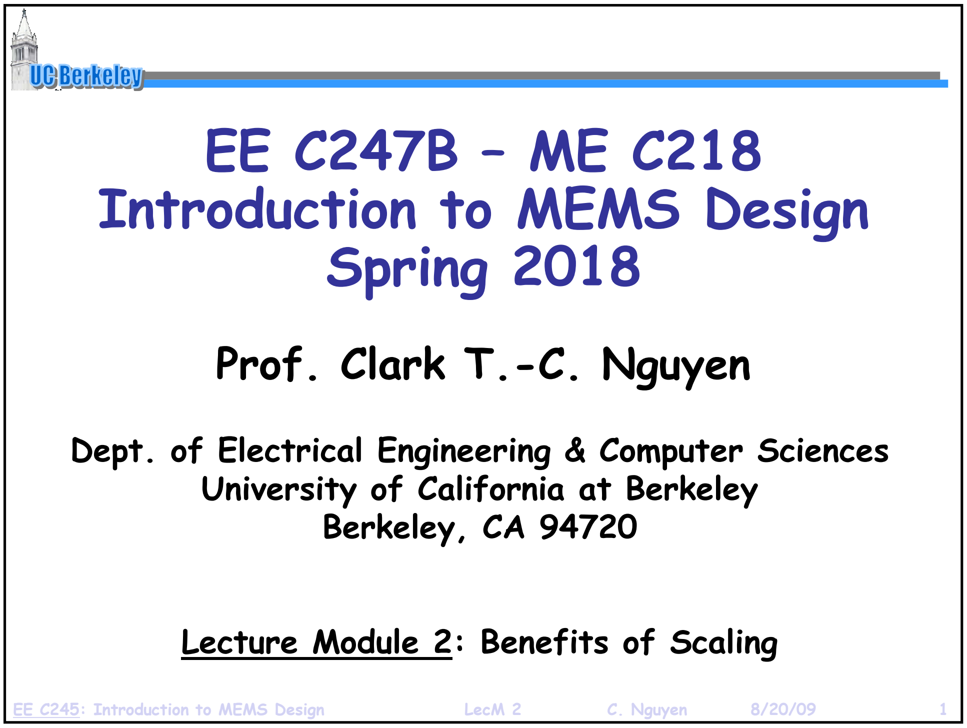

EE C247B – ME C218
Introduction to MEMS Design
Spring 2018

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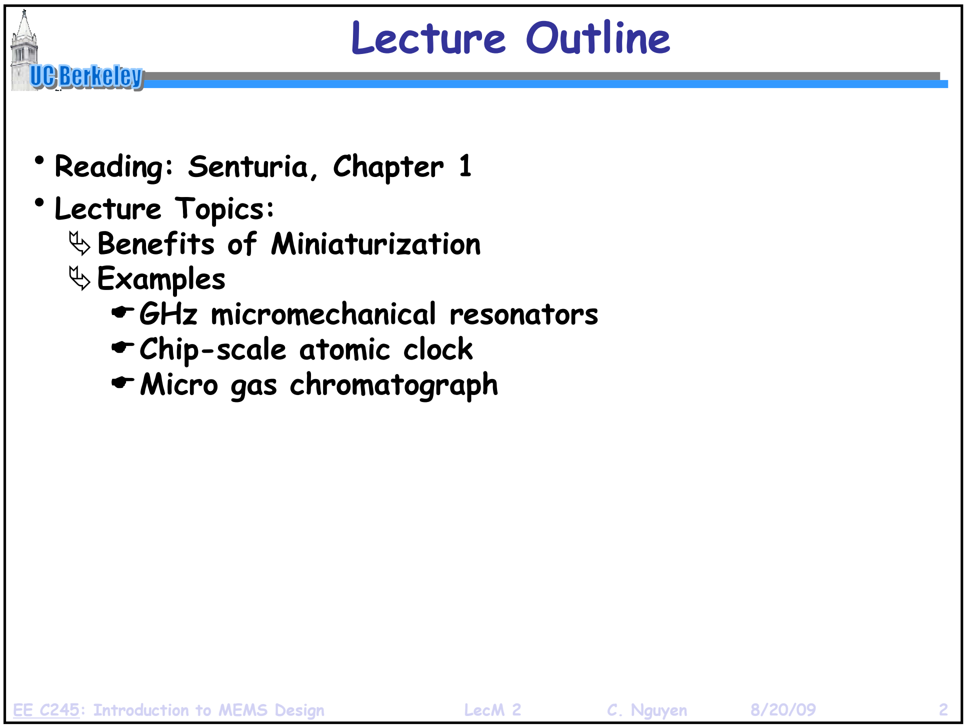
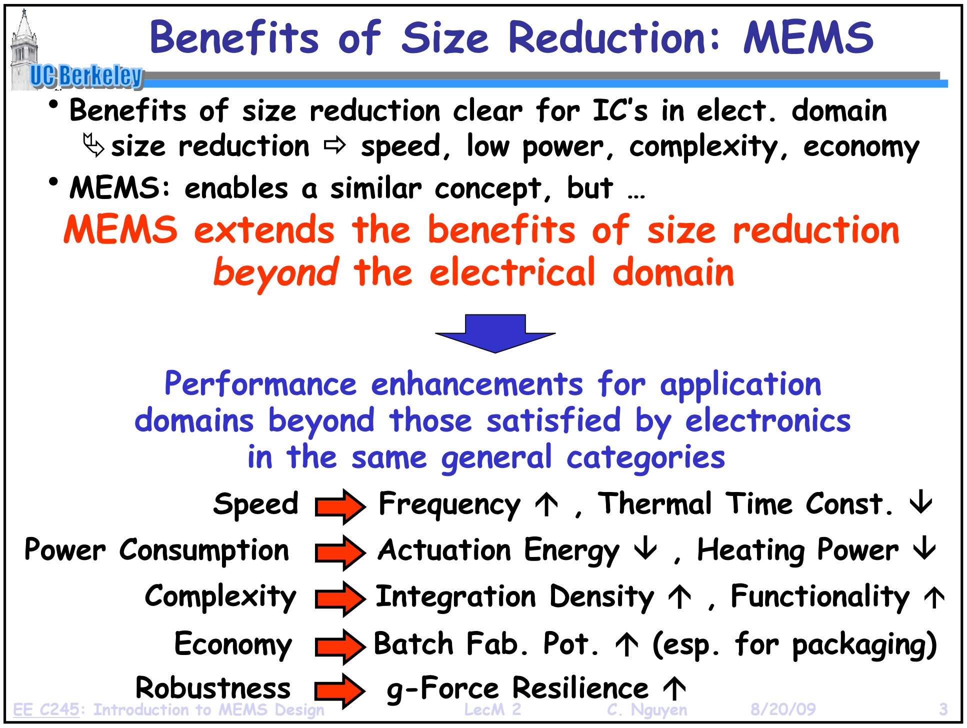
University of California at Berkeley
Berkeley, CA 94720

Lecture Module 2: Benefits of Scaling



Lecture Outline

- Reading: Senturia, Chapter 1
- Lecture Topics:
  - Benefits of Miniaturization
  - Examples
    - GHz micromechanical resonators
    - Chip-scale atomic clock
    - Micro gas chromatograph



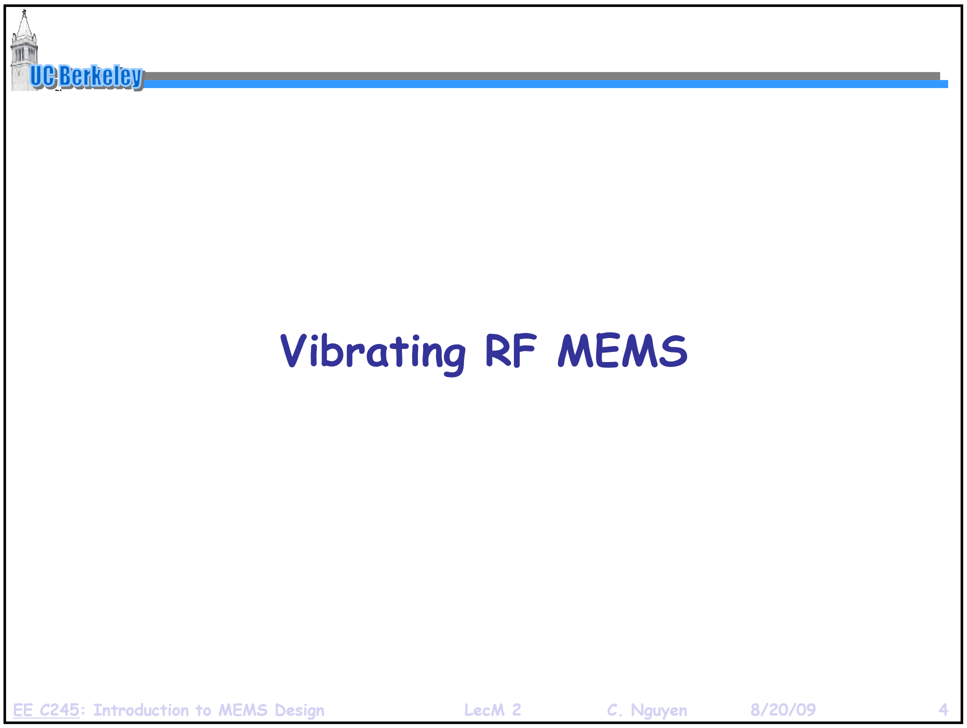
Benefits of Size Reduction: MEMS

- Benefits of size reduction clear for IC's in elect. domain
  - size reduction ⇨ speed, low power, complexity, economy
- MEMS: enables a similar concept, but …

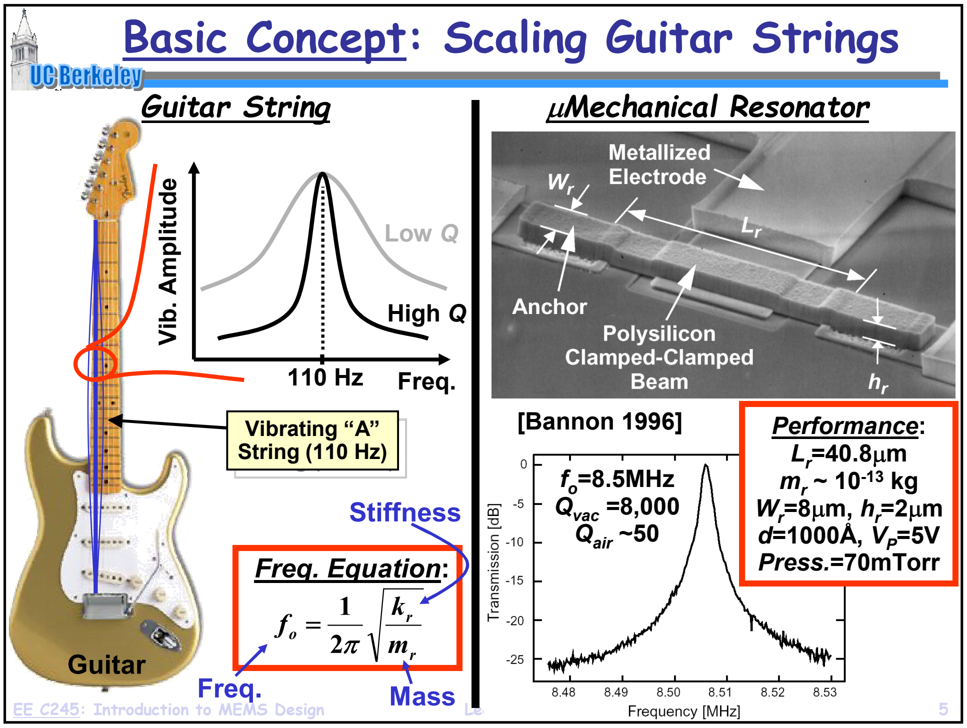
MEMS extends the benefits of size reduction *beyond* the electrical domain

Performance enhancements for application domains beyond those satisfied by electronics in the same general categories

Speed ➡ Frequency ↑ , Thermal Time Const. ↓
Power Consumption ➡ Actuation Energy ↓ , Heating Power ↓
Complexity ➡ Integration Density ↑ , Functionality ↑
Economy ➡ Batch Fab. Pot. ↑ (esp. for packaging)
Robustness ➡ g-Force Resilience ↑



Vibrating RF MEMS



Basic Concept: Scaling Guitar Strings

Guitar String

Freq. Equation:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

μMechanical Resonator

[Bannon 1996]

f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50

Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr

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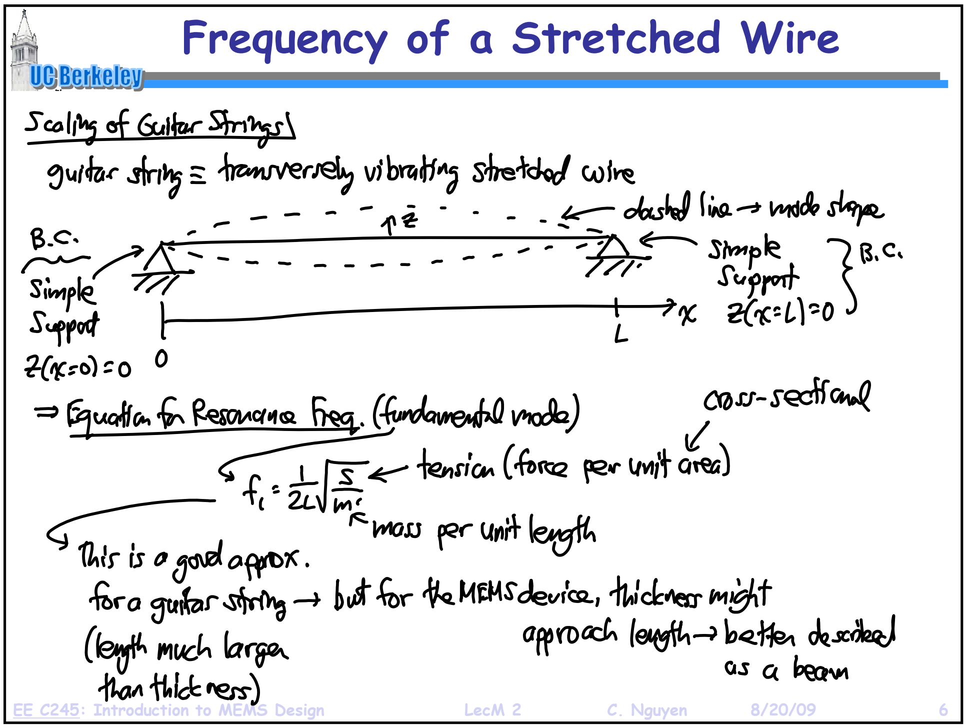

Frequency of a Stretched Wire

Scaling of Guitar Strings

guitar string ≡ transversely vibrating stretched wire

⇒ Equation for Resonance Freq. (fundamental mode)

$$f_1 = \frac{1}{2L}\sqrt{\frac{S}{m_l}}$$

← tension (force per unit area)
cross-sectional
← mass per unit length

This is a good approx.
for a guitar string → but for the MEMS device, thickness might approach length → better described as a beam
(length much larger than thickness)

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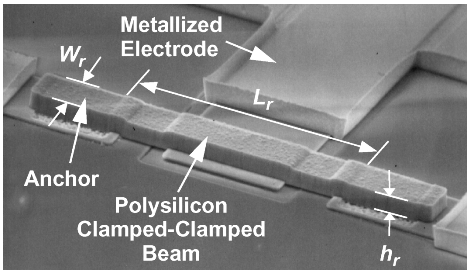
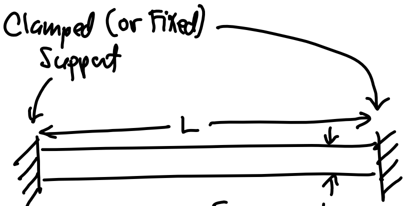
Frequency of a Clamped-Clamped Beam

Clamped-Clamped Beam





⇒ Eq. for Resonance freq.:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = 1.03\sqrt{\frac{E}{\rho}}\,\frac{h}{L^2} \quad (1)$$

where $E \triangleq$ Young's modulus [GPa]
$\rho \triangleq$ density [kg/m³]
$h \triangleq$ thickness [m]
$L \triangleq$ length [m]

Example. $L = 40\mu m$, $h = 2\mu m$
polySi → $E = 150$ GPa, $\rho = 2300$ kg/m³

$$\therefore f_o = \underbrace{(1.03)\sqrt{\frac{150G}{2300}}}_{\text{acoustic velocity} = 8{,}076\, m/s}\frac{2\mu}{(40\mu)^2} \rightarrow \boxed{f_o = 10.4MHz}$$

As L↓ → f_o↑!

Frequency of a Clamped-Clamped Beam

Example. $L = 4\mu m \rightarrow f_o = (1.03)(8076)\frac{2\mu}{(4\mu)^2} \rightarrow \boxed{f_o = 1.04GHz!}$

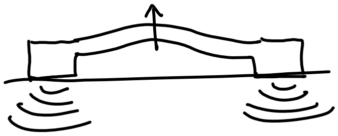
GHz freqs. possible!

Smaller ↓ Faster!

Remarks.

① Eq. (1) not accurate when $L \approx h$. (See HW#1)

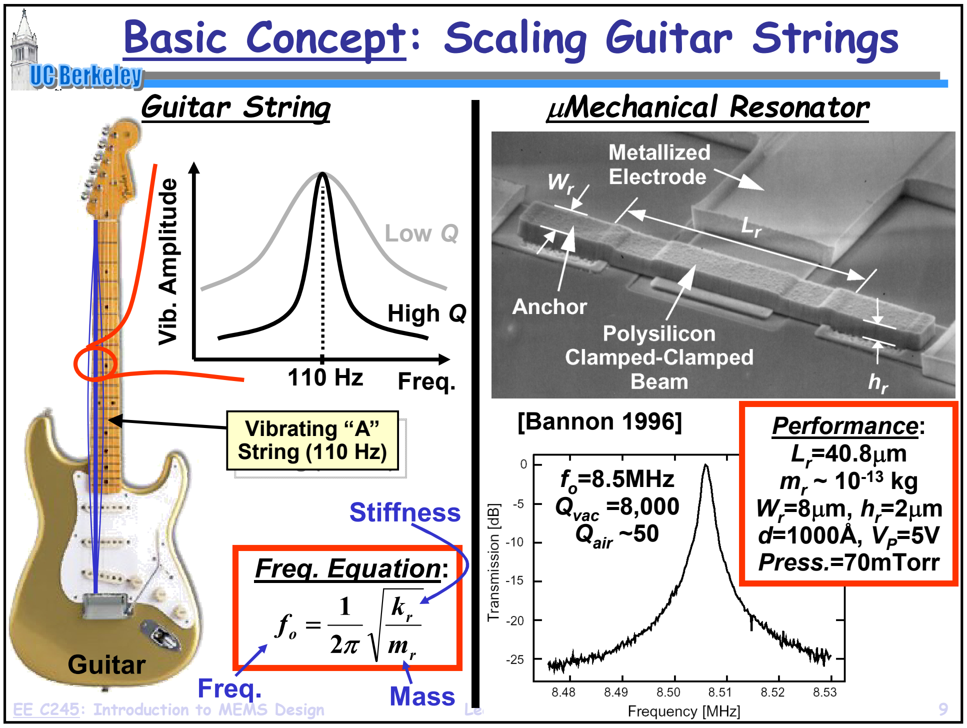
② When $L \approx h$ (or when it isn't more than $10\times h$), anchor losses become an issue



Anchor Radiation → lowers quality factor, Q

③ Solution: nanodimensions? ✓

④ Better Solution: other geometries ✓✓



Basic Concept: Scaling Guitar Strings

Guitar String

Vibrating "A" String (110 Hz)

Freq. Equation:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Stiffness

Freq.

Mass

μMechanical Resonator

[Bannon 1996]

f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50

Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
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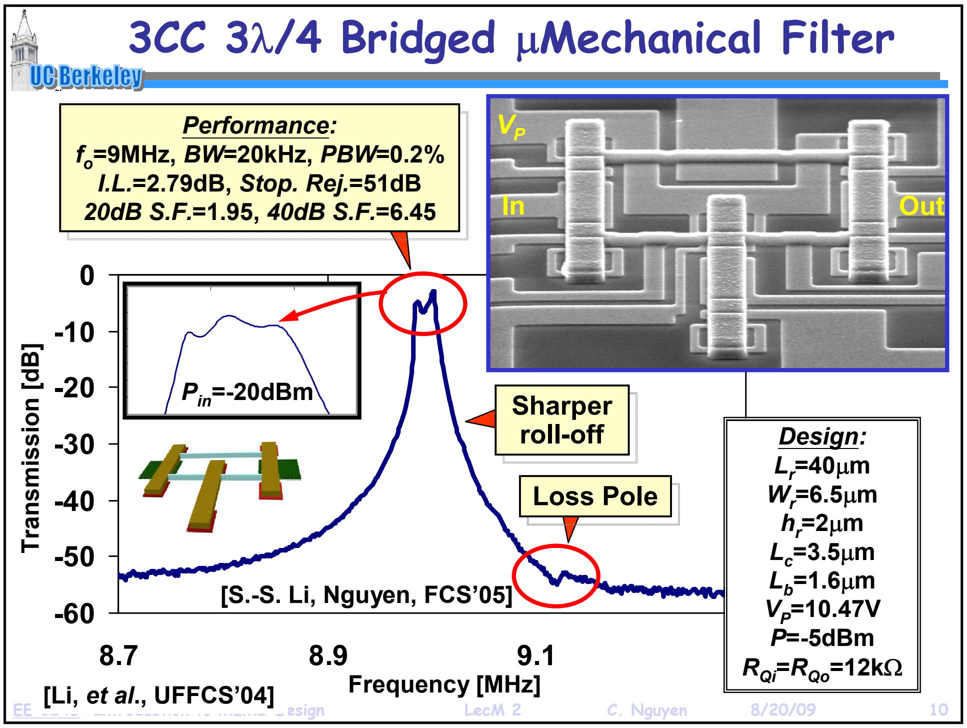


3CC 3λ/4 Bridged μMechanical Filter

Performance:
f_o=9MHz, *BW*=20kHz, *PBW*=0.2%
I.L.=2.79dB, *Stop. Rej.*=51dB
20dB S.F.=1.95, *40dB S.F.*=6.45

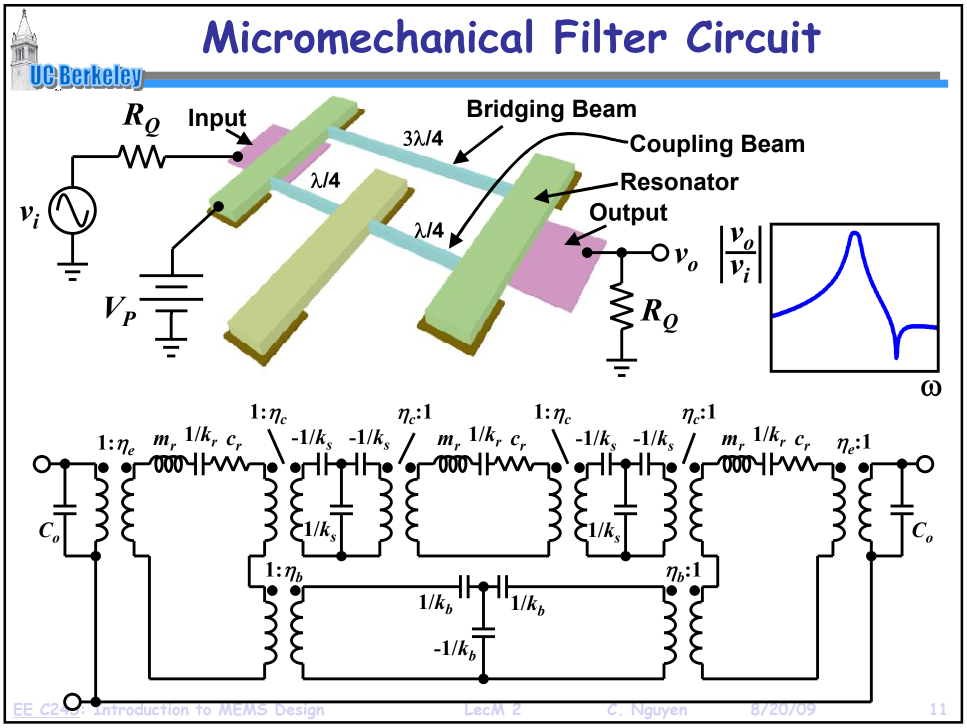
Sharper roll-off

Loss Pole

[S.-S. Li, Nguyen, FCS'05]

Design:
L_r=40μm
W_r=6.5μm
h_r=2μm
L_c=3.5μm
L_b=1.6μm
V_P=10.47V
P=-5dBm
R_{Qi}=R_{Qo}=12kΩ

[Li, *et al.*, UFFCS'04]



Micromechanical Filter Circuit

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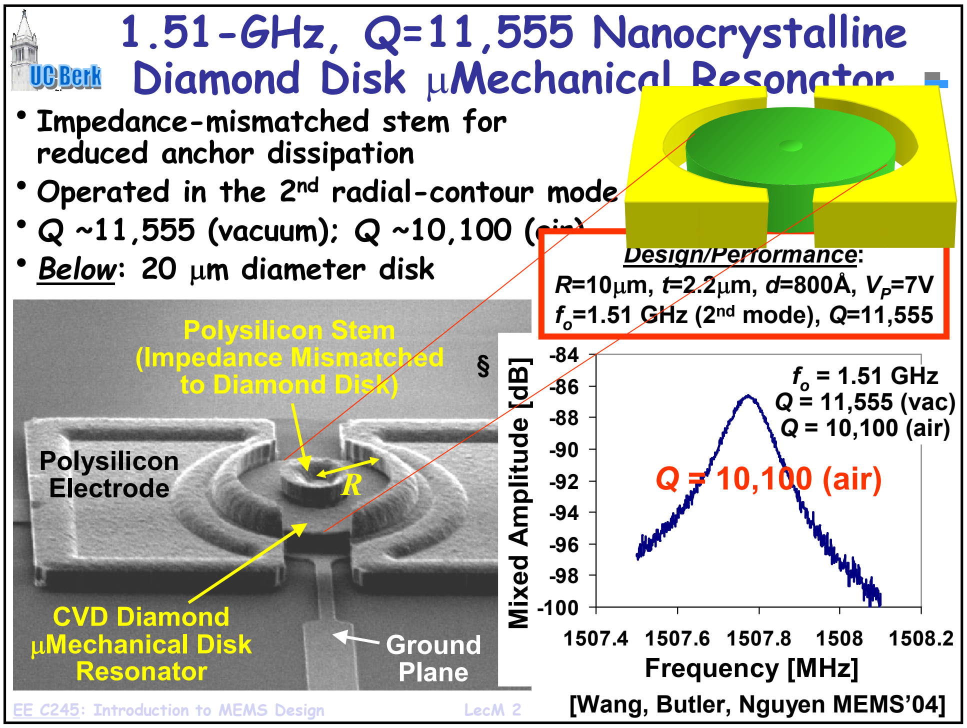

1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- Impedance-mismatched stem for reduced anchor dissipation
- Operated in the 2nd radial-contour mode
- Q ~11,555 (vacuum); Q ~10,100 (air)
- ***Below***: 20 μm diameter disk

Design/Performance:
R=10μm, t=2.2μm, d=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), Q=11,555

[Wang, Butler, Nguyen MEMS'04]

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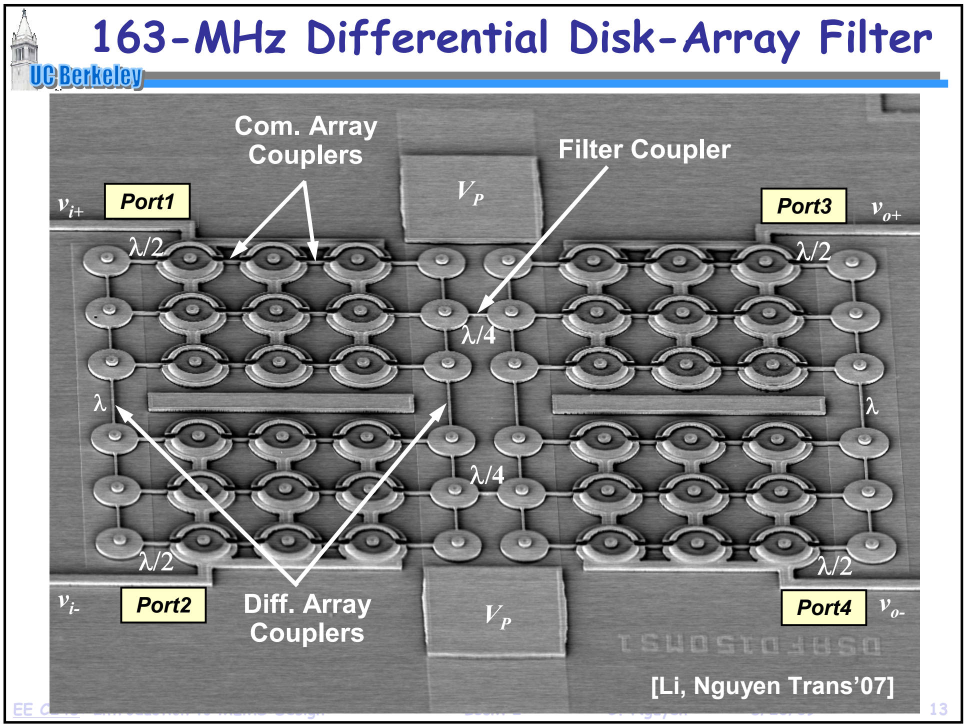
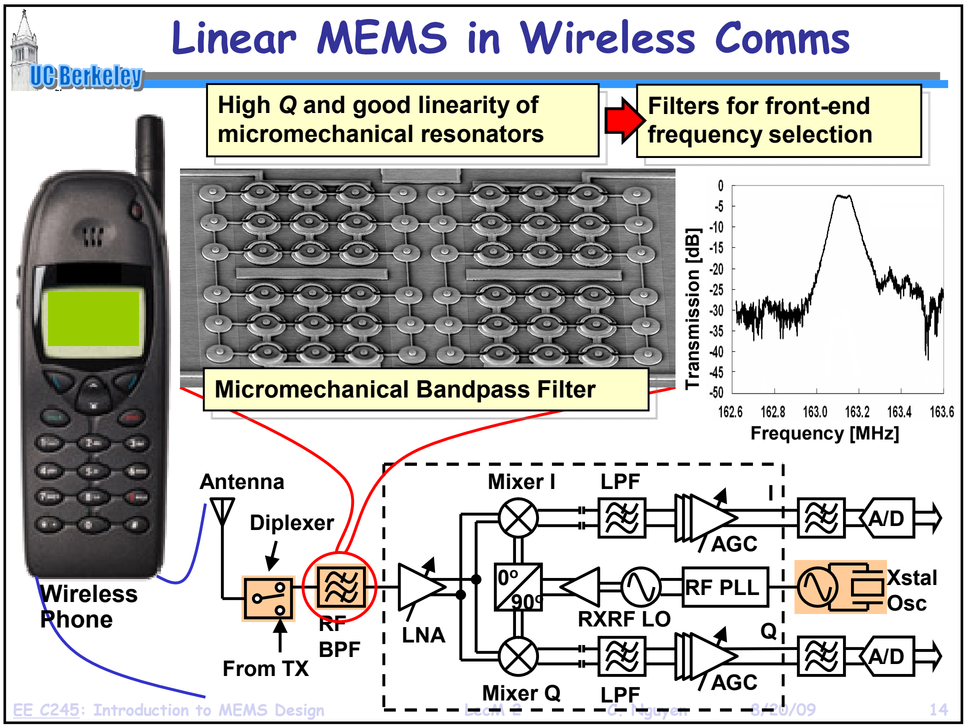


163-MHz Differential Disk-Array Filter

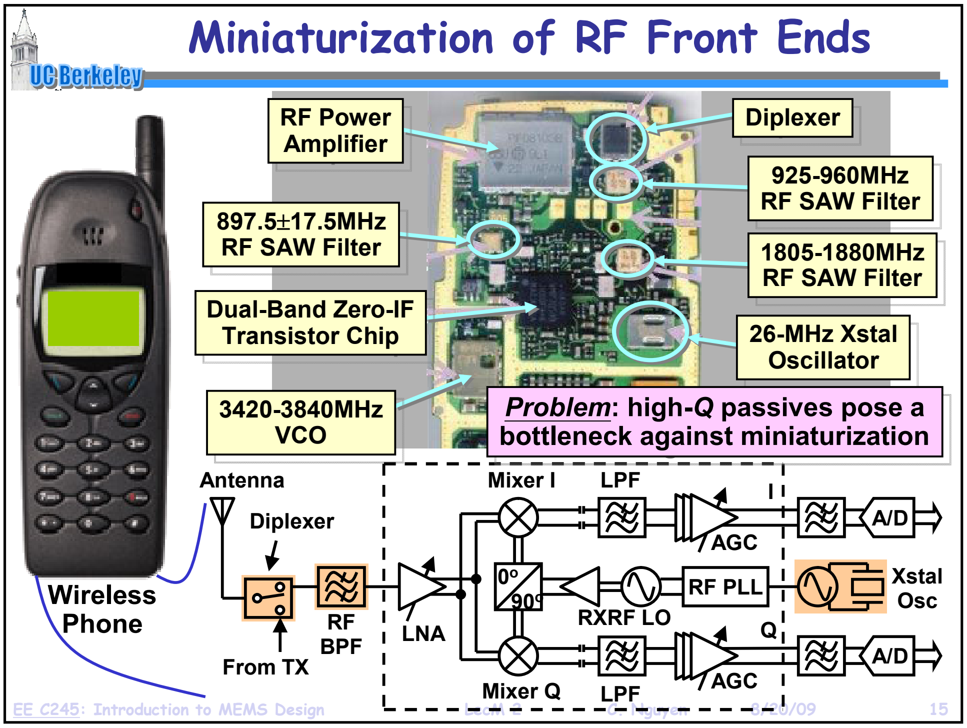
[Li, Nguyen Trans'07]



Linear MEMS in Wireless Comms

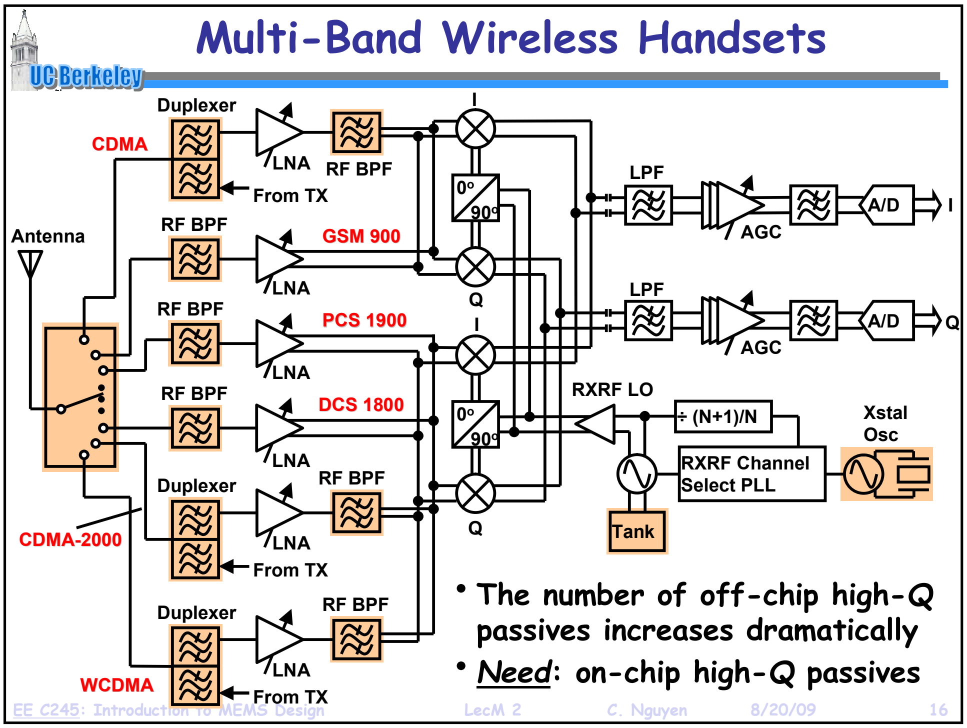
High *Q* and good linearity of micromechanical resonators → Filters for front-end frequency selection

Micromechanical Bandpass Filter



Miniaturization of RF Front Ends

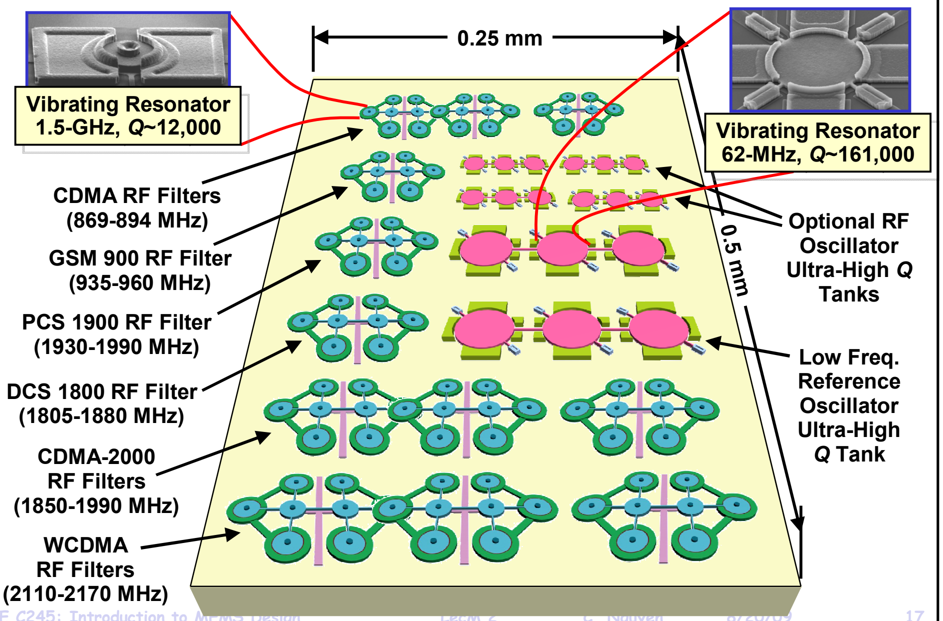
Problem: high-*Q* passives pose a bottleneck against miniaturization



Multi-Band Wireless Handsets

- The number of off-chip high-*Q* passives increases dramatically
- ***Need***: on-chip high-*Q* passives

All High-Q Passives on a Single Chip



Vibrating Resonator
1.5-GHz, Q~12,000

Vibrating Resonator
62-MHz, Q~161,000

0.25 mm

0.5 mm

CDMA RF Filters
(869-894 MHz)

GSM 900 RF Filter
(935-960 MHz)

PCS 1900 RF Filter
(1930-1990 MHz)

DCS 1800 RF Filter
(1805-1880 MHz)

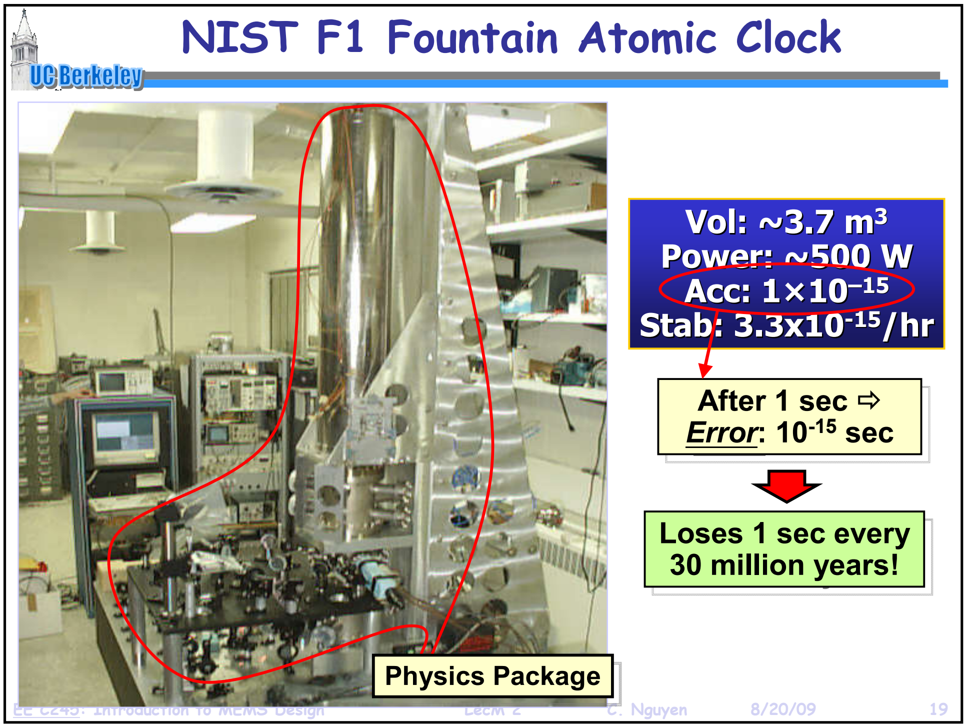
CDMA-2000
RF Filters
(1850-1990 MHz)

WCDMA
RF Filters
(2110-2170 MHz)

Optional RF
Oscillator
Ultra-High Q
Tanks

Low Freq.
Reference
Oscillator
Ultra-High
Q Tank

Chip-Scale Atomic Clocks (CSAC)

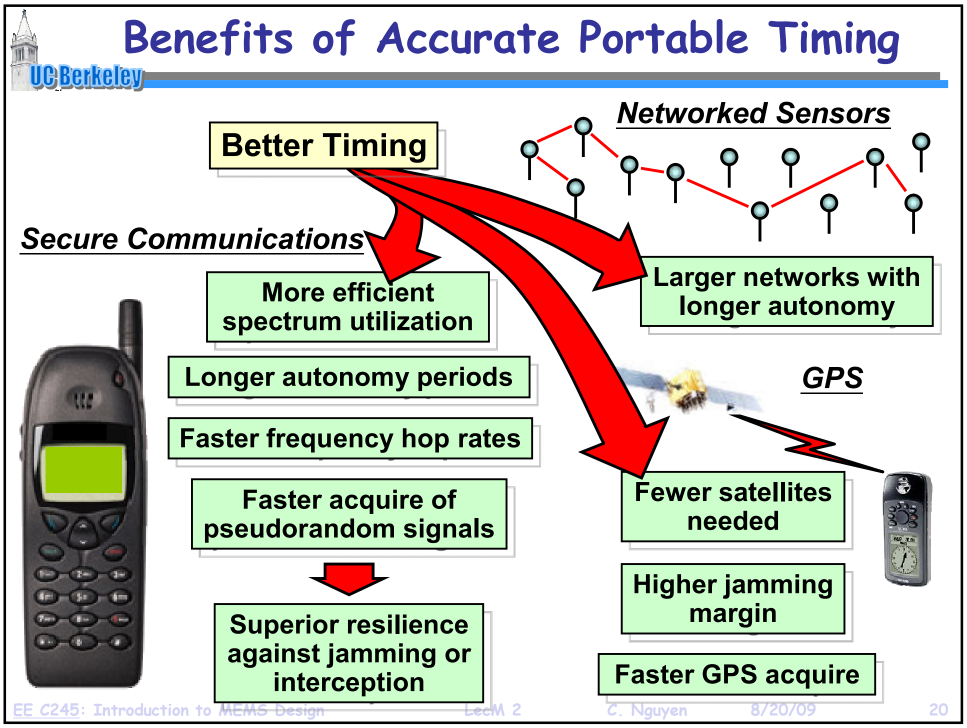


NIST F1 Fountain Atomic Clock

Vol: ~3.7 m^3
Power: ~500 W
Acc: 1×10^{-15}
Stab: 3.3×10^{-15}/hr

After 1 sec ⇨ *Error*: 10^{-15} sec

Loses 1 sec every 30 million years!



Benefits of Accurate Portable Timing

Better Timing

Secure Communications

- More efficient spectrum utilization
- Longer autonomy periods
- Faster frequency hop rates
- Faster acquire of pseudorandom signals

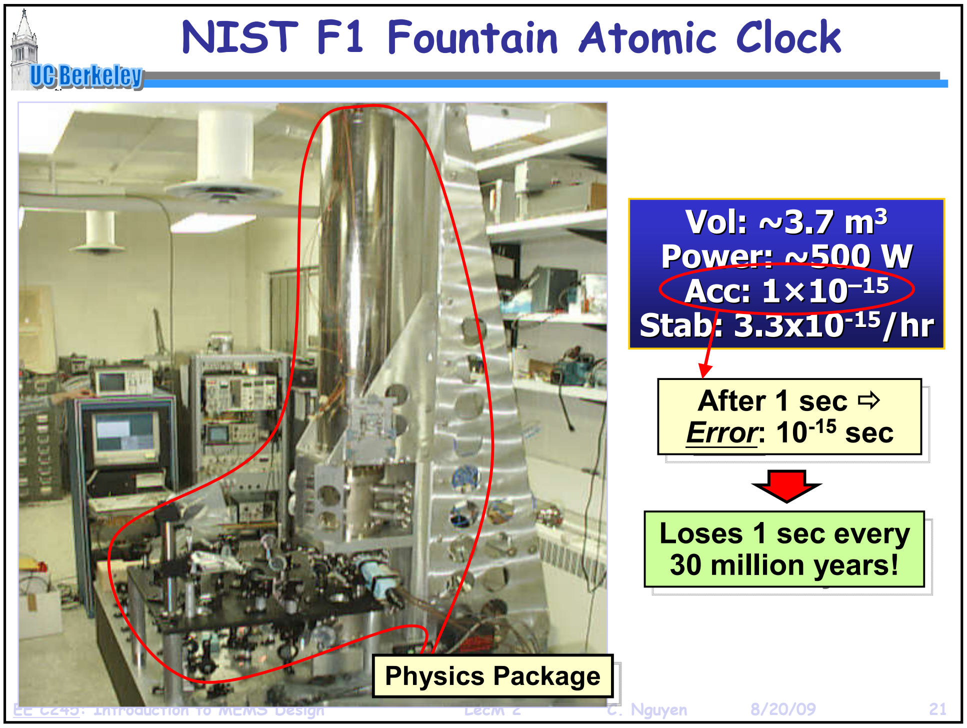
Superior resilience against jamming or interception

Networked Sensors

Larger networks with longer autonomy

GPS

- Fewer satellites needed
- Higher jamming margin
- Faster GPS acquire



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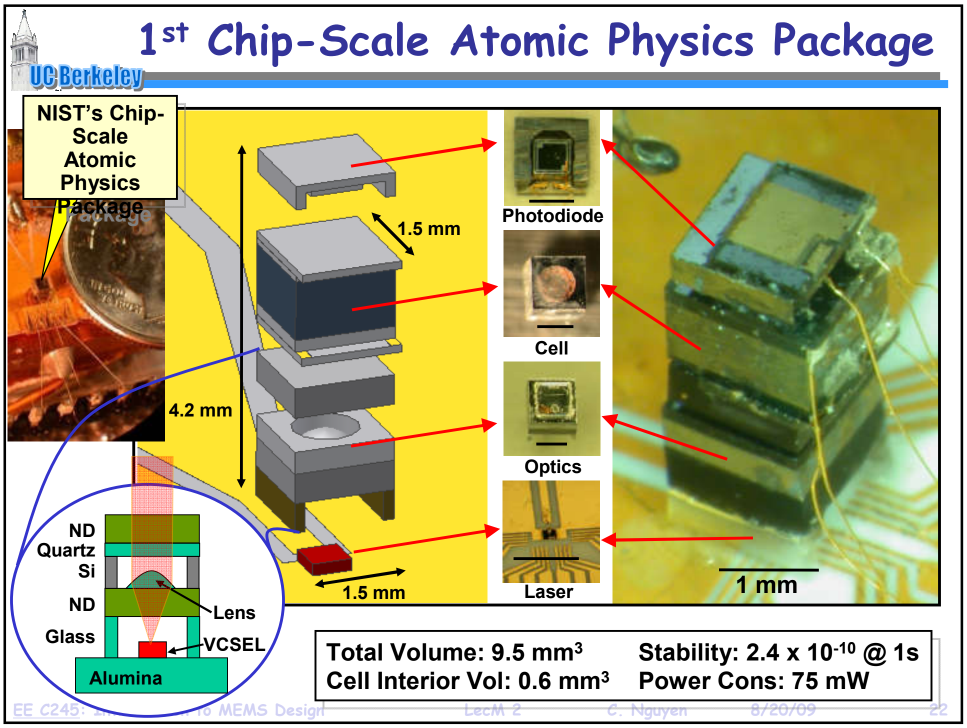
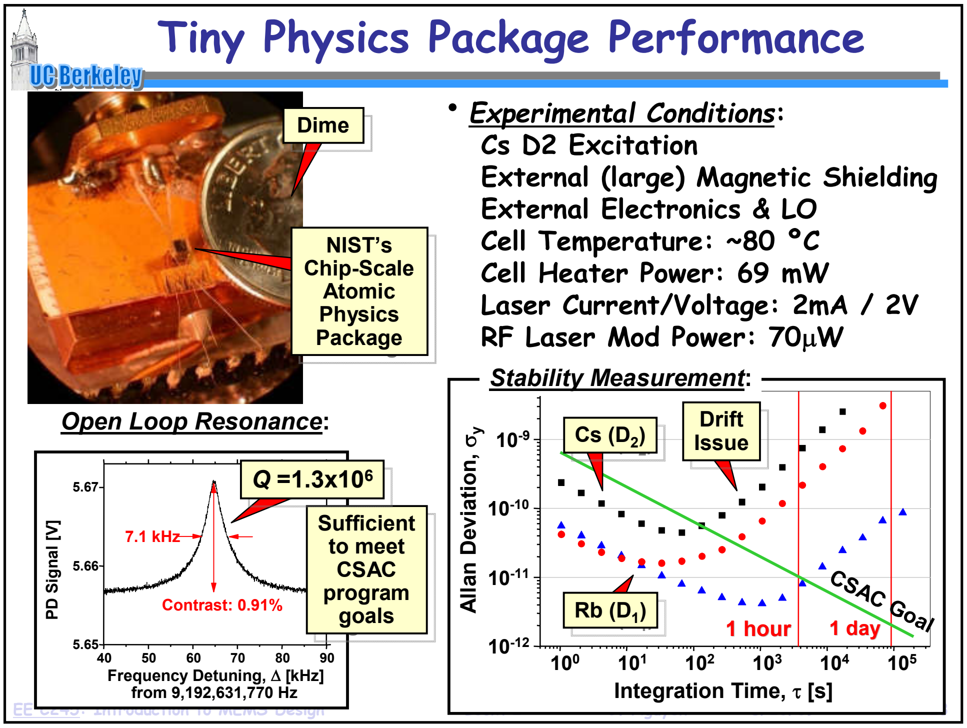
Physics Package



1st Chip-Scale Atomic Physics Package

NIST's Chip-Scale Atomic Physics Package

Total Volume: 9.5 mm^3
Cell Interior Vol: 0.6 mm^3
Stability: 2.4×10^{-10} @ 1s
Power Cons: 75 mW

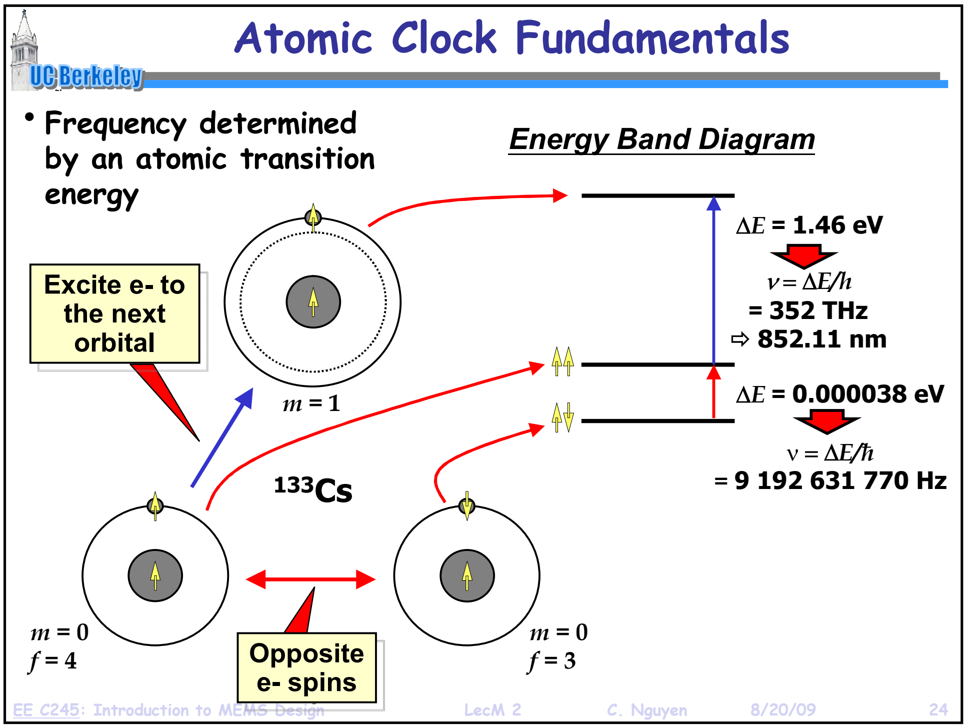


Tiny Physics Package Performance

- *Experimental Conditions*:
  Cs D2 Excitation
  External (large) Magnetic Shielding
  External Electronics & LO
  Cell Temperature: ~80 °C
  Cell Heater Power: 69 mW
  Laser Current/Voltage: 2mA / 2V
  RF Laser Mod Power: 70μW

Open Loop Resonance:

Stability Measurement:



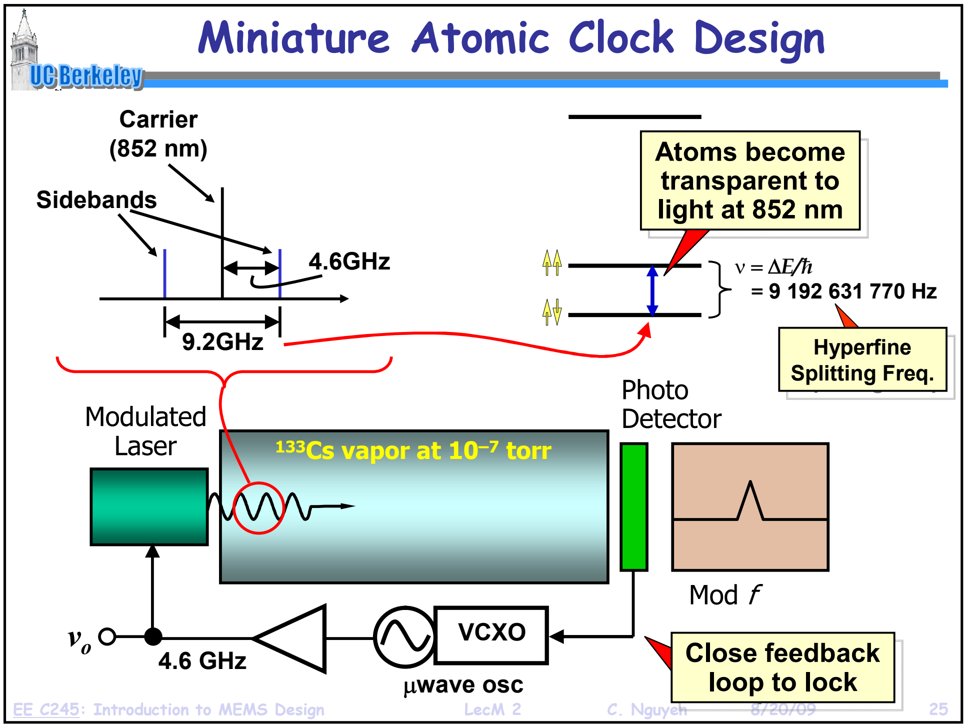
Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

Energy Band Diagram

ΔE = 1.46 eV
$\nu = \Delta E/h$
= 352 THz
⇨ 852.11 nm

ΔE = 0.000038 eV
$\nu = \Delta E/\hbar$
= 9 192 631 770 Hz

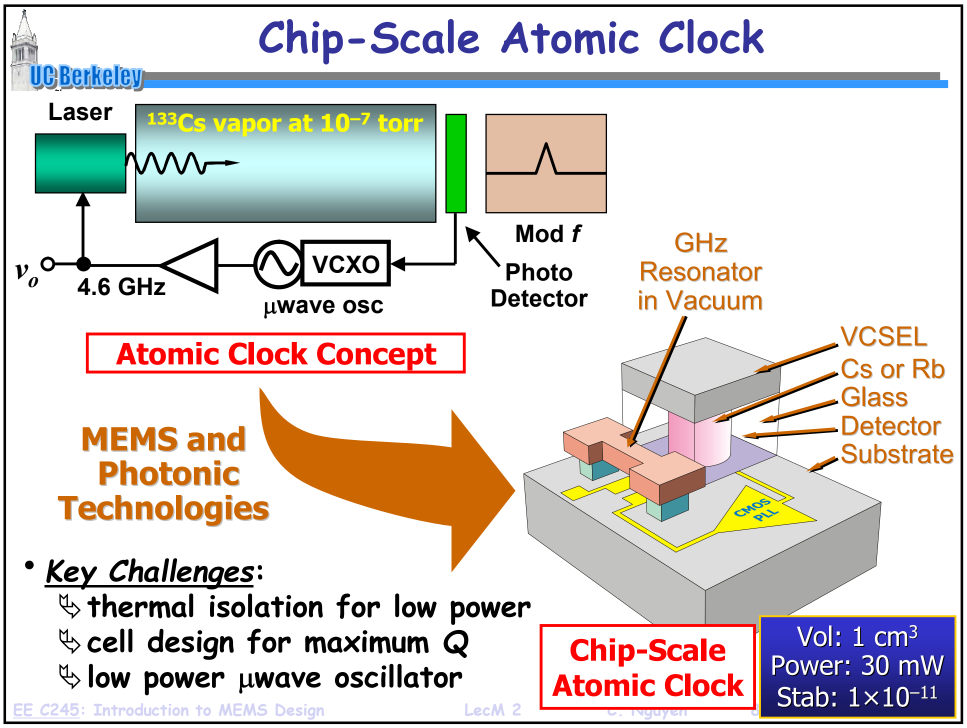


Miniature Atomic Clock Design

Atoms become transparent to light at 852 nm

Hyperfine Splitting Freq.

Close feedback loop to lock



Chip-Scale Atomic Clock

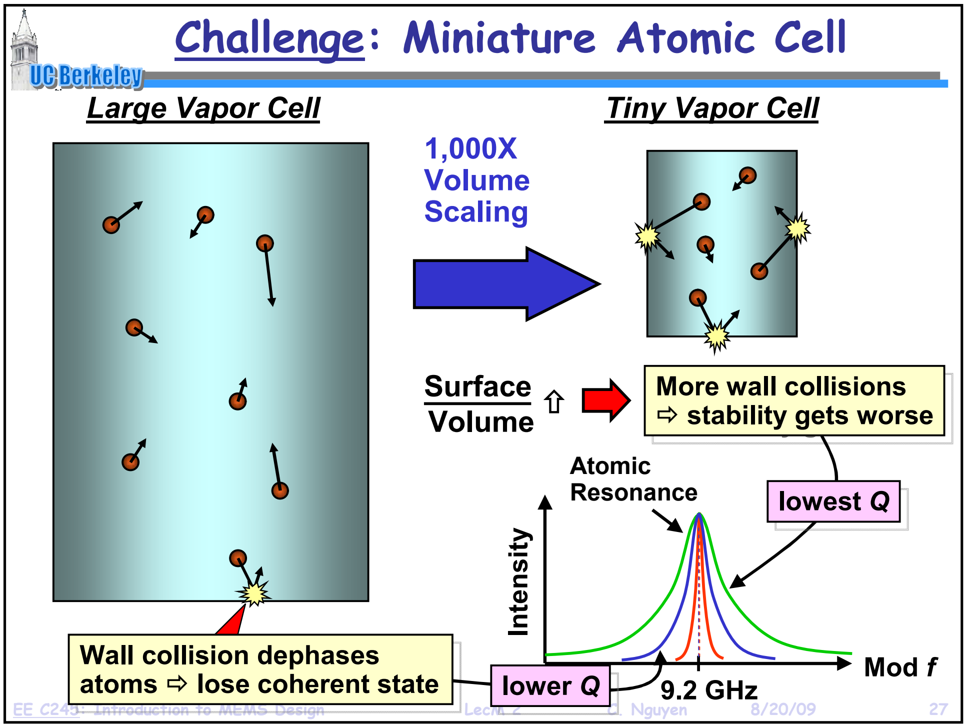
Atomic Clock Concept

MEMS and Photonic Technologies

- *Key Challenges*:
  - thermal isolation for low power
  - cell design for maximum Q
  - low power μwave oscillator

Chip-Scale Atomic Clock

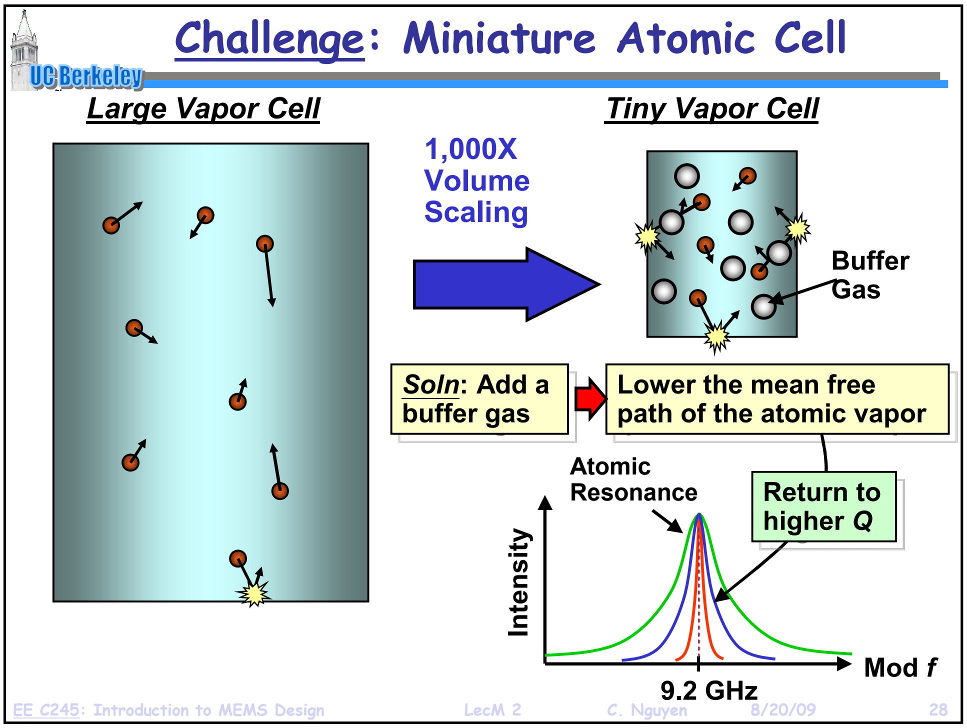
Vol: 1 cm^3
Power: 30 mW
Stab: 1×10^{-11}



Challenge: Miniature Atomic Cell

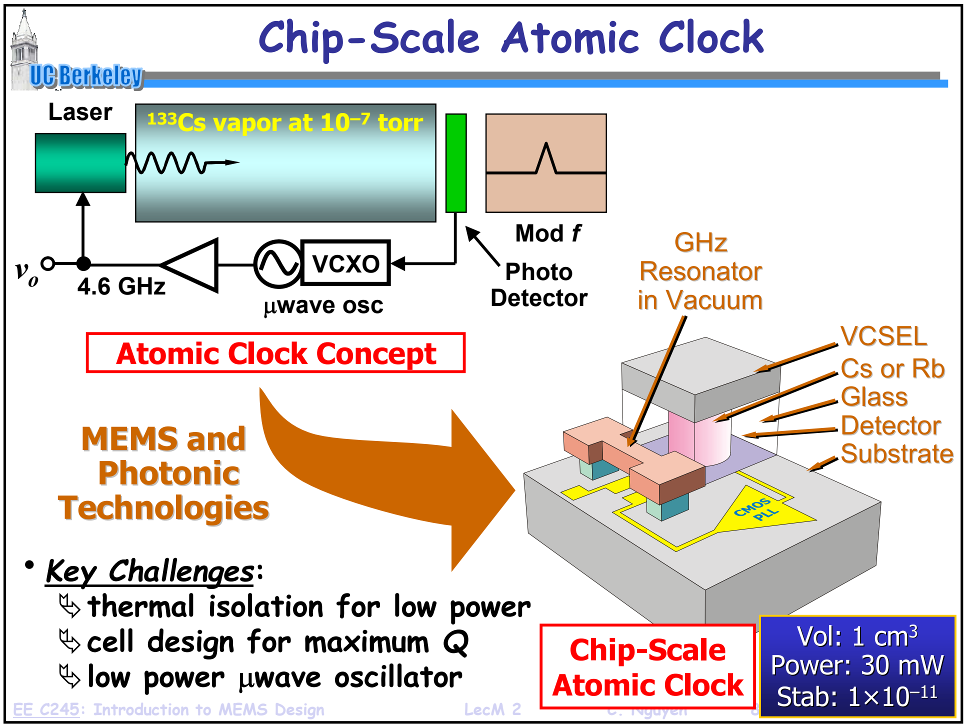
Surface / Volume ⇧ → More wall collisions ⇨ stability gets worse

Wall collision dephases atoms ⇨ lose coherent state



Challenge: Miniature Atomic Cell

Soln: Add a buffer gas → Lower the mean free path of the atomic vapor



Chip-Scale Atomic Clock

Atomic Clock Concept

MEMS and Photonic Technologies

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  - thermal isolation for low power
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Chip-Scale Atomic Clock

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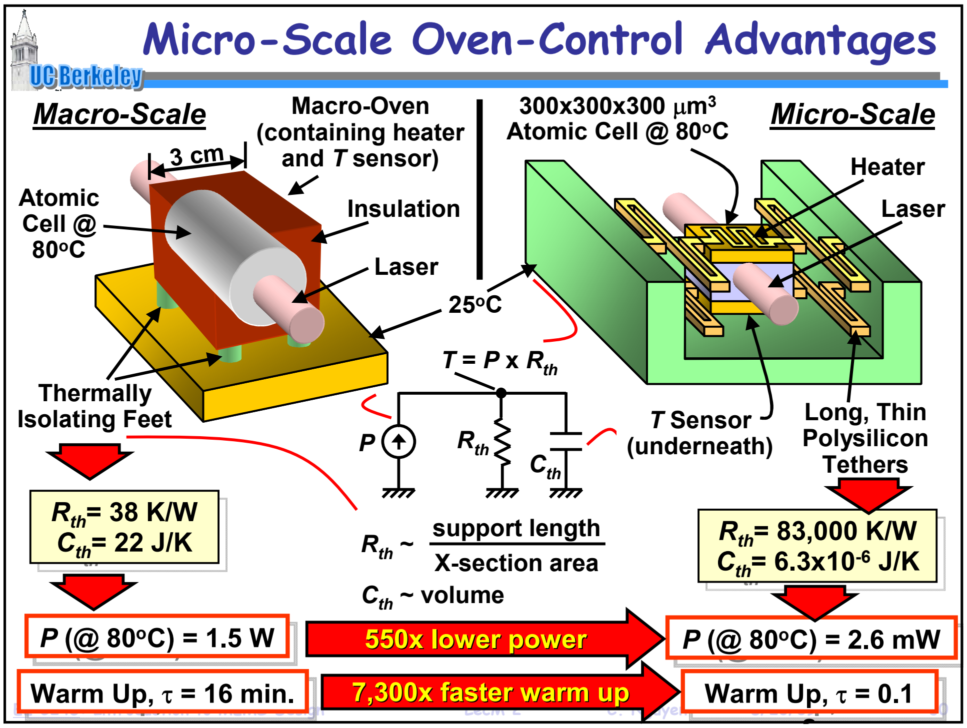


Micro-Scale Oven-Control Advantages

$T = P \times R_{th}$

R_{th}= 38 K/W
C_{th}= 22 J/K

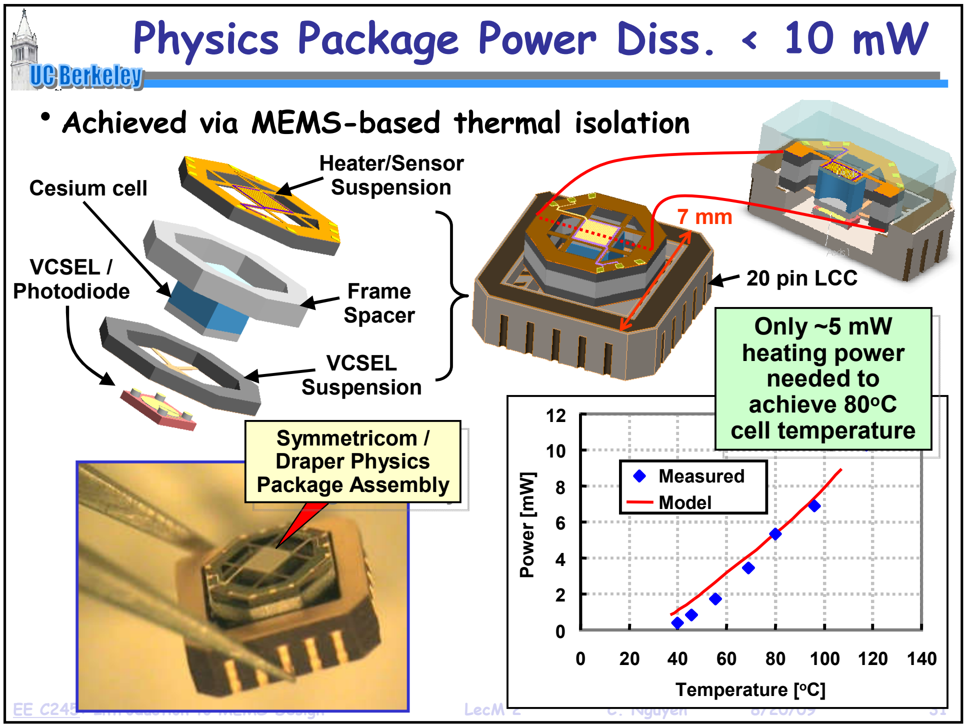
$R_{th} \sim \dfrac{\text{support length}}{\text{X-section area}}$

$C_{th} \sim$ volume

R_{th}= 83,000 K/W
C_{th}= 6.3×10^{-6} J/K

P (@ 80°C) = 1.5 W → **550x lower power** → *P* (@ 80°C) = 2.6 mW

Warm Up, τ = 16 min. → **7,300x faster warm up** → Warm Up, τ = 0.1



Physics Package Power Diss. < 10 mW

- Achieved via MEMS-based thermal isolation

Symmetricom / Draper Physics Package Assembly

Only ~5 mW heating power needed to achieve 80°C cell temperature

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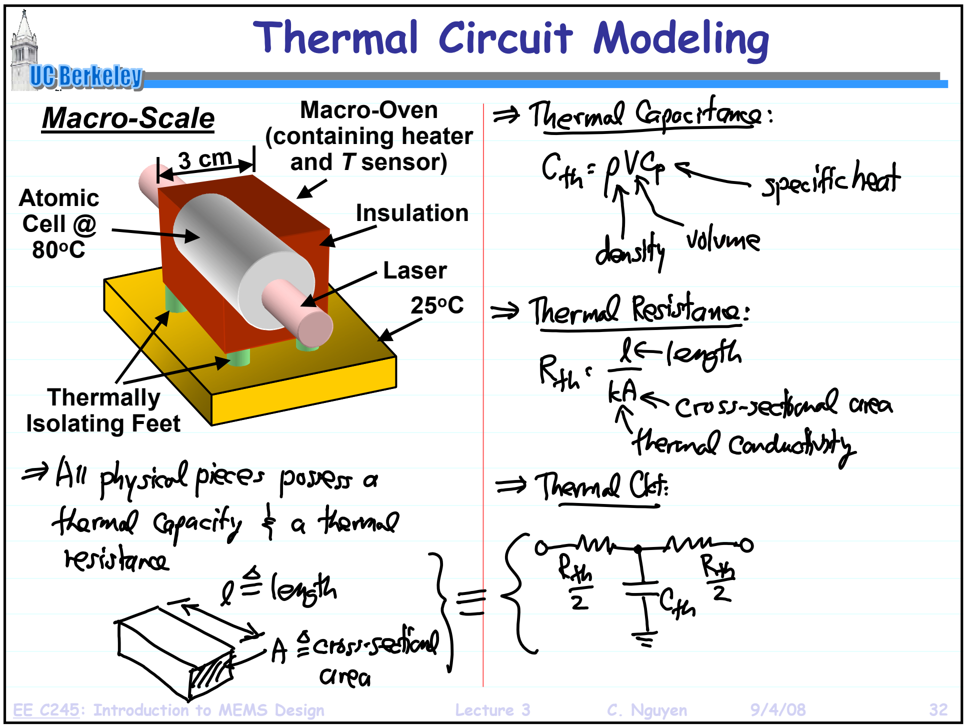

Thermal Circuit Modeling

⇒ All physical pieces possess a thermal capacity & a thermal resistance

$l \triangleq$ length

$A \triangleq$ cross-sectional area

⇒ Thermal Capacitance:

$C_{th} = \rho V C_p$

specific heat, density, volume

⇒ Thermal Resistance:

$R_{th} = \frac{l}{kA}$

length, cross-sectional area, thermal conductivity

⇒ Thermal Ckt:

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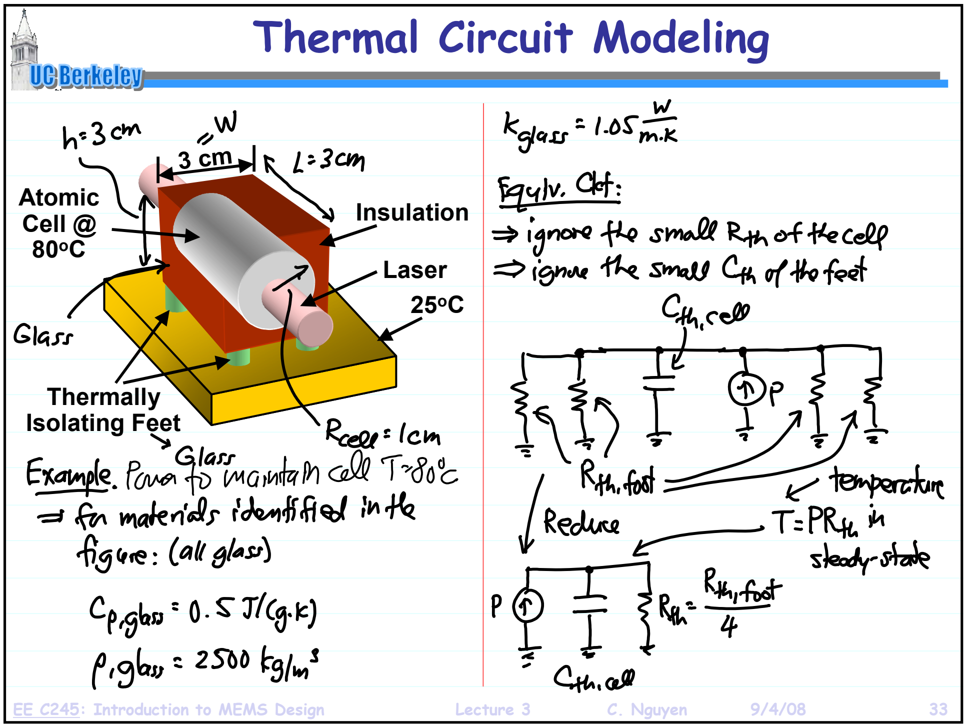


Thermal Circuit Modeling

<u>Example</u>. Power to maintain cell T=80°C
⇒ for materials identified in the figure: (all glass)

$$C_{p,glass} = 0.5\ J/(g\cdot K)$$

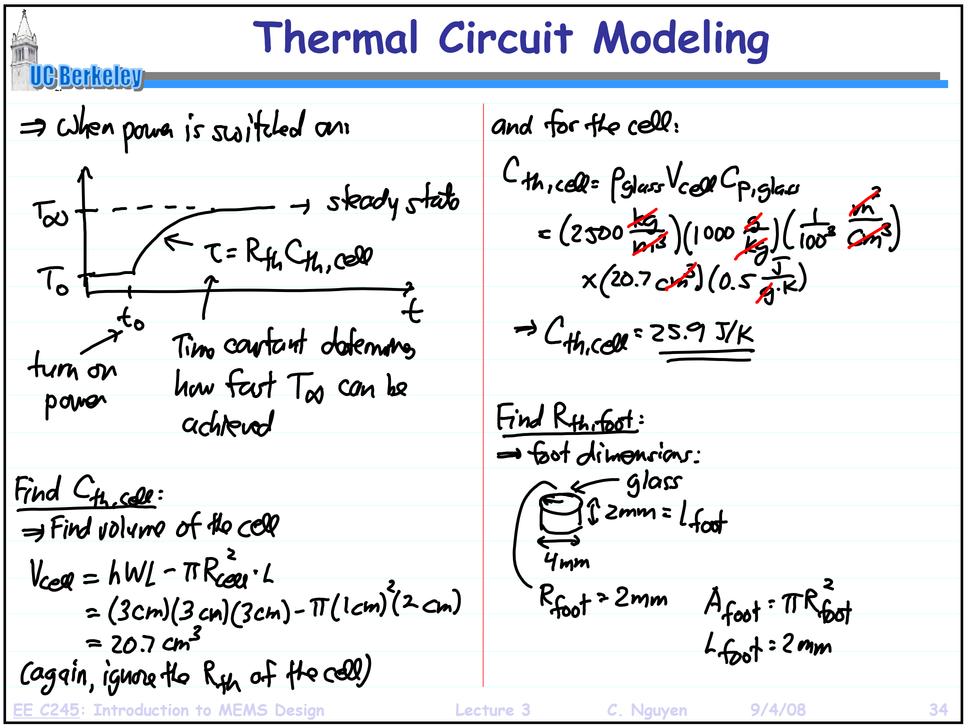
$$\rho_{,glass} = 2500\ kg/m^3$$

$$k_{glass} = 1.05 \frac{W}{m\cdot K}$$

<u>Equiv. Ckt:</u>

⇒ ignore the small R_{th} of the cell
⇒ ignore the small C_{th} of the feet

$T = PR_{th}$ in steady-state



Thermal Circuit Modeling

⇒ When power is switched on:

<u>Find $C_{th,cell}$:</u>

⇒ Find volume of the cell

$$V_{cell} = hWL - \pi R_{cell}^2 \cdot L$$
$$= (3cm)(3cm)(3cm) - \pi(1cm)^2(2cm)$$
$$= 20.7\ cm^3$$

(again, ignore the R_{th} of the cell)

and for the cell:

$$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$$
$$= \left(2500 \frac{\cancel{kg}}{\cancel{m^3}}\right)\left(1000 \frac{\cancel{g}}{\cancel{kg}}\right)\left(\frac{1}{100^3}\frac{\cancel{m^3}}{\cancel{cm^3}}\right)$$
$$\times (20.7\ \cancel{cm^3})\left(0.5 \frac{J}{\cancel{g}\cdot K}\right)$$

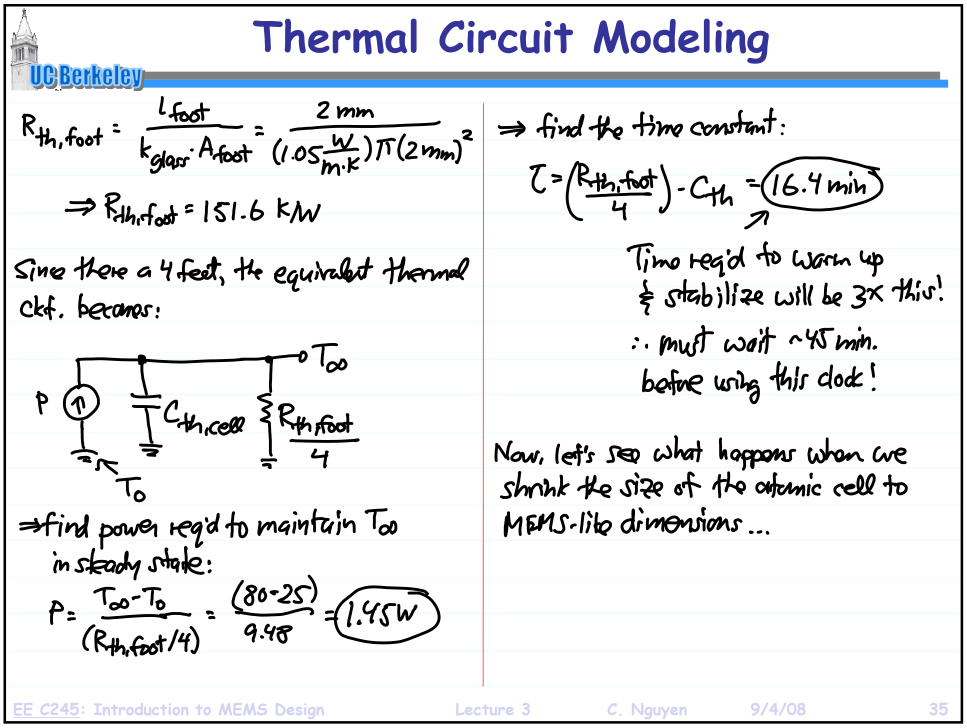
$$\rightarrow C_{th,cell} = \underline{\underline{25.9\ J/K}}$$

<u>Find $R_{th,foot}$:</u>

→ foot dimensions:

R_{foot} = 2mm

$A_{foot} = \pi R_{foot}^2$
L_{foot} = 2mm



Thermal Circuit Modeling

$$R_{th,foot} = \frac{L_{foot}}{k_{glass} \cdot A_{foot}} = \frac{2\,mm}{(1.05\frac{W}{m \cdot K})\pi(2\,mm)^2}$$

$$\Rightarrow R_{th,foot} = 151.6\ K/W$$

Since there a 4 feet, the equivalent thermal ckt. becomes:

$\Rightarrow$ find power req'd to maintain T_∞ in steady state:

$$P = \frac{T_\infty - T_o}{(R_{th,foot}/4)} = \frac{(80-25)}{9.48} = \boxed{1.45W}$$

$\Rightarrow$ find the time constant:

$$\tau = \left(\frac{R_{th,foot}}{4}\right) \cdot C_{th} = \boxed{16.4\,min}$$

Time req'd to warm up & stabilize will be 3x this!

∴ must wait ~45 min. before using this clock!

Now, let's see what happens when we shrink the size of the atomic cell to MEMS-like dimensions ...

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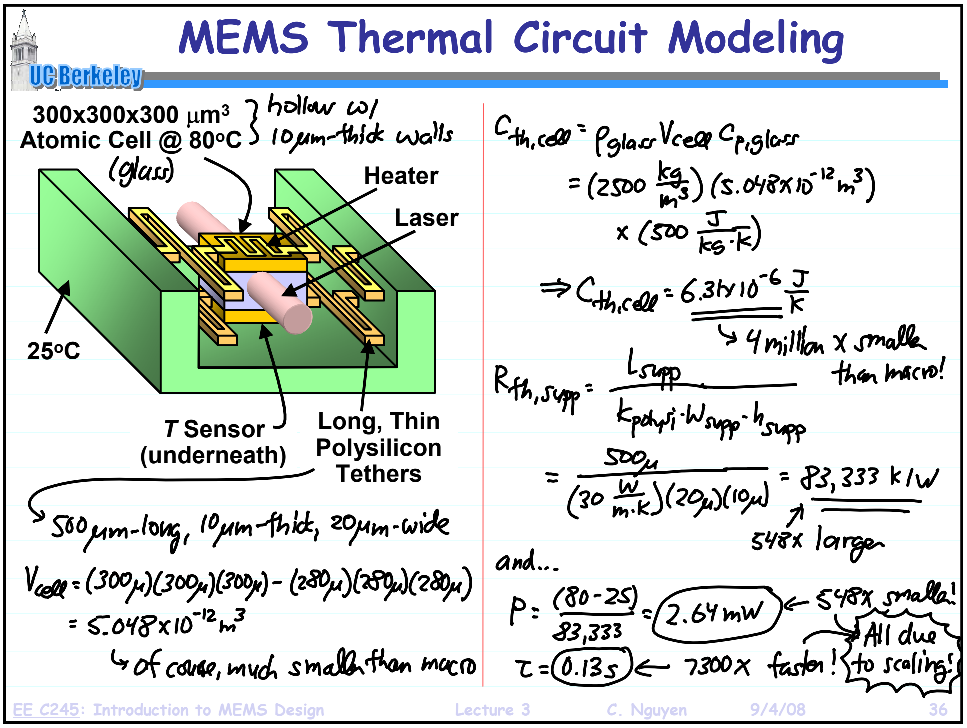

MEMS Thermal Circuit Modeling

300x300x300 µm³ Atomic Cell @ 80°C (glass) } hollow w/ 10µm-thick walls

↳ 500µm-long, 10µm-thick, 20µm-wide

$$V_{cell} = (300\mu)(300\mu)(300\mu) - (280\mu)(280\mu)(280\mu)$$
$$= 5.048 \times 10^{-12}\,m^3$$

↳ of course, much smaller than macro

$$C_{th,cell} = \rho_{glass} V_{cell} c_{p,glass}$$
$$= (2500\,\frac{kg}{m^3})(5.048 \times 10^{-12}\,m^3) \times (500\,\frac{J}{kg \cdot K})$$

$$\Rightarrow C_{th,cell} = \underline{\underline{6.31 \times 10^{-6}}}\ \frac{J}{K}$$

↳ 4 million x smaller than macro!

$$R_{th,supp} = \frac{L_{supp}}{k_{polySi} \cdot W_{supp} \cdot h_{supp}}$$

$$= \frac{500\mu}{(30\,\frac{W}{m \cdot K})(20\mu)(10\mu)} = \underline{\underline{83,333\ K/W}}$$

548x larger

and...

$$P = \frac{(80-25)}{83,333} = \boxed{2.64\,mW} \leftarrow 548x\ smaller!$$

$$\tau = \boxed{0.13s} \leftarrow 7300x\ faster!$$

All due to scaling!

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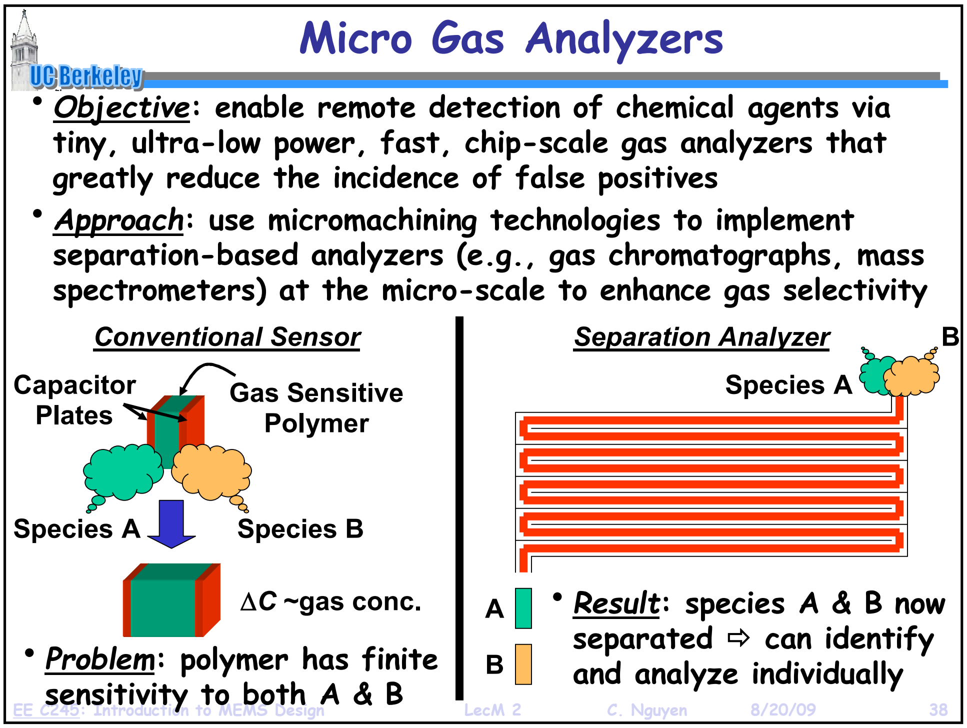
Micro Gas Analyzers (MGA)



Micro Gas Analyzers

- ***Objective***: enable remote detection of chemical agents via tiny, ultra-low power, fast, chip-scale gas analyzers that greatly reduce the incidence of false positives
- ***Approach***: use micromachining technologies to implement separation-based analyzers (e.g., gas chromatographs, mass spectrometers) at the micro-scale to enhance gas selectivity

Conventional Sensor

Capacitor Plates

Gas Sensitive Polymer

Species A

Species B

ΔC ~gas conc.

- ***Problem***: polymer has finite sensitivity to both A & B

Separation Analyzer

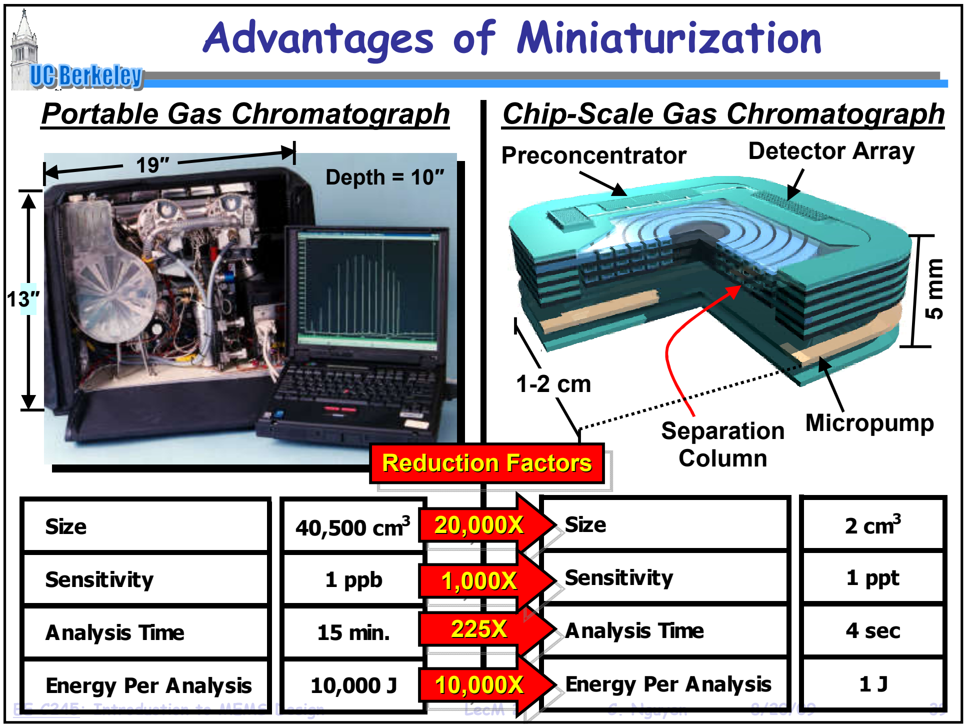
B

Species A

A

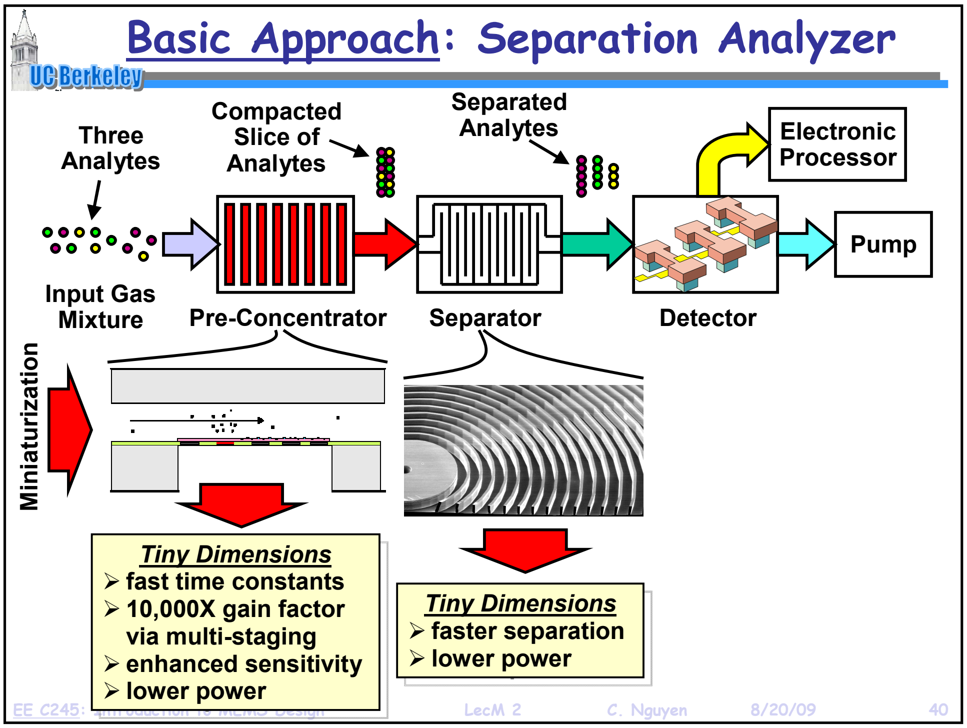
B

- ***Result***: species A & B now separated ⇨ can identify and analyze individually



Advantages of Miniaturization

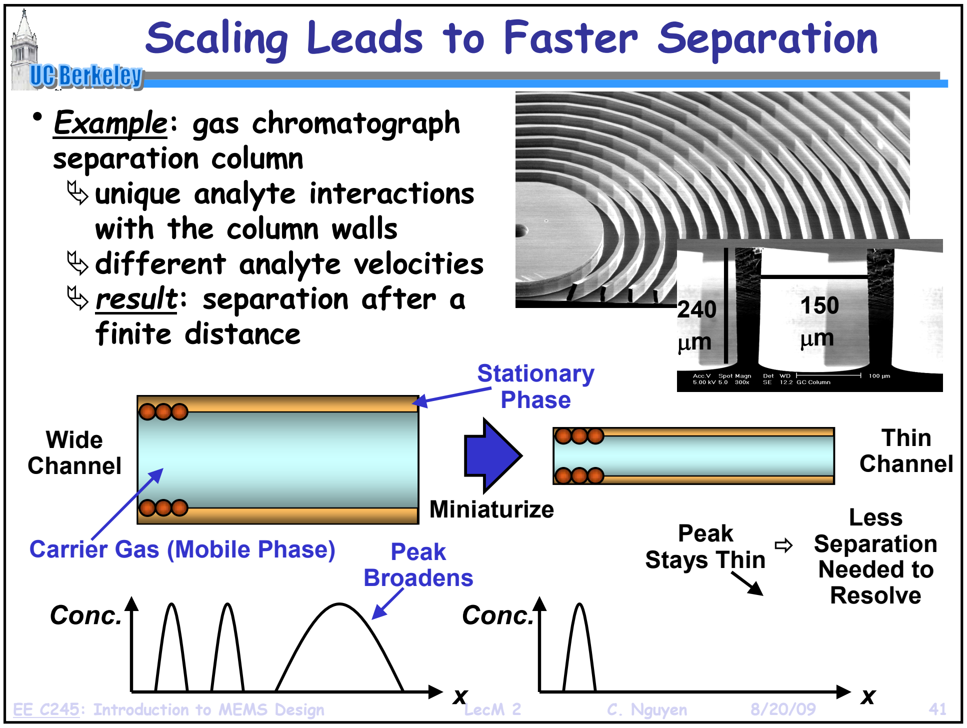
	Portable Gas Chromatograph	Reduction Factors		Chip-Scale Gas Chromatograph
Size	40,500 cm^3	20,000X	Size	2 cm^3
Sensitivity	1 ppb	1,000X	Sensitivity	1 ppt
Analysis Time	15 min.	225X	Analysis Time	4 sec
Energy Per Analysis	10,000 J	10,000X	Energy Per Analysis	1 J



Basic Approach: Separation Analyzer

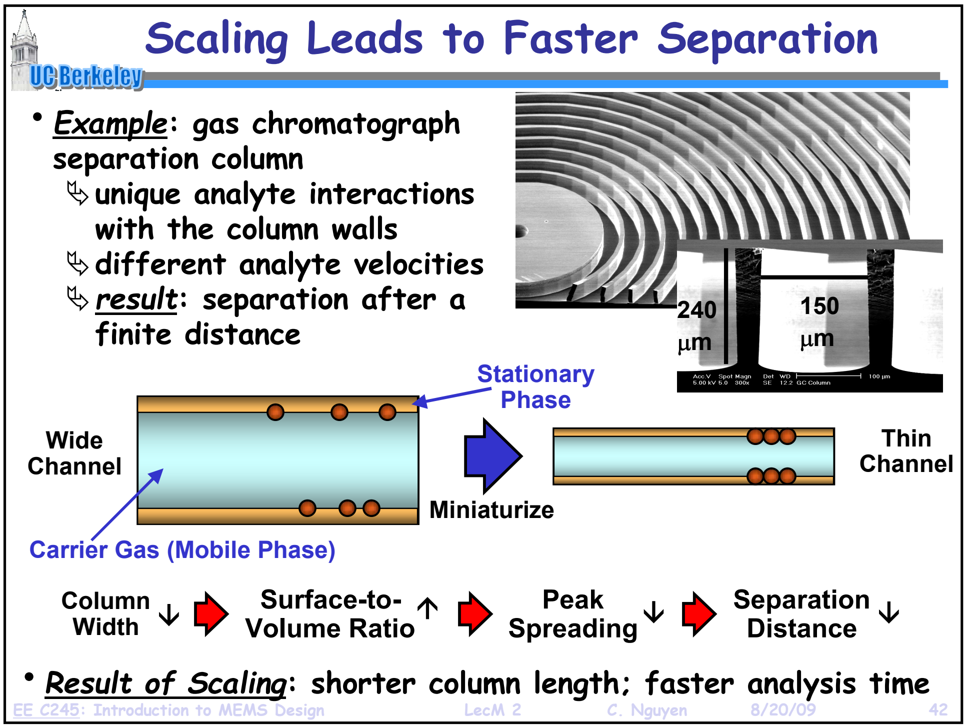
Tiny Dimensions
- fast time constants
- 10,000X gain factor via multi-staging
- enhanced sensitivity
- lower power

Tiny Dimensions
- faster separation
- lower power



Scaling Leads to Faster Separation

- *Example*: gas chromatograph separation column
  - ↳ unique analyte interactions with the column walls
  - ↳ different analyte velocities
  - ↳ *result*: separation after a finite distance

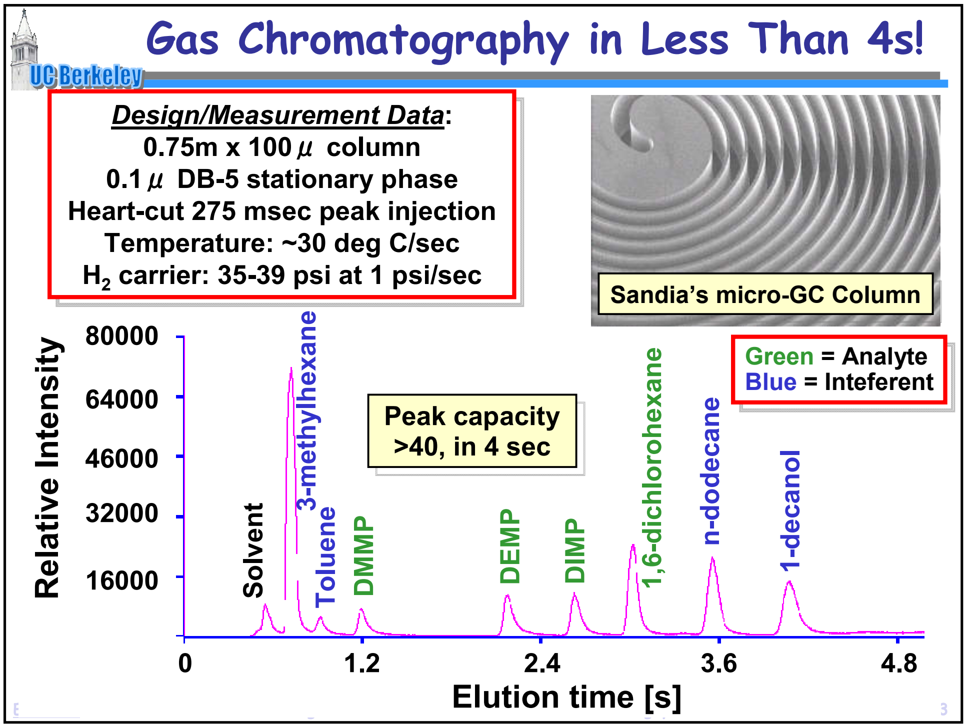


Scaling Leads to Faster Separation

- *Example*: gas chromatograph separation column
  - ↳ unique analyte interactions with the column walls
  - ↳ different analyte velocities
  - ↳ *result*: separation after a finite distance

Column Width ↓ ➡ Surface-to-Volume Ratio ↑ ➡ Peak Spreading ↓ ➡ Separation Distance ↓

- *Result of Scaling*: shorter column length; faster analysis time



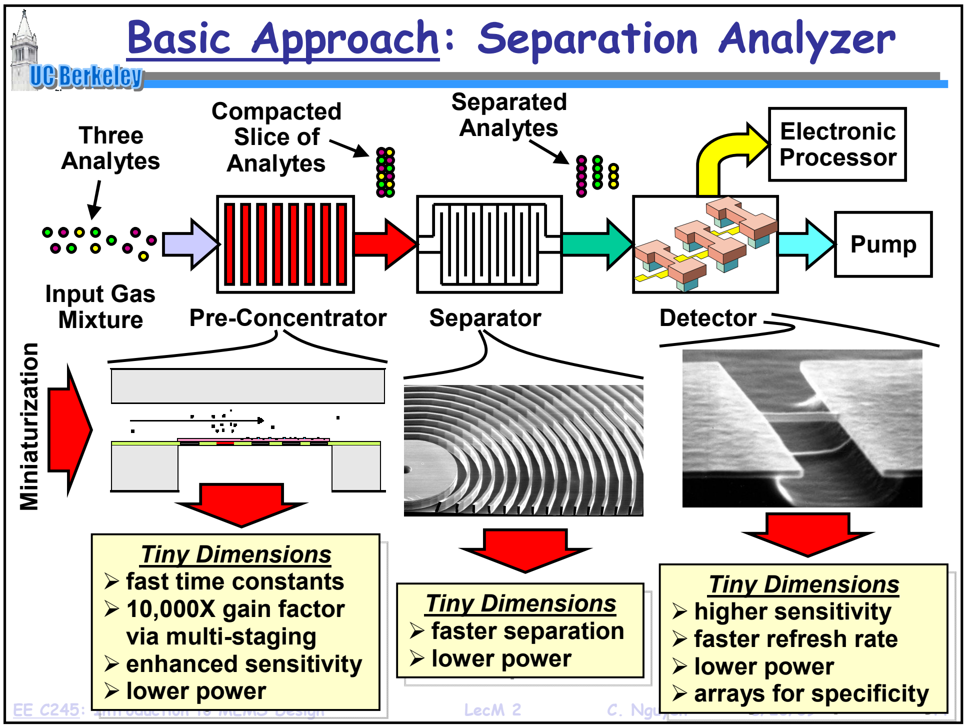
Gas Chromatography in Less Than 4s!

Design/Measurement Data:
0.75m x 100μ column
0.1μ DB-5 stationary phase
Heart-cut 275 msec peak injection
Temperature: ~30 deg C/sec
H_2 carrier: 35-39 psi at 1 psi/sec

Sandia's micro-GC Column

Green = Analyte
Blue = Inteferent

Peak capacity >40, in 4 sec

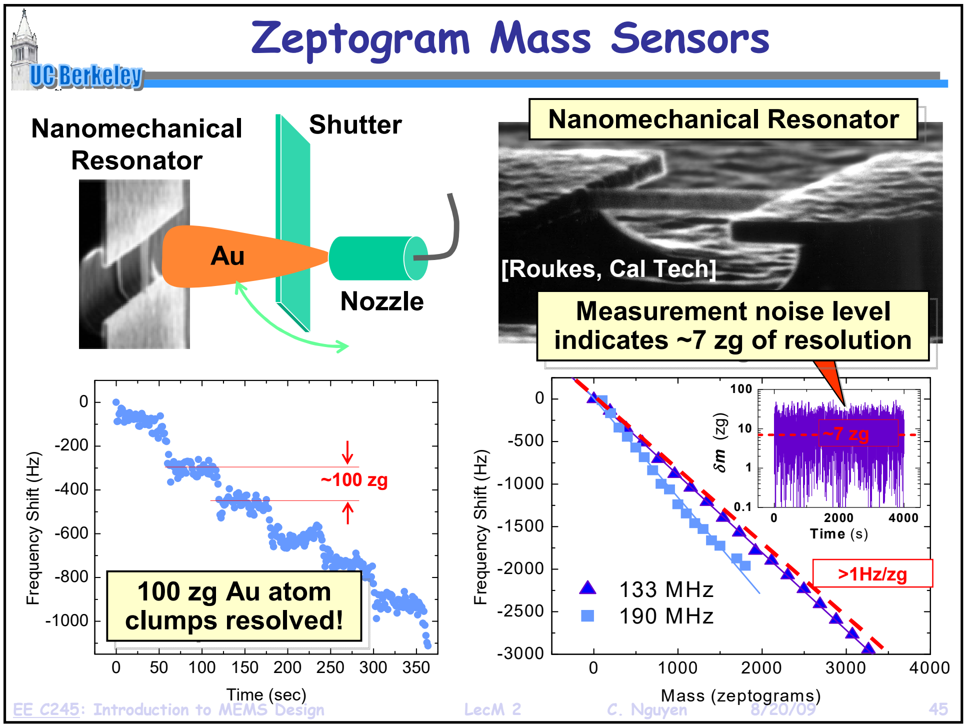


Basic Approach: Separation Analyzer

Tiny Dimensions
- fast time constants
- 10,000X gain factor via multi-staging
- enhanced sensitivity
- lower power

Tiny Dimensions
- faster separation
- lower power

Tiny Dimensions
- higher sensitivity
- faster refresh rate
- lower power
- arrays for specificity

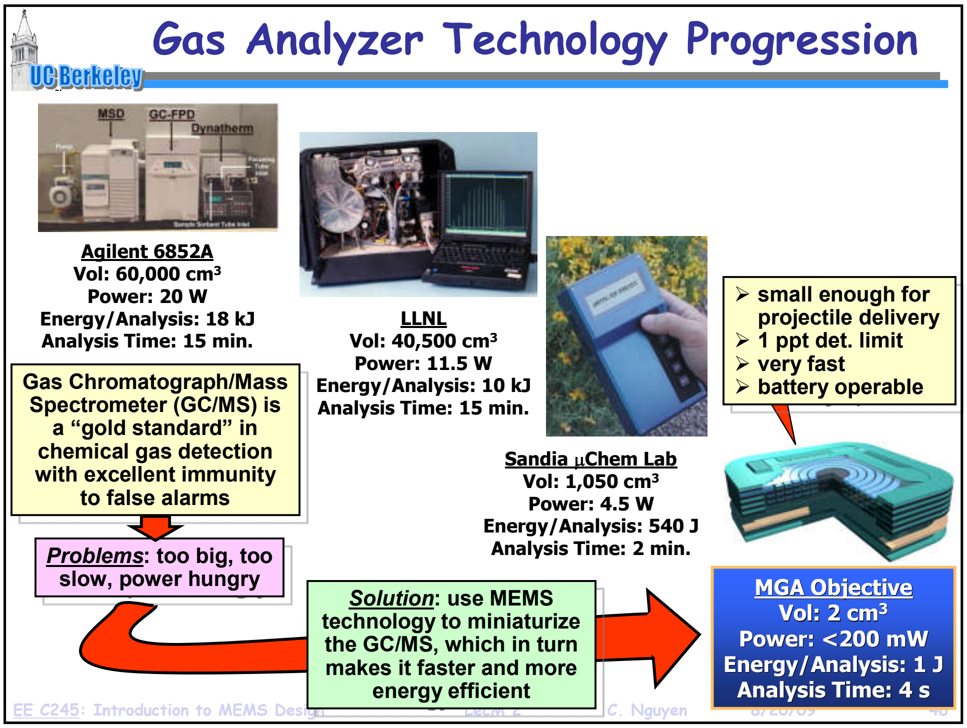


Zeptogram Mass Sensors

[Roukes, Cal Tech]

Measurement noise level indicates ~7 zg of resolution

100 zg Au atom clumps resolved!



Gas Analyzer Technology Progression

Agilent 6852A
Vol: 60,000 cm^3
Power: 20 W
Energy/Analysis: 18 kJ
Analysis Time: 15 min.

LLNL
Vol: 40,500 cm^3
Power: 11.5 W
Energy/Analysis: 10 kJ
Analysis Time: 15 min.

Sandia μChem Lab
Vol: 1,050 cm^3
Power: 4.5 W
Energy/Analysis: 540 J
Analysis Time: 2 min.

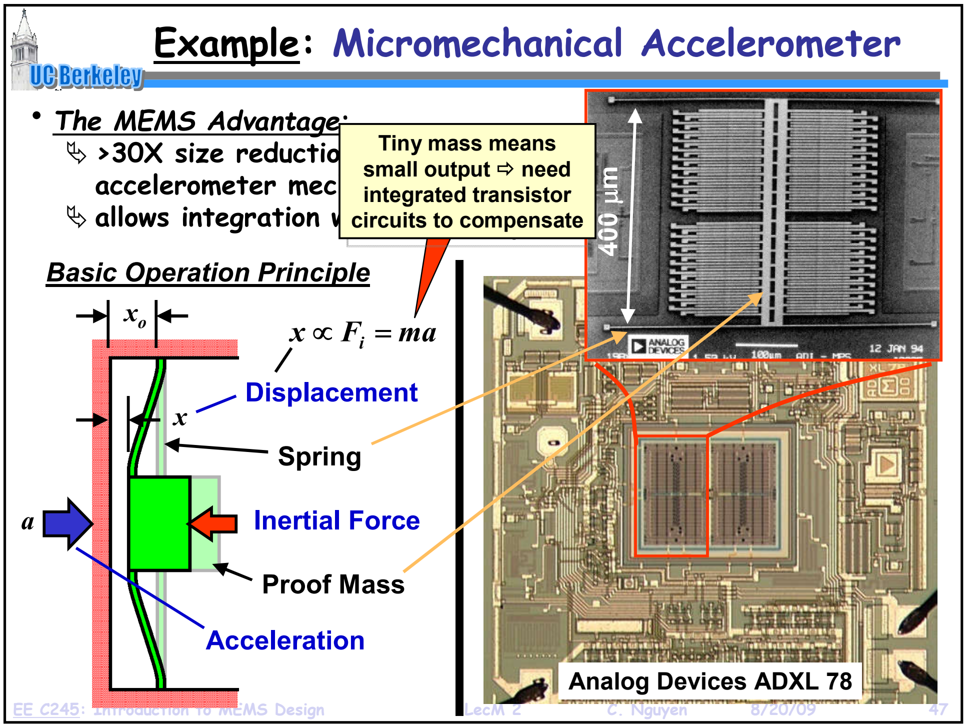
- small enough for projectile delivery
- 1 ppt det. limit
- very fast
- battery operable

Gas Chromatograph/Mass Spectrometer (GC/MS) is a "gold standard" in chemical gas detection with excellent immunity to false alarms

Problems: too big, too slow, power hungry

Solution: use MEMS technology to miniaturize the GC/MS, which in turn makes it faster and more energy efficient

MGA Objective
Vol: 2 cm^3
Power: <200 mW
Energy/Analysis: 1 J
Analysis Time: 4 s



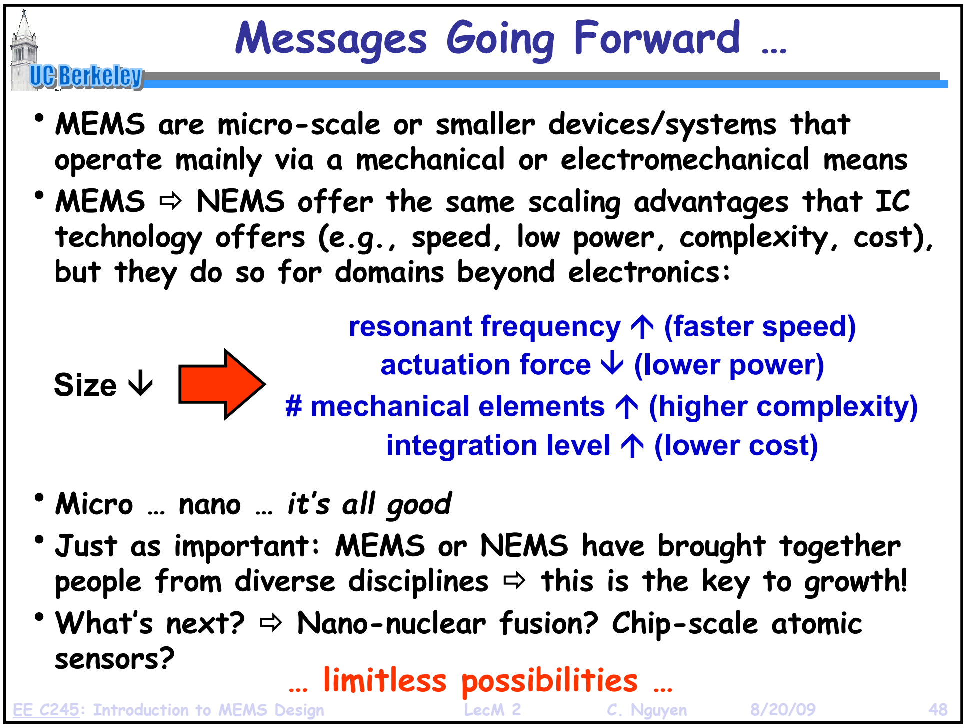
Example: Micromechanical Accelerometer

- *The MEMS Advantage:*
  - >30X size reductio accelerometer mec
  - allows integration w

Tiny mass means small output ⇨ need integrated transistor circuits to compensate

Basic Operation Principle

$x \propto F_i = ma$



Messages Going Forward …

- MEMS are micro-scale or smaller devices/systems that operate mainly via a mechanical or electromechanical means
- MEMS ⇨ NEMS offer the same scaling advantages that IC technology offers (e.g., speed, low power, complexity, cost), but they do so for domains beyond electronics:

Size ↓ ⇨
resonant frequency ↑ (faster speed)
actuation force ↓ (lower power)
mechanical elements ↑ (higher complexity)
integration level ↑ (lower cost)

- Micro … nano … *it's all good*
- Just as important: MEMS or NEMS have brought together people from diverse disciplines ⇨ this is the key to growth!
- What's next? ⇨ Nano-nuclear fusion? Chip-scale atomic sensors?

… limitless possibilities …