

EE C247B - ME C218 Introduction to MEMS Design Spring 2020


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Lecture Module 2: Benefits of Scaling

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Lecture Outline


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

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 **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 ↑

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 **Vibrating RF MEMS**

Vibrating RF MEMS

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Basic Concept: Scaling Guitar Strings

Guitar String

Vib. Amplitude

110 Hz

Low Q

High Q

110 Hz

Freq.

Vibrating "A" String (110 Hz)

Stiffness

Freq. Equation:

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

Freq.

Mass

μ Mechanical Resonator

Metallized Electrode

Anchor

Polysilicon Clamped-Clamped Beam

W_r

L_r

h_r

[Bannon 1996]

Performance:

- $L_r = 40.8 \mu\text{m}$
- $m_r \sim 10^{-13} \text{ kg}$
- $W_r = 8 \mu\text{m}$, $h_r = 2 \mu\text{m}$
- $d = 1000 \text{ \AA}$, $V_p = 5 \text{ V}$
- Press. = 70 mTorr

Transmission [dB]

Frequency [MHz]

$f_o = 8.5 \text{ MHz}$

$Q_{vac} = 8,000$

$Q_{air} \sim 50$

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Frequency of a Stretched Wire

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Scaling of Guitar Strings

guitar string \equiv transversely vibrating stretched wire

B.C. Simple Support $z(x=0)=0$

Simple Support $z(x=L)=0$

L

x

z

dashed line \rightarrow mode shape

\Rightarrow Equation for Resonance Freq. (fundamental mode)

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

S \leftarrow tension (force per unit area)

ρ \leftarrow mass per unit length

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

cross-sectional

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LecM 2

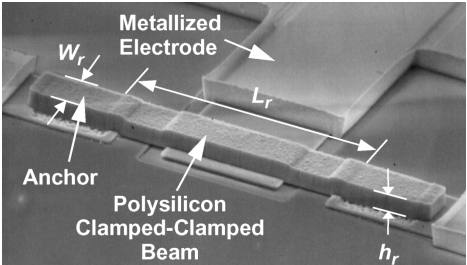
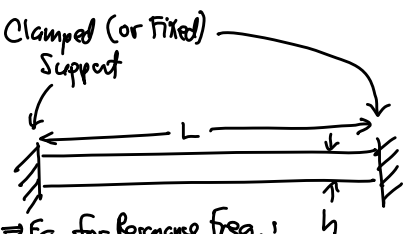
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Frequency of a Clamped-Clamped Beam
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Clamped-Clamped Beam

⇒ Eq. for Resonance Freq. 1

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = 1.03 \sqrt{\frac{E}{\rho}} \frac{h}{L^2} \quad (1)$$

Where $E \hat{=}$ Young's modulus [GPa]
 $\rho \hat{=}$ density [kg/m^3]
 $h \hat{=}$ thickness [m]
 $L \hat{=}$ length [m]

Example $L = 40 \mu\text{m}$, $h = 2 \mu\text{m}$
 polySi $\rightarrow E = 150 \text{ GPa}$, $\rho = 2300 \text{ kg/m}^3$

$$\therefore f_0 = (1.03) \sqrt{\frac{1506}{2300}} \frac{2\mu}{(40\mu)^2} \rightarrow \boxed{f_0 = 10.4 \text{ MHz}}$$

acoustic velocity = 8076 m/s As $L \downarrow \rightarrow f_0 \uparrow$!

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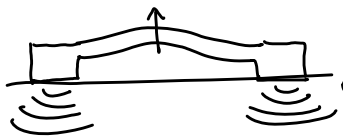
Frequency of a Clamped-Clamped Beam
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Example. $L = 4 \mu\text{m} \rightarrow f_0 = (1.03)(8076) \frac{2\mu}{(4\mu)^2} \rightarrow \boxed{f_0 = 1.04 \text{ GHz}}$

Remarks

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

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



Anchor Radiation \rightarrow lowers quality factor, Q

③ Solution: non-dimensional? ✓

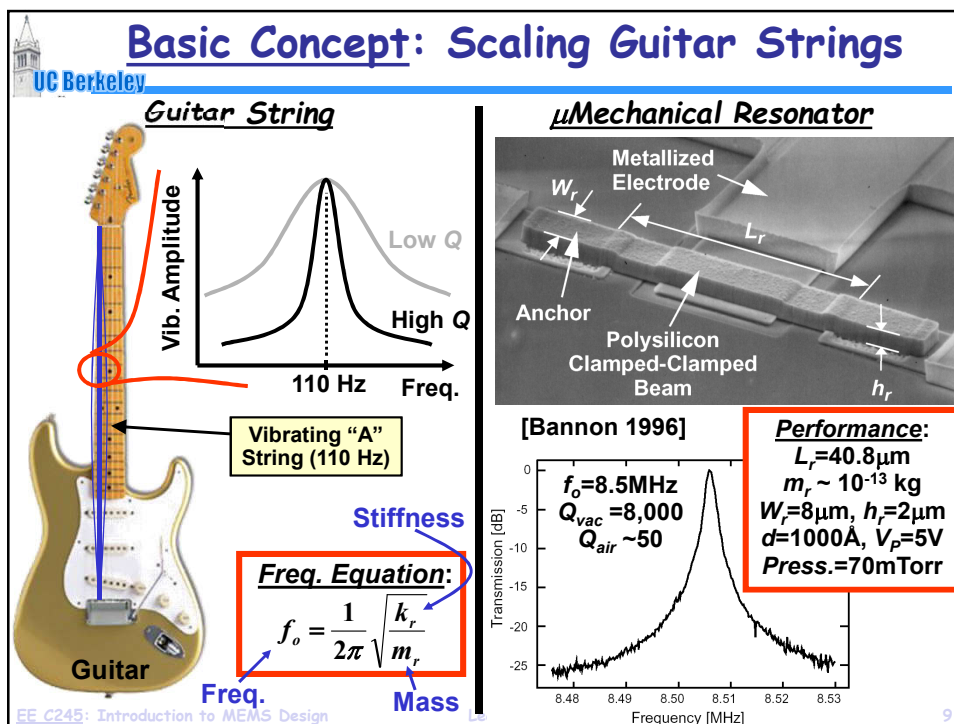
④ Better Solution: other geometries ✓

Smaller \downarrow Faster!

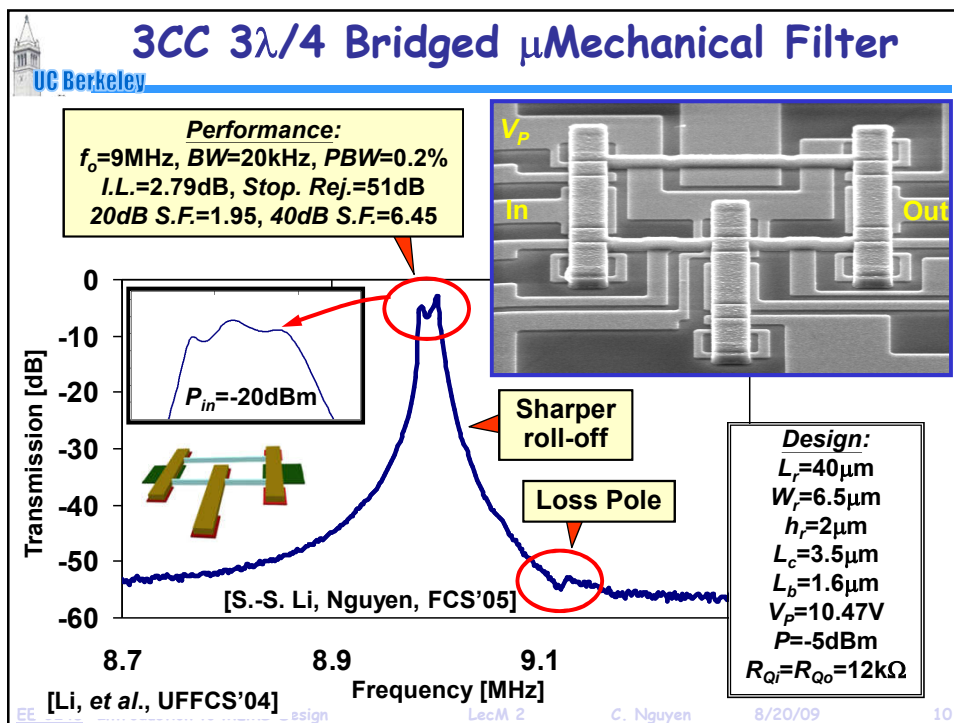
GHz freqs. possible!

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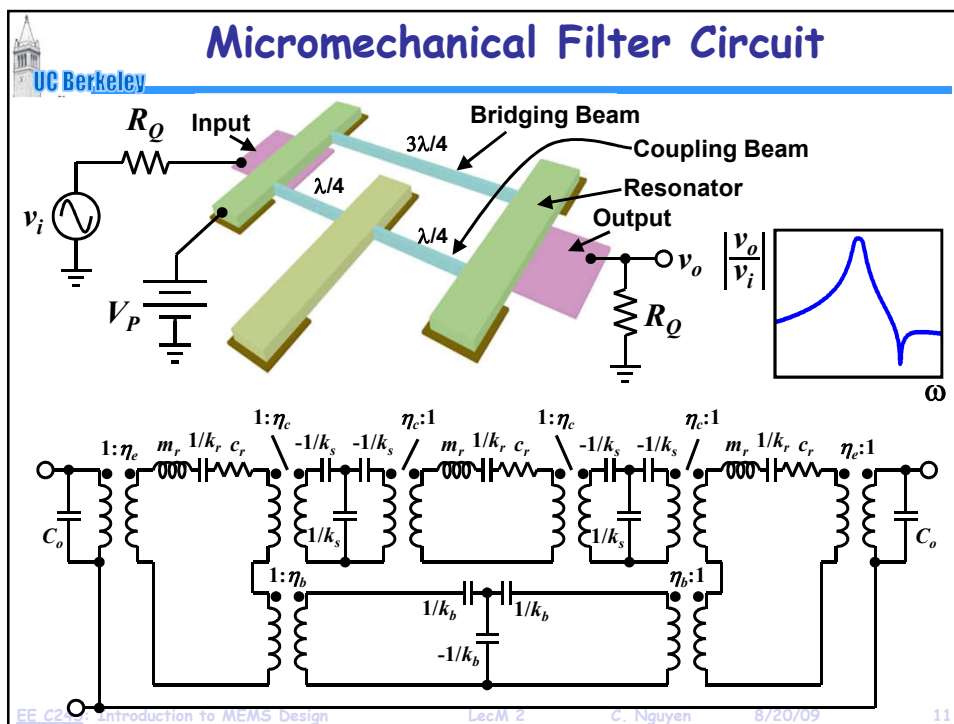
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1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μ Mechanical Resonator

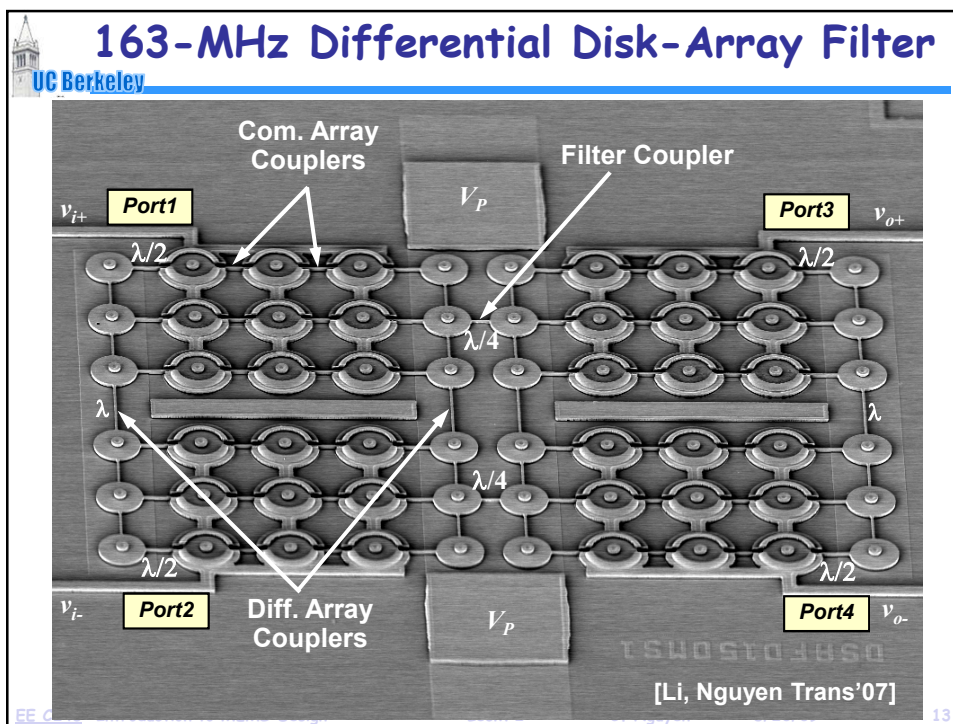
- Impedance-mismatched stem for reduced anchor dissipation
- Operated in the 2nd radial-contour mode
- Q ~11,555 (vacuum); Q ~10,100 (air)
- Below: 20 μ m diameter disk

Design/Performance:
 $R=10\mu\text{m}$, $t=2.2\mu\text{m}$, $d=800\text{\AA}$, $V_p=7\text{V}$
 $f_o=1.51\text{ GHz}$ (2nd mode), $Q=11,555$

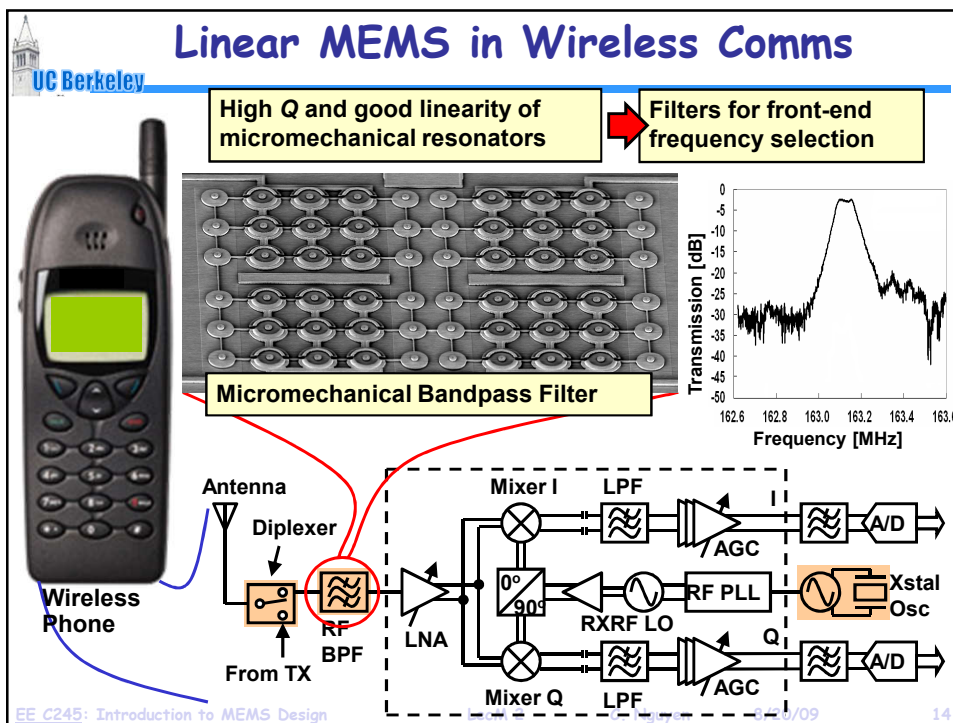
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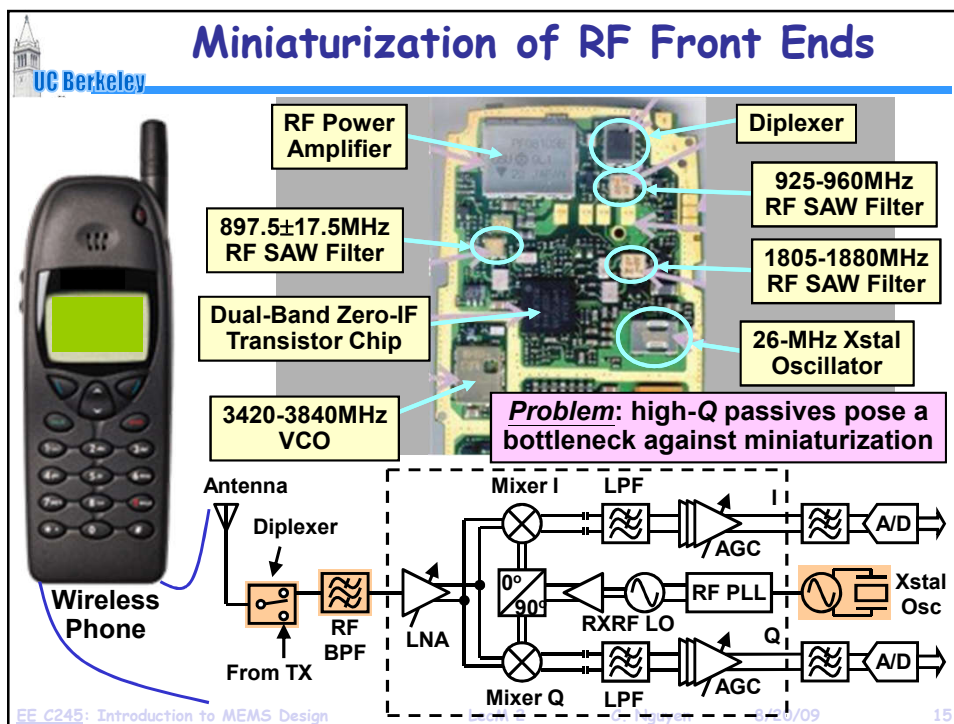
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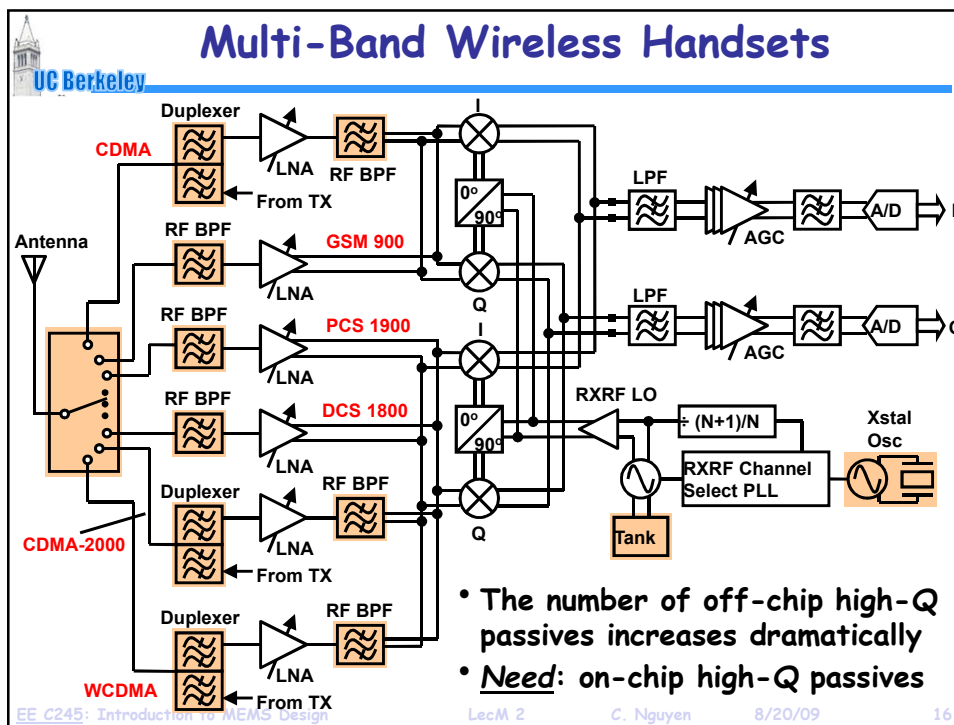
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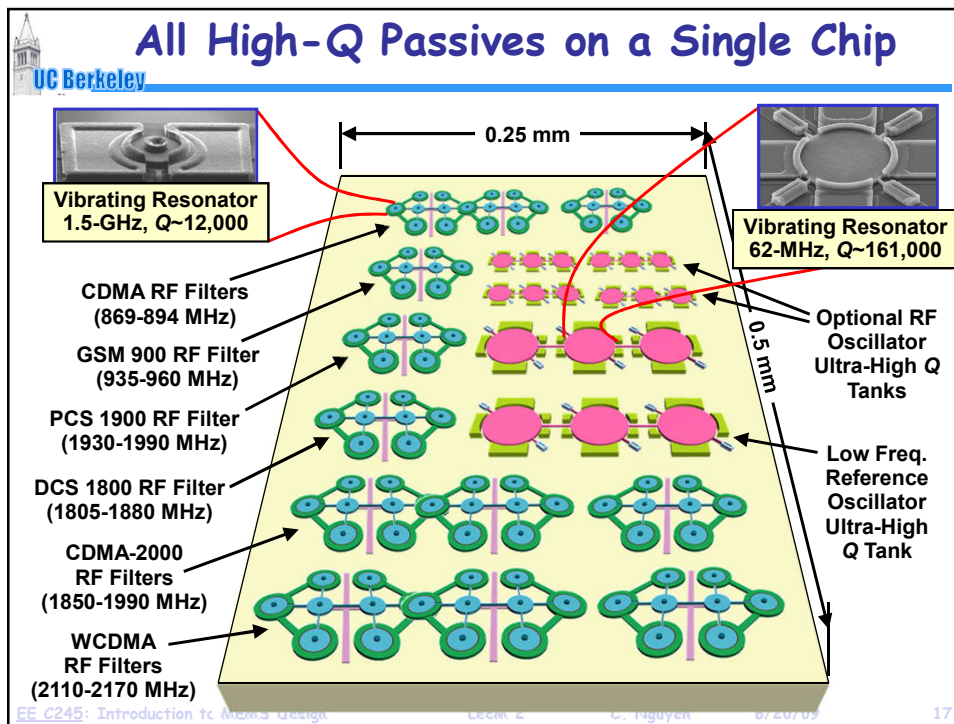
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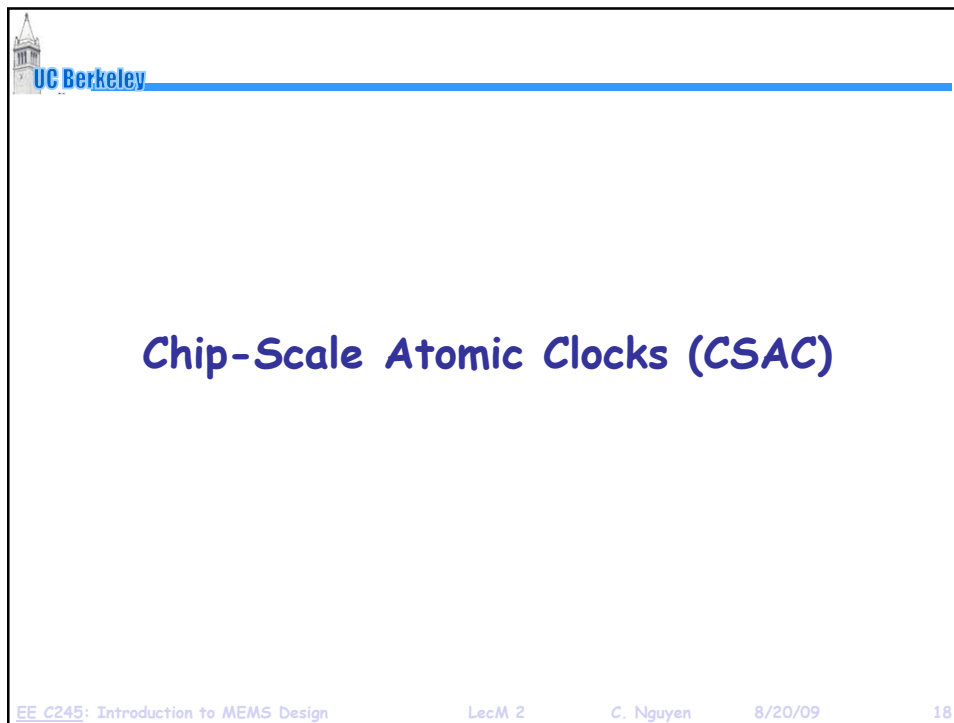
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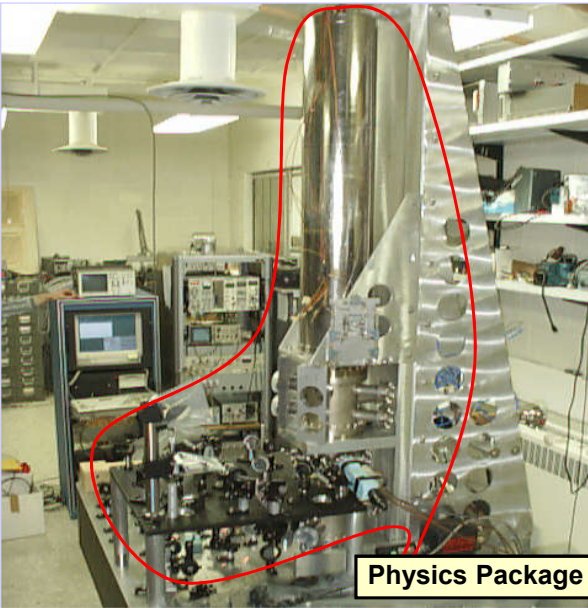
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NIST F1 Fountain Atomic Clock

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**Vol: $\sim 3.7 \text{ m}^3$
 Power: $\sim 500 \text{ W}$
 Acc: 1×10^{-15}
 Stab: $3.3 \times 10^{-15} / \text{hr}$**

After 1 sec \Rightarrow
Error: 10^{-15} sec

Loses 1 sec every 30 million years!

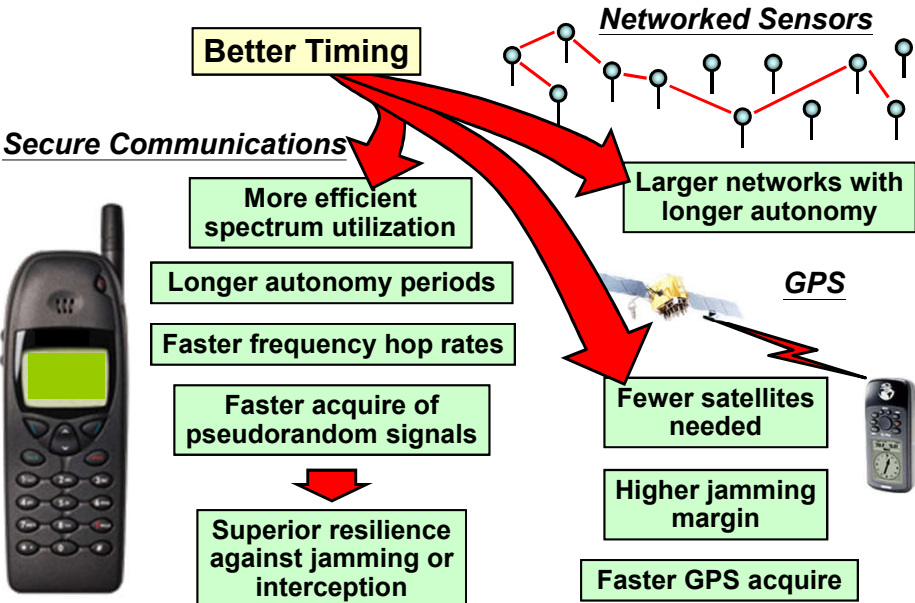
Physics Package

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Benefits of Accurate Portable Timing

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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

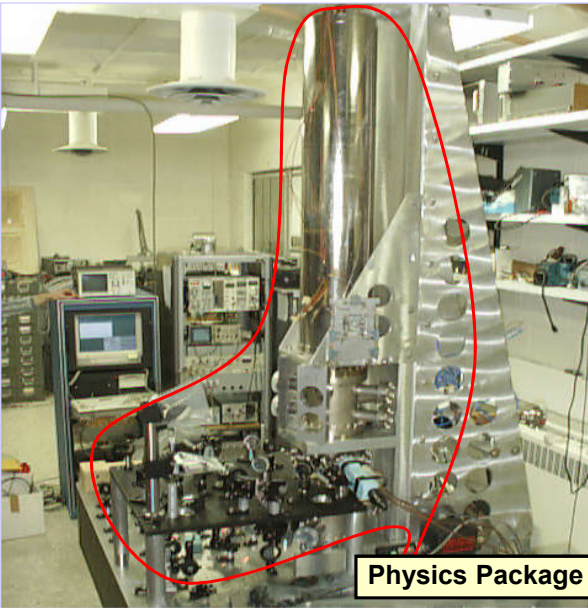
- Fewer satellites needed
- Higher jamming margin
- Faster GPS acquire

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NIST F1 Fountain Atomic Clock

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Vol: $\sim 3.7 \text{ m}^3$
Power: $\sim 500 \text{ W}$
Acc: 1×10^{-15}
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After 1 sec \Rightarrow
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**Loses 1 sec every
 30 million years!**

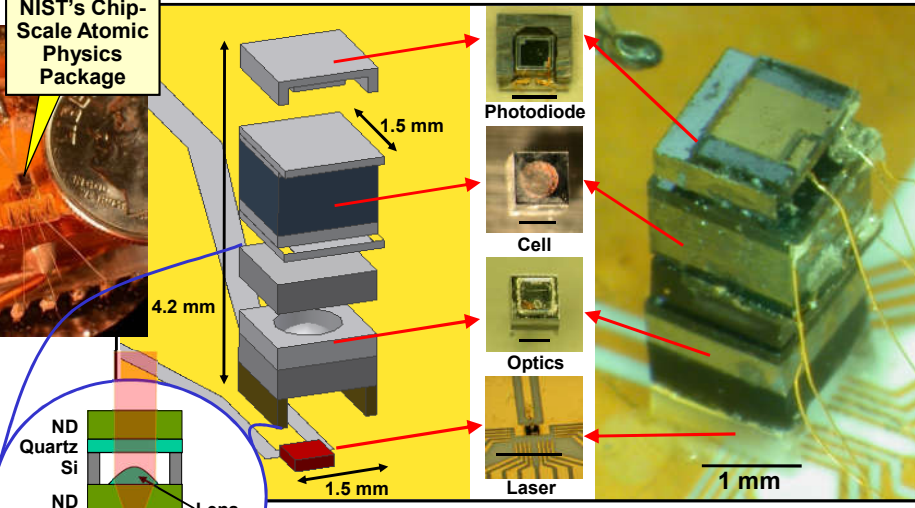
Physics Package

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1st Chip-Scale Atomic Physics Package

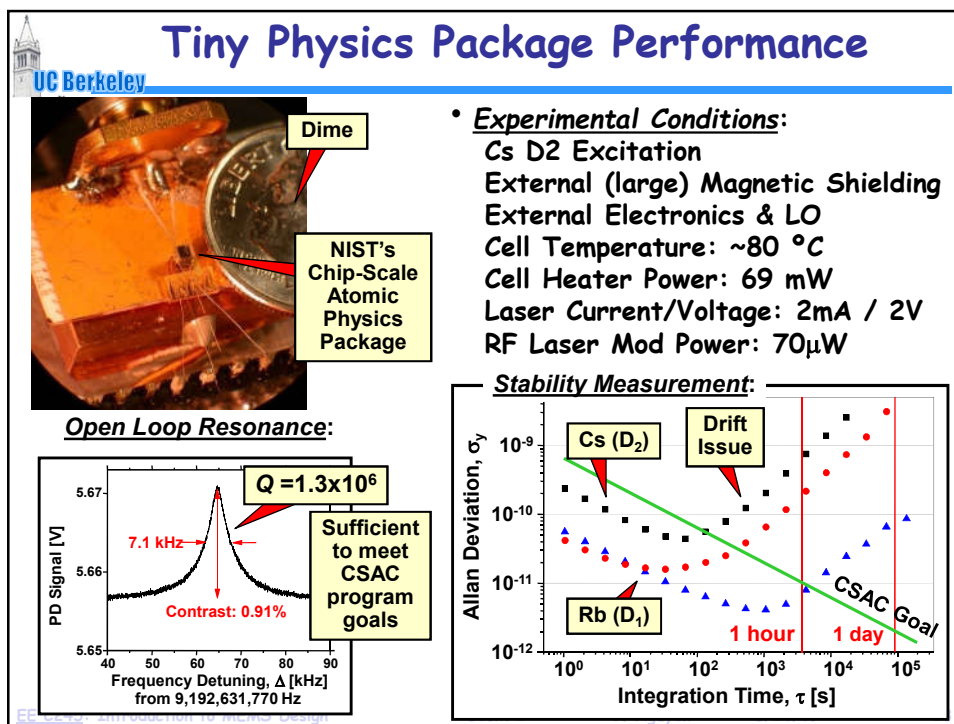
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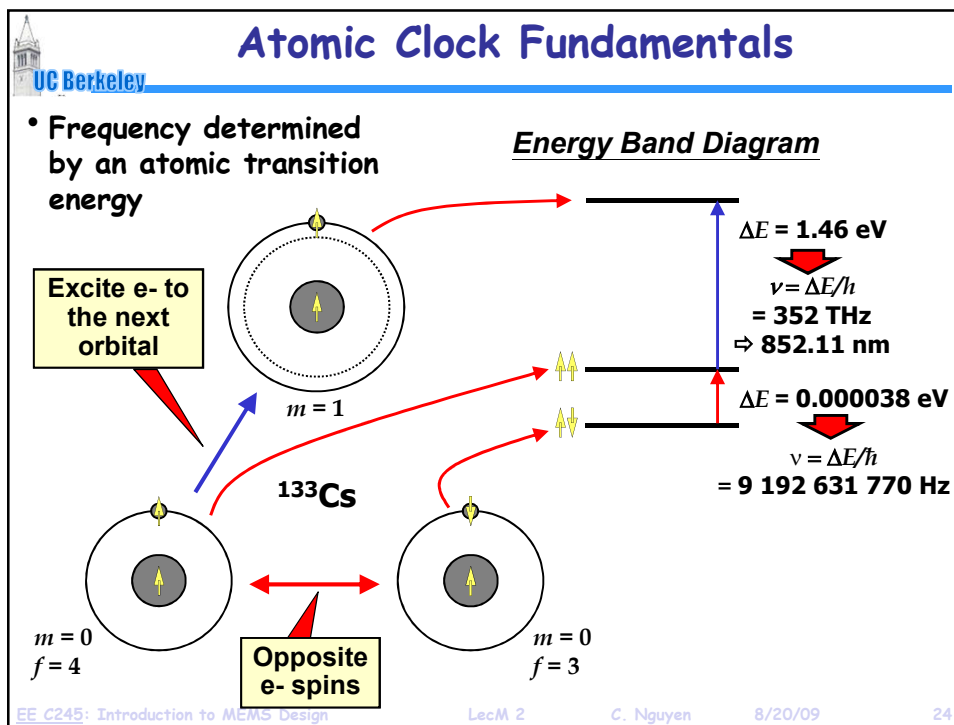
Total Volume: 9.5 mm^3 **Stability: 2.4×10^{-10} @ 1s**
Cell Interior Vol: 0.6 mm^3 **Power Cons: 75 mW**

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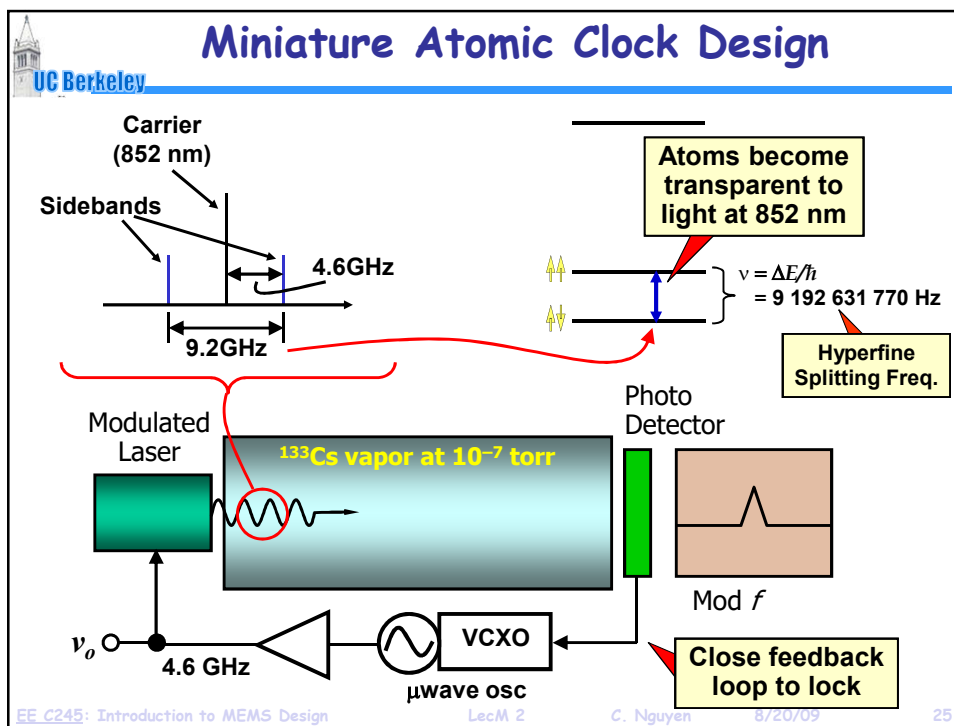
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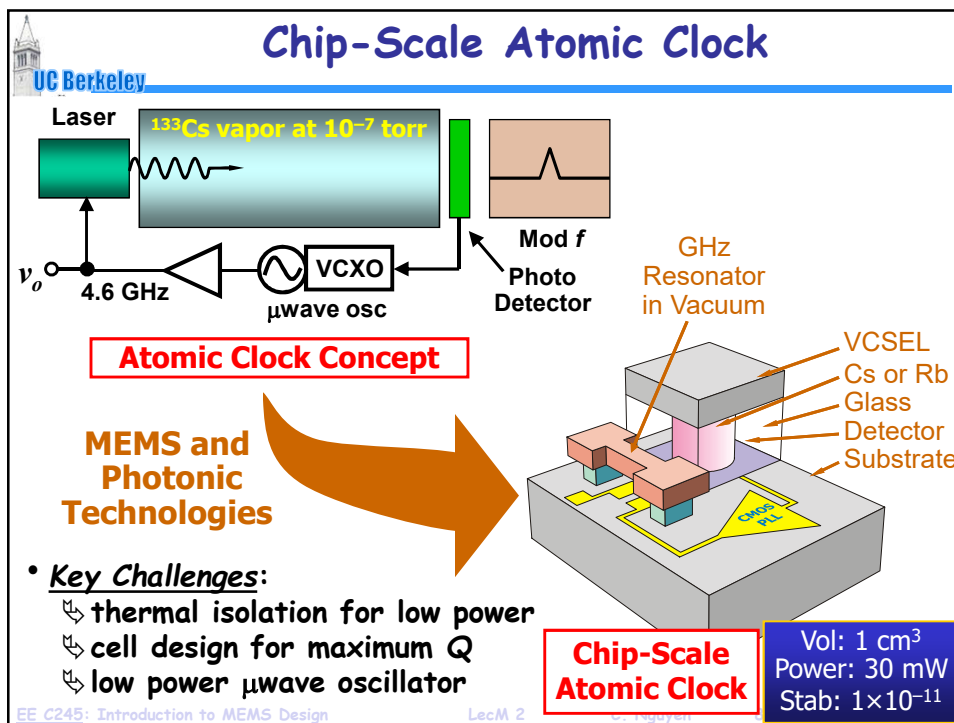
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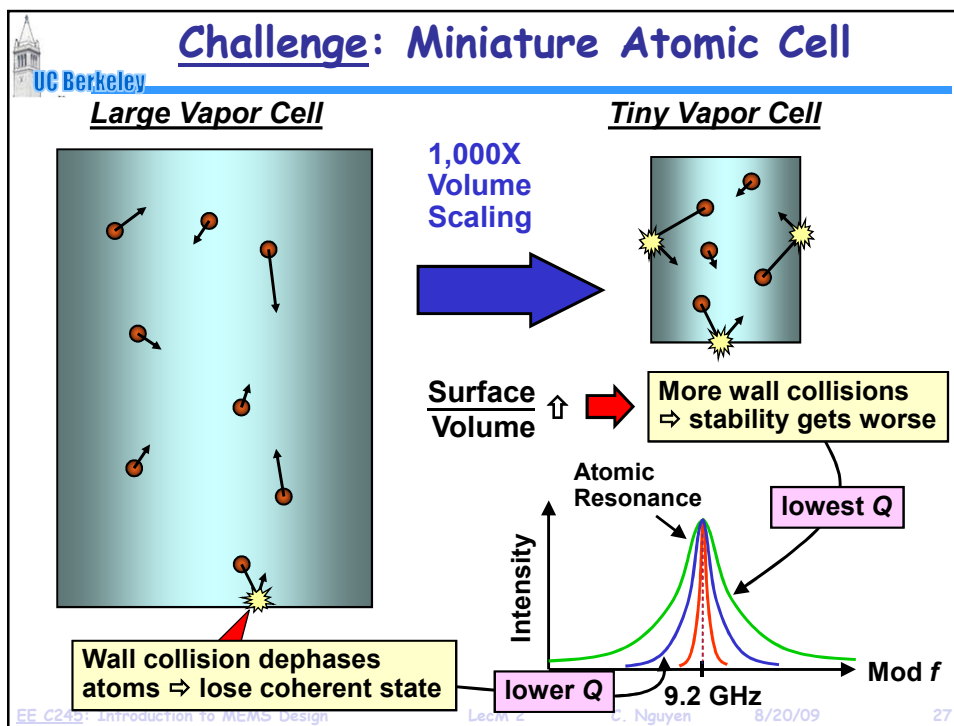
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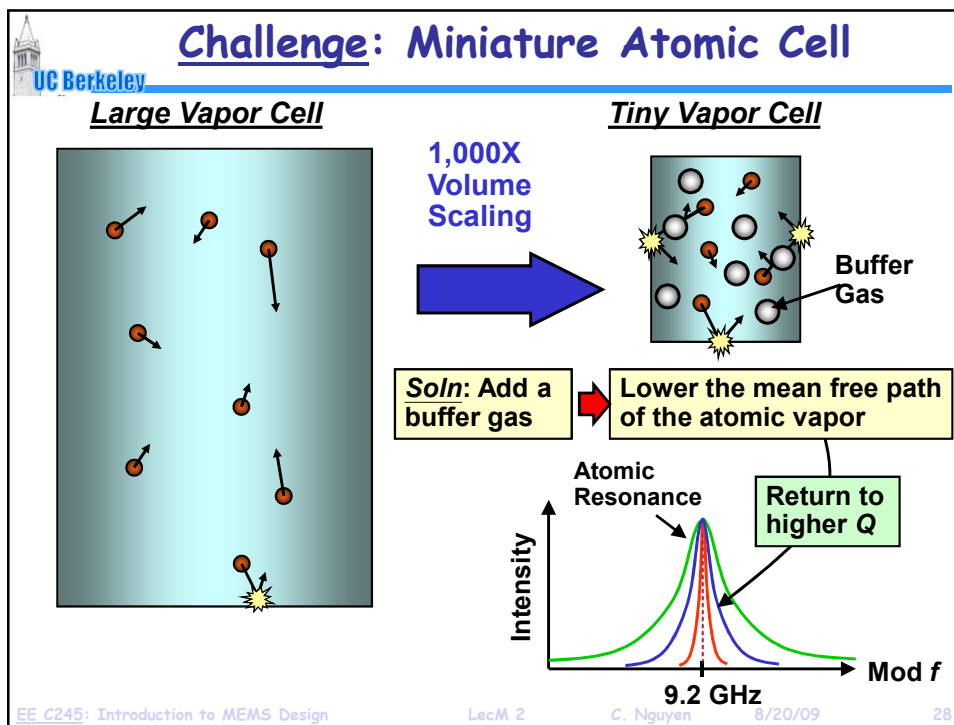
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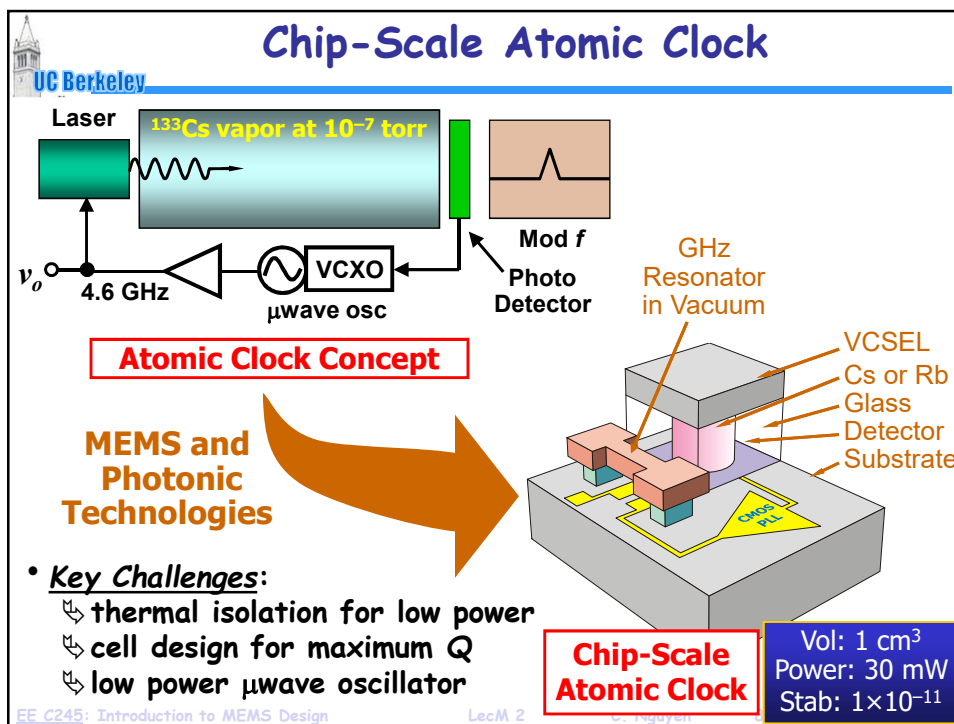
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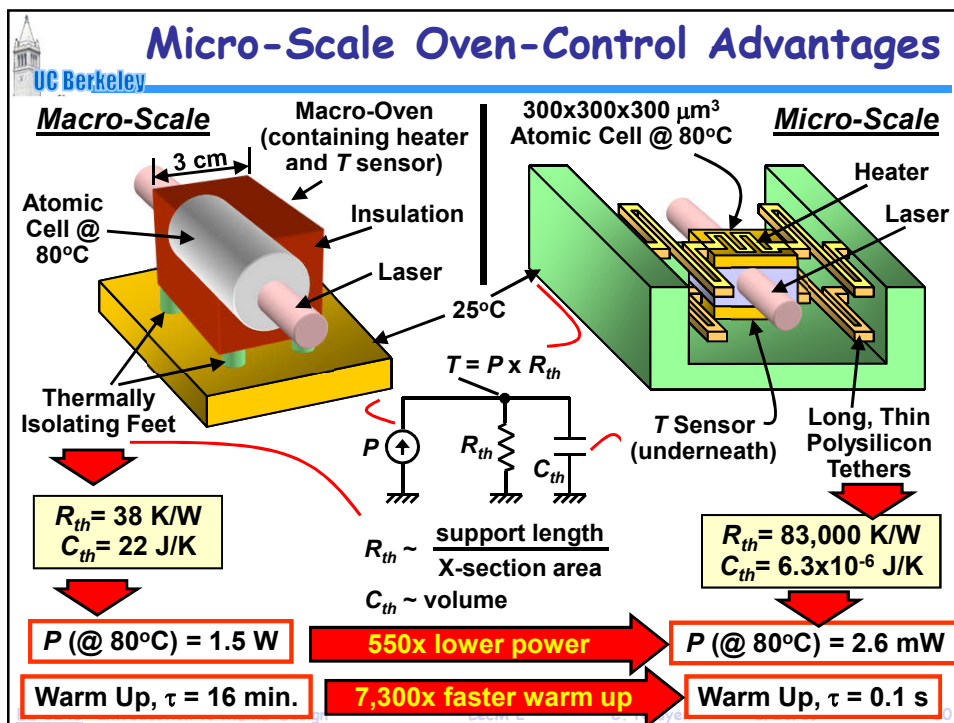
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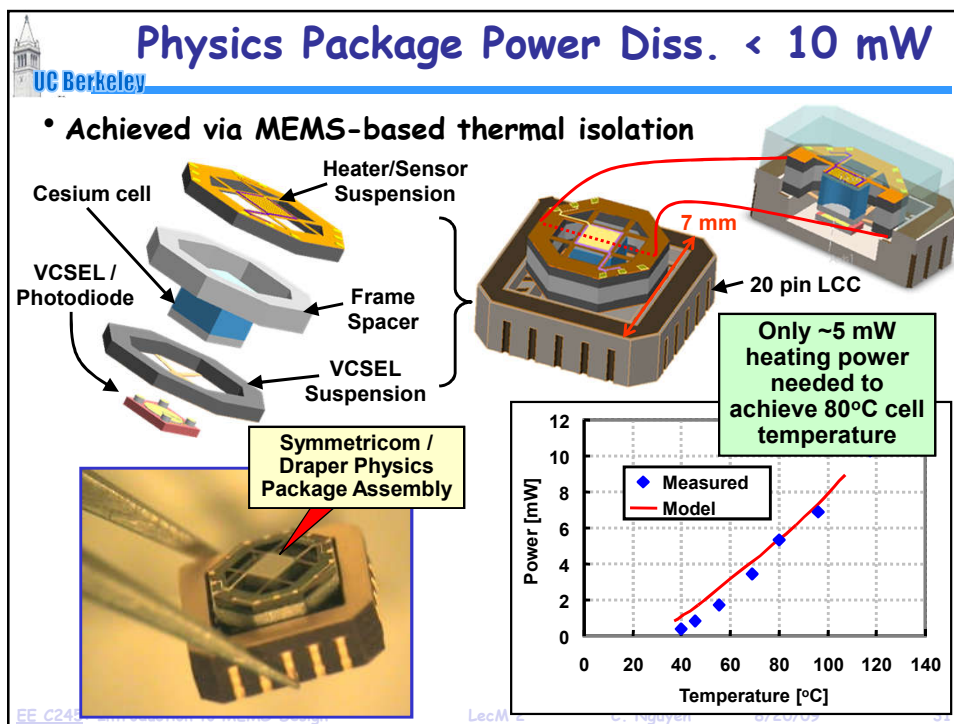
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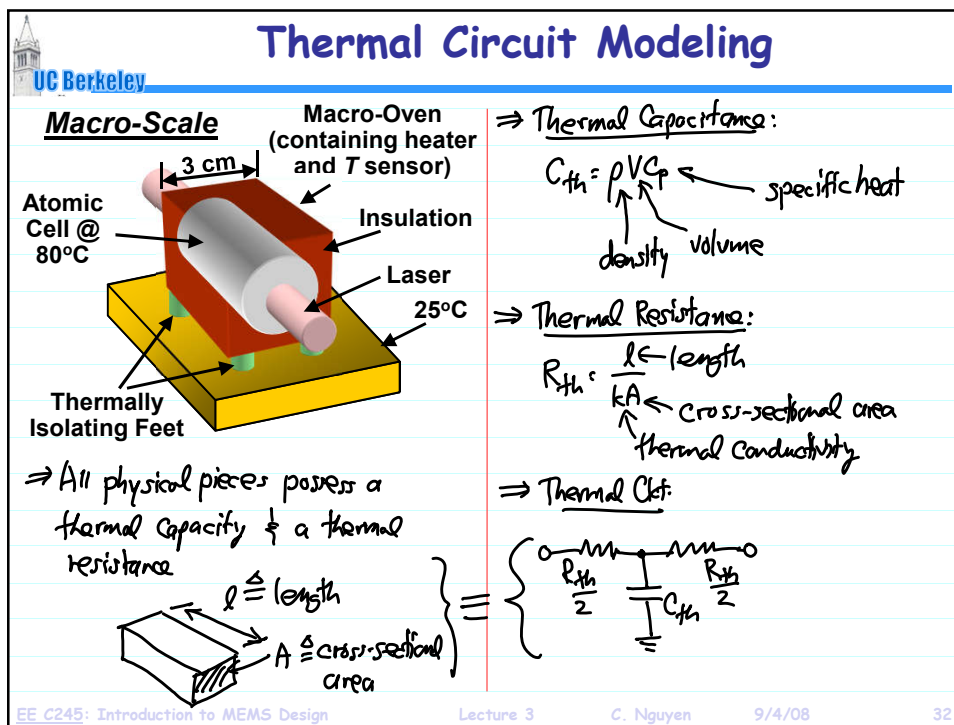
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Thermal Circuit Modeling

$h=3\text{ cm}$
 $W=3\text{ cm}$
 $L=3\text{ cm}$
 Atomic Cell @ 80°C
 Insulation
 Laser
 25°C
 Glass
 Thermally Isolating Feet
 $R_{\text{cell}}=1\text{ cm}$
 Example. Power to maintain cell $T=80^\circ\text{C}$
 \Rightarrow for materials identified in the figure: (all glass)
 $C_{p,\text{glass}}=0.5\text{ J/(g.K)}$
 $\rho_{\text{glass}}=2500\text{ kg/m}^3$

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

Eqv. Ckt:
 \Rightarrow ignore the small R_{th} of the cell
 \Rightarrow ignore the small C_{th} of the feet

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

$R_{\text{th,foot}} = \frac{R_{\text{th,foot}}}{4}$

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Thermal Circuit Modeling

\Rightarrow When power is switched on

Time constant determines how fast T_∞ can be achieved

Find $C_{\text{th,cell}}$:
 \Rightarrow Find volume of the cell
 $V_{\text{cell}} = hWL - \pi R_{\text{cell}}^2 \cdot L$
 $= (3\text{ cm})(3\text{ cm})(3\text{ cm}) - \pi(1\text{ cm})^2(2\text{ cm})$
 $= 20.7\text{ cm}^3$
 (again, ignore the R_{th} of the cell)

and for the cell:

$$C_{\text{th,cell}} = \rho_{\text{glass}} V_{\text{cell}} C_{p,\text{glass}}$$

$$= (2500\frac{\text{kg}}{\text{m}^3})(1000\frac{\text{cm}^3}{100^3\frac{\text{m}^3}{\text{cm}^3}}) \times (20.7\text{ cm}^3)(0.5\frac{\text{J}}{\text{g.K}})$$

$\Rightarrow C_{\text{th,cell}} = 25.9\text{ J/K}$

Find $R_{\text{th,foot}}$:
 \Rightarrow foot dimensions:

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

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Thermal Circuit Modeling

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$$R_{th,foot} = \frac{l_{foot}}{k_{glass} \cdot A_{foot}} = \frac{2 \text{ mm}}{(105 \frac{\text{W}}{\text{m}\cdot\text{K}}) \pi (2 \text{ mm})^2}$$

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

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

\Rightarrow find power req'd to maintain T_{oo} in steady state:

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

\Rightarrow find the time constant.

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

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

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300x300x300 μm^3 } hollow w/
 Atomic Cell @ 80°C } 10 μm -thick walls
 (glass)

Heater
 Laser
 T Sensor (underneath)
 Long, Thin Polysilicon Tethers

25°C

580 μm -long, 10 μm -thick, 20 μm -wide

$$V_{cell} = (300 \mu)(300 \mu)(300 \mu) - (280 \mu)(280 \mu)(280 \mu)$$

$$= 5.048 \times 10^{-12} \text{ m}^3$$

\hookrightarrow of course, much smaller than macro

$$C_{th,cell} = \rho_{glass} V_{cell} C_p, glass$$

$$= (2500 \frac{\text{kg}}{\text{m}^3}) (5.048 \times 10^{-12} \text{ m}^3) \times (500 \frac{\text{J}}{\text{kg}\cdot\text{K}})$$

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

\hookrightarrow 4 million x smaller than macro!

$$R_{th,supp} = \frac{l_{supp}}{k_{polysil} \cdot w_{supp} \cdot h_{supp}}$$

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

\hookrightarrow 548x larger

and...

$$P = \frac{(80 - 25)}{83,333} = 2.64 \text{ mW}$$


\leftarrow 548x smaller! All due to scaling!

$$\tau = 0.13 \text{ s}$$

\leftarrow 7300x faster!

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Micro Gas Analyzers (MGA)

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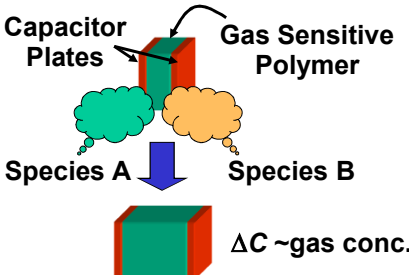
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Micro Gas Analyzers

- **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



Species A Species B

$\Delta C \sim \text{gas conc.}$

Separation Analyzer

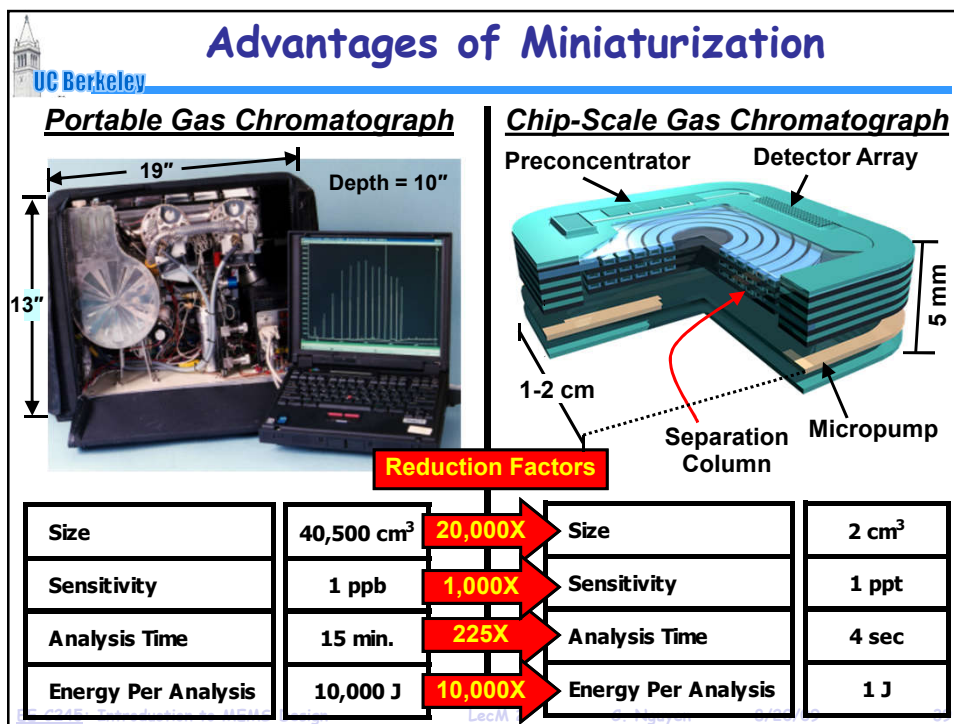


Species A B

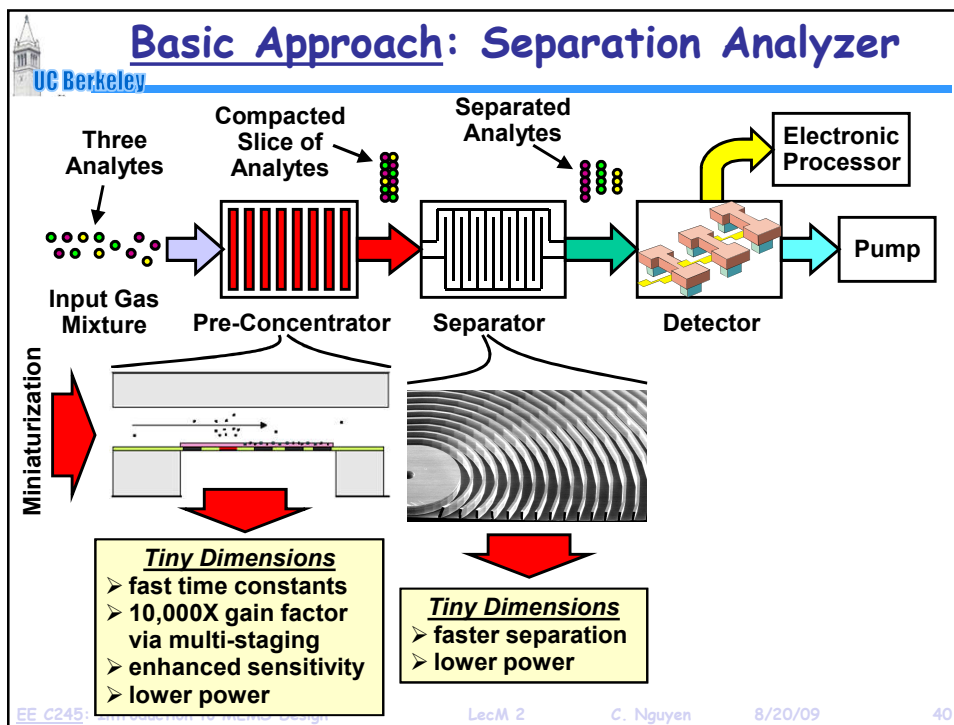
- **Problem:** polymer has finite sensitivity to both A & B
- **Result:** species A & B now separated \Rightarrow can identify and analyze individually

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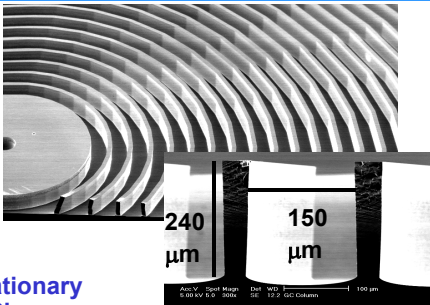
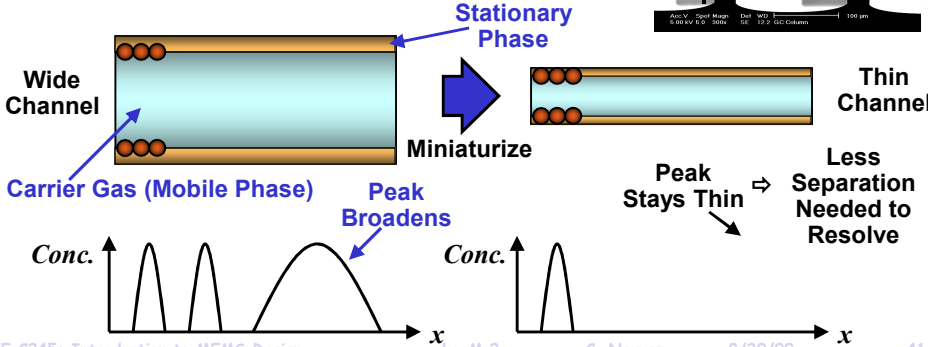
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Scaling Leads to Faster Separation
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- Example:** gas chromatograph separation column
 - ↪ unique analyte interactions with the column walls
 - ↪ different analyte velocities
 - ↪ **result:** separation after a finite distance

Wide Channel → Miniaturize → Thin Channel

Carrier Gas (Mobile Phase) Stationary Phase

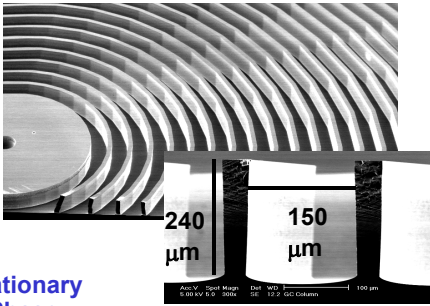
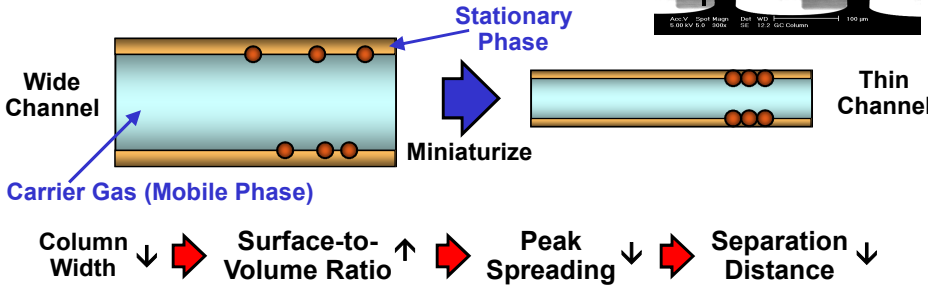
Conc. vs x graph: Peak Broadens (wide channel) vs Peak Stays Thin (thin channel) ⇒ Less Separation Needed to Resolve

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Scaling Leads to Faster Separation
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- Example:** gas chromatograph separation column
 - ↪ unique analyte interactions with the column walls
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Wide Channel → Miniaturize → Thin Channel

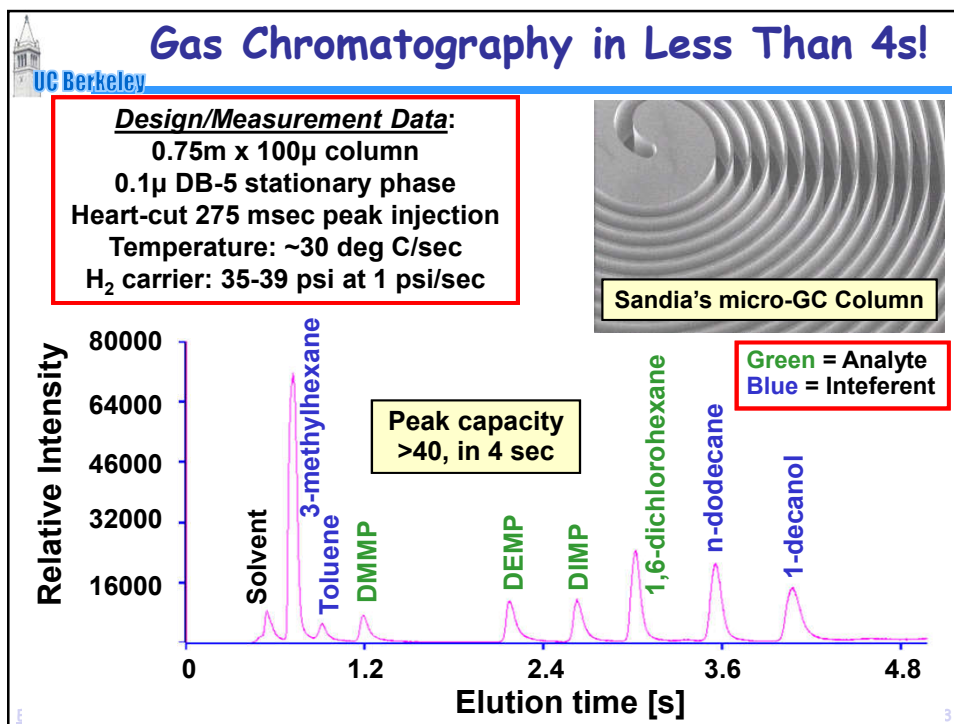
Carrier Gas (Mobile Phase) Stationary Phase

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

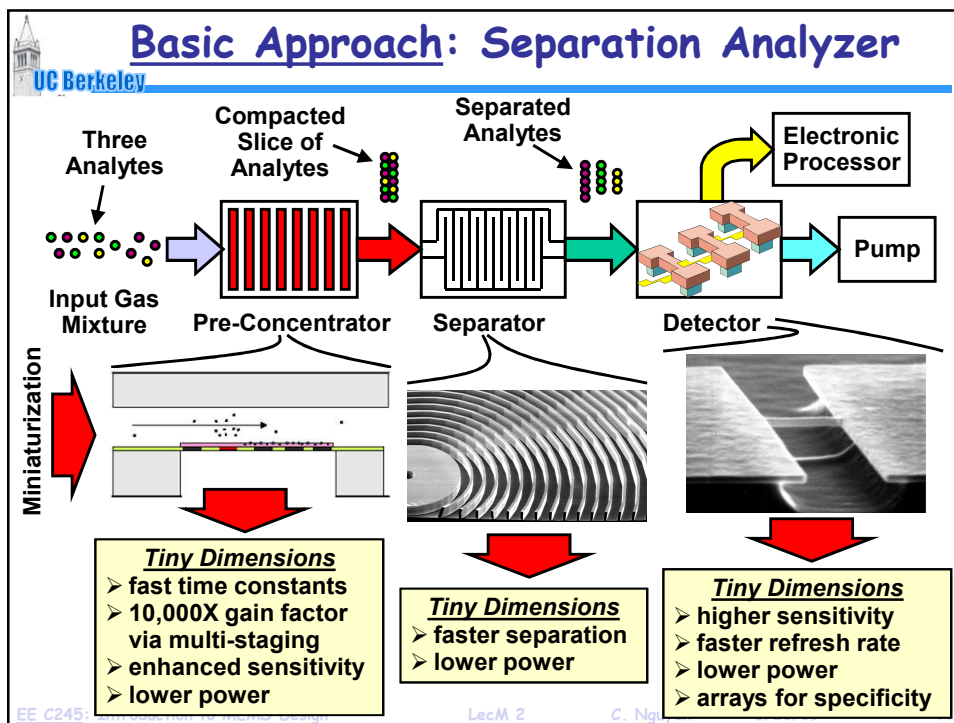
- Result of Scaling:** shorter column length; faster analysis time

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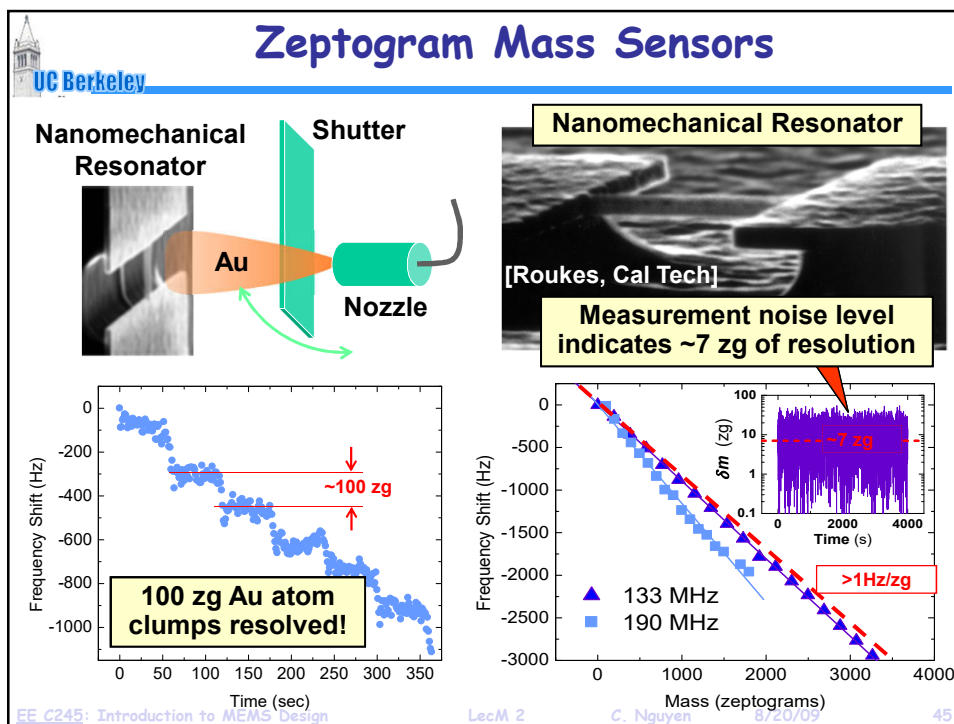
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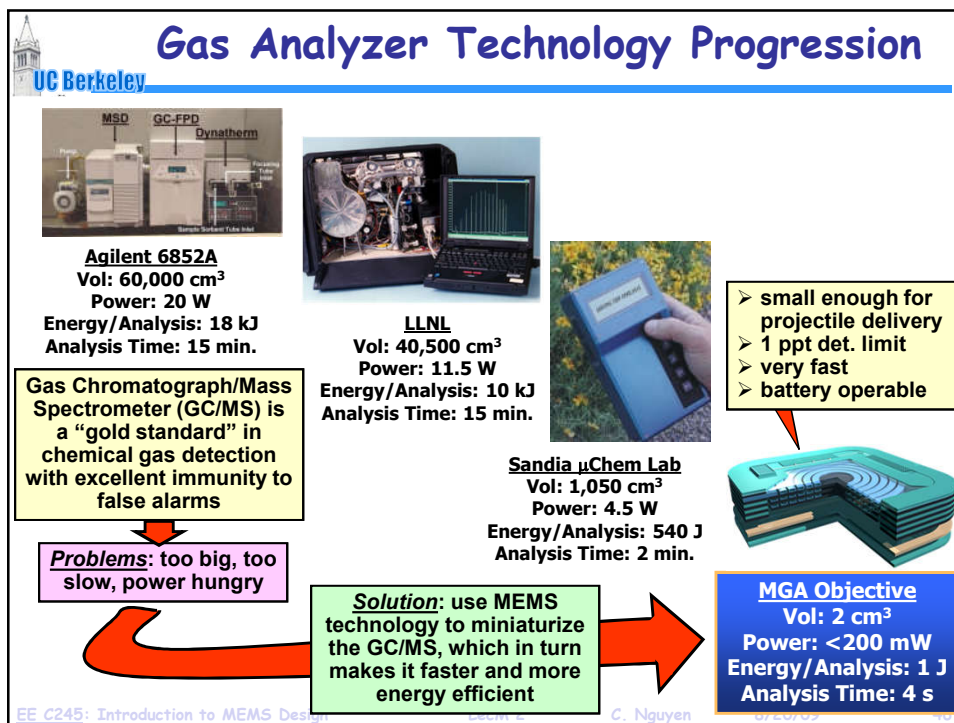
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Example: Micromechanical Accelerometer

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- The MEMS Advantage:**
 - >30X size reduction
 - accelerometer mechanism
 - allows integration with

Tiny mass means small output \Rightarrow need integrated transistor circuits to compensate

Basic Operation Principle

$x \propto F_i = ma$

Displacement x

Spring

Inertial Force

Proof Mass

Acceleration a

400 μm

Analog Devices ADXL 78

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Messages Going Forward ...

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- MEMS are micro-scale or smaller devices/systems that operate mainly via a mechanical or electromechanical means
- MEMS \Rightarrow 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:
 - resonant frequency \uparrow (faster speed)
 - actuation force \downarrow (lower power)
 - # mechanical elements \uparrow (higher complexity)
 - integration level \uparrow (lower cost)

Size \downarrow **...**

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

... limitless possibilities ...

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