EE C247B – ME C218 Introduction to MEMS Design Spring 2014

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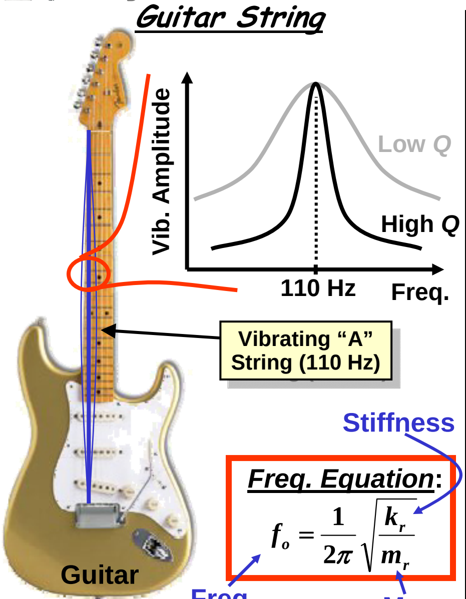
Lecture Module 2: Benefits of Scaling

Basic Concept: Scaling Guitar Strings

Guitar String



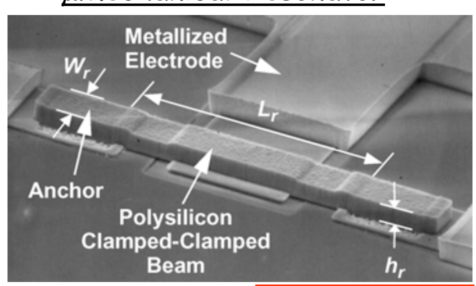
Stiffness

Freq. Equation:

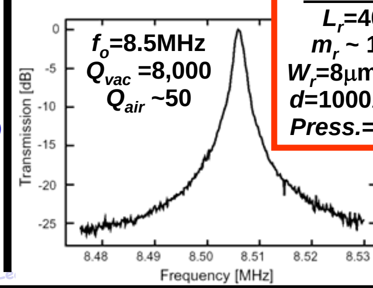
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Freq. Mass

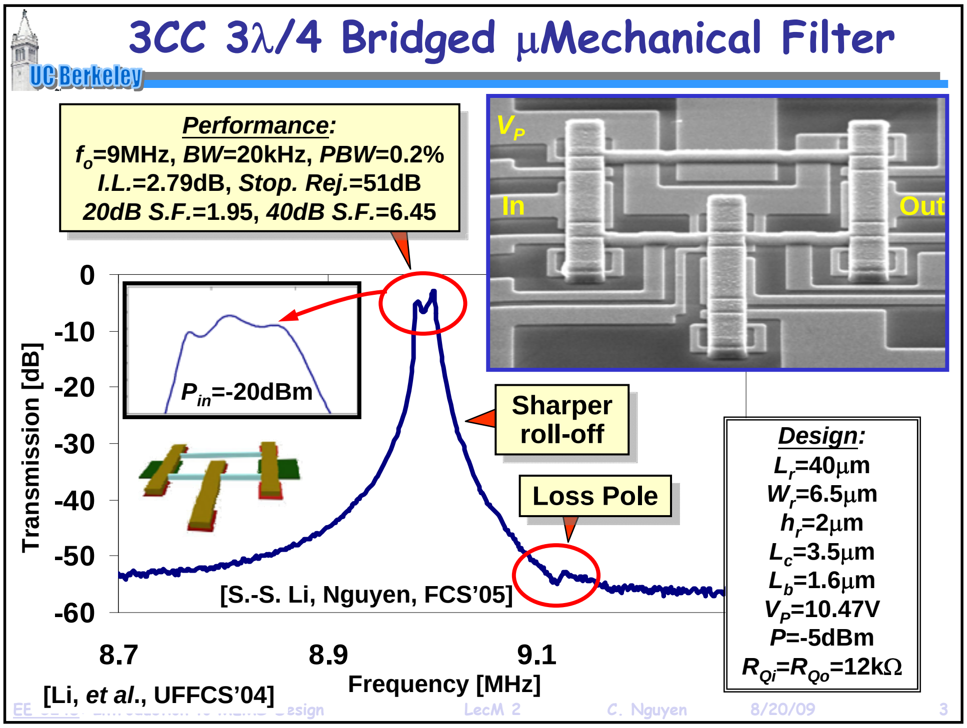
µMechanical Resonator



[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


3CC 3λ/4 Bridged μMechanical Filter
UC Berkeley
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
Sharper roll-off
Loss Pole
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
Transmission [dB]
0
-10
-20
-30
-40
-50
-60
[S.-S. Li, Nguyen, FCS'05]
8.7
8.9
9.1
Frequency [MHz]
[Li, et al., UFFCS'04]
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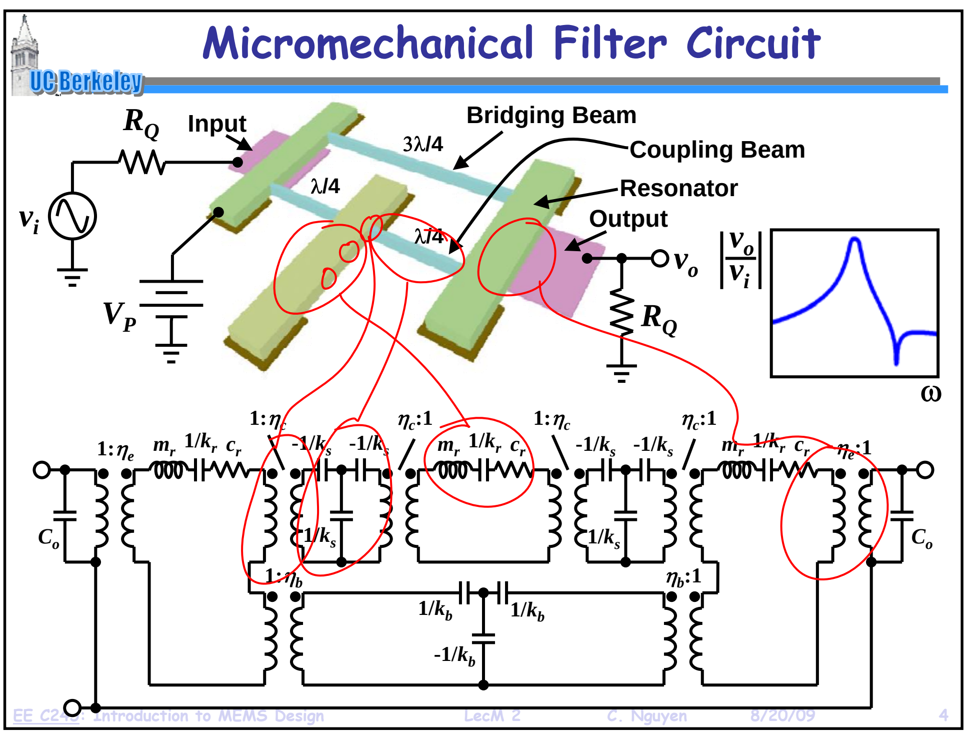
Micromechanical Filter Circuit
UC Berkeley
R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
λ/4
Output
v_i
V_P
v_o
R_Q
$\left|\frac{v_o}{v_i}\right|$
ω
1:η_e
m_r $1/k_r$ c_r
1:η_c
$-1/k_s$ $-1/k_s$
η_c:1
m_r $1/k_r$ c_r
1:η_c
$-1/k_s$ $-1/k_s$
η_c:1
m_r $1/k_r$ c_r
η_e:1
C_o
$1/k_s$
$1/k_s$
C_o
1:η_b
η_b:1
$1/k_b$
$1/k_b$
$-1/k_b$
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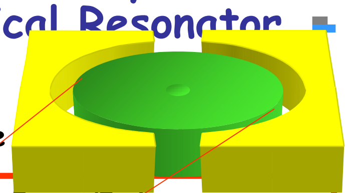
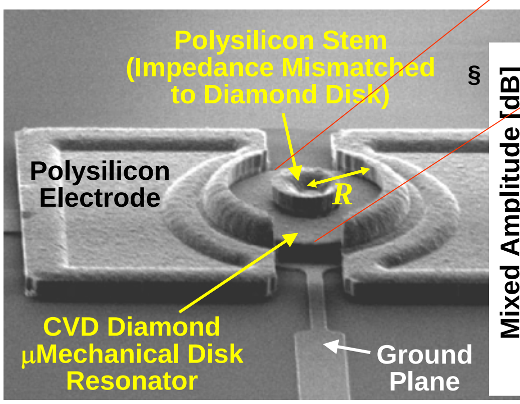
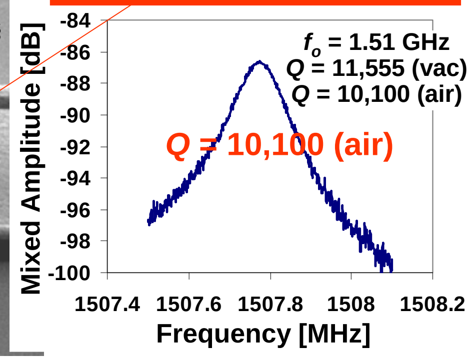
1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

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



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





[Wang, Butler, Nguyen MEMS'04]

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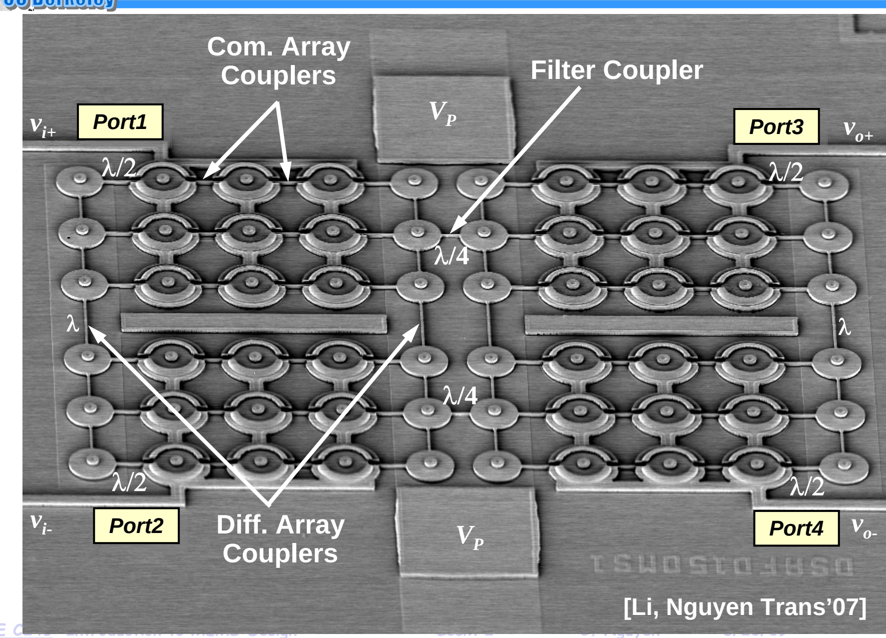
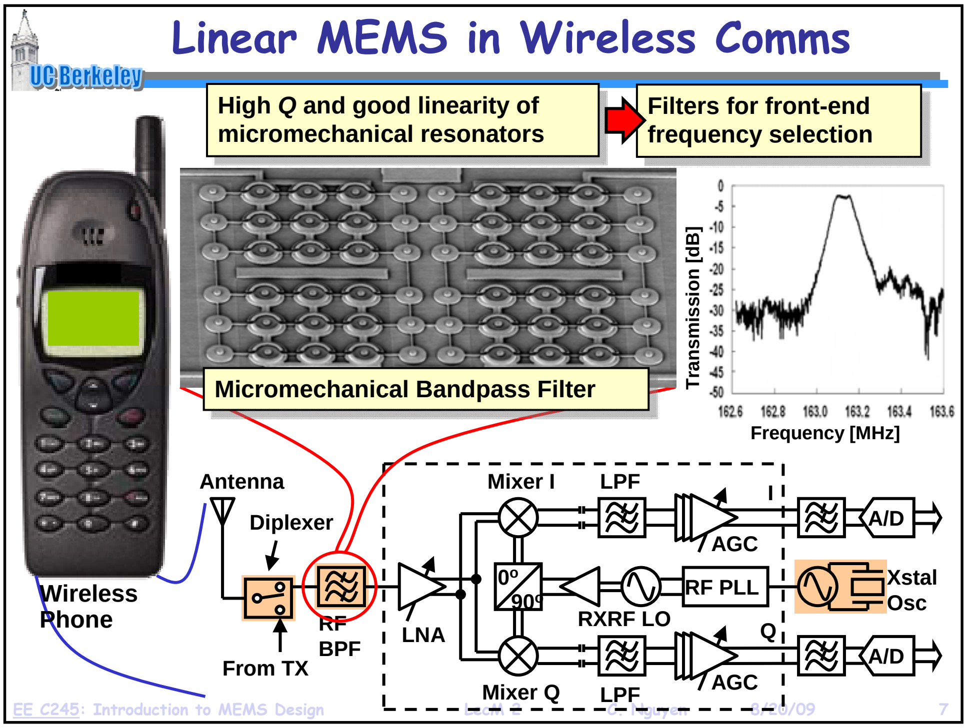
163-MHz Differential Disk-Array Filter



[Li, Nguyen Trans'07]


Linear MEMS in Wireless Comms
UC Berkeley
High Q and good linearity of micromechanical resonators
Filters for front-end frequency selection
Micromechanical Bandpass Filter
Transmission [dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
162.6
162.8
163.0
163.2
163.4
163.6
Frequency [MHz]
Antenna
Diplexer
Wireless Phone
RF BPF
From TX
LNA
Mixer I
LPF
AGC
I
A/D
0°
90°
RXRF LO
RF PLL
Xstal Osc
Q
Mixer Q
LPF
AGC
A/D
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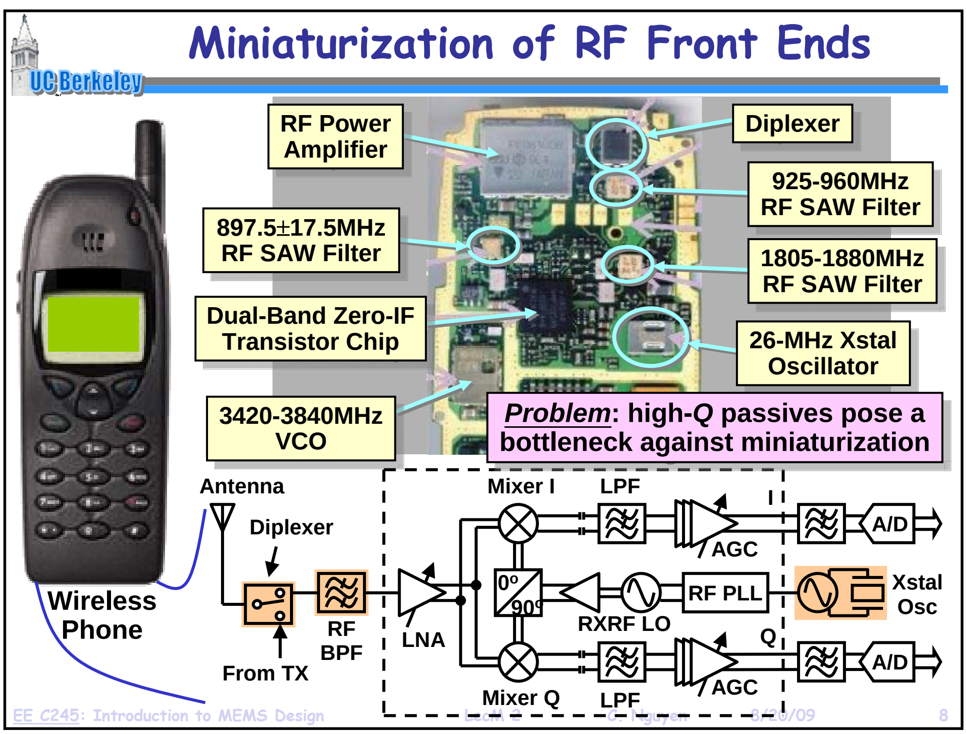
Miniaturization of RF Front Ends
UC Berkeley
RF Power Amplifier
Diplexer
925-960MHz RF SAW Filter
897.5±17.5MHz RF SAW Filter
1805-1880MHz RF SAW Filter
Dual-Band Zero-IF Transistor Chip
26-MHz Xstal Oscillator
3420-3840MHz VCO
Problem: high-Q passives pose a bottleneck against miniaturization
Antenna
Diplexer
Wireless Phone
RF BPF
From TX
LNA
Mixer I
LPF
AGC
I
A/D
0°
90°
RXRF LO
RF PLL
Xstal Osc
Q
Mixer Q
LPF
AGC
A/D
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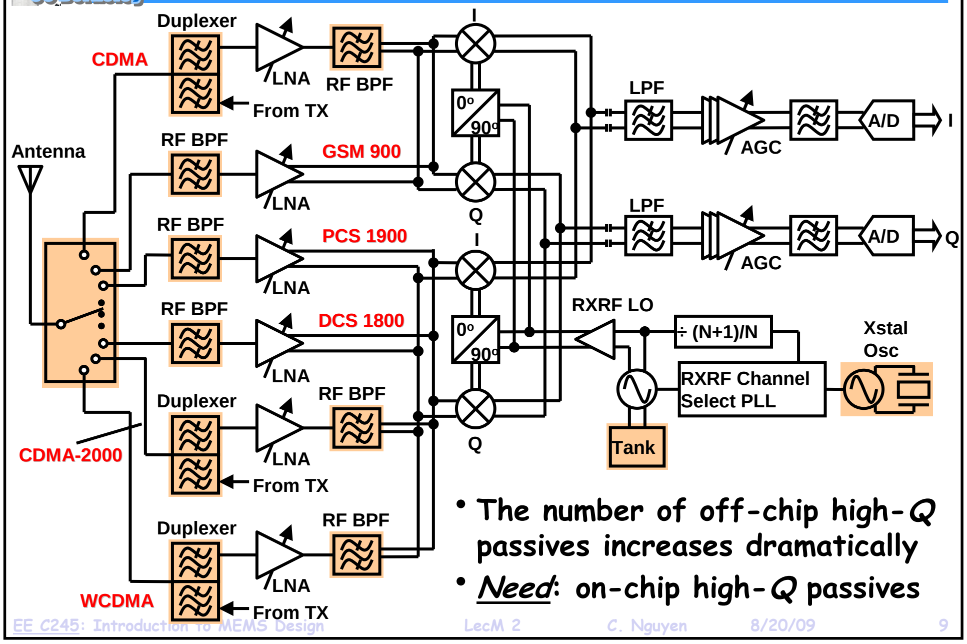
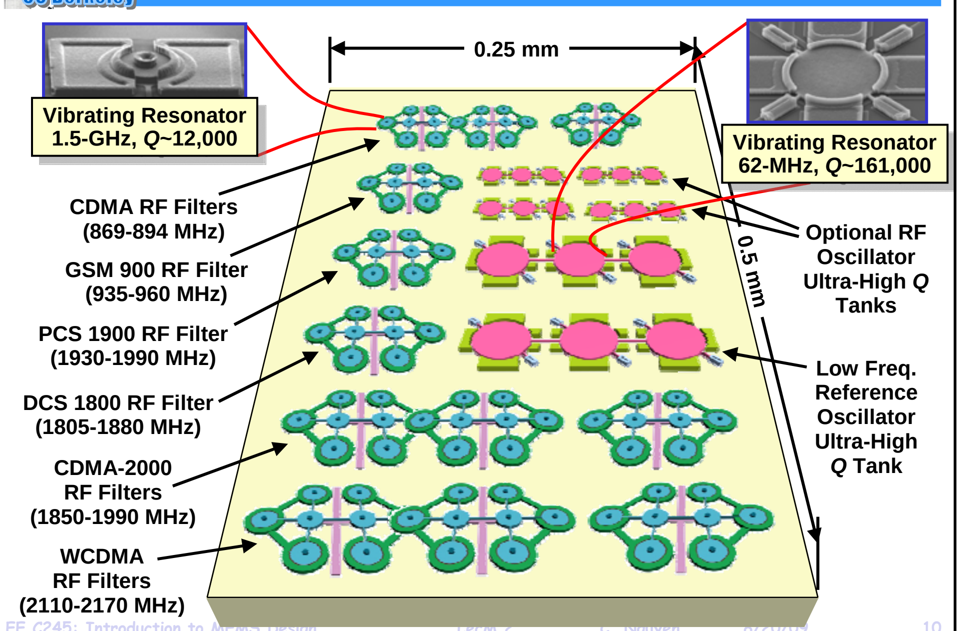
Multi-Band Wireless Handsets



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

All High-Q Passives on a Single Chip



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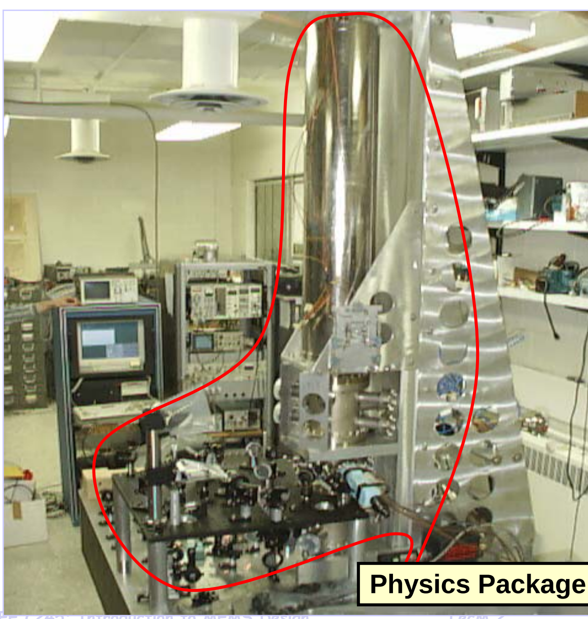
Chip-Scale Atomic Clocks (CSAC)

UC Berkeley

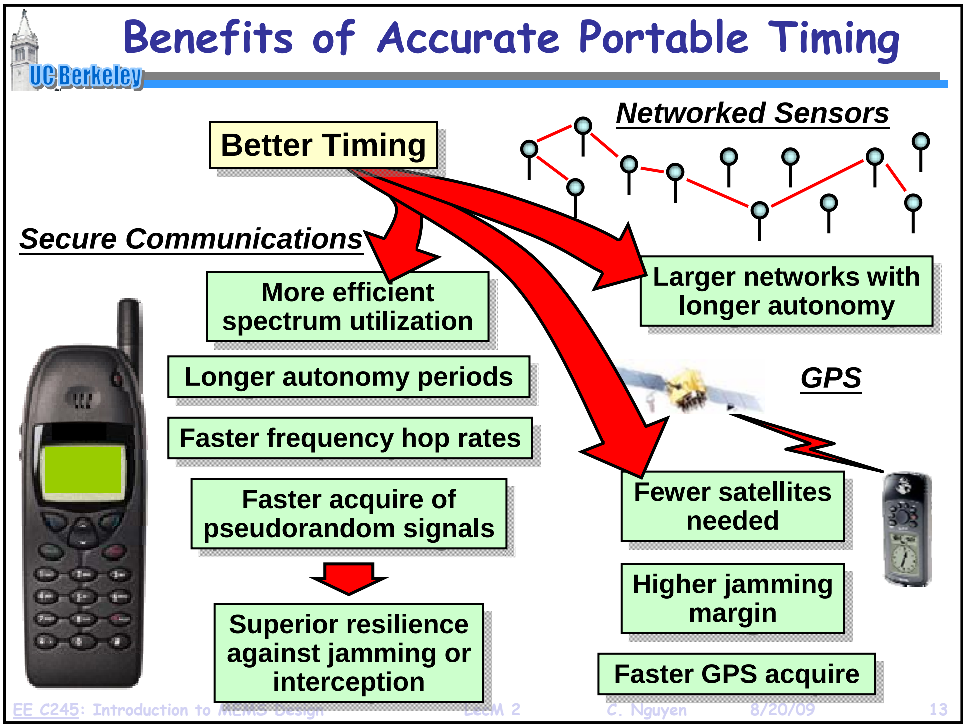
NIST F1 Fountain Atomic Clock



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

After 1 sec ⇨
Error: 10^{-15} sec

Loses 1 sec every 30 million years!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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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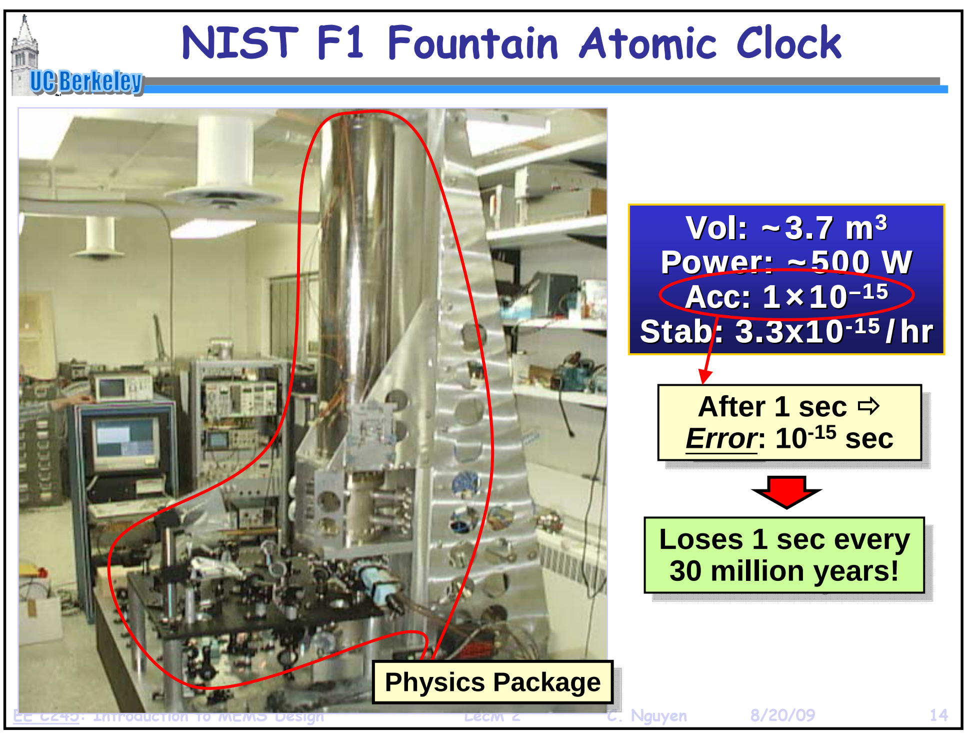
UC Berkeley
NIST F1 Fountain Atomic Clock
Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr
After 1 sec ⇨
Error: 10⁻¹⁵ sec
Loses 1 sec every 30 million years!
Physics Package
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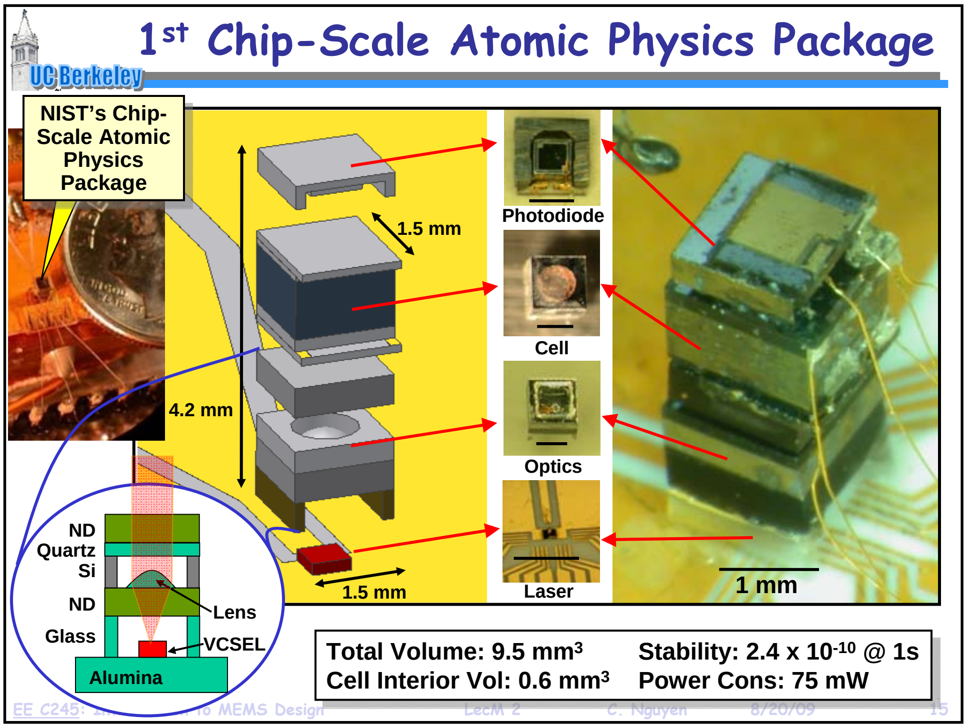
1st Chip-Scale Atomic Physics Package
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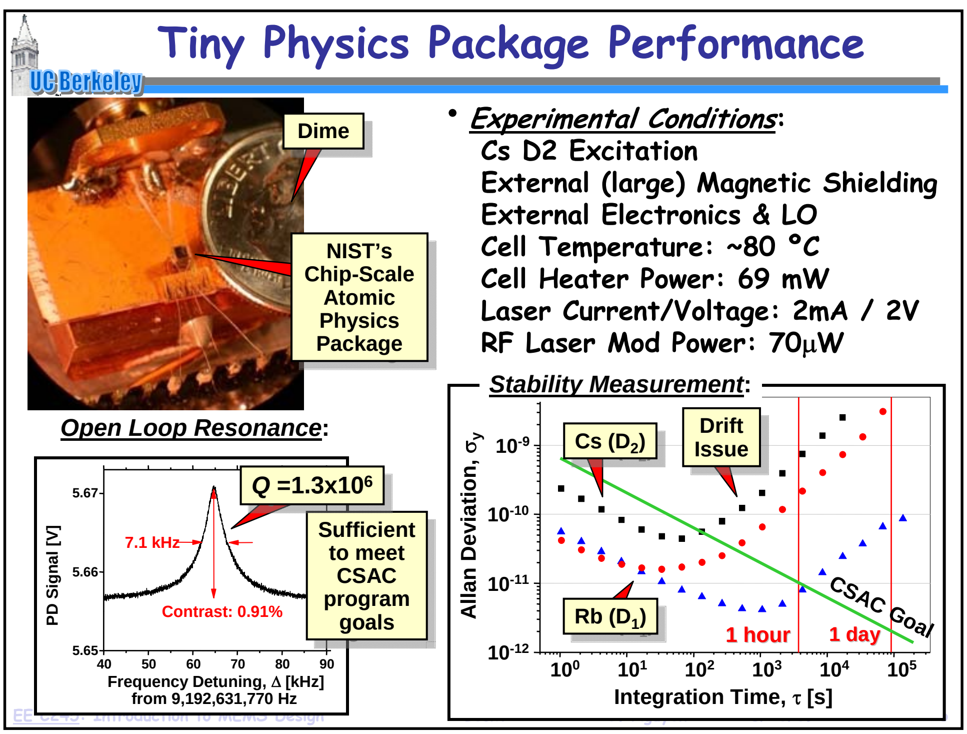
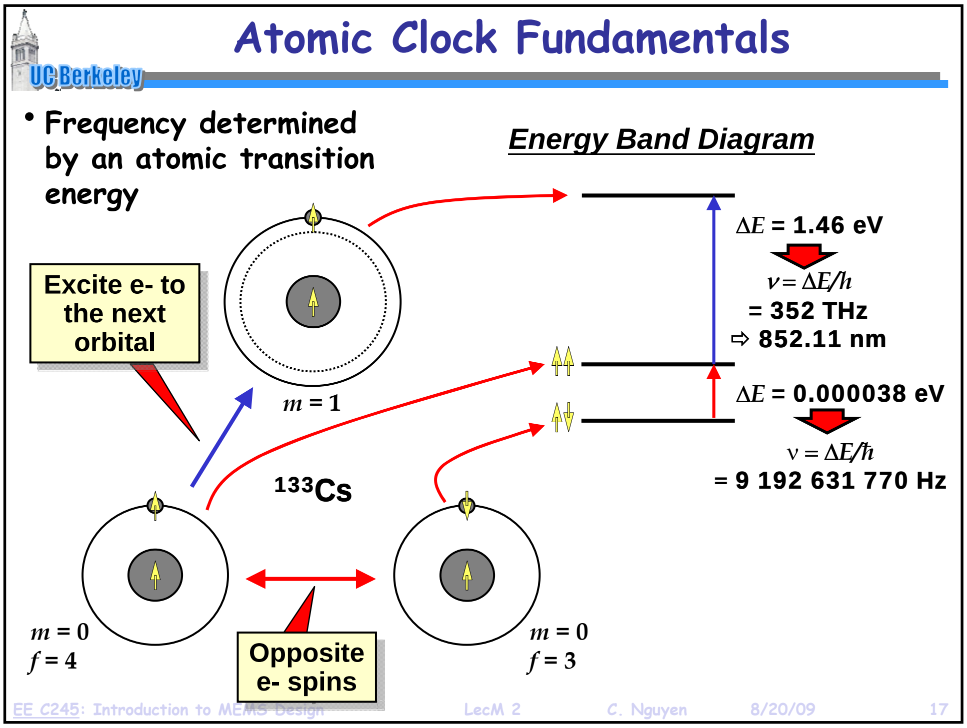
NIST's Chip-Scale Atomic Physics Package
1.5 mm
4.2 mm
1.5 mm
Photodiode
Cell
Optics
Laser
1 mm
ND
Quartz
Si
ND
Glass
Lens
VCSEL
Alumina
Total Volume: 9.5 mm³
Cell Interior Vol: 0.6 mm³
Stability: 2.4 x 10-10 @ 1s
Power Cons: 75 mW


Tiny Physics Package Performance
UC Berkeley
Dime
NIST's Chip-Scale Atomic Physics Package
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:
Q =1.3x10⁶
7.1 kHz
Contrast: 0.91%
PD Signal [V]
Frequency Detuning, Δ [kHz]
from 9,192,631,770 Hz
Sufficient to meet CSAC program goals
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
m = 1
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 = 0
f = 4
Opposite e- spins
m = 0
f = 3
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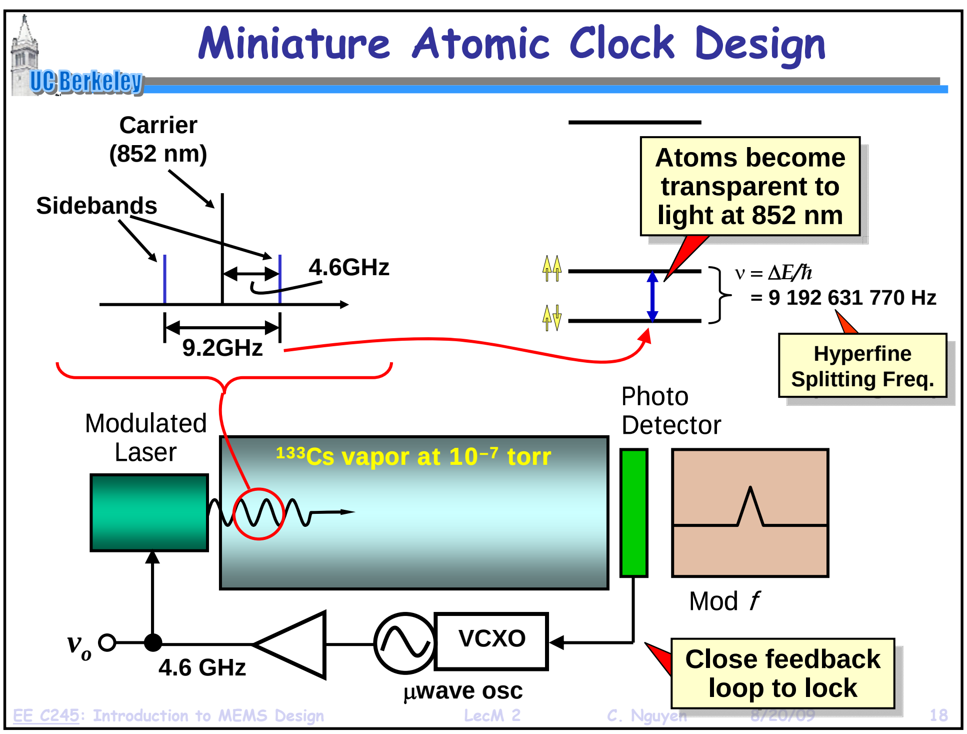
Miniature Atomic Clock Design
UC Berkeley
Carrier
(852 nm)
Sidebands
4.6GHz
9.2GHz
Atoms become transparent to light at 852 nm
ν = ΔE/ħ
= 9 192 631 770 Hz
Hyperfine Splitting Freq.
Modulated Laser
133Cs vapor at 10−7 torr
Photo Detector
Mod f
v_o
4.6 GHz
VCXO
μwave osc
Close feedback loop to lock
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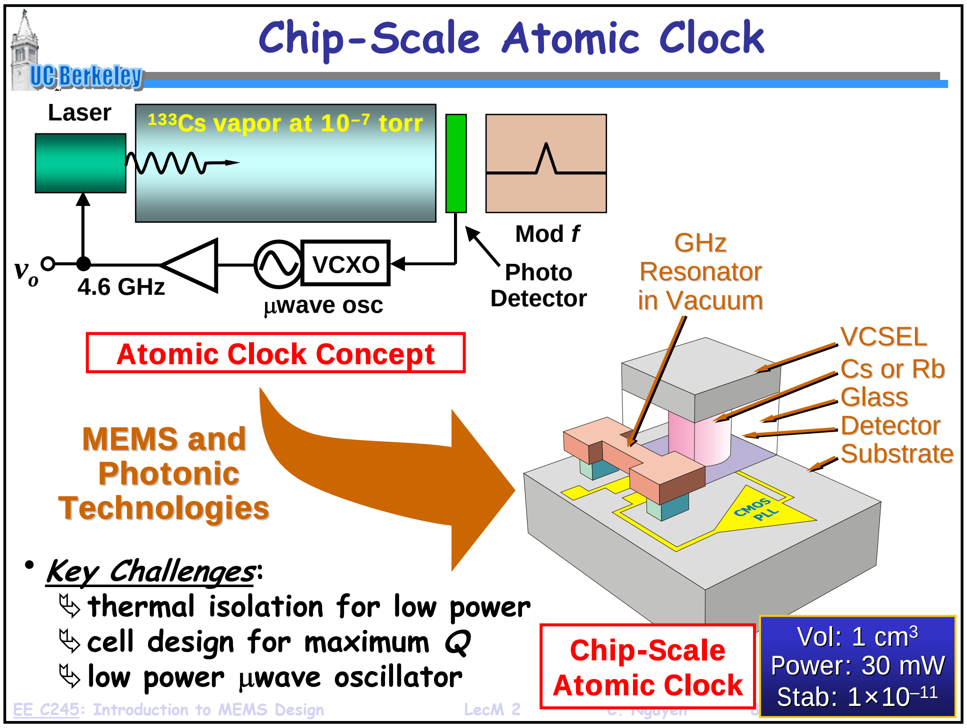
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
VCXO
μwave osc
4.6 GHz
vo
Atomic Clock Concept
GHz Resonator in Vacuum
VCSEL
Cs or Rb
Glass
Detector
Substrate
CMOS PLL
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design 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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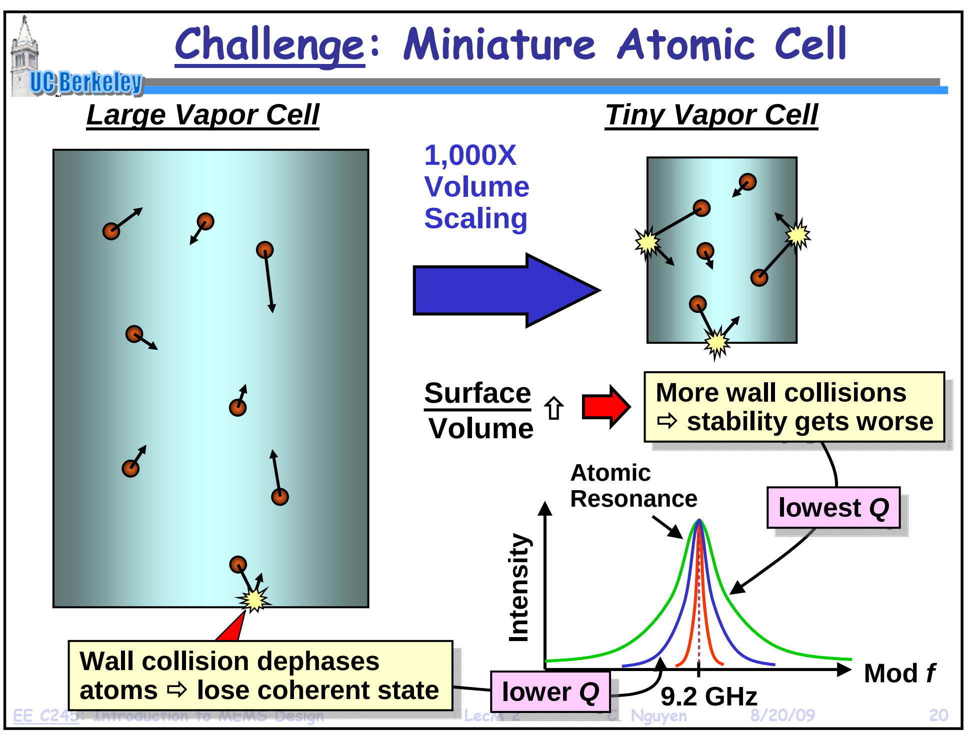
Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Surface / Volume ⇧
More wall collisions ⇨ stability gets worse
Atomic Resonance
lowest Q
Intensity
Mod f
9.2 GHz
lower Q
Wall collision dephases atoms ⇨ lose coherent state
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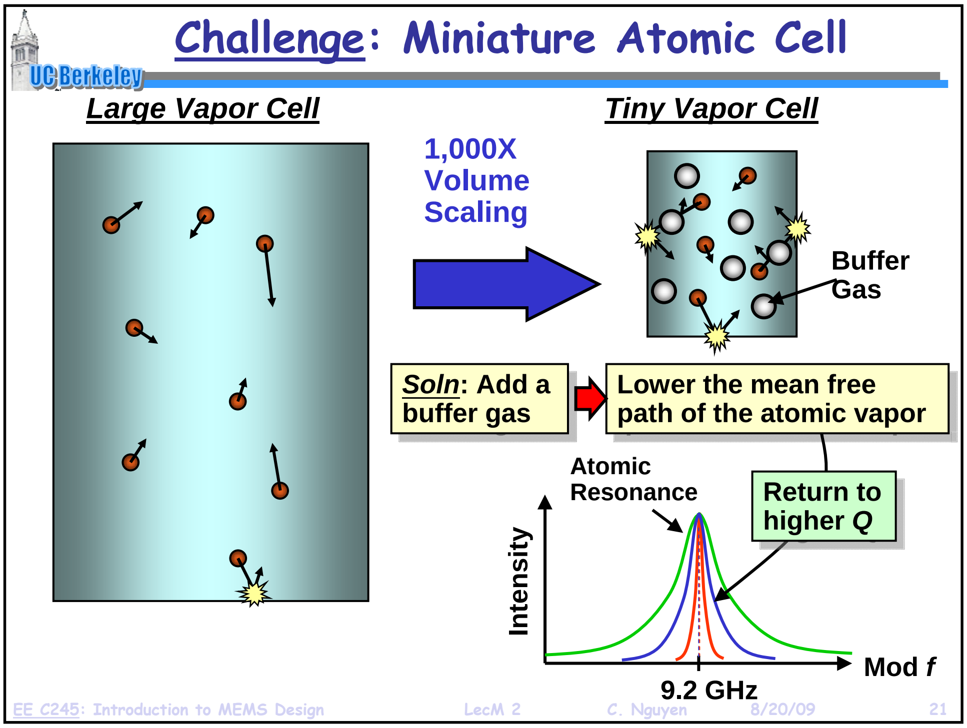
Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Buffer Gas
Soln: Add a buffer gas
Lower the mean free path of the atomic vapor
Atomic Resonance
Return to higher Q
Intensity
Mod f
9.2 GHz
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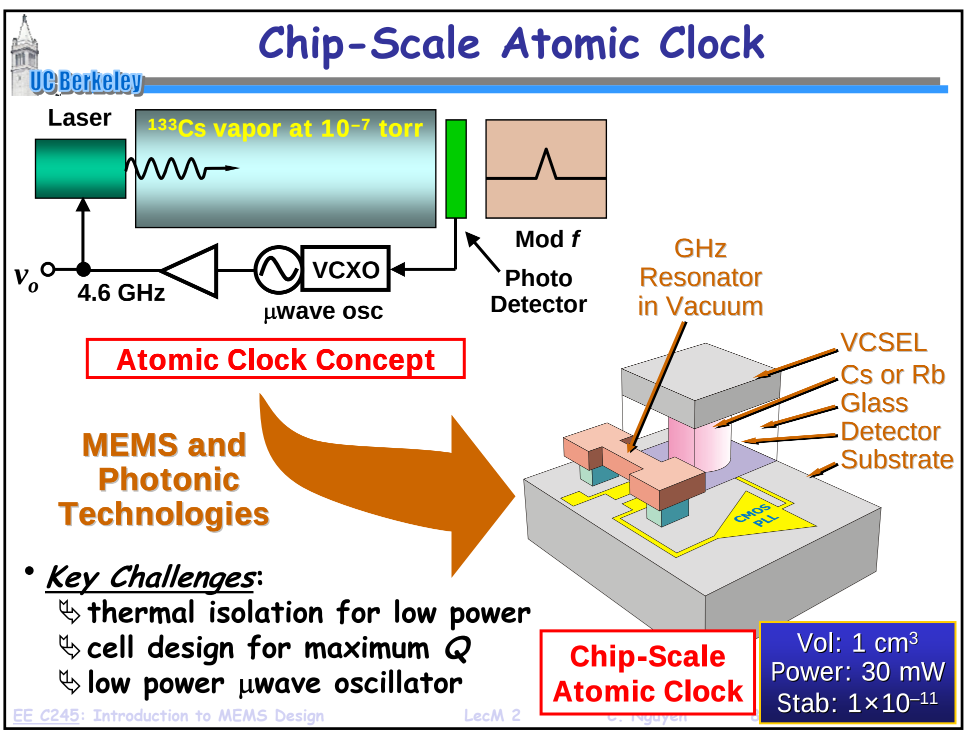
Chip-Scale Atomic Clock
UC Berkeley
Laser
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µwave osc
GHz Resonator in Vacuum
Atomic Clock Concept
VCSEL
Cs or Rb
Glass
Detector
Substrate
CMOS PLL
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power µwave oscillator
Chip-Scale Atomic Clock
Vol: 1 cm3
Power: 30 mW
Stab: 1×10−11
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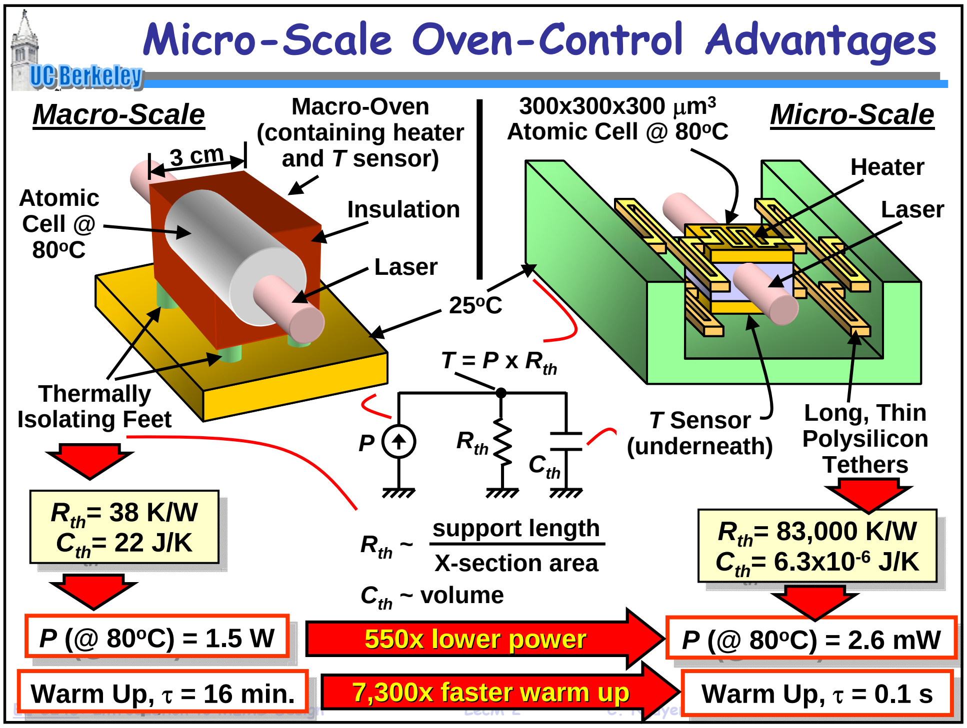
Micro-Scale Oven-Control Advantages
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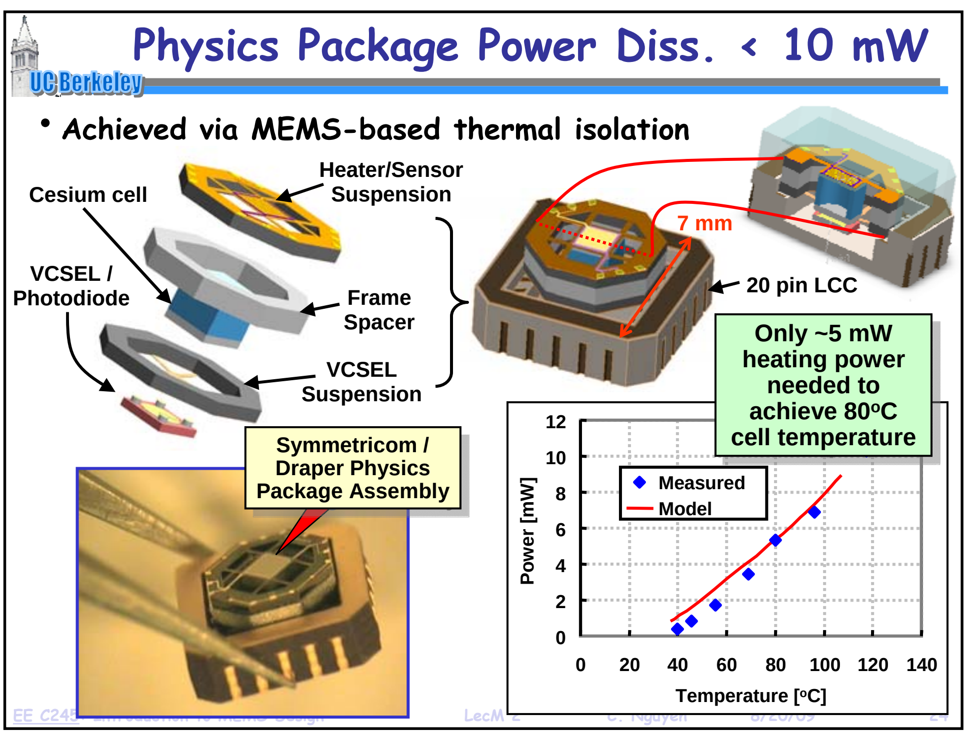
Macro-Scale
Macro-Oven (containing heater and T sensor)
3 cm
Atomic Cell @ 80°C
Insulation
Laser
25°C
Thermally Isolating Feet
300x300x300 μm³ Atomic Cell @ 80°C
Micro-Scale
Heater
Laser
T = P x R_th
P
R_th
C_th
T Sensor (underneath)
Long, Thin Polysilicon Tethers
R_th= 38 K/W
C_th= 22 J/K
R_th ~ support length / X-section area
C_th ~ volume
R_th= 83,000 K/W
C_th= 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 s


Physics Package Power Diss. < 10 mW
UC Berkeley
• Achieved via MEMS-based thermal isolation
Cesium cell
Heater/Sensor Suspension
VCSEL / Photodiode
Frame Spacer
VCSEL Suspension
7 mm
20 pin LCC
Only ~5 mW heating power needed to achieve 80°C cell temperature
Symmetricom / Draper Physics Package Assembly
Measured
Model
Power [mW]
Temperature [°C]
0
2
4
6
8
10
12
20
40
60
80
100
120
140