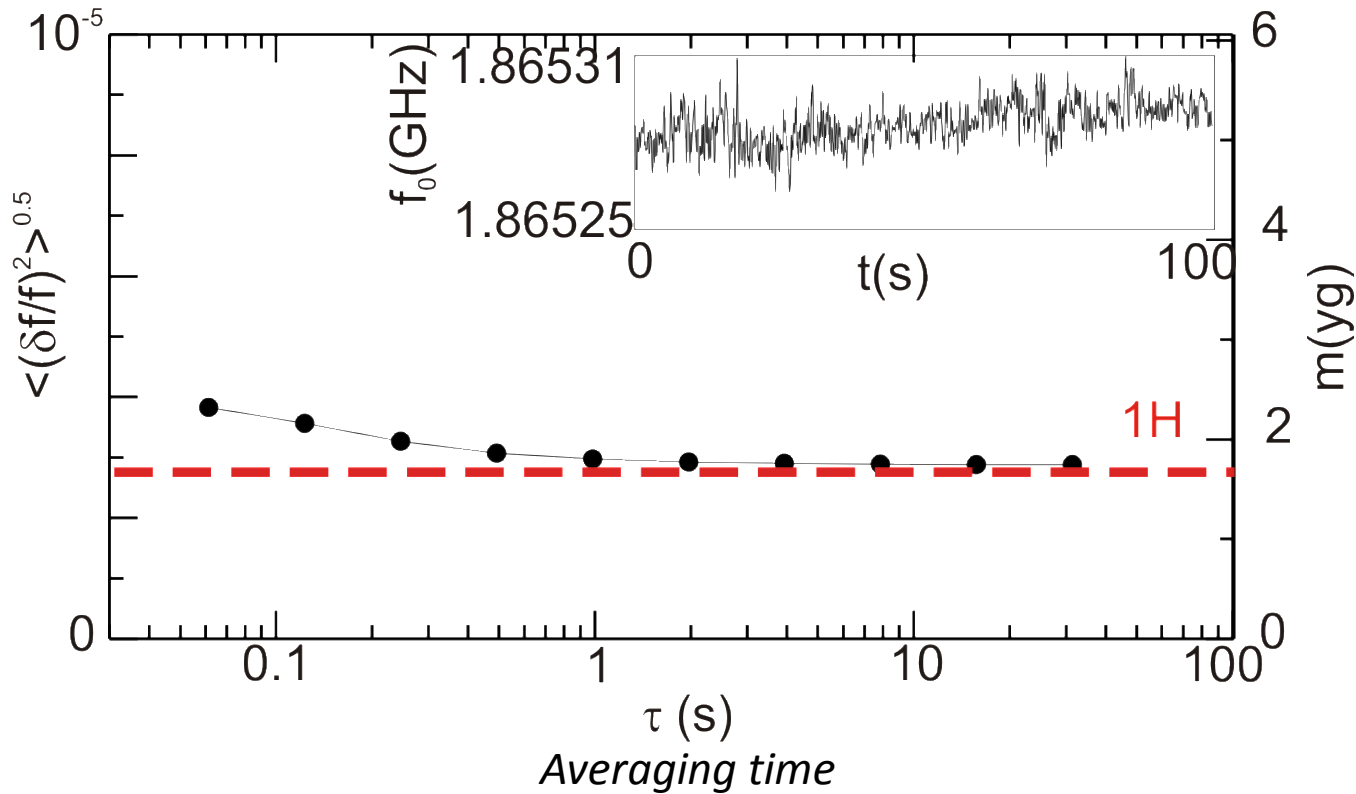
Chemically inert surface

Noise=kinetic of ad-atoms
not electrostatic fluctuators
not electrical current noise
not mechanical instabilities

Cleaning of carbon resonator with current heating



Yoctogram scale mass sensing (10^{-24} g)



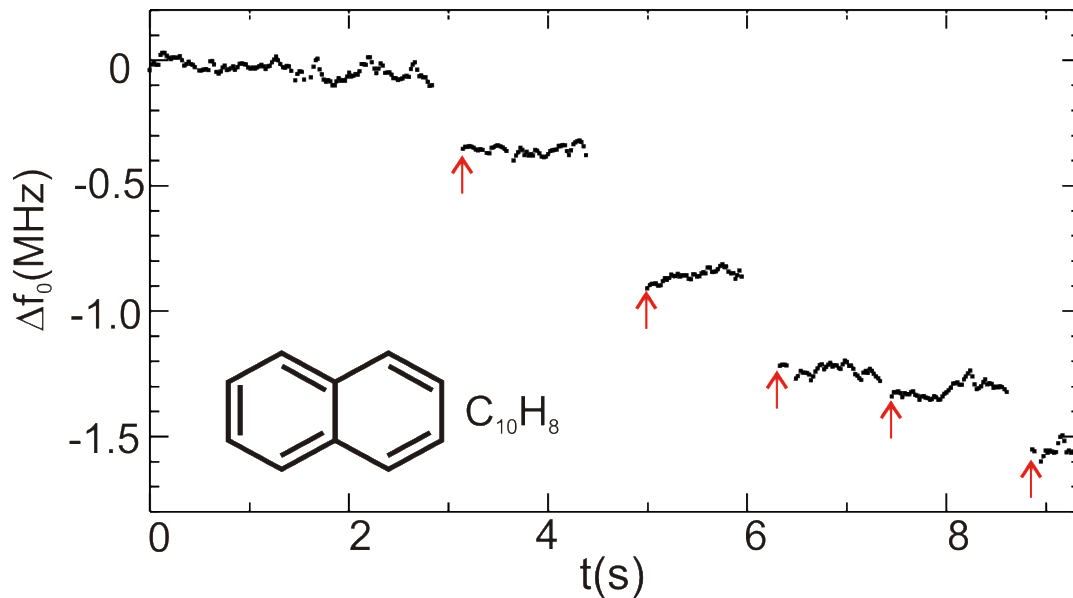
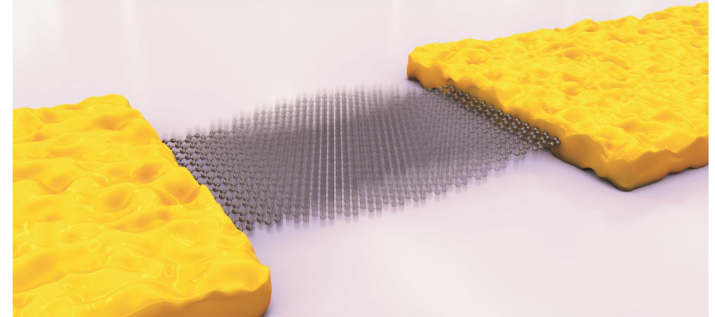
$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$



$$\frac{\delta m}{m} = 2 \cdot \frac{\delta f_0}{f_0}$$

Proton mass = 1,67yg
 Measured standard deviation = 1,7 ($\pm 0,5$)yg

Detection of small molecules one-by-one



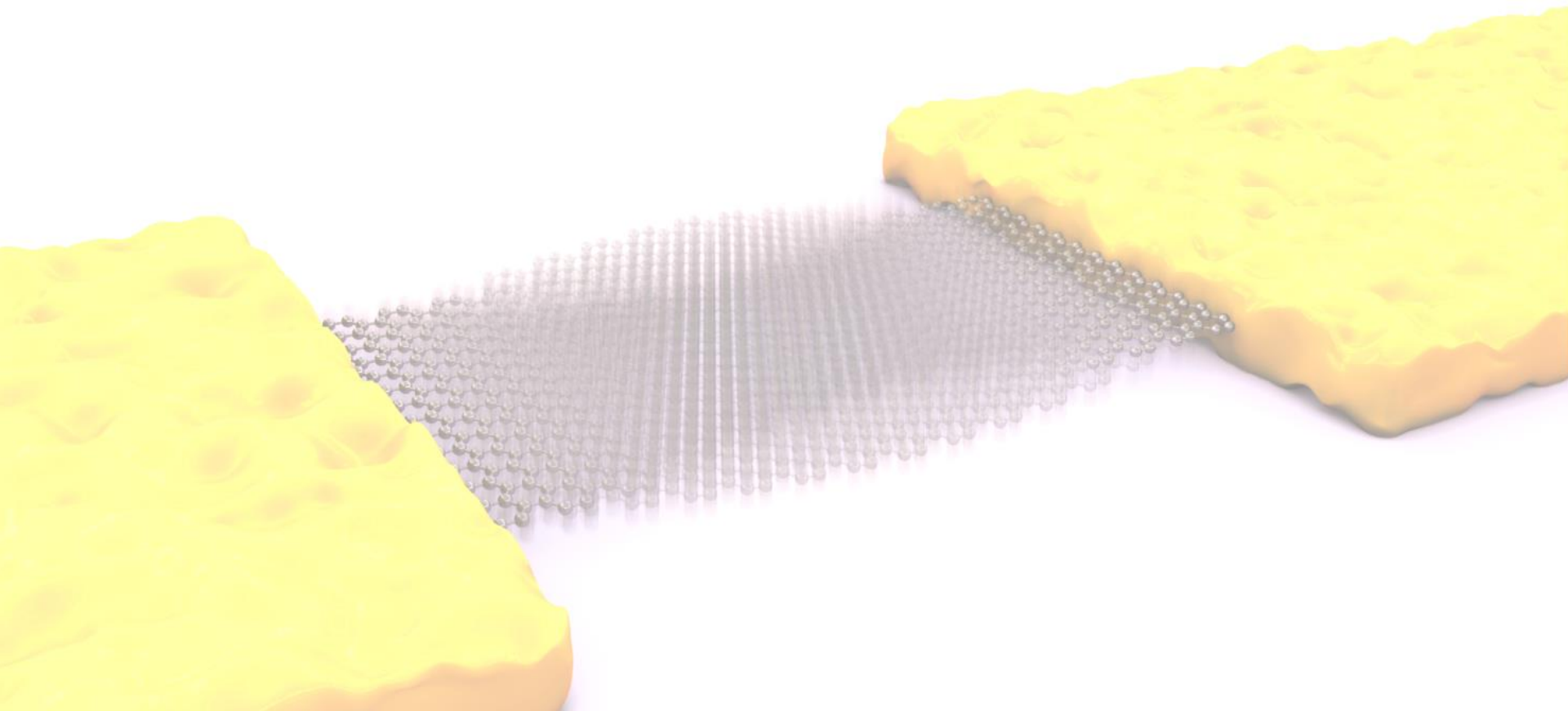
averaging frequency shift
Expected = $-3 \cdot 10^5$ Hz
Measured = $-3,2 \cdot 10^5$ Hz

*But a stable state
difficult to obtain*

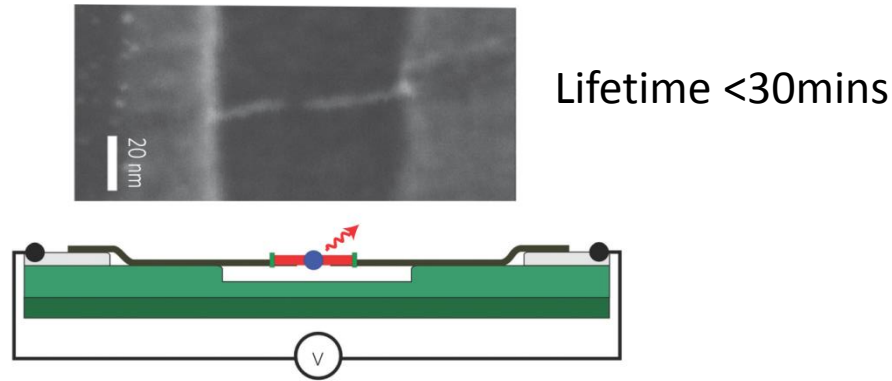
Time scale is consistent with experiment

NanoElectroMechanical Systems

- Motion equation and high frequency
- Ultrasensitive mass detectors
- **Functionalization**

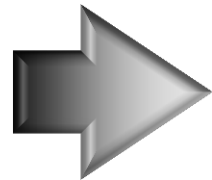
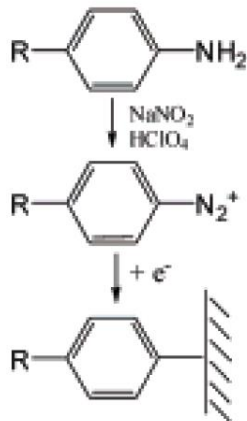


Carbon nanotube is a 1D probe



C.W. Marquardt et al., nature nano.,5,863 (2010)

Solution is grafting



Strong covalent contact
with metal or carbon surfaces

Made by Pascal Martin, Jean-Christophe Lacroix
(ITODYS, Paris 7)

Conclusion

Non-linear damping
GHz frequency

Ultrasensitive detectors for mass, spin, charge,
and force

Surface interaction with carbon devices

- cleaning of surfaces
- diffusion / absorption of ad-atoms (*with MEMs, Y.T. Yang, nanoletters, 11,1753(2011)*)
- phase transitions on nanotube (*with NT, Z. Wang, Science, 327,552 (2010)*)
- chemical reactions
- biological detection (*with MEMs, A. Naik, nature nano., 4,445(2009)*)
- One bohr magnetometers (*with NT, B. Lassagne, PRL, 107,130801 (2011)*)

