Low temperature micro/nano mechanics

E. Collin, ULT group Grenoble - Néel institute, CNRS

Low temp. devices, ULT Group, I. NEEL
Outline

Why micro and nano mechanical systems?
Brief history
& key remarks
Micro-electo-mechanical: MEMS
Nano-electo-mechanical: NEMS
Micro-opto-mechanical: MOMS
Nano-opto-mechanical: NOMS

Introduction to experimental techniques
How to actuate a micro/nano mechanical device?
How to detect a micro/nano mechanical device’s motion?
What type of micro/nano mechanical devices?
Why is “small” different?

Why micro and nano mechanics at low temperatures?
Review of published works; how our works gets inserted in that
& key aspects of low temperature micro/nano mechanics
Why micro and nano mechanical systems?

A bit of History:

1948: Transistor (Bardeen, Brattain, Shockley)
1958: Integrated Circuit (Kilby, Noyce)
1959: Feynman’s famous conference
    “There is plenty of room at the bottom”

Feynman’s competition:
$1000 to create an electrical motor “smaller than 1/64th of an inch”
(i.e. less than 0.4 mm)

Winner William McLellan, using tweezers and a microscope!

Source:
R. Feynman, Journal of microelectromechanical systems 2, 1993
And... the Web!
Why micro and nano mechanical systems?

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1959: Feynman’s famous conference
   “There is plenty of room at the bottom”
1964: First batch fabricated micromechanical device
   (H.C. Nathanson et al.)

Feynman’s point:
**Trying to imagine all what could be done by “micro-machines”!**
Why micro and nano mechanical systems?

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Feynman’s point:
Trying to imagine all what could be done by “micro-machines”!

(mechanical) bridge between the small and the human scale: sensing forces at molecular level, etc…
Why micro and nano mechanical systems?

A bit of History:

Since then: explosion of proposals, applications and research on MEMS/NEMS

(Texas Instrument M. Mehregany)
SEM (false colors) image of a motor a few microns in diameter

(X-ducer, Motorola)
Manometer, membrane 3 x 3 mm, two op-amps on-chip, measures pressures from 10 bar to 40 mbar, differential
Why micro and nano mechanical systems?

A bit of History:

Since then: explosion of proposals, applications and research on MEMS/NEMS

(Silicon Designs, Inc.)
Accelerometer, from 1 g to 20 000 g, one to three axes.
1 mm plane supported by 100 μm x 100 μm x 5 μm pillar; air bag launcher

(Texas Instruments, DID)
Digital projector (Deformable Mirror Device).
Micro mirrors. Each mirror can be switched on/off to modulate the light, creating the image
Why micro and nano mechanical systems?

A bit of History:

Since then: explosion of proposals, applications and research on MEMS/NEMS

... and many more (microfluidics – lab on chip, etc...)

Introductory papers on on-going research:

K. Schwab and M. Roukes, Physics today 2005: claimed “everything moves!”
This is back to Feynman’s argument, but introducing explicitly quantum mechanics

F. Marquardt and S. Girvin, Physics 2009: on “Optomechanics”
Considering the quantum nature of photons interacting with mechanical objects
Why micro and nano mechanical systems?

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Considering the quantum nature of photons interacting with mechanical objects

Both fundamental issues and potential applications!

- Main difficulty: accurate detection of NEMS motion
- Reaching the quantum regime of a macroscopic collective mechanical degree of freedom
An introduction to experimental techniques

How to actuate a micro/nano mechanical device?

• Piezoelectric: a voltage applied on a piezoelectric material generates a displacement of its surface that couples to the device
  R. B. Karabalin et al., APL 95, 103111 (2009)

• Optical: a laser heats the material, it dilates and creates thus the motion
  M. Zalalutdinov et al., APL 78, 3142 (2001)

• Magnetomotive: a current is fed through the device which lies in a magnetic field, \( \vec{F} = I \vec{l} \times \vec{B} \)
  Very simple, used a lot at low temperatures
  E. Collin et al., JLTP 158, 678 (2010)

• Capacitive: a voltage applied between metallic electrodes generates a displacement of (at least) one of the electrodes
  Dustin W. Carr et al., APL 77, 1545 (2000)
An introduction to experimental techniques

How to actuate a micro/nano mechanical device? At the quantum limit?

- **Piezoelectric**: a voltage applied on a piezoelectric material generates a displacement of its surface that couples to the device. 
  R. B. Karabalin et al., APL 95, 103111 (2009)

- **Optical**: a laser heats the material, it dilates and creates thus the motion.
  M. Zalalutdinov et al., APL 78, 3142 (2001)

- **Optical, quantum**: a laser is coupled to a moving mirror through radiation pressure.

- **Magnetomotive**: a current is fed through the device which lies in a magnetic field, $\vec{F} = I \vec{l} \times \vec{B}$
  Very simple, used a lot at low temperatures.
  E. Collin et al., JLTP 158, 678 (2010)

- **Capacitive**: a voltage applied between metallic electrodes generates a displacement of (at least) one of the electrodes.
  Dustin W. Carr et al., APL 77, 1545 (2000)

- **Capacitive or inductive, quantum**: the device is capacitively coupled to a quantum bit.
  M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature 304 2004
An introduction to experimental techniques

How to detect a micro/nano mechanical device’s motion?

- Transport property, e.g. piezoresistivity: the distortion induces a change in the electric resistance of the device

- Optical: a laser is reflected by the device and detected by means of an interferometric setup  T.D. Stowe et al., APL 71, 288 (1997)

- Magnetomotive: the motion in a magnetic field induces a voltage (flux time variation), 
  \[ V = \frac{d\phi}{dt} \quad (\phi = \int\int B dS) \]
  Very simple and used a lot at low temperatures, even on complex designs  R. B. Karabalin et al., Nano Letters 9, 3116 (2009)

- Magnetic: the moving part has a magnetic particle on it that couples to a SQUID  O. Usenko et al., APL 98, 133105 (2011)

- Capacitive: the moving part modulates a capacitance which is measured by an electronic setup (bridge, lock-in, resonant cavity)
  Dustin W. Carr et al., APL 77, 1545 (2000)
An introduction to experimental techniques

How to detect a micro/nano mechanical device’s motion? At the quantum limit?

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- Magnetic: the moving part has a magnetic particle on it that couples to a SQUID
  O. Usenko et al., APL 98, 133105 (2011)

- Capacitive or inductive, quantum: the moving part is coupled to a quantum limited detector (SET, SQUID, microwave cavity)
An introduction to experimental techniques

What type of micro/nano mechanical devices?

• Torsional oscillators: two wings coupled to electrodes which exert a torsion on the central rod, clamped on one side

• Cantilevers: a simply clamped beam with one end moving
  T.D. Stowe et al., APL 71, 288 (1997)

• Doubly clamped beams: a beam clamped on both side with its middle part moving
  M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature 304 2004

• Drums: a moving membrane
  M. Zalalutdinov et al., APL 78, 3142 (2001)

Plus some others (dilatational, shuttle, traveling waves...) and all sorts of “mixtures”! And different materials: silica, silicon, GaAs, diamond, nanotubes, graphene...
Why is “small” different?

**Volumic effects** become small compared to **surface effects**:
New possibilities!


Measuring forces at the molecular scale: Adsorbing molecules creates stress, which also changes the resonance frequency, A. W. McFarland and J. S. Colton, *J. of MEMS* **14** 2005

Biological sensing: these two properties, with a functionalized object can be used for biological detection, J. Dorignac, A. Kalinowski, S. Erramilli, and P. Mohanty, *Phys. Rev. Lett.* **96** 2006

Why is “small” different?

small means also getting closer to the domain where quantum mechanics prevails:
New possibilities!

Casimir force: force due to virtual photons between two metallic surfaces; depends on $F \propto \frac{\text{Area}}{d^4}$

Quantum sensors sensing classical forces: example of gravitational wave detectors (thought of for large objects in the first place)
A.A. Clerk, Phys. Rev. B 70 2004

Mechanical objects in their quantum ground state: small means high frequency, thus possible to reach $k_B T \ll \hbar \omega$, and large zero point motion $\Delta x = \sqrt{\hbar/(2m\omega)}$; quantum signatures and quantum control!
M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature 304 2004
Why micro and nano mechanics at low temperatures?

Benefit from low temperatures:
Low noise, only low energy states populated, high magnetic fields, cryogenic vacuum, superconducting materials, no thermal expansion for T< 30 K, ...

Low temperature standardized sensors:
Better oscillators, well defined and reproducible, new scales and geometries. Replacing “vibrating wires” in quantum fluids; cryogenic pressure gauges, ...

Reaching the regime $\frac{k_B T}{\hbar \omega} \ll 1$:
Ability to measure ground state properties, and manipulate quantum states of quantum mechanical harmonic oscillator; create non-classical states, study their decoherence, ...
Benefit from low temperatures: fundamental (classical) mechanics

Low noise, only low energy states populated, high magnetic fields, cryogenic vacuum, superconducting materials, no thermal expansion for $T < 30$ K, ...

Micro and nano mechanical devices at low temperatures are model systems!

**Address materials study:** the temperature is a control parameter!

Understanding silicon, silica glass, GaAs, SiN, carbon, ...

**Address fundamental issues** of Classical Physics: mimicking complex mechanical dynamics!

Nonlinear dynamics, chaos, coupled dynamics, ...
Benefit from low temperatures: fundamental (classical) mechanics

Use of low temperature techniques: essential for some experiments!

Magnetomotive drive of beams: \[ \vec{F} = I \vec{l} \wedge \vec{B} \] and \[ V = d\phi / dt \quad (\phi = \oint \vec{B} d\vec{S}) \]


FIG. 2. A series of silicon beams with transverse dimensions in the submicron scale.

In 8 T at 4.2 K, with \(10^{-2}\) mTorr

\[ I = I_0 \cos(\omega t), \ B \text{ static} \]

Induced voltage measured by a lock-in

FIG. 5. Measured response to an applied ac drive: (a) the induced emf generated in the gold electrode due to the motion, and (b) the corresponding phase.
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Magnetomotive drive of beams: \( \vec{F} = I \vec{l} \wedge \vec{B} \) and \( V = d\phi / dt \) \( (\phi = \int\int B d\vec{S}) \)


Monocrystalline silicon devices

The Quality factor becomes worse for small devices!

Both fundamental issue (understand why) and a technical issue (make better oscillators)
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

The study of glasses, through mechanical systems: various materials & shapes

R.N. Kleiman, G. Agnolet, D.J. Bishop, PRL 59, 2079 (1987); torsional oscillator
P. Strehlow, C. Enss, S. Hunklinger, PRL 80, 5361 (1998); dielectric measurements
E. Gaganidze, R. König, P. Esquinazi, K. Zimmer, A. Burin, PRL 79, 5038 (1997); vibrating reed
A. D. Fefferman, R. O. Pohl, A. T. Zehnder, and J. M. Parpia, PRL 100, 195501 (2008); torsional oscillator silica
D. R. Southworth, R. A. Barton, S. S. Verbridge, B. Ilic, A. D. Fefferman, H. G. Craighead, and J. M. Parpia,
PRL 102, 225503 (2009); Si$_3$N$_4$ membranes
Many others...
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Glassy properties, extensions of the Standard Tunneling Model:
Resolving the interactions between Two Level Systems in glasses. Linked to many topical questions:
damping in MEMS/NEMS, supersolidity, noise in qu-bits...
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Reaching very-high frequencies with carbon, graphene and nanotubes (up to GHz)! With about $Q \approx 10^4$ around 4 K

Making use of a clever electromechanical **down-mixing scheme** for GHz detection


Changyao Chen et al., Nature nanotech. 4, 861 (2009)
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Reaching very-high frequencies with high-stress silicon nitride, up to 100 MHz devices, and Q up to a million!

Room Temperature MHz device!


10 MHz, 100 mK device, Q \approx 10^6

Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Non-linear damping in materials

Metallic coatings on monocrystalline silicon

Intrinsic in nanotube and graphene devices
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Nonlinear dynamics: frequency pulling and hysteresis

R.E. Mihailovich, J.M. Parpia, Physica B, 165&166, 125 (1990); torsional oscillator
R.L. Badzey, G. Zolfagharkhani, A. Gaidarzhy, P. Mohanty, APL 85, 3587 (2004); beam
E. Collin, Yu. M. Bunkov, and H. Godfrin, PRB 82, 235416 (2010); cantilevers
Many others...
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

\[ F(t) = F_0 \cos(\omega t) \]

In the hysteretic region, two states coexist.
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Dynamic bifurcation

\[ F(t) = F_0 \cos(\omega t) + f_{\text{noise}}(t) \]

Controlled white noise, \( I_N \propto f_{\text{noise}}(\omega) \)


In the hysteretic region, two states coexist. Here, upper state is metastable and relaxes on the lower one. By adding a controlled amount of noise, the system can relax down faster:

exponential activation

\( I_N \) noise intensity
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Dynamic bifurcation

\[ F(t) = F_0 \cos(\omega t) + f_{\text{noise}}(t) \]

Probabilistic process, universal, independent of system!

Brownian: H.A. Kramers, Physica VII, 284 (1940)

\[ \Gamma_0 = \lambda \delta \omega \xi \]
\[ E_a = \eta \delta \omega \xi \]
\[ \Gamma = \Gamma_0 e^{\frac{E_a}{I_N}} \]
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Dynamic bifurcation

C. Stambaugh and H. B. Chan, PRB 73, 172302 (2006):
The most direct park,-wait-and-see experiment on a MEMS torsional oscillator.

J. S. Aldridge and A. N. Cleland, PRL 94, 156403 (2005):
The switching experiment is this time performed on a NEMS while ramping the drive frequency at a slow rate through the bifurcation point.

M. Defoort et al., in preparation. Residence-time on a NEMS device.
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Dynamic bifurcation

Reconstructing the “basins of attraction” of the two stable states of the oscillator in the parameter space by following the dynamical state as a function of the initial position.
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Many other effects that can be addressed at low temperatures...

**Nanomechanical mixing** between a low frequency signal and the NEMS mechanical drive.


E. Collin, T. Moutonet, J.-S. Heron, O. Bourgeois, Yu. M. Bunkov, and H. Godfrin, PRB **84**, 054108 (2011):
**Parametric amplification** (modulation of the spring constant at $2\omega$) of a weak signal and its application.

R. B. Karabalin, S. C. Masmanidis, and M. L. Roukes, APL **97**, 183101 (2010); **highest gain** reported 1000.
Benefit from low temperatures: fundamental (classical) mechanics

**Address fundamental issues** of Classical Physics: nonlinear dynamics, chaos, ...

Many other effects that can be addressed at low temperatures...


Between two different flexural modes (in and out of plane); anticrossings

See Kunal Lulla’s talk; mode coupling at low temperature in SiN beams
Low temperature standardized sensors

Better oscillators, well defined and reproducible, new scales and geometries. Replacing “vibrating wires” in quantum fluids; cryogenic pressure gauges, ...

Micro and nano mechanical devices at low temperatures are excellent probes!

Replace existing technology: Better devices.
Address new possibilities opened by MEMS/NEMS: New quantum fluid physics...

Quantum fluid means $^3$He and $^4$He liquids below 4.2 K
Low temperature standardized sensors

Replace existing technology: Better devices.

“Vibrating wire”

Well known technique for probing Quantum Fluids. Measure friction with fluid in resonant mode.

D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
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Extremely sensitive thermometer!

$4 \times 10^{19} \sqrt{\frac{T}{T_c}} e^{-\frac{\Delta}{kT}}$

$5 \mu m$ diam. NbTi wire

Grenoble vibrating wire mK Thermometry

Normal liquid

Liquid $^3$He

Damping of resonance (Hz)

1000

100

Quasiparticles / cm$^3$

$10^6$

$10^7$

$10^8$

$10^9$

$10^10$

$10^11$

$10^12$

$10^13$

$10^14$

$10^15$

$10^16$

T (µK)

100

120

140

160

180

200

1E10

1E11

1E12

1E13

1E14

1E15

1E16

1E17

1E18

1E19

1E20

1E21

0 bar

5 bar

17 bar

30 bar

100 120 140 160 180 200

$10^4$ e

$kT$ - $\frac{\Delta}{kT}$
Low temperature standardized sensors

Replace existing technology: Better devices.

Silicon “Vibrating wire”

Mimicking vibrating wire with silicon, for probing Quantum Fluids. **Measure friction** with fluid in resonant mode.

- $f_0 = 5 \text{ kHz}$
- $Q = 0.5 \times 10^6$
- Thickness/width: $1 \mu\text{m} - 30 \mu\text{m}$

D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
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Low temperature standardized sensors

Replace existing technology: Better devices.

Well known technique for probing Quantum Fluids. Measure friction with fluid in resonant mode.

“Vibrating wire”

5 µm diam. NbTi wire

Present detection threshold: ~ 1 keV

Extremely sensitive bolometer!

D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
Low temperature standardized sensors

Replace existing technology: Better devices.

Well known technique for probing Quantum Fluids. **Measure friction** with fluid in resonant mode.

“Vibrating wire”

Copper box

Sintered silver

~ 60 µm hole

Outside ~ 100 µK 3He

Lancaster “Black body radiator”

Vibrating Wires (5 µm and 13 µm)

Quantum turbulence devices

“Vortex grid”

“Fork”

D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
Low temperature standardized sensors

Replace existing technology: Better devices.

Adapting shapes, for probing Quantum Fluids. Measure friction with fluid in resonant mode.

Quantum turbulence devices

Silicon “grid”

Lancaster “Black body radiator”

Vibrating Wires (5 µm and 13 µm)

Copper box

Sintered silver

~ 60 µm hole

Outside ~ 100 µK 3He

B-60mT 1mm 5 mm

“Vortex grid”

“Fork”

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A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
Low temperature standardized sensors

Address new possibilities opened by MEMS/NEMS: New quantum fluid physics...

- Interaction with quasi-particles in the bulk, at the scale of $\xi_0 \approx 100$ nm

Resolving elementary excitations of BCS $p$-paired superfluid?

- Probing surface states (Andreev bound states) a 100 nm from a wall


Andreev bound states in $^3$He-B are Majorana Fermions!


Grenoble NEMS goalposts
Low temperature standardized sensors

Address new possibilities opened by MEMS/NEMS: New quantum fluid physics...

➢ Interaction with quasi-particles in the bulk, at the scale of $\xi_0 \approx 100$ nm

➢ Resolving elementary excitations of BCS $p$-paired superfluid?

➢ Probing slab states

In confined 3He experiments,

Peculiar interplay between bulk and boundary relaxation


In the superfluid case: new phases/distorted order parameter!
The density of quasi particles (QP) gives a signature of the order parameter

L. Levitin, A. Casey, J. Saunders NMR works in London (unpublished)
Reaching the Quantum regime of a macroscopic mechanical object

Ability to measure ground state properties, and manipulate quantum states of quantum mechanical harmonic oscillator

Quantum NEMS

**Fundamental physics:** quantum mechanics of a macroscopic collective single degree of freedom, here... *the center-of-mass!*

Probing basic quantum mechanics...

**New type of devices:** New engineering possibilities: mechanical quantum control, new quantum devices for quantum computing, ...
Reaching the Quantum regime of a macroscopic mechanical object

Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom, here... the center-of-mass!

How do microscopic quantum objects transform into classical macroscopic ensembles?
Measurement theory, see e.g. W. Zurek, Physics Today 44, 36 (1991)
A. Leggett, Suppl. of The Progr. of Theor. Phys. 69, 80 (1980)

But: absence of proof is not proof of absence.
No idea about any fundamental decoherence mechanisms of macroscopic mechanical objects...

For instance, possibility of position-state decoherence due to gravitons

For instance, proposal to “test” Quantum Gravity

\[ \Gamma = \frac{Gm^2}{2\hbar L^3} x^2 \]

\[ [x, p] = i\hbar \left( 1 + \beta \left[ \frac{p}{M_p c} \right]^2 \right) \]
Reaching the Quantum regime of a macroscopic mechanical object

**Fundamental physics:** quantum mechanics of a macroscopic collective single degree of freedom, here... the center-of-mass!

Note: macroscopic current in a SQUID loop in a superposed state has no center-of-mass motion! A superconducting current state in a long wire involves only pair correlations!


Matter waves interferometry: “macroscopic”?


Up to 6 910 amu!

**Nanofabricated** devices:
truly macroscopic, but... quantum control very difficult!
Reaching the Quantum regime of a macroscopic mechanical object

**Fundamental physics:** quantum mechanics of a macroscopic collective single degree of freedom, here... the center-of-mass!

Typically 2 classes of experiments:

Nanofabricated devices: NOMS version


Nanofabricated devices: NEMS version... moving towards microwave photons!

Reaching the Quantum regime of a macroscopic mechanical object

**Fundamental physics**: quantum mechanics of a macroscopic collective single degree of freedom, here... the center-of-mass!

Quite a few groups along these lines...

Coupling a mechanical mode to a quantum bit: transferring energy coherently to the NEMS, at the single phonon level!

Reaching the Quantum regime of a macroscopic mechanical object

**New type of devices:** New engineering possibilities...

Quantum sensors sensing classical forces: this reaches **the absolute limit** of sensitivity (i.e. Heisenberg’s principle)

Quantum sensors entangled to other quantum objects: **Opens up** completely new possibilities of control!
For mechanics, for hybrid devices with qubits...

End of the story... In 2012