EE C247B – ME C218
Introduction to MEMS Design
Spring 2015

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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

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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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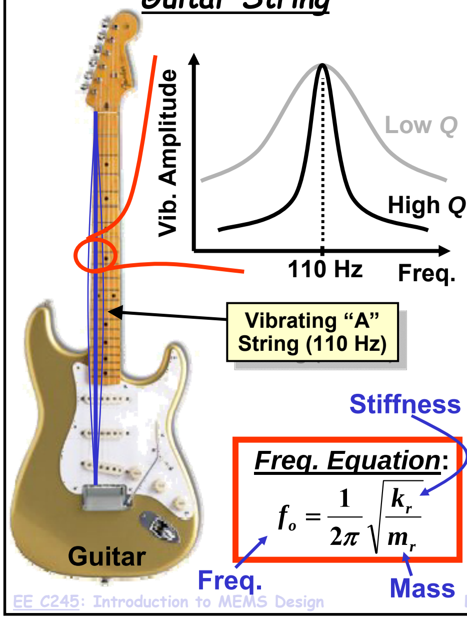
Basic Concept: Scaling Guitar Strings

Guitar String

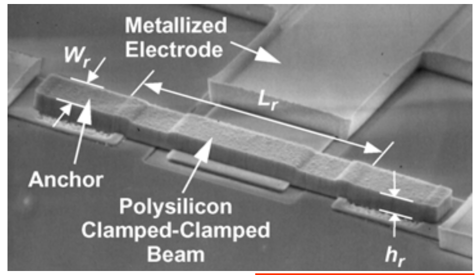


Freq. Equation:

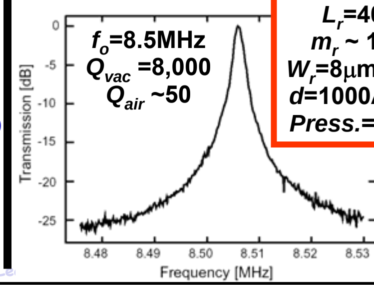
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Stiffness; Freq.; Mass

μMechanical Resonator



[Bannon 1996]

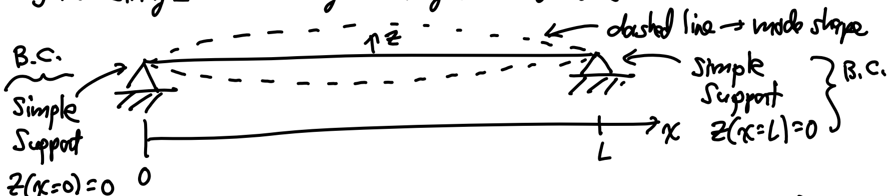


Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr

Frequency of a Stretched Wire

Scaling of Guitar Strings!

guitar string ≡ transversely vibrating stretched wire



⇒ Equation for Resonance Freq. (fundamental mode)

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

← 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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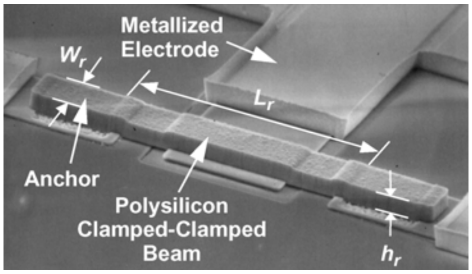
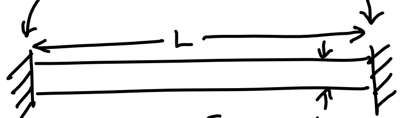
Clamped-Clamped Beam



Clamped (or Fixed) Support



⇒ 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

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

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

→ As L↓ → f_o↑ !

Frequency of a Clamped-Clamped Beam

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

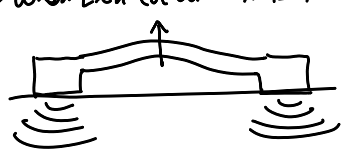
→ GHz freqs. possible!

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: nanodimensions? ✓

④ Better Solution: other geometries ✓✓

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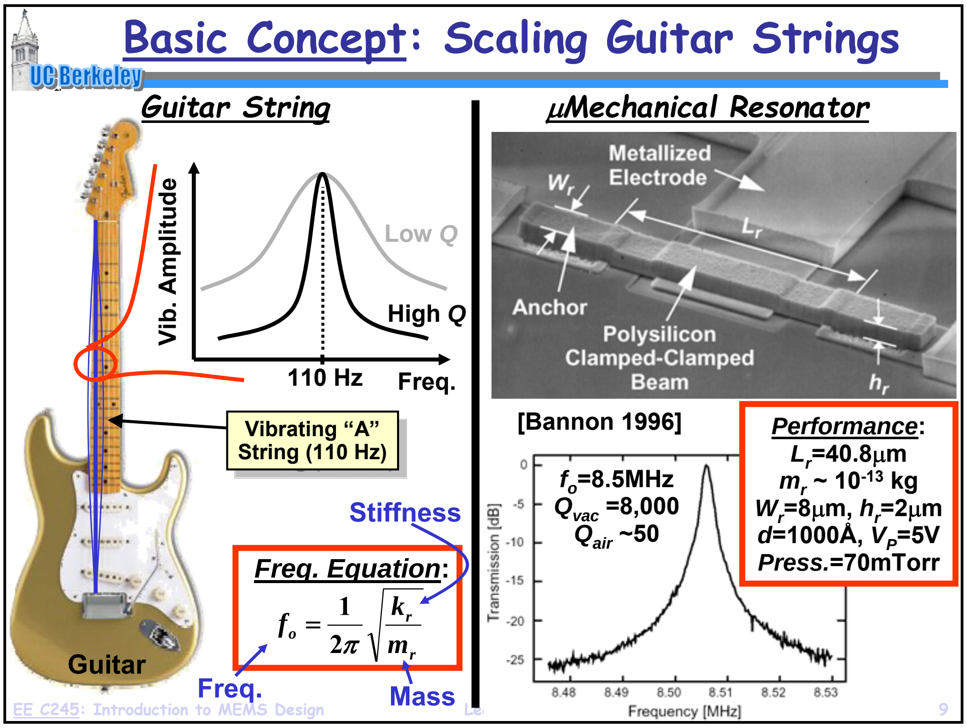
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Basic Concept: Scaling Guitar Strings
Guitar String
μMechanical Resonator
Vib. Amplitude
Low Q
High Q
110 Hz
Freq.
Vibrating "A" String (110 Hz)
Guitar
Stiffness
Freq. Equation:
$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$
Freq.
Mass
Metallized Electrode
W_r
L_r
Anchor
Polysilicon Clamped-Clamped Beam
h_r
[Bannon 1996]
f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50
Transmission [dB]
Frequency [MHz]
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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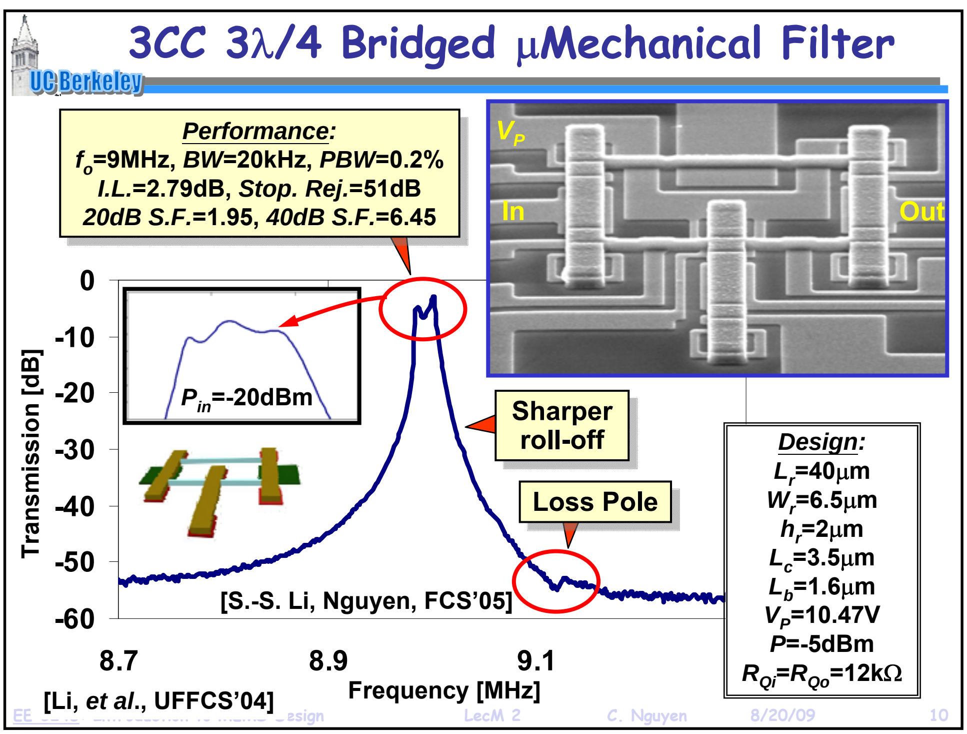
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3CC 3λ/4 Bridged μMechanical Filter
Performance:
f_o=9MHz, BW=20kHz, PBW=0.2%
I.L.=2.79dB, Stop. Rej.=51dB
20dB S.F.=1.95, 40dB S.F.=6.45
V_P
In
Out
P_{in}=-20dBm
Transmission [dB]
Sharper roll-off
Loss Pole
[S.-S. Li, Nguyen, FCS'05]
Frequency [MHz]
[Li, et al., UFFCS'04]
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
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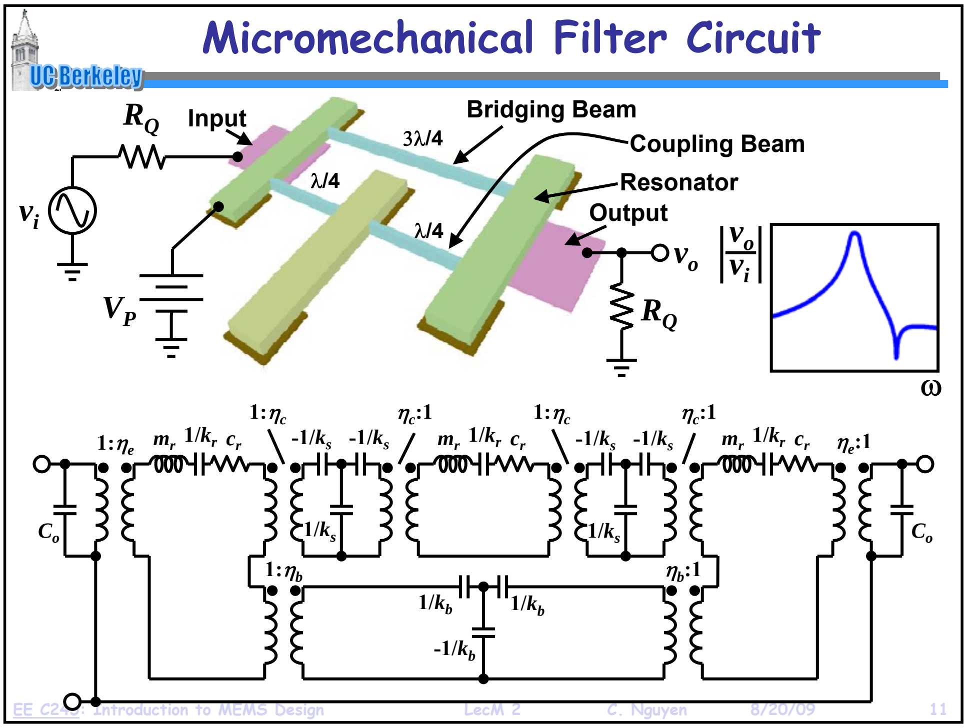

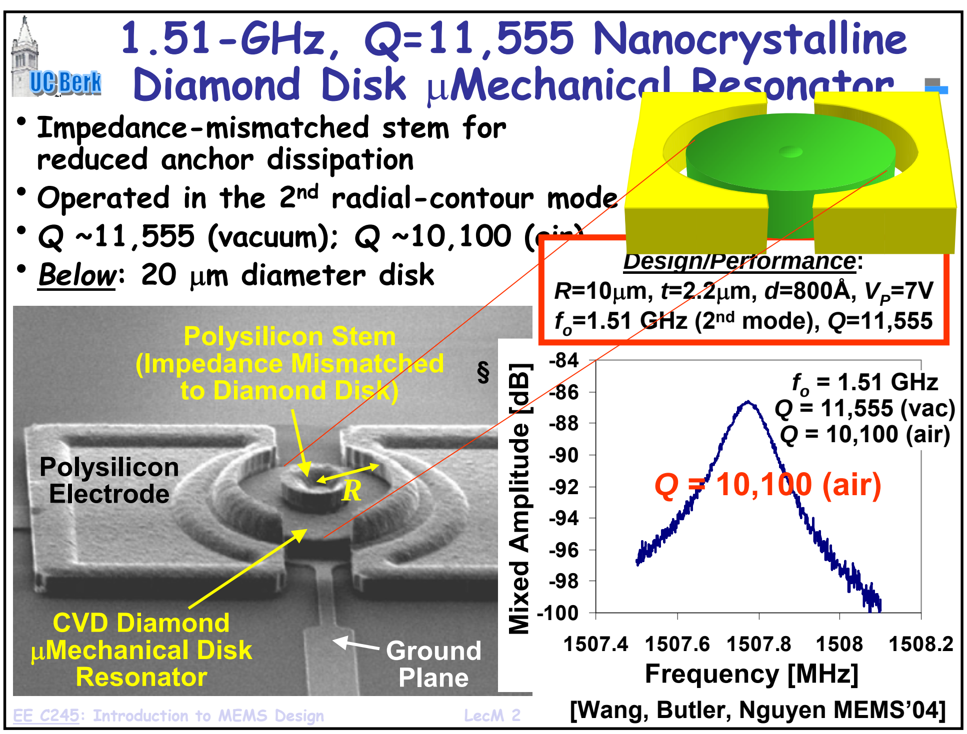

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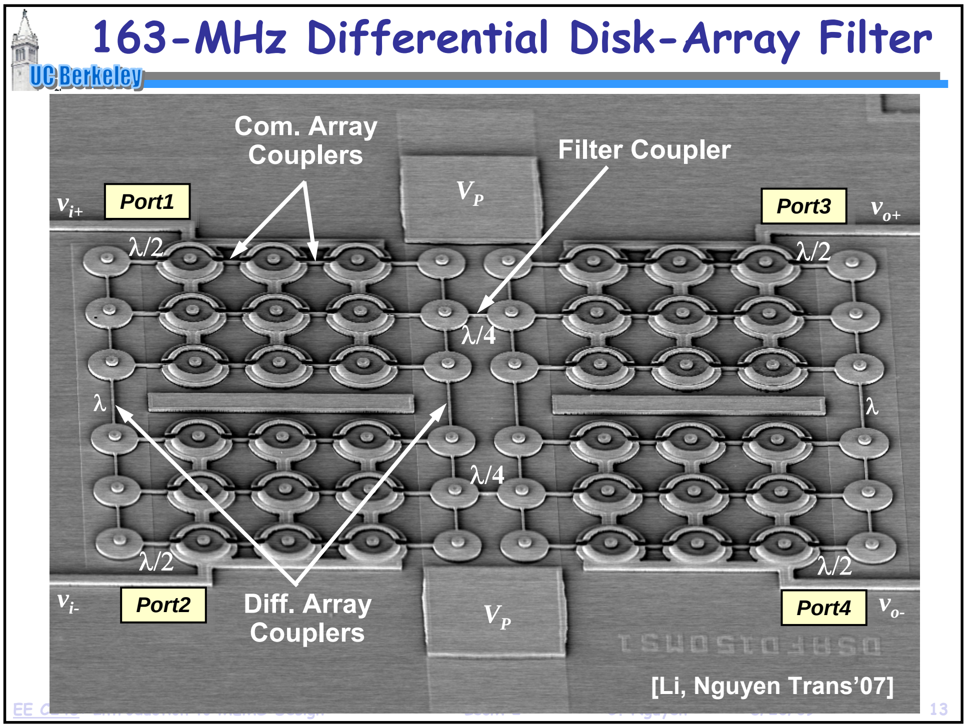

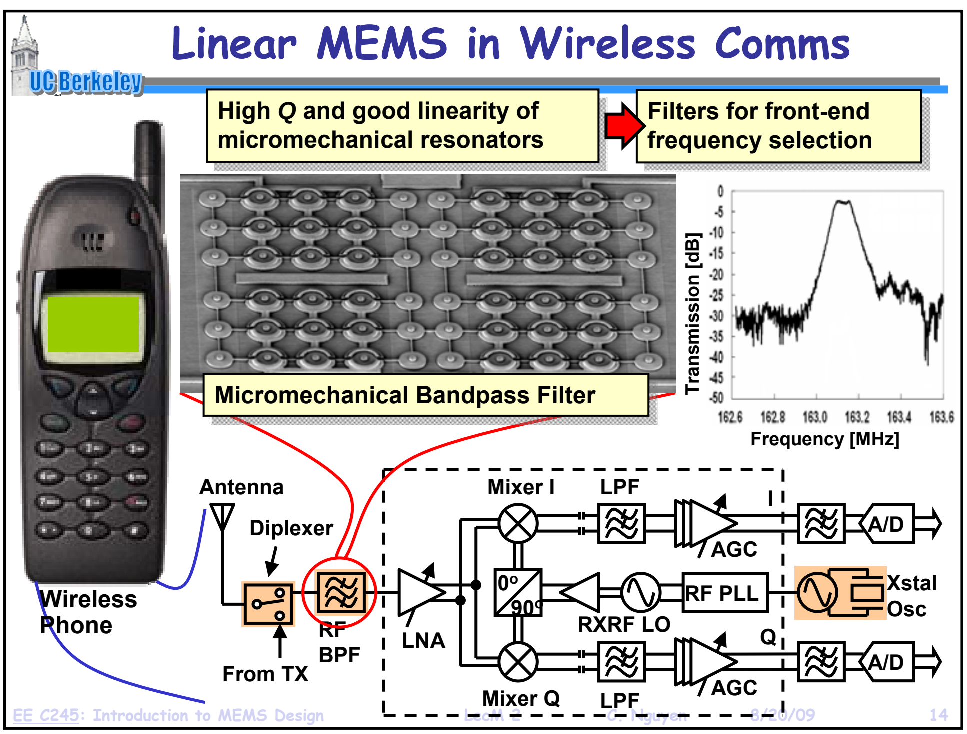

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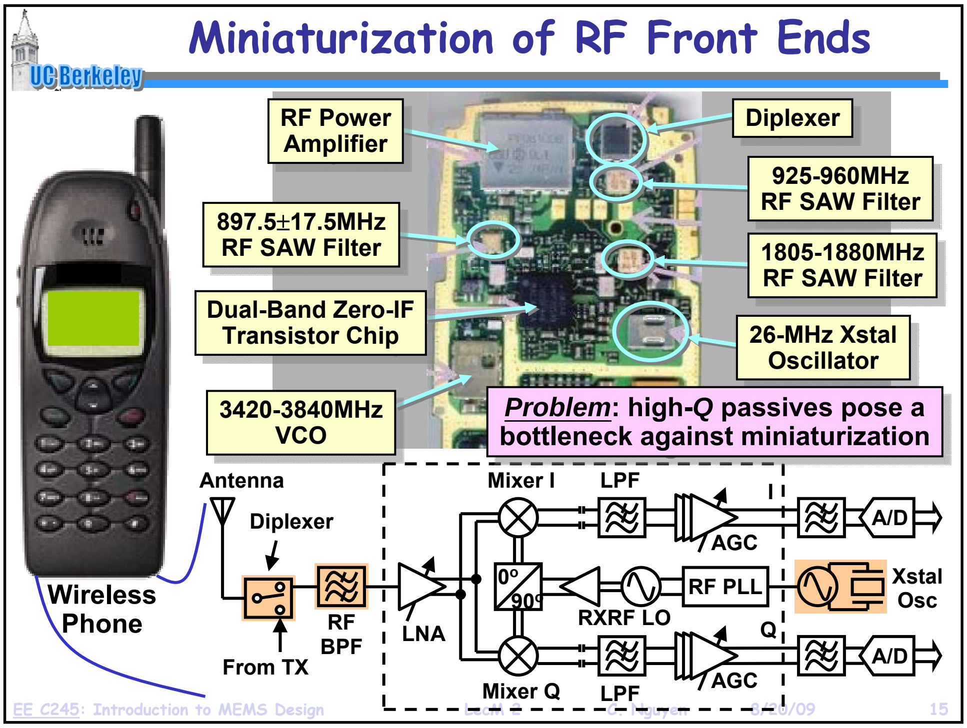
Miniaturization of RF Front Ends
RF Power Amplifier
Diplexer
925-960MHz RF SAW Filter
897.5±17.5MHz RF SAW Filter
1805-1880MHz RF SAW Filter
Dual-Band Zero-IF Transistor Chip
26-MHz Xstal Oscillator
3420-3840MHz VCO
Problem: high-Q passives pose a bottleneck against miniaturization
Wireless Phone
Antenna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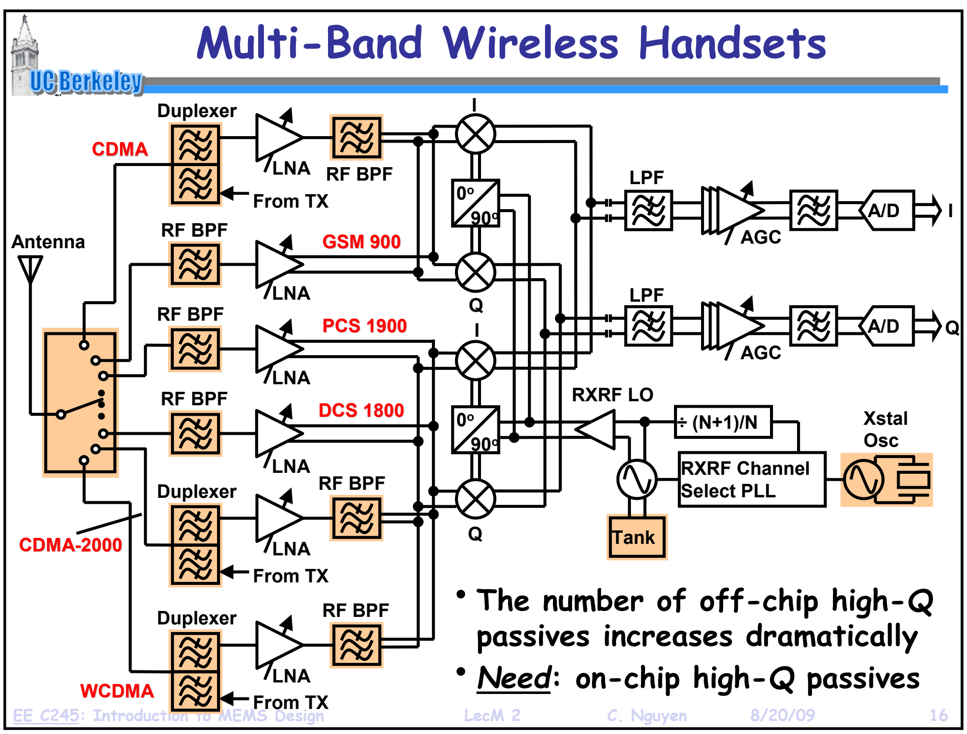
Multi-Band Wireless Handsets
Duplexer
CDMA
LNA
RF BPF
From TX
Antenna
GSM 900
PCS 1900
DCS 1800
CDMA-2000
WCDMA
LPF
AGC
A/D
I
Q
RXRF LO
÷ (N+1)/N
RXRF Channel Select PLL
Xstal Osc
Tank
• The number of off-chip high-Q passives increases dramatically
• Need: on-chip high-Q passives
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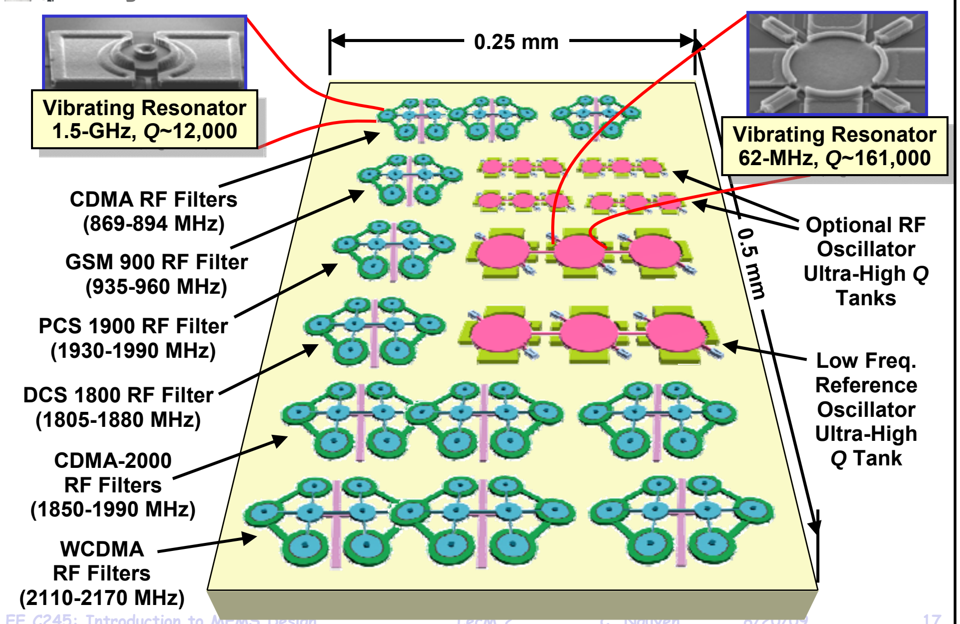
All High-Q Passives on a Single Chip



Chip-Scale Atomic Clocks (CSAC)

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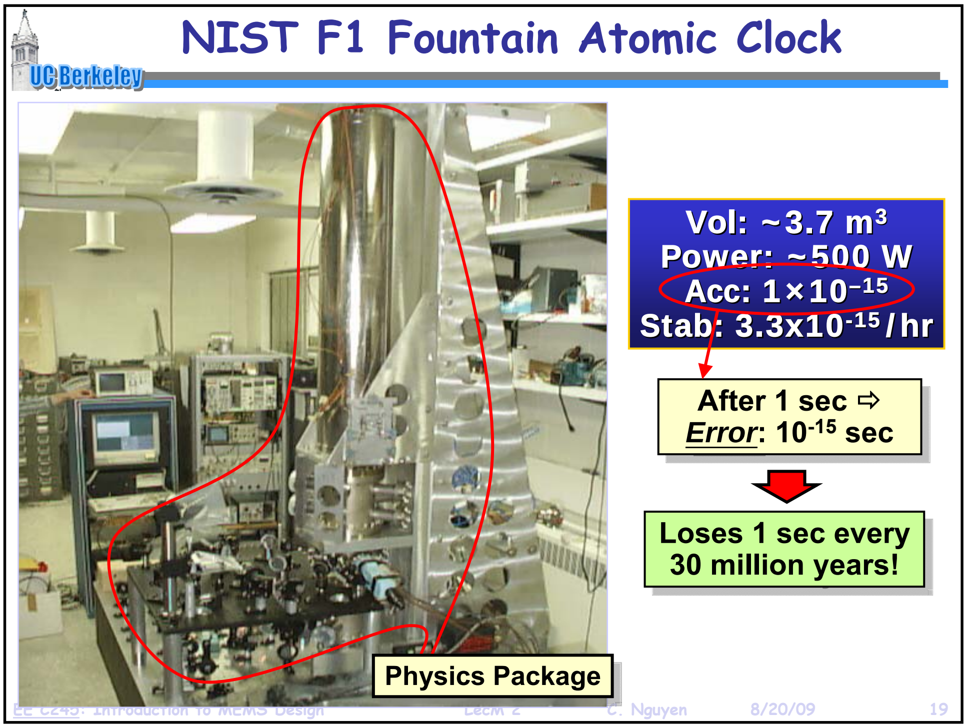
NIST F1 Fountain Atomic Clock
UC Berkeley
Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr
After 1 sec ⇨ Error: 10⁻¹⁵ sec
Loses 1 sec every 30 million years!
Physics Package
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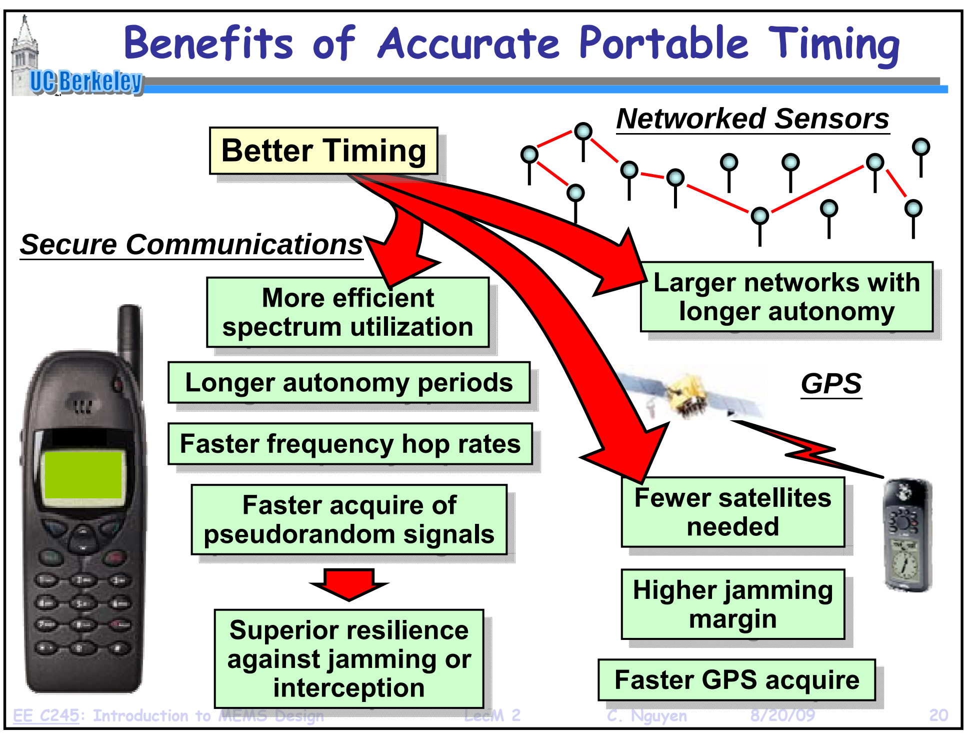
Benefits of Accurate Portable Timing
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Better Timing
Networked Sensors
Secure Communications
More efficient spectrum utilization
Longer autonomy periods
Faster frequency hop rates
Faster acquire of pseudorandom signals
Superior resilience against jamming or interception
Larger networks with longer autonomy
GPS
Fewer satellites needed
Higher jamming margin
Faster GPS acquire
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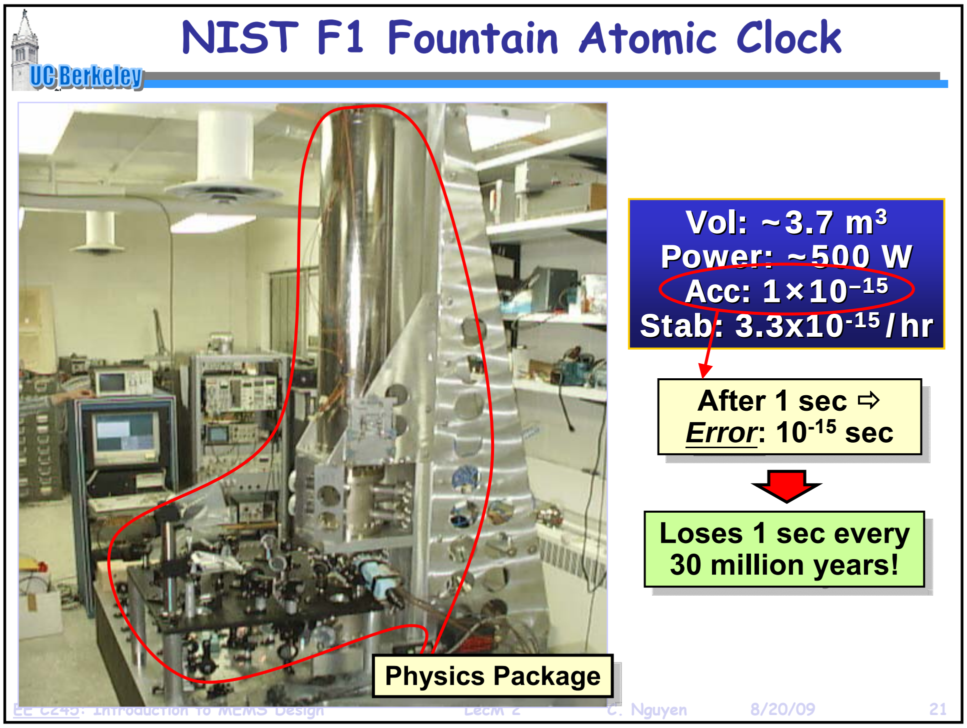

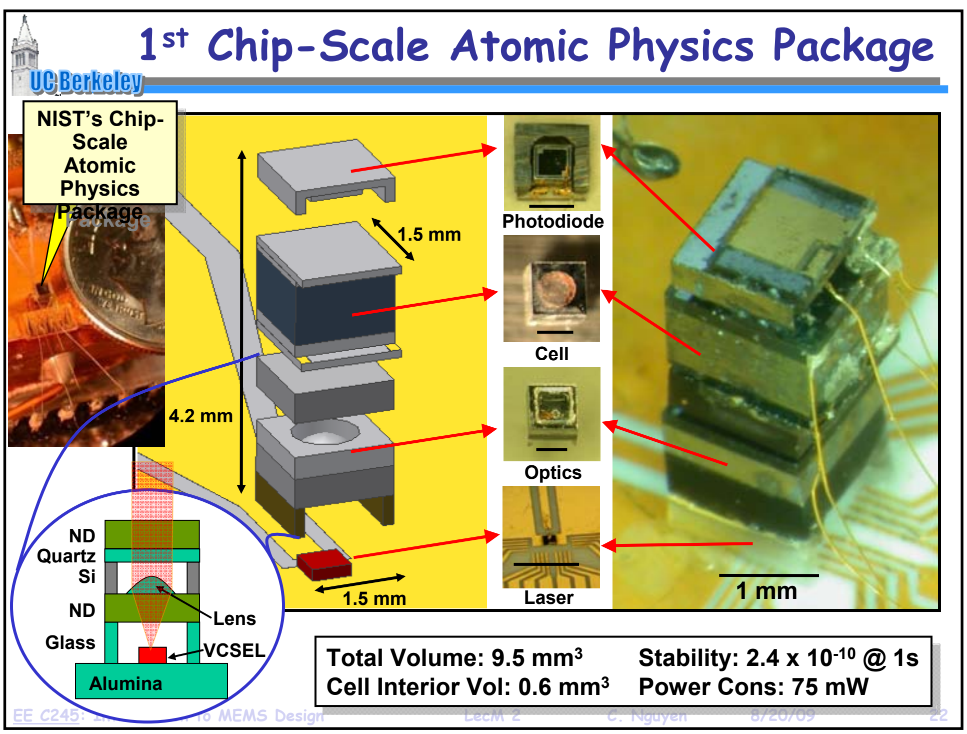

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Tiny Physics Package Performance

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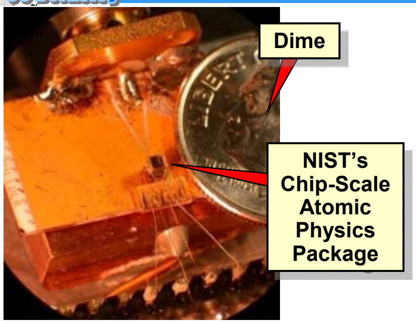
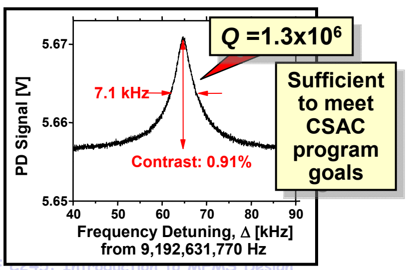
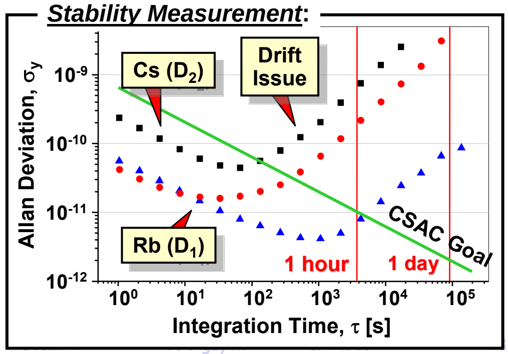


- *Experimental Conditions*:
  Cs D2 Excitation
  External (large) Magnetic Shielding
  External Electronics & LO
  Cell Temperature: ~80 °C
  Cell Heater Power: 69 mW
  Laser Current/Voltage: 2mA / 2V
  RF Laser Mod Power: 70μW

Open Loop Resonance:



Stability Measurement:



Atomic Clock Fundamentals

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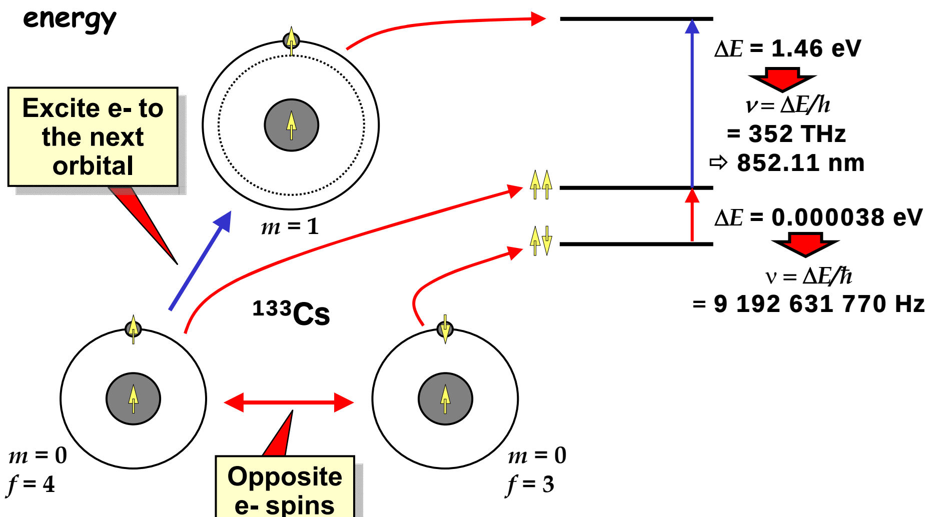
- Frequency determined by an atomic transition energy

Energy Band Diagram



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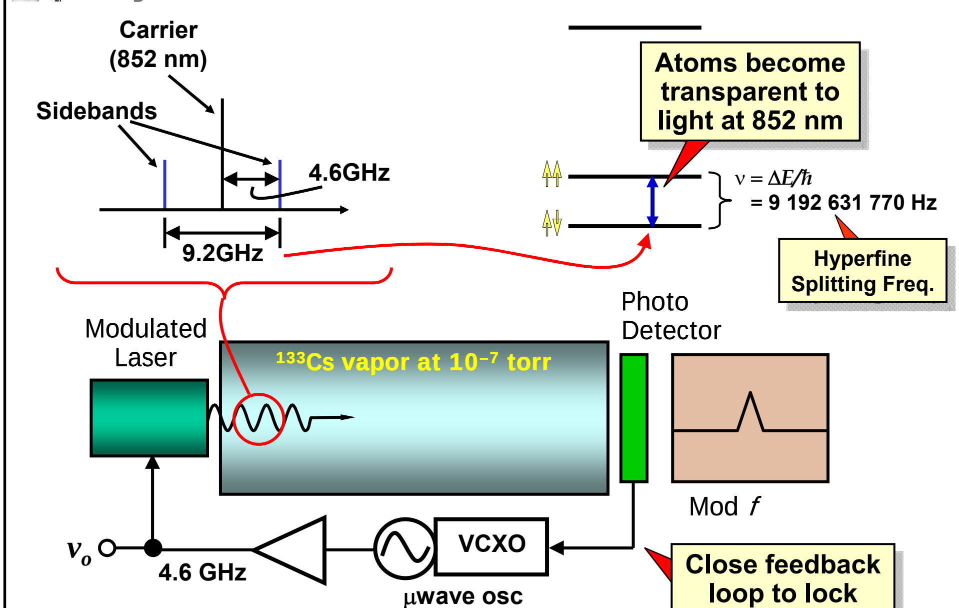
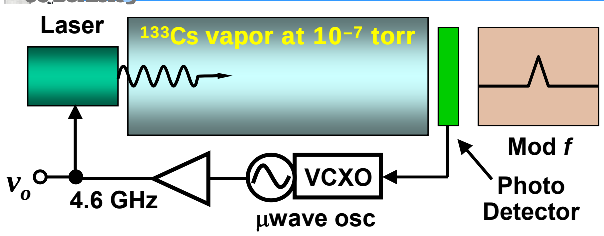
Miniature Atomic Clock Design

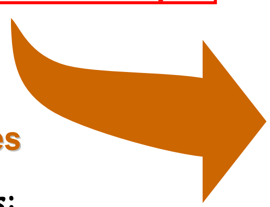


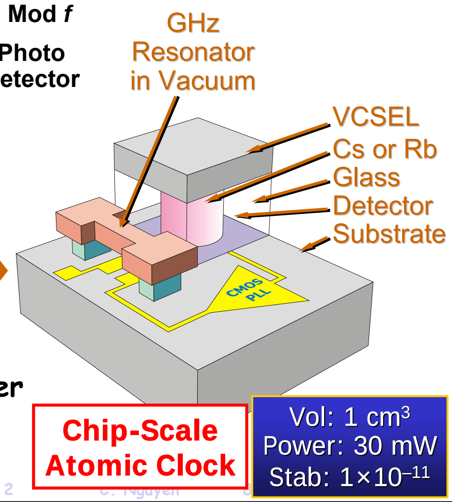
Chip-Scale Atomic Clock



Atomic Clock Concept

MEMS and Photonic Technologies





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

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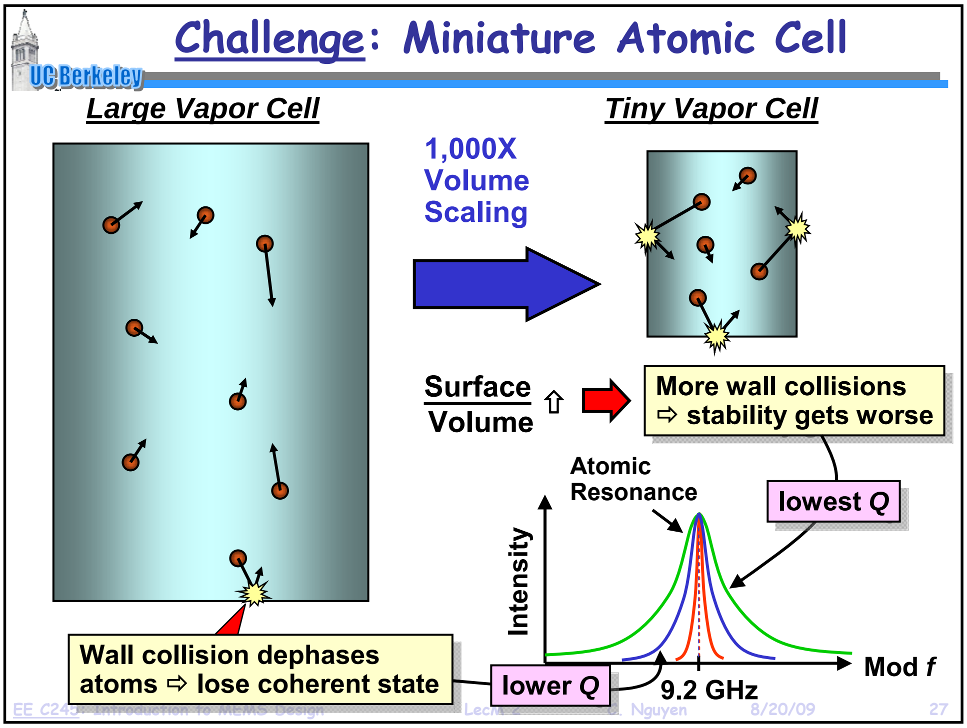

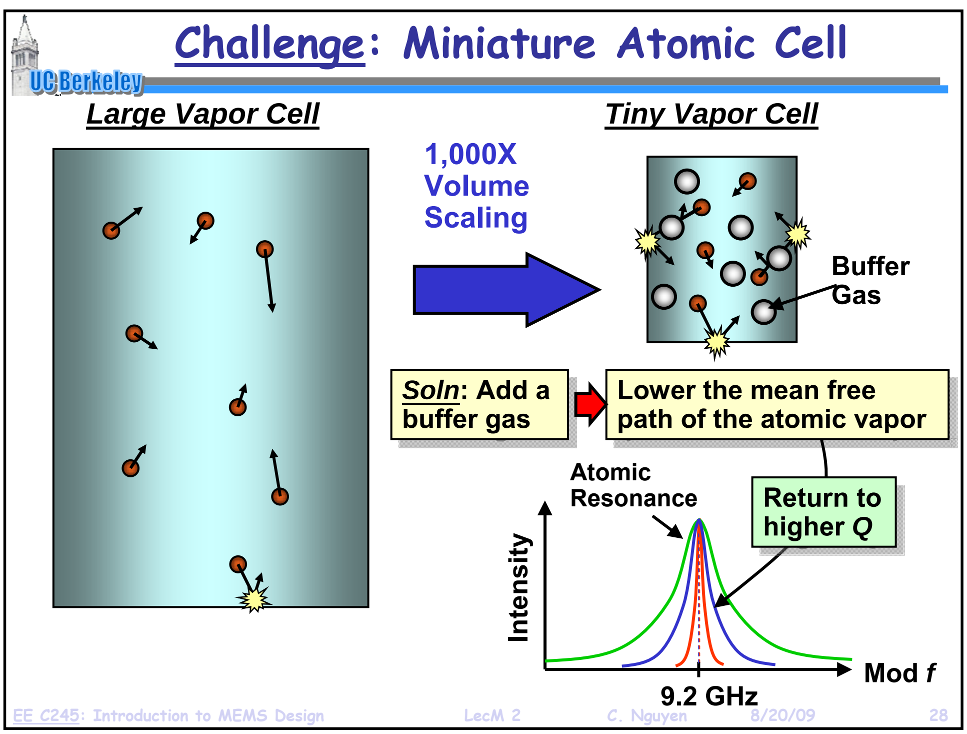

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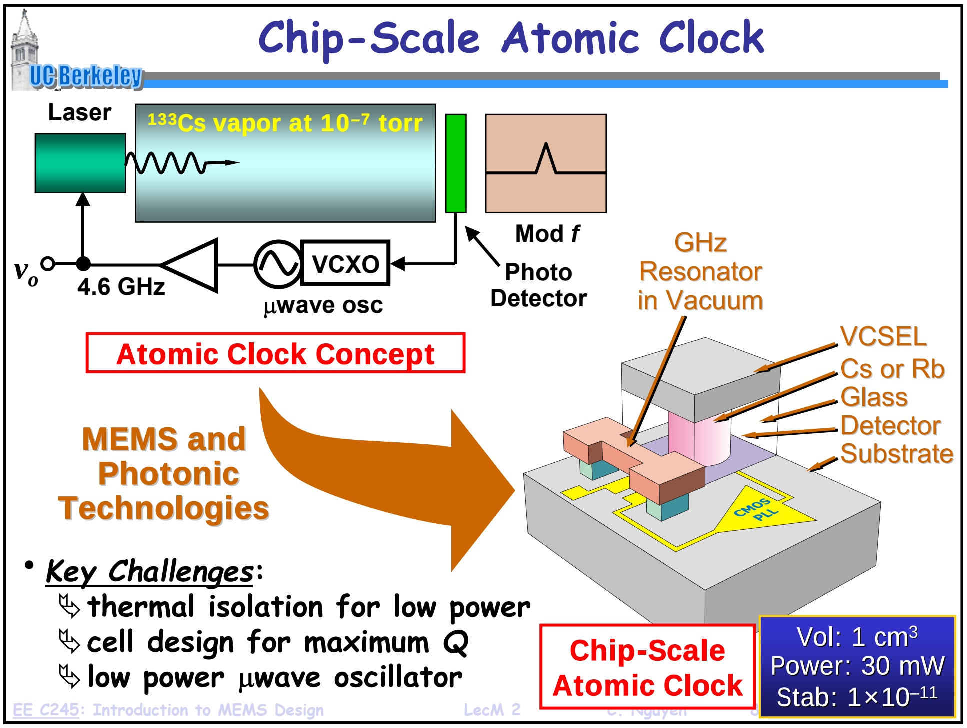
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
VCXO
μwave osc
4.6 GHz
vo
Atomic Clock Concept
GHz Resonator in Vacuum
VCSEL
Cs or Rb
Glass
Detector
Substrate
CMOS PLL
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power μwave oscillator
Chip-Scale Atomic Clock
Vol: 1 cm3
Power: 30 mW
Stab: 1×10−11
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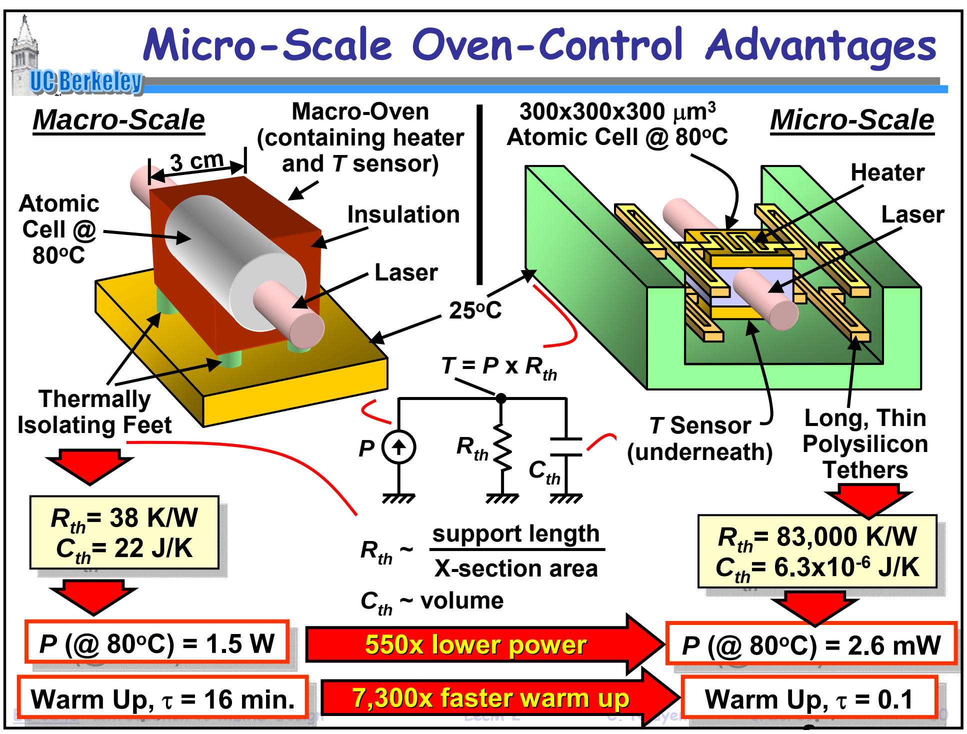
Micro-Scale Oven-Control Advantages
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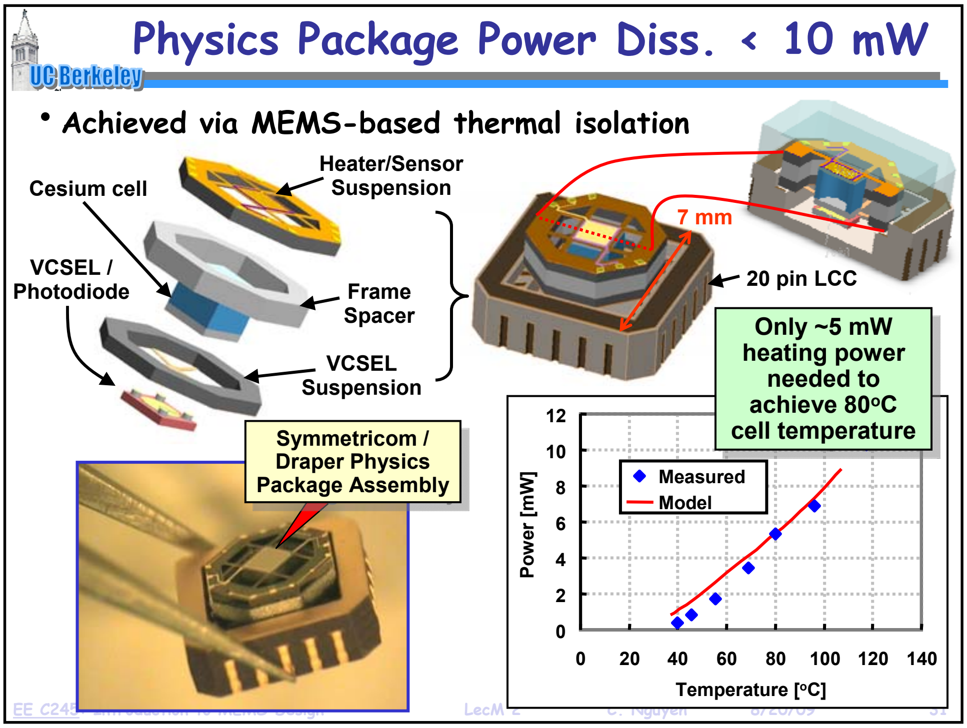
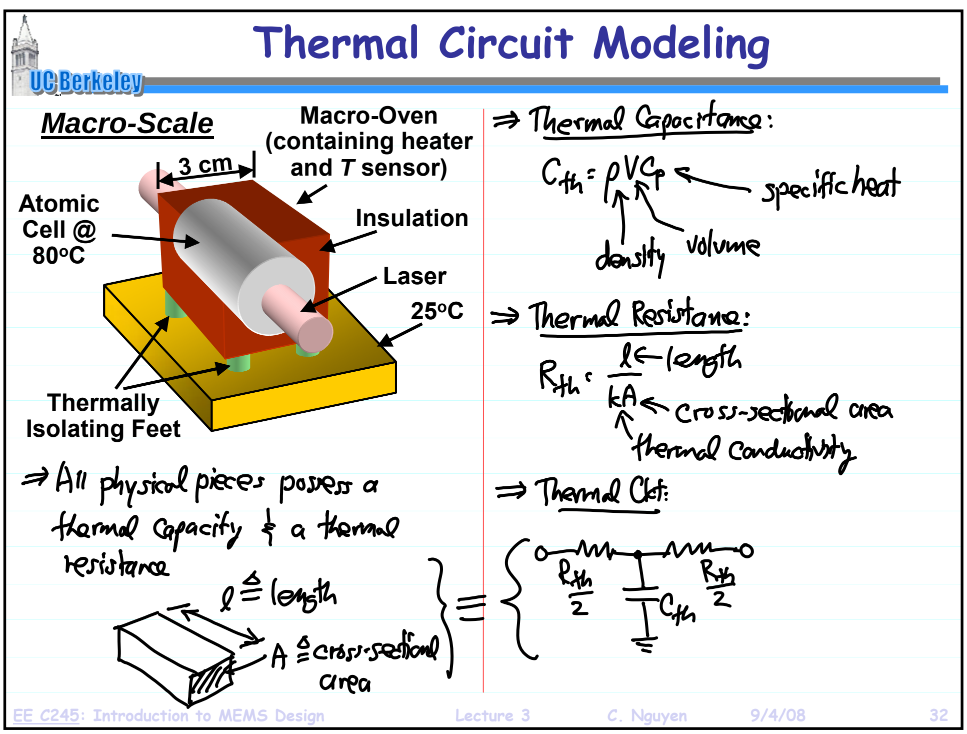
Macro-Scale
Macro-Oven (containing heater and T sensor)
3 cm
Atomic Cell @ 80°C
Insulation
Laser
25°C
Thermally Isolating Feet
300x300x300 μm3 Atomic Cell @ 80°C
Micro-Scale
Heater
Laser
T = P x Rth
P
Rth
Cth
T Sensor (underneath)
Long, Thin Polysilicon Tethers
Rth= 38 K/W
Cth= 22 J/K
Rth ~ support length / X-section area
Cth ~ volume
Rth= 83,000 K/W
Cth= 6.3x10-6 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





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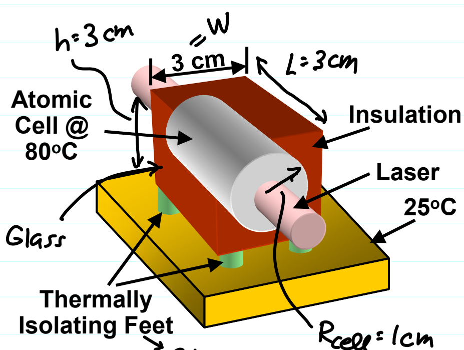
Thermal Circuit Modeling



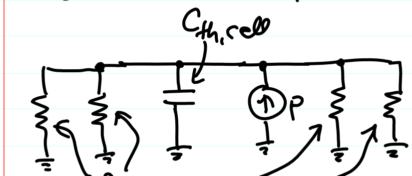
Example. Power to maintain cell T=80°C
⇒ for materials identified in the figure: (all glass)

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

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

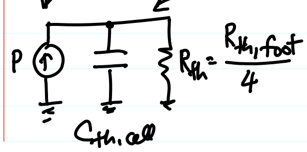
$k_{glass} = 1.05\ \frac{W}{m\cdot K}$

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



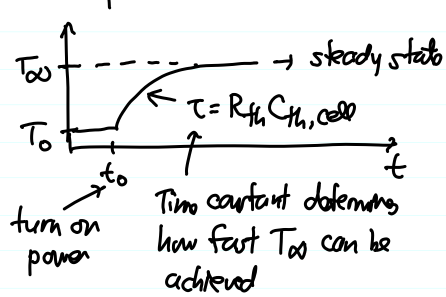
Reduce

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



Thermal Circuit Modeling

⇒ when power is switched on:



Time constant determines how fast T_∞ can be achieved

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

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

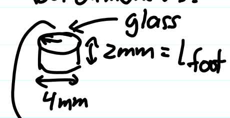
(again, ignore the R_{th} of the cell)

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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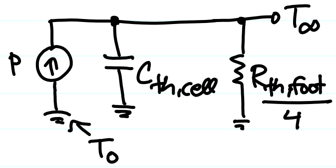
Thermal Circuit Modeling

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

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

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



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

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

⇒ find the time constant:

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

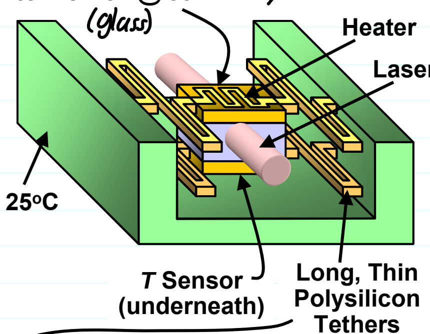
Time req'd to warm up & stabilize will be 3x this!

∴ 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 ...

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

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

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

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

↳ 4 million x smaller than macro!

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

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

↗ 548x larger

and...

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

$\tau = \boxed{0.13s}$ ← 7300x faster! All due to scaling!

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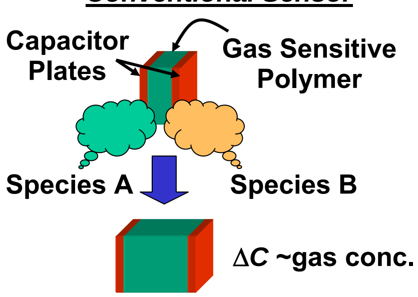
Micro Gas Analyzers (MGA)

Micro Gas Analyzers

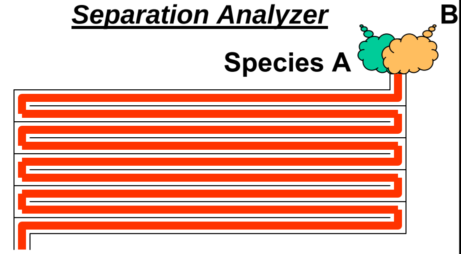
- ***Objective***: enable remote detection of chemical agents via tiny, ultra-low power, fast, chip-scale gas analyzers that greatly reduce the incidence of false positives
- ***Approach***: use micromachining technologies to implement separation-based analyzers (e.g., gas chromatographs, mass spectrometers)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

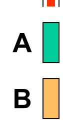
Conventional Sensor



- ***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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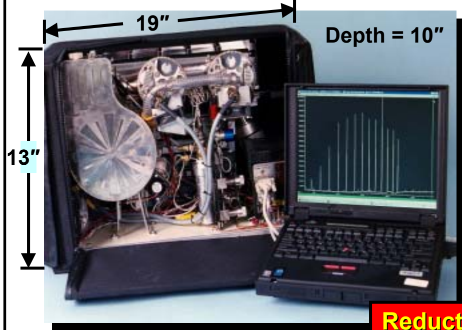
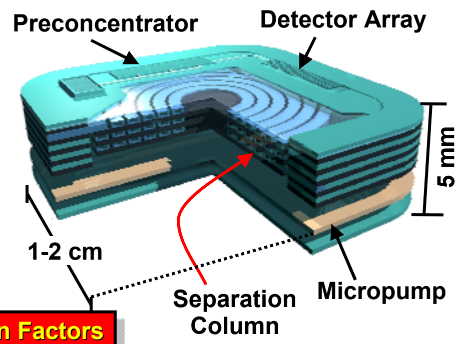
Advantages of Miniaturization

Portable Gas Chromatograph



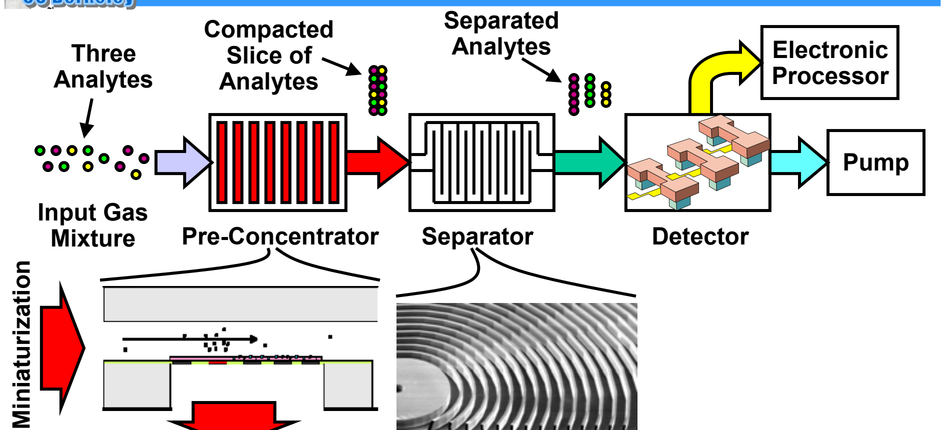
Chip-Scale Gas Chromatograph



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

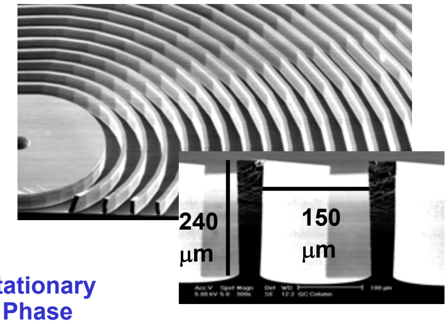


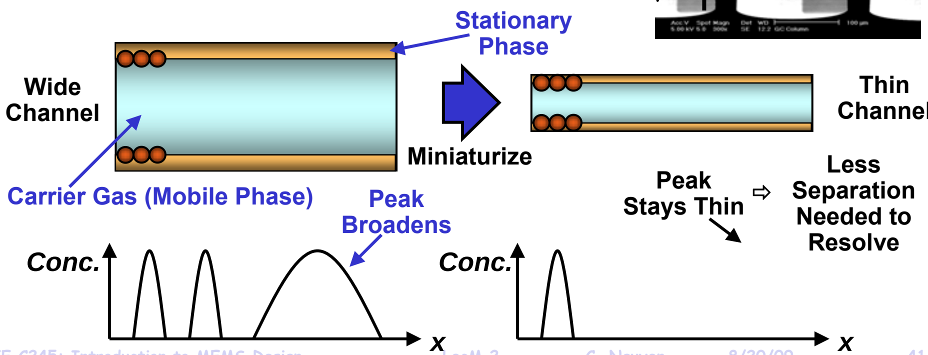
Tiny Dimensions
- fast time constants
- 10,000X gain factor via multi-staging
- enhanced sensitivity
- lower power

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





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  - different analyte velocities
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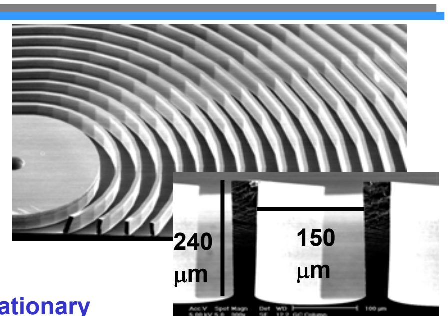
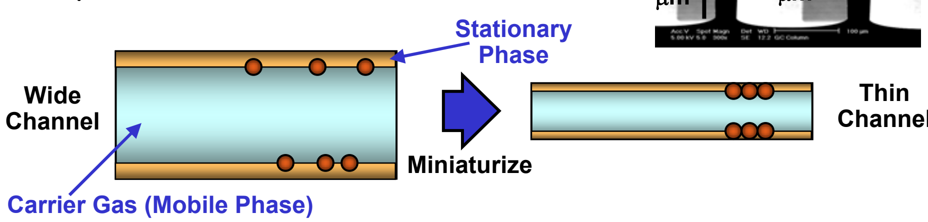
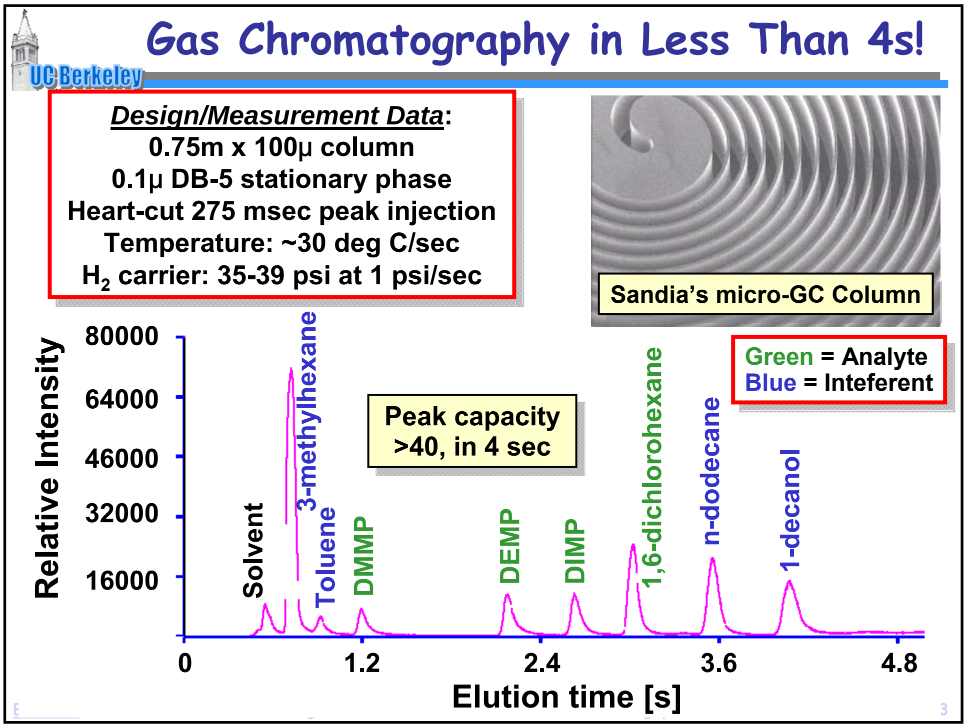
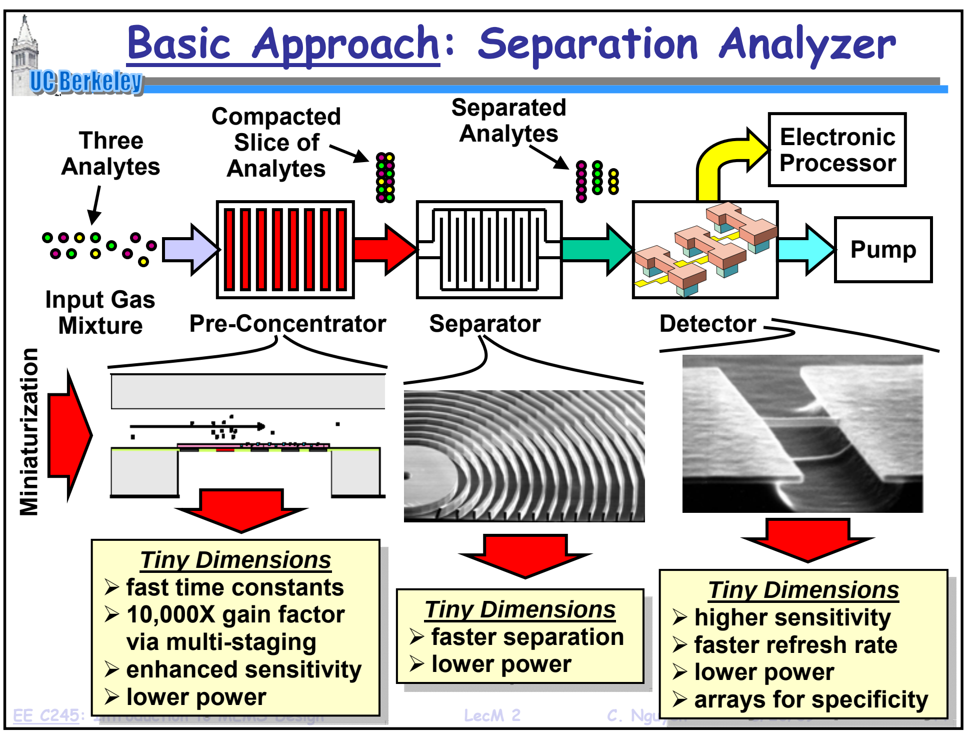




Column Width ↓ ➡ Surface-to-Volume Ratio ↑ ➡ Peak Spreading ↓ ➡ Separation Distance ↓

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





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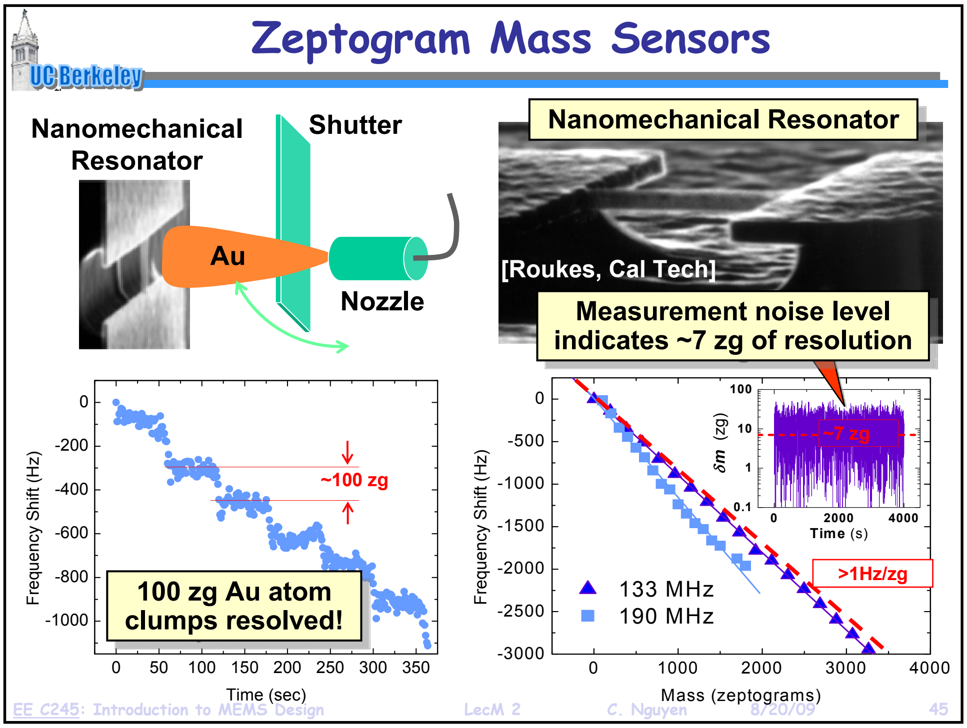
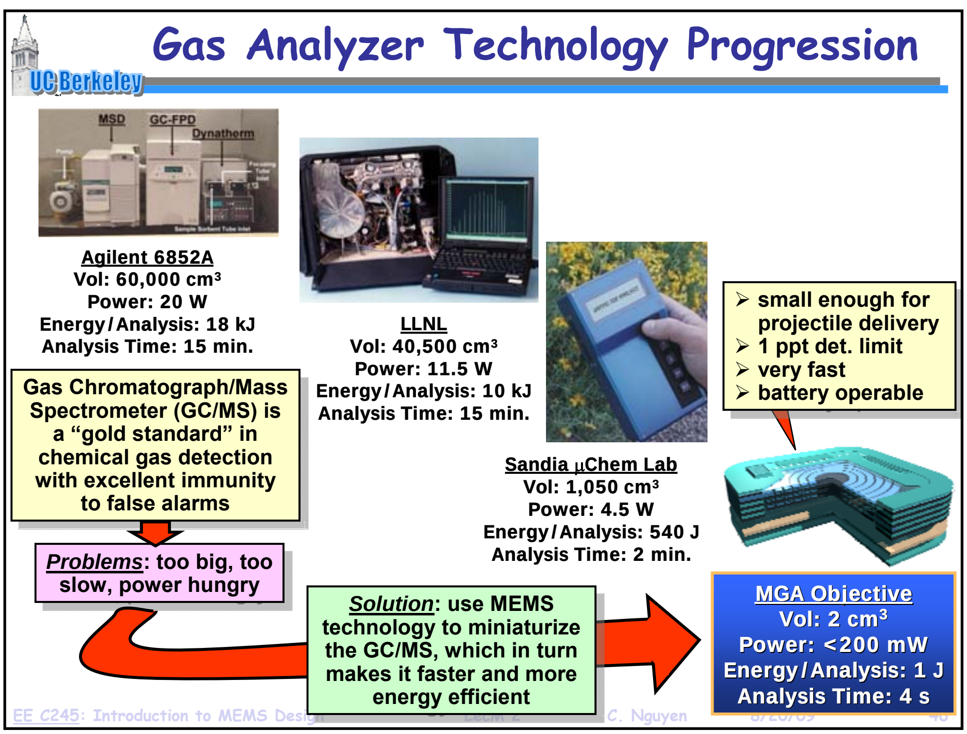
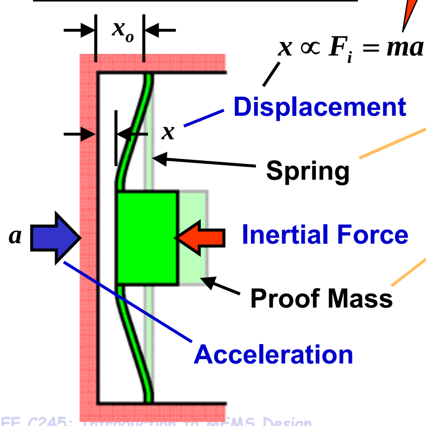

Zeptogram Mass Sensors
UC Berkeley
Nanomechanical Resonator
Shutter
Au
Nozzle
Nanomechanical Resonator
[Roukes, Cal Tech]
Measurement noise level indicates ~7 zg of resolution
Frequency Shift (Hz)
0
-200
-400
-600
-800
-1000
~100 zg
100 zg Au atom clumps resolved!
0 50 100 150 200 250 300 350
Time (sec)
Frequency Shift (Hz)
0
-500
-1000
-1500
-2000
-2500
-3000
δm (zg)
100
10
1
0.1
~7 zg
0 2000 4000
Time (s)
>1Hz/zg
133 MHz
190 MHz
0 1000 2000 3000 4000
Mass (zeptograms)
EE C245: Introduction to MEMS Design
LecM 2
C. Nguyen
8/20/09
45

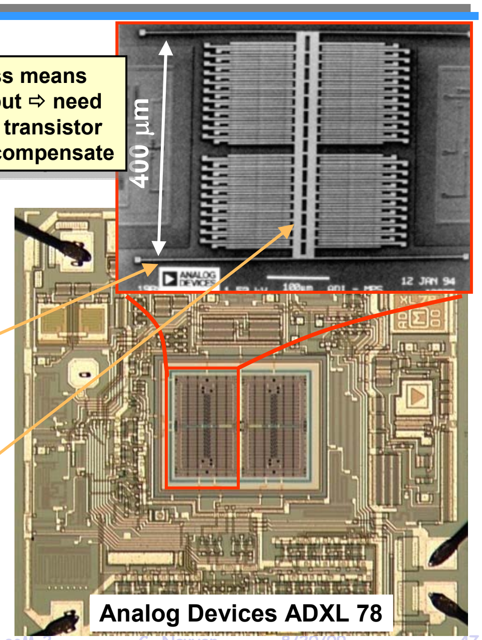

Gas Analyzer Technology Progression
UC Berkeley
MSD
GC-FPD
Dynatherm
Agilent 6852A
Vol: 60,000 cm³
Power: 20 W
Energy/Analysis: 18 kJ
Analysis Time: 15 min.
LLNL
Vol: 40,500 cm³
Power: 11.5 W
Energy/Analysis: 10 kJ
Analysis Time: 15 min.
Sandia µChem Lab
Vol: 1,050 cm³
Power: 4.5 W
Energy/Analysis: 540 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 cm³
Power: <200 mW
Energy/Analysis: 1 J
Analysis Time: 4 s
EE C245: Introduction to MEMS Design
C. Nguyen

Example: Micromechanical Accelerometer

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

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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