Mechanical detection of the vibrations of Carbon Nanotube and Graphene Resonators

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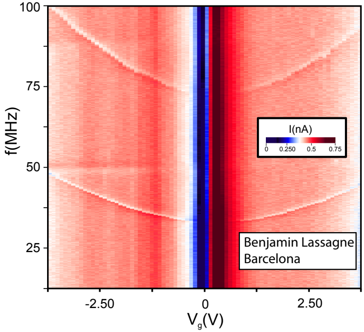
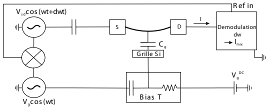
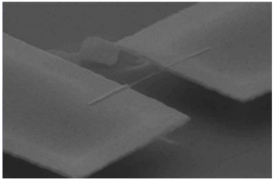
Motivation





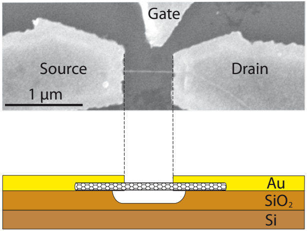


Breakthrough Electrical detection of mechanical vibrations of nanotube resonators *(V. Sazonova et al. Nature **431,** 284 (2004))*

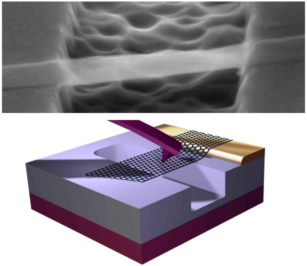
Problem Resonances cannot be assigned to the eigenmodes

SFM Technique

MWNT Resonator



Graphene Resonator

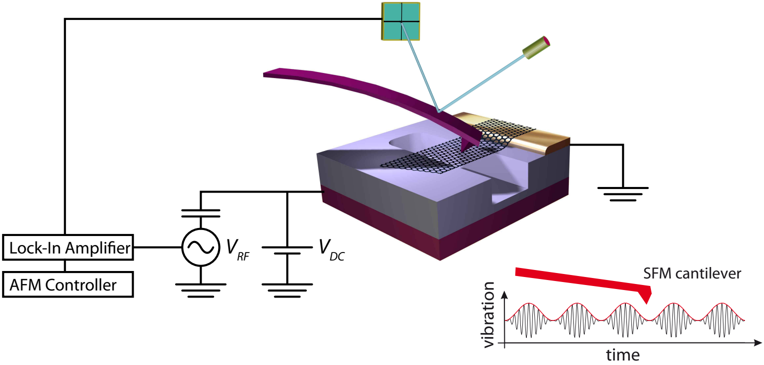


- Tested devices: MWNT, SWNT and Graphene Resonators
- Oscillating electrostatic force due to V_{RF}

$$F_{RF} = \frac{\partial C}{\partial z}(V_{DC} - \phi)V_{RF}$$

- V_{RF} is modulated at f_{mod}, $(1 - \cos(2\pi f_{mod} t))\cos(2\pi f_{RF} t)$

SFM Technique



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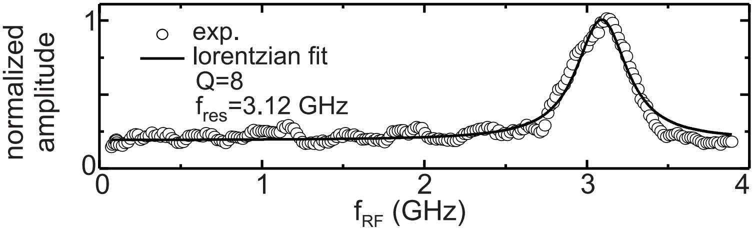
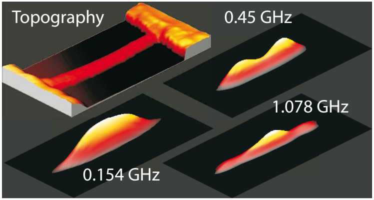


- Detection of resonance at 3.12 GHz
- The highest reported resonance frequency of a double clamped resonator

D. Garcia-Sanchez *et al.* Phys. Rev. Lett. **99,** 085501 (2007).

Imaging Mechanical Eigenmodes



- Topography and first 3 eigenmodes vibration images for a 770nm long MWNT resonator
- Measured eigenmode shape in agreement with the model
- Estimated displacement of 0.2nm

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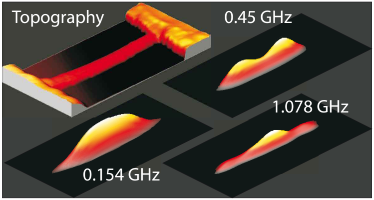

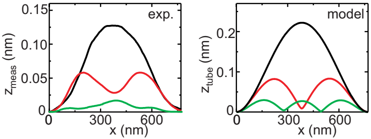

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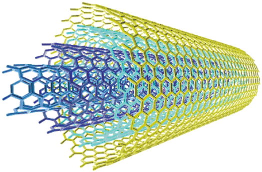
MWNT resonators

		Theoretical	Measured				
L(nm)	d(nm)	f_1^t(MHz)	f_1^m(MHz)	f_2^m(MHz)	f_3^m(MHz)	f_2^m/f_1^m	f_3^m/f_1^m
770	8.4	147	154	475	1078	3,1	7,0
1370	10	55	51	165	291	3,2	5,7
650	10	246	264	935	-	3,5	-
785	16	270	276	-	-	-	-
195	10	2734	2850	-	-	-	-
265	20	2961	3124	-	-	-	-

- Good agreement with the elastic beam theory:

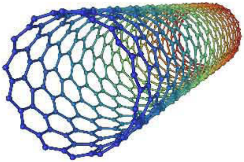
$$f_n = \frac{22.73\,\beta_n}{8\pi}\frac{d}{L^2}\sqrt{\frac{E}{\rho}} \text{ with } \beta_1 = 1,\ \beta_2 = 2.76,\ \beta_3 = 5.41$$



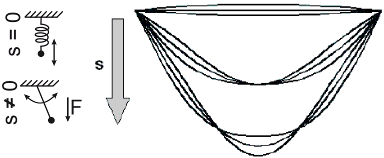
SWNT resonators

		Theoretical	Measured	
L(nm)	d(nm)	f_1^t(MHz)	f_1^m(MHz)	f_2^m(MHz)
640	2,0	92,7	30,0	57,0
465	1,3	114,1	260,0	-
572	4,0	232,0	290,0	-
193	1,5	764,3	573,0	-

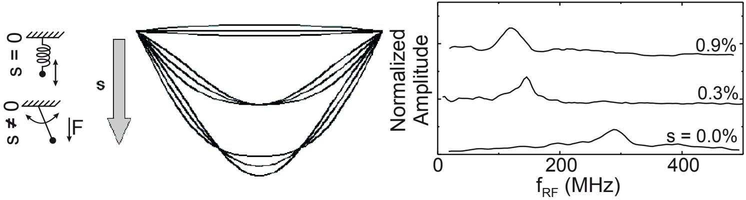
- Bad agreement with the elastic beam theory due to stress or slack



SWNT – Slack



- The slack is similar to a mass attached to a point through a massless rod
- Reduction of f_{res} consistent with theoretical analysis (H. Ustunel *et al.* Nano Lett. *5*, 523 (2005))



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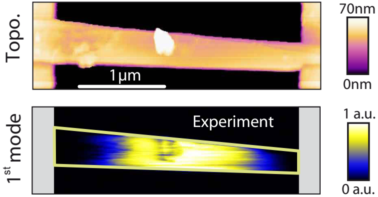
Graphene resonator with no buckling



- Beam with $t = 11nm$ and $l = 2.8, \mu$m
- $f_0 = 31$ MHz
- FEM and elastic beam theory predictions in agreement with measurements

D. Garcia-Sanchez *et al.* Nano Lett. accepted for publication

Graphene resonator with no buckling

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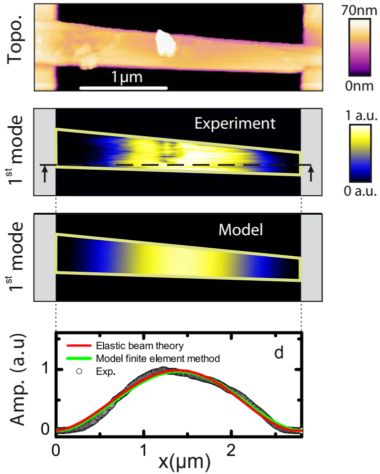

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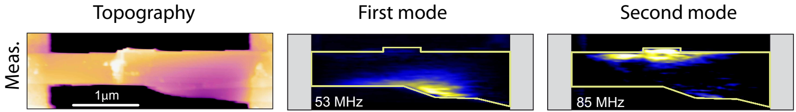
Graphene resonator with local buckling



- Local buckling of 37 nm
- Exotic eigenmodes: *“edge modes”*
- FEM simulations in excellent agreement with measurements
- Very high maximum stress: 1.5 GPa
  - Steel breaks at 690 MPa, MWNTs between 11 and 63 GPa (M.F. Yu *et al.* Science 287, 637 (2000)), and SWNTs between 13 and 52 GPa (M.F. Yu *et al.* 84, 5552 (2000)).

Graphene resonator with local buckling

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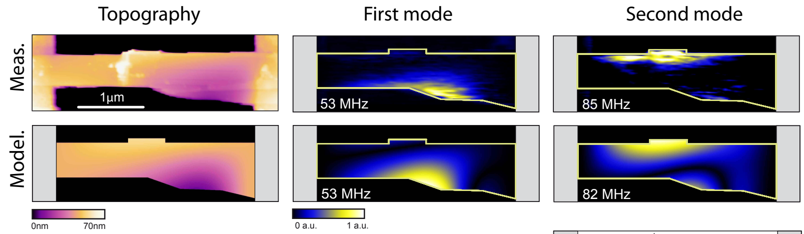

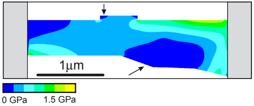

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Conclusions

- The SFM technique can
  - detect very high frequency resonances
  - image the eigenmodes
  - can be applied to any nano-mechanical resonator
- MWNT behave as double clamped beams
- SWNT do not behave as double clamped beams
- Graphene resonators may have edge eigenmodes due to the stress introduce during fabrication

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