Ultra high frequency Nano Cantilevers (NEMS)
Introduction

- NEMS for Nano Electro Mechanical System
- Frontier MEMS/NEMS
  - Device’s size
  - Resolution of measurement

MEMS/NEMS cantilevers

Applications:
- Imaging (AFM, STM)
- Sensing (mass sensor, gas detection, molecular detection)
2 types of measurement:

- **Static deflections:** surface tension due to adsorbed particles

- **Dynamic:** Frequency shift due to mass adsorption on the cantilever
4 important factors to take in account for high performance:

1. Mechanical resonance frequency

2. Sensitivity
   1. Mechanical element
   2. Transducer

3. Quality factor

4. Resolution
Principle:

Mass adsorption induces variation of fundamental mechanical resonance frequency of cantilever.

Mechanical resonance frequency:

$$f_0 + \Delta f \approx cte \cdot \frac{k}{\sqrt{m + \Delta m}}$$
Principle
Frequency resonance (2)

- Resonance frequency vs. size

Sensitivity

\[ \frac{\Delta f}{\Delta m} \approx -\frac{1}{2} \frac{f_0}{m} \]

reduce \( m \) to increase sensitivity

→ Need to build nanocantilever

Nanocantilevers- 9

Why a high quality factor is required?

- Accurate mechanical resonance peak detection
- Q factor is higher in vacuum

\[ Q = 2\pi \frac{\text{maximum energy stored}}{\text{energy dissipated per cycle}} \]
Quality factor (2)

\[ Q \approx cte \left( \frac{t}{l} \right)^2 \sqrt{\frac{E \rho}{P}} \]

3 different type of noise:

- Flicker noise:

\[ S_R^{(1/f)} = \frac{\zeta R^2}{Nf} \]

Negligible for high frequency resonance

- Thermomechanical noise:

\[ S_z^{1/2} = \sqrt{\frac{4k_B T Q}{2\pi f_0 K}} \]

- Johnson noise:

\[ S_T^{1/2} = \sqrt{4Rk_B T \Delta f} \]

Can be reduced with low resistivity coefficient material
Transducer (1)

- Displacement transduction in NEMS:
  - Optical
    - Diffraction effects problems appears
  - Capacitive
    - Inadequate for nanoscale devices due to parasites effects
  - Piezoresistive
    - Integrated: Suitable for nanoscale devices!
Piezoresistive materials for transducers:

- Sensitivity:
  \[
  \frac{\Delta R}{R} = K \cdot \varepsilon \quad \text{with} \quad K_{\text{semiconductor}} \approx 20 \cdot K_{\text{metal}}
  \]

But...

\[noise_{\text{semiconductor}} \approx 10^4 \cdot noise_{\text{metal}}\]

The resolution is given by:

\[
\text{resolution} = \frac{\text{noise}}{\text{sensitivity}}
\]

\[resolution_{\text{metal}} \gg resolution_{\text{semiconductor}}\]
Higher resolution in metals than semiconductors for nanoscales devices

Resolution: down to $1 \text{ag} = 10^{-18} \text{g}$
Conclusion

- Increasing of performance can be achieved by:
  - Higher frequency resonance
  - Low resistivity materials for transducer for nanoscales devices
  - Enhancement of nanofabrication techniques
Static Deflection in Nanomechanical cantilevers

Nanotechnology Seminar

Gabriella Sinicco
Outline

• Introduction
  • Nanomechanical cantilever
  • What is static deflection?
  • How does it work?
  • Challenges
  • Areas of interest
• Why does the cantilever bend?
• How to detect bending
• Applications
  • Biomolecules recognition (advantages…)
  • Artificial nose
• Conclusion
Introduction

The nanomechanical cantilever:

- Thin flexible beam made of silicon (100nm x 100nm x 1um)
- Allows exploring the physics and chemistry of the nanometer world
- Coated with a sensor layer, it serves as a chemical sensor
- Deflection is at nanometer scale

Lang – Nanotechnology 2002

Diffusion into polymer

Biomolecular recognition

Static Mode (surface stress)

Dynamic Mode (microbalance)

Thermogravimetry

Biochemistry
Introduction

What is static deflection?

- In “nanomechanics”: bending of a nanomechanical cantilever due to the action of a force.
- The entity to be sensed will determine the force.
- The entity is sensitive to the surface coating.
Introduction

How does it work?
Introduction

Challenges

- Improve sensitivity by decreasing the dimensions
- Selective bending of the cantilever allowing entity recognition and measurement

Motivations:
- No labeling needed for detection
- Easy and "cheap" production (Si technology)
- Can operate in air, vacuum, or liquid environments
- Fast analysis (within some minutes)
- Cyclic operations after purging
- Arrays:
  - Differential as well as simultaneous measurements
  - Individual coating of each cantilever allows measurement of multiple substances within a mixture
Areas of interest:

- Biochemical /medical analysis
- Gas sensing
- Quality control (food, chemicals, air)
- Fragrance design
- Oenology
- Forensic investigations
- Drugs and explosives detection
- Research
Bending origins

Why does the cantilever bend?

- Contact with target substance: chemical reaction → mechanical response: bending due to surface stress.
- Forces causing stress depend on entity at the surface (electrostatic, steric, hydrophobic interactions ...)
- Tiny dimensions of the cantilever → extremely high sensitivity.

Chemisorption of thiol molecules on gold coated cantilever
Adsorption induces reduction of the interfacial stress.

Analyte-induced deformation due to permeable-analyte coating swelling (polymers)
Detection of bending

How to detect bending

**Beam Deflection Principle**

- Mechanical motion can be measured directly by deflecting a light beam from the cantilever surface.

http://monet.physik.unibas.ch
Applications

Artificial nose

• Basic idea:
  → Use an array of mixture
  → Response of cantilever
  → Processing data

Examples

• Alcohols
• Solvents
• Flavors
• Perfume oils
• Soft Drinks

Cantilever sensor array with polymer coatings
Baller – Ultramicroscopy - 2000

Nanomechanics – Static Deflection- 10
Applications

Biosensing application

• Basic idea:

  → **Coat** each cantilever specifically to each protein / ssDNA

  → Expose to different analytes and observe bendings → **specific bindings**

  → **Differential** measurement to have reliable responses

Fritz – Science - 2000
Conclusions

Current research:

• Improvements in **reproducibility** and sensitivity, and integration of microfluidics and detection systems

Future trends:

• **New fabrication methods** to enhance cantilever response: nanostructuration to increase surface area

• **Portable biosensor microsystem** for high-throughput screening: integrate optical (or piezo-resistive) read-out and micro fluidics
Key messages

• Sensing **without labeling** $\rightarrow$ you save time

• Static deflection allows quantifying very small quantities (nm deflections detectable $\rightarrow$ ng/ml, nM concentrations) $\rightarrow$ **very sensitive**

• Versatile: can be operated in **various environments**

• **Fast** and **reusable**
SMFS
Single molecule force spectroscopy
Principe

- Mesurer les forces de liaison au sein d’une molécule
- Mesure de la force à la rupture entre deux molécules (ex: anticorps - antigène)
- Propriétés mécaniques des molécules (élasticité)
Ordre de grandeur

- Entropic Elasticity, Polymer Disentangling
- RNA Unwinding, Suramolecular Rearrangements
- Protein Unfolding, Ligand Unbinding,
- Bond Angle Deformation
- Chemistry, Bond Rupture

$k_B T$
Rappel biologie

- Conformation des molécules – structure tertiaire
- Sites de liaison entre molécules
- Changement de conformation dues aux conditions extérieures (chimique, mécanique, etc.)

→ Études des propriétés mécanique des molécules de leur liaison dans le but de comprendre les paramètres de ces phénomène

Comportement mécanique → fonctions biologiques
Méthodes de mesure

• **AFM**
  – Fonctionnalisation de la pointe

• **« Optical tweezers »**
  – Bille diélectrique
  – Détection de [pN] et déplacements [nm]

• **Bille magnétique**
  – Torsion possible
  – Sensibilité : Femtonewton

• **Microfibre**
  – Moins bonne résolution
Méthodes de mesure : AFM

- diode laser
- cantilever
- position detector
- avidine
- biotine
- Piezoelectric stage
- Laser
- Cantilever
- AFM-tip
- Linker molecule
- Ligand
- Receptor
- Linker molecule
- Piezo pulling direction
Méthodes de mesure : Optical tweezers
Méthodes de mesure : Magnetic bead
Méthodes de mesure : Microfibre

(b)

- beam entrance
- optical fiber
- DNA
- bead
- pipette
- glass surface
- objective
Applications

- **Conformation** : élongation forcée
  - Signature du diagramme force / extension propre à la conformation
  - Hystérésis lors de la relaxation
Applications

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Courbe force-extension d’une fragment d’ARN
Applications

• « Unzipping » DNA

→ Un outil potentiel de séquençage
Applications

- Force de rupture
• Formules de mécanique statistique

\[
P(r) = \frac{4b^3 r^2}{\sqrt{\pi}} \exp[-b^2 r^2] \quad \text{where} \quad b = \sqrt{\frac{3}{2na^2}}
\]

\[
S(r) = k_B \ln \left[ \frac{4b^3 r^2}{\sqrt{\pi}} \exp[-b^2 r^2] \right]
\]

\[
A(r) = \left[ \frac{3k_B T}{2na^2} \right] r^2 = \left[ \frac{3k_B T}{2L_c a} \right] r^2
\]

\[
f(r) = -\left[ \frac{3k_B T}{na^2} \right] r = \left[ \frac{3k_B T}{L_c a} \right] r
\]

\[
k(r) = \left[ \frac{3k_B T}{na^2} \right] = \left[ \frac{3k_B T}{L_c a} \right] = \text{cons tan t}
\]
Analyse

- Modèles pour ADN / polymères
  - FJC (Free joint chain)
    - Equiprobabilité de la distribution des liaisons (non-corrélés)
    - Rotation libre aux jonctions des liaisons
    - Pas d’effets de volume
  - WLC (Worm-like chain)
    - Plus réaliste que le FJC → flexible partout

Limitations : interaction du polymer avec lui même, supercoiling, etc.
Take home message

- Grand potentiel dans la recherche en biologie

- Actuellement pas encore de commercialisation

- Difficulté de modélisation du comportement des chaînes polymériques

- Outils de manipulation d’objets nanométrique disponibles
Références


- C. Storm and P. C. Nelson, Theory of high-force DNA stretching and overstretching, PHYSICAL REVIEW E 67, 051906 ~2003

- Vogel H., Nano-Biotechnologies, force spectroscopy, course 4th, 2007
Questions ?
Nanotechnologie
Séminaire de nanomécanique

Casimir Forces :
Physics and applications

Lysandre Bonjour 2007
Introduction

Physics of the Casimir forces
  • Theory
  • How to measure it

MEMS – NEMS
  • Nonlinear oscillators
  • Nanoscale position sensors
  • Quantum floatation

QED torque

Conclusion

References
1948: Casimir showed that by approaching two parallel plates made out of ideal metal (unit reflectivity at all wavelength), they should attract each other at very short distances in vacuum even if they are electrically neutral.

Generalization in the Lifshitz theory linking Casimir with Van der Waals.

- Dominant interaction mechanism between neutral objects at submicron distances!
Physics of the Casimir forces: Theory

- Fluctuating virtual particles exert a "radiation pressure" on the plates which, on average is greater outside the plates than between them.

- Produce a net attractive force! (usually)

- Linked to VdW forces in the retarded regimes
Micromachined torsional device to measure the Casimir force.

Use a rigid wire with a polystyrene sphere of R=100um covered by 10nm of gold as a tip.
For ultra thin metallic coating comparable to the skin-depth of the wavelengths oscillating between the surfaces, the layer gets transparent to electromagnetic waves.

Effect appears for thicknesses around 10nm and thinner.

Thick vs thin metallic layer

Sphere:
Red) 2.93nm of titanium + 9.23 nm of palladium
Black) +200nm
MEMS – NEMS: Nonlinear oscillators

- Torsional mode of oscillation excited by an AC signal on an underlying electrode.
- Casimir force vs restoring force

“First observation of bistability and hysteresis caused by a QED effect”

- Frequency shifts to lower frequencies as the sphere comes closer and hysteresis appears.

The distance $d$ between the oscillator and the sphere is $3.3\mu$m, 141 nm, 116.5 nm, and 98 nm for peaks I, II, III, and IV, respectively.
MEMS – NEMS: Nanoscale position sensors

- Can be used as a nanometric **position sensor** using the amplitude of resonance at different frequencies
Happens if the plates are immersed in a third medium with the following dielectric functions:

\[ \varepsilon_1(i\xi) < \varepsilon_3(i\xi) < \varepsilon_2(i\xi) \]

or

\[ \varepsilon_2(i\xi) < \varepsilon_3(i\xi) < \varepsilon_1(i\xi) \]

One can calculate the Hamaker constant. If <0 → repulsive force using the full Lifshitz theory.

Also valid for VdW non-retarded.
MEMS – NEMS: Casimir levitation II (Devices)

- Can be used to develop ultrasensitive force/torque sensor
- Plates can rotate, translate without static friction
- Limited by viscosity (dynamical damping)
The electromagnetic field allowed to take place between the plates depends on the optical axis orientation.

- Lead to a torque that tend to align the principal axes in order to minimize the system energy.

- Detect the angle by the change of intensity of transmitted laser light.
Casimir effect is a QED phenomena that can be sensed at large distances (100-200nm).

It is closely related to VdW forces.

It can be attractive or repulsive.

It might thus take a growing importance in the design of NEMS.
References


- M. Lisanti, D. Iannuzzi, and F. Capasso, “Observation of the skin-depth effect on the Casimir force between metallic surfaces”, PNAS 2005, 102, 11989-11992

- http://courses.washington.edu/overney/ChemE554_Course_Mat/course_material/surface_forces.pdf