EE C247B – ME C218
Introduction to MEMS Design
Spring 2017

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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

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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 ↑

Vibrating RF MEMS

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Basic Concept: Scaling Guitar Strings

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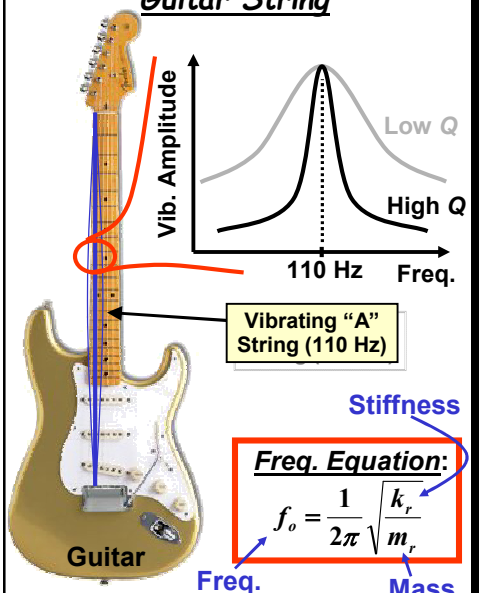
Guitar String

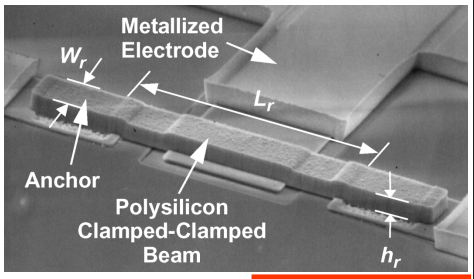


Freq. Equation:

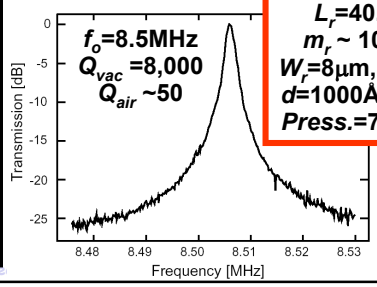
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Stiffness
Freq.
Mass

μMechanical Resonator



[Bannon 1996]



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

Frequency of a Stretched Wire

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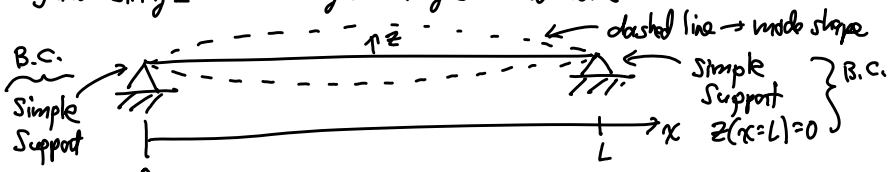
Scaling of Guitar Strings!

guitar string ≡ transversely vibrating stretched wire



⇒ Equation for Resonance Freq. (fundamental mode)

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

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

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

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Frequency of a Clamped-Clamped Beam

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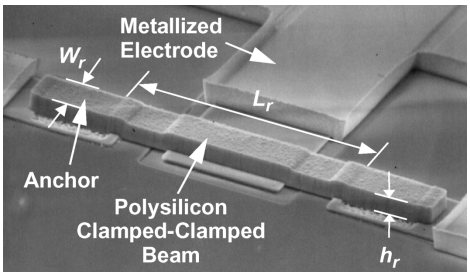
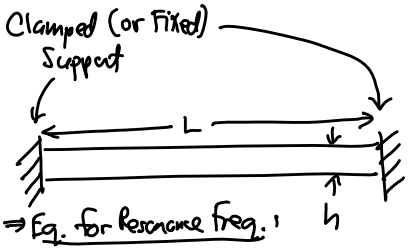
Clamped-Clamped Beam





⇒ 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/m^3]
$h \triangleq$ thickness [m]
$L \triangleq$ length [m]

Example. $L = 40\mu m$, $h = 2\mu m$
polysi → $E = 150$ GPa, $\rho = 2300$ kg/m^3

$$\therefore f_o = (1.03)\sqrt{\frac{150G}{2300}}\left(\frac{2\mu}{(40\mu)^2}\right) \rightarrow \boxed{f_o = 10.4\,MHz}$$

$\sqrt{\frac{150G}{2300}}$ = acoustic velocity = 8,076 m/s

As $L \downarrow \rightarrow f_o \uparrow$!

Frequency of a Clamped-Clamped Beam

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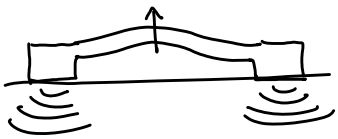
Example. $L = 4\mu m$ → $f_o = (1.03)(8076)\left(\frac{2\mu}{(4\mu)^2}\right) \rightarrow \boxed{f_o = 1.04\,GHz}$!

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×h), anchor losses become an issue



← Anchor Radiation → lowers quality factor, Q

③ Solution: nondimensions? ✓

④ Better Solution: other geometries ✓✓

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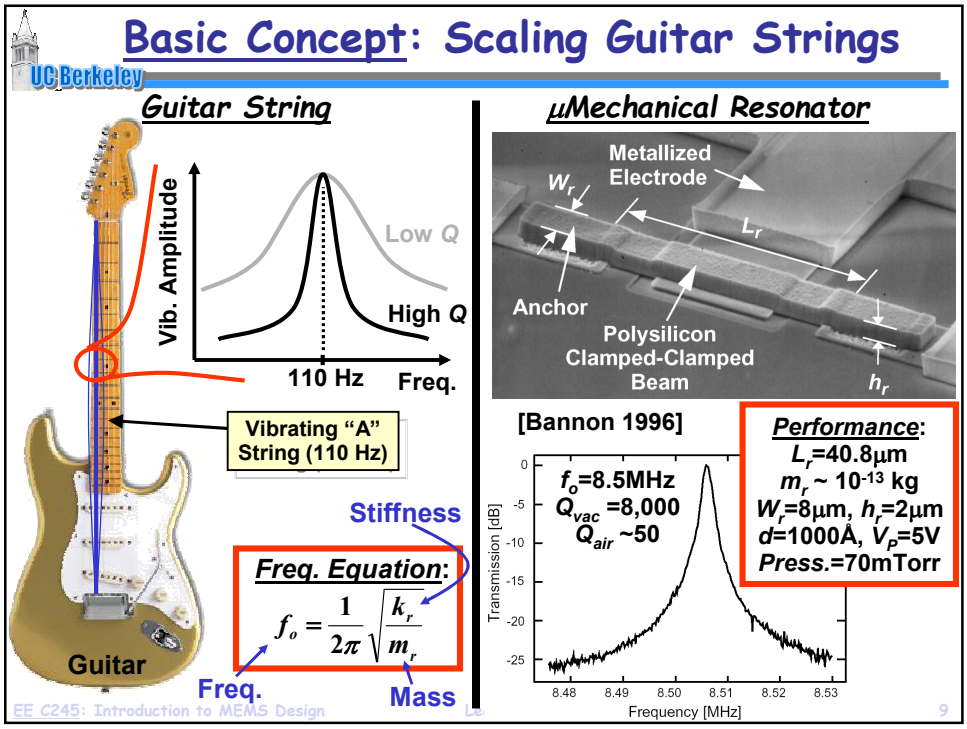

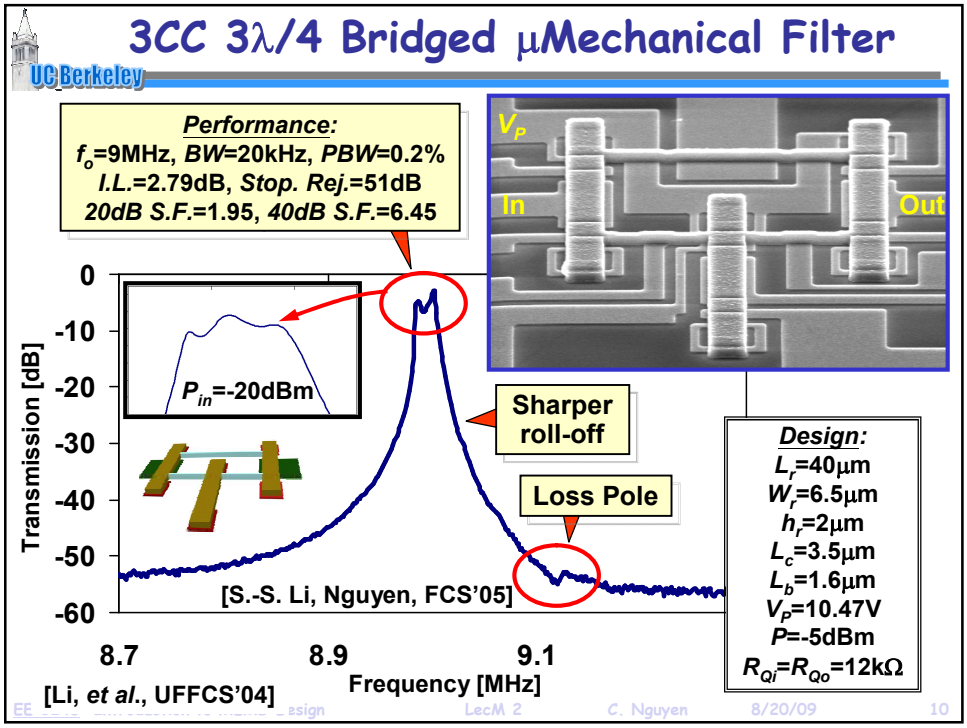

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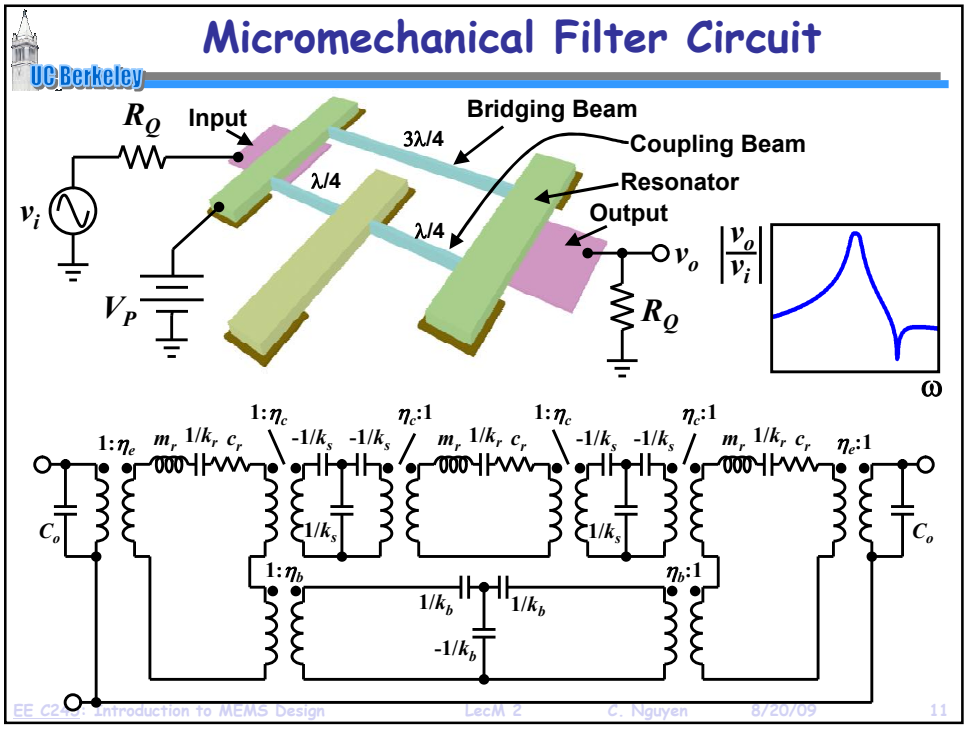

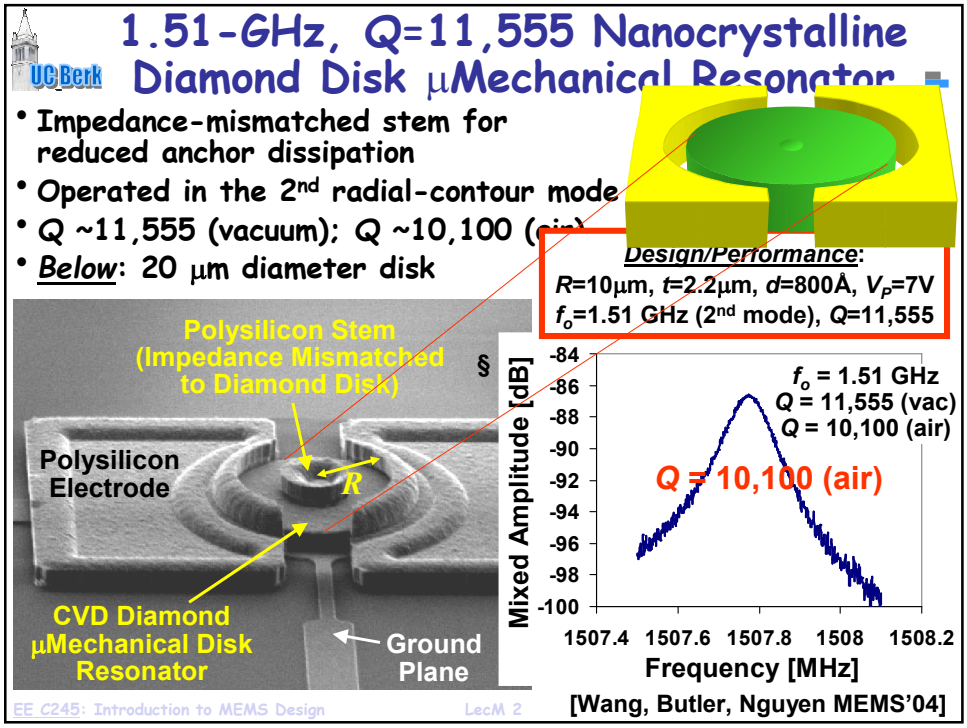

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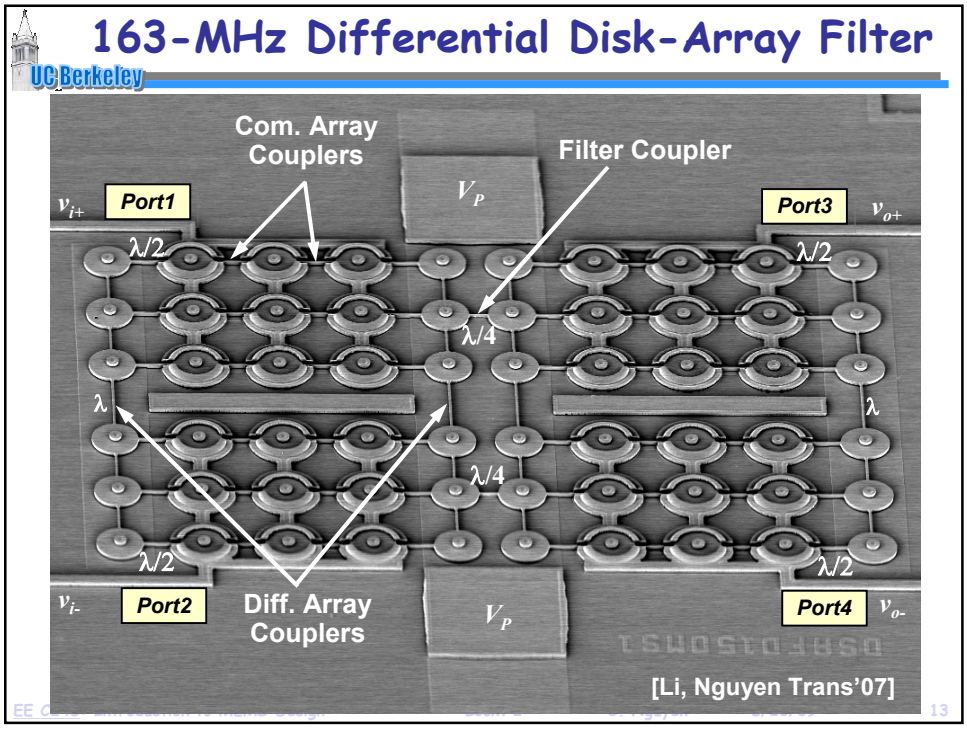

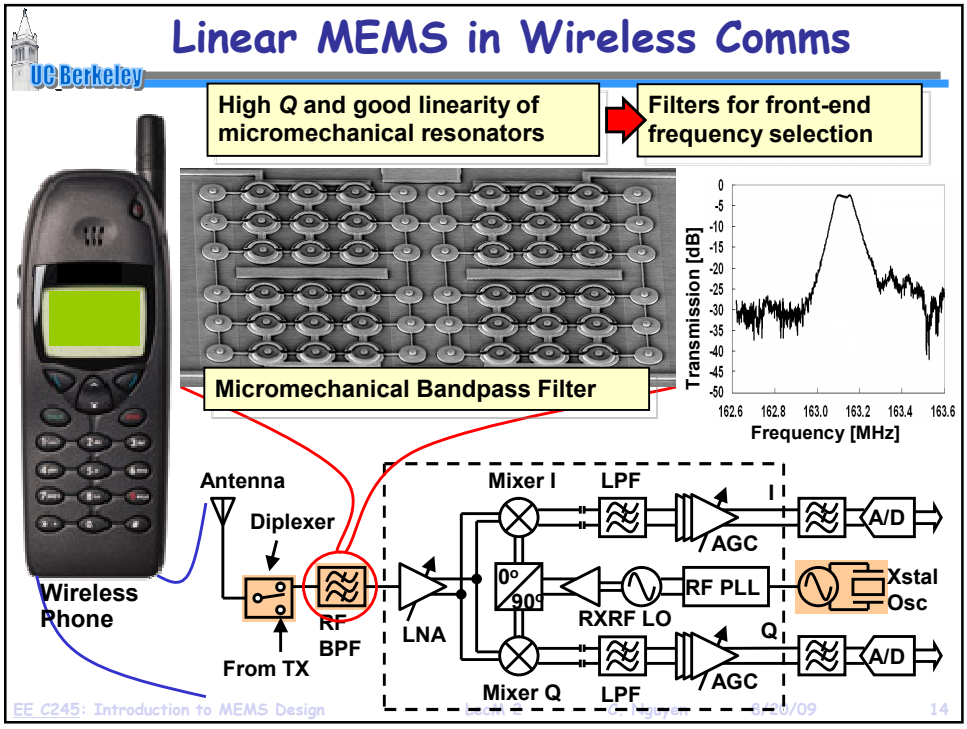

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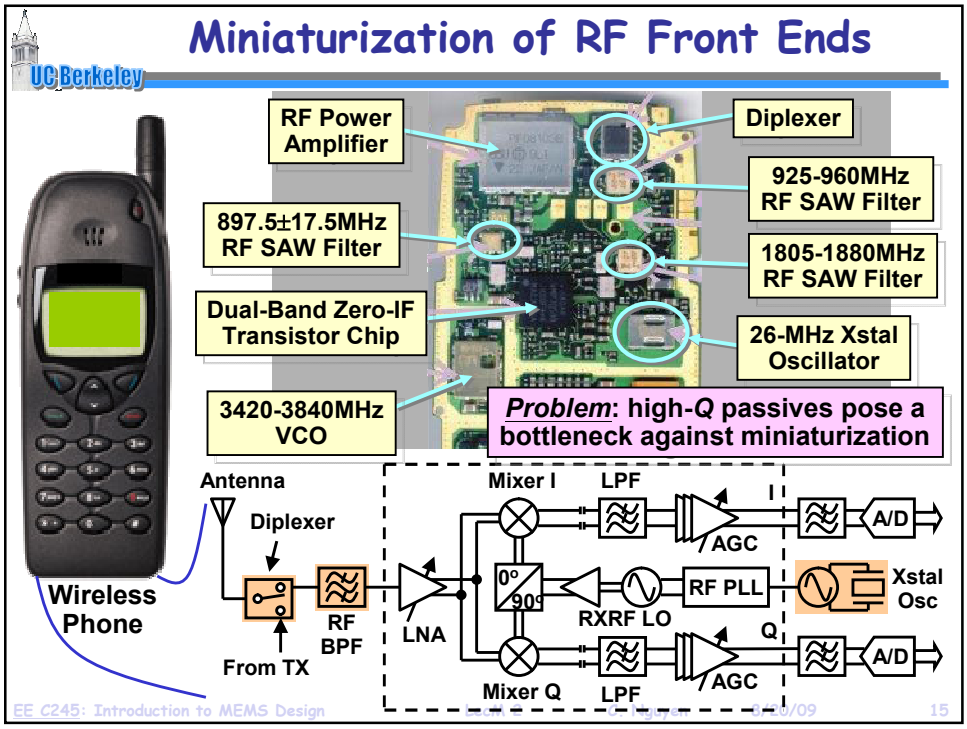
Miniaturization of RF Front Ends
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RF Power Amplifier
Diplexer
925-960MHz RF SAW Filter
897.5±17.5MHz RF SAW Filter
1805-1880MHz RF SAW Filter
Dual-Band Zero-IF Transistor Chip
26-MHz Xstal Oscillator
3420-3840MHz VCO
Problem: high-Q passives pose a bottleneck against miniaturization
Antenna
Diplexer
Wireless Phone
RF BPF
From TX
LNA
Mixer I
LPF
AGC
A/D
0°
90°
RF PLL
Xstal Osc
RXRF LO
Q
Mixer Q
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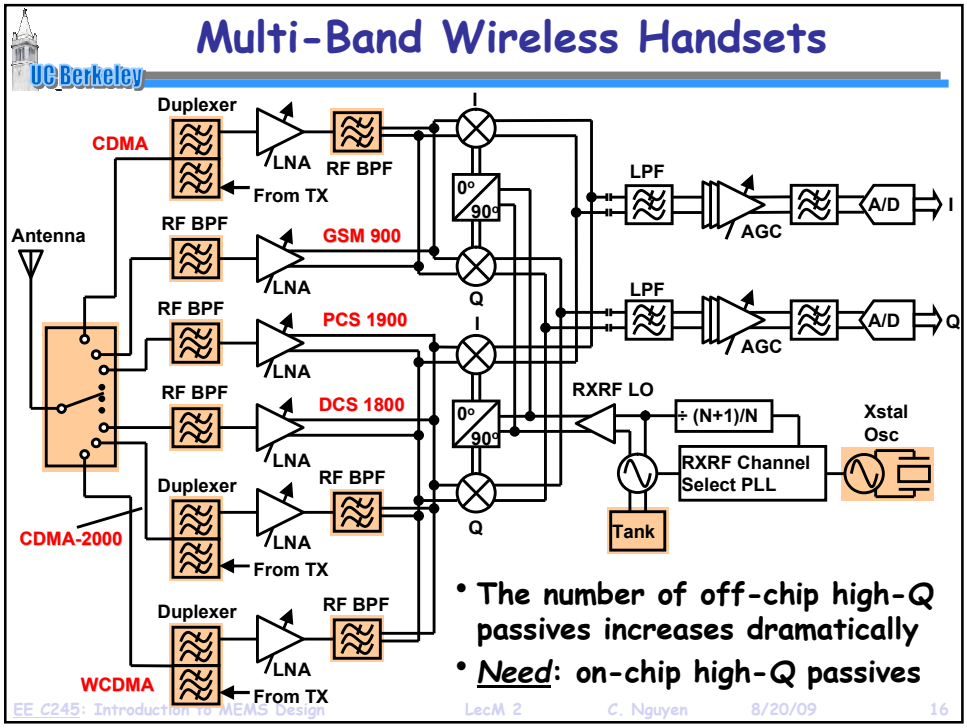
Multi-Band Wireless Handsets
UC Berkeley
Duplexer
CDMA
LNA
RF BPF
From TX
Antenna
GSM 900
PCS 1900
DCS 1800
CDMA-2000
WCDMA
I
Q
0°
90°
LPF
AGC
A/D
RXRF LO
÷ (N+1)/N
RXRF Channel Select PLL
Xstal Osc
Tank
• The number of off-chip high-Q passives increases dramatically
• Need: on-chip high-Q passives
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LecM 2
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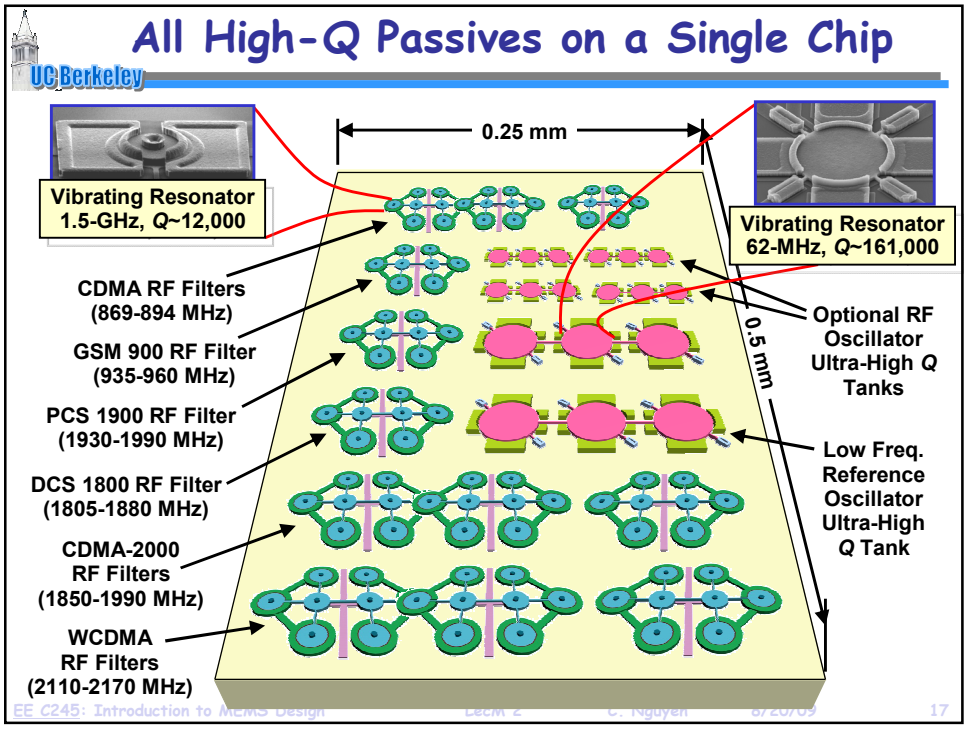
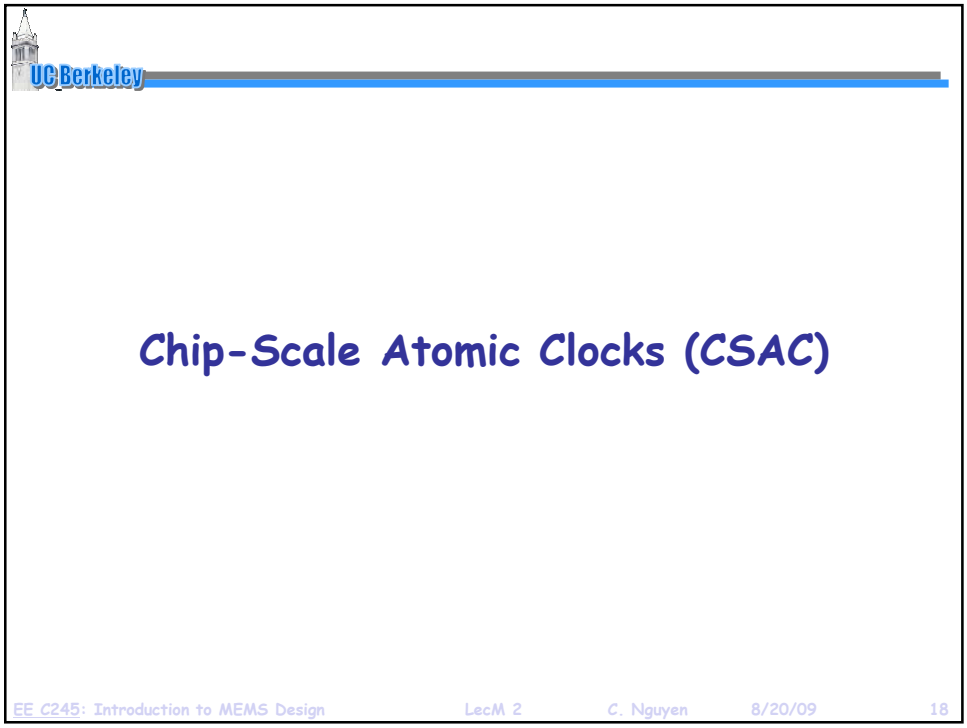
8/20/09
16





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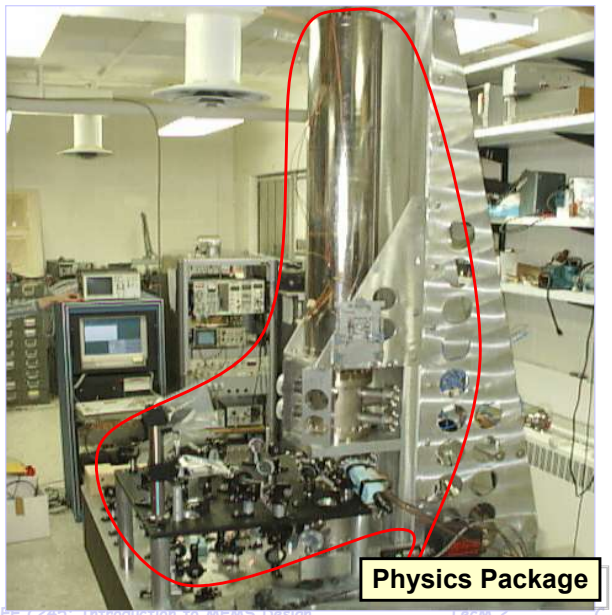
NIST F1 Fountain Atomic Clock



Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

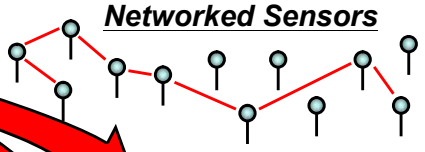
After 1 sec ⇨
Error: 10⁻¹⁵ sec

Loses 1 sec every 30 million years!

Benefits of Accurate Portable Timing

Better Timing

Networked Sensors



Secure Communications

More efficient spectrum utilization

Longer autonomy periods

Faster frequency hop rates

Faster acquire of pseudorandom signals

Superior resilience against jamming or interception

Larger networks with longer autonomy

GPS

Fewer satellites needed

Higher jamming margin

Faster GPS acquire

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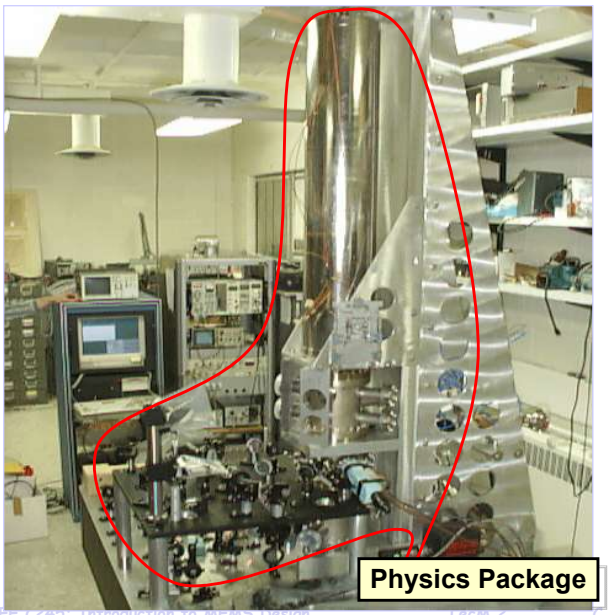
NIST F1 Fountain Atomic Clock



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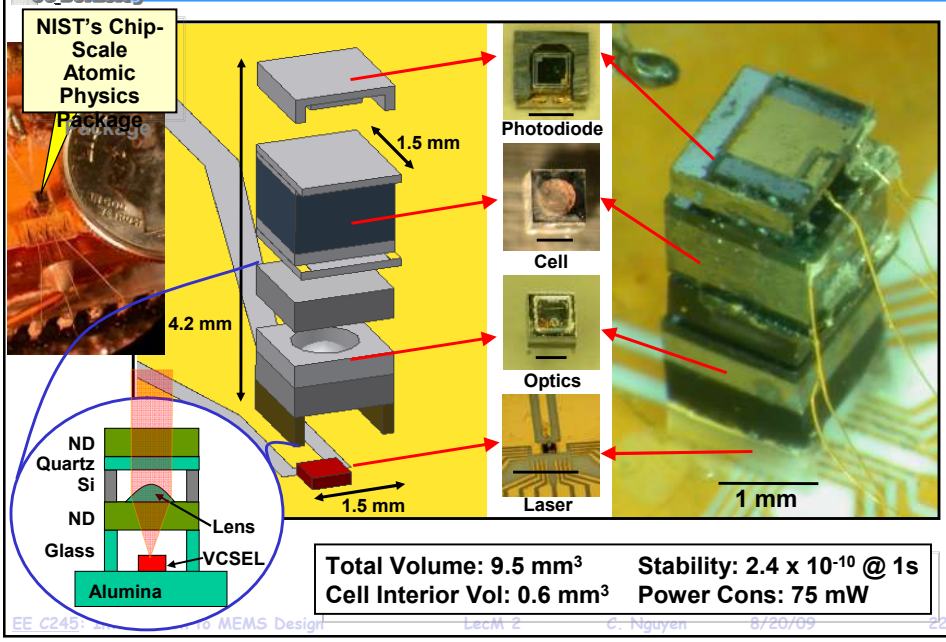
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

After 1 sec ⇨
Error: 10⁻¹⁵ sec

Loses 1 sec every 30 million years!

1st Chip-Scale Atomic Physics Package



Total Volume: 9.5 mm³
Cell Interior Vol: 0.6 mm³
Stability: 2.4 x 10⁻¹⁰ @ 1s
Power Cons: 75 mW

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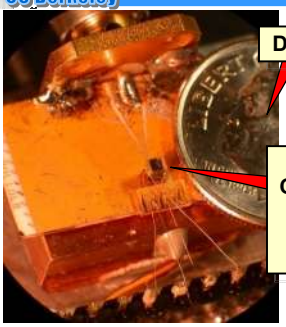
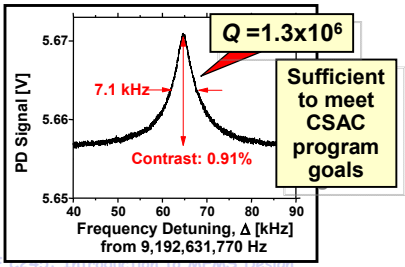
Tiny Physics Package Performance

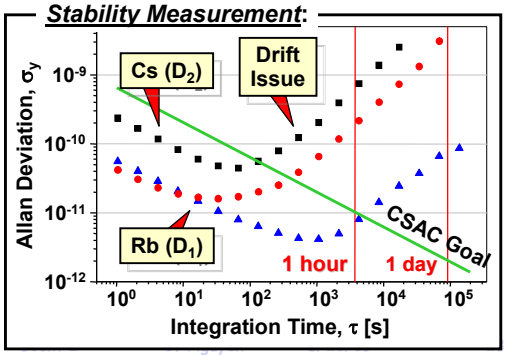


- *Experimental Conditions*:
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: ~80 °C
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70μW

Open Loop Resonance:



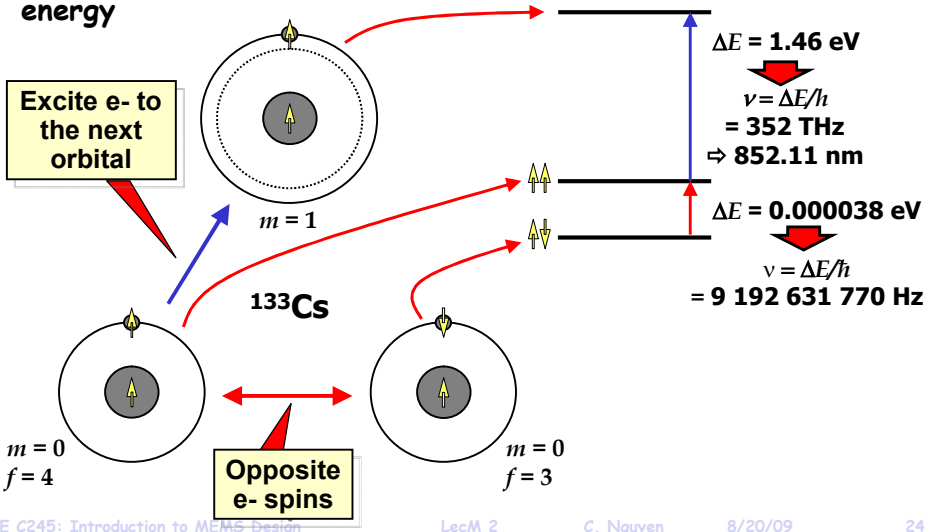
Stability Measurement:



Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

Energy Band Diagram



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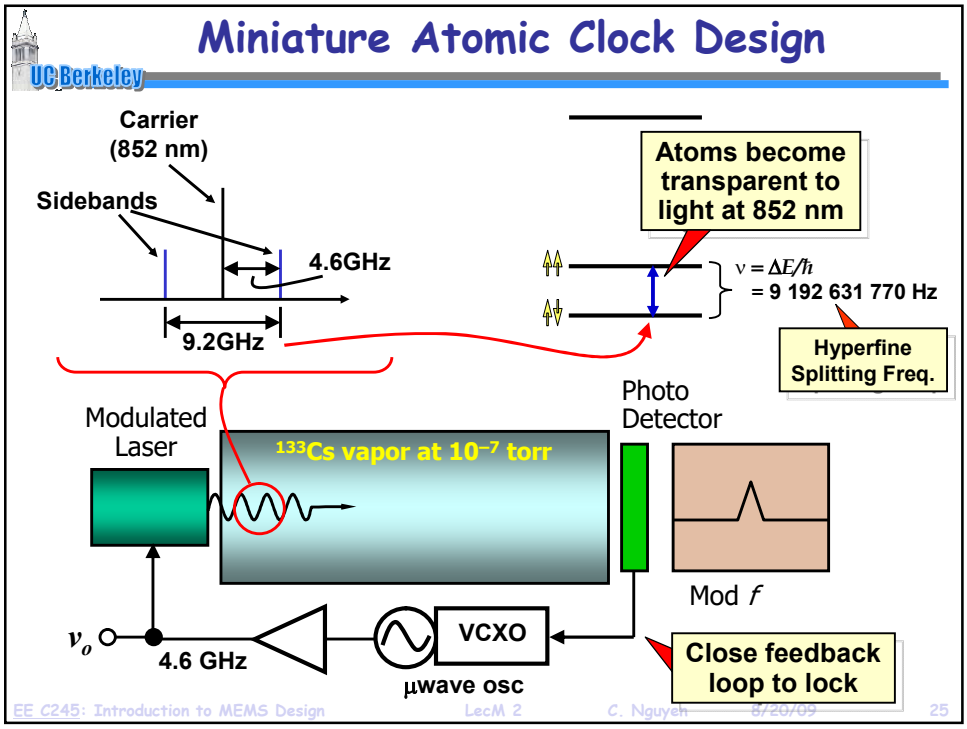

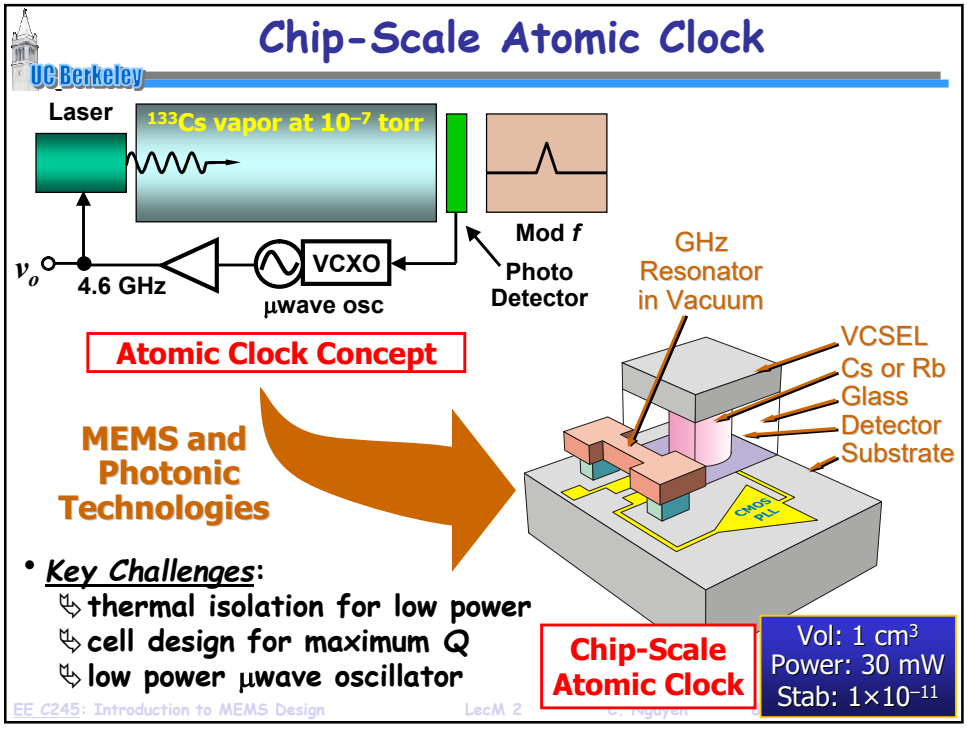

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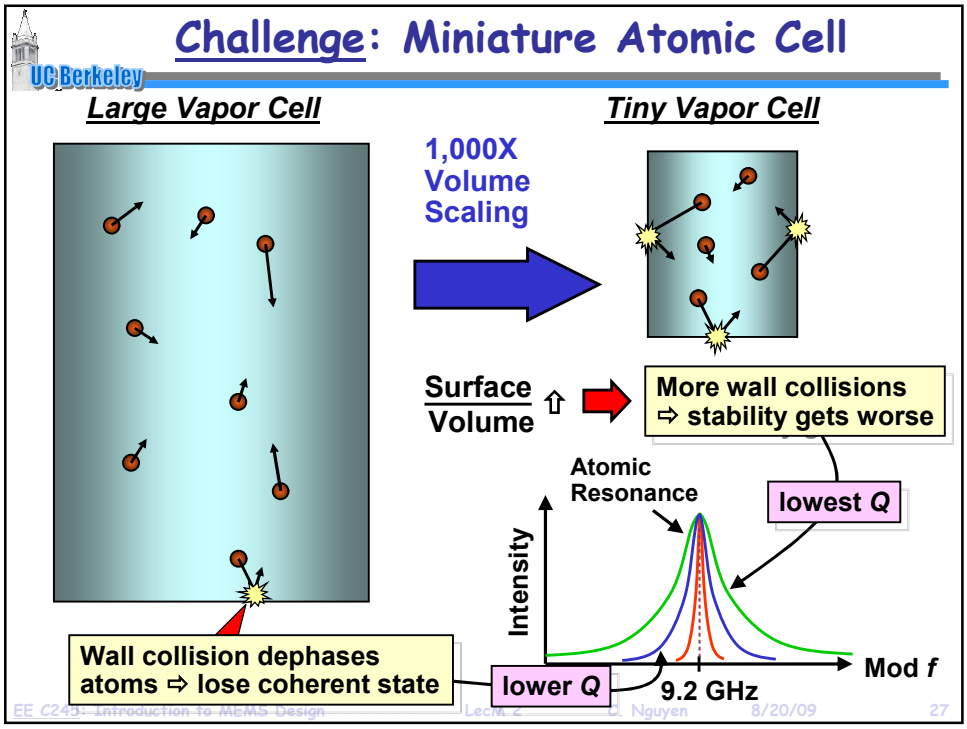

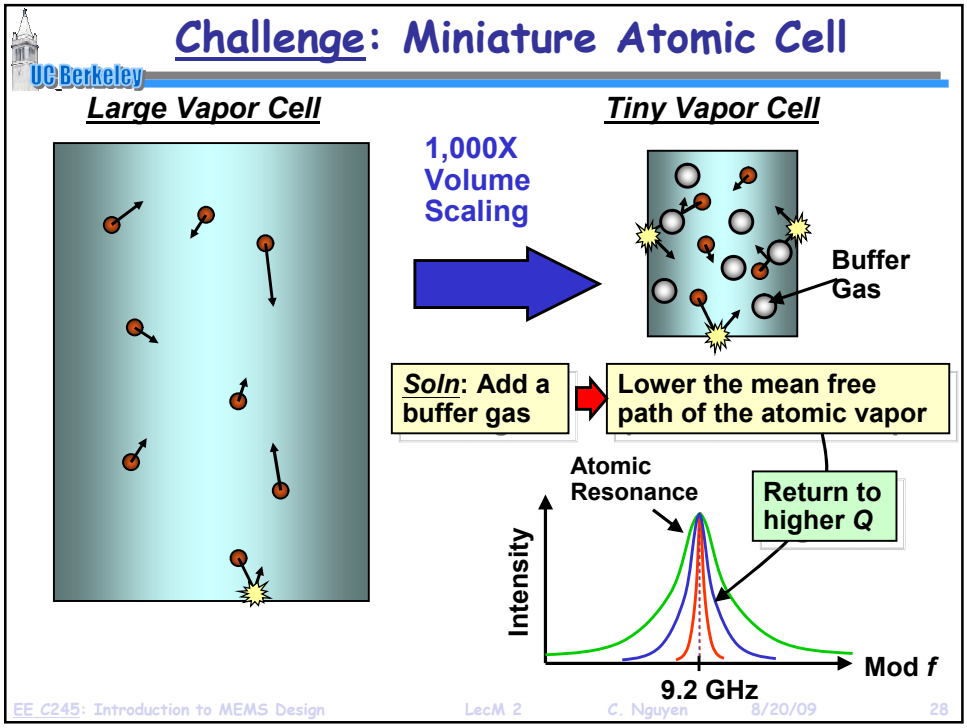

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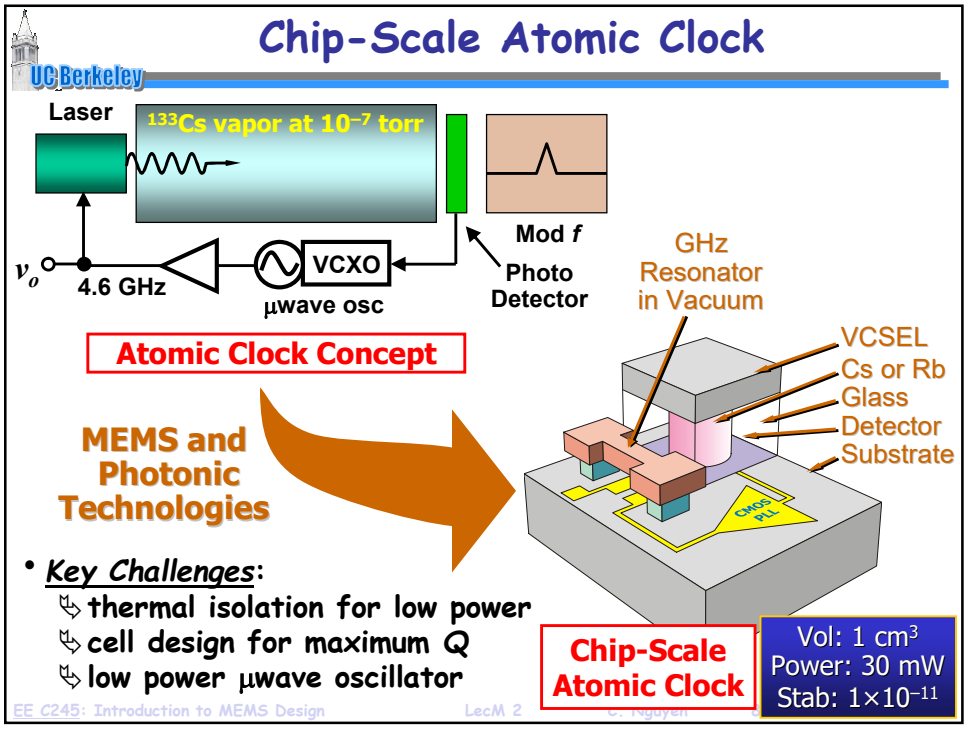

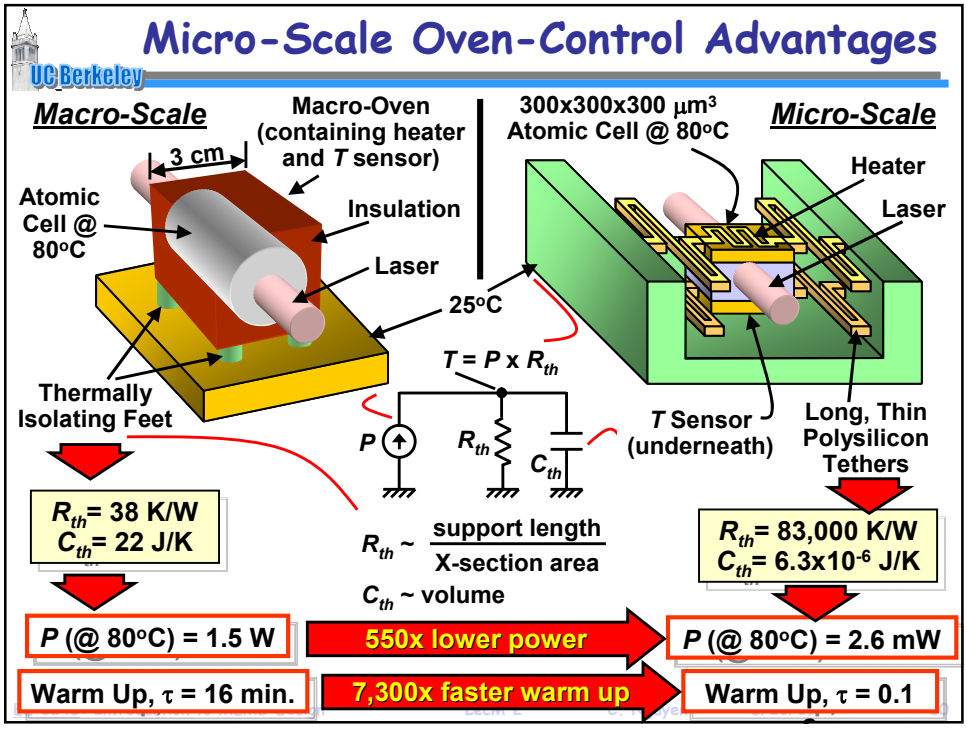

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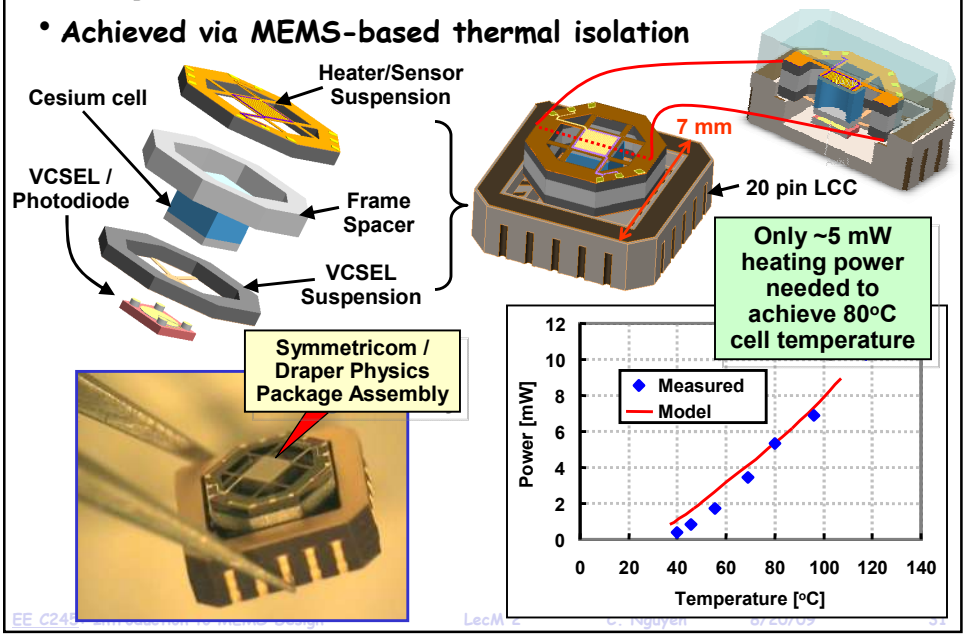
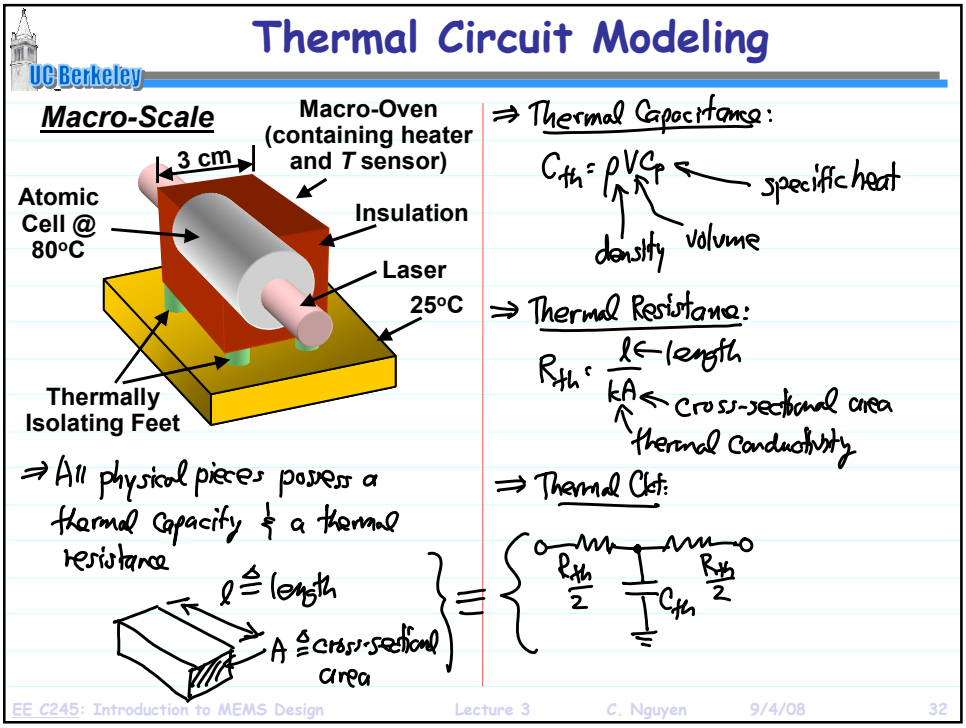
Physics Package Power Diss. < 10 mW

- Achieved via MEMS-based thermal isolation



Thermal Circuit Modeling



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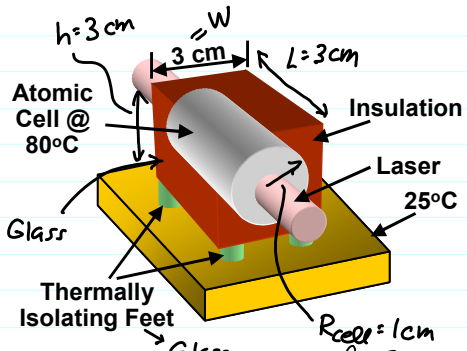
Thermal Circuit Modeling



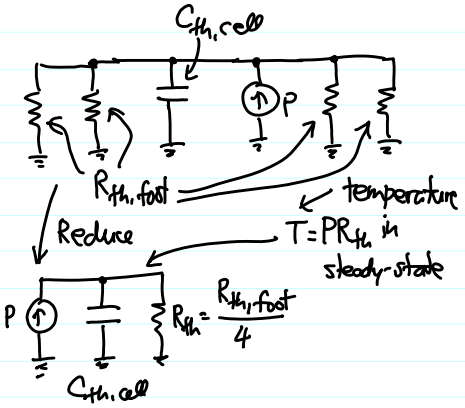
Example. Power to maintain cell T=80°C
⇒ for materials identified in the figure: (all glass)

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

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

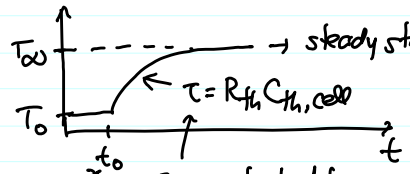
$k_{glass} = 1.05 \frac{W}{m \cdot K}$

Equiv. Cct:
⇒ ignore the small R_{th} of the cell
⇒ ignore the small C_{th} of the feet



Thermal Circuit Modeling

⇒ When power is switched on:



turn on power

Time constant determines how fast T_∞ can be achieved

Find $C_{th,cell}$:
⇒ Find volume of the cell

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

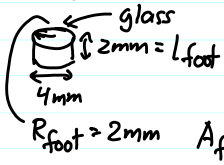
(again, ignore the R_{th} of the cell)

and for the cell:

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

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

Find $R_{th,foot}$:
⇒ foot dimensions:



$R_{foot} = 2mm$

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

$L_{foot} = 2mm$

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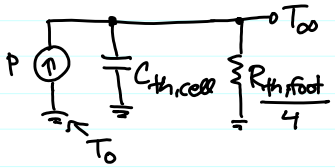
Thermal Circuit Modeling

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

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

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



⇒find power req'd to maintain T_∞ in steady state:

$P = \frac{T_\infty - T_0}{(R_{th,foot}/4)} = \frac{(80-25)}{9.48} = 1.45W$

⇒ find the time constant:

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

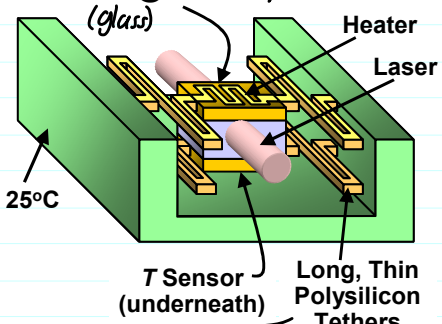
Time req'd to warm up & stabilize will be 3x this!

∴ 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...

MEMS Thermal Circuit Modeling

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



↳ 500μm-long, 10μm-thick, 20μm-wide

$V_{cell} = (300\mu)(300\mu)(300\mu) - (280\mu)(280\mu)(280\mu)$
$= 5.048\times10^{-12}\,m^3$

↳ of course, much smaller than macro

$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$
$= (2500\frac{kg}{m^3})(5.048\times10^{-12}\,m^3) \times (500\frac{J}{kg\cdot K})$

$\Rightarrow C_{th,cell} = 6.31\times10^{-6}\frac{J}{K}$

↳ 4 million x smaller than macro!

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

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

↳ 548x larger

and...

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

$\tau = 0.13\,s$ ← 7300x faster! All due to scaling!

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Micro Gas Analyzers (MGA)

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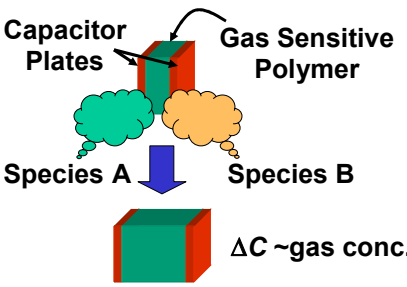
Micro Gas Analyzers

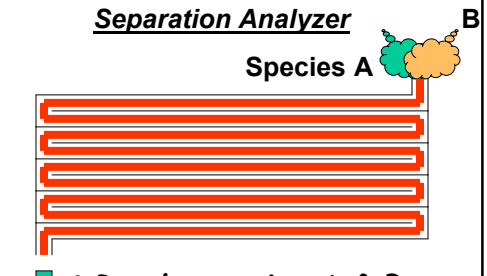
- *Objective*: enable remote detection of chemical agents via tiny, ultra-low power, fast, chip-scale gas analyzers that greatly reduce the incidence of false positives
- *Approach*: use micromachining technologies to implement separation-based analyzers (e.g., gas chromatographs, mass spectrometers)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

Conventional Sensor



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

Separation Analyzer



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

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Advantages of Miniaturization

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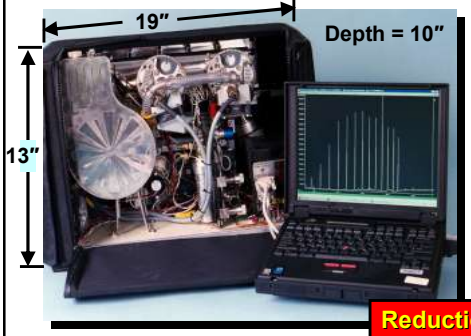
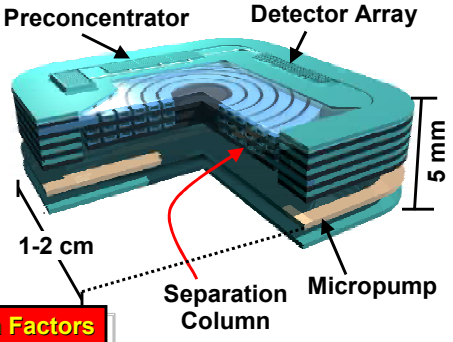
Portable Gas Chromatograph



Chip-Scale Gas Chromatograph



Reduction Factors

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

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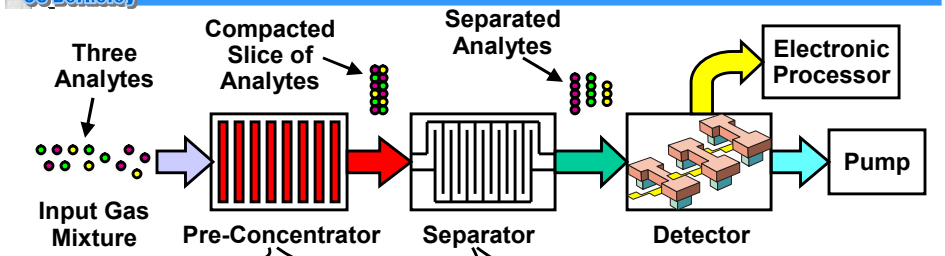
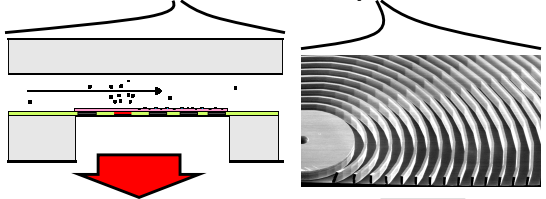


Miniaturization



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

Tiny Dimensions
- faster separation
- lower power

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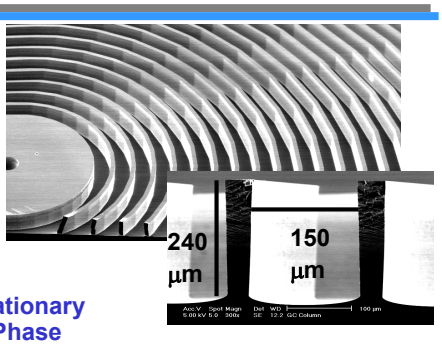
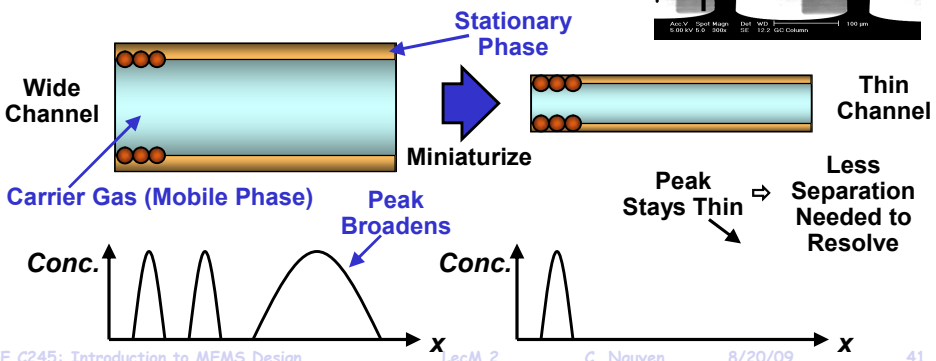
Scaling Leads to Faster Separation

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





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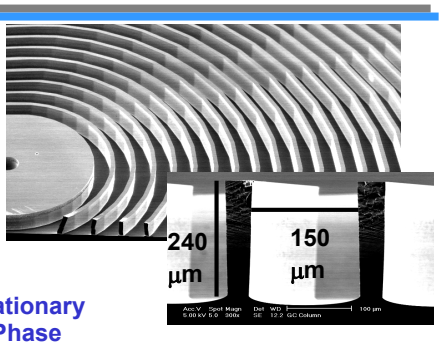

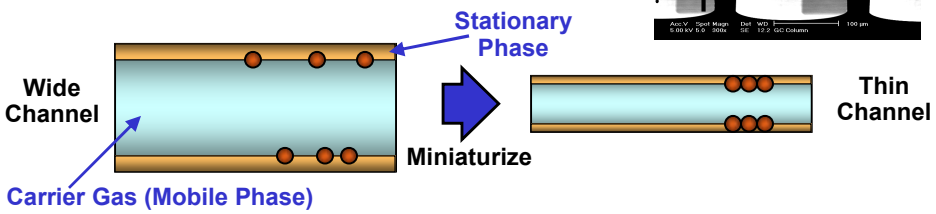

Column Width ↓ → Surface-to-Volume Ratio ↑ → Peak Spreading ↓ → Separation Distance ↓

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

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Gas Chromatography in Less Than 4s!

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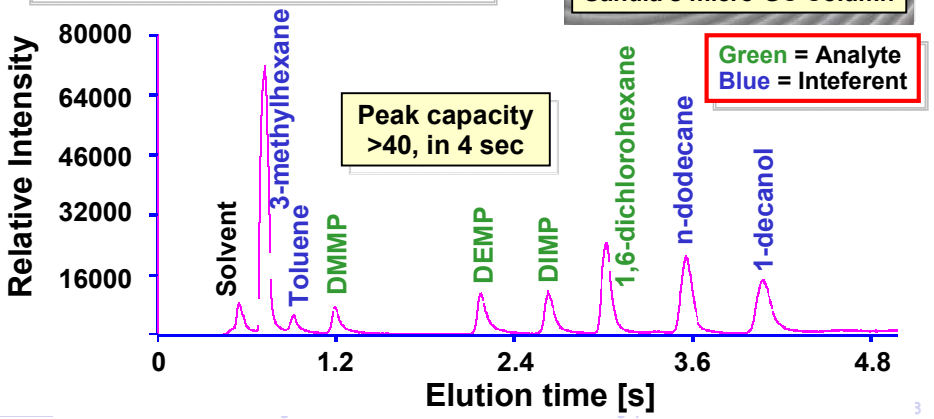
Design/Measurement Data:
0.75m x 100µ column
0.1µ DB-5 stationary phase
Heart-cut 275 msec peak injection
Temperature: ~30 deg C/sec
H_2 carrier: 35-39 psi at 1 psi/sec



Basic Approach: Separation Analyzer

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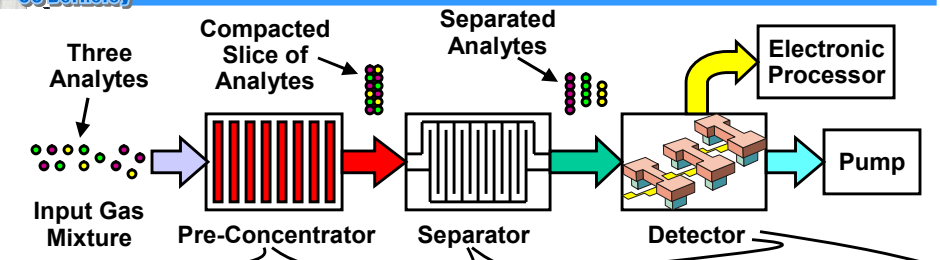
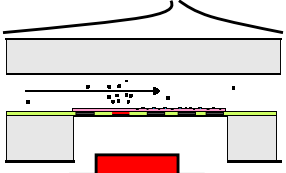
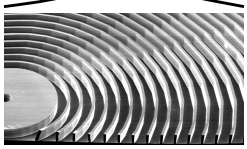
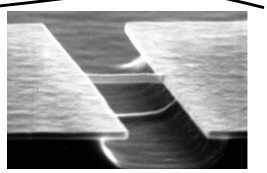


Miniaturization







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

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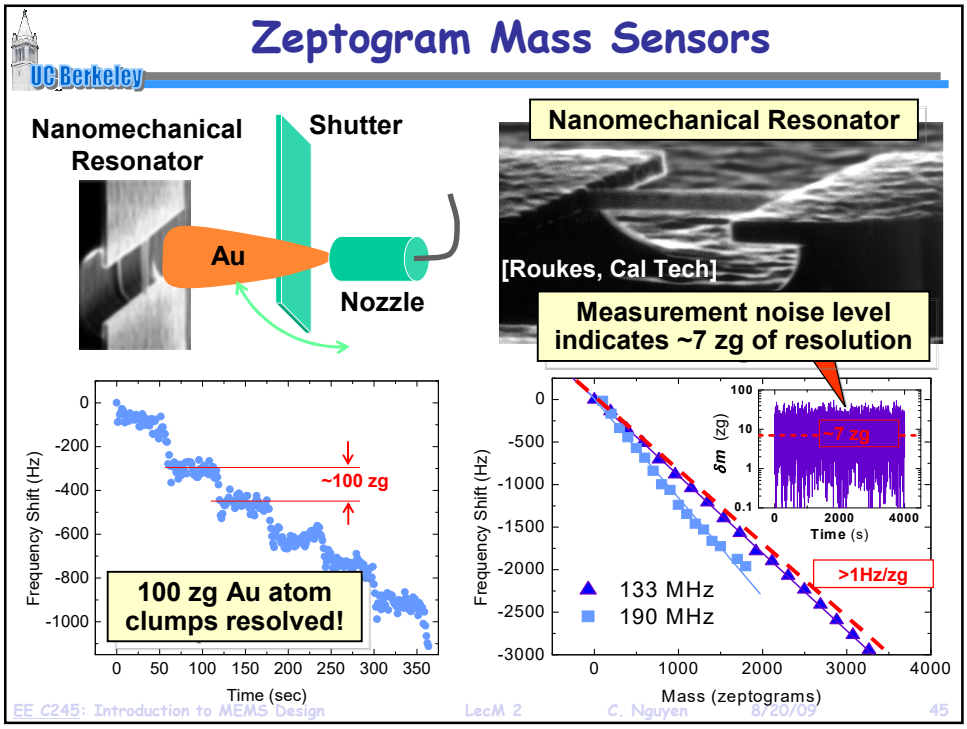

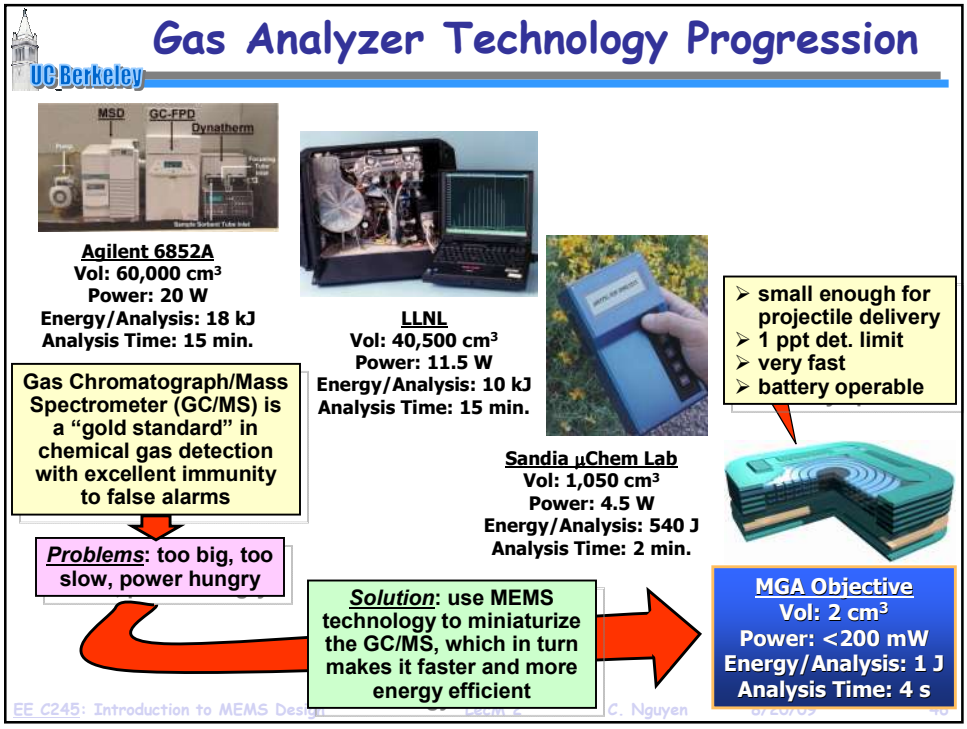

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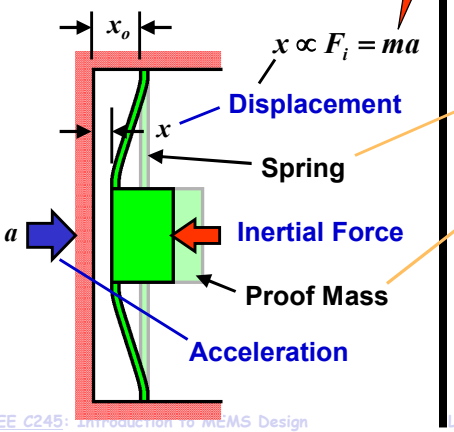
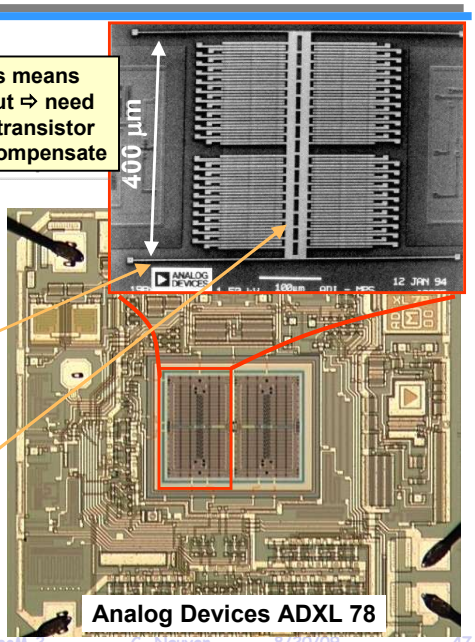
Example: Micromechanical Accelerometer

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

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

Basic Operation Principle





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 …

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