EE C247B – ME C218 Introduction to MEMS Design Spring 2019

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Berkeley, CA 94720

Lecture Module 2: Benefits of Scaling

UC Berkeley

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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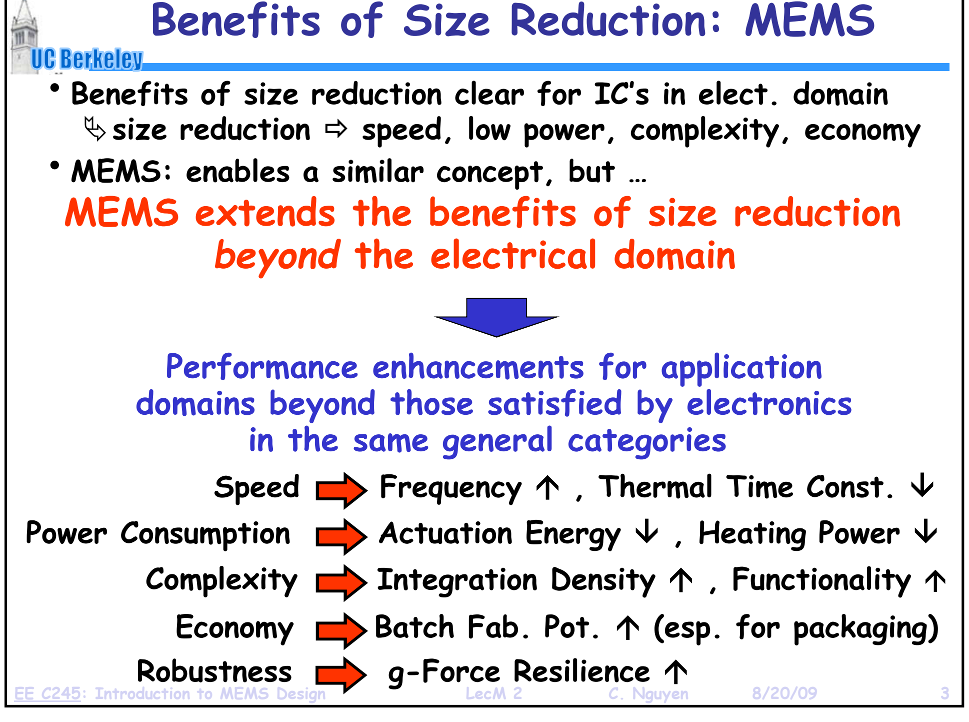

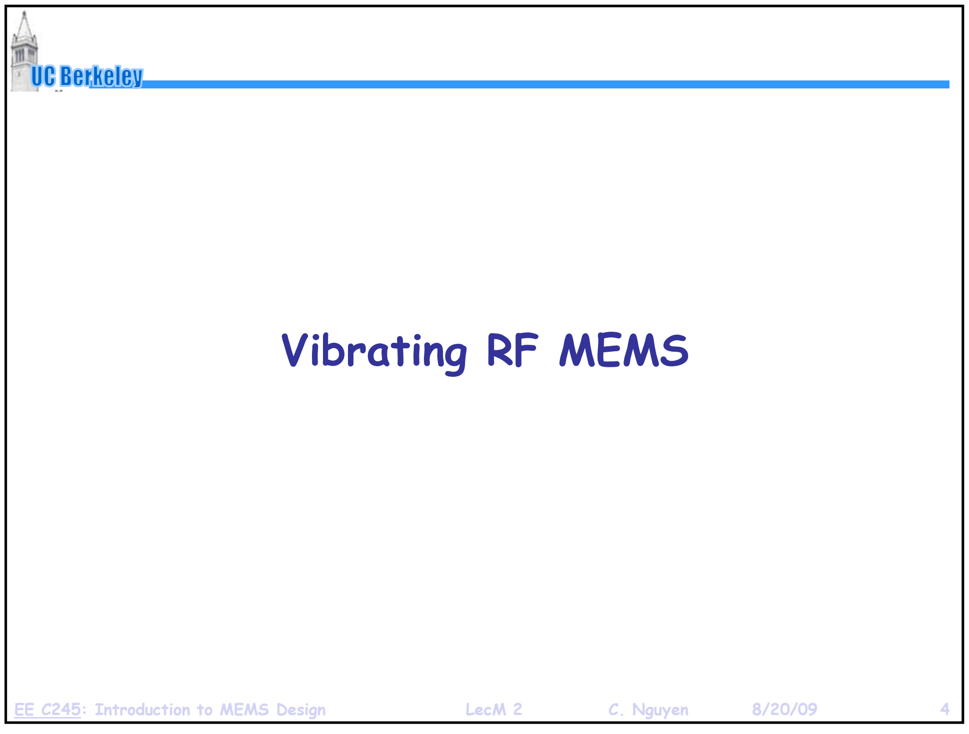

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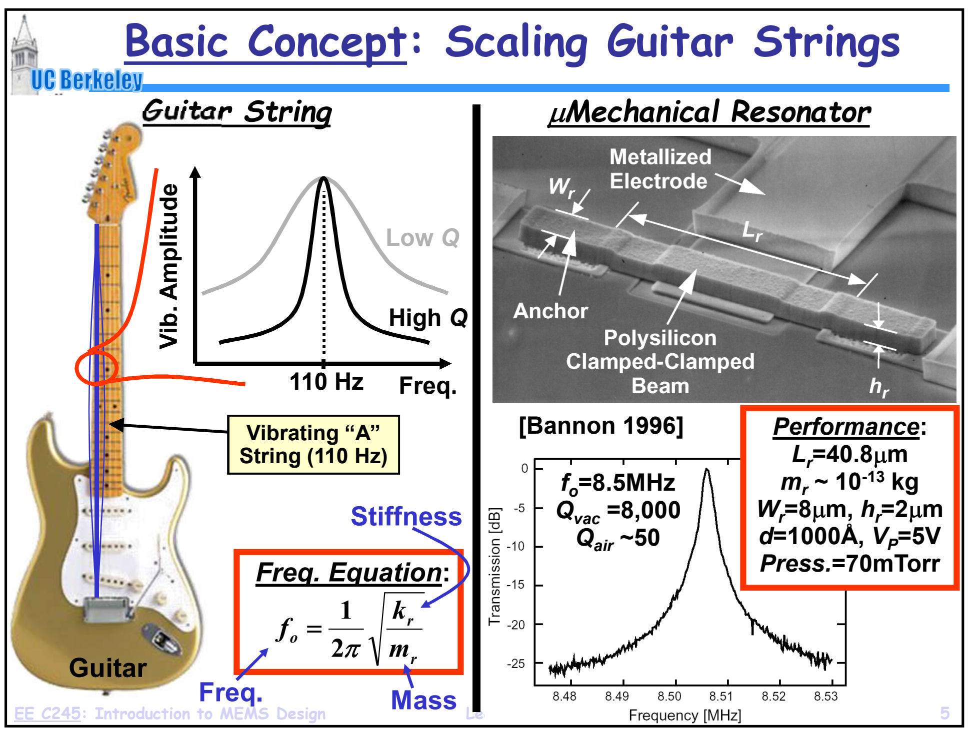
Basic Concept: Scaling Guitar Strings
UC Berkeley
Guitar String
μMechanical Resonator
Vib. Amplitude
Low Q
High Q
110 Hz
Freq.
Vibrating "A" String (110 Hz)
Guitar
Stiffness
Freq. Equation:
$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$
Freq.
Mass
Metallized Electrode
W_r
L_r
Anchor
Polysilicon Clamped-Clamped Beam
h_r
[Bannon 1996]
f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50
Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr
Transmission [dB]
Frequency [MHz]
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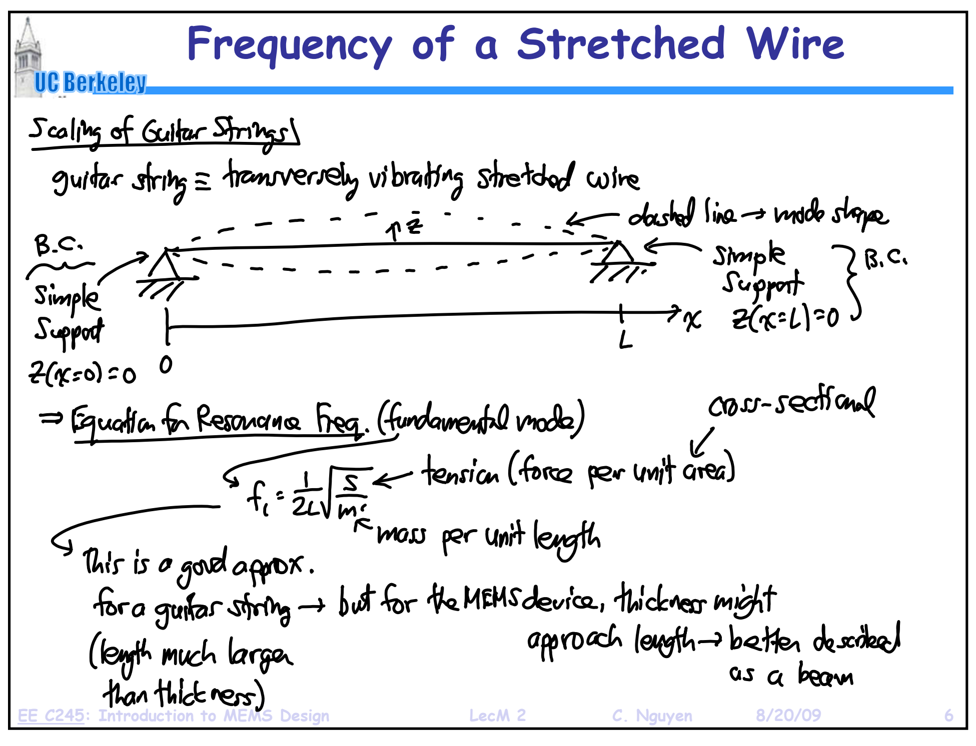
Frequency of a Stretched Wire
UC Berkeley
Scaling of Guitar Strings:
guitar string ≡ transversely vibrating stretched wire
dashed line → mode shape
B.C.
Simple Support
z(x=0)=0
Simple Support
z(x=L)=0
B.C.
0
L
x
z
⇒ Equation for Resonance Freq. (fundamental mode)
$f_1 = \frac{1}{2L}\sqrt{\frac{S}{m_l}}$
tension (force per unit area)
cross-sectional
mass per unit length
This is a good approx. for a guitar string (length much larger than thickness)
→ but for the MEMS device, thickness might approach length → better described as a beam
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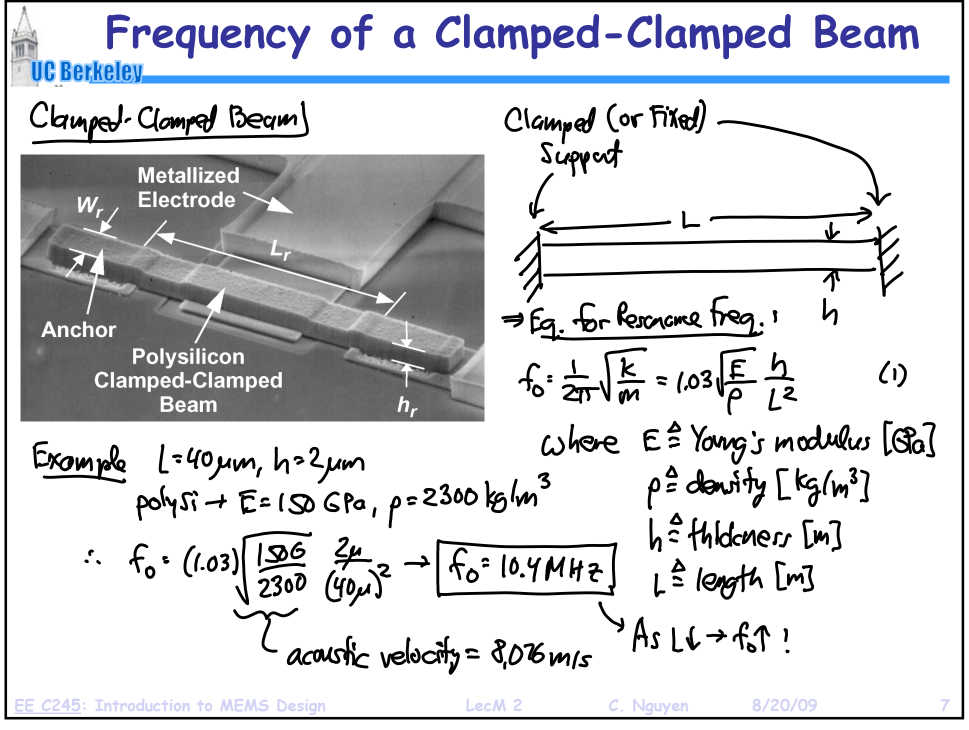

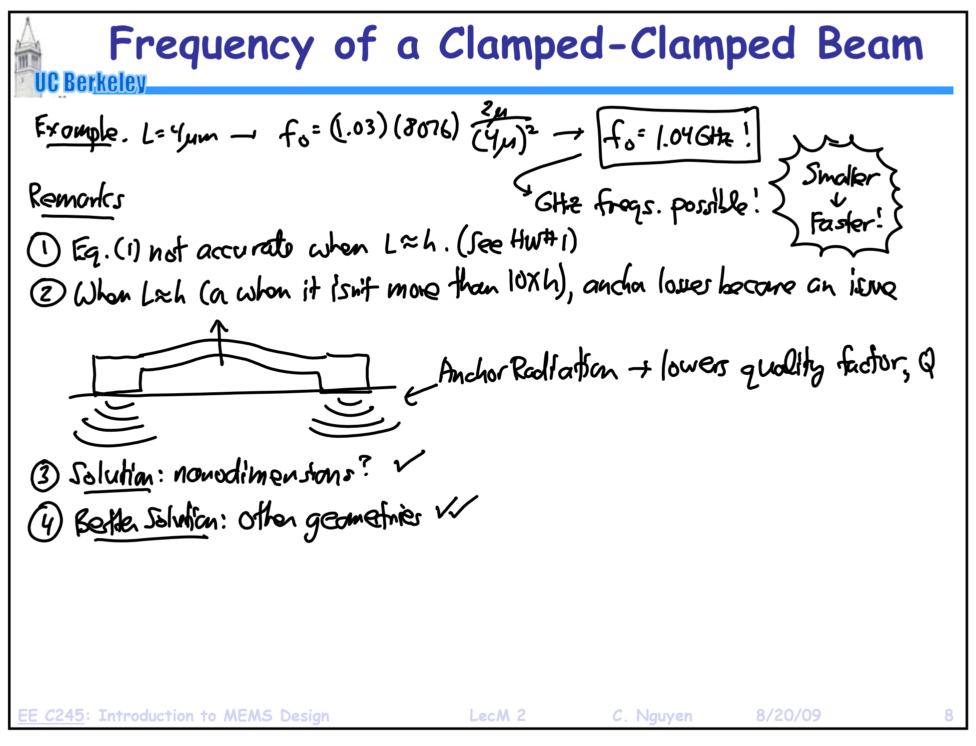

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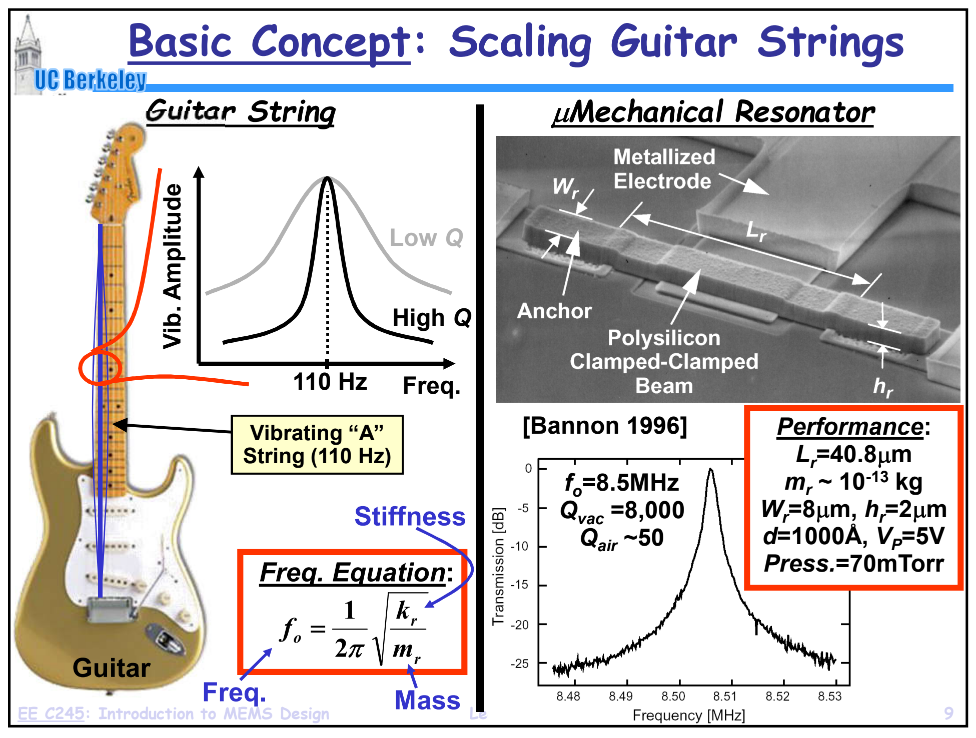

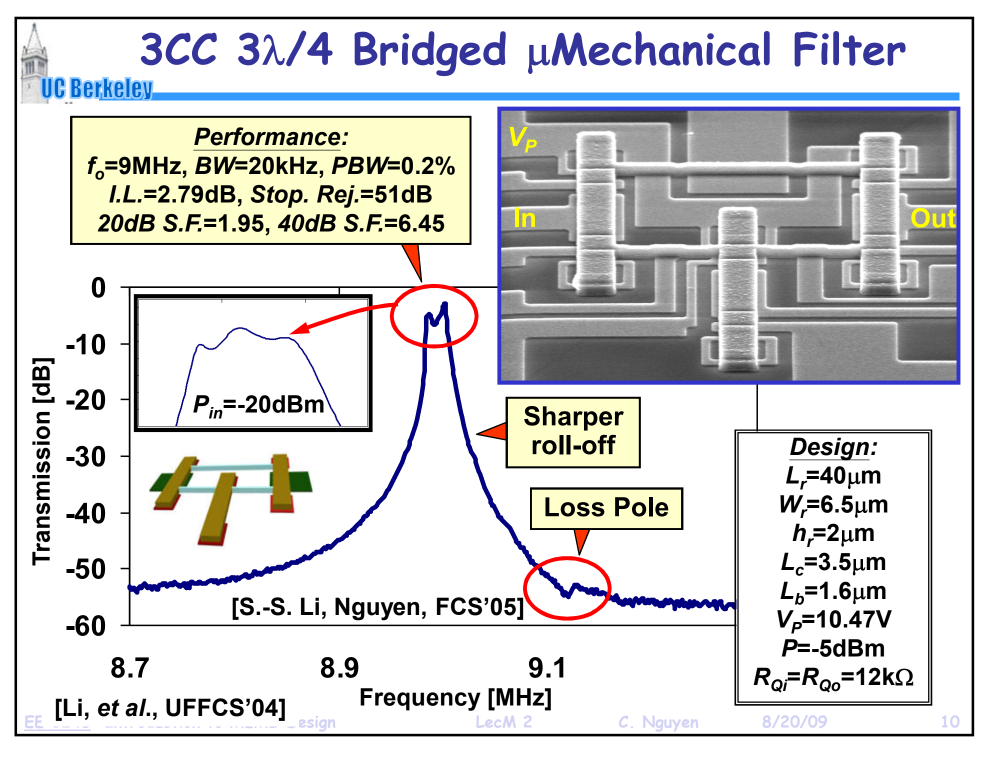

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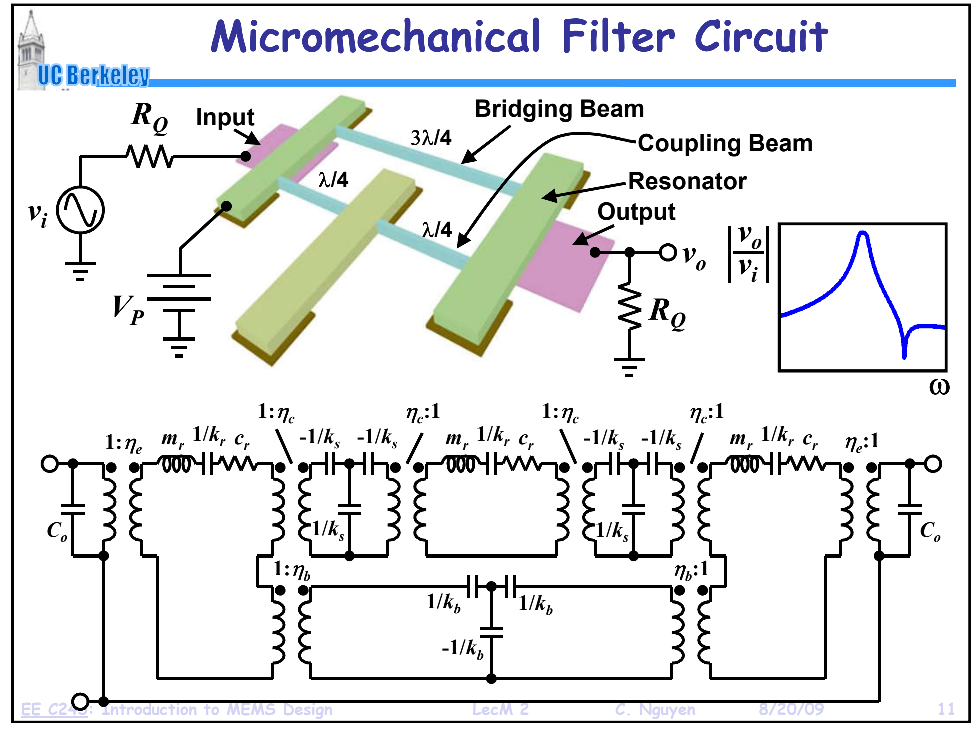

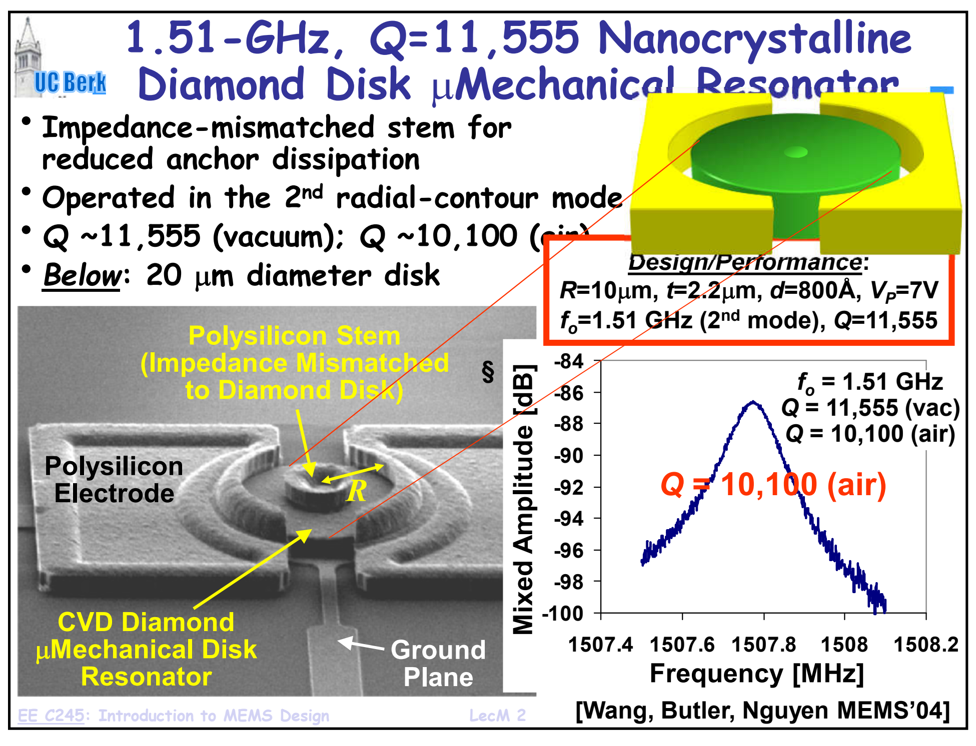

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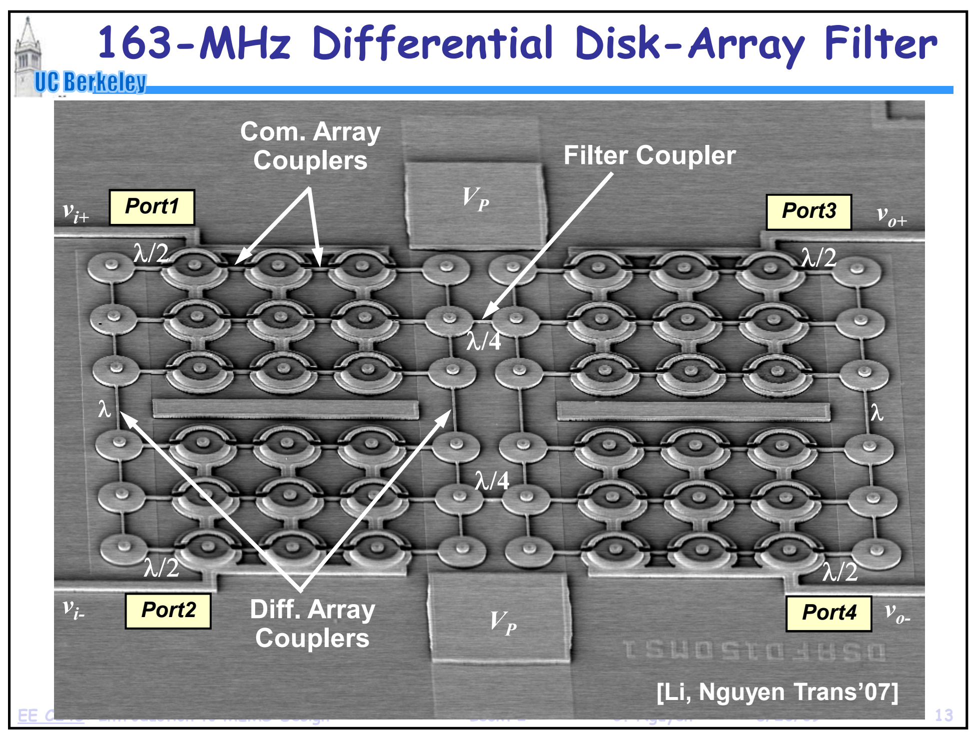
163-MHz Differential Disk-Array Filter
UC Berkeley
Com. Array Couplers
Filter Coupler
V_P
Port1
Port2
Port3
Port4
v_{i+}
v_{i-}
v_{o+}
v_{o-}
λ/2
λ/4
λ
Diff. Array Couplers
[Li, Nguyen Trans'07]
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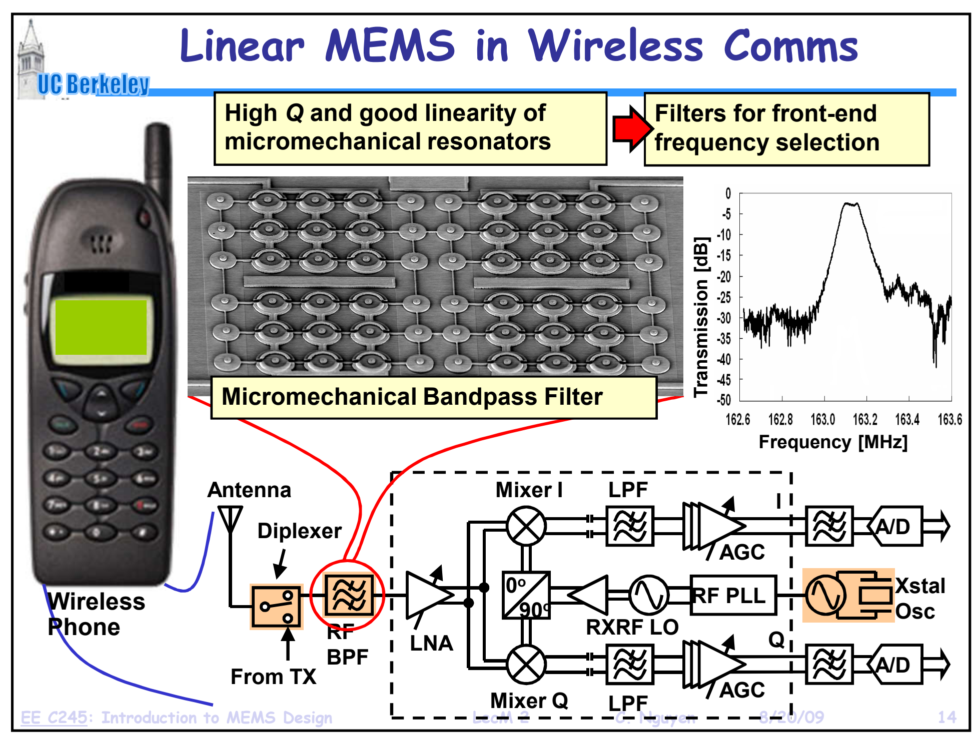
Linear MEMS in Wireless Comms
UC Berkeley
High Q and good linearity of micromechanical resonators
Filters for front-end frequency selection
Micromechanical Bandpass Filter
Transmission [dB]
Frequency [MHz]
162.6
162.8
163.0
163.2
163.4
163.6
Wireless Phone
Antenna
Diplexer
From TX
RF BPF
LNA
Mixer I
Mixer Q
LPF
AGC
RXRF LO
RF PLL
Xstal Osc
A/D
I
Q
0°
90°
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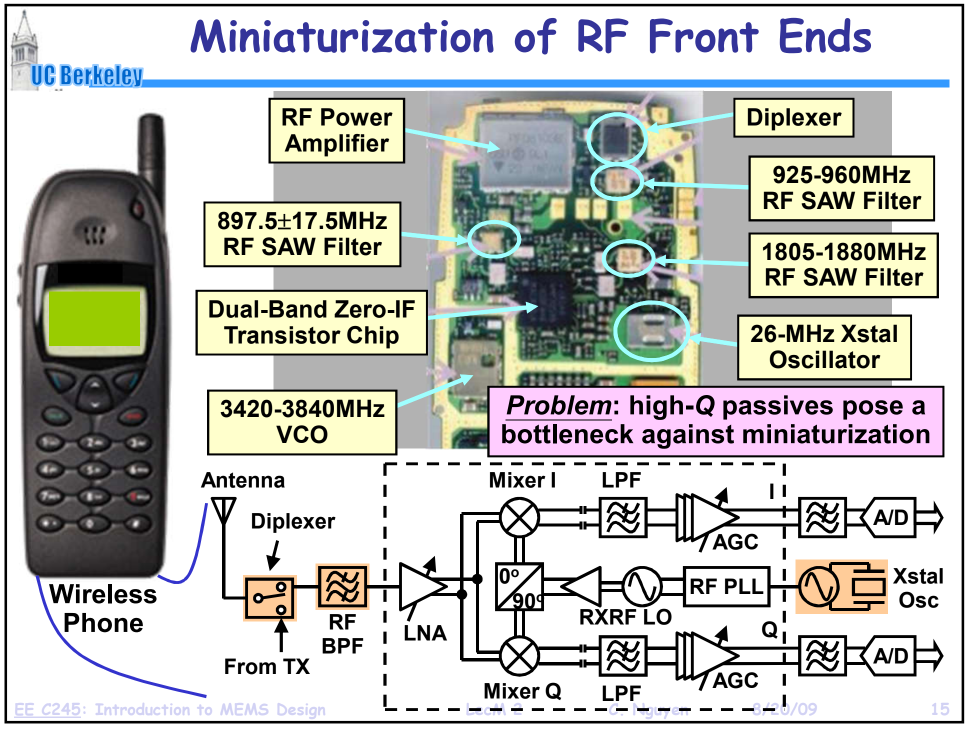

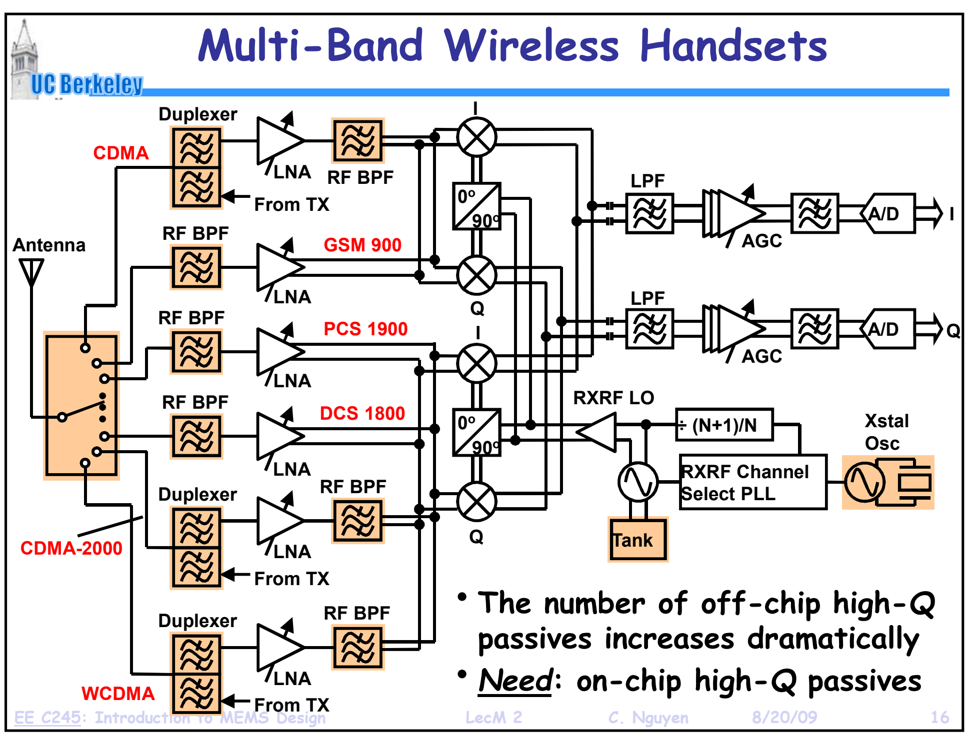

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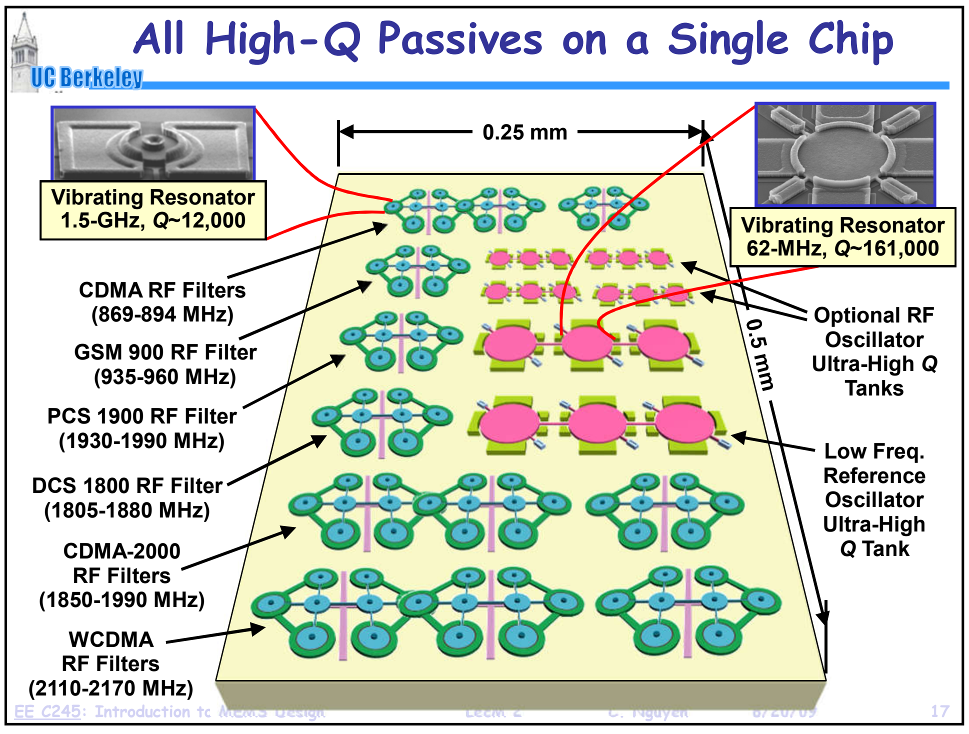

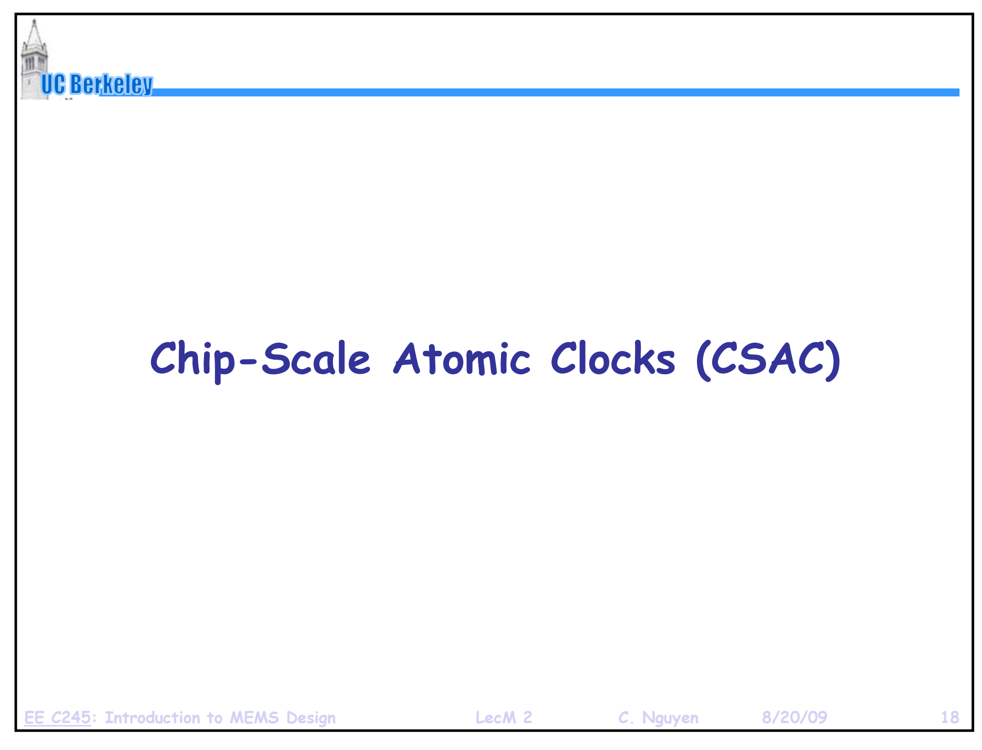

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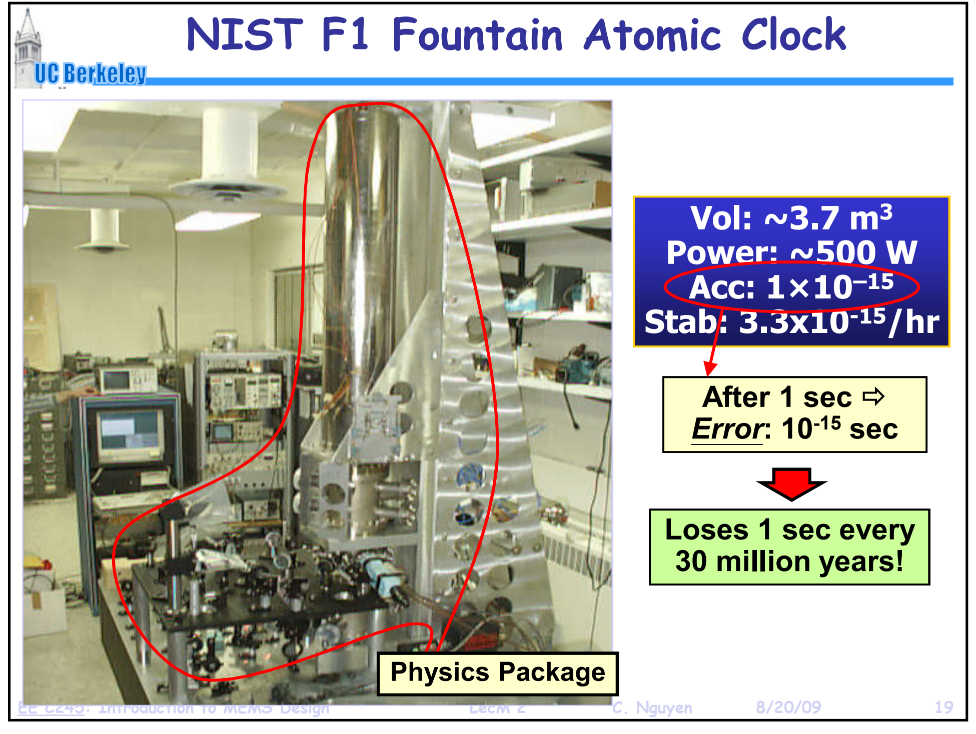

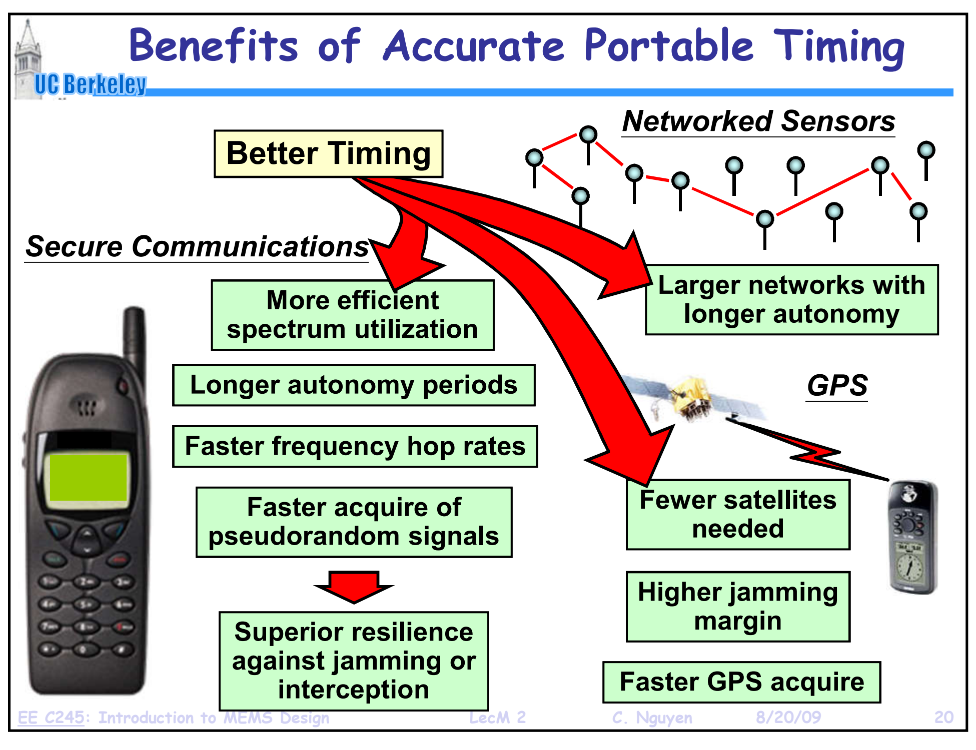

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NIST F1 Fountain Atomic Clock

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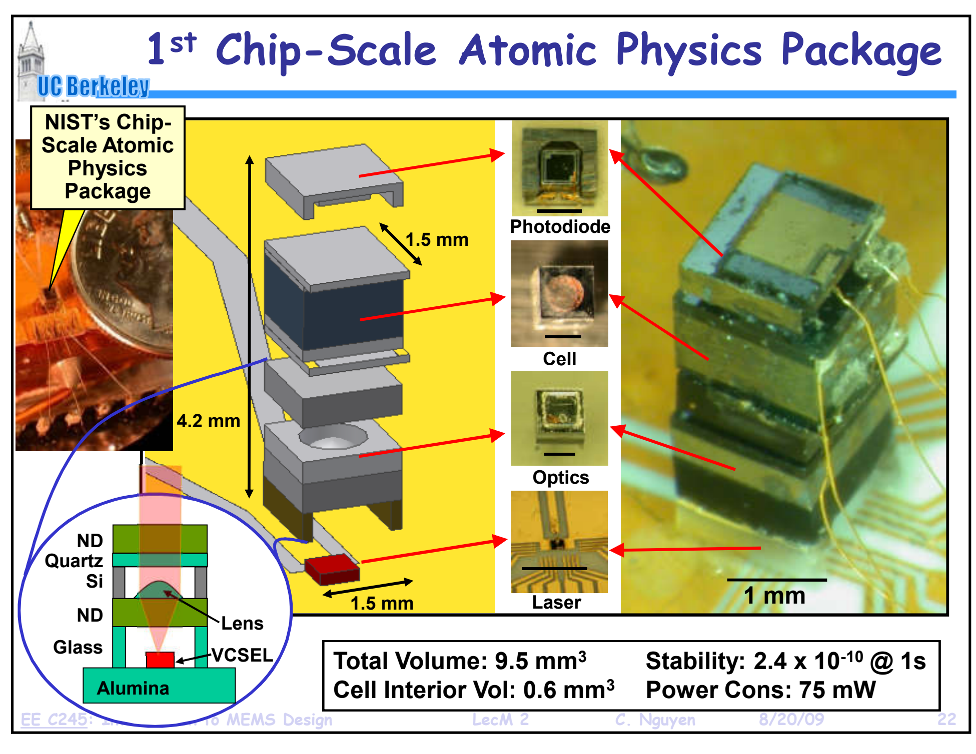
- Vol: ~3.7 m^3
- Power: ~500 W
- Acc: 1×10^{-15}
- Stab: $3.3\text{x}10^{-15}$/hr

After 1 sec ⇨ *Error*: 10^{-15} sec

Loses 1 sec every 30 million years!

Physics Package



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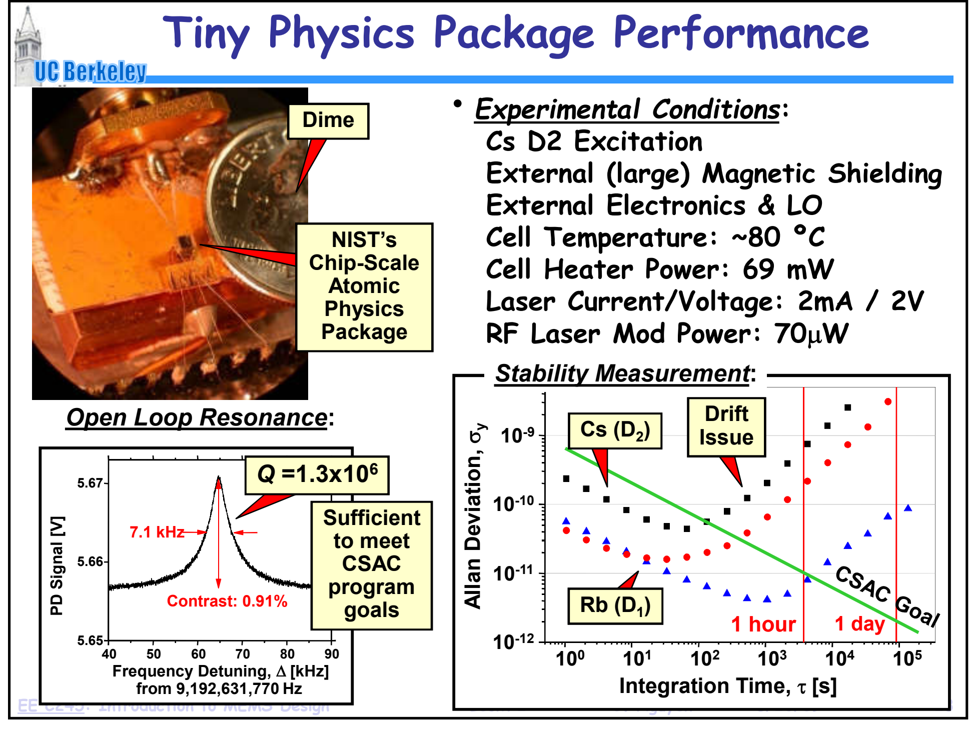
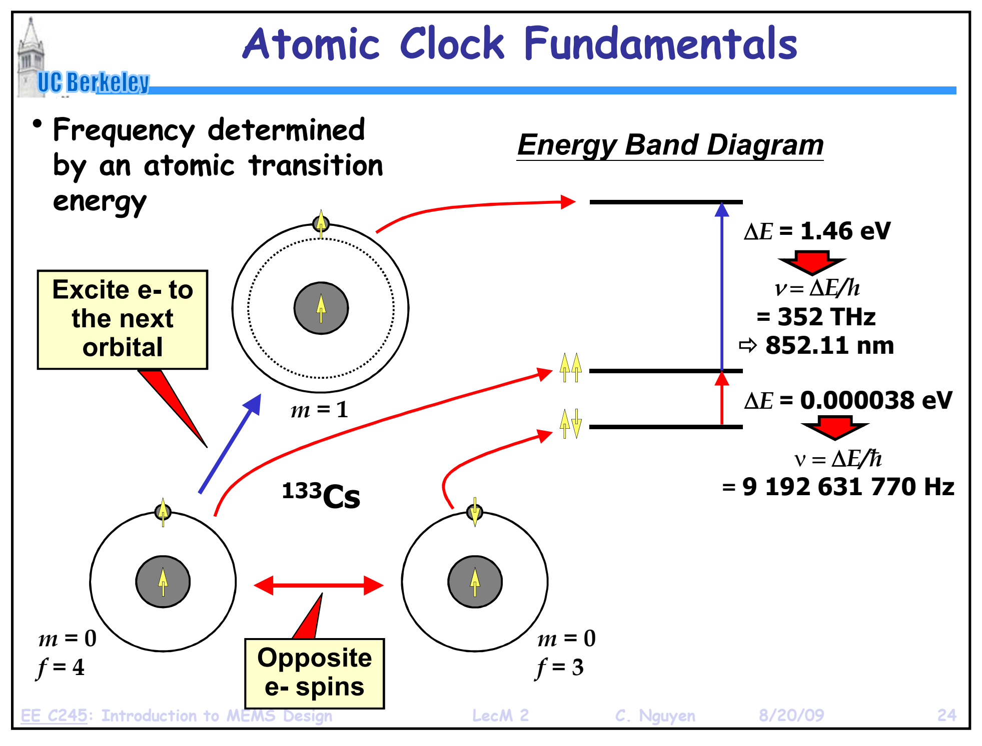

Tiny Physics Package Performance
UC Berkeley
Dime
NIST's Chip-Scale Atomic Physics Package
Open Loop Resonance:
Q =1.3x10^6
Sufficient to meet CSAC program goals
7.1 kHz
Contrast: 0.91%
PD Signal [V]
Frequency Detuning, Δ [kHz] from 9,192,631,770 Hz
Experimental Conditions:
Cs D2 Excitation
External (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
Stability Measurement:
Cs (D2)
Drift Issue
Rb (D1)
CSAC Goal
1 hour
1 day
Allan Deviation, σy
Integration Time, τ [s]


Atomic Clock Fundamentals
UC Berkeley
Frequency determined by an atomic transition energy
Energy Band Diagram
Excite e- to the next orbital
ΔE = 1.46 eV
ν = ΔE/ħ
= 352 THz
⇨ 852.11 nm
ΔE = 0.000038 eV
ν = ΔE/ħ
= 9 192 631 770 Hz
133Cs
m = 1
m = 0
f = 4
m = 0
f = 3
Opposite e- spins
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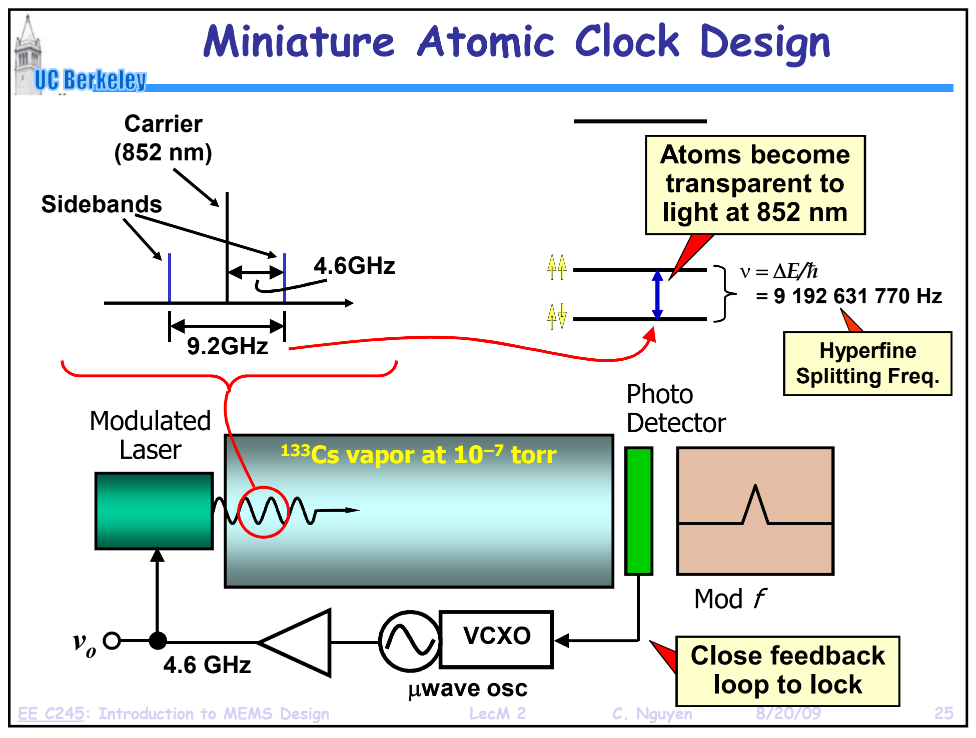

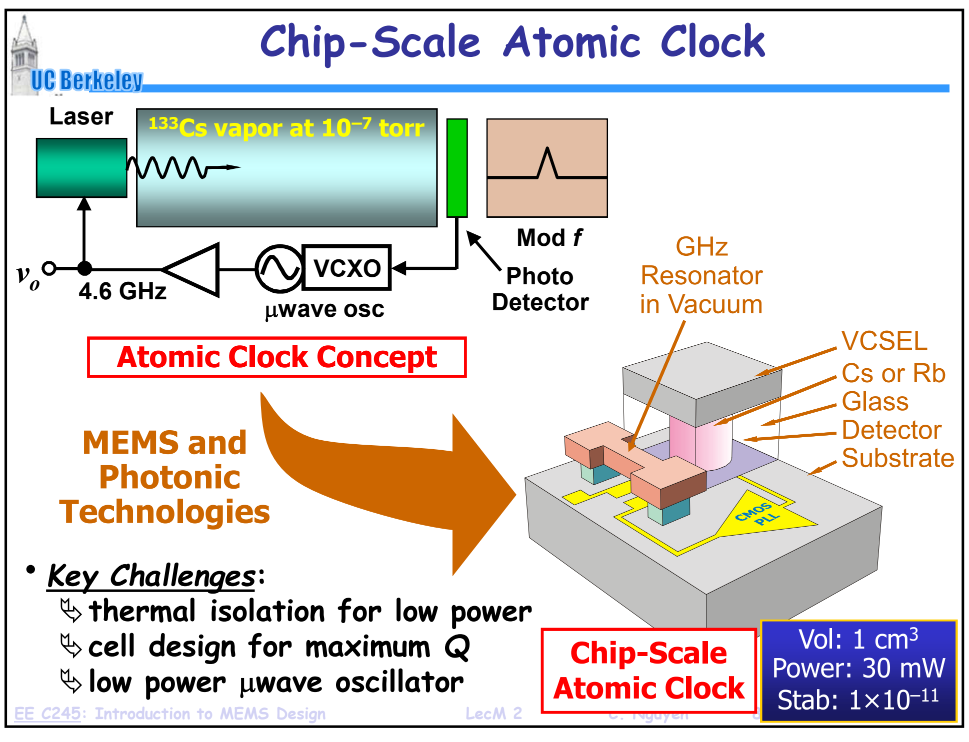

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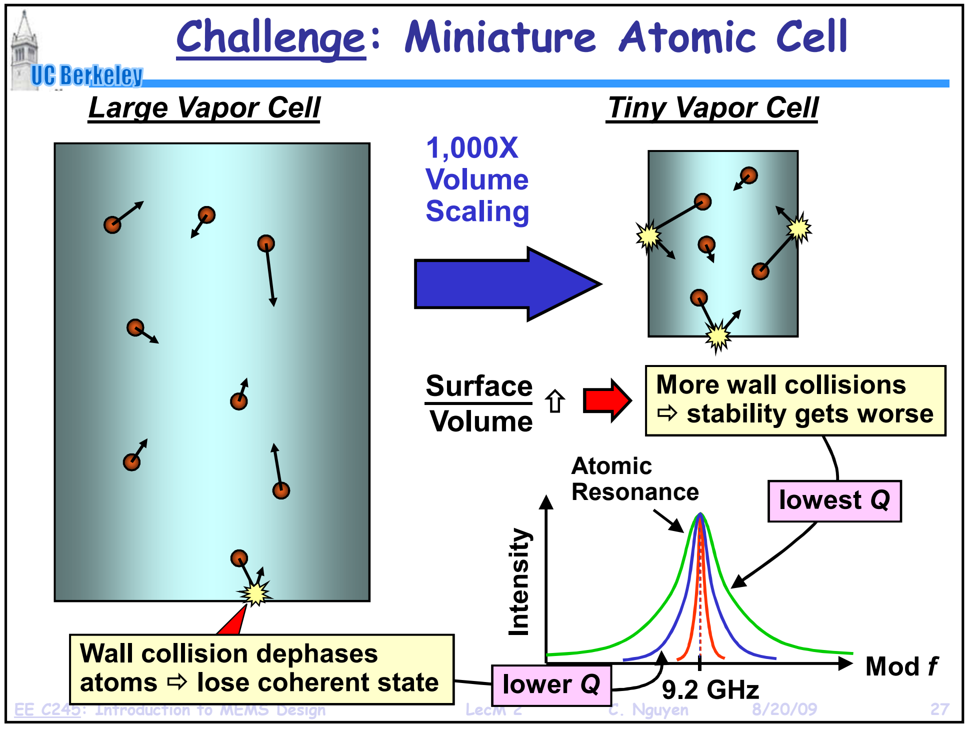

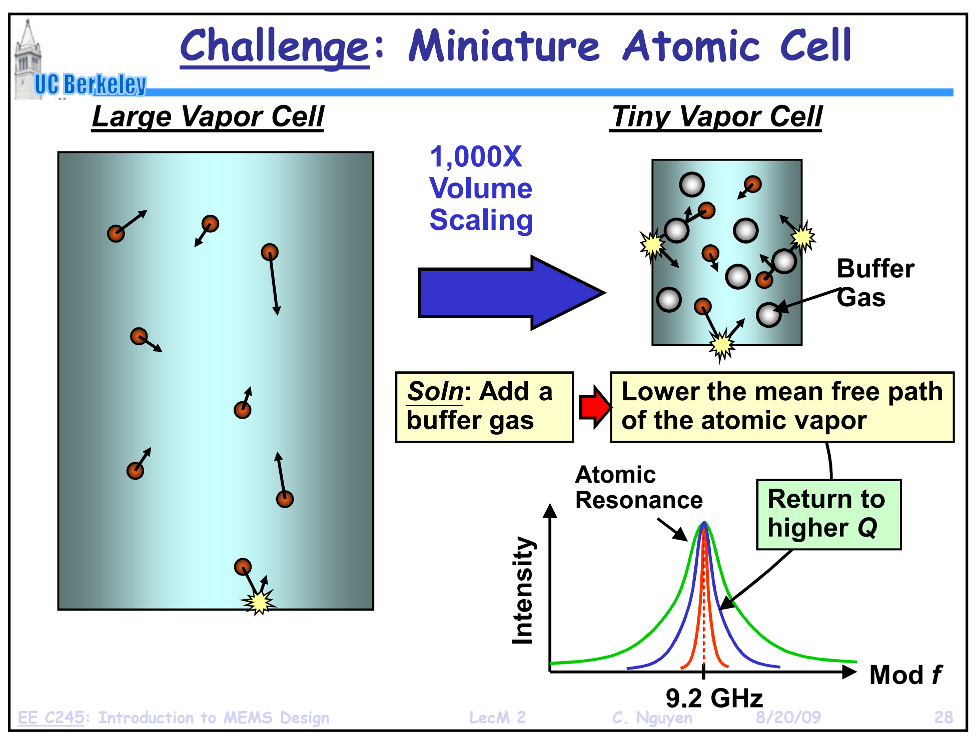

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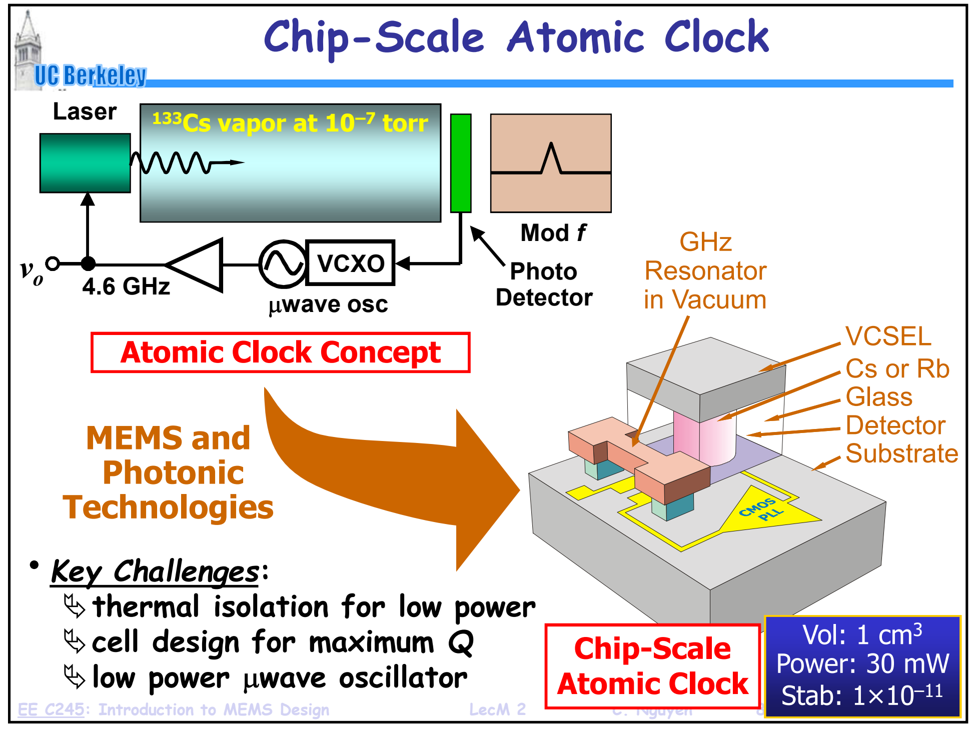

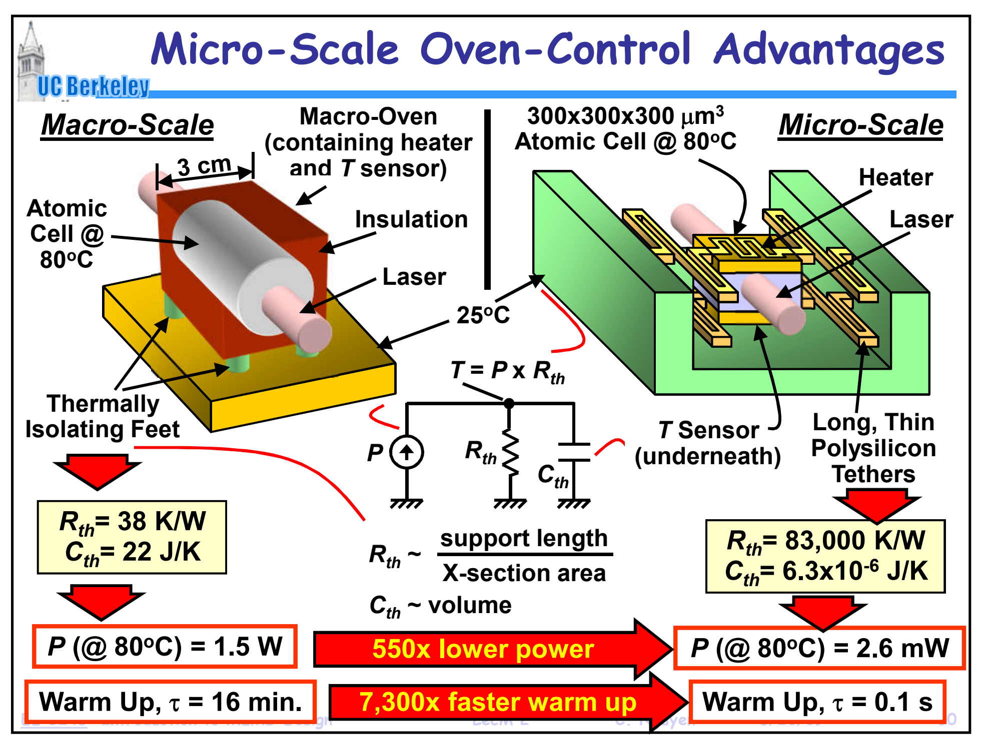

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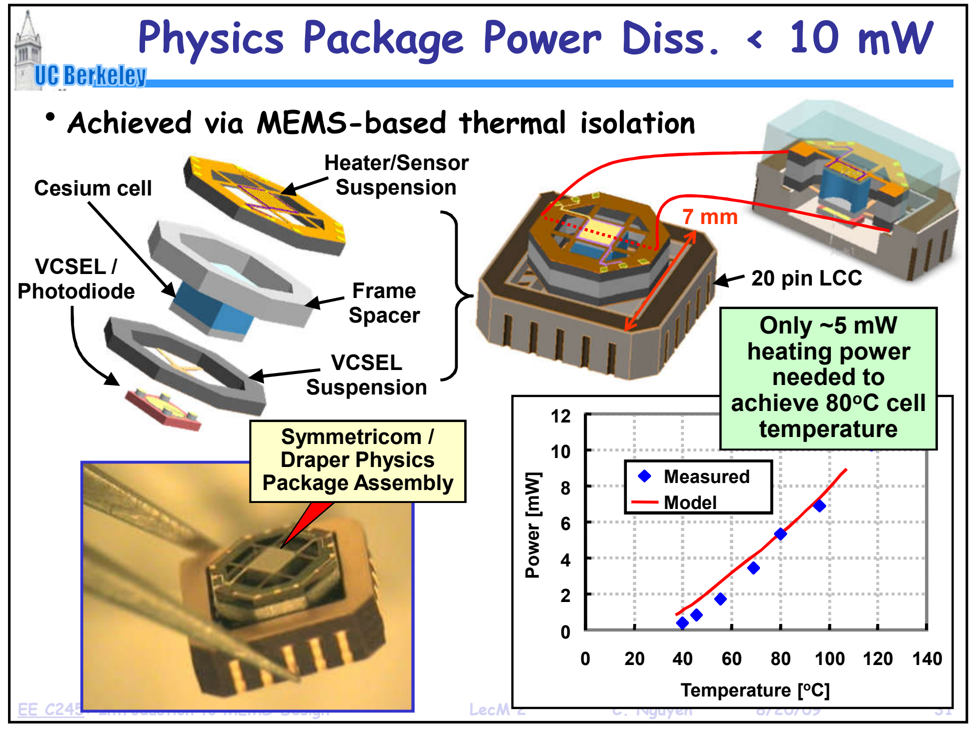

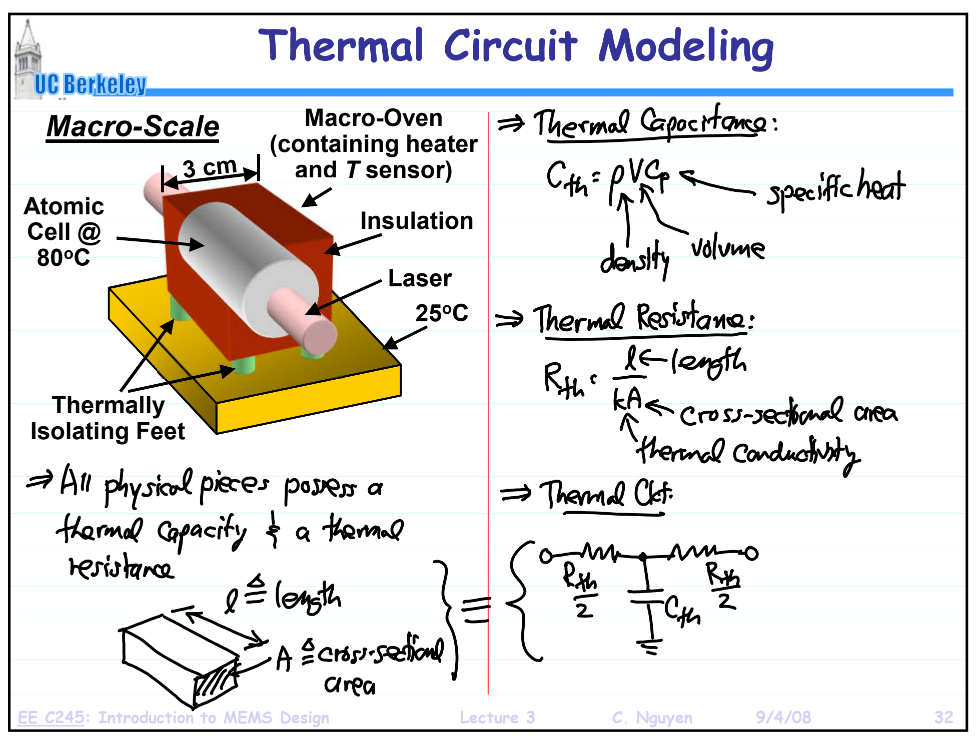

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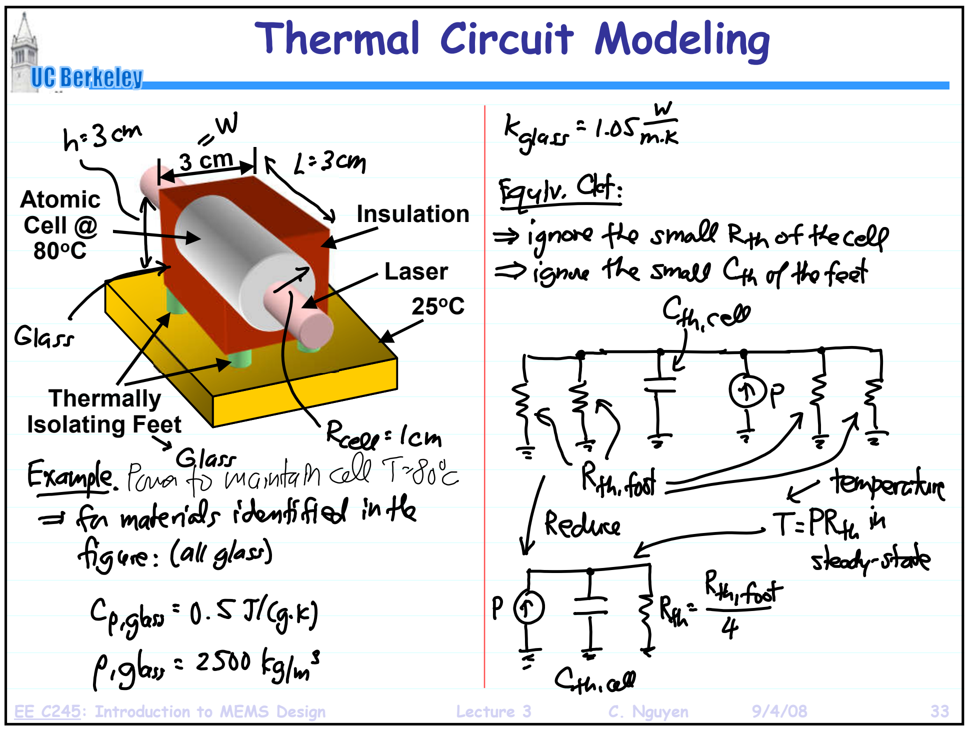
Thermal Circuit Modeling
UC Berkeley
h=3cm
=W
3 cm
L=3cm
Atomic
Cell @
80°C
Insulation
Laser
25°C
Glass
Thermally
Isolating Feet
Glass
Rcell=1cm
Example. Power to maintain cell T=80°C
⇒ for materials identified in the
figure: (all glass)
Cp,glass = 0.5 J/(g·K)
ρ,glass = 2500 kg/m³
kglass = 1.05 W/m·K
Equiv. Ckt:
⇒ ignore the small Rth of the cell
⇒ ignore the small Cth of the feet
Cth,cell
P
Rth,foot
temperature
Reduce
T=PRth in
steady-state
Rth = Rth,foot / 4
Cth,cell
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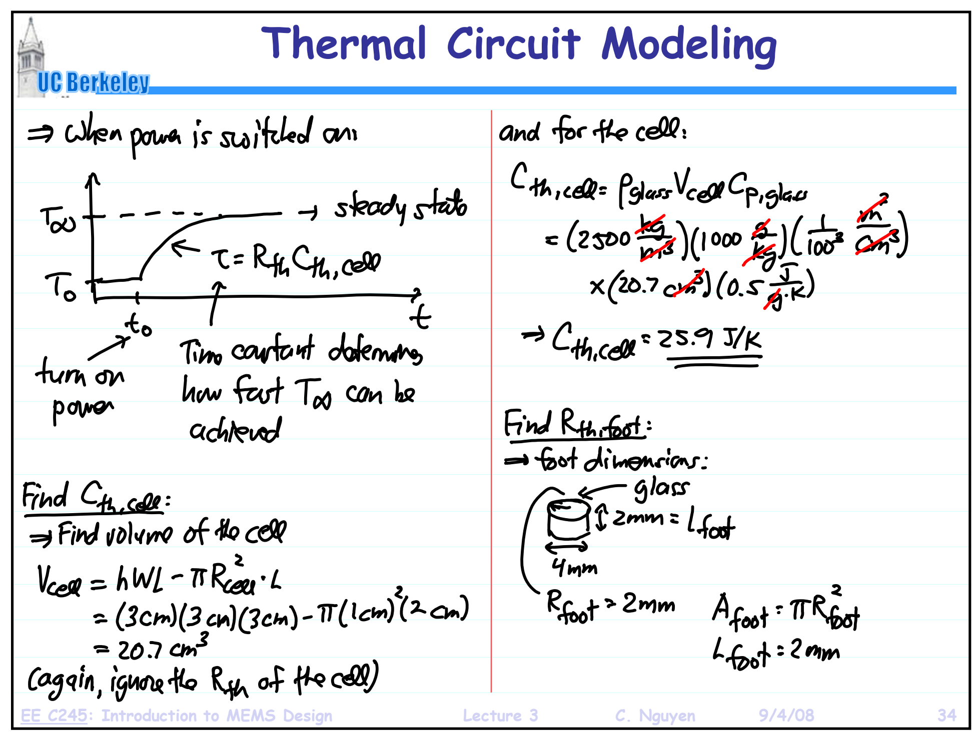
Thermal Circuit Modeling
UC Berkeley
⇒ when power is switched on
T∞
steady state
τ = Rth Cth,cell
To
to
t
turn on
power
Time constant determines
how fast T∞ can be
achieved
Find Cth,cell:
⇒ Find volume of the cell
Vcell = hWL − πRcell²·L
= (3cm)(3cm)(3cm) − π(1cm)²(2cm)
= 20.7 cm³
(again, ignore the Rth of the cell)
and for the cell:
Cth,cell = ρglass Vcell Cp,glass
= (2500 kg/m³)(1000 g/kg)(1/100³ m³/cm³)
× (20.7 cm³)(0.5 J/g·K)
→ Cth,cell = 25.9 J/K
Find Rth,foot:
⇒ foot dimensions:
glass
2mm = Lfoot
4mm
Rfoot = 2mm
Afoot = πRfoot²
Lfoot = 2mm
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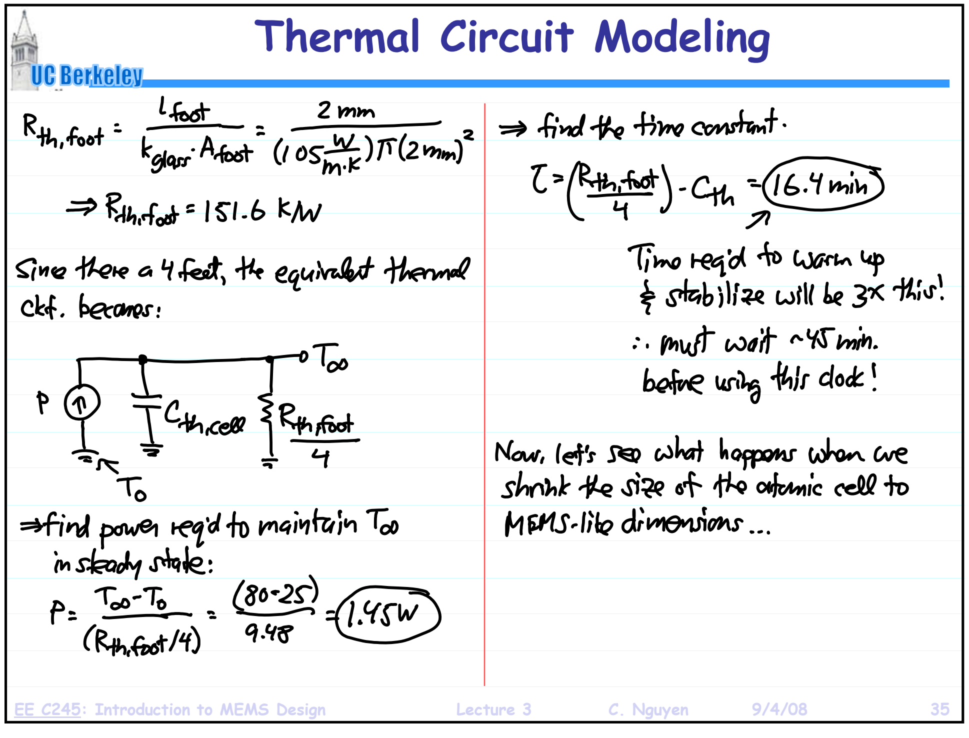

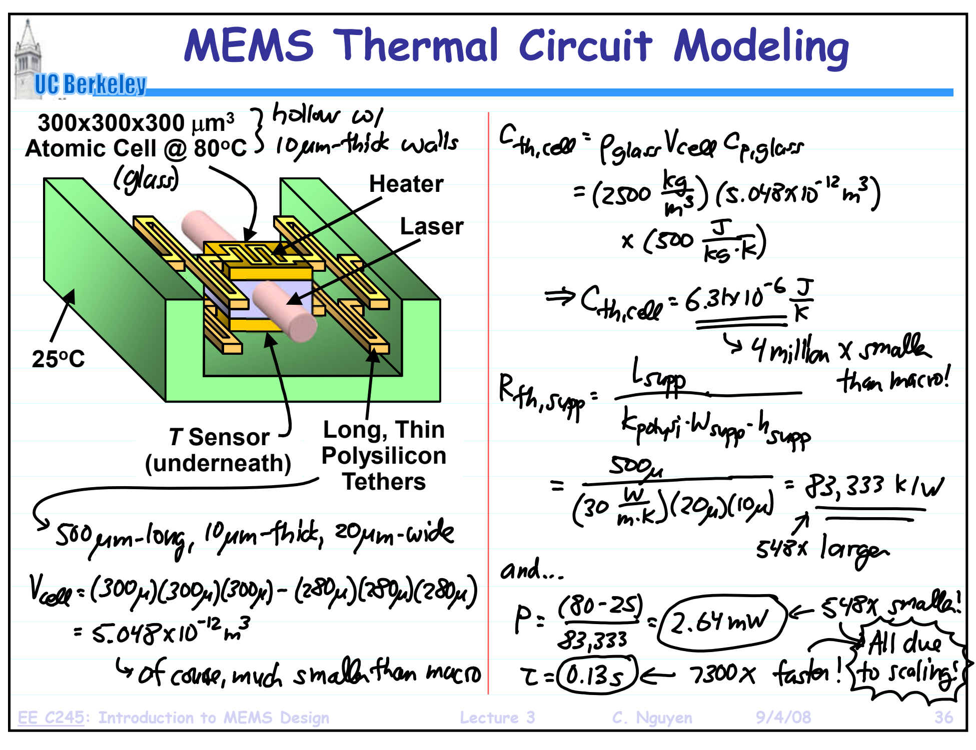

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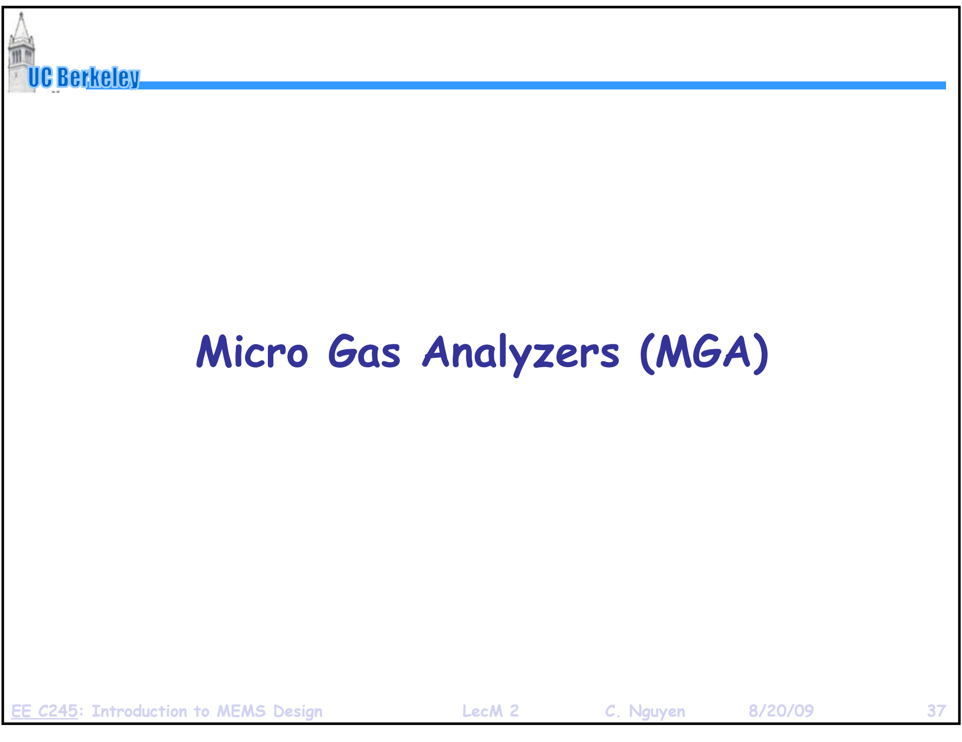

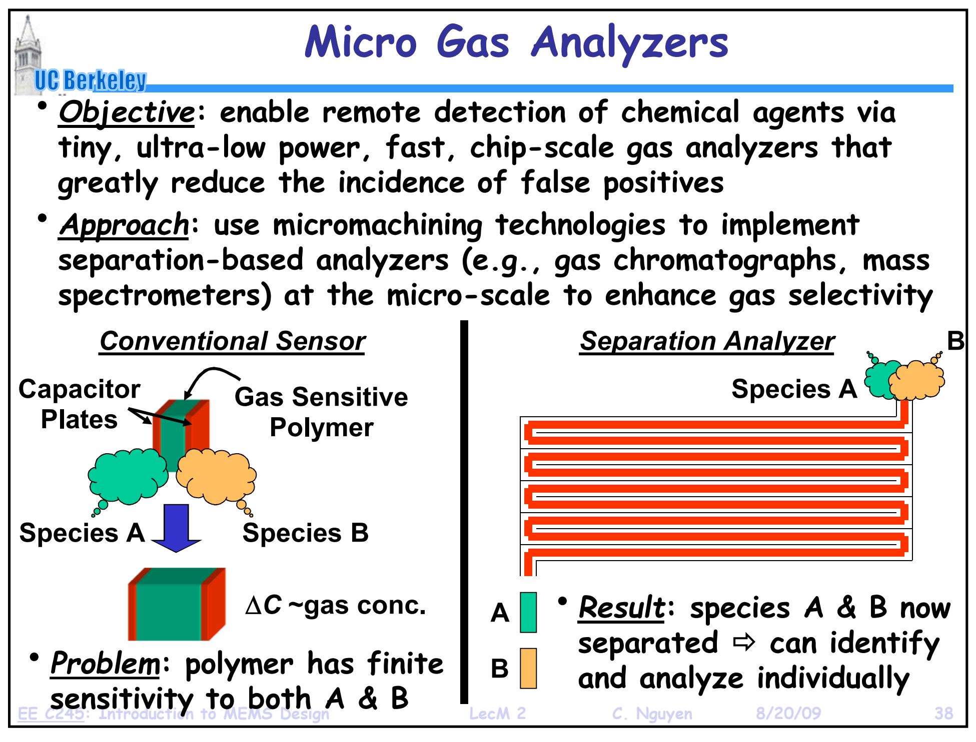

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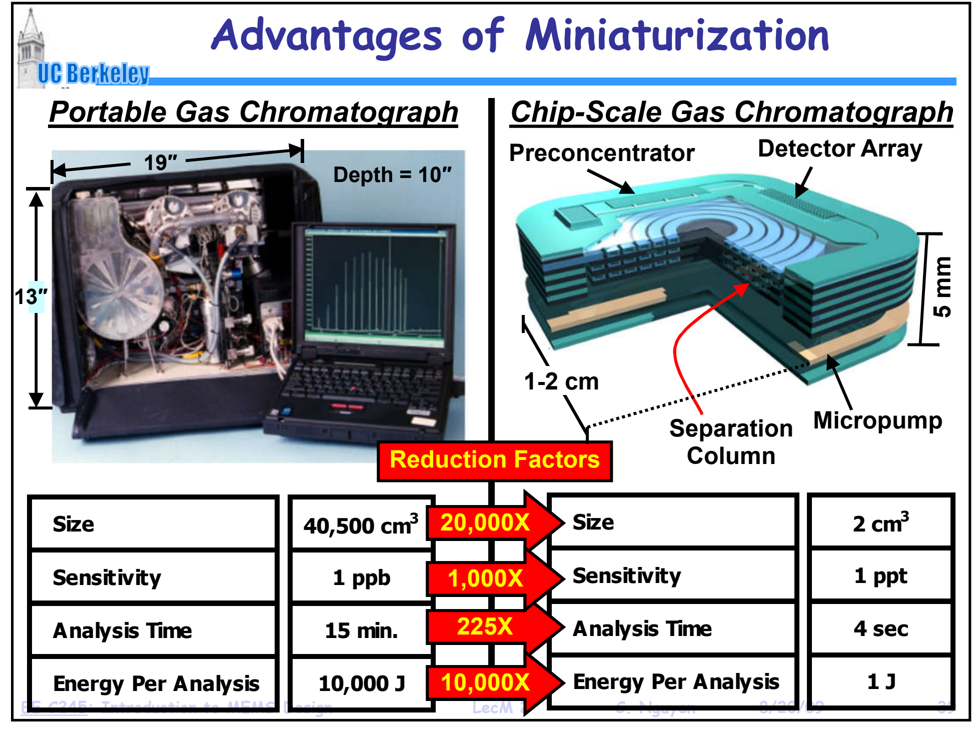

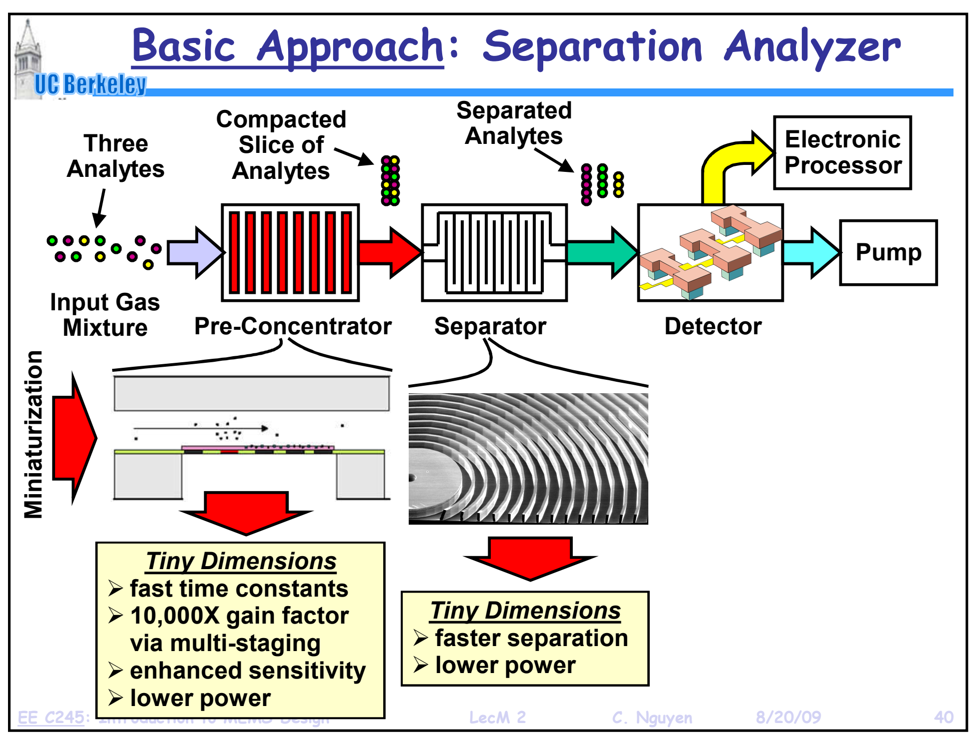

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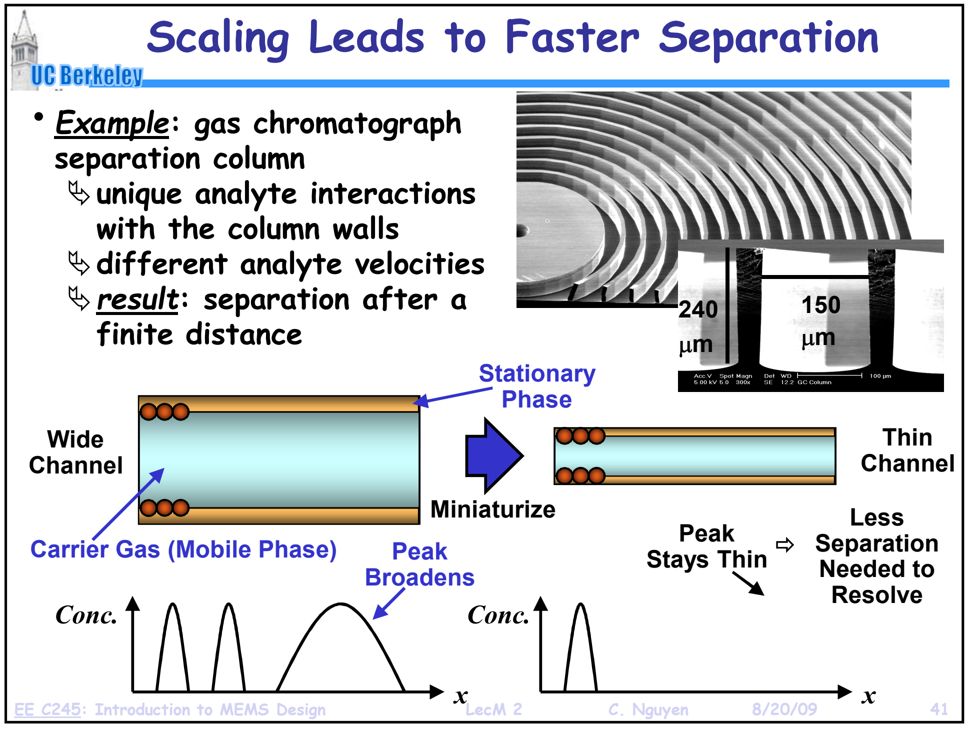

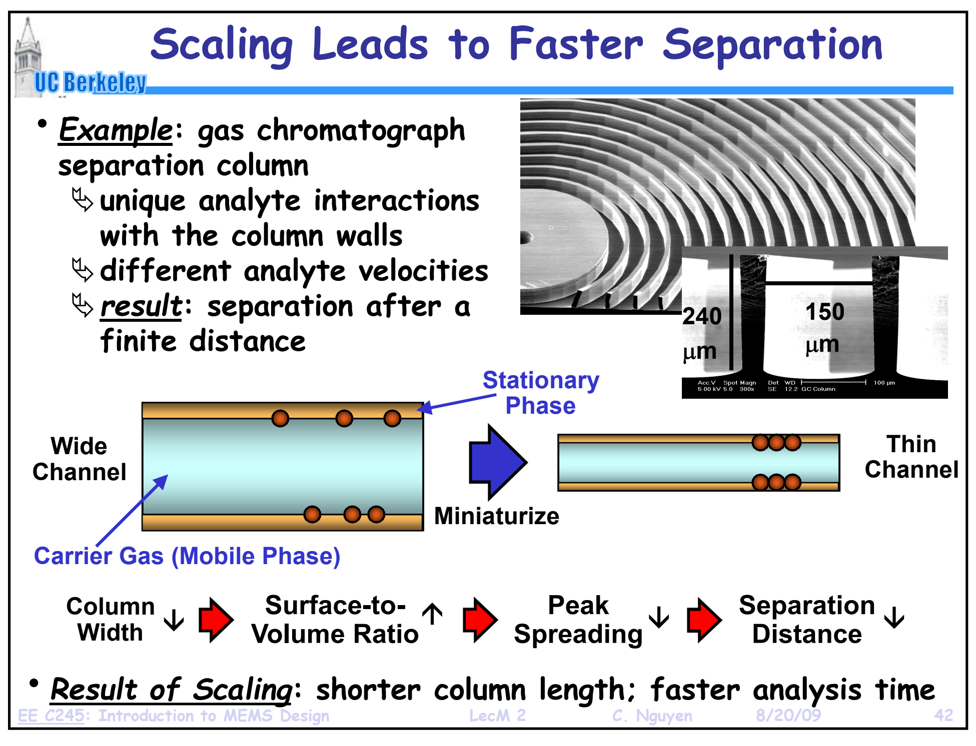

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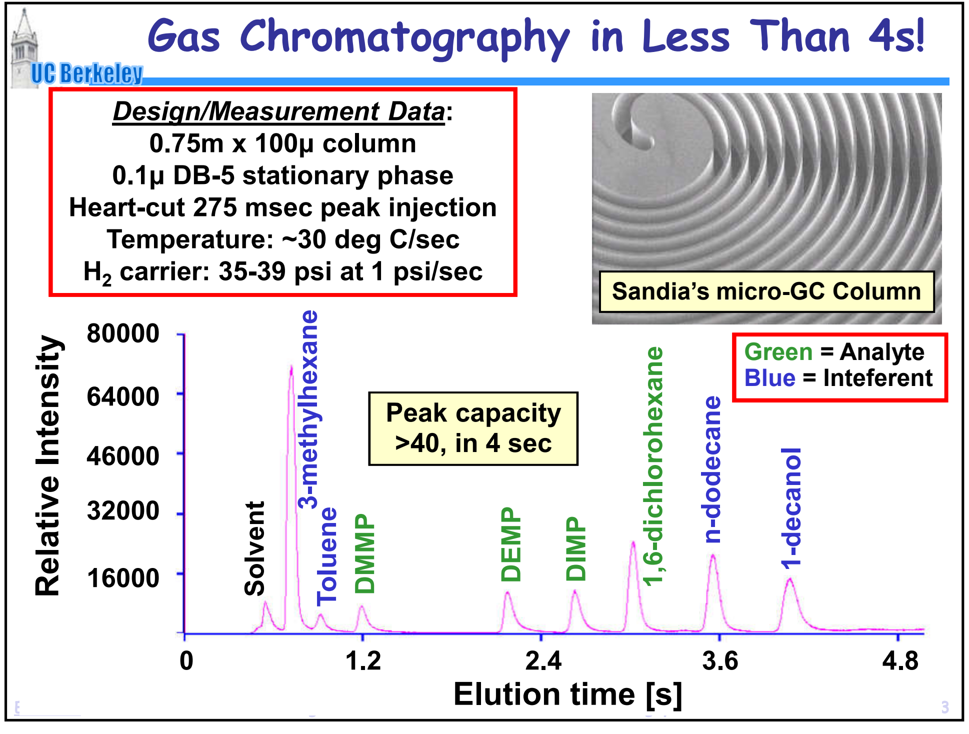
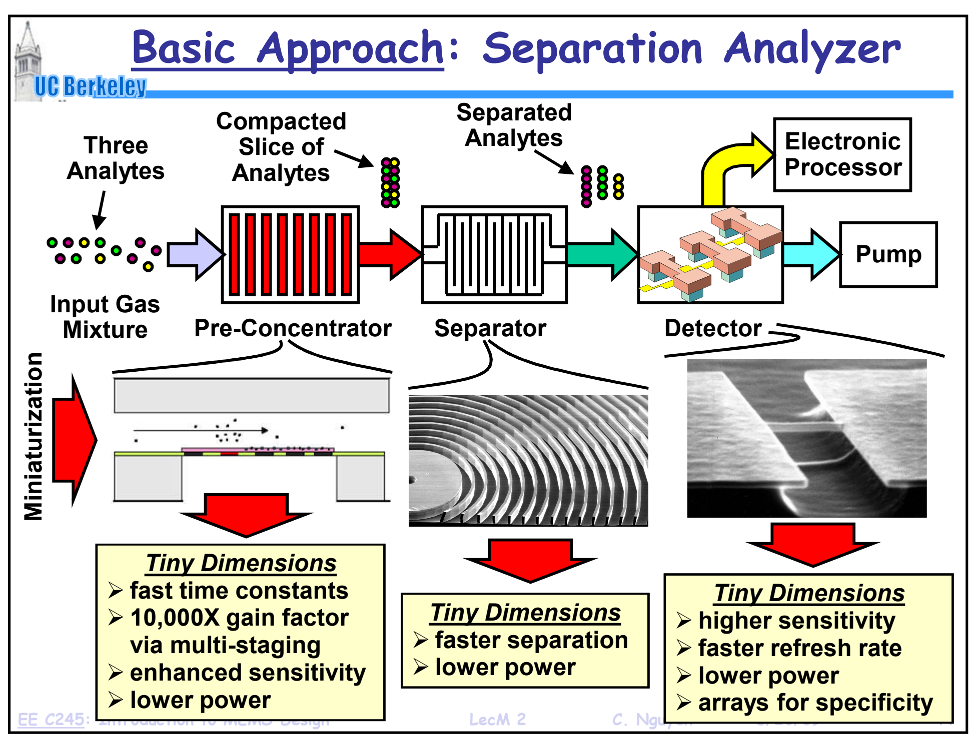
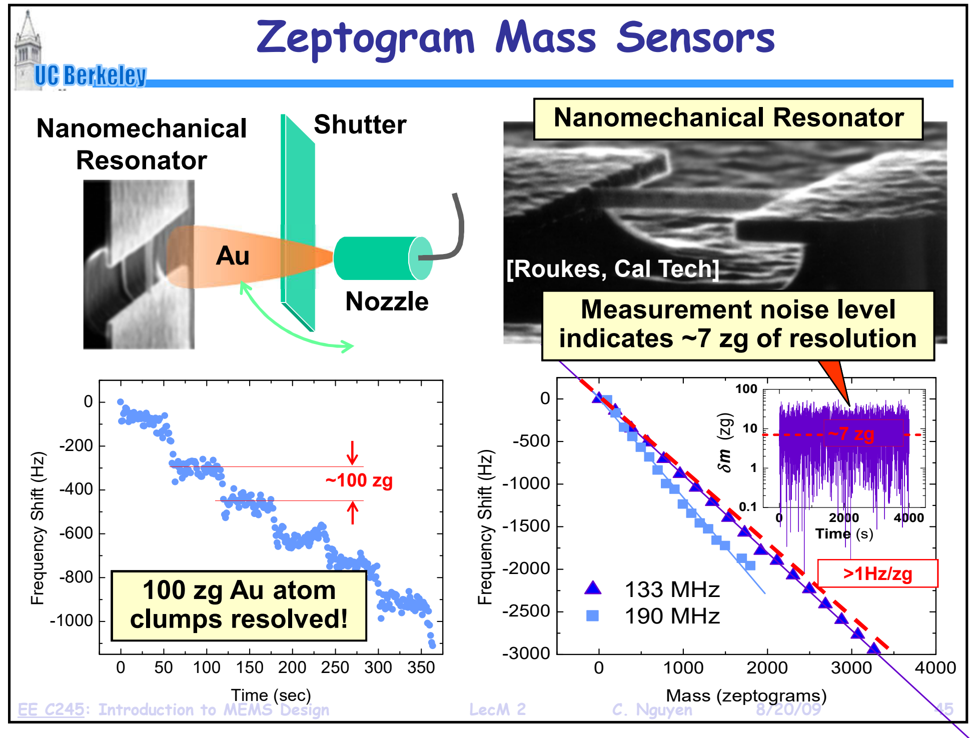

Gas Chromatography in Less Than 4s!
UC Berkeley
Design/Measurement Data:
0.75m x 100μ column
0.1μ DB-5 stationary phase
Heart-cut 275 msec peak injection
Temperature: ~30 deg C/sec
H2 carrier: 35-39 psi at 1 psi/sec
Sandia's micro-GC Column
Green = Analyte
Blue = Inteferent
Peak capacity
>40, in 4 sec
Relative Intensity
80000
64000
46000
32000
16000
Solvent
3-methylhexane
Toluene
DMMP
DEMP
DIMP
1,6-dichlorohexane
n-dodecane
1-decanol
0
1.2
2.4
3.6
4.8
Elution time [s]


Basic Approach: Separation Analyzer
UC Berkeley
Three Analytes
Compacted Slice of Analytes
Separated Analytes
Electronic Processor
Pump
Input Gas Mixture
Pre-Concentrator
Separator
Detector
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


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)
~100 zg
100 zg Au atom clumps resolved!
Time (sec)
~7 zg
>1Hz/zg
133 MHz
190 MHz
Mass (zeptograms)
Time (s)
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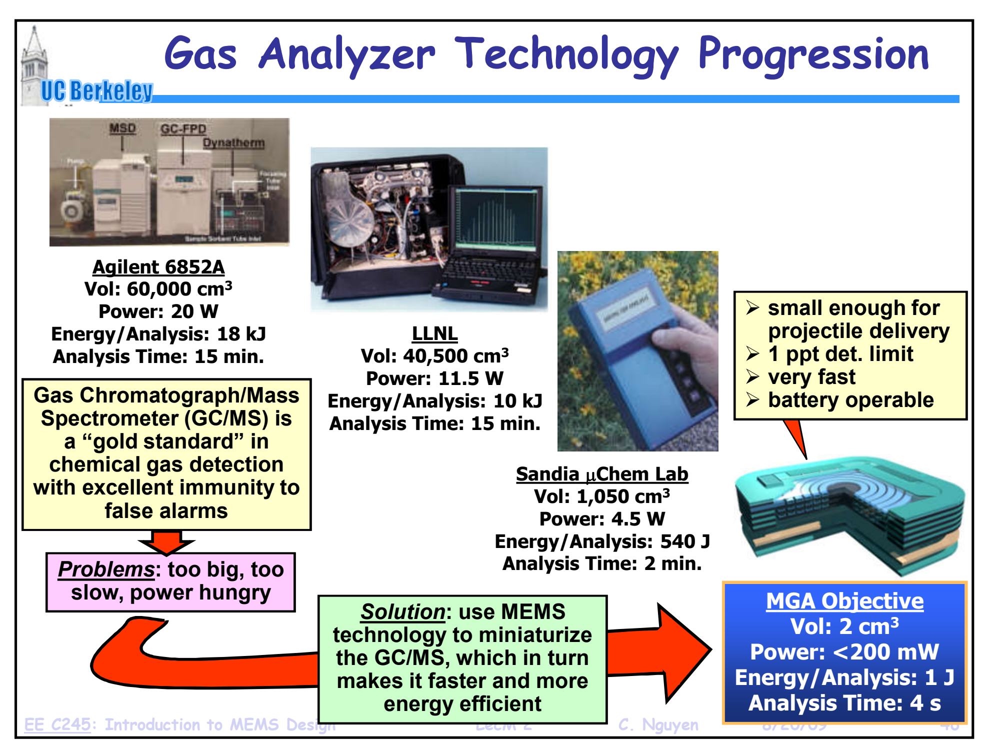
Gas Analyzer Technology Progression
UC Berkeley
MSD
GC-FPD
Dynatherm
Agilent 6852A
Vol: 60,000 cm³
Power: 20 W
Energy/Analysis: 18 kJ
Analysis Time: 15 min.
LLNL
Vol: 40,500 cm³
Power: 11.5 W
Energy/Analysis: 10 kJ
Analysis Time: 15 min.
Sandia µChem Lab
Vol: 1,050 cm³
Power: 4.5 W
Energy/Analysis: 540 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
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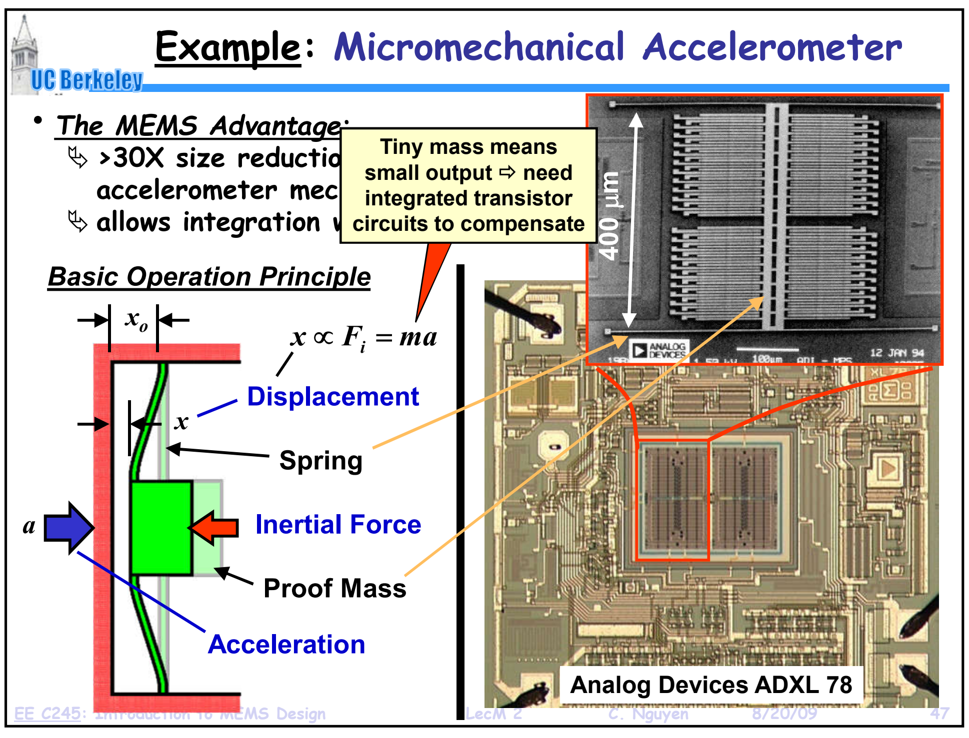

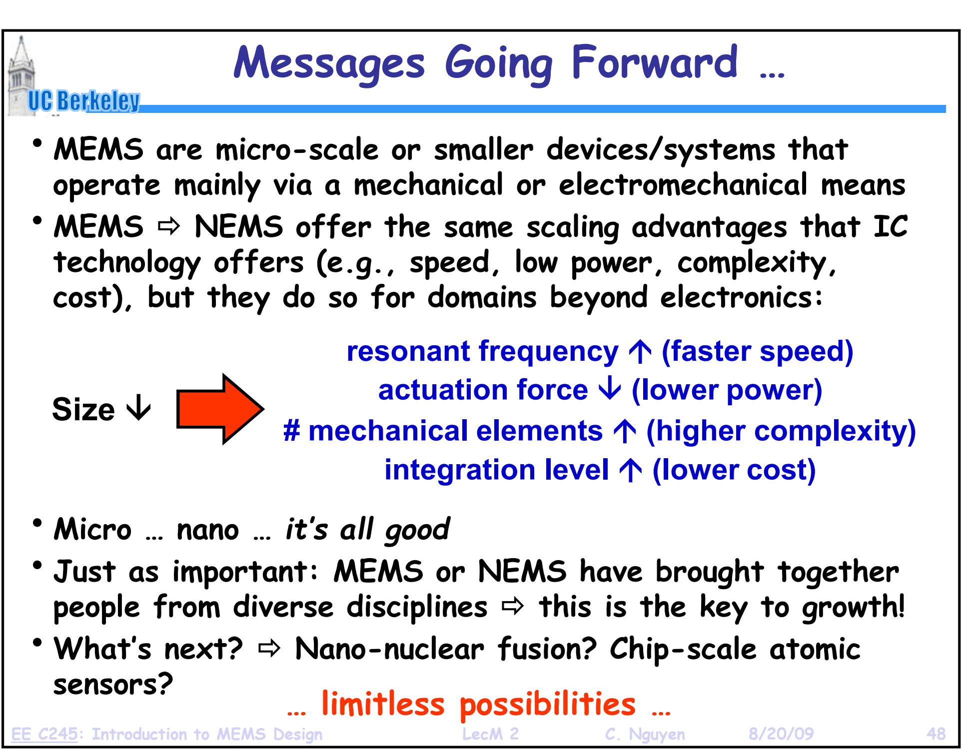

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