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Nanoscale Electromechanical Resonators and Oscillators

Philip Feng, Ph.D.

Electrical Engineering, Case School of Engineering
Case Western Reserve University
Cleveland, OH 44106, USA

Email: philip.feng@case.edu

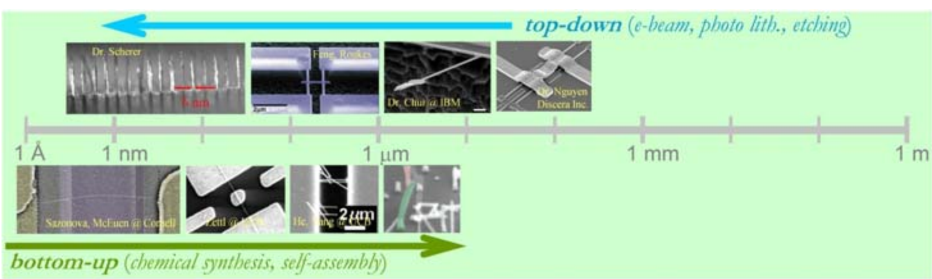
Visiting Associate, Kavli Nanoscience Institute
California Institute of Technology
Pasadena, CA 91125, USA

Outline

- Introduction to Nanoelectromechanical Systems (NEMS)
- Nanofabrication & Prototype Devices
- Radio-Frequency (RF)/Microwave NEMS Resonators
- VHF/UHF NEMS Oscillators
- Examples of Emerging Technological Applications
  - On Sensing: Mass, Force, Displacement
  - With Advanced Materials: Nanowires/Tubes, Carbon Materials, *etc.*
  - …
- Summary, Challenges & Outlook

Introduction to Nanoelectromechanical Systems (NEMS)

Suspended **Nanomechanical** Structures & Scaling



- Suspended Nanoscale Mechanical Structures & Devices: *comparable to transistors, cells and bio-molecules → significant implications.*
- Great opportunities in the regime ***where top-down meets bottom-up***: *new devices, systems, & tools…for new applications*
  - Excellent objects and tools for fundamental research: probing mesoscopic phenomena, "single-quanta" events and behavior, *etc.*
  - Stimulate *New Engineering* and generate *New Technologies*.

NEMS Resonators' Superb Attributes

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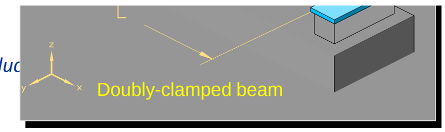
Ultra-Low Power Consumption

Exploit Mechanical Properties of Mainstream Semiconduc
Compatible & Integrable with Modern ICs



NEMS resonators: VERY high (fundamental) resonant frequency

	Resonator Dimensions ($L \times w \times t$, in μm)			
	100 × 3 × 0.1	10 × 0.2 × 0.1	1 × 0.05 × 0.05	0.1 × 0.01 × 0.01
Doubly-Clamped (Free-Free) Beams	*120 KHz* [77] (42)	*12 MHz* [7.7] (4.2)	*590 MHz* [380] (205)	*12 GHz* [7.7] (4.2)
Cantilevers	*19 KHz* [12] (6.5)	*1.9 MHz* [1.2] (0.65)	*93 MHz* [60] (32)	*1.9 GHz* [1.2] (0.65)

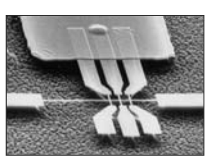
frequencies for SiC, [Si], and (GaAs) devices

VHF/UHF/Microwave Frequencies Achievable with Advanced Nanofabrication Technologies…

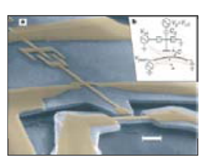
Significance in Fundamental Mesoscopic Physics

- NEMS can be extremely "cool" in probing quantum effects in "ordinary" things (no only in electrons, photons, *etc.*, but also in a nanoscale mechanical device)
- Quantum Electro Mechanics (QEM)
- Quantum Opto Mechanics (QOM), & Cavity QOM
- Currently, researchers racing to:
  - Cool the device down to ground state;
  - Displacement sensitivity approaching the SQL (4.3x);
  - QND, and eventually operational states for quantum computing

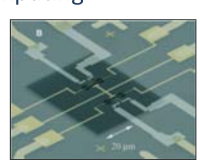
quantum thermal conductance
Schwab & Roukes, et al.
Nature (2000)



'quantum jump'
Huang & Roukes, (2002)



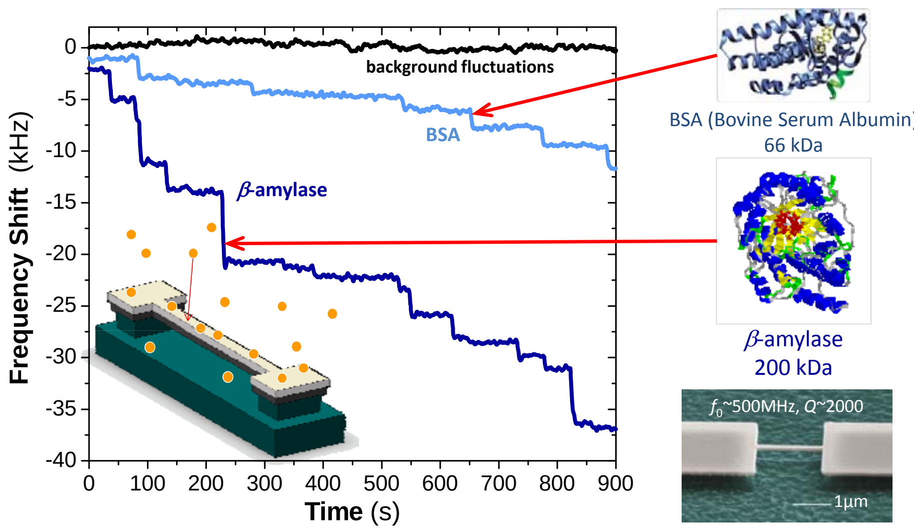
~100 x_{SQL}
Knobel & Cleland, et al.
Nature (2003)



~4.3 x_{SQL}
LaHaye & Schwab, et al.
Science (2004)

Single-BioMolecule NEMS Mass Sensing (latest milestone)

- Single-molecule events (*precipitous frequency jumps*) in real-time
  (Hallmark of single-molecule *nanomechanical* sensing and mass spectrometry)



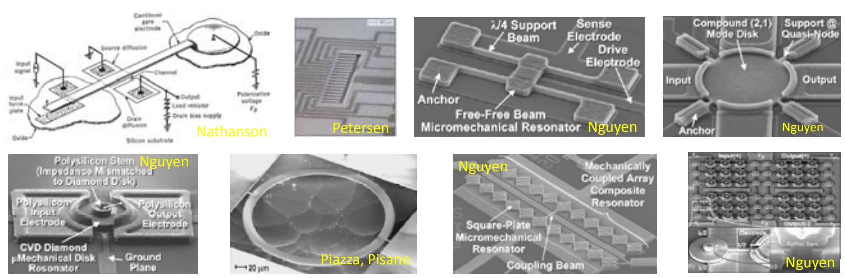
Naik, Hanay, Hiebert, Feng, Roukes, *Nature Nanotechnology* **4**, 445-449 (2009)

Technological Motivation – Acoustic Signal Processing

Nathanson, **Petersen**, **Howe**, *et al.*, 1960's ~ 1980's (→ Early Demonstrations)

Nguyen, and several others, 1990's ~ 2000's (→ μMech Signal Processors)

Growing Functionality, Performance, Complexity

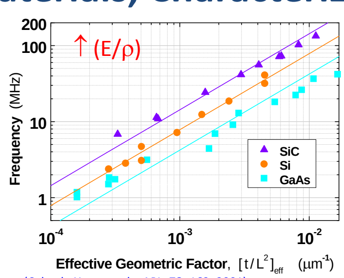


Going to Mainstream

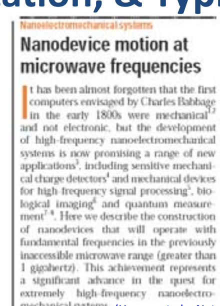
Discera SiTime Mobius Microsystems SILICON CLOCKS

Enabling Devices:
Materials, Design, Nanofabrication

Materials, Characterization, & Typical Device Design



(Caltech, Yang, et al., APL, **78**: 162, 2001)

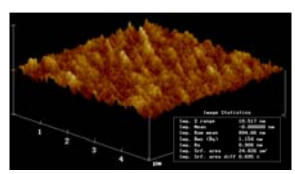

Nanoelectromechanical systems

Nanodevice motion at microwave frequencies

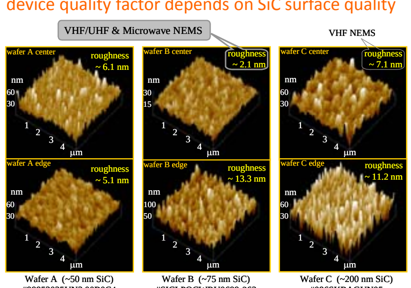
It has been almost forgotten that the first computers envisaged by Charles Babbage in the early 1800s were mechanical[1,2] and not electronic, but the development of high-frequency nanoelectromechanical systems is now promising a range of new applications[3], including sensitive mechanical charge detectors[4] and mechanical devices for high-frequency signal processing[5], biological imaging[6] and quantum measurement[7,8]. Here we describe the construction of nanodevices that will operate with fundamental frequencies in the previously inaccessible microwave range (greater than 1 gigahertz). This achievement represents a significant advance in the quest for extremely high-frequency nanoelectromechanical systems.

(Huang, et al., Nature, 2003)

measured surface roughness of the present SiC (on Si) wafer: ~2nm



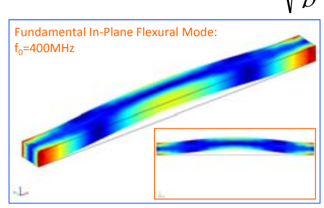
device quality factor depends on SiC surface quality



(Huang, et al., Transducers'03)

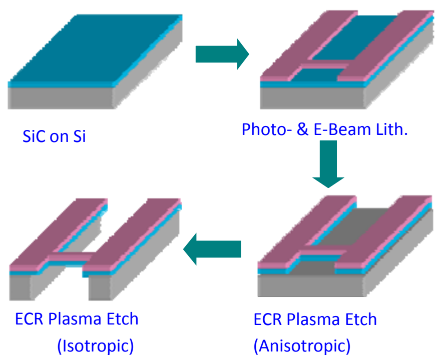
Doubly-Clamped Beam: $$f_1 = 1.03\sqrt{\frac{E}{\rho}}\frac{t}{L^2}$$

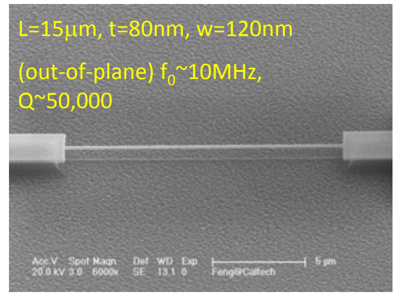
Cantilever Beam: $$f_1 = 0.1615\sqrt{\frac{E}{\rho}}\frac{t}{L^2}$$

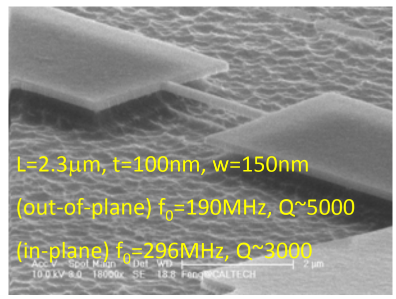


Top-Down Resonator Device Fabrication

Surface Nanomachining







Typical Structural Layer / Sacrificial Layer:

3C-SiC / Si

Si / SiO_2

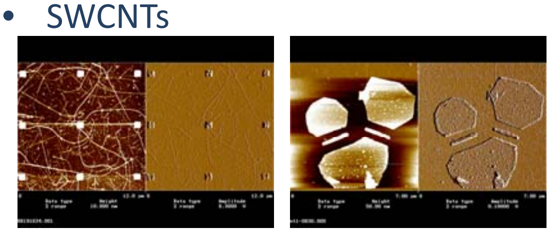
GaAs / $Al_xGa_{1-x}As$

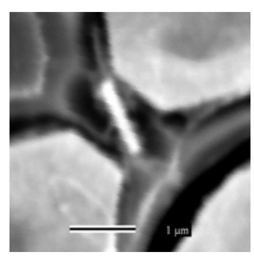
SiN / Si

Mask: Metal, Ox, etc.

NEMS Device Nanofabrication (Bottom-Up)

- SWCNTs

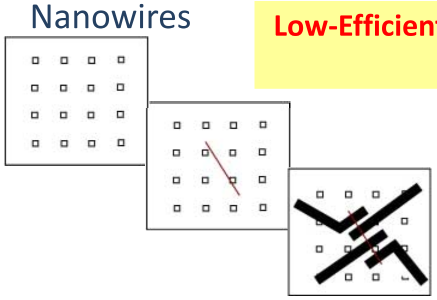


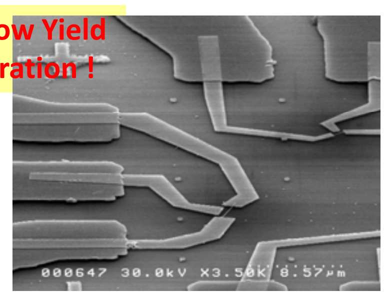


Feng, Huang, Postma, Roukes , *Unpublished*, Caltech (2003)

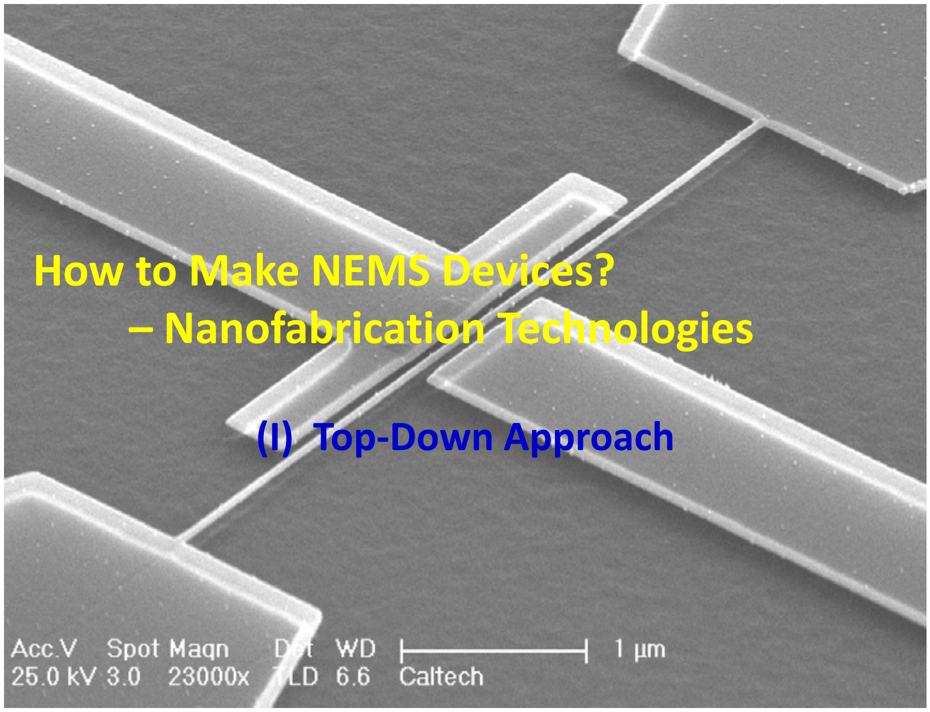
- Nanowires

Low-Efficient, Low Yield gration !





Husain & Roukes, *et al.*, *Appl. Phys. Lett.*, (2003)

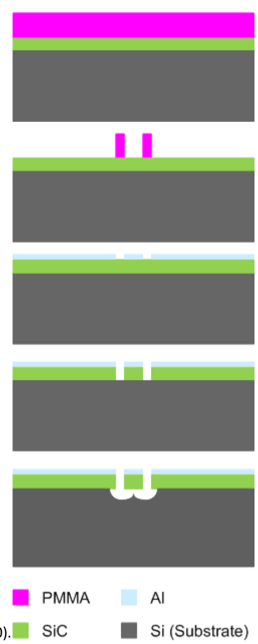


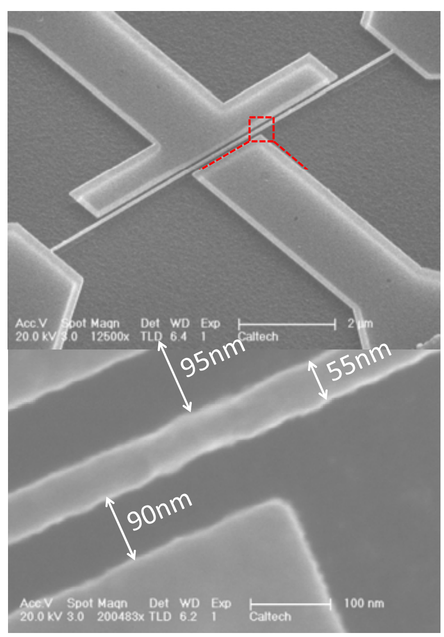
How to Make NEMS Devices?
– Nanofabrication Technologies

(I) Top-Down Approach

NEMS by EBL: State-of-the-Art (Liftoff), Nanowires

1. Spin Coating of PMMA on 50nm SiC on Si
2. High-Resolution Electron-Beam Lithography (EBL)
3. Metallization (~30–40nm Al) and Lift-Off
4. Anisotropic Dry Etch (ECR Plasma)
5. Isotropic Dry Etch of Si

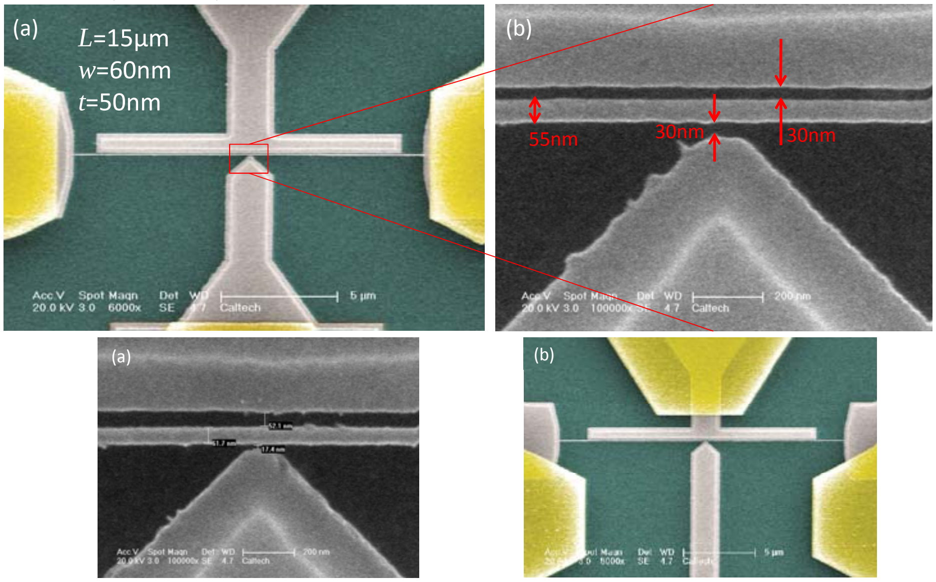




Feng, Matheny, Roukes, *et al.*, *Nano Lett.* **10**, 2891-2896 (2010).

NEMS by EBL: State-of-the-Art (Liftoff), Nanowires

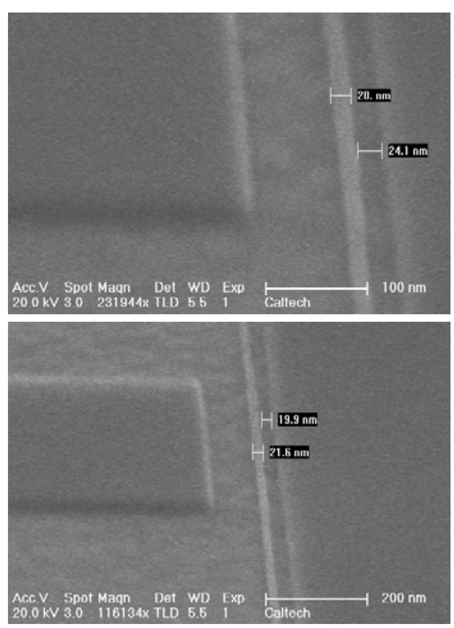
- Examples of Top-Down SiC Nanowire NEMS



Feng, Matheny, Roukes, *et al.*, *Nano Lett.* **10**, 2891-2896 (2010).

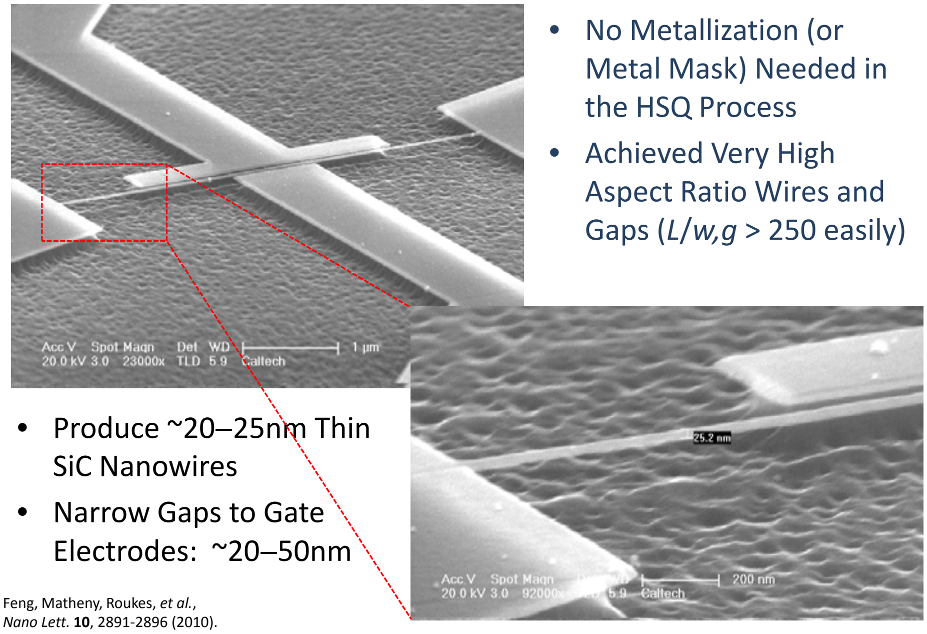
NEMS by EBL: State-of-the-Art (Negative Mask)

1. Spin Coating of HSQ (FOX) on 50nm SiC on Si
2. High-Resolution Electron-Beam Lithography (EBL)
3. Anisotropic Dry Etch (ECR Plasma)
4. Removal of HSQ Mask (Vapor HF or HF)
5. Isotropic Dry Etch of Si



Feng, Matheny, Roukes, *et al.*, *Nano Lett.* **10**, 2891-2896 (2010).

NEMS by EBL: State-of-the-Art (Negative Mask)

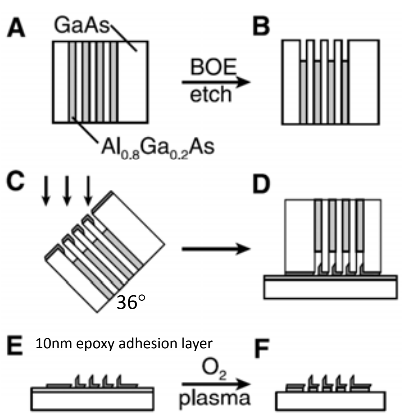


- No Metallization (or Metal Mask) Needed in the HSQ Process
- Achieved Very High Aspect Ratio Wires and Gaps ($L/w,g$ > 250 easily)

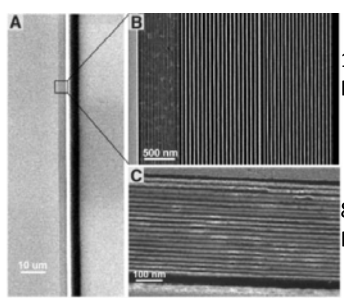
- Produce ~20–25nm Thin SiC Nanowires
- Narrow Gaps to Gate Electrodes: ~20–50nm

Feng, Matheny, Roukes, *et al.*, *Nano Lett.* **10**, 2891-2896 (2010).

Superlattice Nanowire Pattern Transfer (SNAP)



- MBE SL as physical template
- Not rely on photolith or EBL, thinner wires/pitches
- No liftoff of metal needed, separate wires already

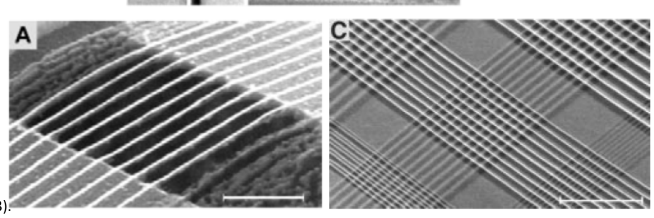


10nm Pt wires
Pitch: 30nm, 60nm

8nm Pt wires
Pitch: 16nm

Au, Cr, Al, Ti, Nb, Pt, Ni, *etc.*
Also masking SOI, *etc.*

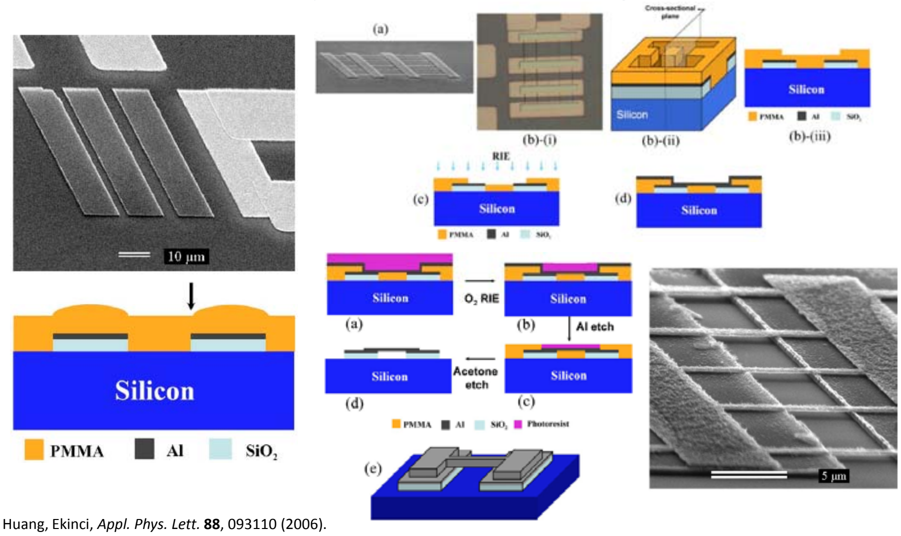
Suspended Pt NWs:
20nm diameter
0.75um length



Melosh, Heath, *et al.*, *Science* **300**, 112 (2003).

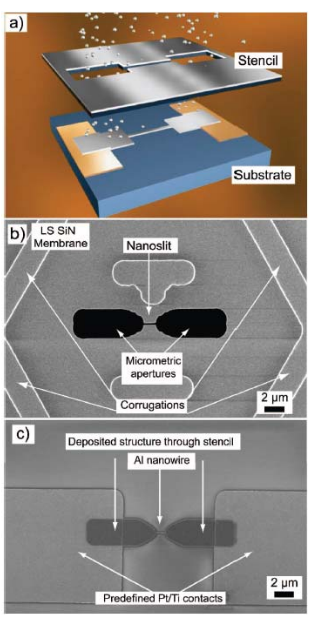
Nano-Imprint Lithography (NIL)

- High volume (parallel, in contrast to EBL), low cost,
- High-resolution (→5nm) [see, e.g., S.Y. Chou group work @ Princeton]
- Can do additive (not only subtractive) nanomachining

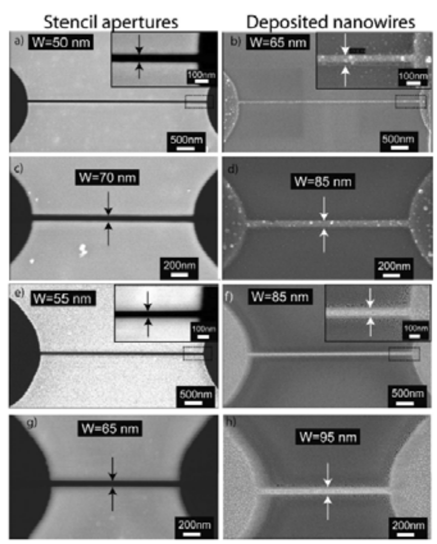


Huang, Ekinci, *Appl. Phys. Lett.* **88**, 093110 (2006).

Wafer-Scale Stencil Lithography → Metallic NWs

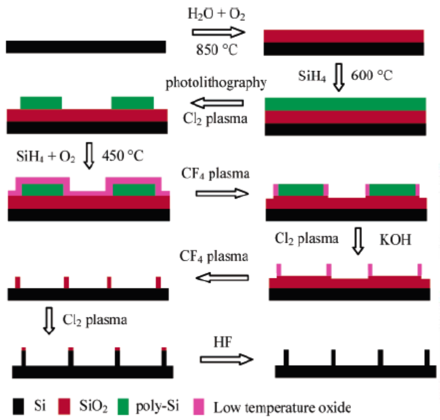


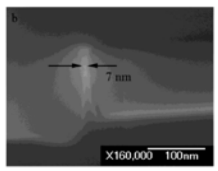
- Al, Au, *etc.,* nanowires, using 4 inch stencil wafer
- Features (nano slits) on stencil: focused ion beam (FIB)
- Resultant feature: 70nm thin metallic NWs, 5um long



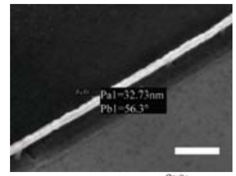
Vazquez-Mena, Brugger, *et al.*, *Nano Lett.* **8**, 3675-3682 (2008).

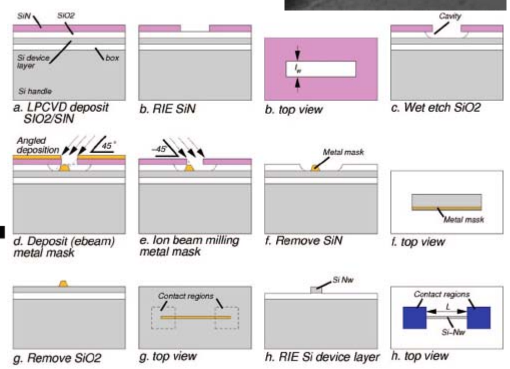
Other Ways of Making Thin Si Wires





Jeff Bokor Group,
1994-2005
A few variants



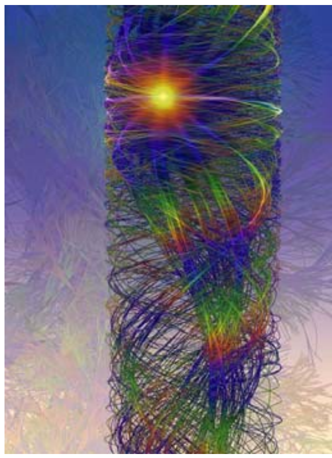


Wafer Scale
van der Berg, Nano Lett. (2009)
can do sub-50nm ones

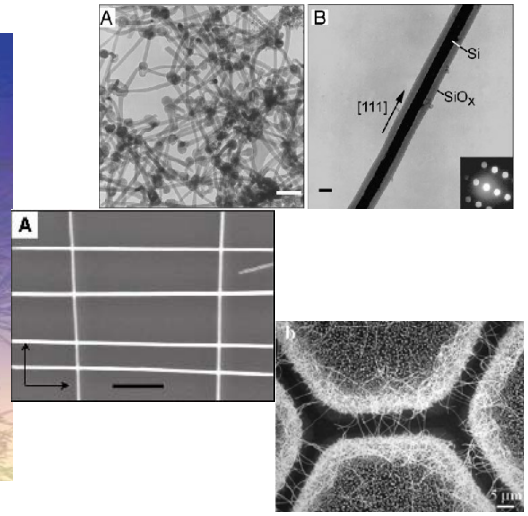
How to Make NEMS Devices?
– Nanofabrication Technologies

(II) Bottom-Up Approach
& Hybrid Bottom-Up/Top-Down Methods

Nanowires – At the First Glance…



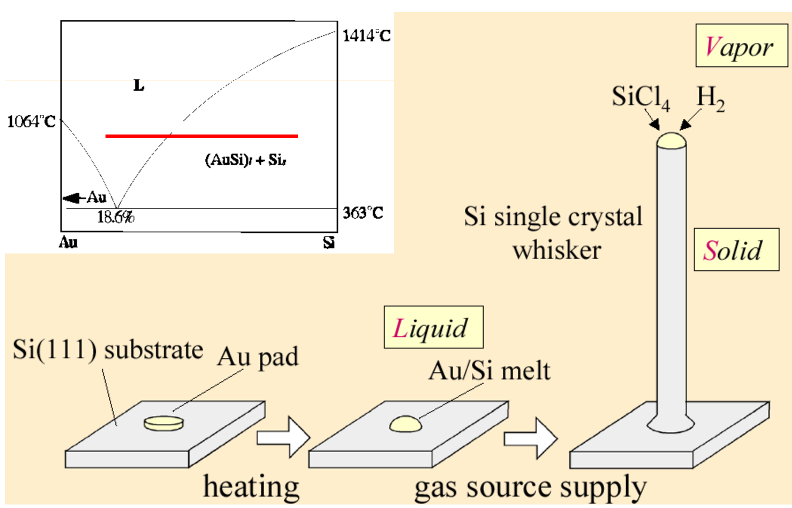
Portrait of NWs by a Computer Artist



Real NWs produced by researchers
C.M. Lieber Group @ Harvard University
Peidong Yang Group @ UC-Berkeley

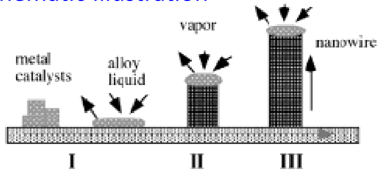
Vapor-Liquid-Solid (VLS) Growth Mechanism

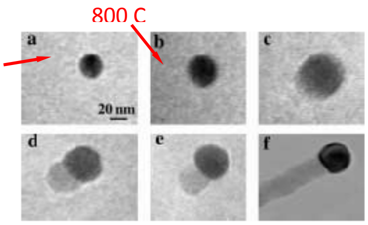
- ***Synthesis of NWs: how to achieve kinetically anisotropic growth?***



Evidence: Real-time In Situ Observation

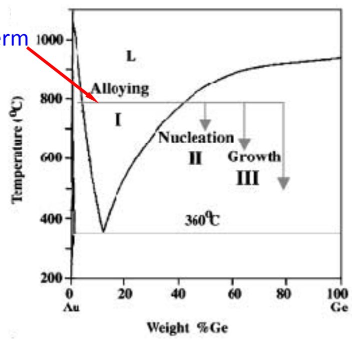
Schematic Illustration





In Situ TEM Images

Isotherm



I: Alloying (b,c)⟹Au (solid)+Au/Ge(alloy)
- By increasing Ge vapor condensation

II: Nucleation (d,e)⟹Au/Ge(alloy)+Ge(crystal)
- Starts at ~50-60% Ge
- In supersaturated alloy liquid

II: Aixal Growth (d,e,f)
- Increasing Ge vapor condensation & dissolution
- Engery cost ⟹ 2nd nucleation is suppressed

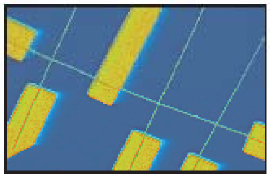
Linear Relation: $D_{Ge\_wire} \sim D_{Au\_nanoparticle}$

Refer to Yang, 2002, Chem. Euro. J.;& 2001, J. Am. Chem. Soc.

Table Summary

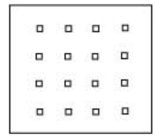
Nanowire	Precursor	Catalysts	Temperature	Lattice	Growth Direction
Si	$SiCl_4$ (l)	Au, Pt, Fe, Ti	850 °C	FCC	<111>
ZnO	ZnO+C (s) Zn	Au	900 °C	Hexagonal	<0001>
GaN	$Ga(CH_3)_3$ (l), NH_3 (g) Ga, NH_3	Co,Fe, Ni, Au	900 °C	Hexagonal	<0001> <1 $\bar{1}$00>
SiC	$(CH_3)SiCl_3$ (l)	Ni,Pt	1200 °C	FCC	<111>

Assembling, Connectors, and Electrodes

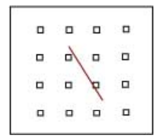


Nanowires

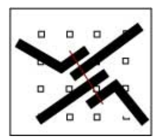
Step 1. Define markers on SiO_2/*p*-Si substrate (use E-beam lithography)



Step 2. Deposit nanowire solution onto the substrate and locate the nanowires.



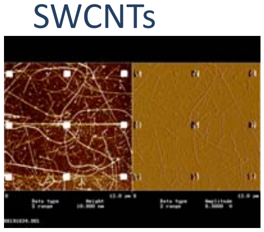
Step 3. Define contact leads onto the nanowires.

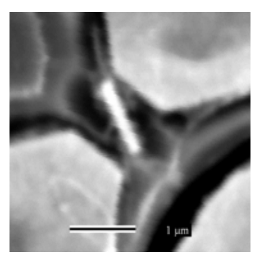


Ref. C.M. Lieber, 2001, Scientific American

Major Challenge: Bottom-Up Assembly

- SWCNTs

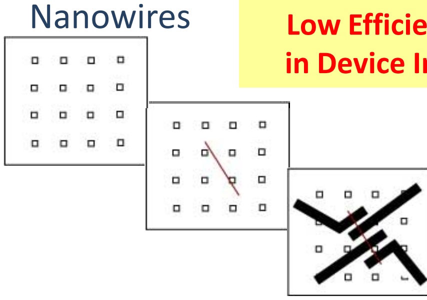


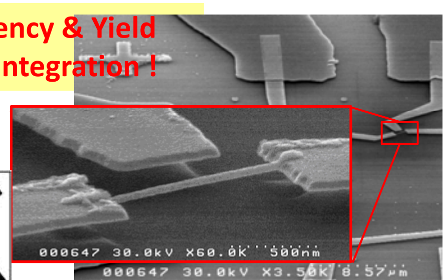


Feng, Huang, Postma, Roukes , *Unpublished*, Caltech (2003)

- Nanowires

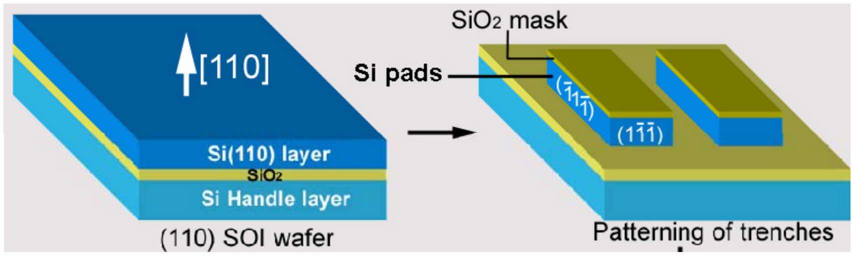
Low Efficiency & Yield in Device Integration !





Husain & Roukes, *et al.*, *Appl. Phys. Lett.*, (2003)

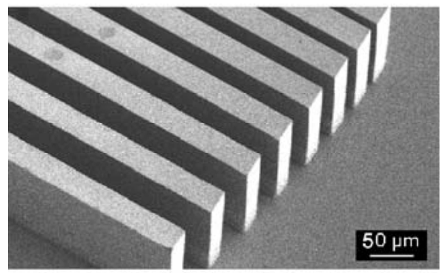
A New Hybrid Bottom-Up/Top-Down Fabrication



The basis for growth:

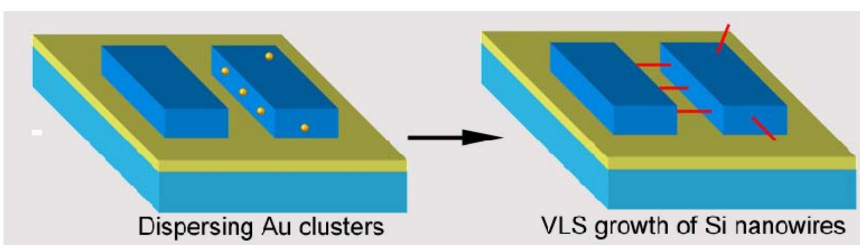
Growth direction of Si nanowires is <111>

Epitaxial growth on Si {111} Substrates



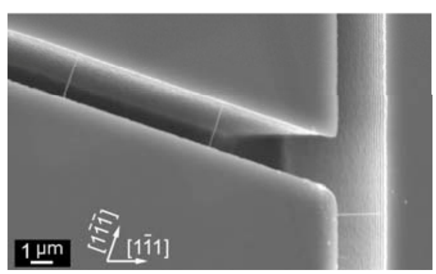
Ref: He, Gao, Fan, Hochbaum, Carraro, Maboudian, Yang, *Adv. Mater.* **17**, 2098-2102 (2005).

A New Hybrid Bottom-Up/Top-Down Fabrication



Integration of synthesis into device fabrication**:**

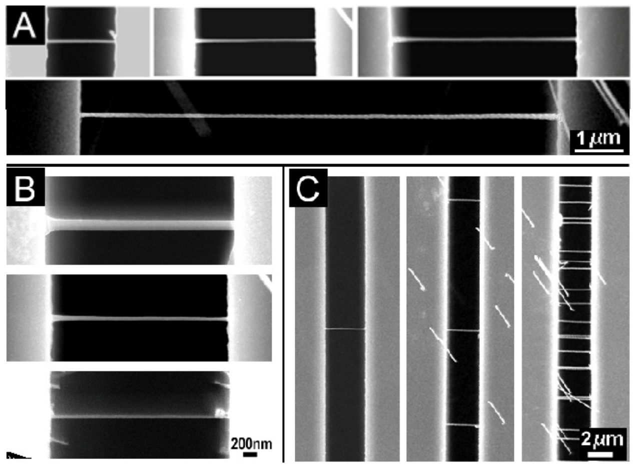
Si pads will serve as electrodes, mechanical supports and even microfluidic channels after growth



Ref: He, Gao, Fan, Hochbaum, Carraro, Maboudian, Yang, *Adv. Mater.* **17**, 2098-2102 (2005).

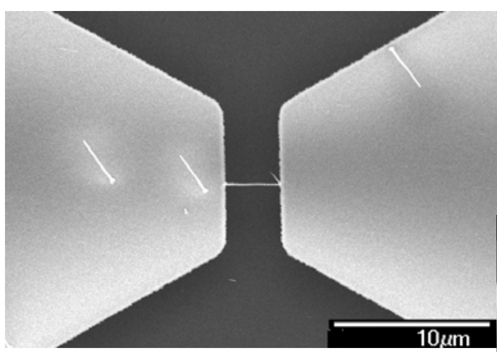
More Control

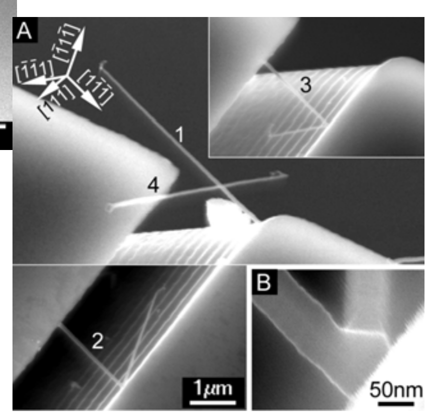
- Control of Length, Diameter, and Number Density



(A) Lengths of 4 nanowires with similar diameters of ~75nm are 1.5, 1.5, 4, and 10µm.
(B) Diameters of the 3 nanowires are 140nm, 70nm, and 35nm, respectively.
(C) Densities are 1 wire/50µm, 4 wires/50µm, and 40 wires/50µm, respectively.

Examples of Devices





Things we were interested in:

Mechanical rigidity of anchors?
Strength?
Devices? (NEMS, Suspended FET)

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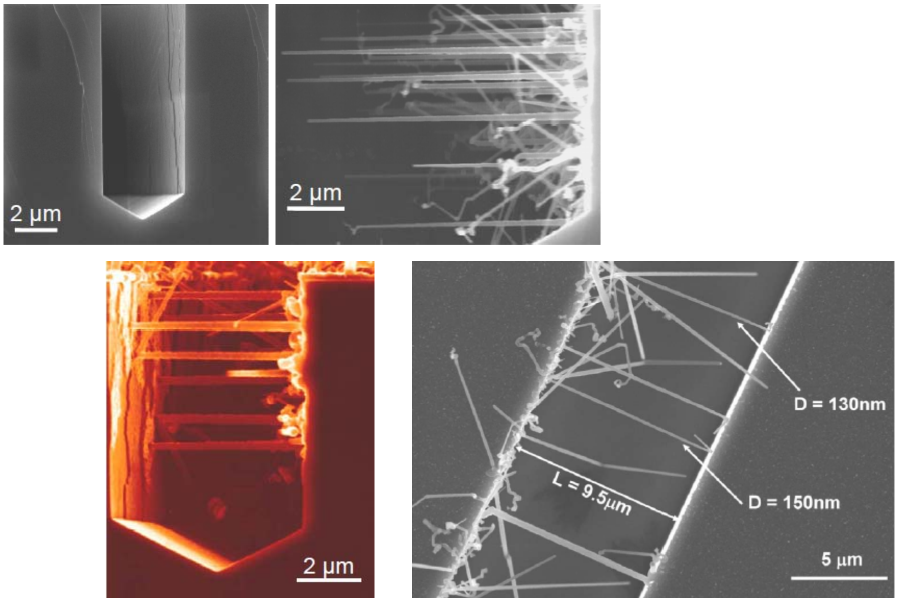
If Nanowire Number Density is Not Controlled

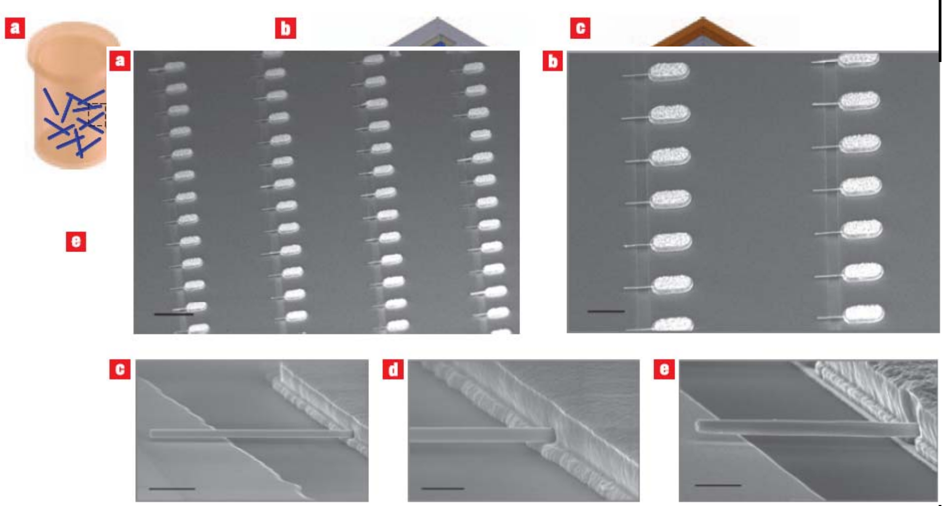


/ɛůĂŵ, ^ŚĂƌŵĂ, <ĂŵŝŶƐ, tŝůůŝĂŵƐ, EĂŶŽƚĞĐŚŶŽůŽŐLJ ϭϱ, >ϱ Ɵ ;ϮϬϬϰ

Ref: T.I. Kamins, *et al.*, HP Lab

Hybrid Bottom-Up/Top-Down Assembly

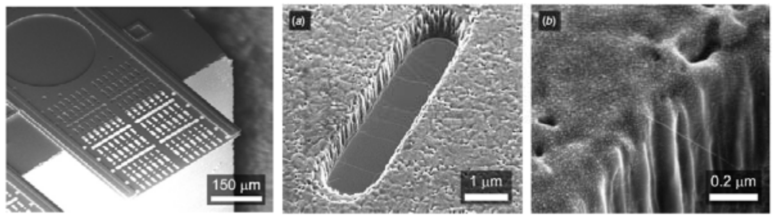
- Metallic (Rh) & semiconductor (Si)
- Biochemistry enhanced, electric field facilitated assembly in ufluidics
- Features:

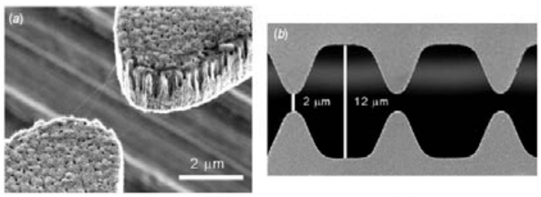


Li, Bhiladvala, *et al.*, *Nature Nanotech.* **3**, 88 (2008).

Synthesized SWCNT Bridges in MEMS Platform

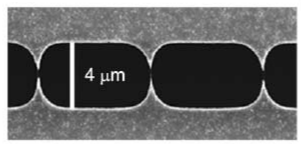
- Combination of CVD chemical synthesis with poly-Si MEMS

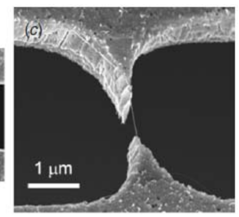




Towards individual bridges via localized growth between MEMS tips

Simple over-etching leads to sharper tips and hence single CNT devices



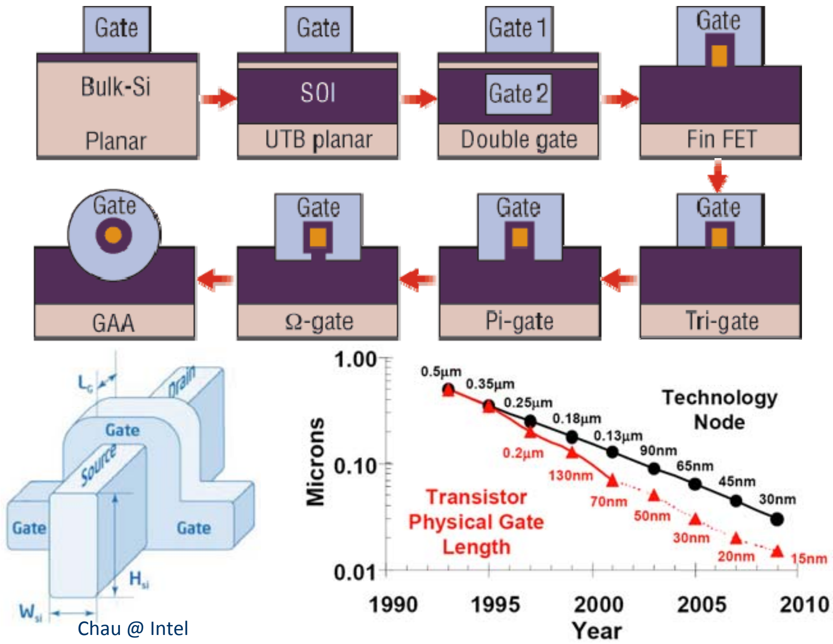


Jungen, Hierold, *et al.*, *J. Micromech. Microeng.* **17**, 603-608 (2007).

How to Make NEMS Devices?
– Nanofabrication Technologies

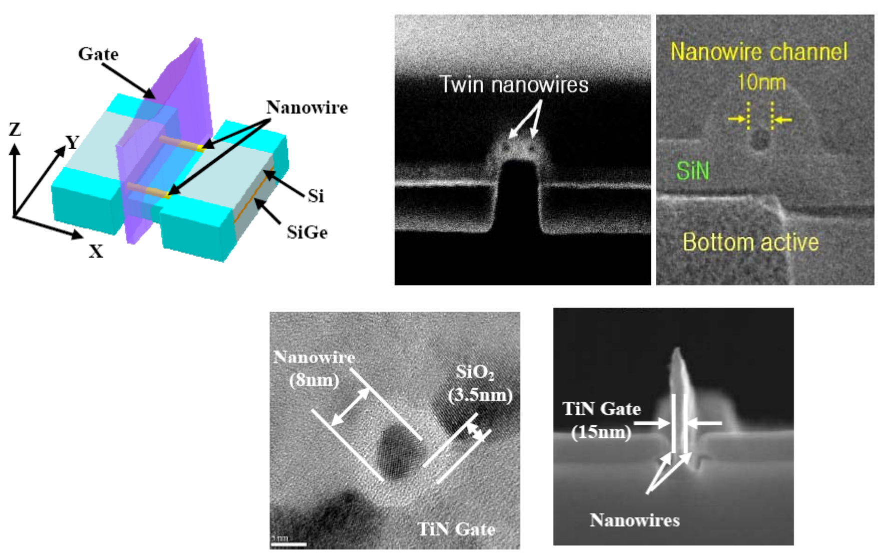
(III) Industry Capabilities

MOSFET Structural Evolution with Roadmap



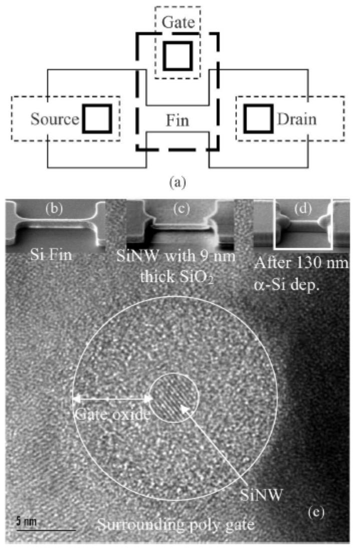
Example: GAA-TSiNWFET

- Gate-All-Around, Twin Silicon Nanowire FET

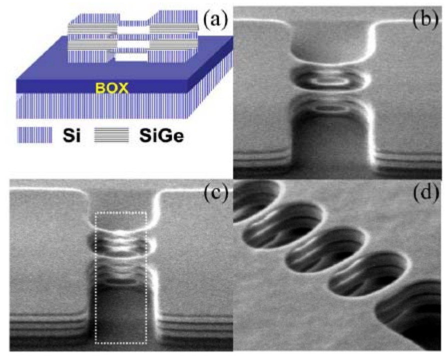


Samsung, IEDM (2005, 2006)

Example: 4nm GAA SiNWFET, SiGe NW Stacks

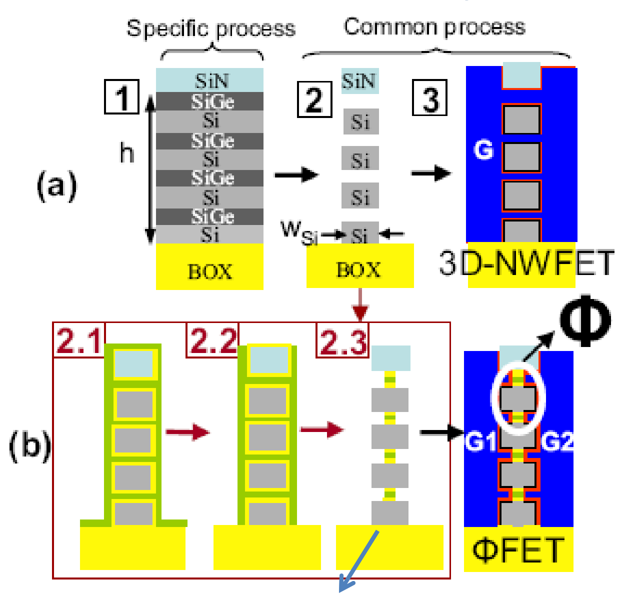


SiGe oxides faster than Si
5 cycles of oxidation and annealing
Fully oxide SiGe, and remove
Leave with SiNWs with Ge-rich surfaces



IME@A*STAR, Singapore, IEEE EDL (2006, 2007), George E. Smith Award of IEEE-EDS, 2007

Example: Si NW FETs – Stacks & Arrays @ Wafer Scale

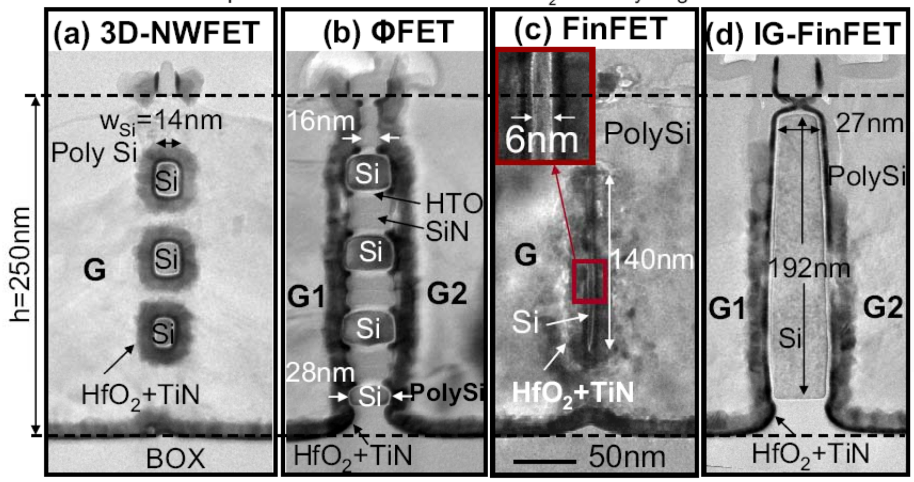


- Excellent byproduct: Suspended Si NW Arrays

Ernst, Dupré, *et al.*, IEDM (2006-2008)

Example: Si NW FETs – Stacks & Arrays @ Wafer Scale

Co-processed architectures with HfO_2 TiN Poly Si gate stack



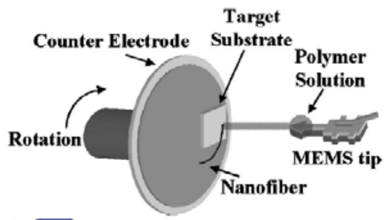
- Impressive process as an interesting technology enabler
- Today's state-of-the-art (at wafer scale?): d<5nm

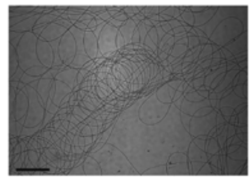
Ernst, Dupré, *et al.*, IEDM (2006-2008)

How to Make NEMS Devices?
– Nanofabrication Technologies

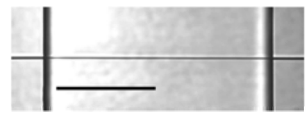
(IV) Non-Lithographic Approach

Electrospinning for Nanofibers

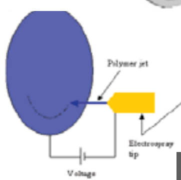


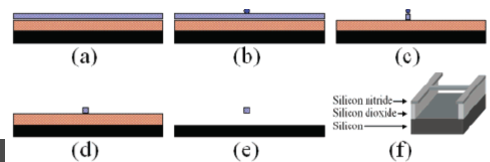


Polymeric fiber, PMMA, glass

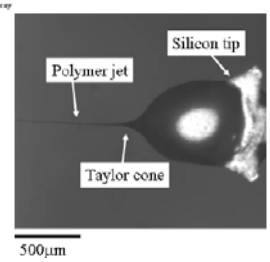


Use as masks for patterning

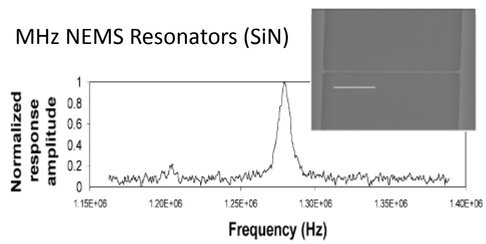




Features:
~70nm thin
~100nm thin routinely

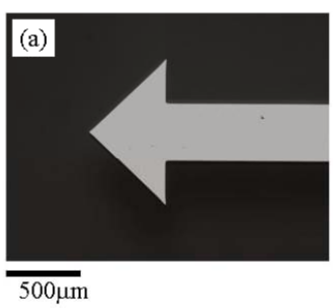


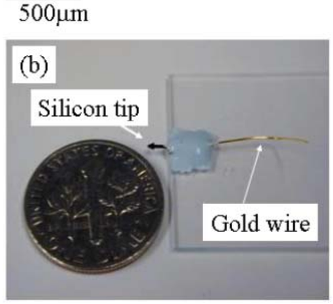
MHz NEMS Resonators (SiN)

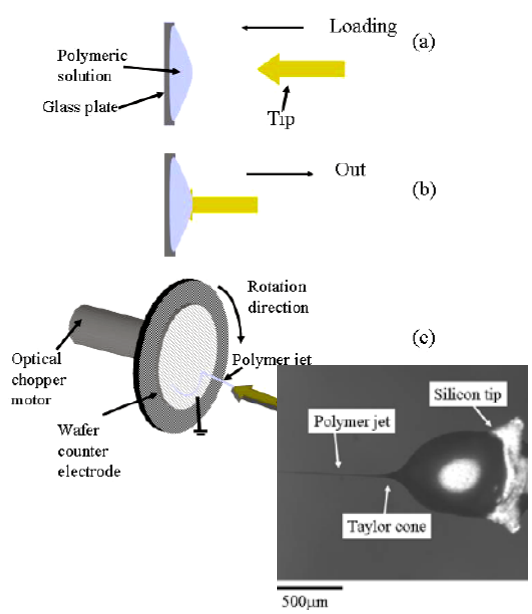


Refs: many papers from Craighead group at Cornell (2003-now).

Electrospinning for Nanofibers

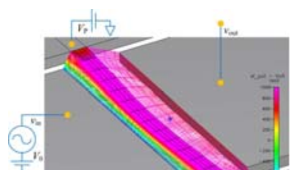




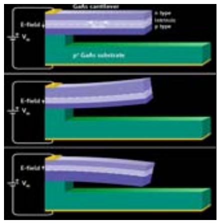


Device Characterization: VHF/UHF Signal Transduction & Readout

Transduction (Excitation + Detection)

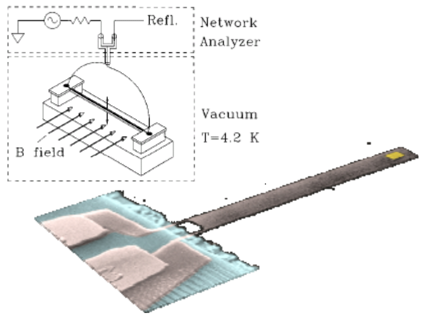


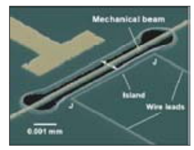
- Electrostatic
  - Naturally integrated on-chip
  - Scaling elusive to nanoscale
  - Often high R_m
- Optical
  - Easy to implement in labs
  - Often decoupled from drive
  - Limited by diffraction
  - Not integrated on-chip (long way to go probably…)
- Piezoelectric
  - Integrated on-chip
  - Depends on materials

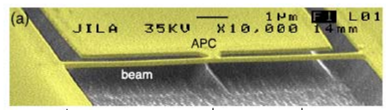


Transduction (Excitation + Detection)

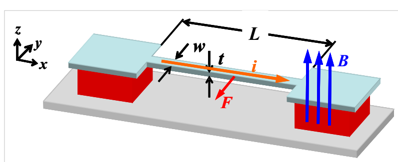
- Magnetomotive (electromotive)
  - Efficient, scaling well
  - Need high B-field, bulky
- Piezoresistive
  - Nice in sensing at nanoscale
  - Patterning, frequency conversion
- Single Electron Transistor (SET)
  - Very sensitive for NEMS
  - Often at Low-T, non trivial
- Atomic/Quantum Point Contact
  - Very sensitive for NEMS
  - Need impedance matching
  - Bandwidth







Transduction of VHF/UHF SiC NEMS: Magnetomotive Technique



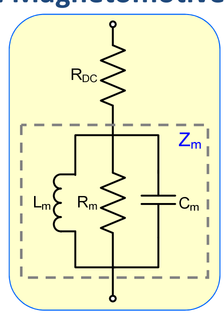
Beam bearing RF current is forced to vibrate in the B field, and thus generates the emf voltage, which reaches max. when the RF current frequency hits the beam's resonance…

$$m\frac{d^2x(t)}{dt^2}+\gamma m\frac{dx(t)}{dt}+kx(t)=F(t)$$

$$F(t)=BlI(t)=BlI_0e^{-j\omega t}$$

$$v_{emf}=\xi Bl\frac{dx(t)}{dt}=\frac{\xi B^2l^2(-j\omega_0)}{-m\omega_0{}^2-j\gamma m\omega_0+k}I(t)$$

$$\frac{1}{Z(\omega_0)}=\frac{m\omega_0}{j\xi B^2l^2}+\frac{\gamma m}{\xi B^2l^2}+\frac{jk}{\xi B^2l^2\omega_0}$$



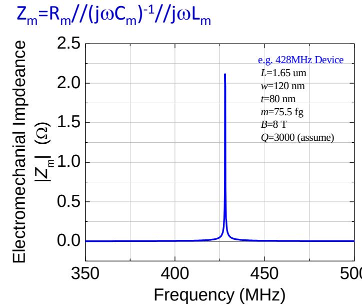
$$R_m=\frac{\xi B^2l^2}{\gamma m}$$

$$C_m=\frac{k}{\xi B^2l^2\omega_0{}^2}$$

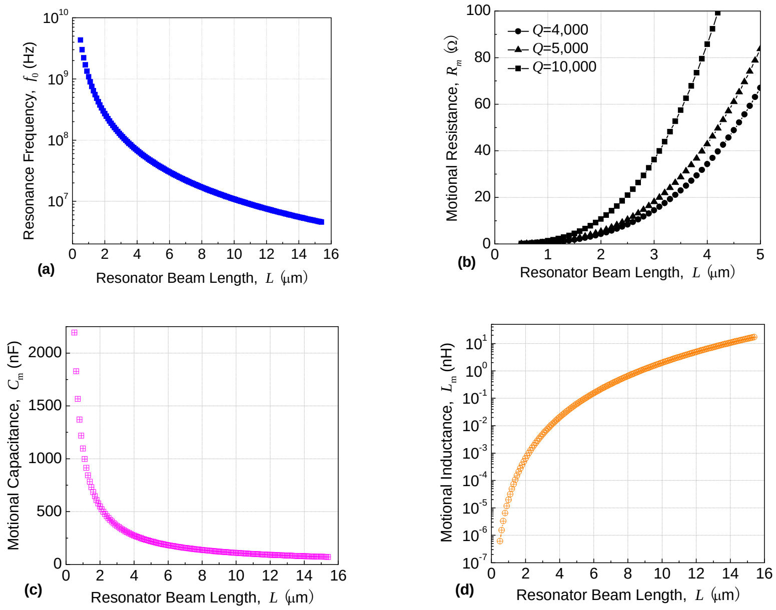
$$L_m=\frac{\xi B^2l^2}{m\omega_0{}^2}$$

Circuit model for the electromechanical impedance

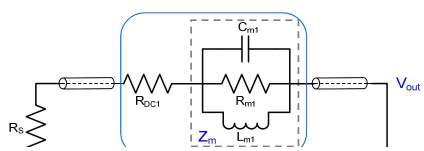
$Z_m=R_m//(j\omega C_m)^{-1}//j\omega L_m$

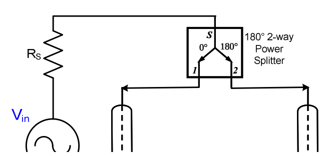


Dimensional Scaling

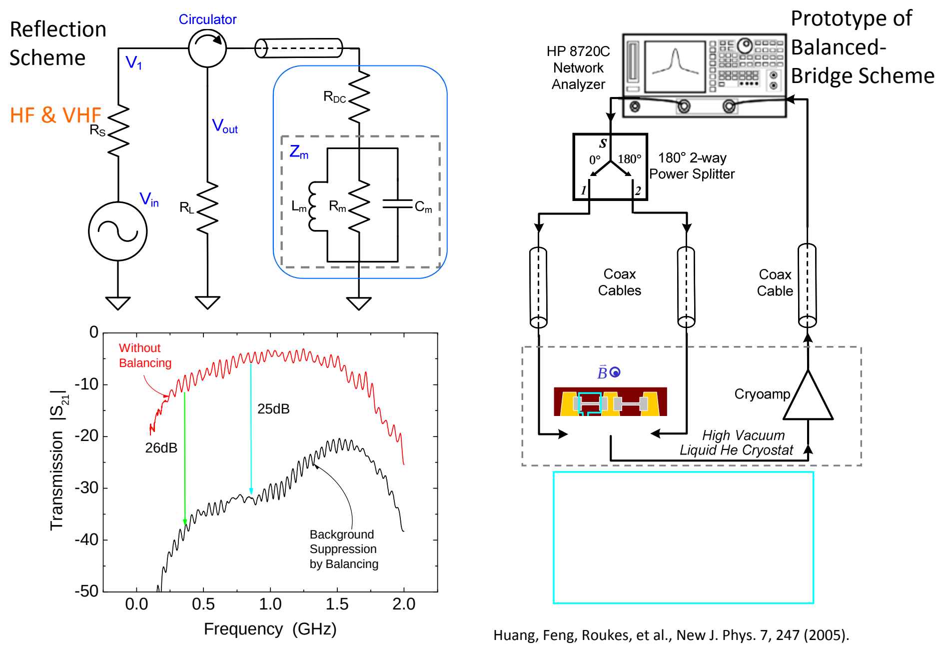


VHF/UHF Resonance Detection Techniques



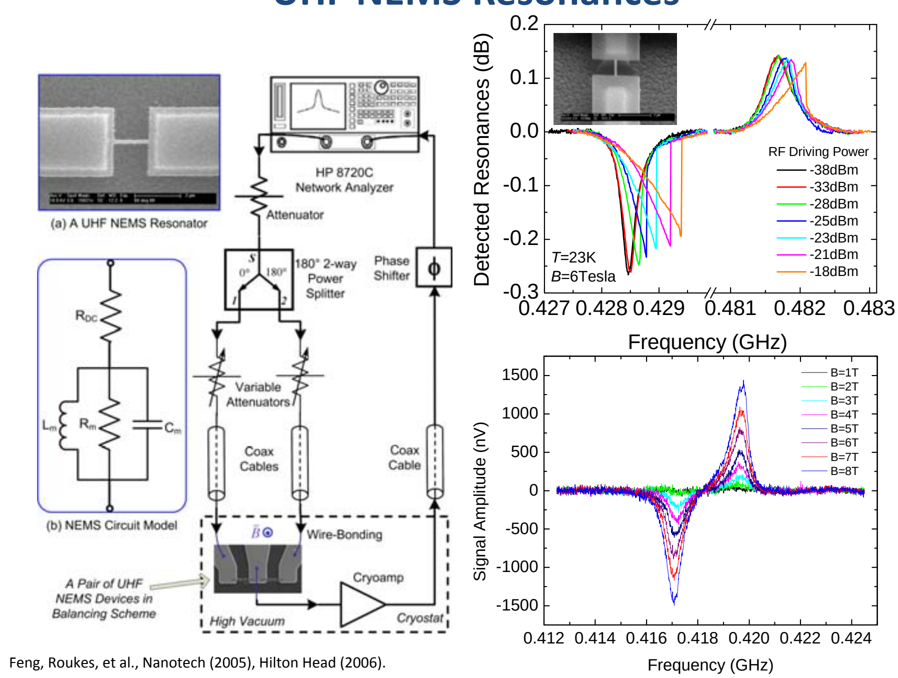


UHF NEMS Resonance Detection



Huang, Feng, Roukes, et al., New J. Phys. 7, 247 (2005).

UHF NEMS Resonances



Feng, Roukes, et al., Nanotech (2005), Hilton Head (2006).

Example: GHz Nanomechanical Resonators

Nanoelectromechanical systems

Nanodevice motion at microwave frequencies

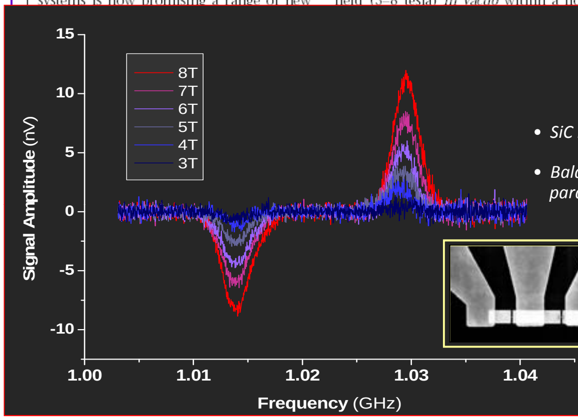
It has been almost forgotten that the first computers envisaged by Charles Babbage in the early 1800s were mechanical[1,2] and not electronic, but the development of high-frequency nanoelectromechanical systems is now promising a range of new

(30 nm of aluminium, followed by 5 nm of titanium), deposited by e-beam evaporation and patterned by lift-off, remains on the beams and is used as the electrode for displacement transduction. The devices consist of two nominally identical, doubly clamped beams, roughly 1.1 μm long, 120 nm wide and 75 nm thick.

Each doubly clamped beam pair is positioned perpendicular to a strong magnetic field (3–8 tesla) *in vacuo* within a liquid-

*Condensed Matter Physics, California Institute of Technology 114-36, Pasadena, California 91125, USA
e-mail: roukes@caltech.edu
†Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, Ohio 44106, USA

1. Roukes, M. L. *Sci. Am.* **285**, 48–57 (2001).
2. Swade, D. *The Difference Engine: Charles Babbage and the Quest to Build the First Computer* (Viking-Penguin, New York, 2001).
3. Roukes, M. L. *Phys. World* **14**, 25–31 (2001).



- *SiC NEMS yields increased frequency*
- *Balanced transduction permits nulling of parasitic (static) background impedance*

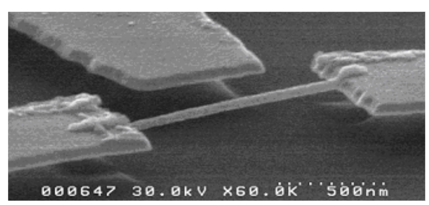
Huang, Zorman, Mehregany, Roukes, *Nature* **421**, 496 (2003)

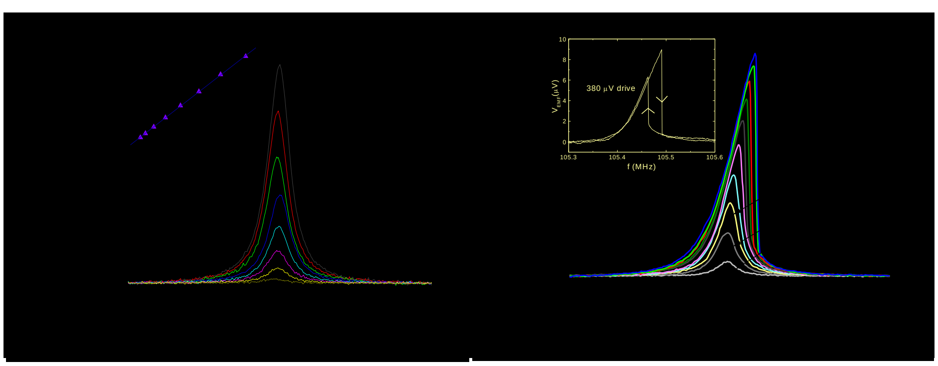
Example: Pt Bottom-Up Nanowire NEMS

VHF Nanowire Resonator

Pt nanowire, ~40nm diameter

f~105 MHz, Q~8,500

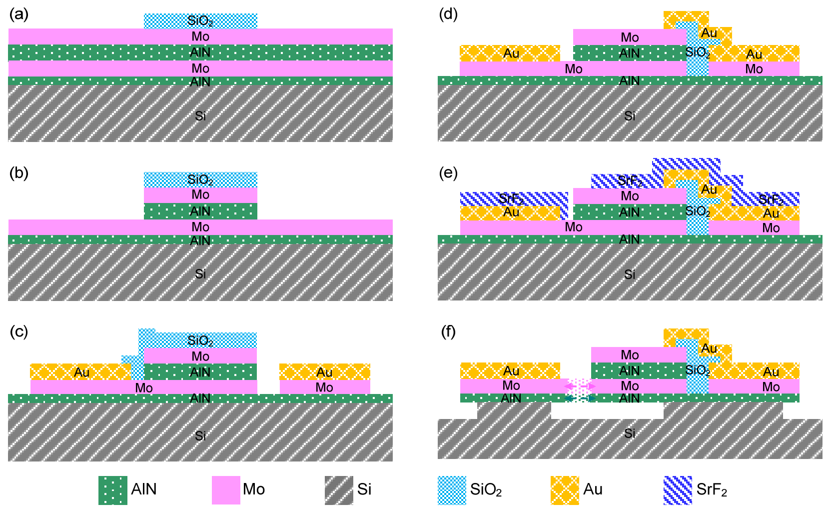




Husain, Hone, Postma, Huang, Drake, Barbic, Scherer, Roukes, *Appl. Phys. Lett.* **83**, 1240-1242 (2003).

NEMS via Nanoscale Active Piezoelectric AlN Films

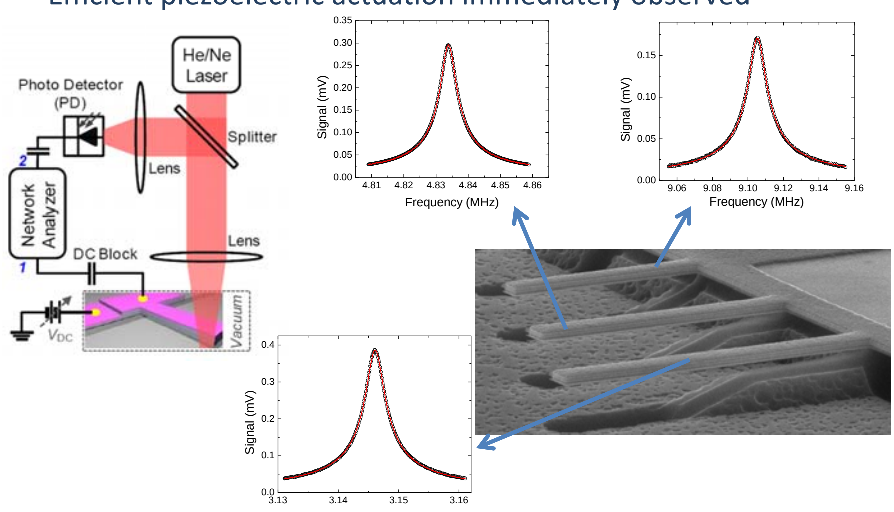
- Stacking (from top): 50-100nm Mo/50-100nm AlN/50-100nm Mo/20nm Seed AlN



Karabalin, Matheny, Feng, Roukes, *et al.*, *Appl. Phys. Lett.* **95**, 103111 (2009).

Piezoelectricity Check

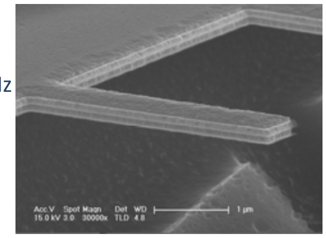
- In optical interferometric measurement setup
- Efficient piezoelectric actuation immediately observed

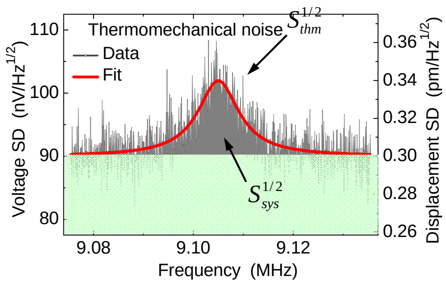


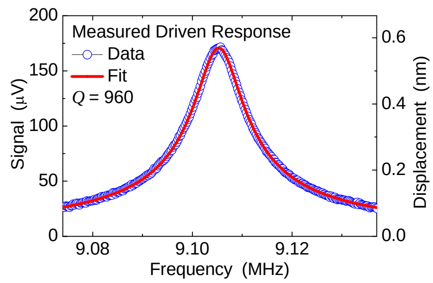
Karabalin, Matheny, Feng, Roukes, *et al.*, *Appl. Phys. Lett.* **95**, 103111 (2009).

Experimental Data 6µm Cantilever

- thermomechanical noise analysis yields:
  - Noise floor $S_{sys}^{1/2}$ =90 nV/√Hz
  - Noise amplitude on resonance $S_{thm}^{1/2}$ =48 nV/√Hz
  - Expected thermomechanical noise $S_{thm}^{1/2}$ =0.16 pm/√Hz
- Driven displacement of 0.54nm at 1mV drive (FEM)
- Responsivity is 300µV/nm
- Displacement sensitivity is 0.3pm/√Hz
- Piezoelectric coefficient d_{31} = 2.4 pm/V



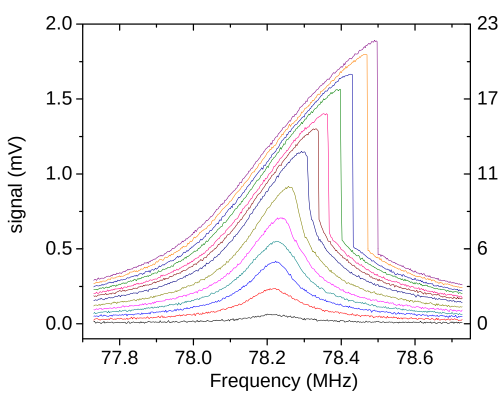


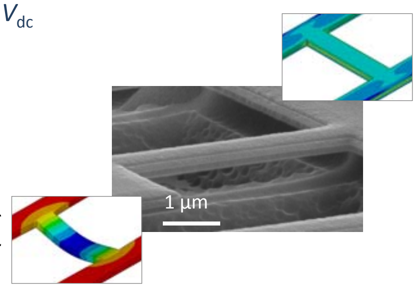


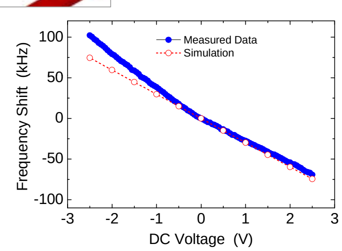
Karabalin, Matheny, Feng, Roukes, *et al.*, *Appl. Phys. Lett.* **95**, 103111 (2009).

Tunable Doubly Clamped Beam Resonators

- Doubly clamped beams are efficiently actuated
- Resonance frequency is tuned via external V_{dc}
- Piezoelectric coefficient d_{31} = 2.4 pm/V







Karabalin, Matheny, Feng, Roukes, *et al.*, *Appl. Phys. Lett.* **95**, 103111 (2009).

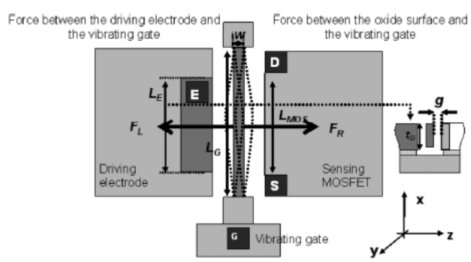
Further Reading – Just Some Partial Lists…

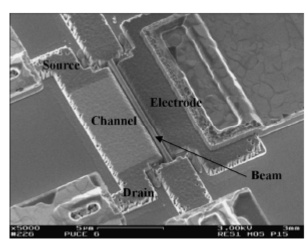
- Piezoresistive (PZR) Devices (many groups):
  - Stanford (Kenny Group)
  - Stanford (Pruitt Group)
  - Denmark (Boisen Group)
  - …

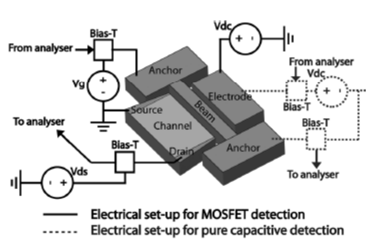
- Piezoelectric (PZE) Devices
  - Berkeley (Pisano Group, Nguyen Group)
  - U Penn (Piazza Group)
  - USC (Kim Group)
  - Gatech (Ayazi Group)
  - UC Irvine (Tang Group)
  - HRL (Kubena Group)
  - Maryland (DeVoe Group)
  - EPFL (Muralt Group)
  - …

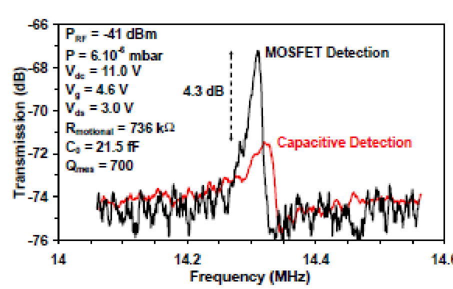
Example: Emerging Interesting Transduction

- NEMS-MOSFET Readout – 'Resonant Gate Transistor'







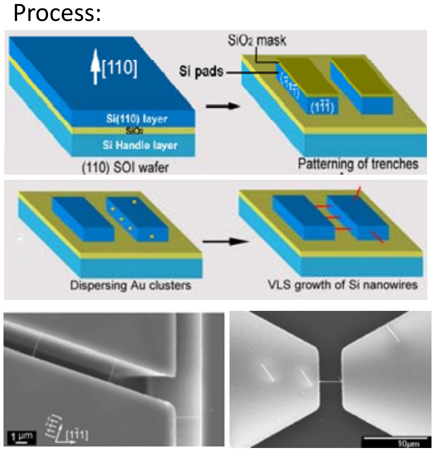


Refs: Colinet, Ionescu, *et al*. LETI & EPFL Collaboration, *J. Solid-State Circuits* **44**, 247 (2009). More in recent IEDM, MEMS conferences

Nanowire NEMS: Hybrid Bottom-Up/Top-Down Devices

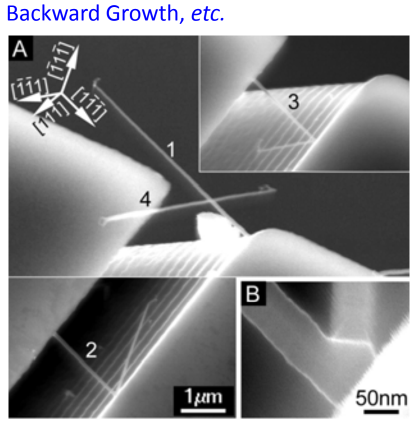
Naturally Suspended Single-Crystal Si Nanowires

Process:



Also have some Control upon Length, Diameter, and SiNWs' Number Density

Aligned Epitaxial Growth,
Interface Cleanliness,
Self-Welding (Anchoring Points),
Backward Growth, *etc.*

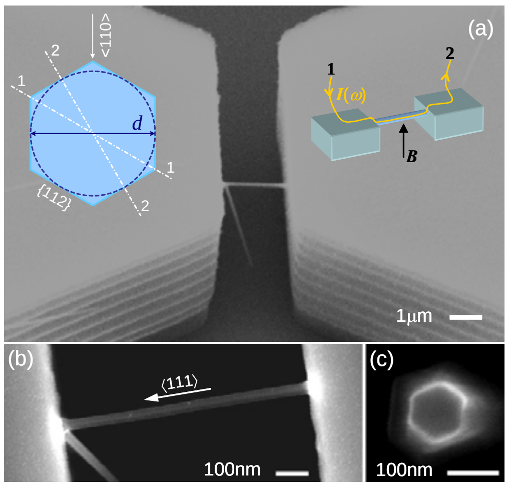


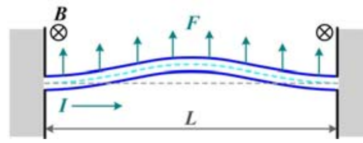
Can we engineer them into functional devices? Are they robust ?

R. He, P. Yang, *et al., Adv. Mater.* **17**: 2098-2102 (2005)

1st Gen. SiNW NEMS Resonators & Transduction

Hexagonal Cross Section, Well-faceted Surfaces
SiNW Suspended in Deep Trench, H~4μm
Typical SiNWs: L~2μm, d~50-150nm





Device Config. Well Suited for Magnetomotive Transduction

$$I_{11} = I_{22} = I = 5\sqrt{3}d^4/144$$

$$f_0 \equiv \frac{\omega_0}{2\pi} = 0.9395\frac{d}{L^2}\sqrt{\frac{E_Y}{\rho}}$$

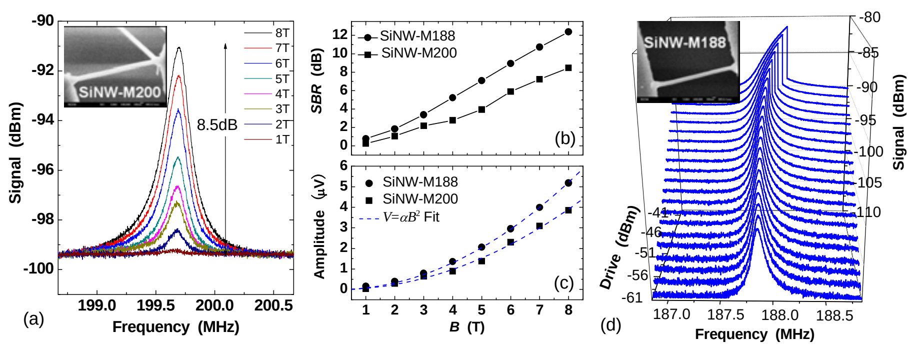
$$V_{EMF}(\omega) = BLv(\omega)\cdot\frac{1}{L}\int_{-L/2}^{L/2}u_0(x)dx = j\omega\eta BL\boldsymbol{a}(\omega)$$ (η=0.5232)

$$\boldsymbol{a}(\omega) = \frac{BL\boldsymbol{I}(\omega)}{M_{eff}\left[(\omega_0^2-\omega^2)+j\omega_0\omega/Q\right]}$$

Feng, He, Yang, Roukes, *Nano Lett.* **7**, 1953-1959 (2007).

1st Gen. VHF SiNW Resonators – Metallized

Metallization: 30nm Al + 5nm Ti
Device Resistance Matched to **50 Ω**
Unprecedented **Signal-to-Background Ratio** (up to 12.5dB)
(using a high-resolution balanced bridge electronic detection)

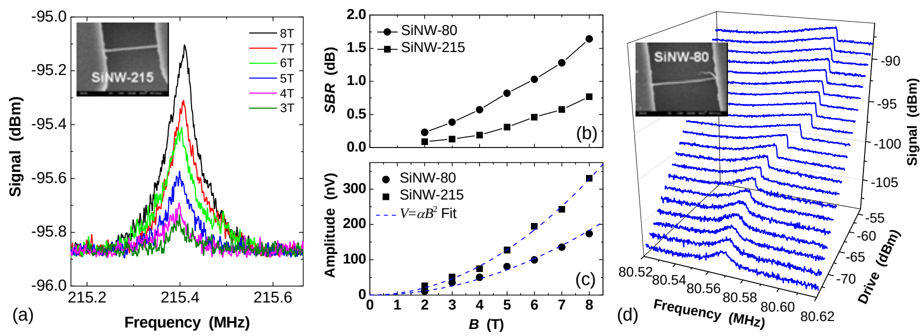


SiNW-M200: L=2.25μm, d=142nm, Q≈2000
SiNW-M188: L=2.1μm, d=118nm, Q≈2500

Feng, He, Yang, Roukes, *Nano Lett.* **7**, 1953-1959 (2007).

1st Gen. VHF SiNW Resonators – Pristine

Non-Metallizated
Device Resistance Not Matched, **~10's of kΩ to ~100's of kΩ**
Still Achieved Large **Signal-to-Background Ratio** (1–2dB)

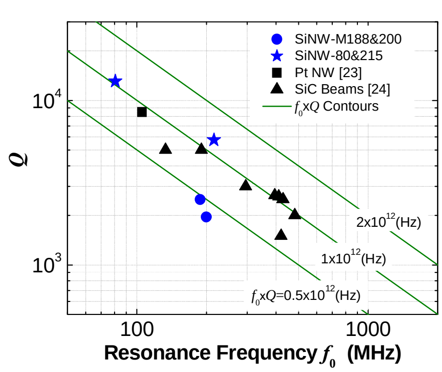


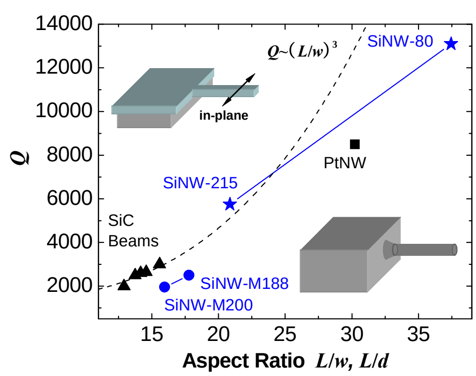
SiNW-215: L=1.69μm, d=81nm, Q≈5750
SiNW-80: L=2.77μm, d=74nm, Q≈13100

Feng, He, Yang, Roukes, *Nano Lett.* **7**, 1953-1959 (2007).

SiNWs' Quality Factors (Q's)

- Well-known f_0–Q trade-off confirmed
- VHF/UHF devices: clamping losses important as f_0 scales up

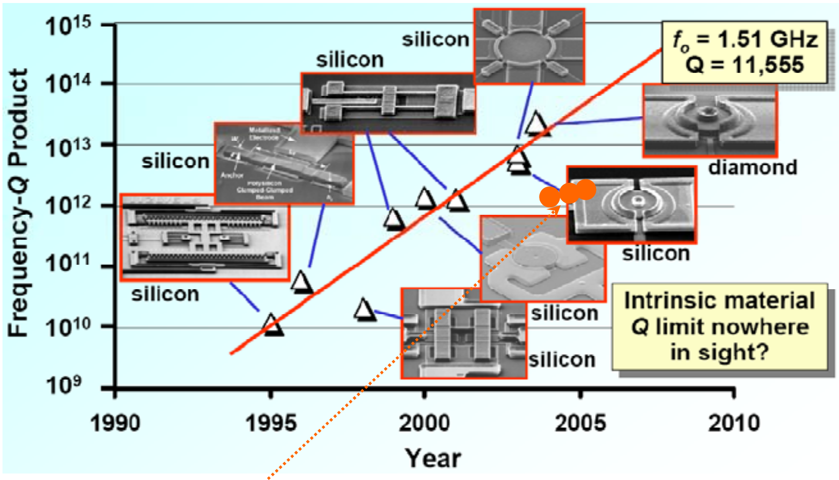




Feng, He, Yang, Roukes, *Nano Lett.* **7**, 1953-1959 (2007).
Feng, Zorman, Mehregany, Roukes, et al., *Hilton Head'06*, pp. 86-89 (2006).
Cross, Lifshitz, *Phys. Rev. B* **64**, 085324 (2001).

$f_0 \times Q$ Product: Roadmap of MEMS/NEMS Resonators

- $f_0 \times Q$ product rising exponentially over the past years

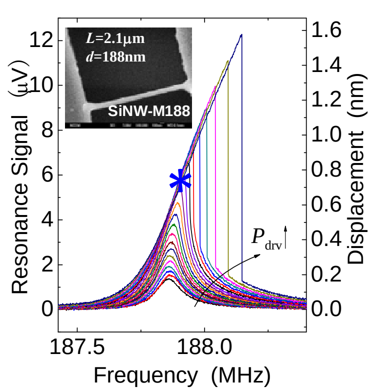


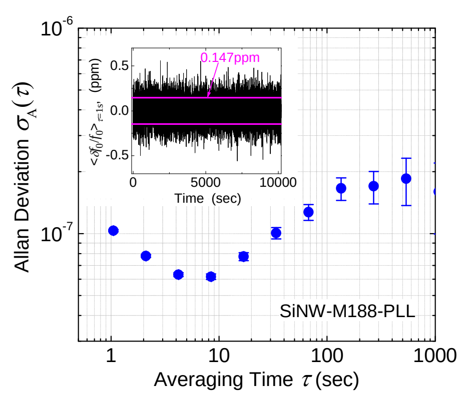
- Caltech UHF SiC beams & SiNWs match the MEMS beams ($f_0 \times Q \geq 10^{12}$, *e.g.*, with ~500MHz beams having $Q \geq 2000$)

Courtesy: Dr. C.T.-C. Nguyen (UC Berkeley)

Measured Frequency Stability – Si Nanowires

- SiNW operating at 188MHz, embedded in phase-locked circuit
- "Instantaneous" fractional frequency fluctuation: ~0.1ppm
- Mass responsivity: $\Re \approx 2.1$Hz/zg
- Mass sensitivity: $\delta M \approx 5$zg (5×10^{-21}g)

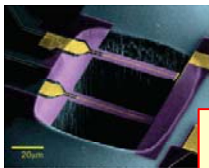


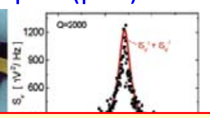


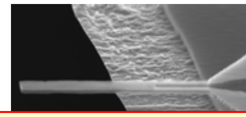
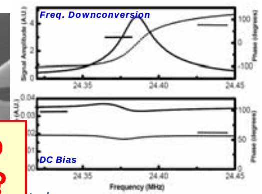
Feng, He, Yang, Roukes, *IEEE Transducers'07*, 327-330 (2007).

Transduction: Piezoresistive Self-Sensing for NEMS

Piezoresistive Doped (p++) Si NEMS



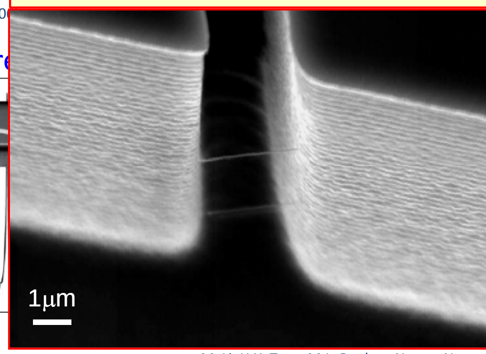


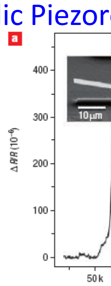
J.L. Arlett, J.R. Maloney, M.L. R... *Nano Lett.* **6**: 1000-1006 (200...

...t al.,

How to make a piezoresistor loop on a sub-50nm thin Si nanowire ?



Metallic Piezore...

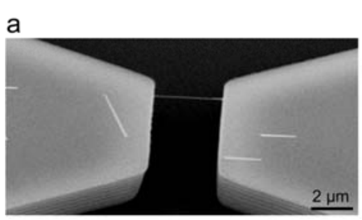


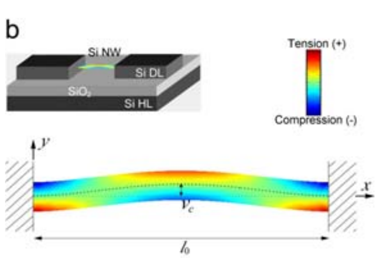
M. Li, H.X. Tang, M.L. Roukes, *Nature Nanotechnology* **2**: 114-120 (2007)

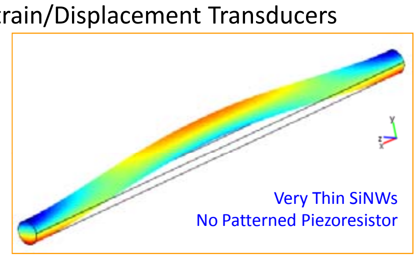
Strain Engineering for Integrated Si Nanowire Resonators

Doped Si NWs → Integrated Piezoresistive Strain/Displacement Transducers

Very strong piezoresistive effect
[He & Yang, *Nature Nanotech.* **1**, 42 (2006)]







Integral of 1st order strain vanishes
→ No signal due to 1st order strain

Longitudinal strain due to elongation:

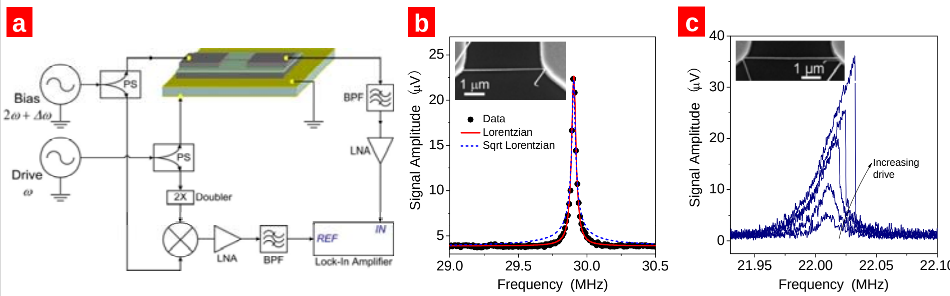
$$\varepsilon_l = \frac{\Delta l}{l_0} \approx \frac{1}{2l_0}\int_0^{l_0}\left(\frac{dv}{dx}\right)^2 dx = 2.44\left(\frac{v_c}{l_0}\right)^2$$

Elongated twice in each vibration cycle → piezoresistive signal at 2ω

He*, Feng*, Roukes, Yang, *Nano Lett.* **8**, 1756-1761 (2008).

2ω-Piezoresistive Self-Sensing SiNWs
(Piezo Shaker Excitation)

- Mechanical actuation (via mechanical 'shaking' coupling from a piezo-actuator)
- Clean evidences of 2ω-piezoresistive self-sensing
- x^2-detection; and stiffening nonlinearity



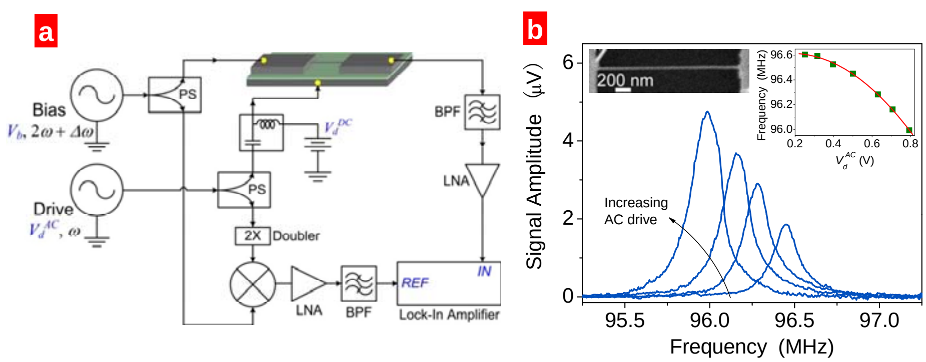
d=80nm, L=4.6µm
f_0~30MHz
Fitting verifies x^2-detection

d=88nm, L=4.9µm
f_0~22MHz
Stiffening Nonlinearity

He*, Feng*, Roukes, Yang, *Nano Lett.* **8**, 1756-1761 (2008).

40nm Si Nanowire NEMS with Integrated Transduction

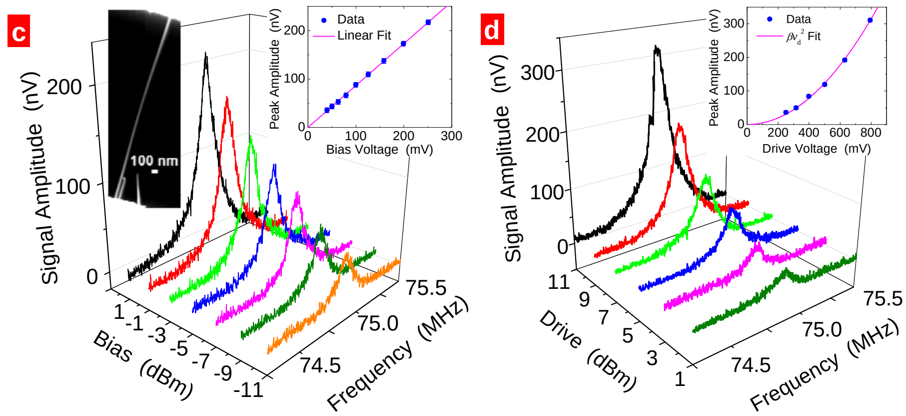
- On-Chip Electrostatic Actuation + Piezoresistive Detection
- Fully Integrated Transduction (T~300K, p~1mTorr)
- Device Spec & Performance: d=40nm, L=1.8µm, f_0=96MHz, Q~800



He*, Feng*, Roukes, Yang, *Nano Lett.* **8**, 1756-1761 (2008).

30nm Si Nanowire NEMS with Integrated Transduction

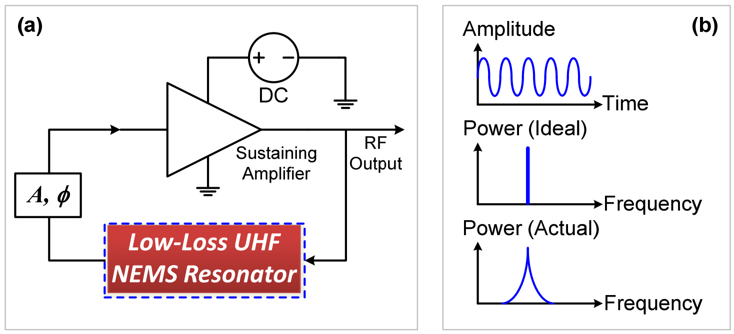
- On-Chip Electrostatic Actuation + Piezoresistive Detection
- Fully Integrated Transduction (T~300K, p~1mTorr)
- Device Spec & Performance: d=30nm, L=1.8μm, f_0=75MHz, Q~1000
- Sub-Zeptogram Mass Sensitivity: δM = 500yg, $\Re$ = 15Hz/zg



VHF/UHF NEMS Oscillators:
Recent Prototype Examples

Can a NEMS Resonator be a Frequency Reference ?

- Basic Principle: DC→RF, Active Signal/Function Generator/"Clock"

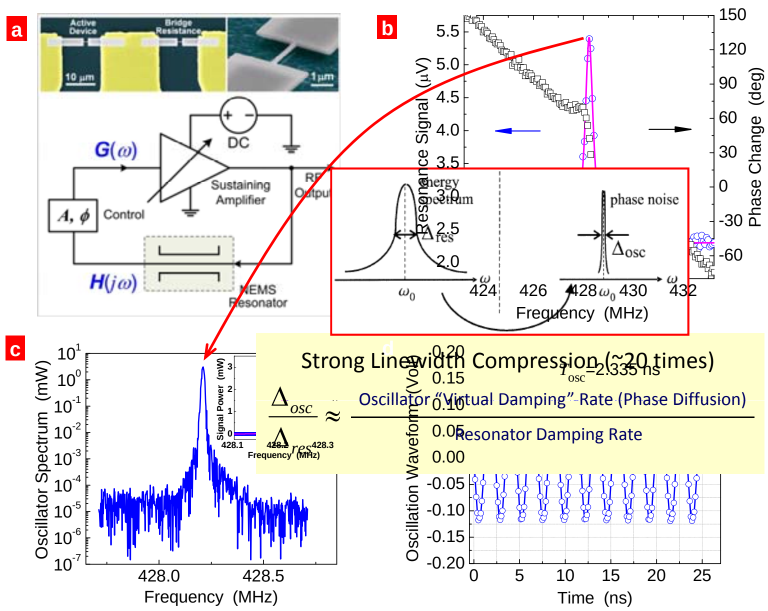


Barkhausen Criteria for Self-Sustaining Oscillation:

Loop Gain: $|H(\omega)| \geq 1$ (0dB)

Loop Phase Change: $\Delta\phi\,[H(\omega)] = 2n\pi$ (n is an integer)

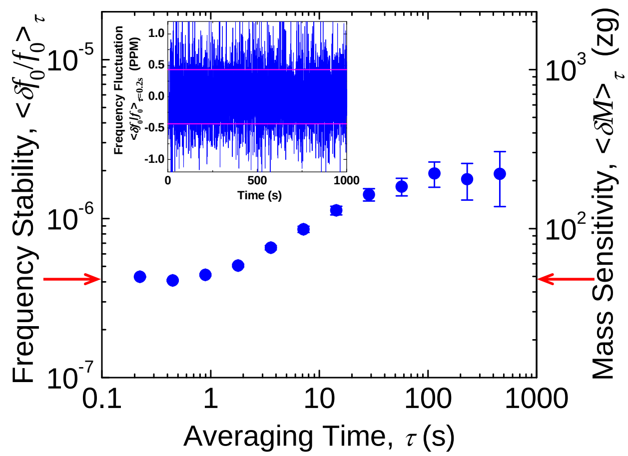
Self-Sustaining UHF NEMS Oscillator @ 428MHz



Feng, White, Hajimiri, Roukes, *Nature Nanotech.* **3**, 342-346 (2008). Ham & Hajimiri, *IEEE JSSC* **38**, 407-418 (2003)

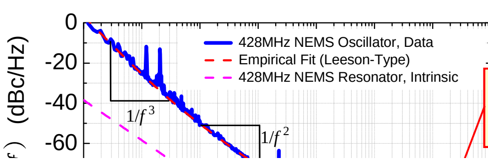
Frequency Stability Data

- Short-term fluctuation: ~4×10^{-7}
- Mass sensitivity: ~49zg (device mass ~55fg)
- Self-sustaining NEMS oscillators (with Si nanowires) → "NEMSIC"



Feng, White, Hajimiri, Roukes, *Nature Nanotech.* **3**, 342-346 (2008).

Phase Noise Data



Leeson's Model

$$L(f) = 10\log\left[\frac{2F_n k_B T}{P_C}\cdot\left(1+\frac{f_0}{2Qf}\right)^2\left(1+\frac{f_{1/f^3}}{f}\right)\right]$$

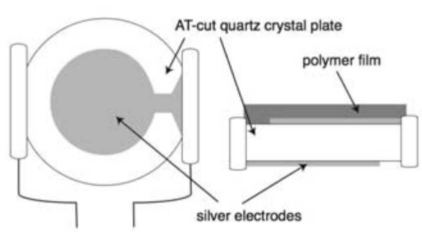
- Phase noise mostly dominated by thermal (Johnson) and amplifier noise. Fit well with Leeson-type model.
- Device intrinsic phase noise limit set by thermomechanical noise, readout not matched to this limit. Still possible to improve.

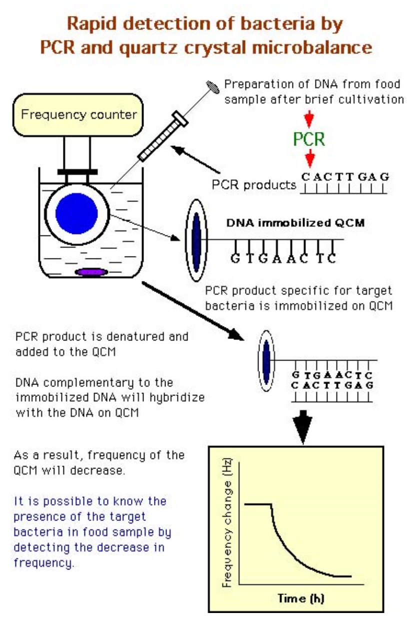
Feng, White, Hajimiri, Roukes, *Nature Nanotech.* **3**, 342-346 (2008).

Emerging Applications #1
– Ultrasensitive Mass Detection

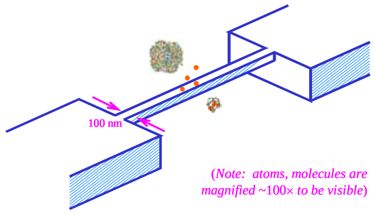
Towards Single-Molecule Mass Sensing

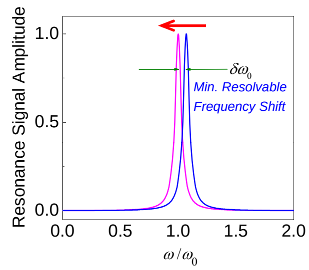
Quartz Crystal Microbalance (QCM)





NEMS Resonant Mass Sensing: Basic Principle & Metrics





Physical Process: mass loading effect upon the resonator → resonance frequency shift
Sensing: resonance frequency shift measurement → detected mass
Advantage: frequency shift/variation can be measured with great accuracy

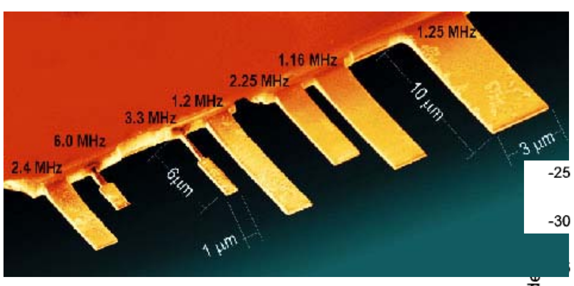
Resonant Mass Sensing: Sensitivity

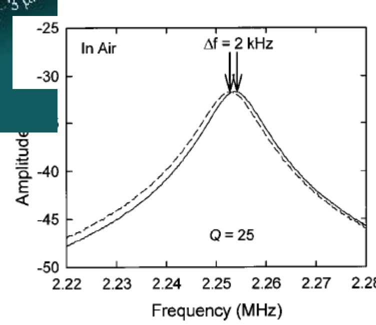
$$\delta M \approx \frac{\partial M_{eff}}{\partial \omega_0} \cdot \delta\omega_0 = \Re^{-1} \cdot \delta\omega_0$$

Mass Responsivity: $\Re \equiv \dfrac{\partial \omega_0}{\partial M_{eff}}$ *Frequency Shift Resolution*: $\delta\omega_0$

Femtogram (10^{-15}g) Sensitivity

- Au-coated Si cantilevers, 1-10MHz, 50-100nm thick, 2-10um long, 1-3um wide
- Devices FIB'ed from commercial, much bigger devices
- 5.5fg, chemisorption of 11-mercaptoundecanoic acid
- Photothermal actuation, interferometric readout, room-T, in air
- Separate measurements, before and after the exposure to vapor

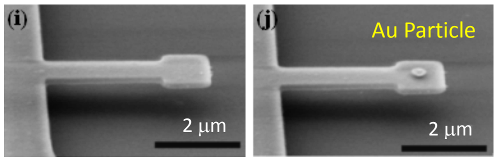


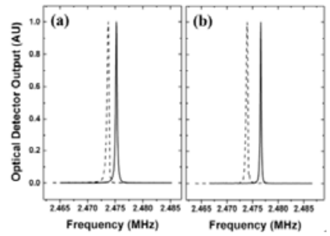


Lavrik, Datskos, *et al.*, *Appl. Phys. Lett.* **82,** 2697(2003).

Other Similar Measurements

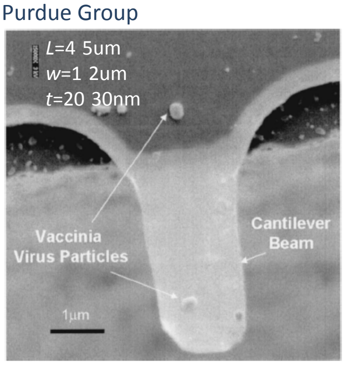
- Cornell Group

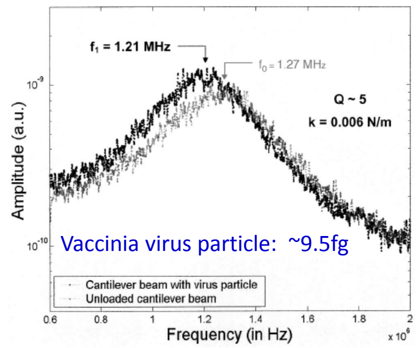




Deposited Au as added mass, do resonance measurement separately, before and after the fabrication processes of the added Au.

- Purdue Group

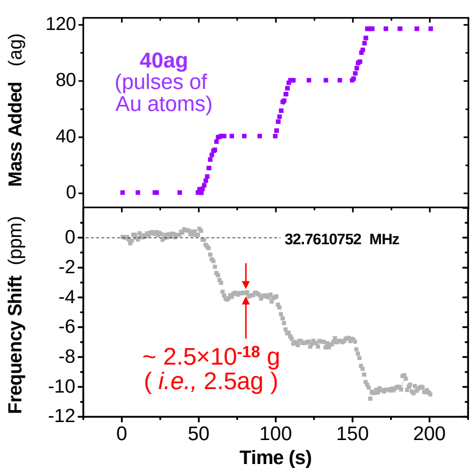


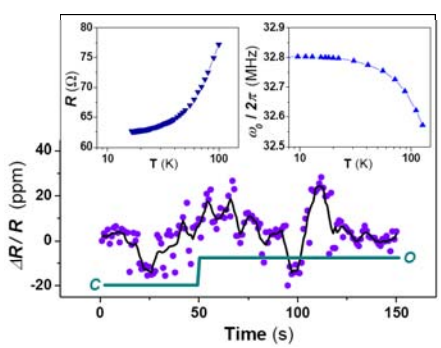


Refs: Ilic, et al., *J. Appl. Phys.*, **95,** 3694 (2004), and more from Craighead group; Gupta, Akin, Bashir, *Appl. Phys. Lett.* **84**, 1976 (2004).

Attogram (10^{-18}g) NEMS Mass Sensing (1st milestone)

- Controlled pulses of Au atoms, flux also calibrated by a QCM
- $f_0 \approx$ 32.8 MHz doubly-clamped beam, low-noise PLL readout
- Device: $L \times w \times t$ = 14μm × 650nm × 260nm, $\mathfrak{R}$ = 2.6Hz/ag (mass responsivity)





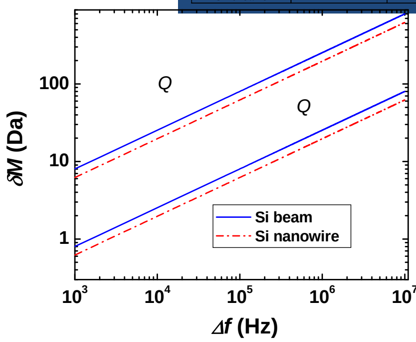
Careful control experiments verifying excellent thermal stability

Ekinci, Huang, Roukes, *Appl. Phys. Lett.* **84**, 4469-4471 (2004)

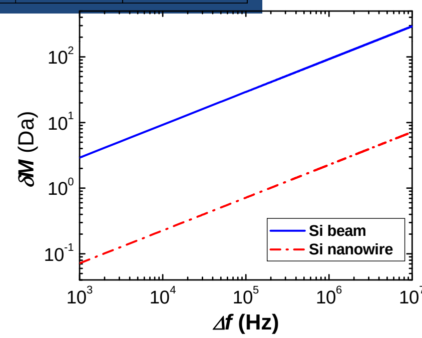
Look into Fundamentals → Ultimate Limits: (I)

Parameters of the two representative 1GHz NEMS resonators

$w \times t \times \ell$ (nm)	$M_{eff} = 0.735wlt\rho$ (g)	κ_{eff} (N/m)	$\langle x_c \rangle$ (nm)	$E_c = M_{eff}\omega_0^2\langle x_c^2 \rangle$ (J)	*DR* at 300 K $DR=10\log(E_c/k_BT)$ (dB)
50 × 80 × 780 Si Beam	5.30×10^{-15}	~290	42	3.7×10^{-13}	~80
15 × 15 × 340 Si nanowire	1.30×10^{-16}	~6.73	8	3.5×10^{-16}	~50



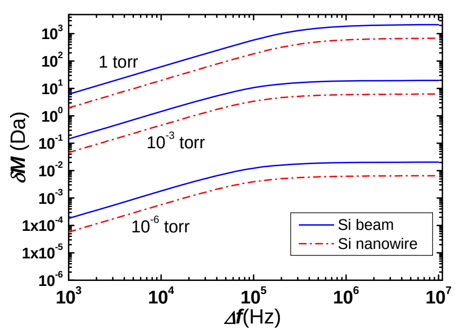
Limits to mass sensitivity δM, in units of Daltons (Da), imposed by ***thermomechanical fluctuations***, as a function of the measurement bandwidth, Δf, for the two representative 1 GHz resonators.



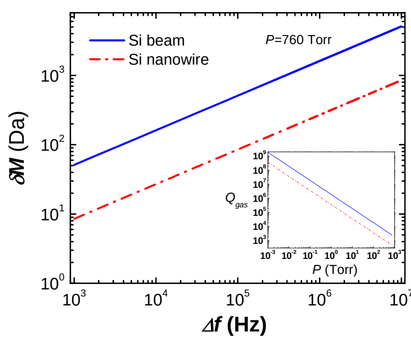
Mass sensitivity limits imposed by ***temperature fluctuations*** as a function of measurement bandwidth, for the two representative 1 GHz silicon resonators, for operation at T=300 K.

Ekinci, Yang, Roukes, *J. Appl. Phys.* **95**, 2682-2689 (2004)

Fundamentals → Ultimate Limits: (II)



Limits to mass sensitivity imposed by ***adsorption-desorption processes***, for the two representative 1 GHz NEMS resonators. The calculations displayed are for three different pressures of N_2.

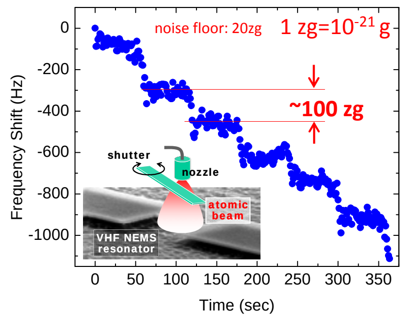


Limits to mass sensitivity set by ***momentum exchange noise*** between the resonator and gas molecules for a resonator intrinsic Q of $Q_U=10^5$ at atmospheric pressure of N_2 (p=760Torr). The inset shows Q_{gas} as a function of the gas pressure for both resonators.

Ekinci, Yang, Roukes, *J. Appl. Phys.* **95**, 2682-2689 (2004)

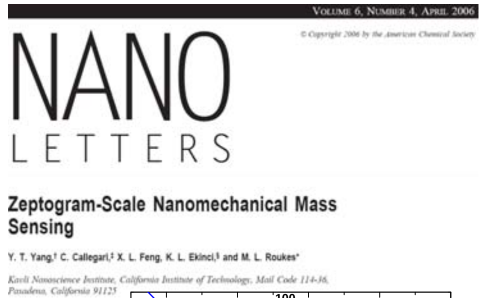
Zeptogram (10^{-21}g) NEMS Mass Sensing (2nd milestone)

real-time steps with respect to mass loading



Min. Noise Floor Achieved → 7 zg

equivalent to single (4 kDa) macromolecule
...or about 32 Xe atoms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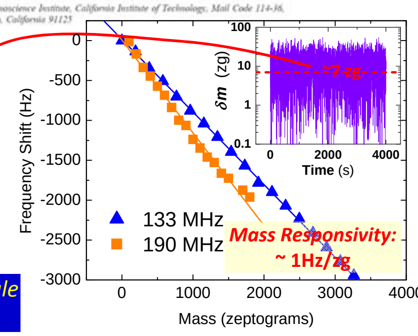
NANO LETTERS

Zeptogram-Scale Nanomechanical Mass Sensing

Y. T. Yang, C. Callegari, X. L. Feng, K. L. Ekinci, and M. L. Roukes*

Kavli Nanoscience Institute, California Institute of Technology, Mail Code 114-36, Pasadena, California 91125



A route to weighing single-molecule with single Dalton resolution...

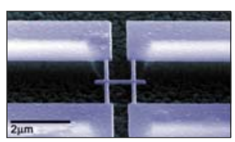
Zeptogram (10^{-21}g) NEMS Mass Sensing (2nd milestone)

Science NEWSFOCUS

PHYSICS

Tipping the Scales—Just Barely

Researchers are making big strides in a race to build nano-sized devices capable of weighing a single proton



nature

RESEARCH HIGHLIGHTS

MEASUREMENT SCIENCE

Small scale

Nano Lett. **6**, 583–586 (2006)

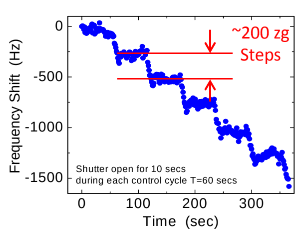
Researchers in the United States have fine-tuned a sensing technique to measure mass with zeptogram (10^{-21} g) resolution. In principle, this should make it possible to weigh tens of atoms or a single molecule.

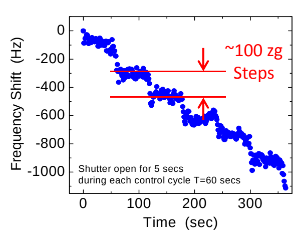
AMERICAN INSTITUTE OF PHYSICS "Top-10 Physics Stories"

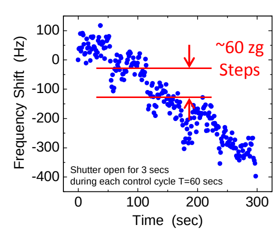
BBC NEWS **Scales tip with tiniest mass yet**

NewScientist

- Highly repeatable measurements with good controls

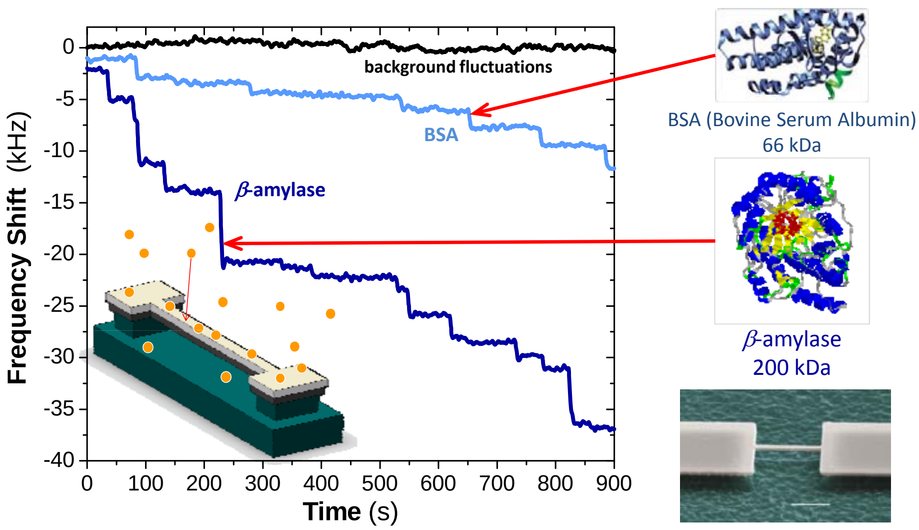






Single-BioMolecule NEMS Mass Sensing (latest milestone)

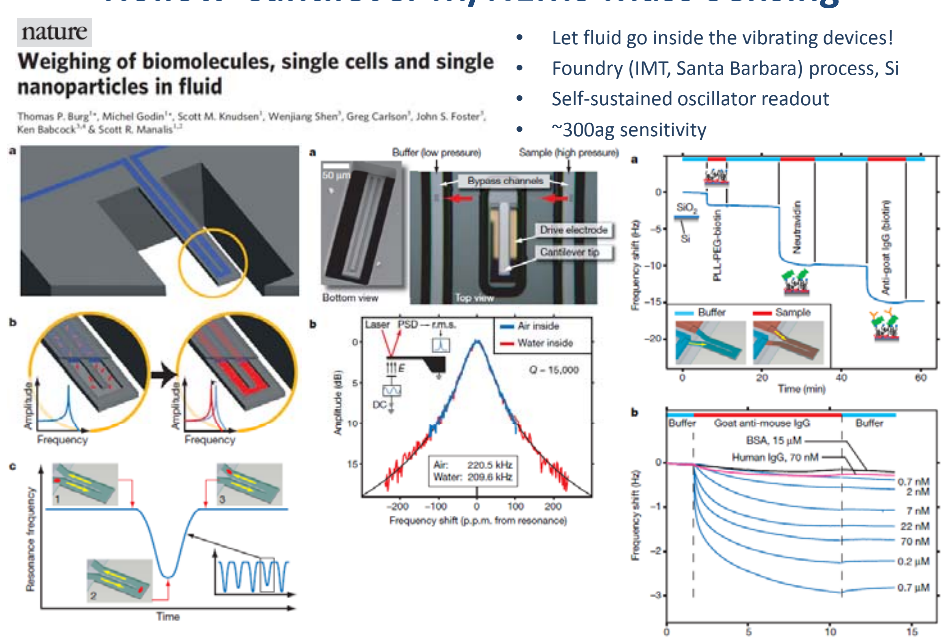
- Single-molecule events (*precipitous frequency jumps*) in real-time
  (Hallmark of single-molecule *nanomechanical* sensing and mass spectrometry)



Naik, Hanay, Hiebert, Feng, Roukes, *Nature Nanotechnology* **4**, 445-449 (2009)

Hollow-Cantilever M/NEMS Mass Sensing

- Let fluid go inside the vibrating devices!
- Foundry (IMT, Santa Barbara) process, Si
- Self-sustained oscillator readout
- ~300ag sensitivity



Burg, Godin, Manalis, *et al.*, *Nature* **446**, 1066 (2007)

Summary, Current & Upcoming Challenges

- Summary of major lab setting milestones
  - Single molecule/atom sensitivity in vacuum
  - Single large (bio)molecule sensitivity in vacuum and in fluids
  - A number of relevant technological ingridients developed
  - Mostly at device level
- Challenges:
  - Detection in fluids / real biofluidics, concentration & capturing
  - Devices & system engineering w.r.t. nanofluidics (*Re* number)
  - Readout
  - System-level integration & packaging

Further Reading…

- Carbon Nanotube (CNT) NEMS Resonators
  - Berkeley (Zettl)
  - Cornell (McEuen)
  - Delft (van der Zant)
  - Caltech→UC Riverside (Bockrath)
  - …
- Silicon Nanowires
  - NINT, Canada (Hiebert, Freeman)
  - Michigan (Lu)
  - HP (Williams)
  - …
- Graphene NEMS
  - Cornell, Boulder (McEuen, Craighead, Bunch)
  - Columbia (Kim, Hone)
  - …