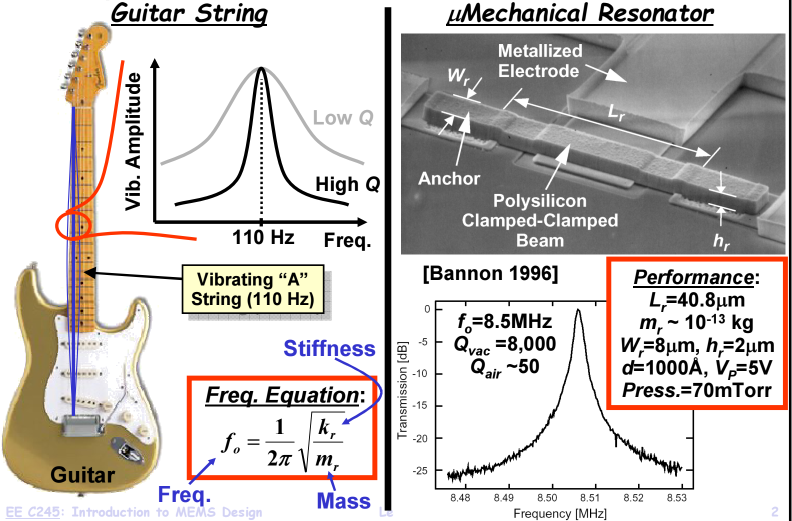
# EE C247B - ME C218
# Introduction to MEMS Design
# Spring 2015

Prof. Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Sciences
University of California at Berkeley
Berkeley, CA 94720

Lecture Module 2: Benefits of Scaling

## Basic Concept: Scaling Guitar Strings



**Freq. Equation:**

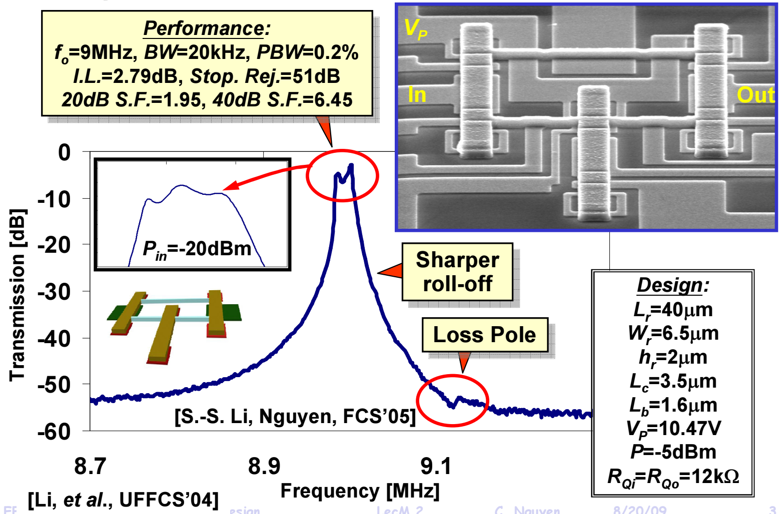
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

[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

## 3CC 3λ/4 Bridged µMechanical Filter



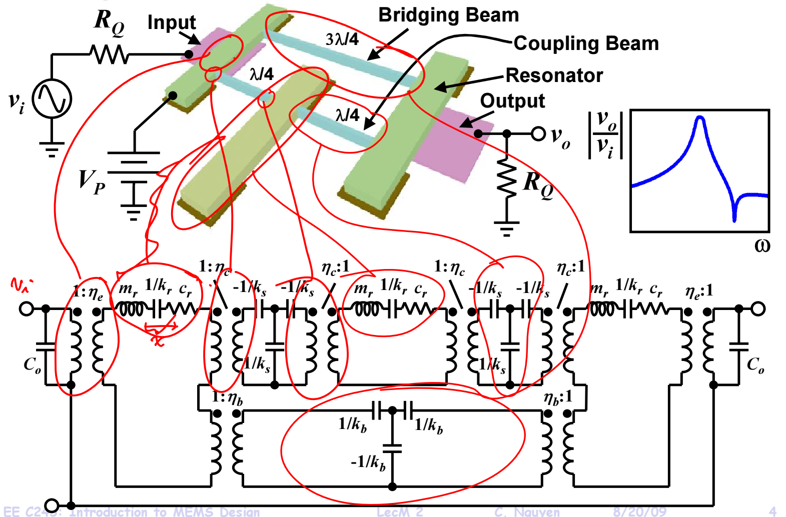
**Performance:**
$f_o$=9MHz, $BW$=20kHz, $PBW$=0.2%
$I.L.$=2.79dB, $Stop.\ Rej.$=51dB
$20dB\ S.F.$=1.95, $40dB\ S.F.$=6.45

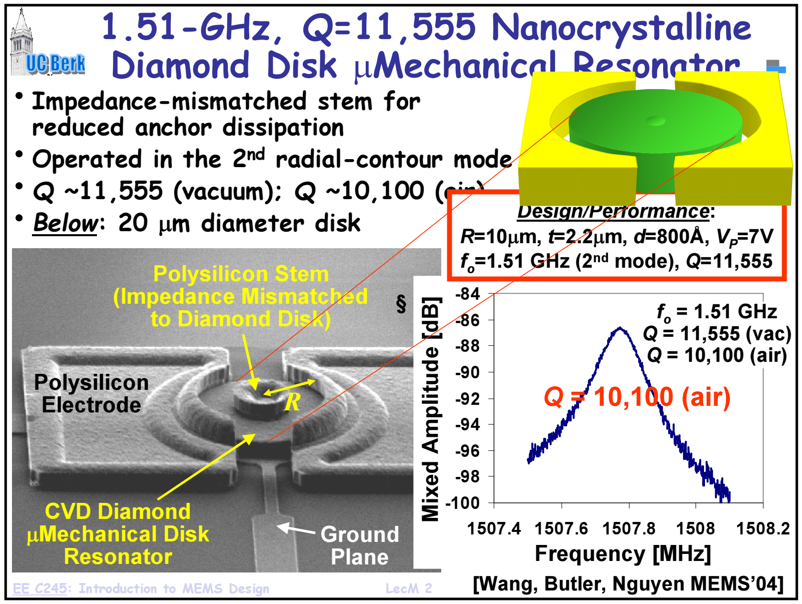
[S.-S. Li, Nguyen, FCS'05]

**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

[Li, *et al.*, UFFCS'04]

## Micromechanical Filter Circuit



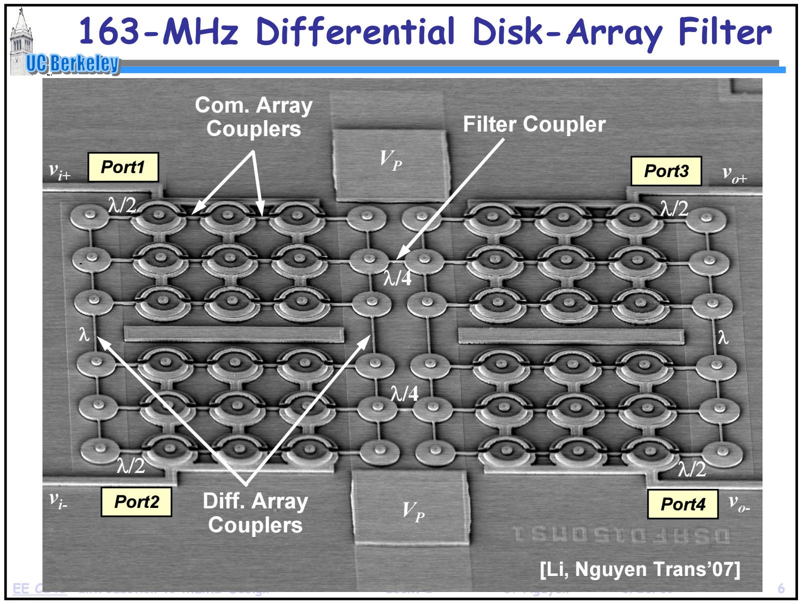


## 1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- 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

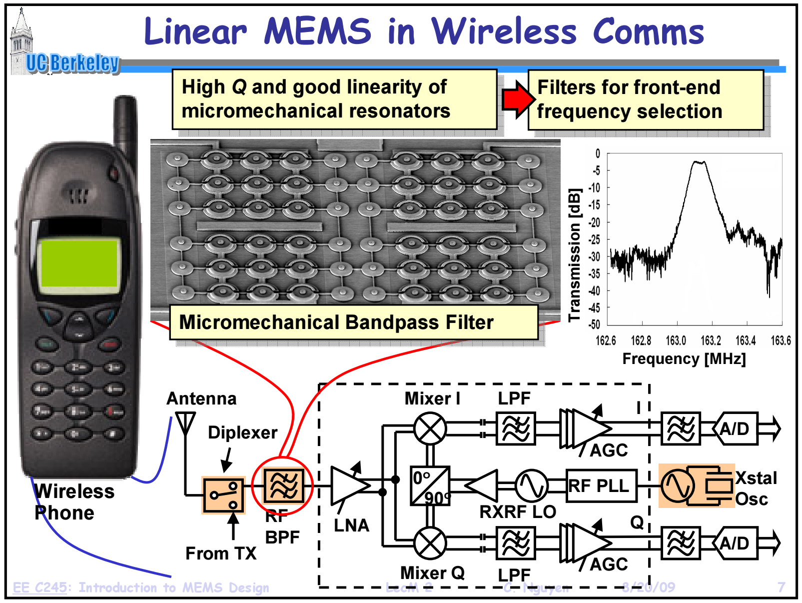
**Design/Performance**: $R$=10μm, $t$=2.2μm, $d$=800Å, $V_P$=7V, $f_o$=1.51 GHz (2nd mode), $Q$=11,555

[Wang, Butler, Nguyen MEMS'04]



## 163-MHz Differential Disk-Array Filter

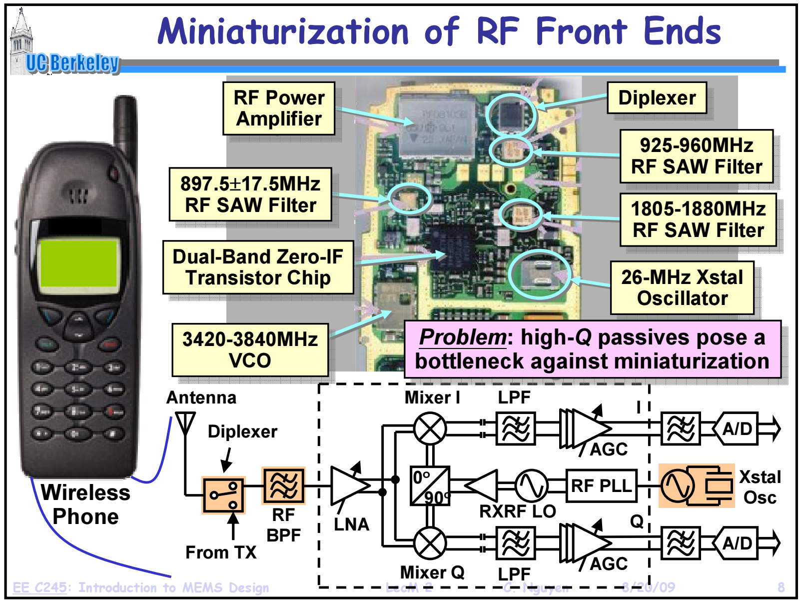
[Li, Nguyen Trans'07]



## Linear MEMS in Wireless Comms

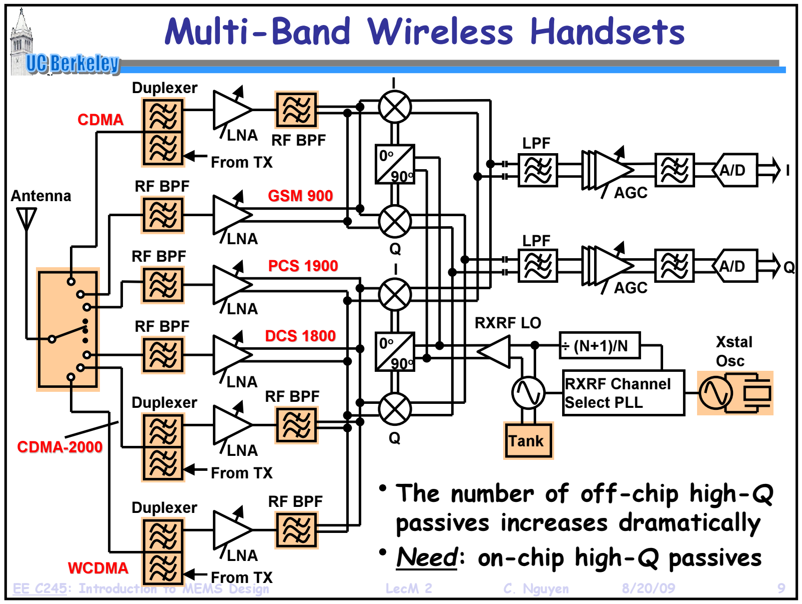
High $Q$ and good linearity of micromechanical resonators → Filters for front-end frequency selection

Micromechanical Bandpass Filter



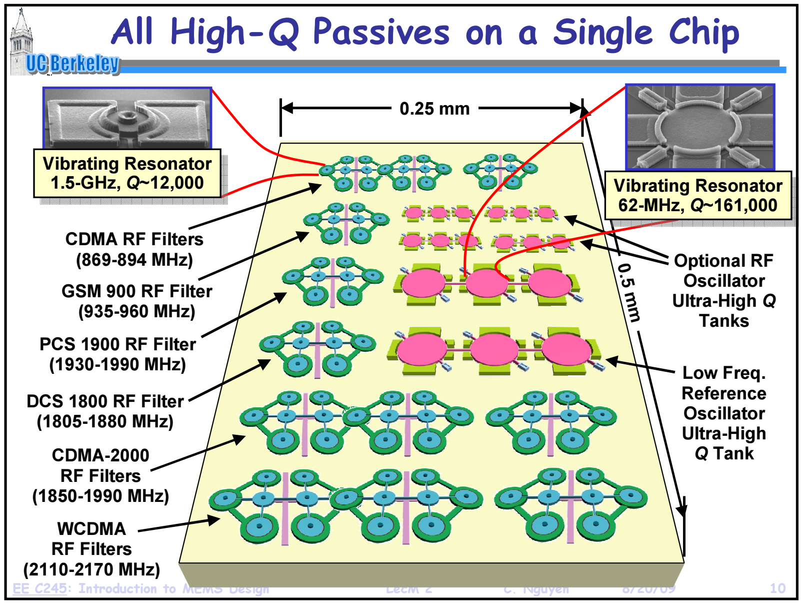
## Miniaturization of RF Front Ends

***Problem***: high-Q passives pose a bottleneck against miniaturization



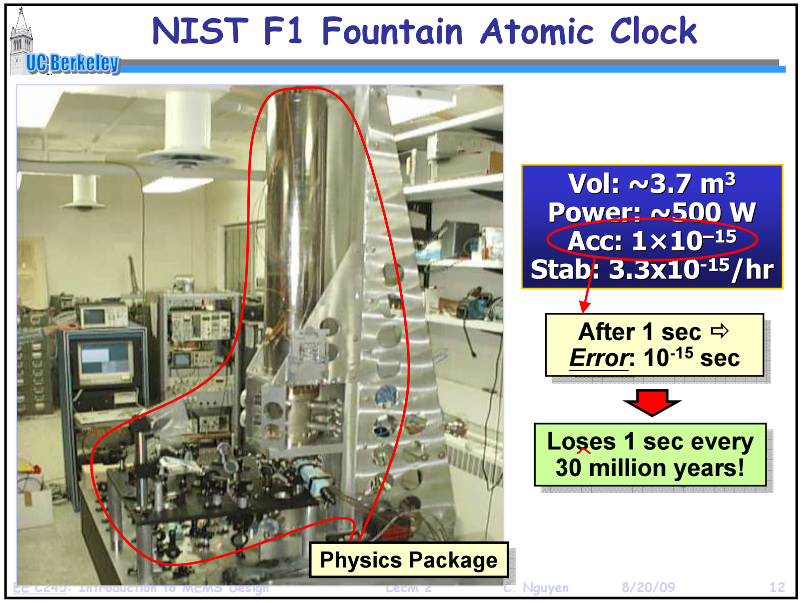
## Multi-Band Wireless Handsets

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



## All High-Q Passives on a Single Chip

## Chip-Scale Atomic Clocks (CSAC)



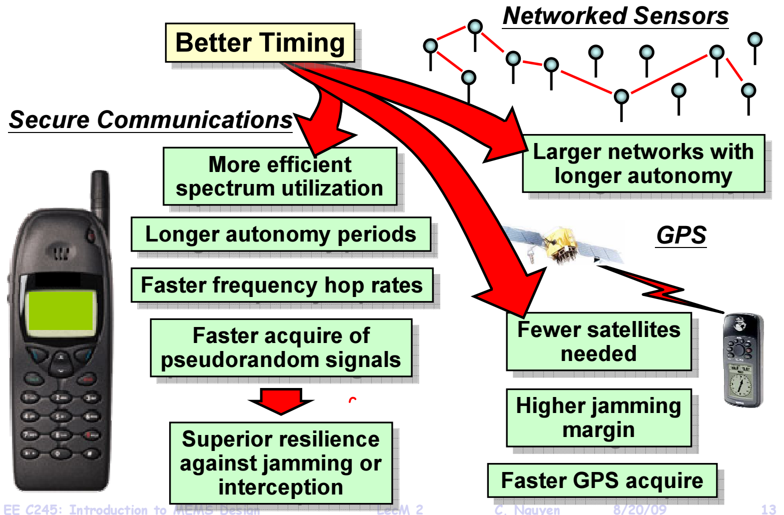
## NIST F1 Fountain Atomic Clock

Vol: ~3.7 $m^3$
Power: ~500 W
Acc: $1\times10^{-15}$
Stab: $3.3\times10^{-15}$/hr

After 1 sec ⇨ *Error*: $10^{-15}$ sec

Loses 1 sec every 30 million years!

## Benefits of Accurate Portable Timing



**Better Timing**

More efficient spectrum utilization

Longer autonomy periods

Faster frequency hop rates

Faster acquire of pseudorandom signals

Superior resilience against jamming or interception

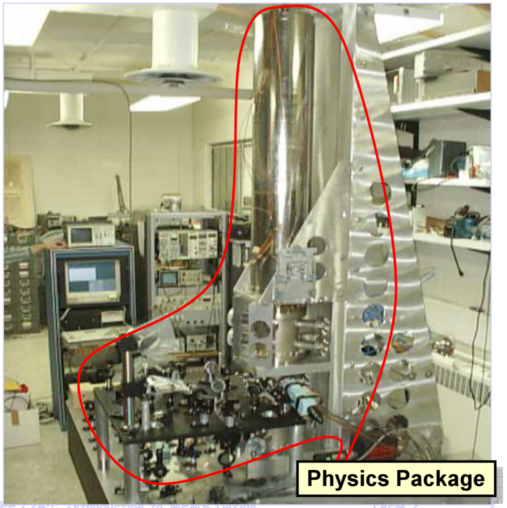
Larger networks with longer autonomy

Fewer satellites needed

Higher jamming margin

Faster GPS acquire

## NIST F1 Fountain Atomic Clock

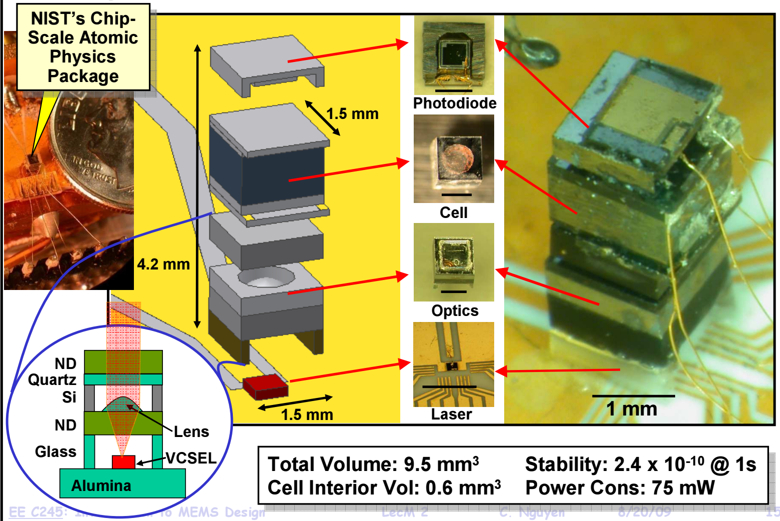


**Vol: ~3.7 m$^3$**
**Power: ~500 W**
**Acc: 1×10$^{-15}$**
**Stab: 3.3x10$^{-15}$/hr**

After 1 sec ⇨ *Error*: 10$^{-15}$ sec

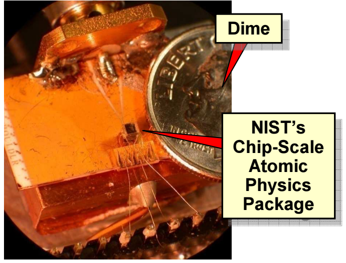
Loses 1 sec every 30 million years!

## 1st Chip-Scale Atomic Physics Package



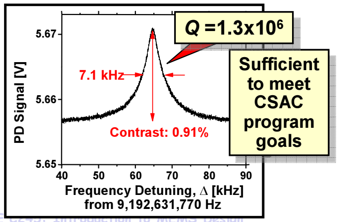
Total Volume: 9.5 mm$^3$
Cell Interior Vol: 0.6 mm$^3$
Stability: 2.4 x 10$^{-10}$ @ 1s
Power Cons: 75 mW

## Tiny Physics Package Performance

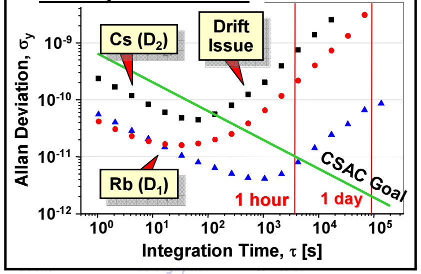


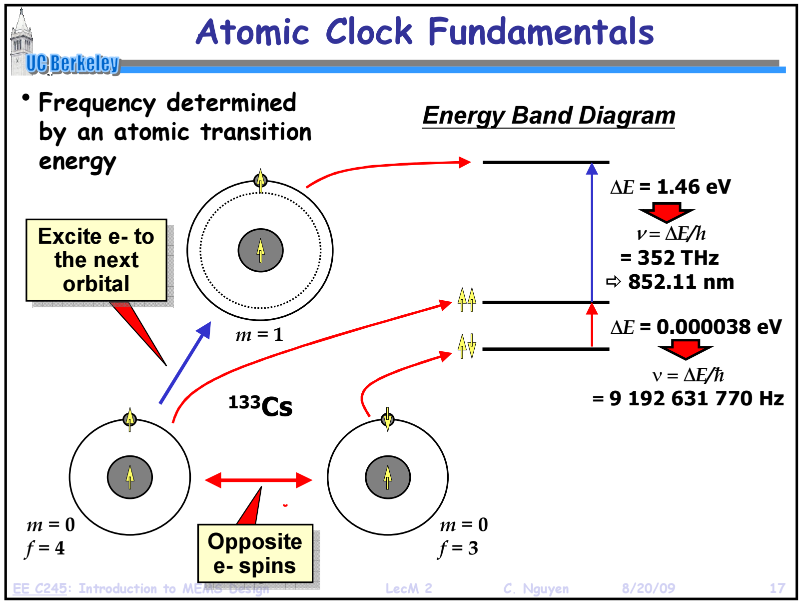
- *Experimental Conditions*:
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: ~80 °C
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70μW

*Open Loop Resonance*:



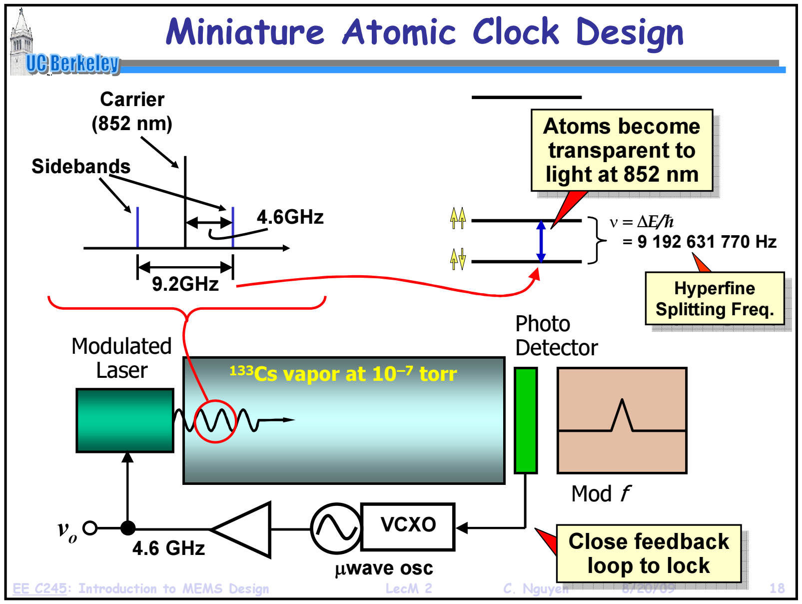
*Stability Measurement*:



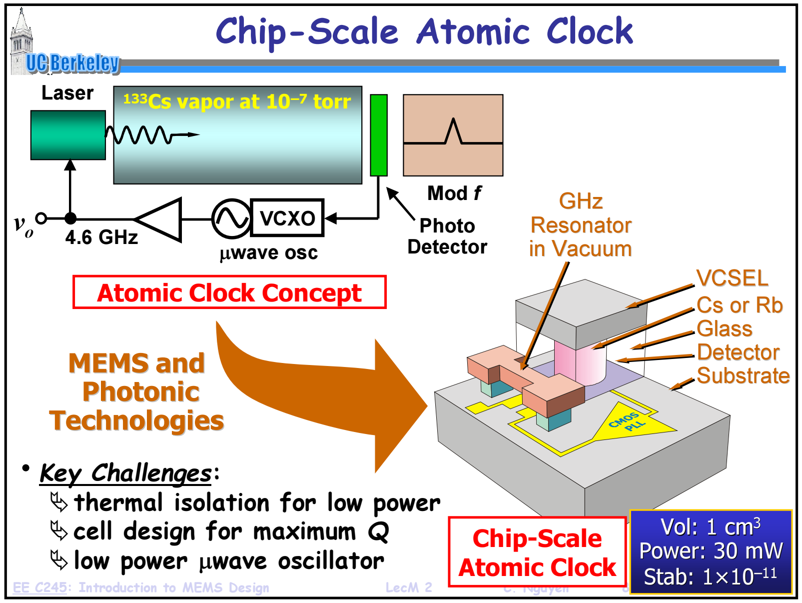


## Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

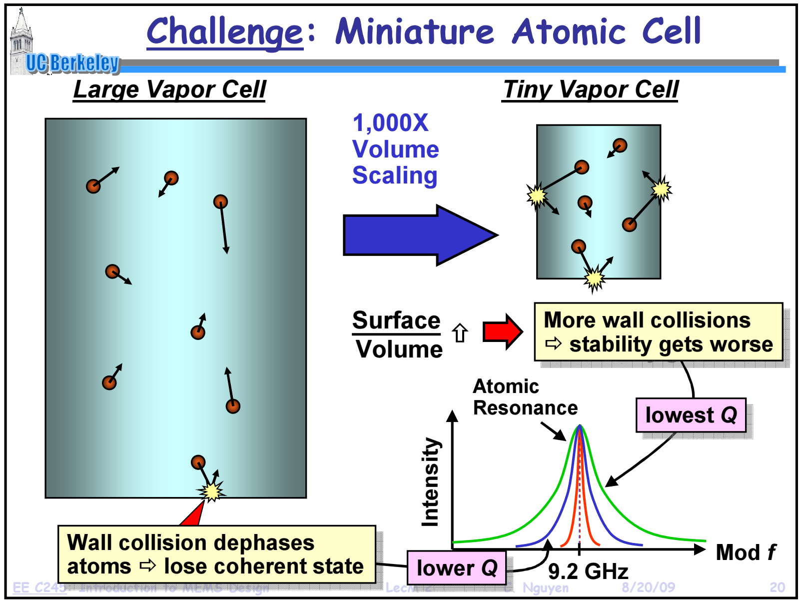


## Miniature Atomic Clock Design

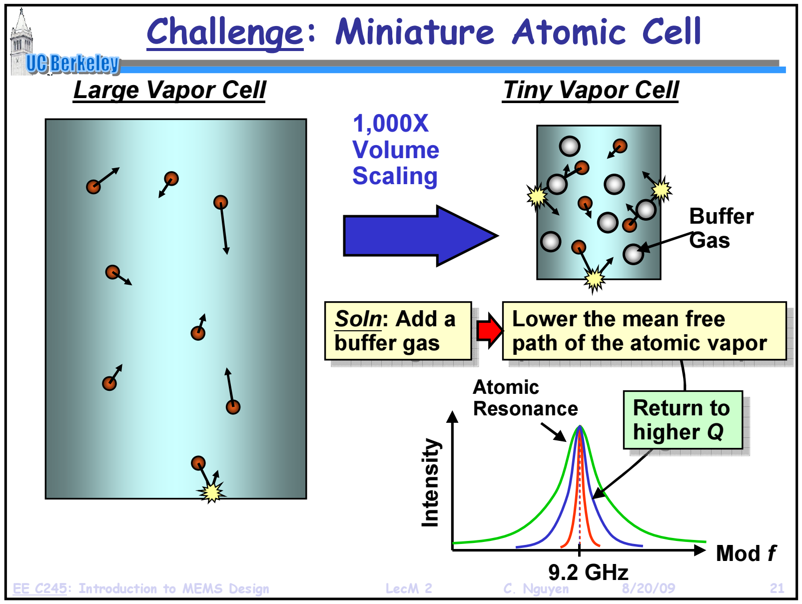


## Chip-Scale Atomic Clock

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

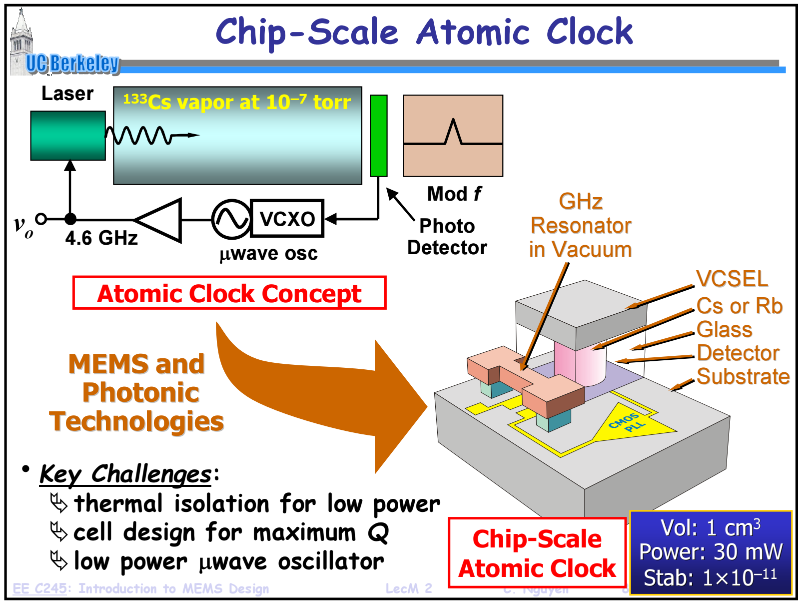


## Challenge: Miniature Atomic Cell



### Challenge: Miniature Atomic Cell

*Soln*: Add a buffer gas → Lower the mean free path of the atomic vapor



### Chip-Scale Atomic Clock

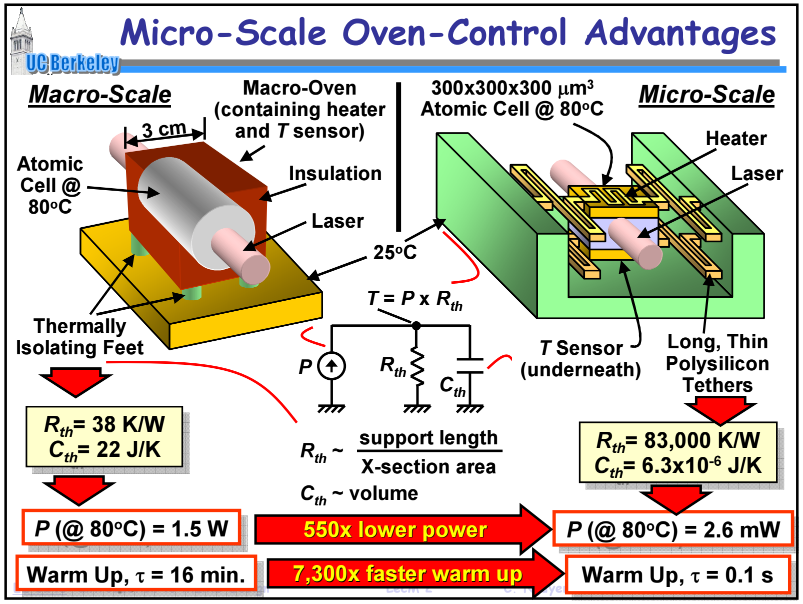
**Atomic Clock Concept**

**MEMS and Photonic Technologies**

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

**Chip-Scale Atomic Clock**

Vol: 1 cm$^3$
Power: 30 mW
Stab: $1\times10^{-11}$



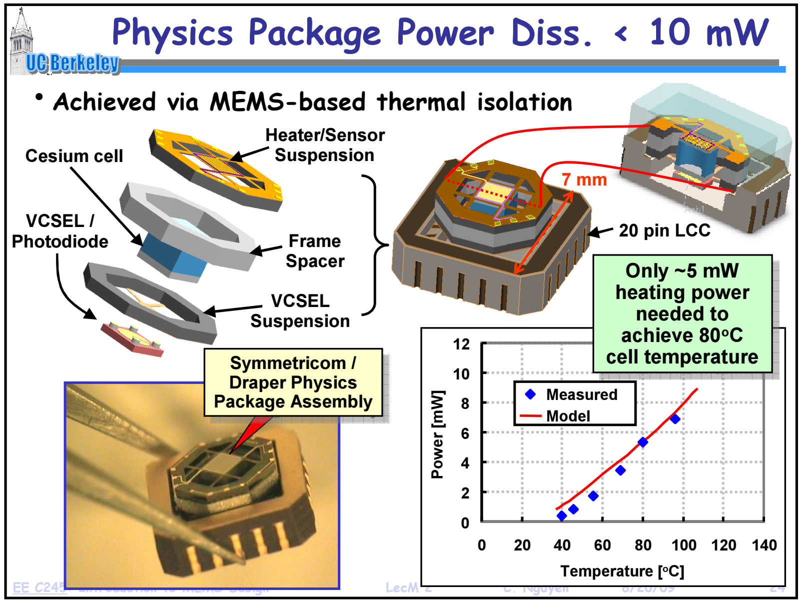
### Micro-Scale Oven-Control Advantages

$T = P \times R_{th}$

$R_{th} \sim \frac{\text{support length}}{\text{X-section area}}$

$C_{th} \sim$ volume

| Macro-Scale | | Micro-Scale |
|---|---|---|
| $R_{th}$= 38 K/W<br>$C_{th}$= 22 J/K | | $R_{th}$= 83,000 K/W<br>$C_{th}$= 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

- Achieved via MEMS-based thermal isolation

Symmetricom / Draper Physics Package Assembly

Only ~5 mW heating power needed to achieve 80°C cell temperature