Introduction to microelectromechanical systems

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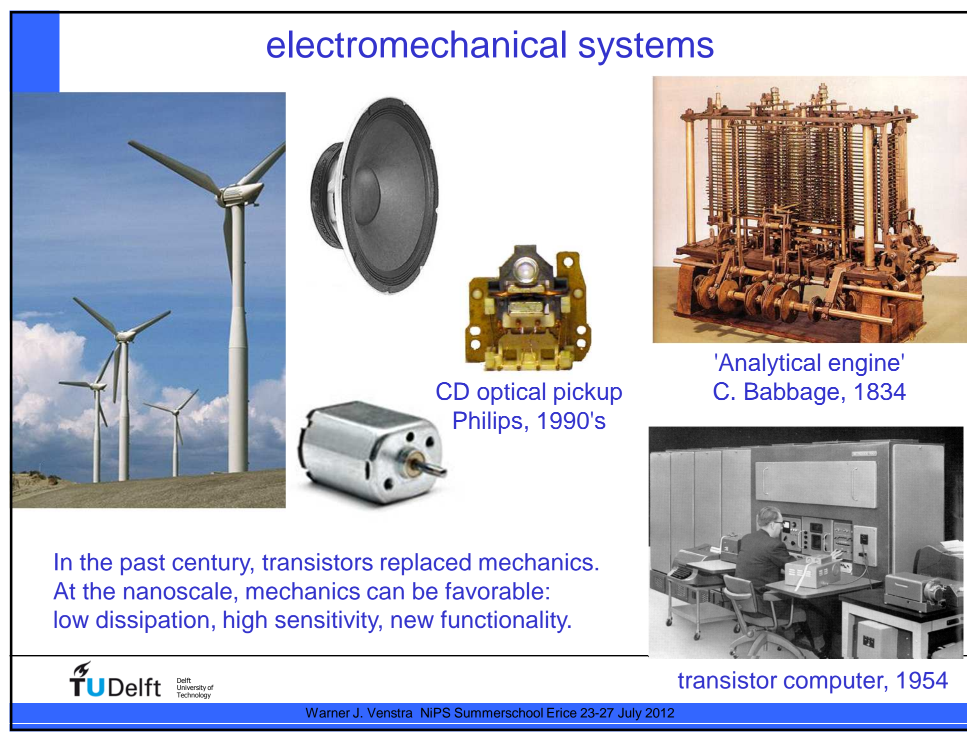
Summerschool ‘Energy harvesting at micro- and nanoscales’
Workshop ‘Energy harvesting: models and applications’
Erice (IT), July 23-27 2012.

I. introduction

II. fabrication and characterization

III. damping and amplification of motion


electromechanical systems
CD optical pickup
Philips, 1990's
'Analytical engine'
C. Babbage, 1834
In the past century, transistors replaced mechanics.
At the nanoscale, mechanics can be favorable:
low dissipation, high sensitivity, new functionality.
transistor computer, 1954
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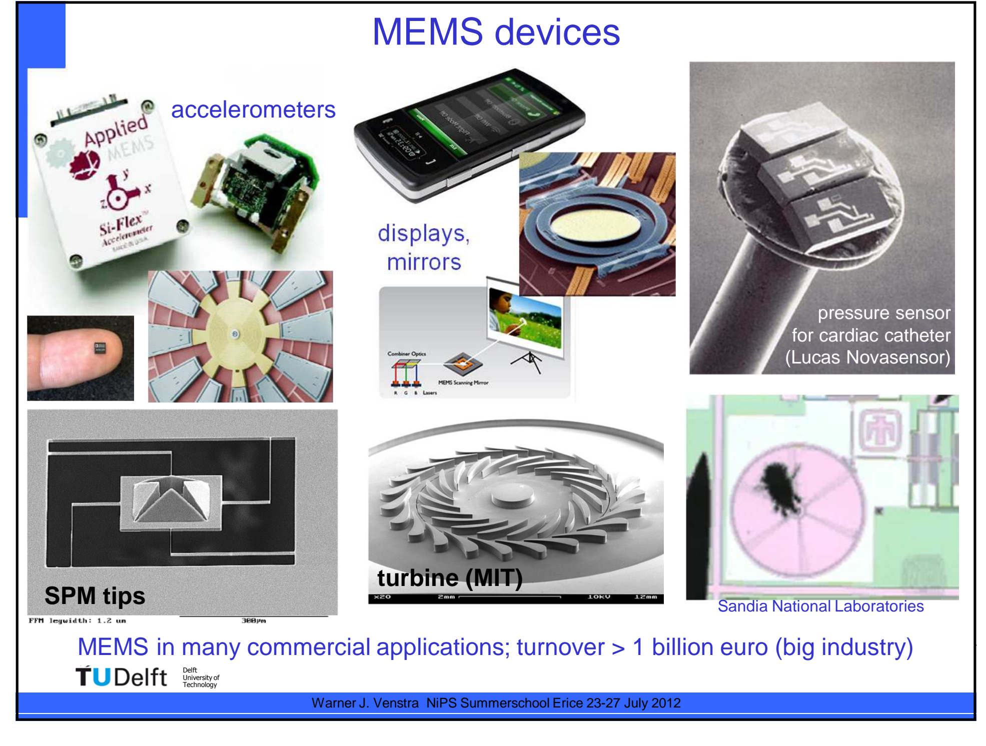
MEMS devices
accelerometers
displays,
mirrors
pressure sensor
for cardiac catheter
(Lucas Novasensor)
SPM tips
turbine (MIT)
Sandia National Laboratories
MEMS in many commercial applications; turnover > 1 billion euro (big industry)
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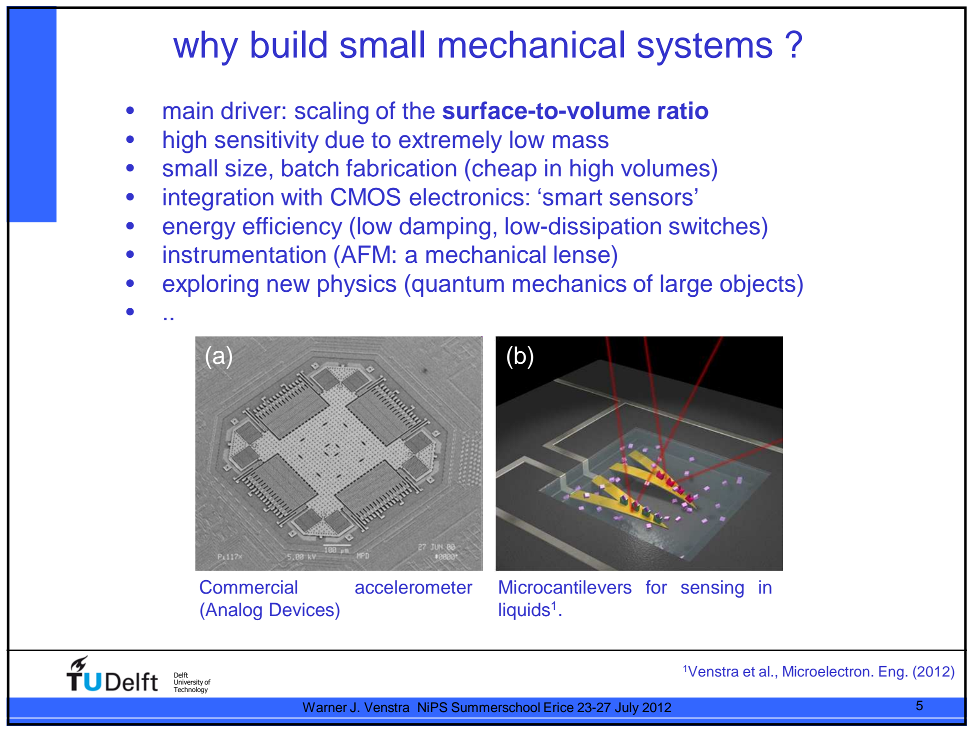
why build small mechanical systems ?
• main driver: scaling of the surface-to-volume ratio
• high sensitivity due to extremely low mass
• small size, batch fabrication (cheap in high volumes)
• integration with CMOS electronics: 'smart sensors'
• energy efficiency (low damping, low-dissipation switches)
• instrumentation (AFM: a mechanical lense)
• exploring new physics (quantum mechanics of large objects)
• ..
(a)
(b)
Commercial accelerometer (Analog Devices)
Microcantilevers for sensing in liquids[1].
[1]Venstra et al., Microelectron. Eng. (2012)
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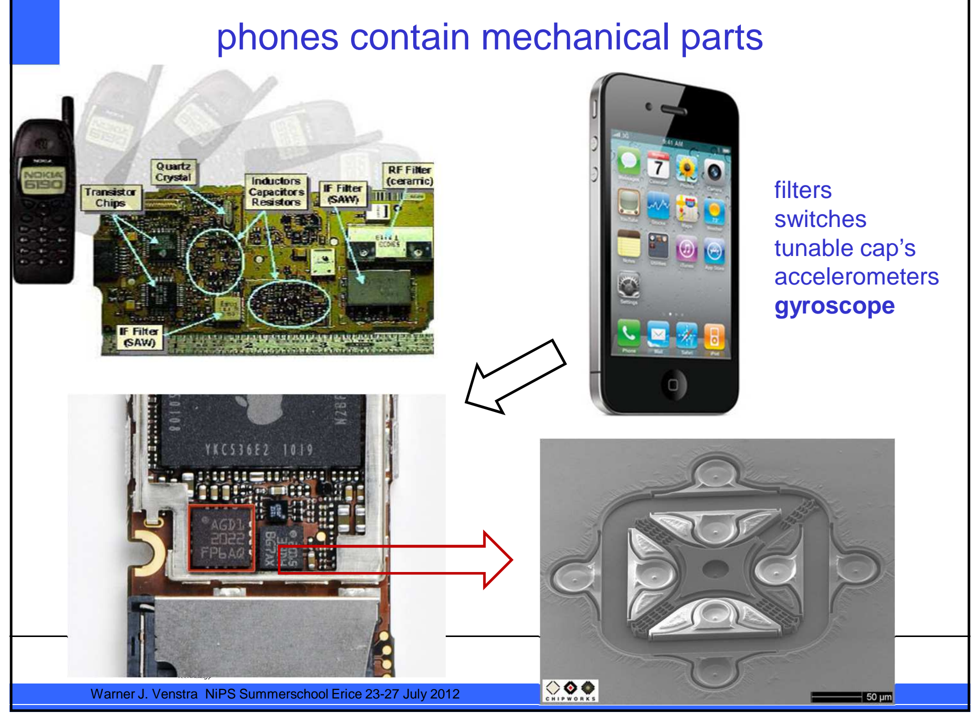
phones contain mechanical parts
Quartz Crystal
Transistor Chips
Inductors Capacitors Resistors
IF Filter (SAW)
RF Filter (ceramic)
IF Filter (SAW)
filters
switches
tunable cap's
accelerometers
gyroscope
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50 µm

top-down and bottom-up fabrication

top-down

1. film deposition
2. patterning
3. etching

many layers, complex structures,
commercial, CMOS-integration,
repeatable (batch fabrication)

bottom-up

1. synthesis
2. (self-) aligment
3. interface

simple, ultra-small/clean structures
one-of-a-kind to study physics
poor control over dimensions

Texas Instruments Digital Mirror Device (pitch 15 µm)

suspended carbon nanotube

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B. Witkamp, Nano Lett. (2008)

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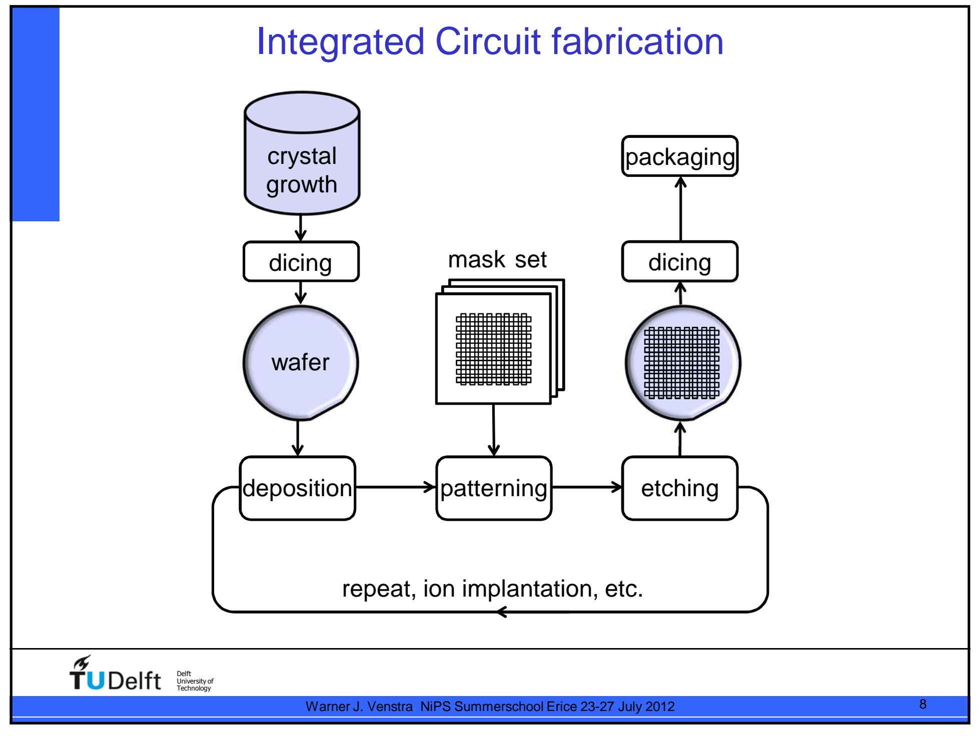

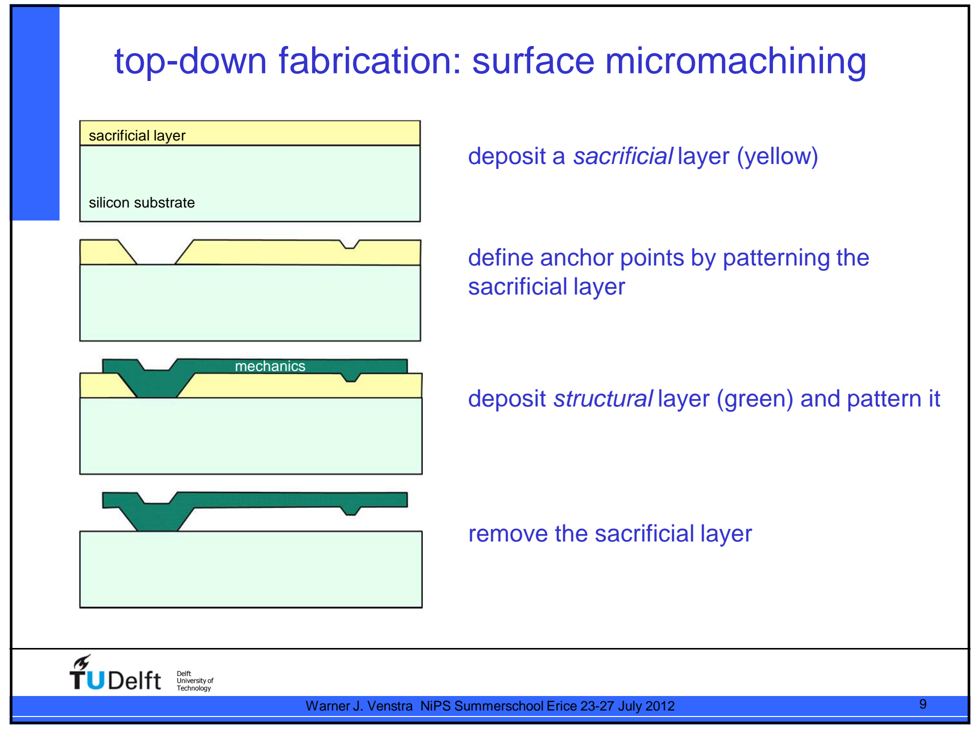
top-down fabrication: surface micromachining
sacrificial layer
silicon substrate
deposit a sacrificial layer (yellow)
define anchor points by patterning the sacrificial layer
mechanics
deposit structural layer (green) and pattern it
remove the sacrificial layer
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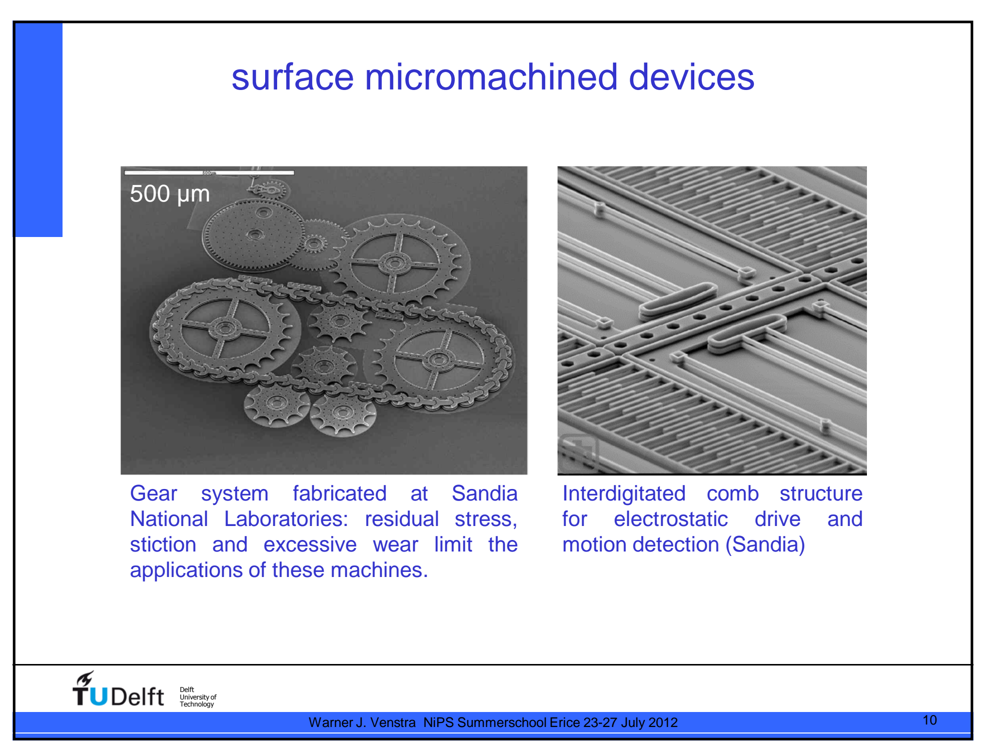
surface micromachined devices
500 µm
Gear system fabricated at Sandia National Laboratories: residual stress, stiction and excessive wear limit the applications of these machines.
Interdigitated comb structure for electrostatic drive and motion detection (Sandia)
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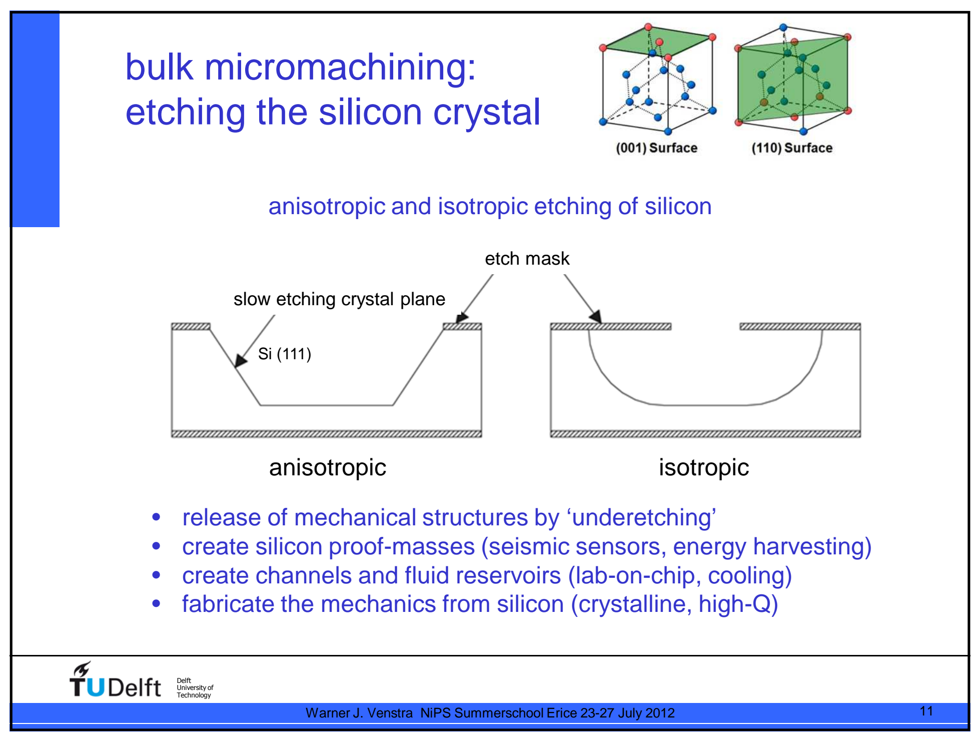
bulk micromachining:
etching the silicon crystal
(001) Surface
(110) Surface
anisotropic and isotropic etching of silicon
etch mask
slow etching crystal plane
Si (111)
anisotropic
isotropic
• release of mechanical structures by 'underetching'
• create silicon proof-masses (seismic sensors, energy harvesting)
• create channels and fluid reservoirs (lab-on-chip, cooling)
• fabricate the mechanics from silicon (crystalline, high-Q)
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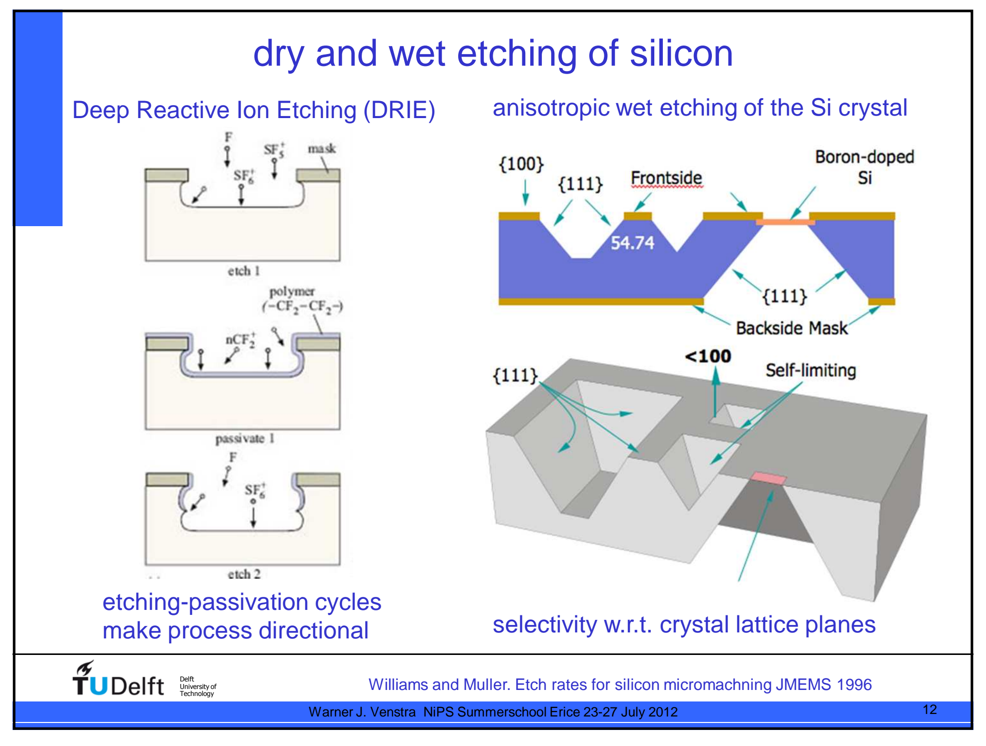
dry and wet etching of silicon
Deep Reactive Ion Etching (DRIE)
anisotropic wet etching of the Si crystal
F
mask
etch 1
polymer
passivate 1
etch 2
{100}
{111}
Frontside
Boron-doped
Si
54.74
{111}
Backside Mask
<100
Self-limiting
{111}
etching-passivation cycles
make process directional
selectivity w.r.t. crystal lattice planes
TU Delft Delft University of Technology
Williams and Muller. Etch rates for silicon micromachning JMEMS 1996
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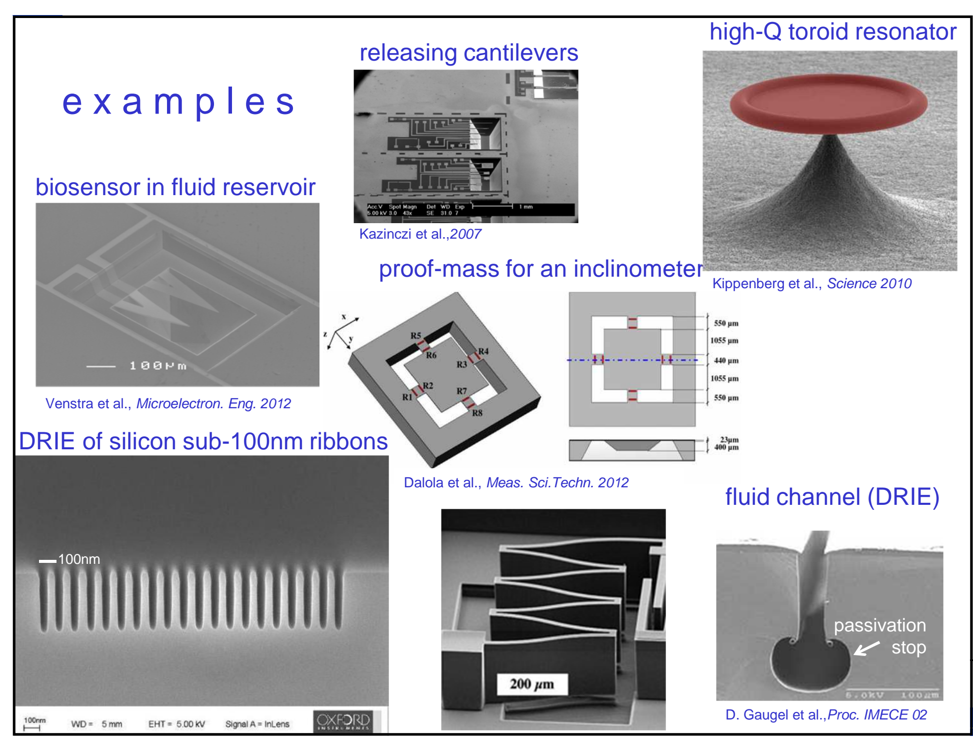
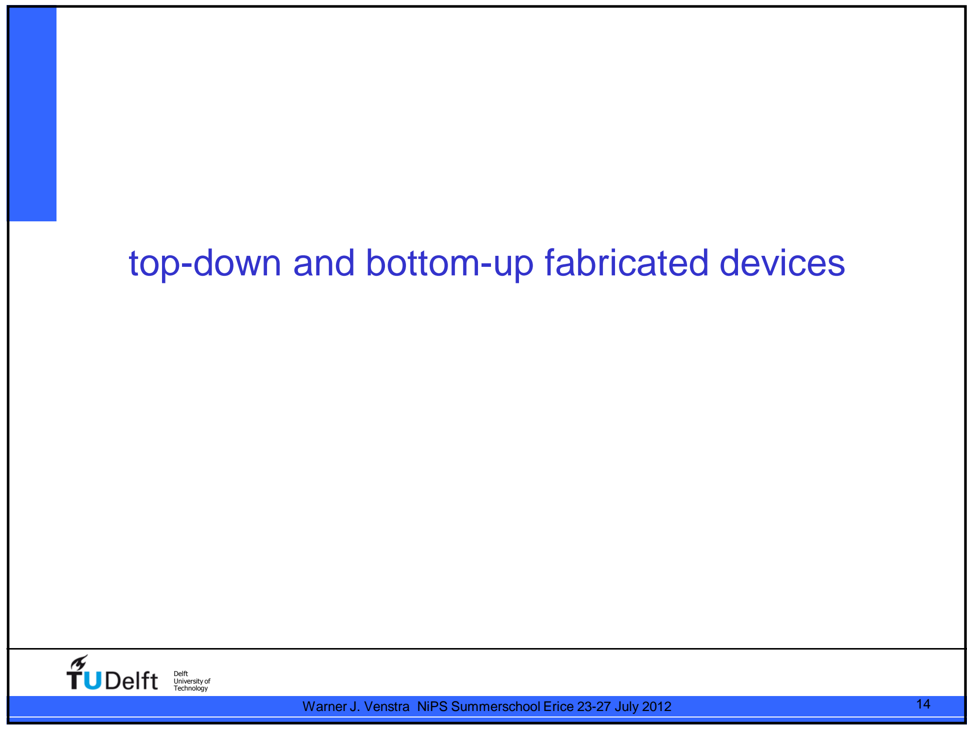

examples
releasing cantilevers
high-Q toroid resonator
biosensor in fluid reservoir
100μm
Kazinczi et al.,2007
proof-mass for an inclinometer
Kippenberg et al., Science 2010
Venstra et al., Microelectron. Eng. 2012
DRIE of silicon sub-100nm ribbons
100nm
Dalola et al., Meas. Sci.Techn. 2012
fluid channel (DRIE)
200 μm
passivation
stop
D. Gaugel et al.,Proc. IMECE 02


top-down and bottom-up fabricated devices
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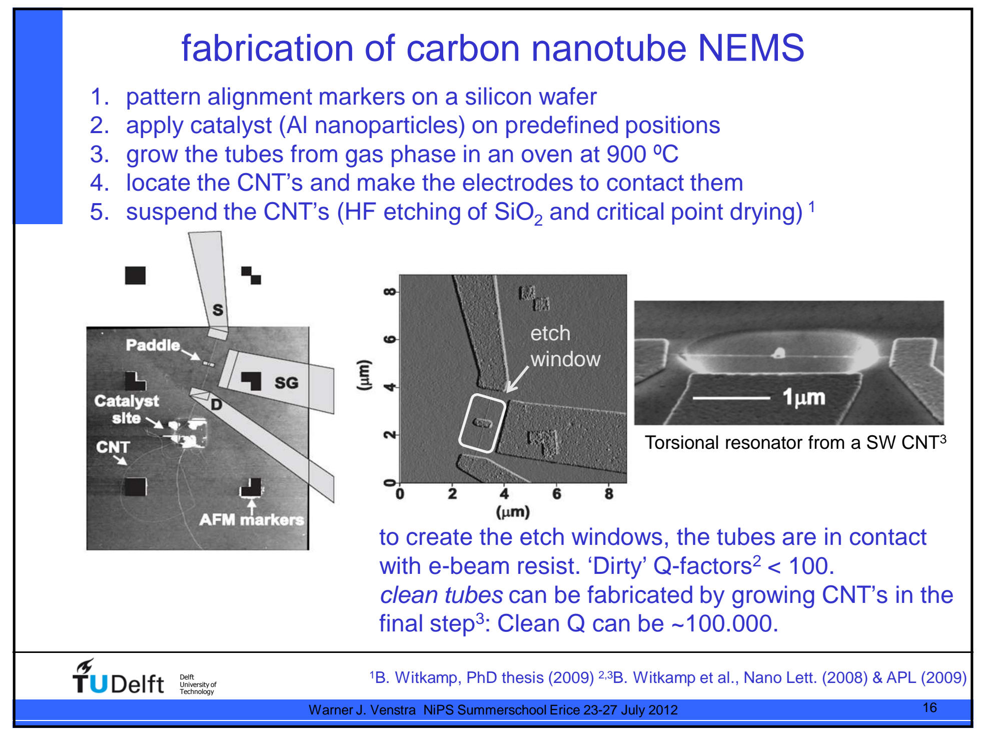
bottom up: NEMS with a carbon nanotube

- extraordinary Young's modulus: ~1.2 TPa
- very low bending rigidity (d = 2 nm)
- smooth on atomic level: high-Q
- large thermal / zero-point fluctuations:
- route to quantum nanomechanics
- mass sensing at unprecedented resolution
- tunable over a wide range (gate)
- defect-free

S. Sapmaz et al. PRB 67 (2003)

fabrication of carbon nanotube NEMS

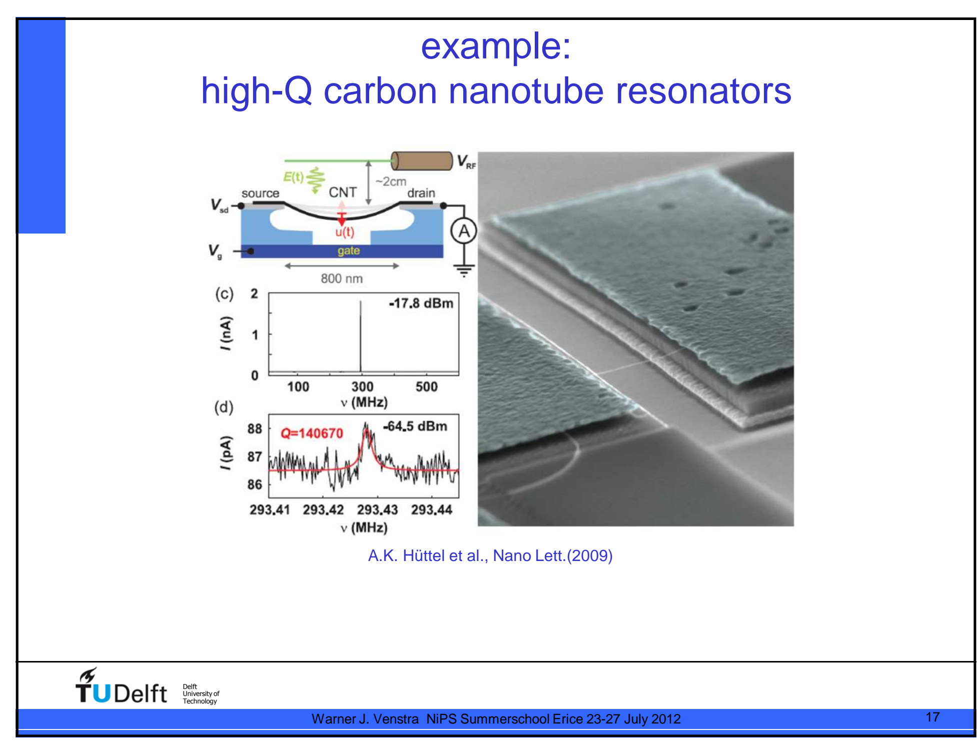
1. pattern alignment markers on a silicon wafer
2. apply catalyst (Al nanoparticles) on predefined positions
3. grow the tubes from gas phase in an oven at 900 ºC
4. locate the CNT's and make the electrodes to contact them
5. suspend the CNT's (HF etching of SiO_2 and critical point drying) [1]



Torsional resonator from a SW CNT[3]

to create the etch windows, the tubes are in contact with e-beam resist. 'Dirty' Q-factors[2] < 100.
clean tubes can be fabricated by growing CNT's in the final step[3]: Clean Q can be ~100.000.

[1]B. Witkamp, PhD thesis (2009) [2,3]B. Witkamp et al., Nano Lett. (2008) & APL (2009)


example:
high-Q carbon nanotube resonators
source
CNT
drain
gate
800 nm
~2cm
u(t)
-17.8 dBm
Q=140670
-64.5 dBm
I (nA)
I (pA)
ν (MHz)
A.K. Hüttel et al., Nano Lett.(2009)
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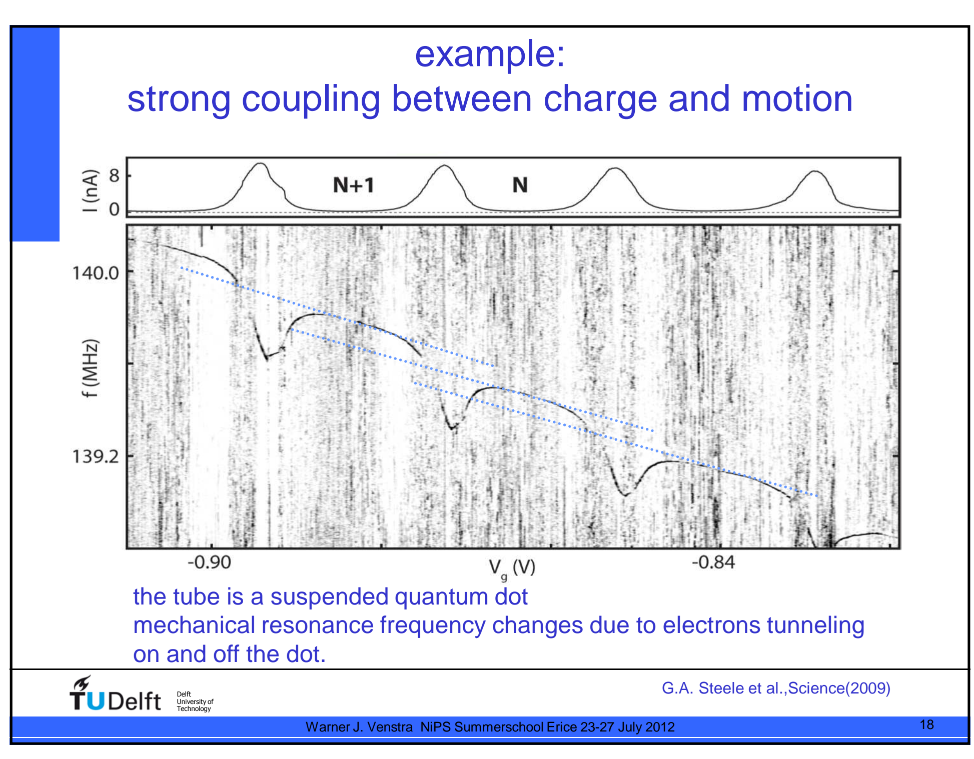
example:
strong coupling between charge and motion
N+1
N
I (nA)
f (MHz)
140.0
139.2
-0.90
-0.84
the tube is a suspended quantum dot
mechanical resonance frequency changes due to electrons tunneling on and off the dot.
G.A. Steele et al.,Science(2009)
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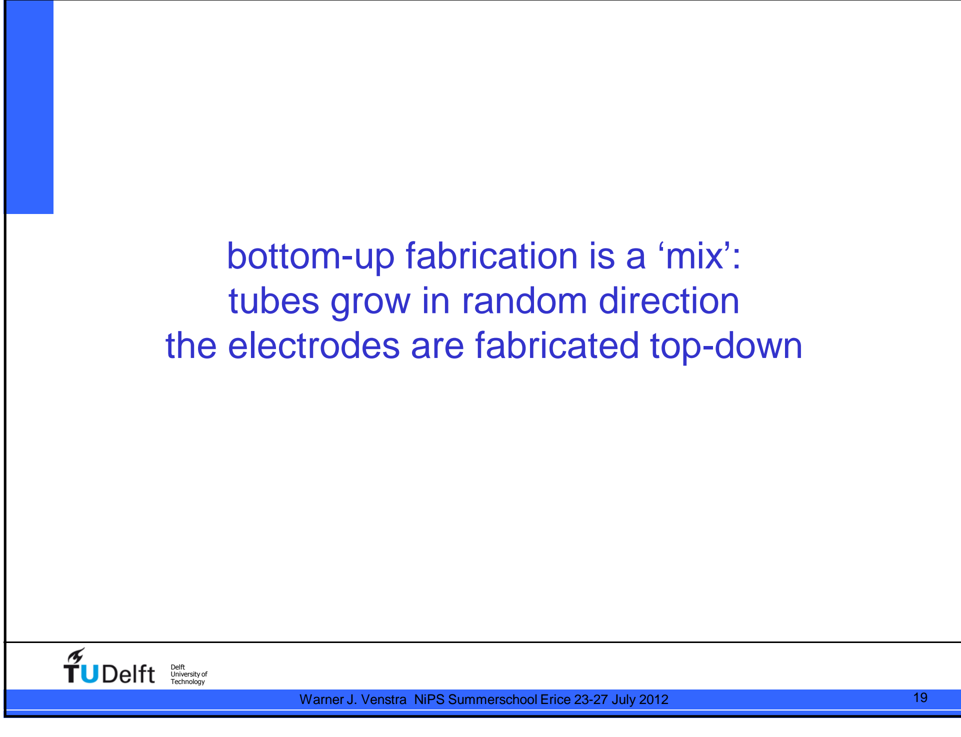
bottom-up fabrication is a 'mix':
tubes grow in random direction
the electrodes are fabricated top-down
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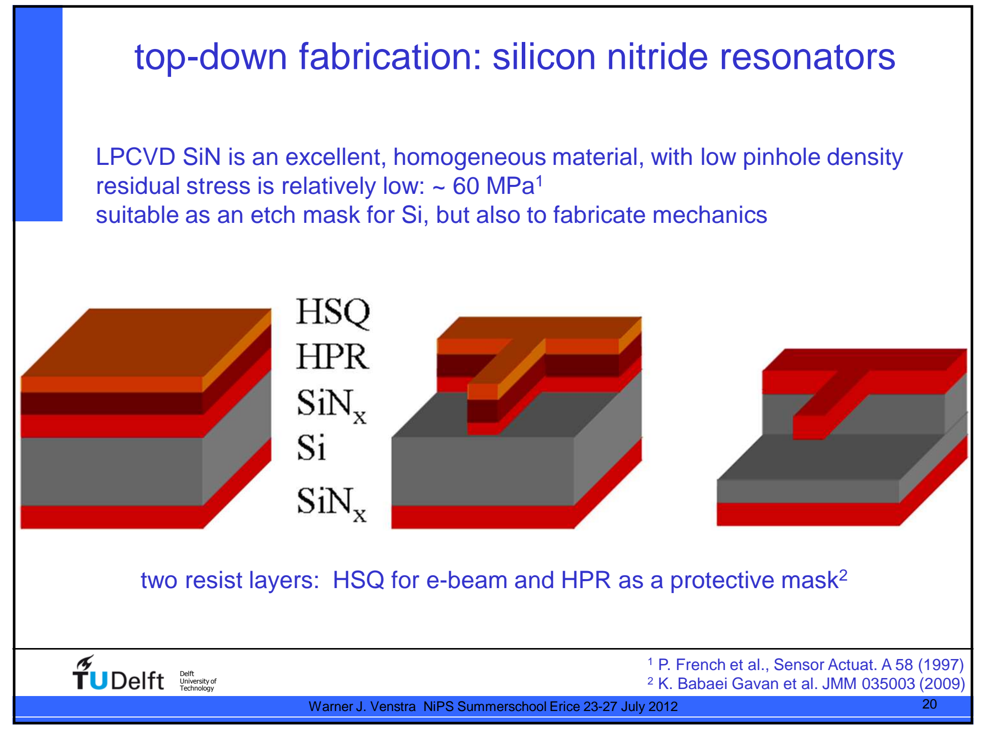
top-down fabrication: silicon nitride resonators
LPCVD SiN is an excellent, homogeneous material, with low pinhole density
residual stress is relatively low: ~ 60 MPa1
suitable as an etch mask for Si, but also to fabricate mechanics
HSQ
HPR
SiNx
Si
SiNx
two resist layers: HSQ for e-beam and HPR as a protective mask2
1 P. French et al., Sensor Actuat. A 58 (1997)
2 K. Babaei Gavan et al. JMM 035003 (2009)
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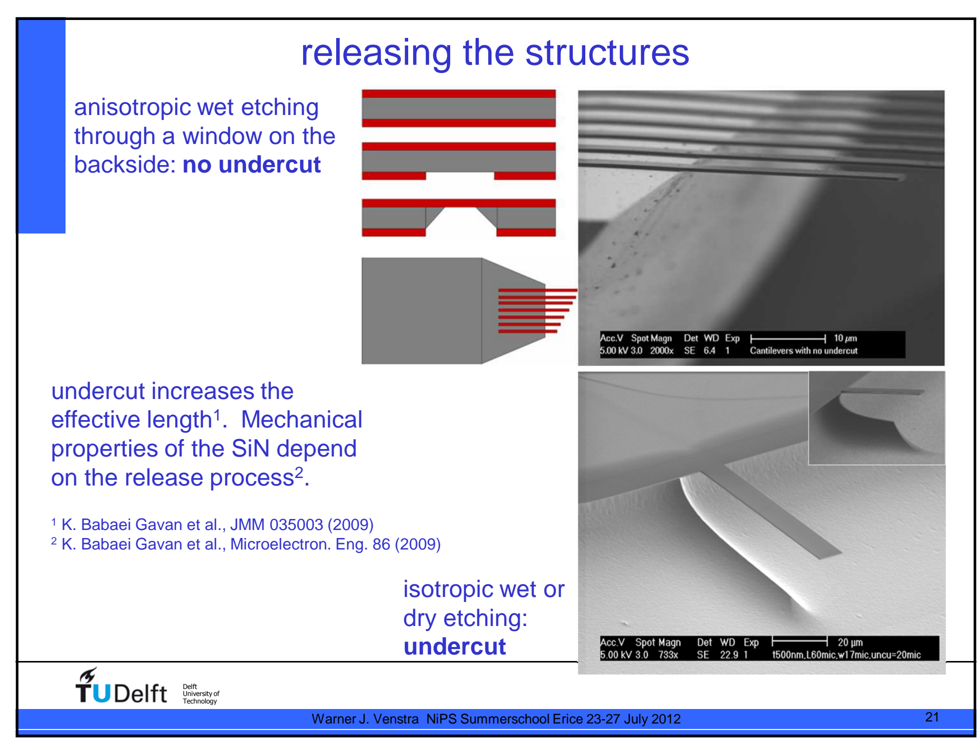
releasing the structures
anisotropic wet etching through a window on the backside: **no undercut**
Acc.V Spot Magn Det WD Exp 10 μm
5.00 kV 3.0 2000x SE 6.4 1 Cantilevers with no undercut
undercut increases the effective length[1]. Mechanical properties of the SiN depend on the release process[2].
[1] K. Babaei Gavan et al., JMM 035003 (2009)
[2] K. Babaei Gavan et al., Microelectron. Eng. 86 (2009)
isotropic wet or dry etching: **undercut**
Acc.V Spot Magn Det WD Exp 20 μm
5.00 kV 3.0 733x SE 22.9 1 t500nm,L60mic,w17mic,uncu=20mic
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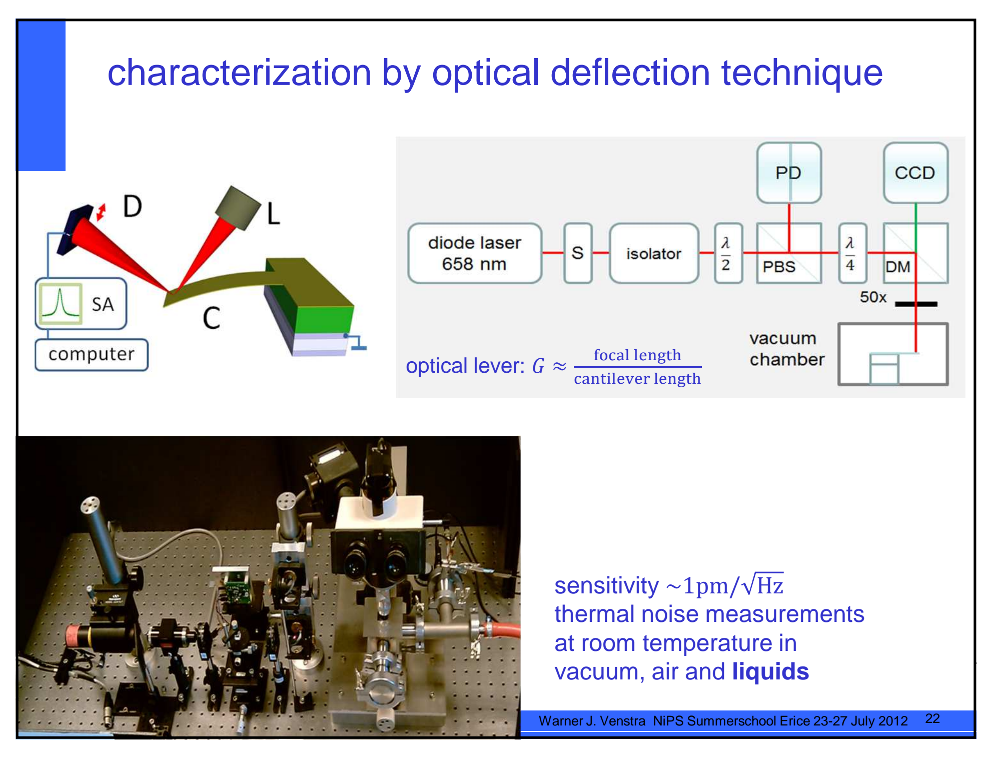
characterization by optical deflection technique
D
L
SA
C
computer
PD
CCD
diode laser
658 nm
S
isolator
λ/2
PBS
λ/4
DM
50x
vacuum
chamber
optical lever: $G \approx \frac{\text{focal length}}{\text{cantilever length}}$
sensitivity $\sim 1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
thermal noise measurements at room temperature in vacuum, air and **liquids**
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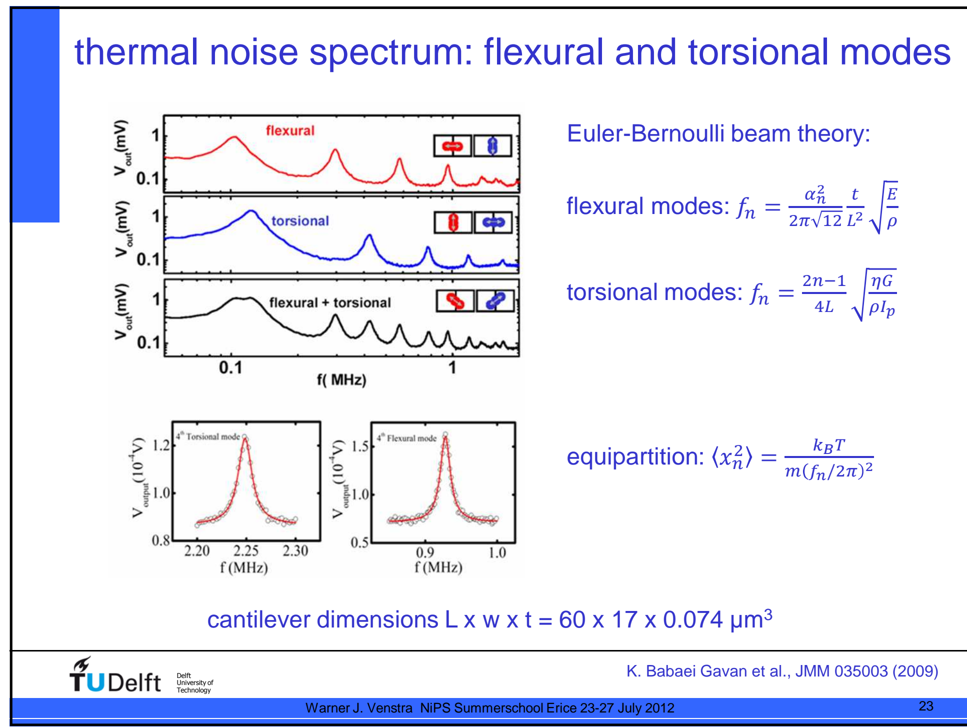
thermal noise spectrum: flexural and torsional modes
flexural
torsional
flexural + torsional
V_{out}(mV)
f(MHz)
f (MHz)
Euler-Bernoulli beam theory:
flexural modes: $f_n = \frac{\alpha_n^2}{2\pi\sqrt{12}} \frac{t}{L^2} \sqrt{\frac{E}{\rho}}$
torsional modes: $f_n = \frac{2n-1}{4L} \sqrt{\frac{\eta G}{\rho I_p}}$
equipartition: $\langle x_n^2 \rangle = \frac{k_B T}{m(f_n/2\pi)^2}$
cantilever dimensions L x w x t = 60 x 17 x 0.074 μm³
K. Babaei Gavan et al., JMM 035003 (2009)
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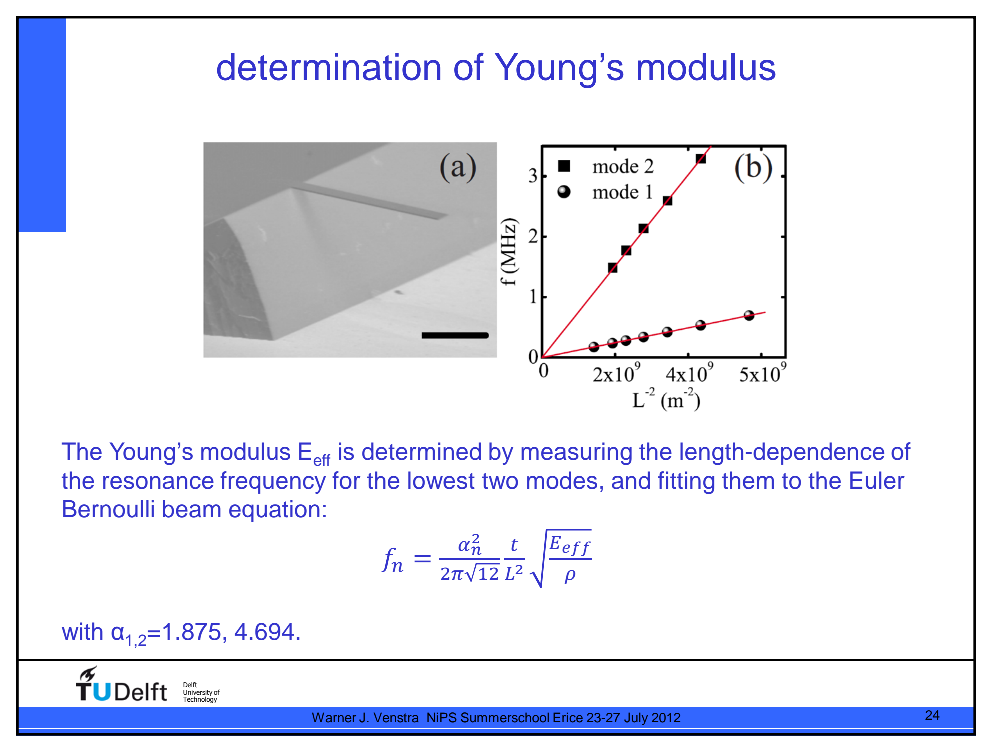
determination of Young's modulus
(a)
(b)
mode 2
mode 1
f (MHz)
L^{-2} (m^{-2})
The Young's modulus E_{eff} is determined by measuring the length-dependence of the resonance frequency for the lowest two modes, and fitting them to the Euler Bernoulli beam equation:
$f_n = \frac{\alpha_n^2}{2\pi\sqrt{12}} \frac{t}{L^2} \sqrt{\frac{E_{eff}}{\rho}}$
with $\alpha_{1,2}$=1.875, 4.694.
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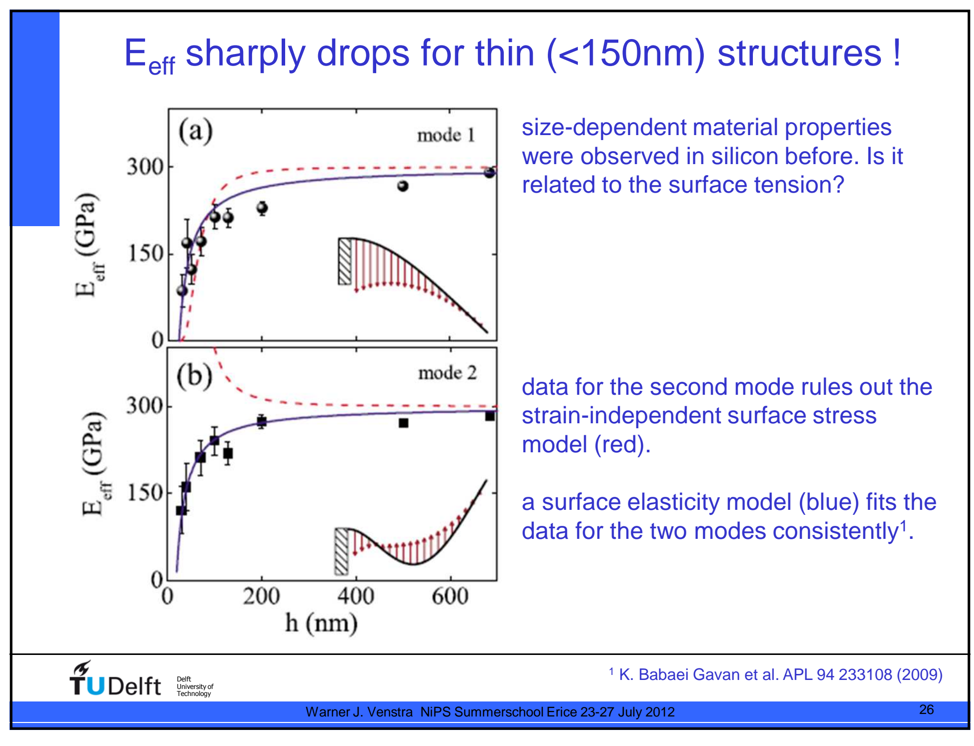
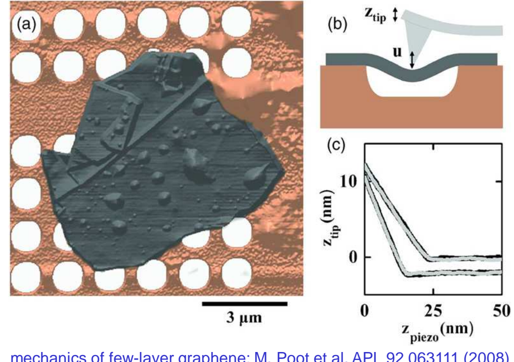
In thin devices, the surface free-energy[1] should give rise to a decrease in the observed Young's modulus

[1]energy to create a surface out of the bulk, in liquids known as surface tension



surface tension studies require thinner and more homogeneous structures: few-layer graphene?



mechanics of few-layer graphene: M. Poot et al. APL 92 063111 (2008)

small dimensions → large tolerances

poorly defined mechanics[1] due to:

- undercut
- process-dependent material props
- inhomogeneity across the thickness of deposited layers
- surface elasticity
- residual stress gradients
- bad definition of clamps (cnt's, Si beams)
- creep and relaxation ('burn-in')
- geometric effects due to pattern transfer
- ...

tolerance (relative uncertainty in the dimensions) increases upon scaling down

but: easy tuning since small systems are compliant and couple strongly

on-chip calibration in applications such as resonant sensors, mirror devices, air-bag sensors etc.

imperfections break the symmetry, and become important when designing mechanical systems with low energy barriers such as switches

[1] briefly reviewed in R. van Leeuwen et al., JMM 075011 (2011)

a route towards well-defined micromechanics

Silicon wafers are typically diced along the (100) surface;
when diced along (110), the (111) sidewalls are vertical.

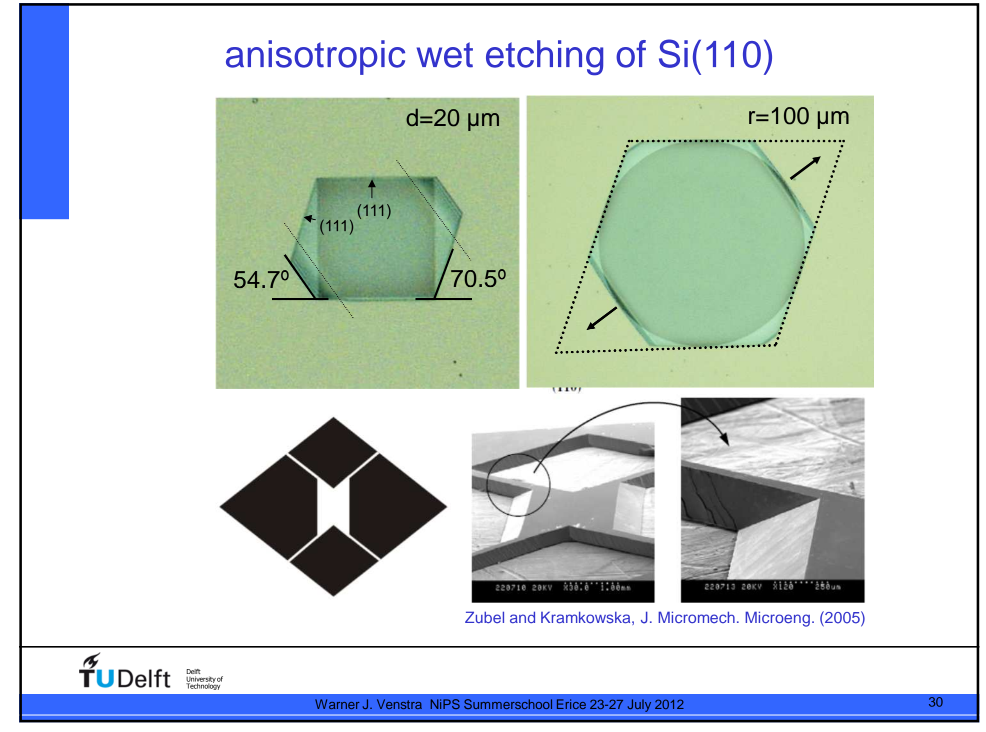
high aspect-ratio, well-defined geometry and clamps, low surface roughness

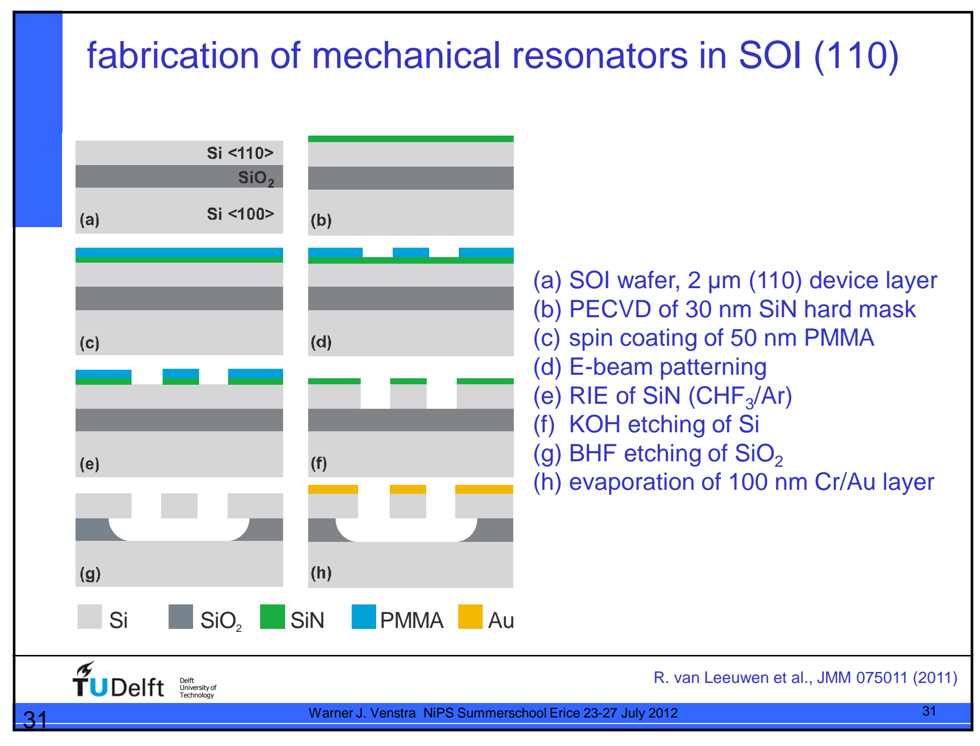
IOP PUBLISHING JOURNAL OF MICROMECHANICS AND MICROENGINEERING
J. Micromech. Microeng. **21** (2011) 075011 (5pp) doi:10.1088/0960-1317/21/7/075011

Fabrication of tunable clamped–clamped microresonators in silicon (1 1 0)

R van Leeuwen, P H R Lew, E W J M van der Drift, H S J van der Zant and W J Venstra

Kavli Institute of Nanoscience, Lorentzweg 1, 2628CJ Delft, The Netherlands




fabrication of mechanical resonators in SOI (110)
Si <110>
SiO_2
Si <100>
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(a) SOI wafer, 2 μm (110) device layer
(b) PECVD of 30 nm SiN hard mask
(c) spin coating of 50 nm PMMA
(d) E-beam patterning
(e) RIE of SiN (CHF_3/Ar)
(f) KOH etching of Si
(g) BHF etching of SiO_2
(h) evaporation of 100 nm Cr/Au layer
Si
SiO_2
SiN
PMMA
Au
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R. van Leeuwen et al., JMM 075011 (2011)
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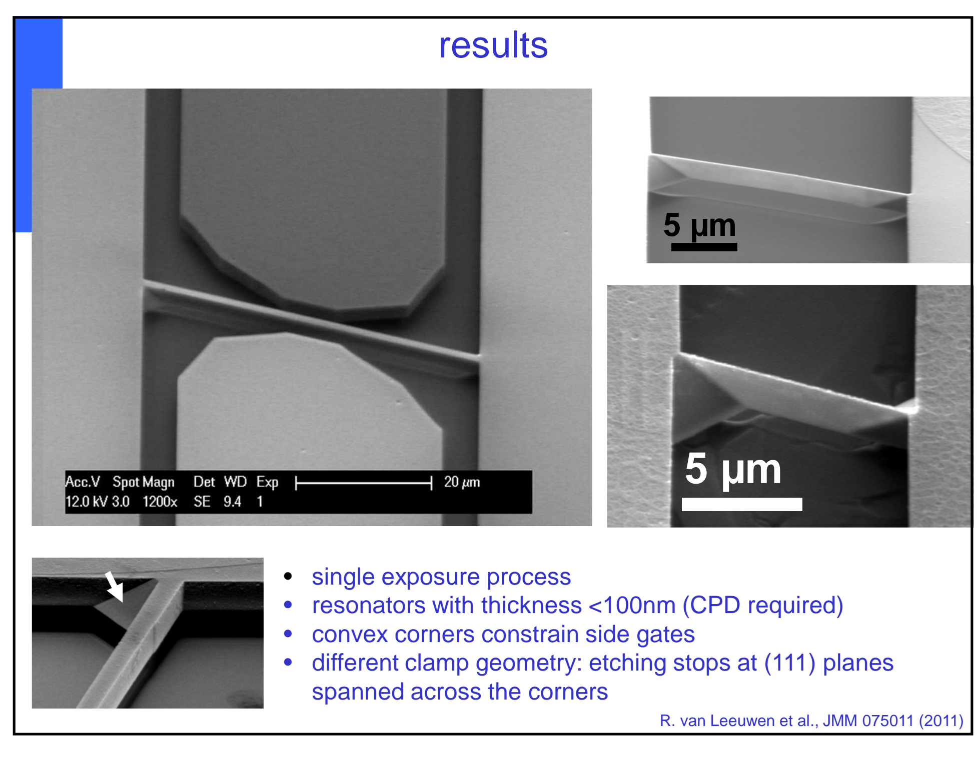

results
Acc.V Spot Magn Det WD Exp 20 μm
12.0 kV 3.0 1200x SE 9.4 1
5 μm
5 μm
single exposure process
resonators with thickness <100nm (CPD required)
convex corners constrain side gates
different clamp geometry: etching stops at (111) planes spanned across the corners
R. van Leeuwen et al., JMM 075011 (2011)

characterization

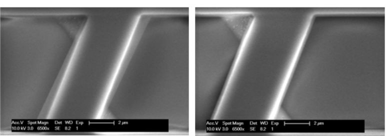
composite beam: $f_n = \frac{\alpha_n^2}{2\pi L^2}\sqrt{\frac{\sum_i E_i I_i}{\sum_i \rho_i A_i}}$

i: layer index
E_i: Young's modulus
I_i: moment of inertia ($I = \frac{wt^3}{12}$)
ρ_i: mass density
A_i: cross section area

For L × w × t = 150× 1.6 × 2 μm^3, the calculated frequencies are:
f_1=500 kHz; f3=2.70 MHz. The measured ones are f1=513 kHz; f3=2.76 MHz.

- clamped-clamped resonators in SOI (110): stress-free crystals, smooth sidewalls
- critical geometry is determined by slowly etching (111) planes
- gate-tuning over a few percent

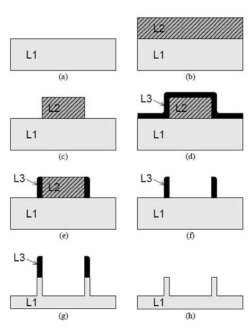
accuracy frequency of the devices matches the calculation within 5 %

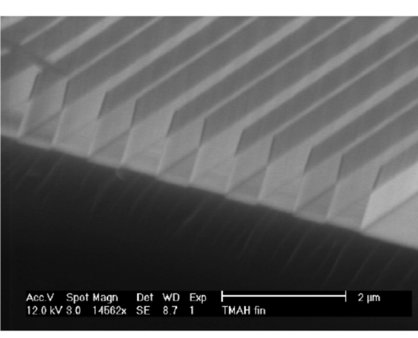


critical parameter: alignment between mask and crystal lattice

self-aligned mask

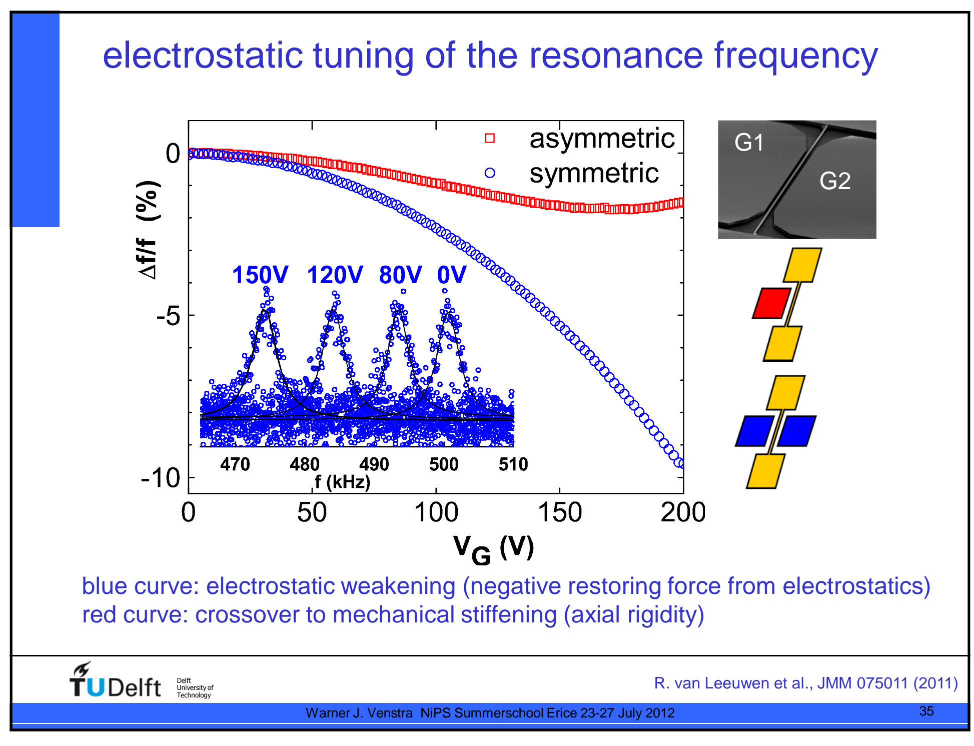
define the mask on a (111) sidewall (cf. 10nm Fin-FET's)





V. Jovanović et al., 2002

a 'suspended fin' resonator
challenge: definition of clamping points


electrostatic tuning of the resonance frequency
asymmetric
symmetric
Δf/f (%)
0
-5
-10
150V 120V 80V 0V
470 480 490 500 510
f (kHz)
0 50 100 150 200
VG (V)
G1
G2
blue curve: electrostatic weakening (negative restoring force from electrostatics)
red curve: crossover to mechanical stiffening (axial rigidity)
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R. van Leeuwen et al., JMM 075011 (2011)
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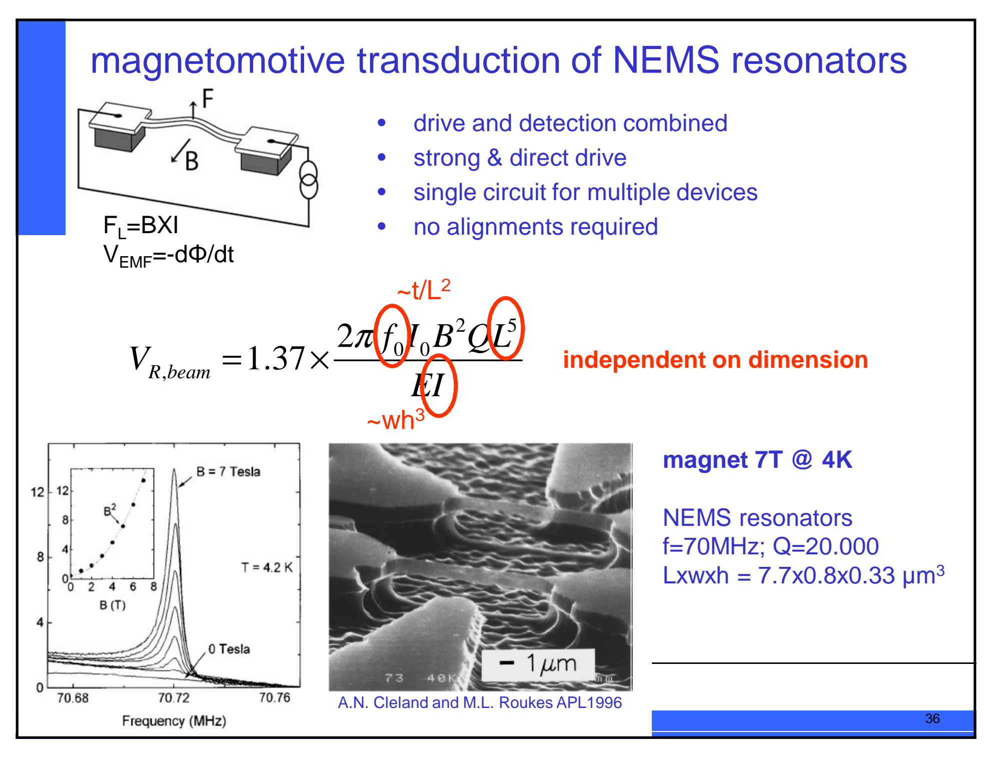
magnetomotive transduction of NEMS resonators
F
B
F_L=BXI
V_EMF=-dΦ/dt
drive and detection combined
strong & direct drive
single circuit for multiple devices
no alignments required
~t/L²
$V_{R,beam} = 1.37 \times \frac{2\pi f_0 I_0 B^2 Q L^5}{EI}$
~wh³
independent on dimension
B = 7 Tesla
T = 4.2 K
0 Tesla
B²
B (T)
Frequency (MHz)
70.68 70.72 70.76
1 μm
A.N. Cleland and M.L. Roukes APL1996
magnet 7T @ 4K
NEMS resonators
f=70MHz; Q=20.000
Lxwxh = 7.7x0.8x0.33 μm³
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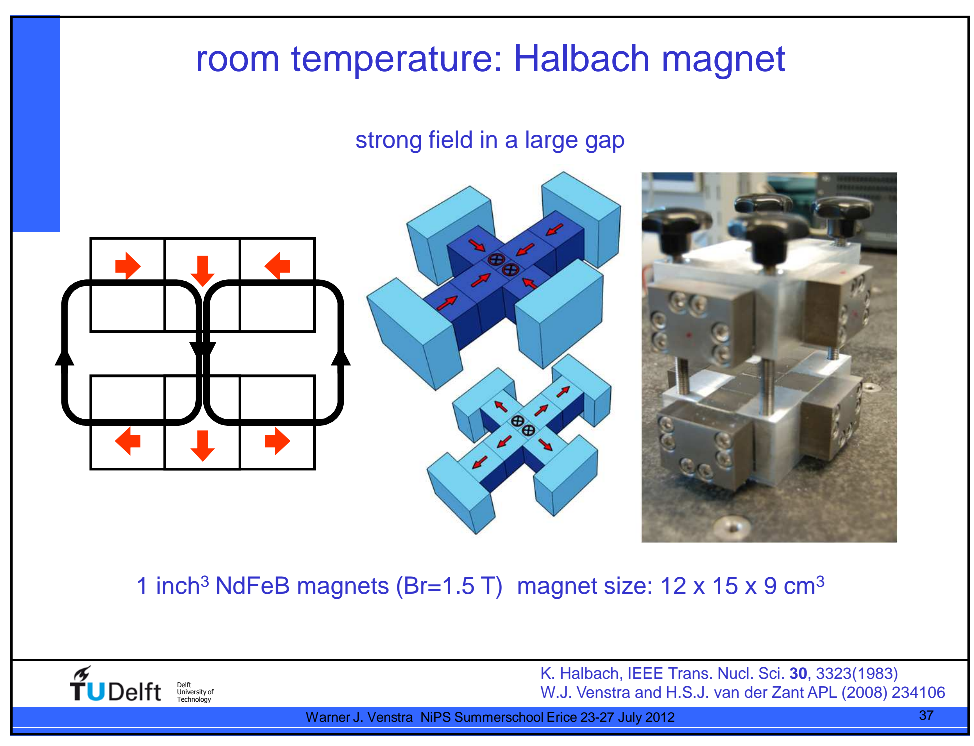
room temperature: Halbach magnet
strong field in a large gap
1 inch³ NdFeB magnets (Br=1.5 T) magnet size: 12 x 15 x 9 cm³
K. Halbach, IEEE Trans. Nucl. Sci. 30, 3323(1983)
W.J. Venstra and H.S.J. van der Zant APL (2008) 234106
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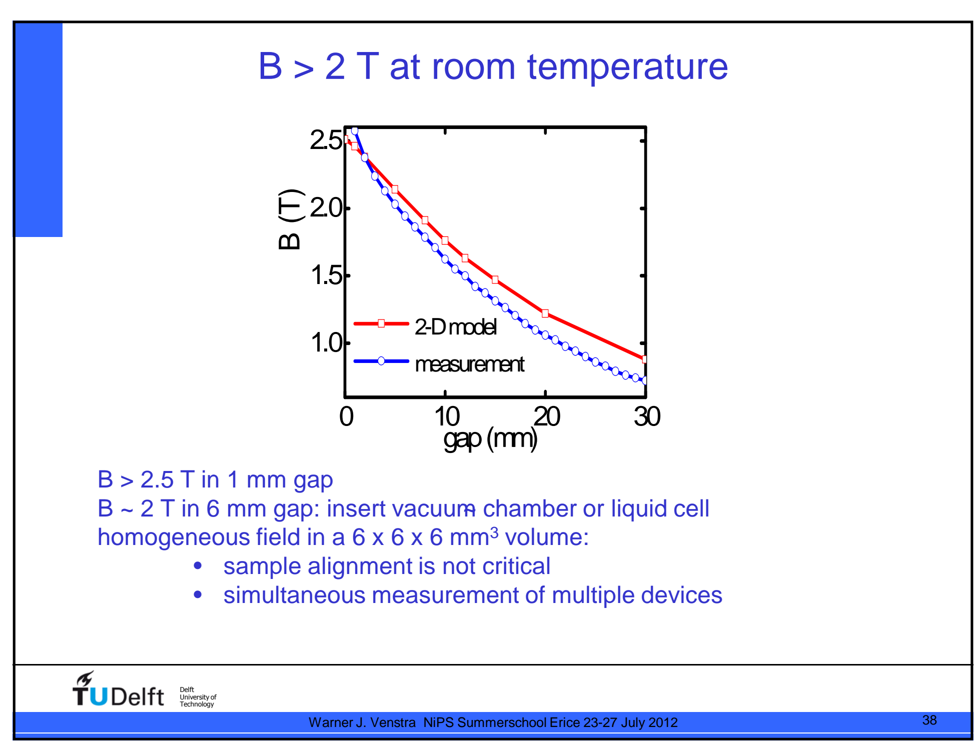
B > 2 T at room temperature
2.5
2.0
1.5
1.0
B (T)
0
10
20
30
gap (mm)
2-D model
measurement
B > 2.5 T in 1 mm gap
B ~ 2 T in 6 mm gap: insert vacuum chamber or liquid cell
homogeneous field in a 6 x 6 x 6 mm³ volume:
• sample alignment is not critical
• simultaneous measurement of multiple devices
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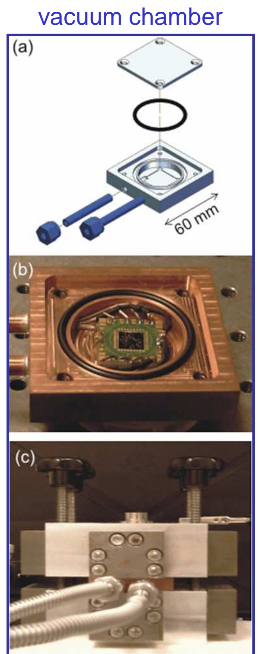
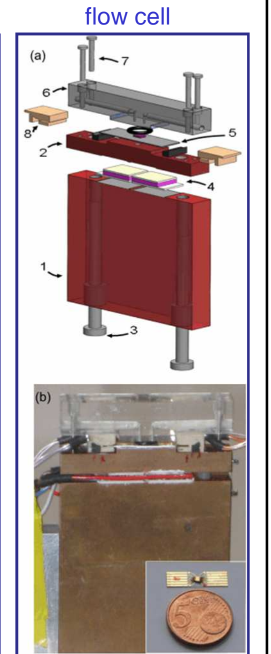
motion detection in vacuum air liquids

- thermal noise in vacuum
- in water: strong driving
- nonlinear behavior
- readout of resonator arrays

vacuum chamber



flow cell



summary

- fabrication technologies: top-down and bottom-up
- unique property: large surface-to-volume ratio
- small-scale mechanics: large tolerances
- detection methods:
  - *electrostatic mixing (CNT's)*
  - *optical deflection*
  - *magnetomotive*
  - *on-chip piezoelectric transducers*
  - *capacitive*
- growing number of applications
  - *instrumentation*
  - *signal processing*

damping and amplification of motion in micromechanical resonators

I. damping mechanisms in mechanical resonators
   - dissipation to environment
   - internal damping

II. modifcation of the damping in mechanical resonators
   - parametric excitation
   - external feedback

III. damping and amplifcation via coupled modes

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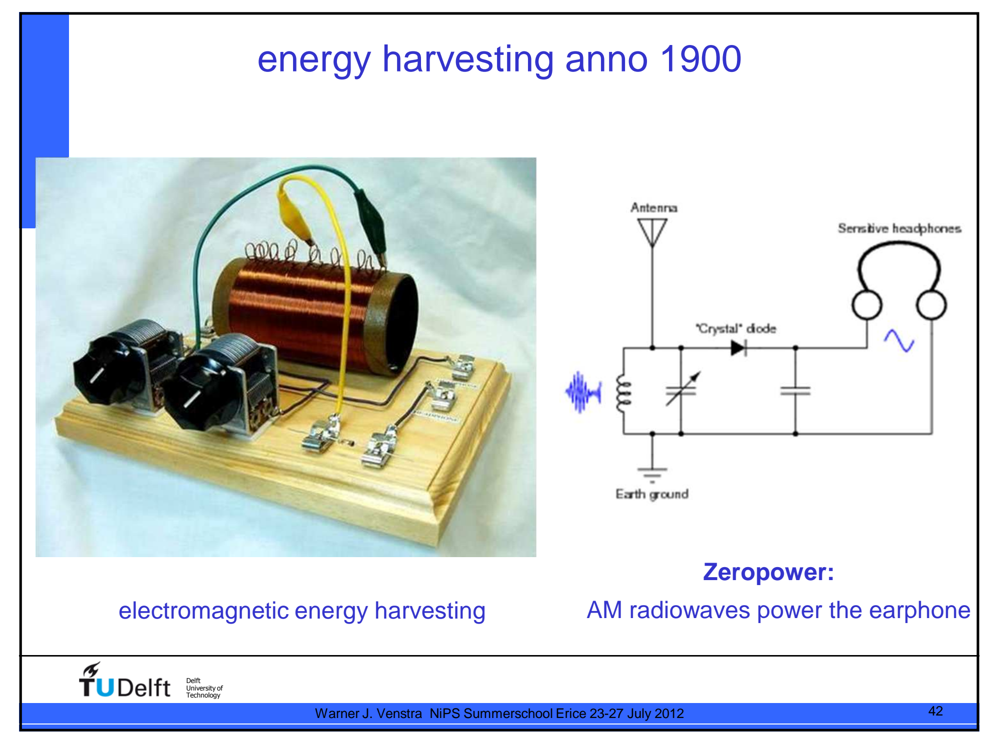

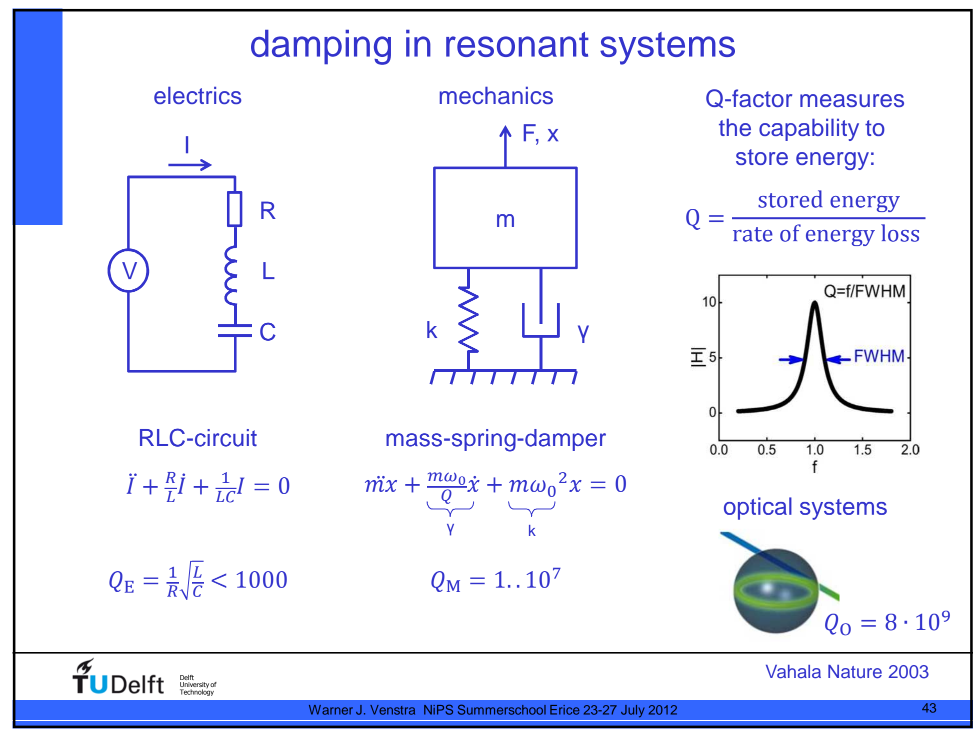

damping in resonant systems
electrics
mechanics
Q-factor measures the capability to store energy:
$Q = \frac{\text{stored energy}}{\text{rate of energy loss}}$
I
R
L
C
V
F, x
m
k
γ
Q=f/FWHM
FWHM
|H|
f
RLC-circuit
mass-spring-damper
$\ddot{I} + \frac{R}{L}\dot{I} + \frac{1}{LC}I = 0$
$m\ddot{x} + \frac{m\omega_0}{Q}\dot{x} + m{\omega_0}^2 x = 0$
optical systems
$Q_E = \frac{1}{R}\sqrt{\frac{L}{C}} < 1000$
$Q_M = 1..10^7$
$Q_O = 8 \cdot 10^9$
Vahala Nature 2003
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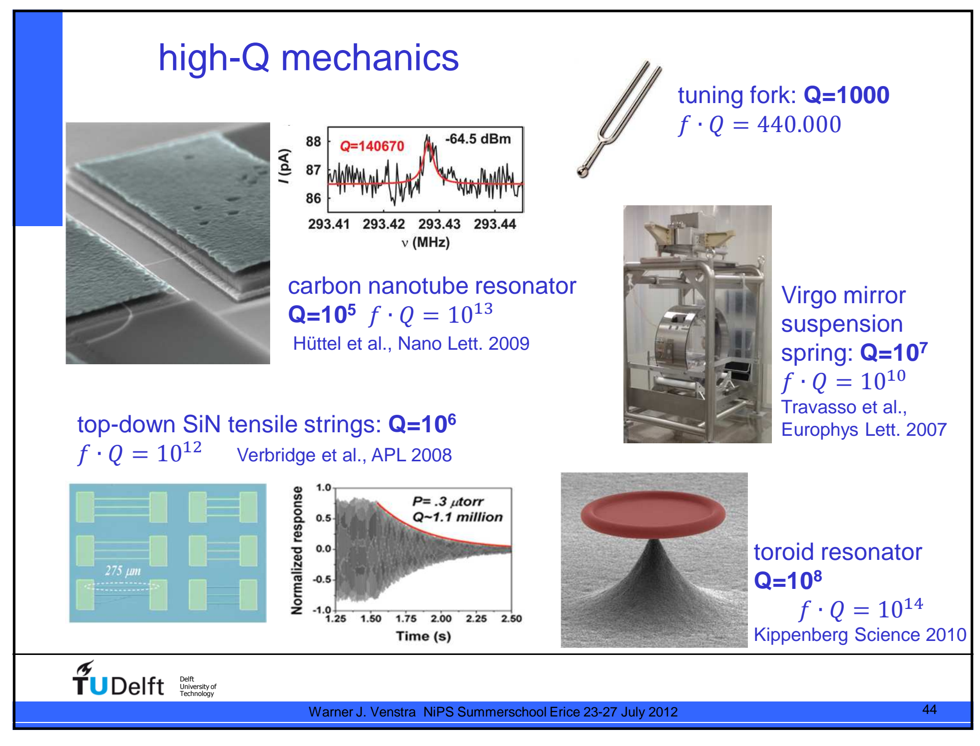

high-Q mechanics
tuning fork: Q=1000
$f \cdot Q = 440.000$
Q=140670
-64.5 dBm
I (pA)
ν (MHz)
carbon nanotube resonator
Q=10^5 $f \cdot Q = 10^{13}$
Hüttel et al., Nano Lett. 2009
Virgo mirror suspension spring: Q=10^7
$f \cdot Q = 10^{10}$
Travasso et al., Europhys Lett. 2007
top-down SiN tensile strings: Q=10^6
$f \cdot Q = 10^{12}$
Verbridge et al., APL 2008
275 μm
P= .3 μtorr
Q~1.1 million
Normalized response
Time (s)
toroid resonator
Q=10^8
$f \cdot Q = 10^{14}$
Kippenberg Science 2010
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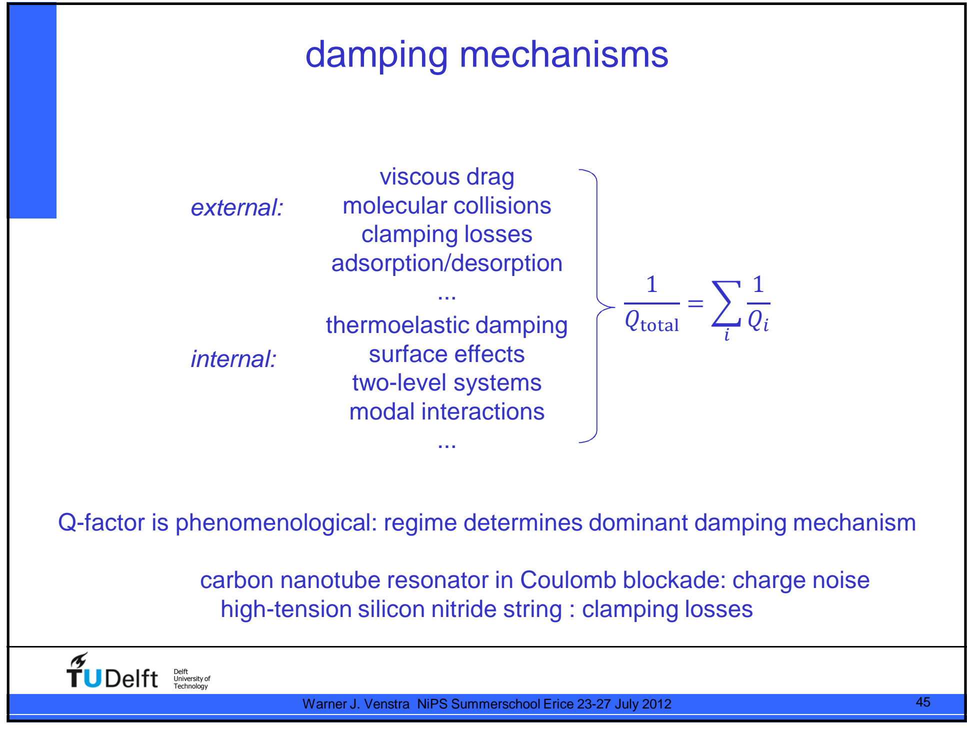
damping mechanisms
external:
viscous drag
molecular collisions
clamping losses
adsorption/desorption
...
thermoelastic damping
internal:
surface effects
two-level systems
modal interactions
...
$\frac{1}{Q_{\text{total}}} = \sum_i \frac{1}{Q_i}$
Q-factor is phenomenological: regime determines dominant damping mechanism
carbon nanotube resonator in Coulomb blockade: charge noise
high-tension silicon nitride string : clamping losses
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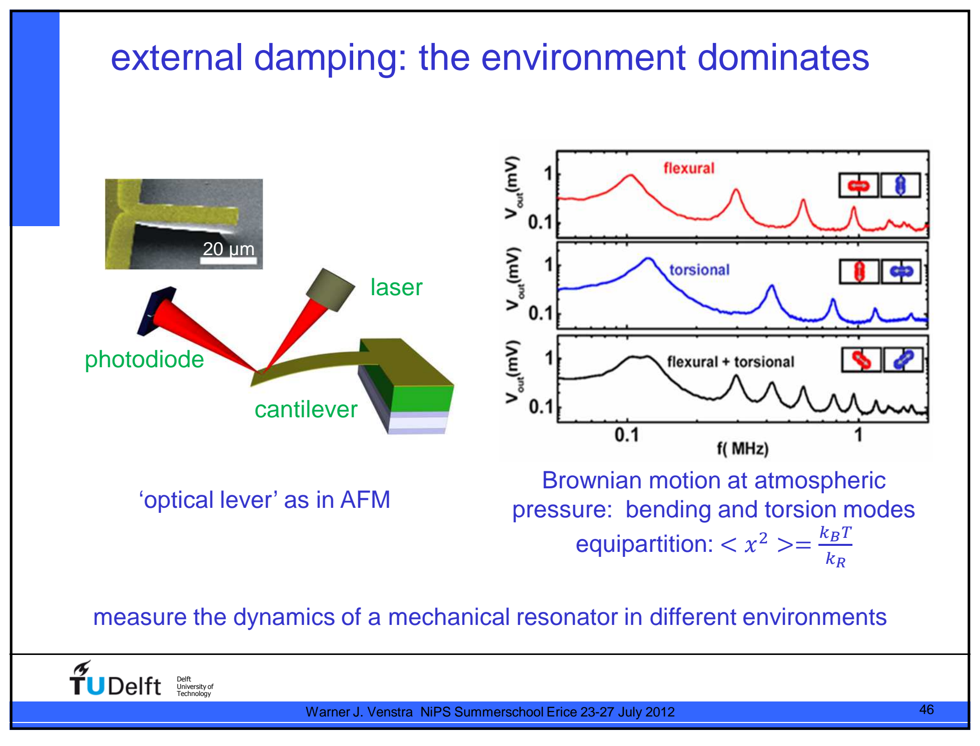
external damping: the environment dominates
20 µm
laser
photodiode
cantilever
'optical lever' as in AFM
flexural
torsional
flexural + torsional
V_{out}(mV)
1
0.1
f(MHz)
Brownian motion at atmospheric pressure: bending and torsion modes
equipartition: $< x^2 >= \frac{k_B T}{k_R}$
measure the dynamics of a mechanical resonator in different environments
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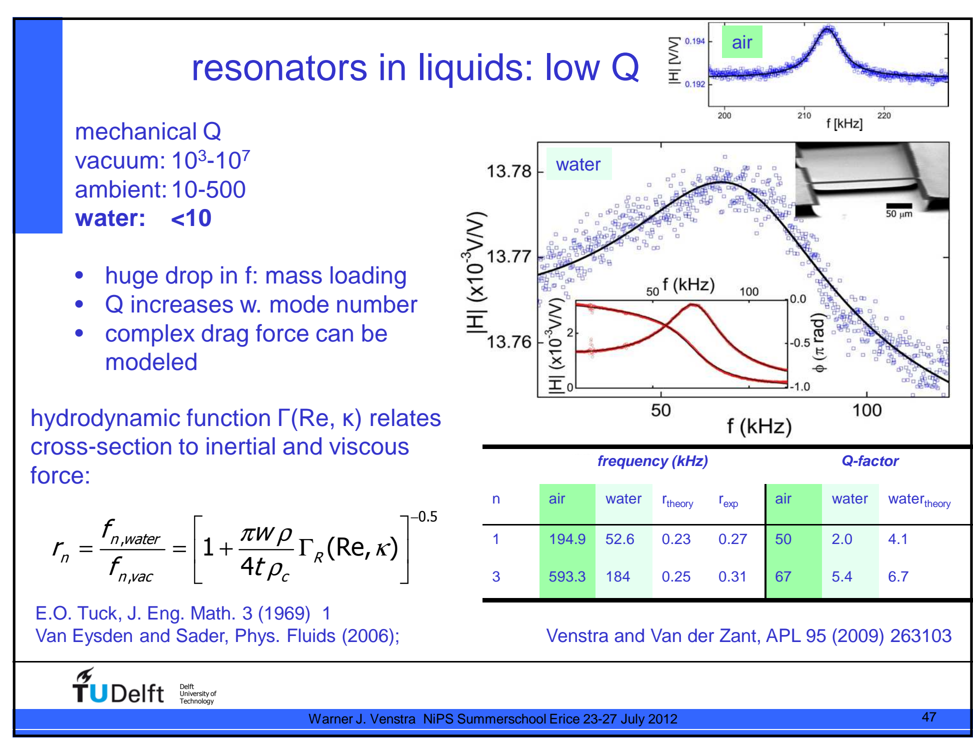
resonators in liquids: low Q
mechanical Q
vacuum: 10^3-10^7
ambient: 10-500
water: <10
• huge drop in f: mass loading
• Q increases w. mode number
• complex drag force can be modeled
hydrodynamic function Γ(Re, κ) relates cross-section to inertial and viscous force:
$r_n = \frac{f_{n,water}}{f_{n,vac}} = \left[1 + \frac{\pi w \rho}{4 t \rho_c}\Gamma_R(\mathrm{Re},\kappa)\right]^{-0.5}$
E.O. Tuck, J. Eng. Math. 3 (1969) 1
Van Eysden and Sader, Phys. Fluids (2006);
air
|H| [V/V]
f [kHz]
water
|H| (x10^-3 V/V)
f (kHz)
φ (π rad)
50 μm
frequency (kHz)
Q-factor
n | air | water | r_theory | r_exp | air | water | water_theory
1 | 194.9 | 52.6 | 0.23 | 0.27 | 50 | 2.0 | 4.1
3 | 593.3 | 184 | 0.25 | 0.31 | 67 | 5.4 | 6.7
Venstra and Van der Zant, APL 95 (2009) 263103
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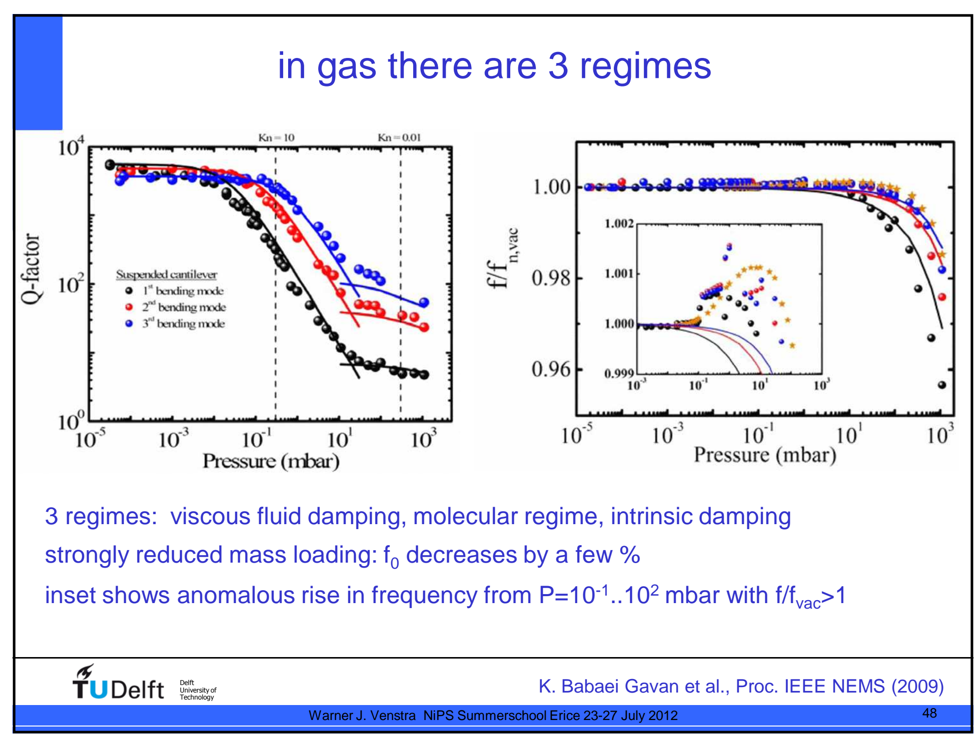
in gas there are 3 regimes
Q-factor
Kn = 10
Kn = 0.01
Suspended cantilever
1st bending mode
2nd bending mode
3rd bending mode
Pressure (mbar)
f/f_n,vac
3 regimes: viscous fluid damping, molecular regime, intrinsic damping
strongly reduced mass loading: f_0 decreases by a few %
inset shows anomalous rise in frequency from P=10^-1..10^2 mbar with f/f_vac>1
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K. Babaei Gavan et al., Proc. IEEE NEMS (2009)
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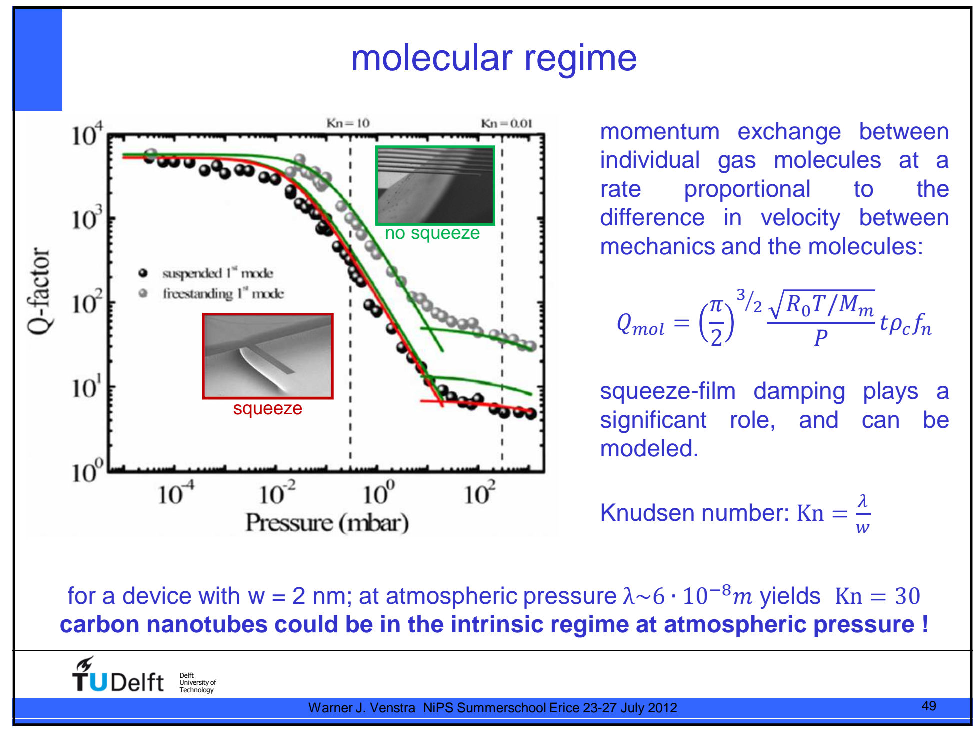
molecular regime
Kn = 10
Kn = 0.01
no squeeze
suspended 1st mode
freestanding 1st mode
squeeze
Q-factor
Pressure (mbar)
momentum exchange between individual gas molecules at a rate proportional to the difference in velocity between mechanics and the molecules:
$Q_{mol} = \left(\frac{\pi}{2}\right)^{3/2} \frac{\sqrt{R_0 T / M_m}}{P} t \rho_c f_n$
squeeze-film damping plays a significant role, and can be modeled.
Knudsen number: $\mathrm{Kn} = \frac{\lambda}{w}$
for a device with w = 2 nm; at atmospheric pressure $\lambda \sim 6 \cdot 10^{-8} m$ yields $\mathrm{Kn} = 30$
carbon nanotubes could be in the intrinsic regime at atmospheric pressure !
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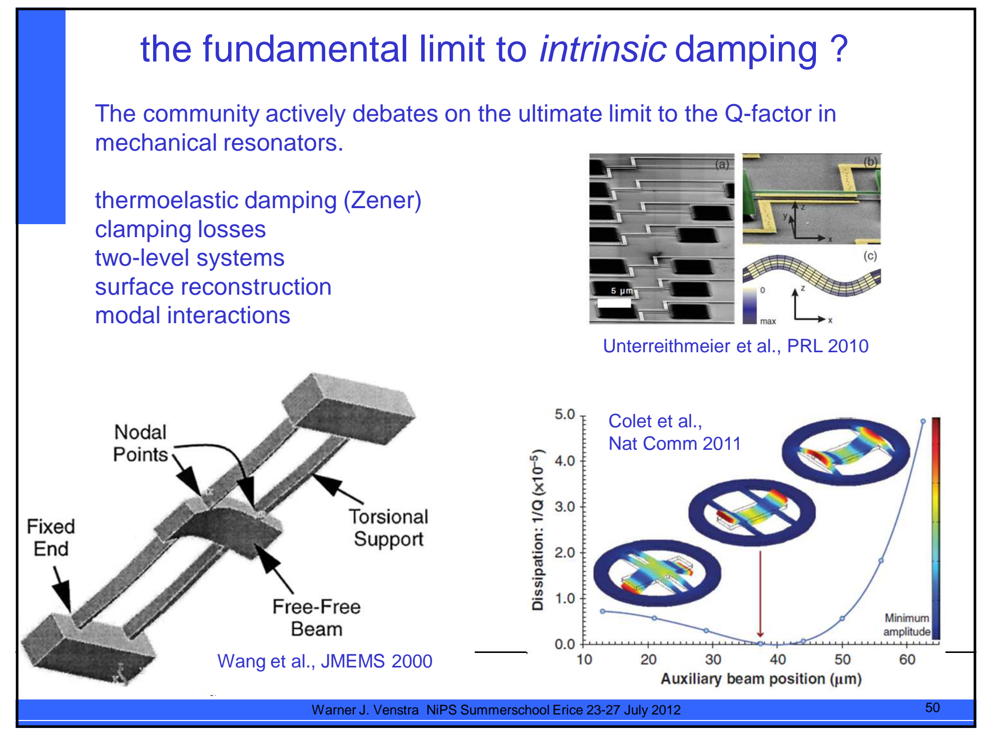
the fundamental limit to intrinsic damping ?
The community actively debates on the ultimate limit to the Q-factor in mechanical resonators.
thermoelastic damping (Zener)
clamping losses
two-level systems
surface reconstruction
modal interactions
Unterreithmeier et al., PRL 2010
Nodal Points
Fixed End
Torsional Support
Free-Free Beam
Wang et al., JMEMS 2000
Colet et al.,
Nat Comm 2011
Dissipation: 1/Q (x10−5)
Auxiliary beam position (µm)
Minimum amplitude
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MODIFYING THE DAMPING

parametric amplification ($f_{drive} \neq f_{res}$)

Instead of periodically varying the force, vary ('pump') a system parameter, for example the spring constant:

parametric excitation **direct excitation**

$$m\ddot{x} + \frac{m\omega_R}{Q}\dot{x} + \left[m{\omega_R}^2 + k_p \sin(2\Omega t + \varphi)\right]x + \alpha x^3 = F\cos(\Omega t)$$

this can be used for

- amplification of the vibration without broadening of the response (Q_{eff} enhances)
- beyond threshold: self-sustained oscillation (amplitude limited by nonlinearities)

technologically of great interest:

pre-amplification in the mechanical domain for detectors of force, mass etc.

First demo in a microresonator by Rugar and Grütter (PRL 67(6)1991):

VOLUME 67, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 1991

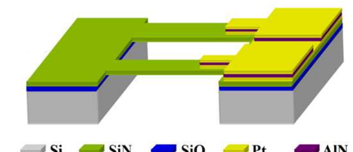
Mechanical Parametric Amplification and Thermomechanical Noise Squeezing

D. Rugar and P. Grütter[a]

IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120

(Received 20 May 1991)

parametric amplification in piezo-resonators

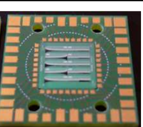


parametric excitation — direct excitation

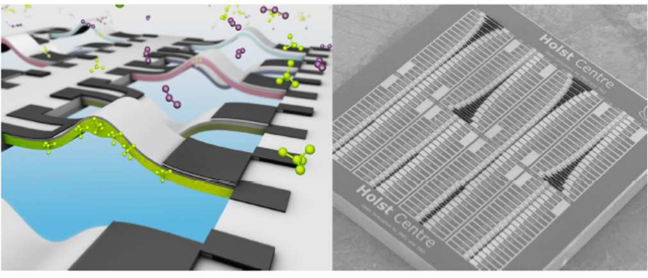
$$m\ddot{x} + \frac{m\omega_R}{Q}\dot{x} + \left[m{\omega_R}^2 + k_p \sin(2\Omega t + \varphi)\right]x + \alpha x^3 = F\cos(\Omega t)$$

- voltage on piezo modulates the spring constant by changing the stress in the beam
- gain on resonance: $G(\varphi) = \sqrt{\frac{\cos^2(\varphi+\pi/4)}{(1+k_p/k_t)^2} + \frac{\sin^2(\varphi+\pi/4)}{(1-k_p/k_t)^2}}$
- instability at $k_p=k_t$
- non-Lorentzian response: $A = \frac{F_0 Q}{m{\omega_0}^2} \cdot \frac{2Q(\omega_D-\omega_R)-i\omega_R}{\frac{-4Q^2}{\omega_0(\omega_D-\omega_R)}^2+4iQ(\omega_D-\omega_R)+\omega_R(1-\frac{k_p^2}{k_t^2})}$

resonators with on-chip piezo transducer

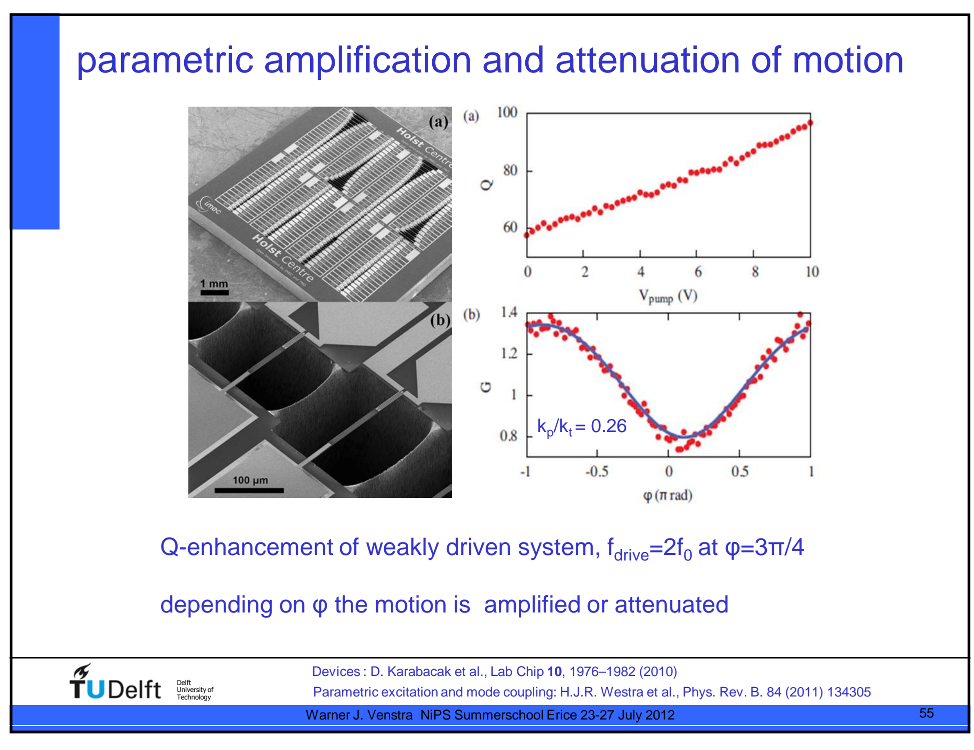


Enhanced Volatile Detection with Low Power Integrated Micromechanical Resonators
D. M. Karabacak, S. Brongersma and M. Crego-Calama



Polymer coated, very high aspect ratio doubly-clamped beam resonators with integrated transducers are demonstrated for ultra-low power, high sensitivity detection of volatile compounds.

D. Karabacak et al., Lab on Chip, 2010


parametric amplification and attenuation of motion
(a)
(b)
1 mm
100 µm
Q
V_{pump} (V)
G
$k_p/k_t = 0.26$
φ (π rad)
Q-enhancement of weakly driven system, $f_{drive}=2f_0$ at φ=3π/4
depending on φ the motion is amplified or attenuated
Devices : D. Karabacak et al., Lab Chip 10, 1976–1982 (2010)
Parametric excitation and mode coupling: H.J.R. Westra et al., Phys. Rev. B. 84 (2011) 134305
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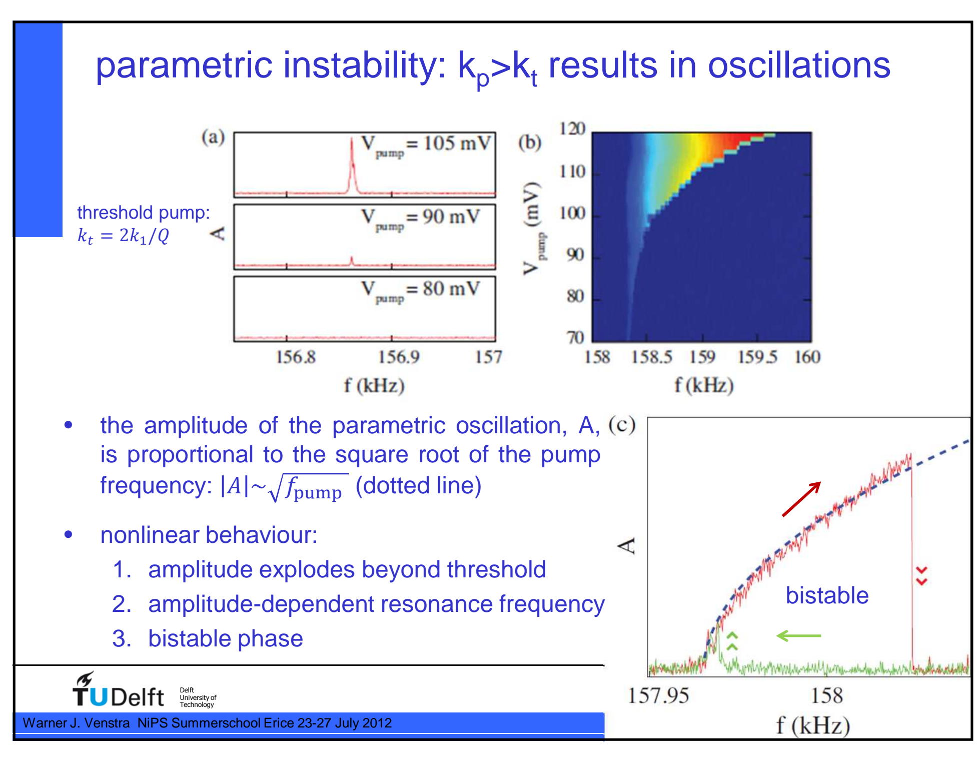
parametric instability: $k_p>k_t$ results in oscillations
threshold pump:
$k_t = 2k_1/Q$
(a)
V_{pump} = 105 mV
V_{pump} = 90 mV
V_{pump} = 80 mV
A
f (kHz)
(b)
V_{pump} (mV)
f (kHz)
the amplitude of the parametric oscillation, A, is proportional to the square root of the pump frequency: $|A| \sim \sqrt{f_{pump}}$ (dotted line)
nonlinear behaviour:
1. amplitude explodes beyond threshold
2. amplitude-dependent resonance frequency
3. bistable phase
(c)
A
bistable
f (kHz)
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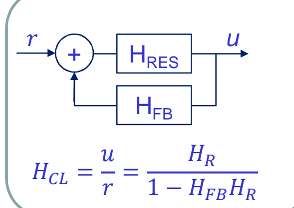
feedback

transfer functions:

resonator: $H_{RES} = \frac{1/k}{1 - \left(\frac{\omega}{\omega_0}\right)^2 + \frac{i\omega}{Q\omega_0}}$

feedback: $H_{FB} = Ge^{i\varphi}$



$H_{CL} = \frac{u}{r} = \frac{H_R}{1 - H_{FB}H_R}$

stiffness damping

closed-loop: $H_{CL} = \frac{H_{RES}}{1 - H_{FB}H_{RES}} = \frac{\frac{1}{k}\left(1 - \frac{\omega^2}{\omega_0^2} - \frac{G}{k}\cos\varphi\right) - \frac{i}{k}\left(\frac{\omega}{Q\omega_0} - \frac{G}{k}\sin\varphi\right)}{\left(1 - \frac{\omega^2}{\omega_0^2} - \frac{G}{k}\cos\varphi\right)^2 + \left(\frac{\omega}{Q\omega_0} - \frac{G}{k}\sin\varphi\right)^2}$

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feedback: special cases

velocity-proportional feedback when $\varphi = \frac{2n-1}{2}\pi$ $n = 1,2,..$

the damping is modified: $\frac{1}{Q_{eff}} = \frac{1}{Q} - \frac{G}{k}$

displacement-proportional feedback ($\varphi = n\pi$) the spring constant is modified

limited stability

gain on resonance: $|H_{CL}| = \left((G\cos\varphi)^2 + \left(\frac{k}{Q} - G\sin\varphi\right)^2\right)^{-\frac{1}{2}}$

$\varphi = \frac{\pi}{2}, G = \frac{k}{Q}$ (or equivalently: $\varphi = \frac{3\pi}{2}, G = -\frac{k}{Q}$): ‘Barkhausen criterion’

in practice φ is the result of a delay time in the system

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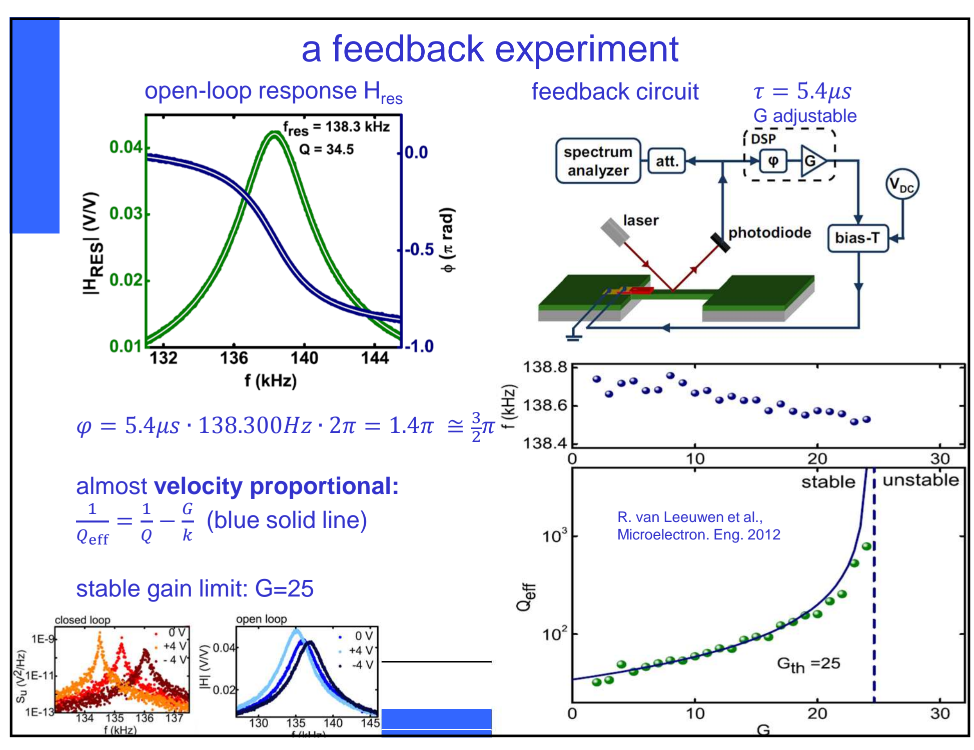
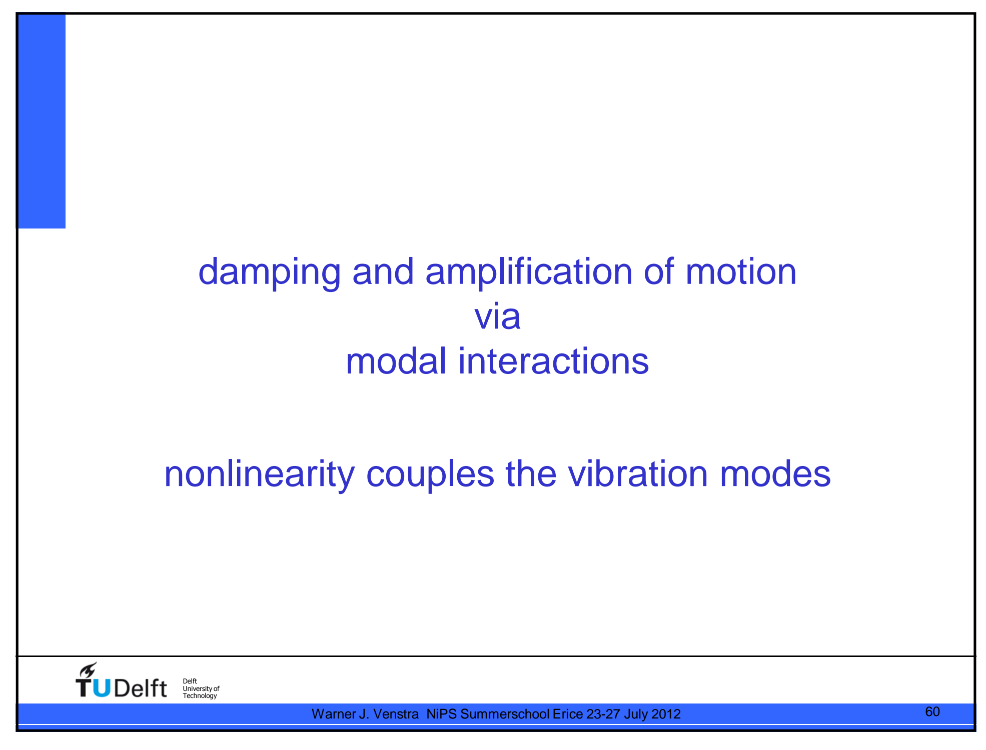

a feedback experiment
open-loop response H_{res}
feedback circuit
$\tau = 5.4\mu s$
G adjustable
f_{res} = 138.3 kHz
Q = 34.5
spectrum analyzer
att.
DSP
laser
photodiode
bias-T
V_{DC}
$|H_{RES}|$ (V/V)
ϕ (π rad)
f (kHz)
$\varphi = 5.4\mu s \cdot 138.300 Hz \cdot 2\pi = 1.4\pi \cong \frac{3}{2}\pi$
almost velocity proportional:
$\frac{1}{Q_{eff}} = \frac{1}{Q} - \frac{G}{k}$ (blue solid line)
stable gain limit: G=25
closed loop
open loop
stable
unstable
R. van Leeuwen et al., Microelectron. Eng. 2012
Q_{eff}
G_{th} =25
G


damping and amplification of motion
via
modal interactions
nonlinearity couples the vibration modes
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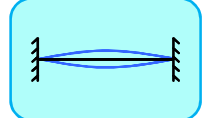
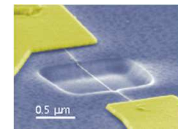
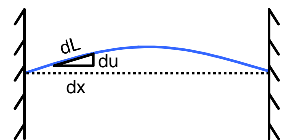
extensional: fixed on two sides (bridges, membranes)





origin of nonlinearity: displacement-induced tension



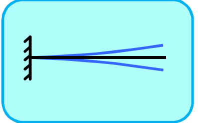
$$dL = \sqrt{du^2 + dx^2} = dx\sqrt{1 + \left(\frac{du}{dx}\right)^2}$$

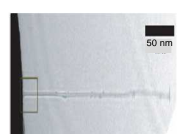
Elongation against the axial rigidity EA/L results in a tension T:

$$T = \frac{EA}{2L}\int_0^L \left(\frac{du}{dx}\right)^2 dx$$

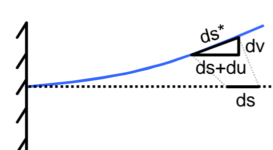
E: Young's modulus
A: cross section

inextensional: displacements without extending (cantilever)





origin of nonlinearity: inextensionality condition

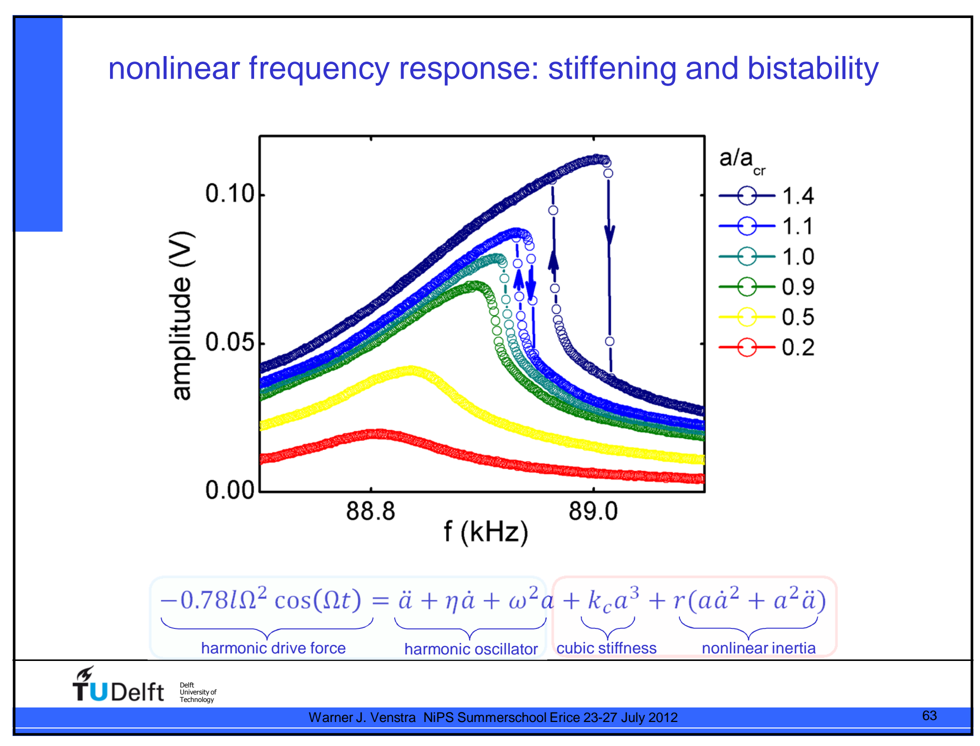


strain: $\epsilon = \frac{ds^* - ds}{ds} = \frac{\sqrt{(ds+du)^2 + dv^2}}{ds} = \sqrt{(1+u')^2 + v'^2} - 1$

inextensionality: $\epsilon = 0$

coupling: $(1+u')^2 + v'^2 = 1$

no extension of the neutral axis
geometry couples horizontal and vertical displacements for all modes
horizontal displacement (u) couples the flexural modes
flexure couples also to torsion


nonlinear frequency response: stiffening and bistability
amplitude (V)
0.10
0.05
0.00
88.8
89.0
f (kHz)
a/a_cr
1.4
1.1
1.0
0.9
0.5
0.2
$-0.78l\Omega^2\cos(\Omega t) = \ddot{a} + \eta\dot{a} + \omega^2 a + k_c a^3 + r(a\dot{a}^2 + a^2\ddot{a})$
harmonic drive force
harmonic oscillator
cubic stiffness
nonlinear inertia
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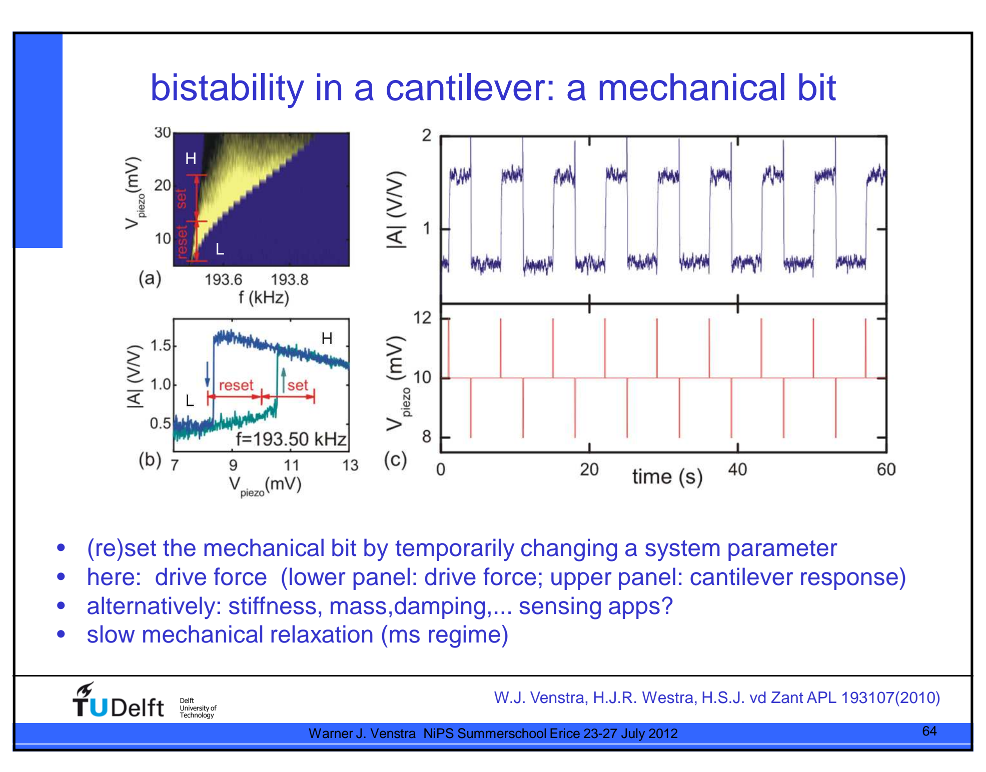
bistability in a cantilever: a mechanical bit
(a)
H
L
set
reset
193.6
193.8
f (kHz)
(b)
reset
set
f=193.50 kHz
(c)
|A| (V/V)
time (s)
• (re)set the mechanical bit by temporarily changing a system parameter
• here: drive force (lower panel: drive force; upper panel: cantilever response)
• alternatively: stiffness, mass,damping,... sensing apps?
• slow mechanical relaxation (ms regime)
W.J. Venstra, H.J.R. Westra, H.S.J. vd Zant APL 193107(2010)
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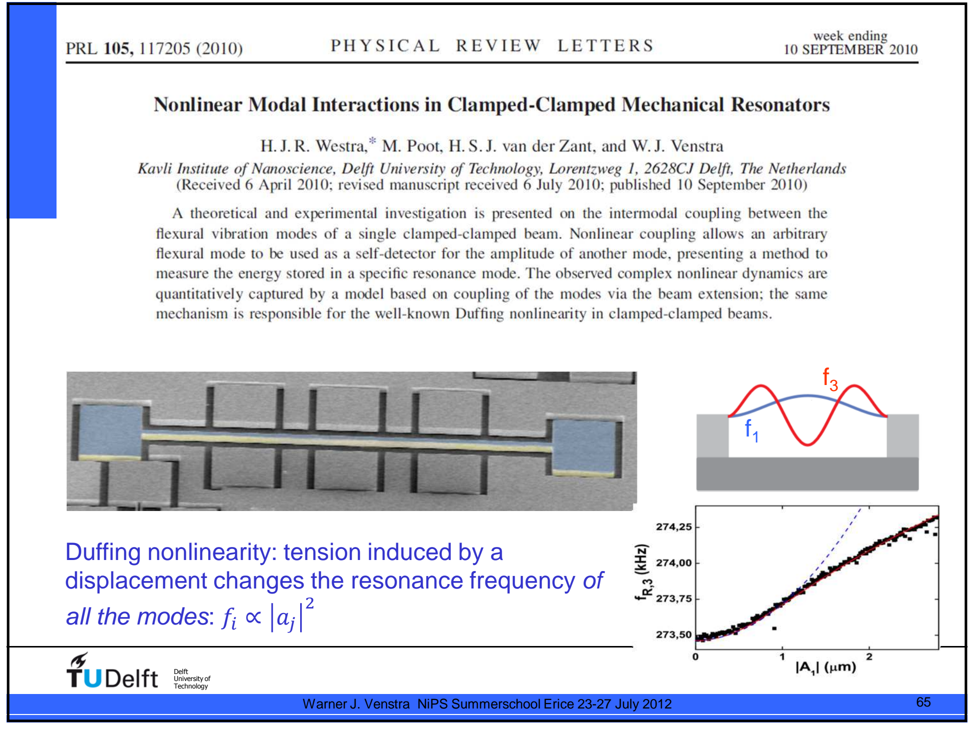
PRL 105, 117205 (2010)
PHYSICAL REVIEW LETTERS
week ending 10 SEPTEMBER 2010
Nonlinear Modal Interactions in Clamped-Clamped Mechanical Resonators
H. J. R. Westra,* M. Poot, H. S. J. van der Zant, and W. J. Venstra
Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628CJ Delft, The Netherlands
(Received 6 April 2010; revised manuscript received 6 July 2010; published 10 September 2010)
A theoretical and experimental investigation is presented on the intermodal coupling between the flexural vibration modes of a single clamped-clamped beam. Nonlinear coupling allows an arbitrary flexural mode to be used as a self-detector for the amplitude of another mode, presenting a method to measure the energy stored in a specific resonance mode. The observed complex nonlinear dynamics are quantitatively captured by a model based on coupling of the modes via the beam extension; the same mechanism is responsible for the well-known Duffing nonlinearity in clamped-clamped beams.
f3
f1
274,25
274,00
273,75
273,50
fR,3 (kHz)
0
1
2
|A1| (μm)
Duffing nonlinearity: tension induced by a displacement changes the resonance frequency of all the modes: $f_i \propto |a_j|^2$
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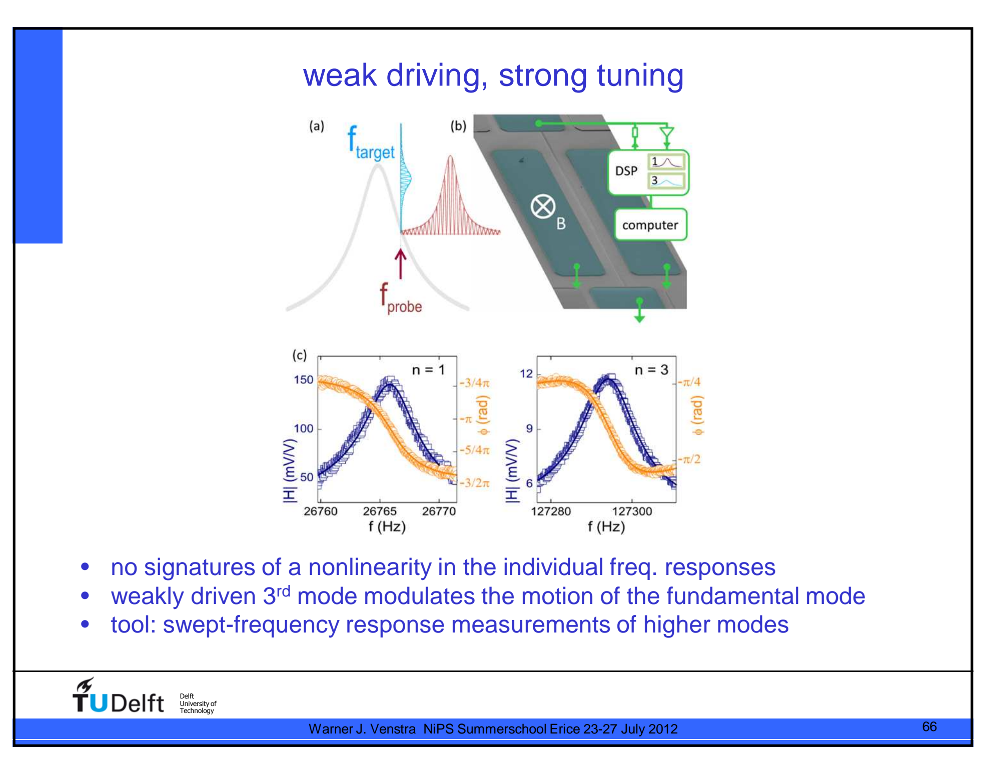
weak driving, strong tuning
(a)
(b)
f target
f probe
DSP
computer
B
(c)
n = 1
n = 3
150
100
50
|H| (mV/V)
26760
26765
26770
f (Hz)
-3/4π
-π
-5/4π
-3/2π
ϕ (rad)
12
9
6
127280
127300
-π/4
-π/2
• no signatures of a nonlinearity in the individual freq. responses
• weakly driven 3rd mode modulates the motion of the fundamental mode
• tool: swept-frequency response measurements of higher modes
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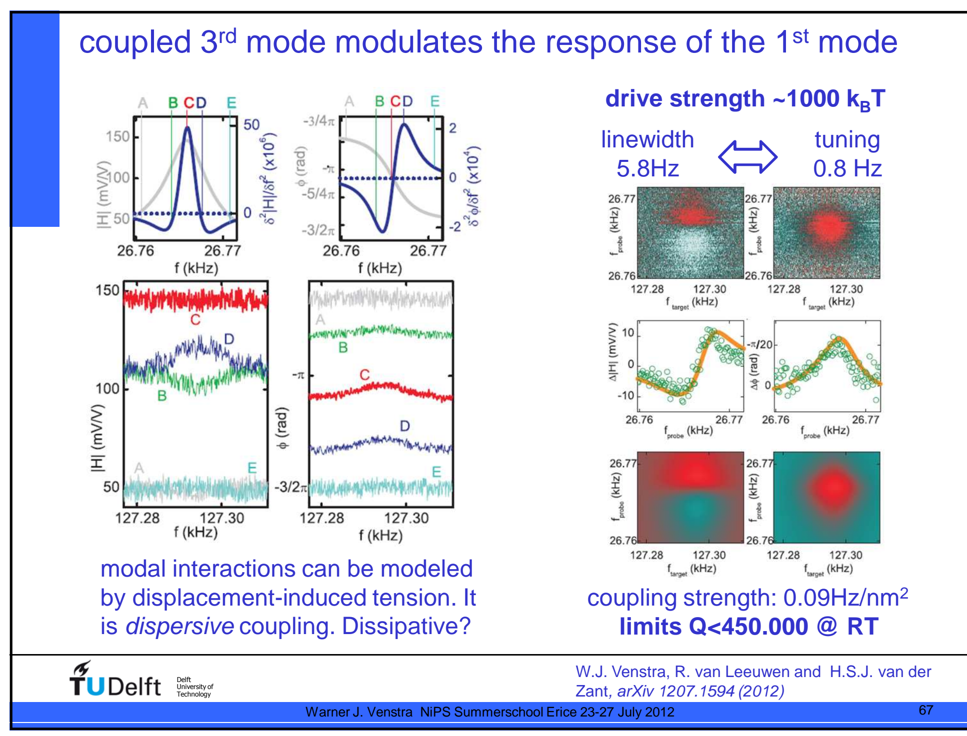


nonlinear interactions between flexural modes

eq. of motion including the coupling

$$\ddot{u}_i + \eta_i \dot{u}_i + \omega_i^2 u_i + \sum_{j=1}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} \left(\alpha_{ijkl} u_j u_k u_l + \frac{1}{2} \beta_{ijkl} u_j (u_k u_l)^{\cdot\cdot} \right) = f_i \cos(\Omega_i t)$$

again, the coupling coefficients are the integrated modeshapes

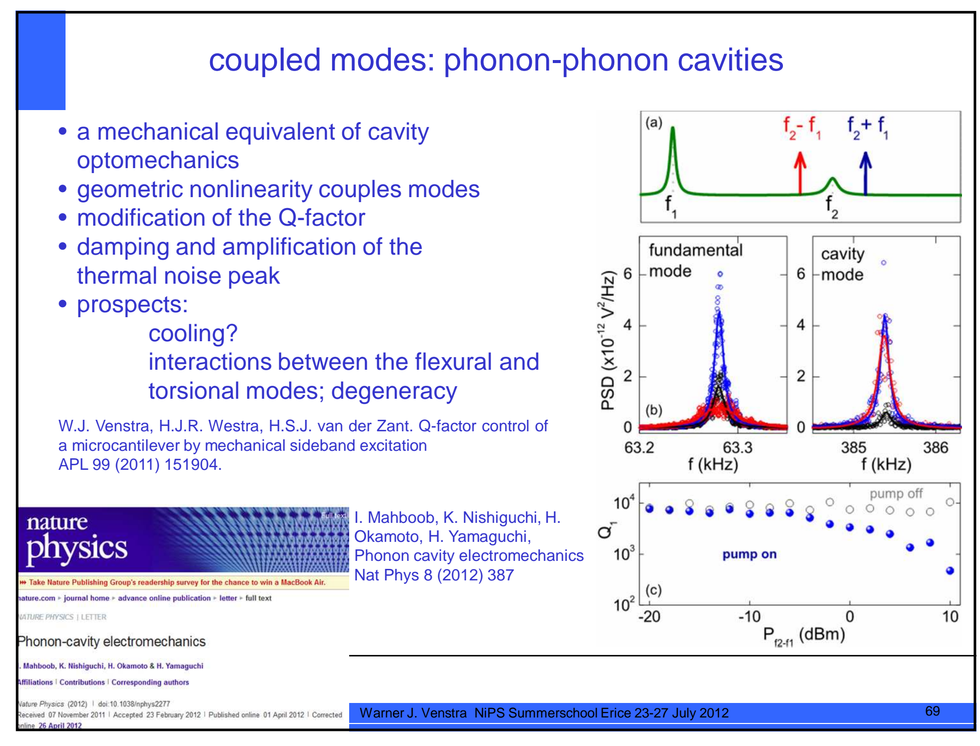
$$\alpha_{ijkl} = \int_0^1 \xi_i \{ \xi_j' (\xi_k' \xi_l'')' \}' ds,$$

$$\beta_{ijkl} = \int_0^1 \xi_i \left(\xi_j' \int_1^s \int_0^{s_2} \xi_k' \xi_l' ds_1 \, ds_2 \right)' ds.$$

(a) P (dBm); f (kHz); (b) P=-38 dBm; P=-100 dBm; PSD (x10^-5 V²/Hz); f (kHz)

evidence of coupling: motional sidebands at mixing frequencies of mode 1 and 2

M.R.M. Crespo da Silva and C.C. Glynn J. Struct. Mech.,6(4), 43748 (1978)
W.J. Venstra, H.J.R. Westra, H.S.J. van der Zant, APL 99(2011)151904
H.J.R. Westra, H.S.J. van der Zant, W.J. Venstra Ultramicroscopy 120 (2012) 41


coupled modes: phonon-phonon cavities
• a mechanical equivalent of cavity optomechanics
• geometric nonlinearity couples modes
• modification of the Q-factor
• damping and amplification of the thermal noise peak
• prospects:
cooling?
interactions between the flexural and torsional modes; degeneracy
W.J. Venstra, H.J.R. Westra, H.S.J. van der Zant. Q-factor control of a microcantilever by mechanical sideband excitation APL 99 (2011) 151904.
nature physics
Phonon-cavity electromechanics
I. Mahboob, K. Nishiguchi, H. Okamoto, H. Yamaguchi, Phonon cavity electromechanics Nat Phys 8 (2012) 387
(a)
f2 - f1
f2 + f1
f1
f2
fundamental mode
cavity mode
PSD (x10^-12 V²/Hz)
(b)
63.2
63.3
f (kHz)
385
386
f (kHz)
pump off
pump on
(c)
-20
-10
0
10
(dBm)
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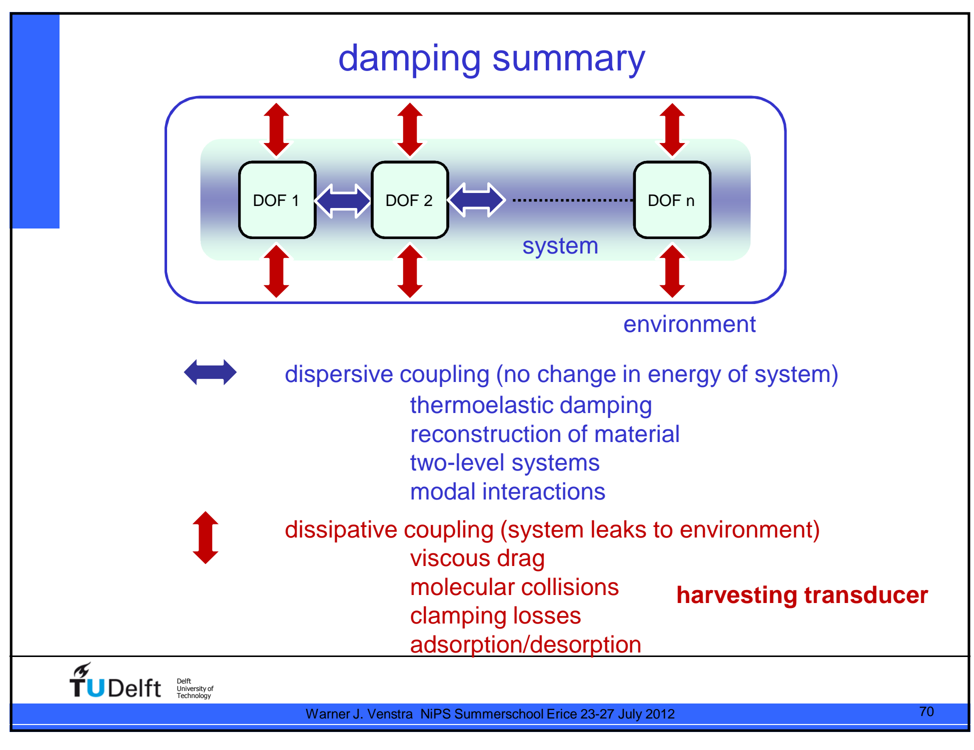
damping summary
DOF 1
DOF 2
DOF n
system
environment
dispersive coupling (no change in energy of system)
thermoelastic damping
reconstruction of material
two-level systems
modal interactions
dissipative coupling (system leaks to environment)
viscous drag
molecular collisions
clamping losses
adsorption/desorption
harvesting transducer
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Thank You
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