Mechanical detection of the vibrations of Carbon Nanotube and Graphene Resonators

D. Garcia-Sanchez\textsuperscript{1,2} A. Bachtold\textsuperscript{1,2}

\textsuperscript{1}ICN Barcelona, Campus UAB
Bellaterra, Spain

\textsuperscript{2}CNM-CSIC Barcelona, Campus UAB
Bellaterra, Spain

NanoSpain 15/04/2008
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
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 $f_{mod}$, $(1 - \cos(2\pi f_{mod} t)) \cos(2\pi f_{RF} t)$
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 $f_{mod}$, $(1 - \cos(2\pi f_{mod} t)) \cos(2\pi f_{RF} t)$
Detection of resonance at 3.12 GHz
The highest reported resonance frequency of a double clamped resonator

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
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
## MWNT resonators

### Theoretical

<table>
<thead>
<tr>
<th>L(nm)</th>
<th>d(nm)</th>
<th>$f_1^t$(MHz)</th>
<th>$f_2^m$(MHz)</th>
<th>$f_3^m$(MHz)</th>
<th>$f_2^m/f_1^m$</th>
<th>$f_3^m/f_1^m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>770</td>
<td>8.4</td>
<td>147</td>
<td>154</td>
<td>475</td>
<td>3.1</td>
<td>7.0</td>
</tr>
<tr>
<td>1370</td>
<td>10</td>
<td>55</td>
<td>51</td>
<td>165</td>
<td>3.2</td>
<td>5.7</td>
</tr>
<tr>
<td>650</td>
<td>10</td>
<td>246</td>
<td>264</td>
<td>935</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>785</td>
<td>16</td>
<td>270</td>
<td>276</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>195</td>
<td>10</td>
<td>2734</td>
<td>2850</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>265</td>
<td>20</td>
<td>2961</td>
<td>3124</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Measured

Good agreement with the elastic beam theory:

$$f_n = \frac{22.73 \beta_n d}{8\pi L^2} \sqrt{\frac{E}{\rho}}$$  with $\beta_1 = 1$, $\beta_2 = 2.76$, $\beta_3 = 5.41$
Bad agreement with the elastic beam theory due to stress or 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))
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))
Graphene resonator with no buckling

- Beam with $t = 11\, nm$ 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

- Beam with $t = 11\,nm$ 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
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

- 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)).
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
Acknowledgments

ICN
- Adrian Bachtold
- Benjamin Lassagne
- Amelia Barreiro
- Joel Moser
- Maria Jose Esplandiu
- Mariusz Zdrojek

UPC
- Albert Aguasca

CNM
- Alvaro San Paulo
- Francesc Perez

Cornell
- Arend van der Zande
- Paul McEuen