# EE C245 - ME C218
# Introduction to MEMS Design
# Fall 2010

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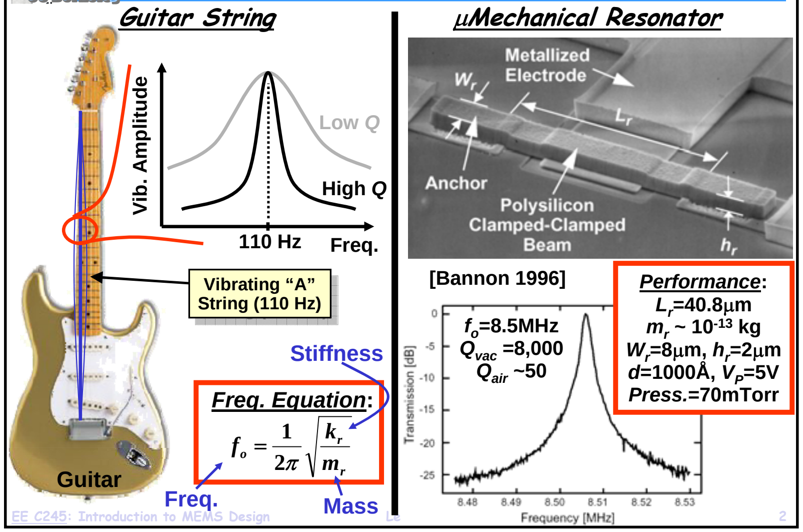
Lecture Module 2: Benefits of Scaling



## Basic Concept: Scaling Guitar Strings




**Freq. Equation:**

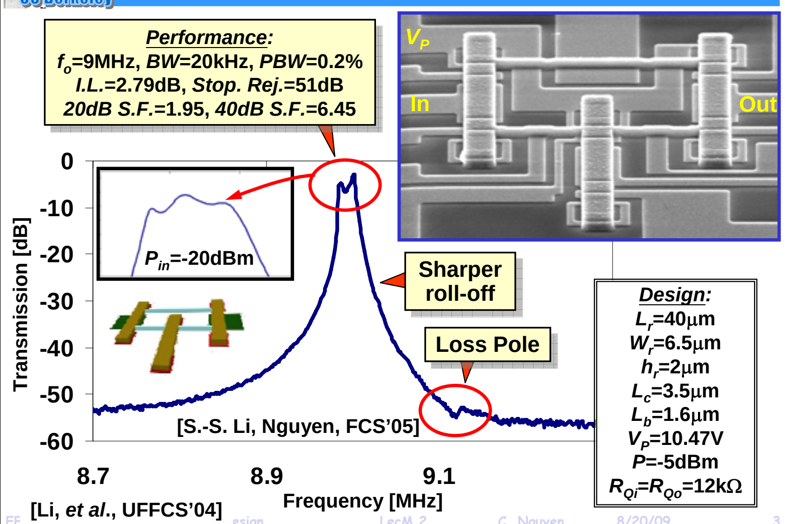
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

**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

**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

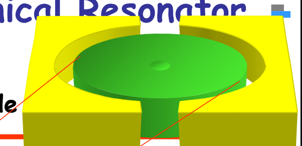



**Design:**
$L_r$=40μm
$W_r$=6.5μm
$h_r$=2μm
$L_c$=3.5μm
$L_b$=1.6μm
$V_P$=10.47V
P=-5dBm
$R_{Qi}$=$R_{Qo}$=12kΩ

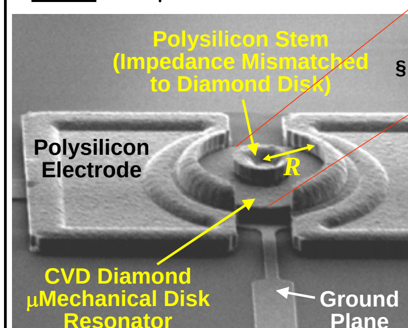


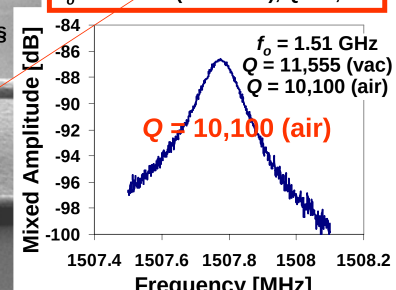
## 1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- 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



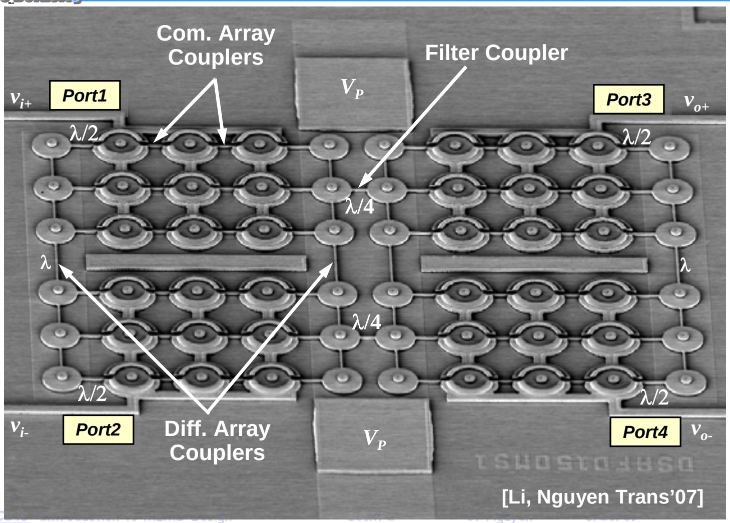
**Design/Performance:**
R=10μm, t=2.2μm, d=800Å, $V_P$=7V
$f_o$=1.51 GHz (2nd mode), Q=11,555



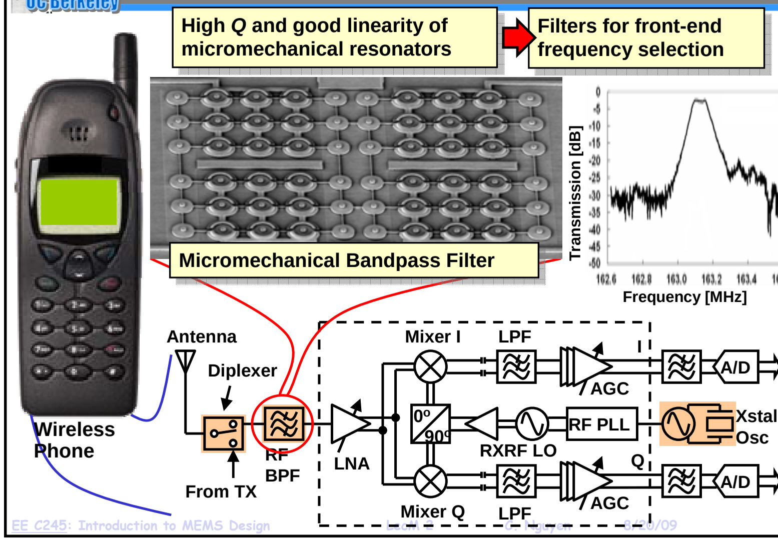

[Wang, Butler, Nguyen MEMS'04]

## 163-MHz Differential Disk-Array Filter



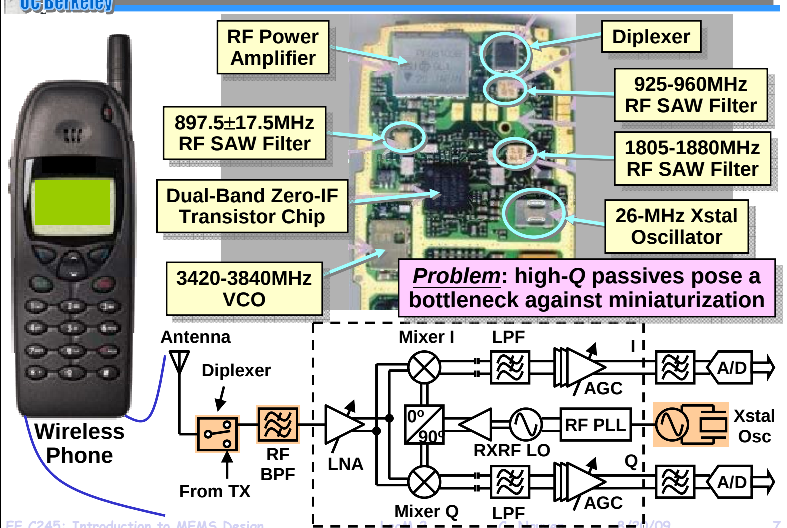



## Linear MEMS in Wireless Comms



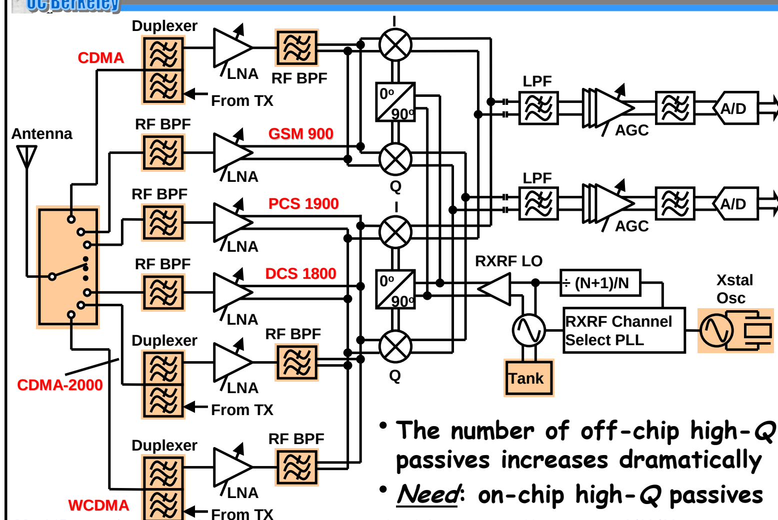



## Miniaturization of RF Front Ends






## 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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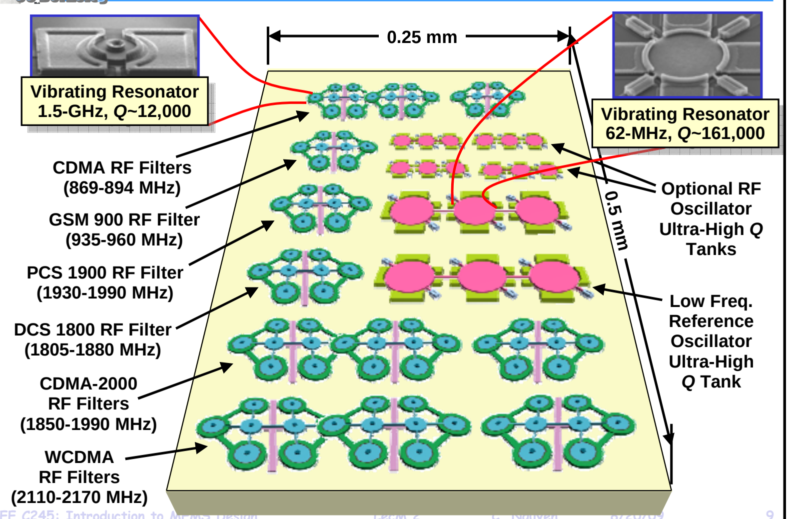




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## Chip-Scale Atomic Clocks (CSAC)



## NIST F1 Fountain Atomic Clock

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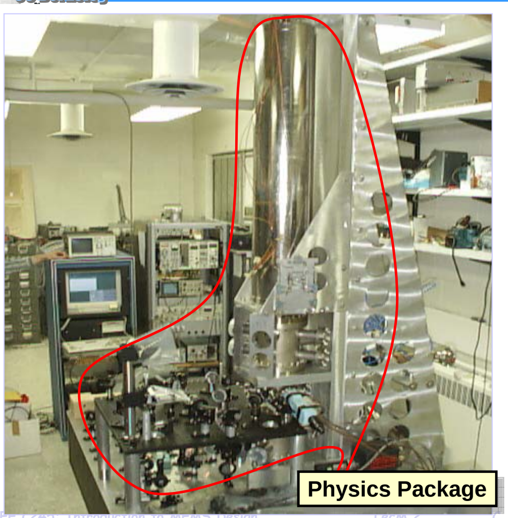


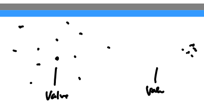

Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

After 1 sec ⇨
*Error*: 10⁻¹⁵ sec

Loses 1 sec every 30 million years!



## Benefits of Accurate Portable Timing

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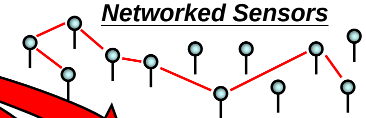
Better Timing

*Secure Communications*

- More efficient spectrum utilization
- Longer autonomy periods
- Faster frequency hop rates
- Faster acquire of pseudorandom signals

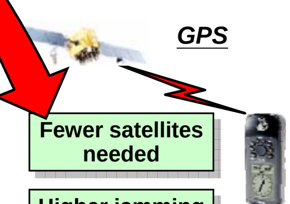
Superior resilience against jamming or interception

*Networked Sensors*



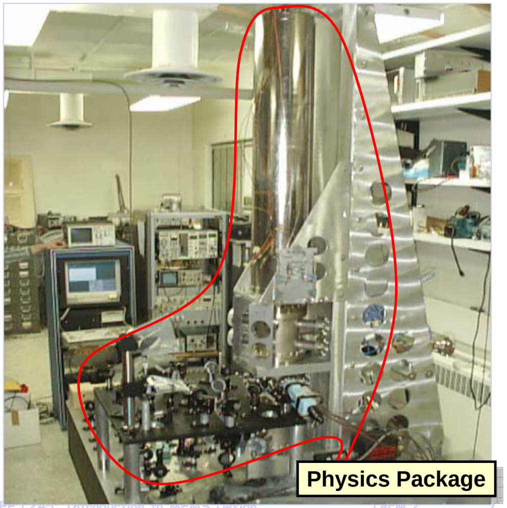
Larger networks with longer autonomy

*GPS*



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

## NIST F1 Fountain Atomic Clock



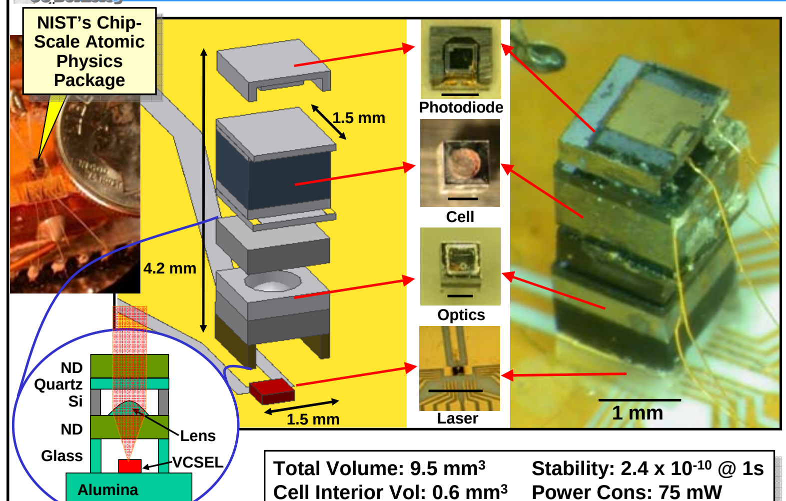

Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

After 1 sec ⇨ *Error*: $10^{-15}$ sec

Loses 1 sec every 30 million years!



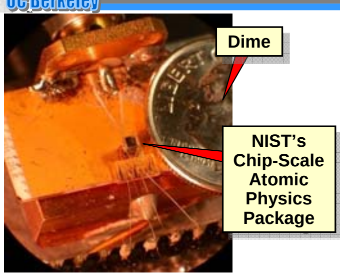
## 1st Chip-Scale Atomic Physics Package



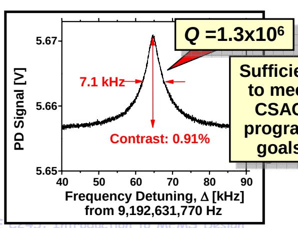

Total Volume: 9.5 mm³ Stability: 2.4 x $10^{-10}$ @ 1s
Cell Interior Vol: 0.6 mm³ Power Cons: 75 mW



## Tiny Physics Package Performance

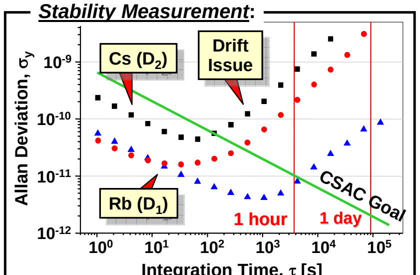



*Open Loop Resonance*:




- *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*:

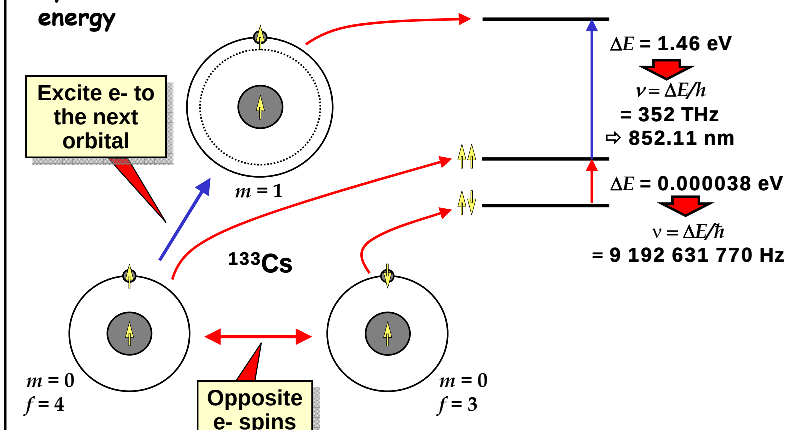


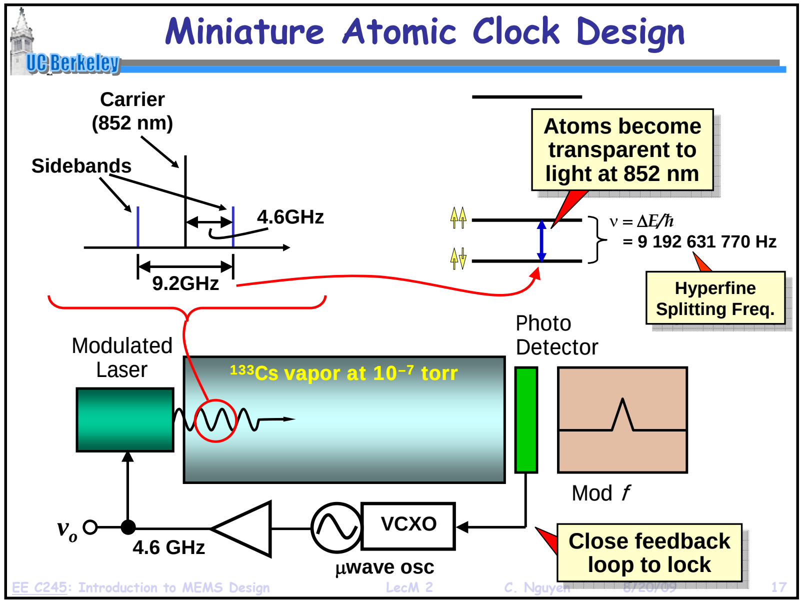



## Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

*Energy Band Diagram*




Miniature Atomic Clock Design
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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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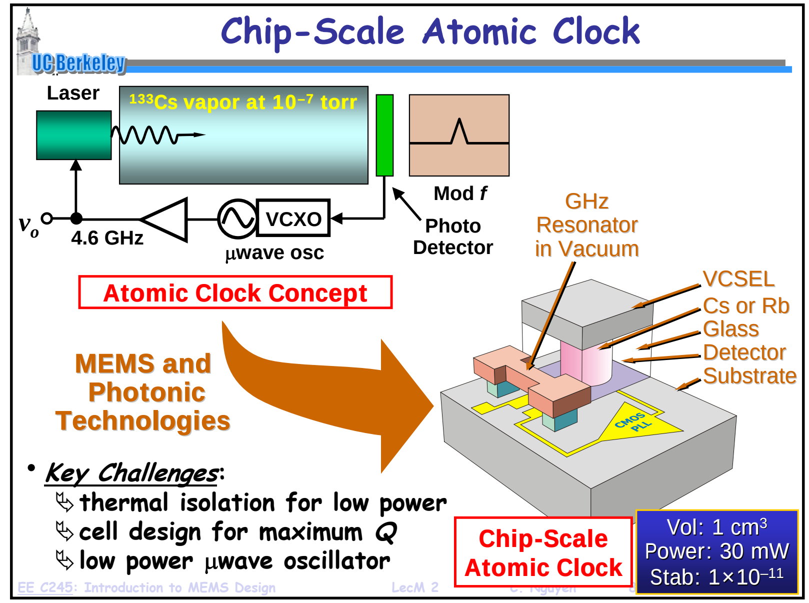
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
v_o
4.6 GHz
VCXO
μwave osc
Atomic Clock Concept
GHz Resonator in Vacuum
VCSEL
Cs or Rb
Glass
Detector
Substrate
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power μwave oscillator
Chip-Scale Atomic Clock
Vol: 1 cm³
Power: 30 mW
Stab: 1×10−11
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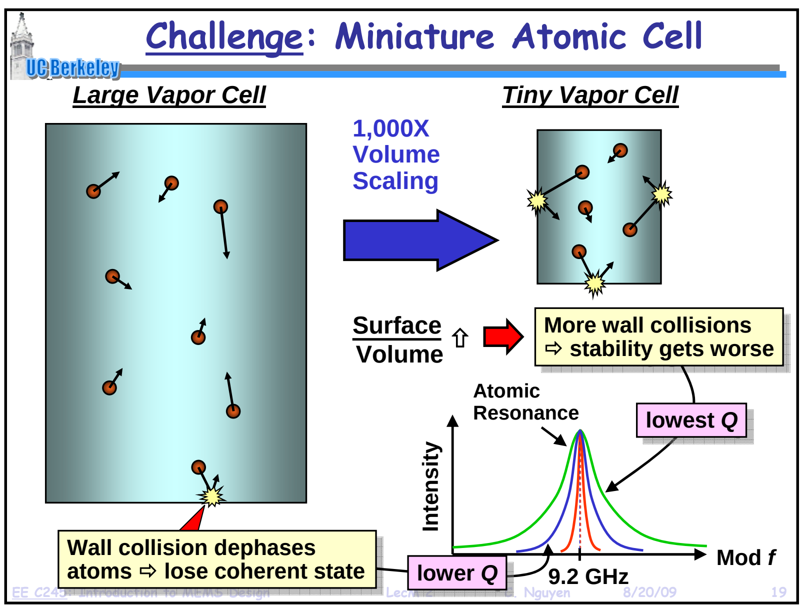
Challenge: Miniature Atomic Cell
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Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Surface / Volume ⇧
More wall collisions ⇨ stability gets worse
Atomic Resonance
lowest Q
Intensity
Mod f
9.2 GHz
Wall collision dephases atoms ⇨ lose coherent state
lower Q
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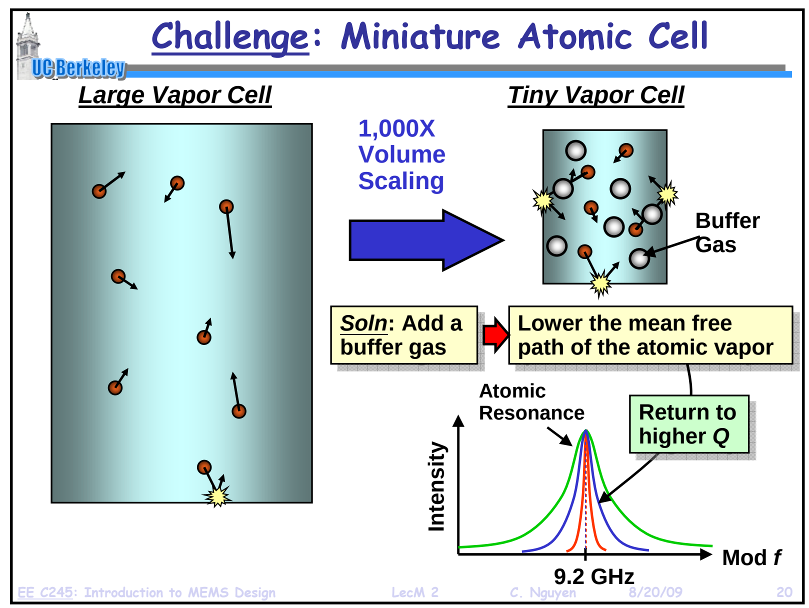
Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Buffer Gas
Soln: Add a buffer gas
Lower the mean free path of the atomic vapor
Atomic Resonance
Return to higher Q
Intensity
Mod f
9.2 GHz
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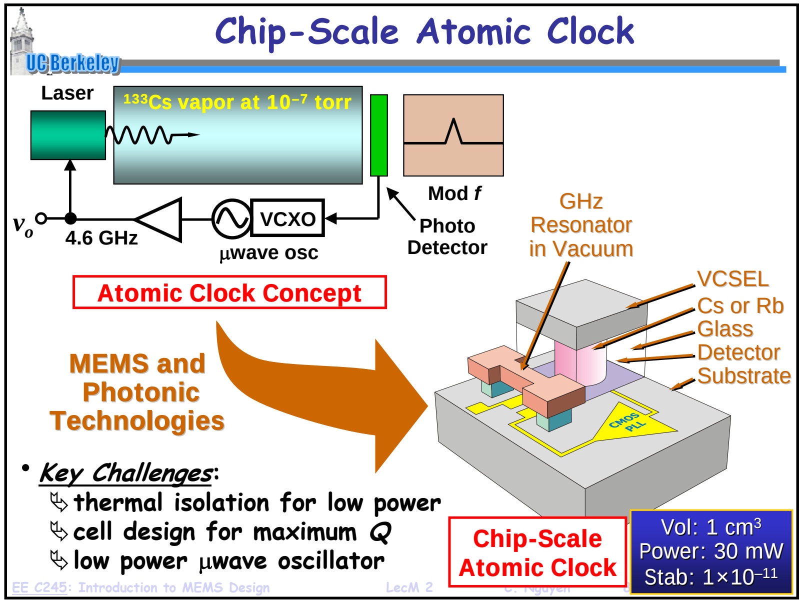
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
vo
4.6 GHz
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GHz Resonator in Vacuum
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Cs or Rb
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MEMS and Photonic 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
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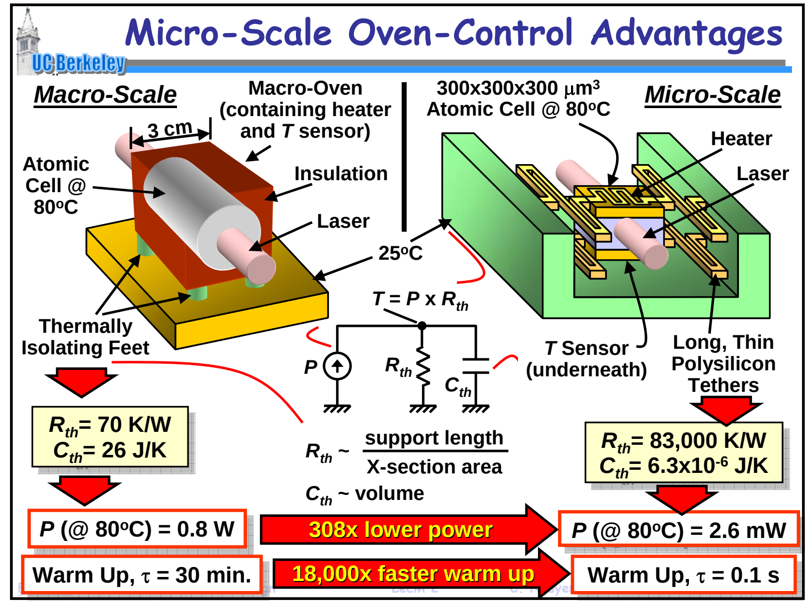
Micro-Scale Oven-Control Advantages
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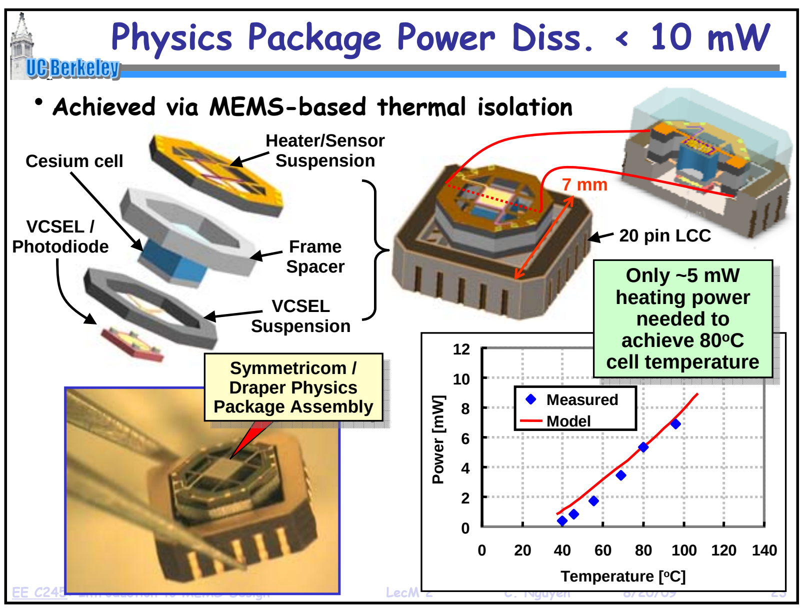
Macro-Scale
Macro-Oven (containing heater and T sensor)
300x300x300 μm3 Atomic Cell @ 80oC
Micro-Scale
3 cm
Atomic Cell @ 80oC
Insulation
Laser
25oC
Heater
Laser
Thermally Isolating Feet
T = P x Rth
P
Rth
Cth
T Sensor (underneath)
Long, Thin Polysilicon Tethers
Rth= 70 K/W
Cth= 26 J/K
Rth ~ support length / X-section area
Cth ~ volume
Rth= 83,000 K/W
Cth= 6.3x10-6 J/K
P (@ 80oC) = 0.8 W
308x lower power
P (@ 80oC) = 2.6 mW
Warm Up, τ = 30 min.
18,000x faster warm up
Warm Up, τ = 0.1 s


Physics Package Power Diss. < 10 mW
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• 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 80oC cell temperature
Symmetricom / Draper Physics Package Assembly
Measured
Model
Power [mW]
Temperature [oC]
0 2 4 6 8 10 12
0 20 40 60 80 100 120 140