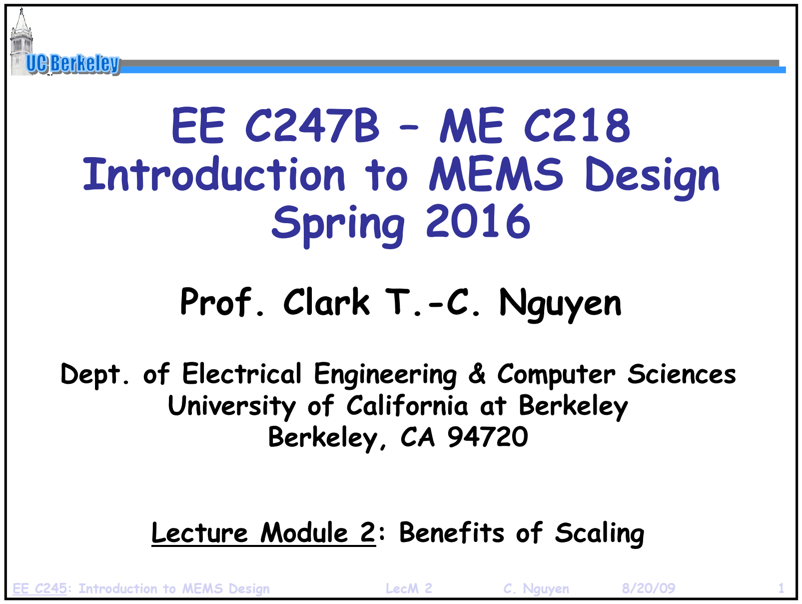

EE C247B – ME C218 Introduction to MEMS Design Spring 2016

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Berkeley, CA 94720

Lecture Module 2: Benefits of Scaling

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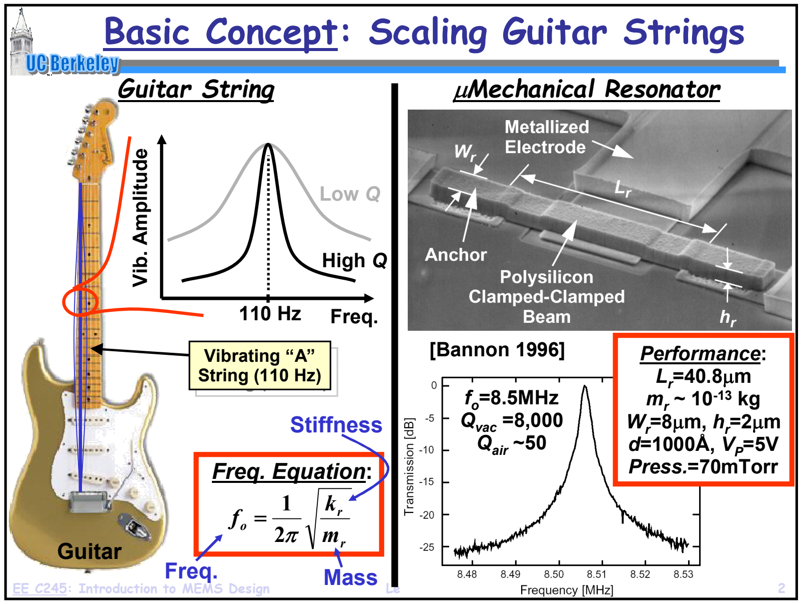

Basic Concept: Scaling Guitar Strings

Guitar String

Vibrating "A" String (110 Hz)

Freq. Equation:

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

μMechanical Resonator

[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

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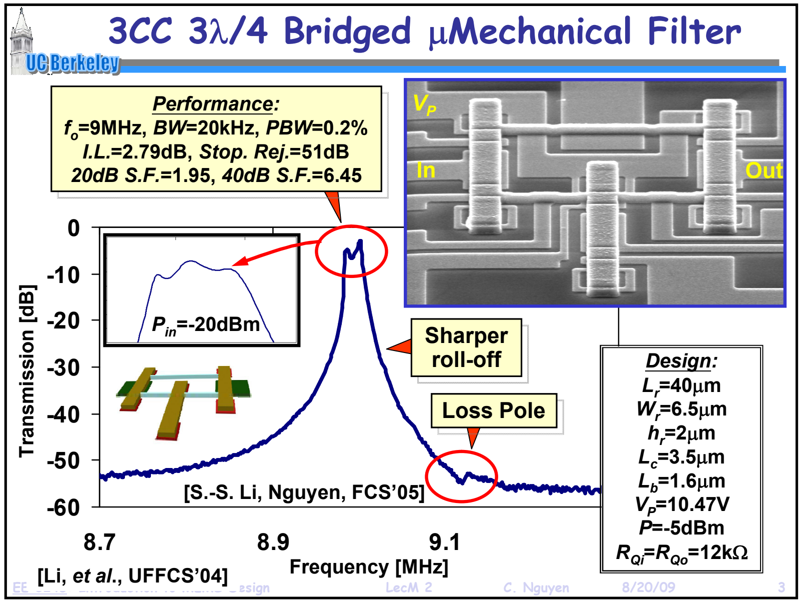

3CC 3λ/4 Bridged μMechanical Filter

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

Sharper roll-off

Loss Pole

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

[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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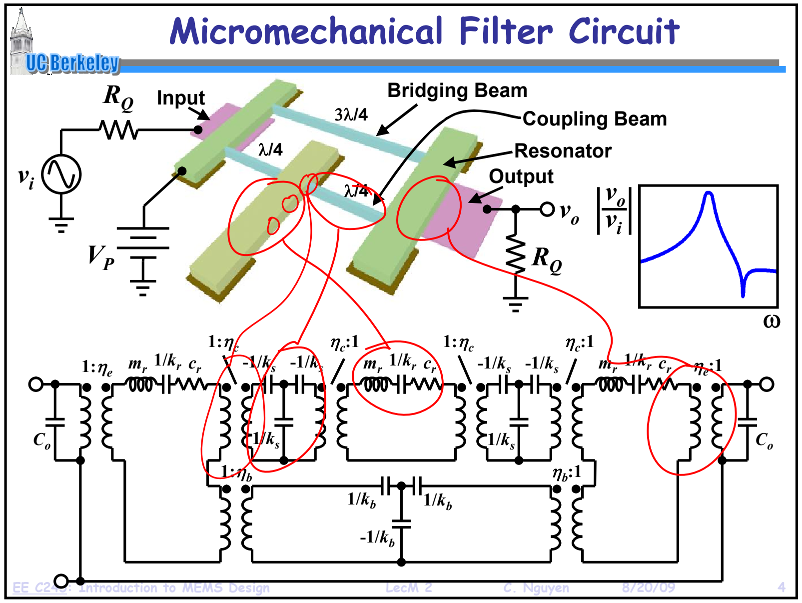

Micromechanical Filter Circuit

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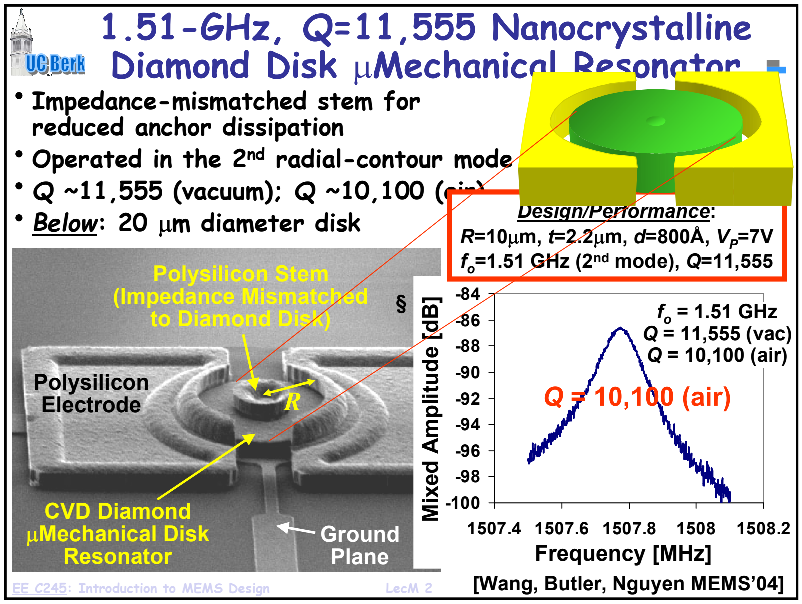
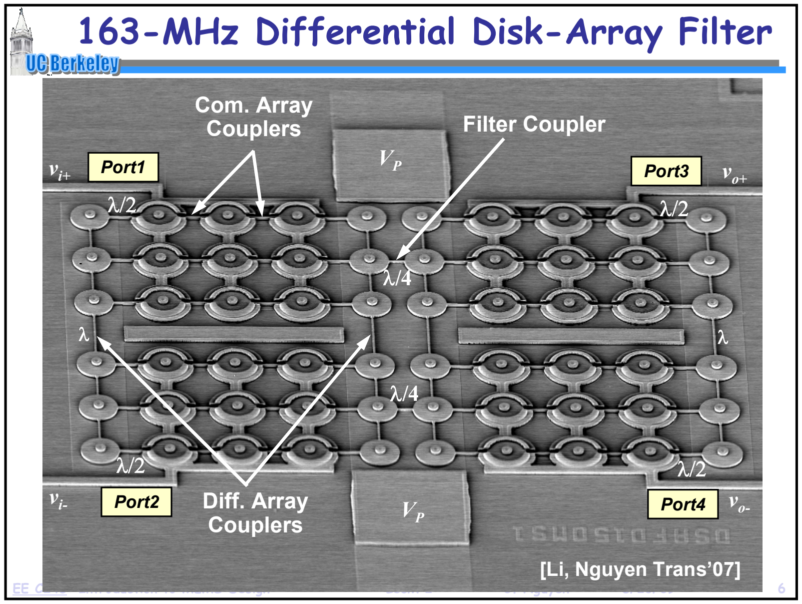


1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- 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

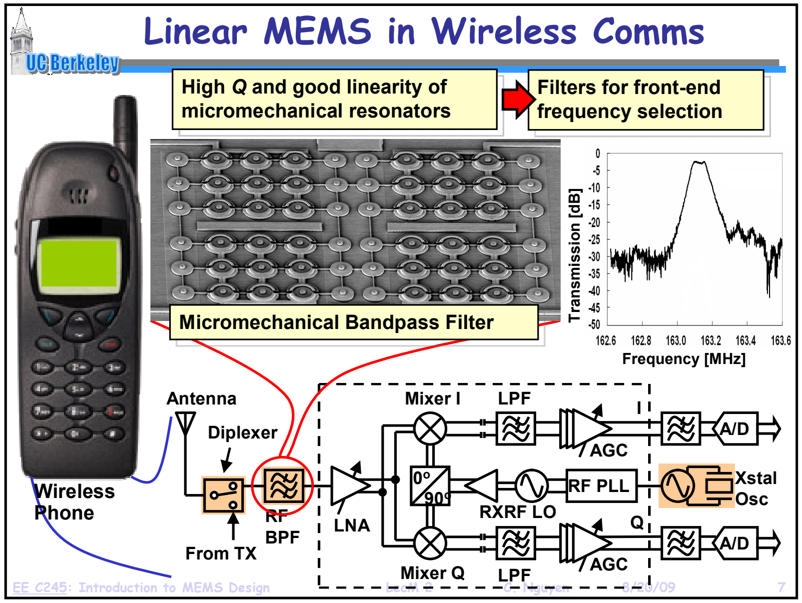
Design/Performance:
R=10μm, t=2.2μm, d=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), Q=11,555

[Wang, Butler, Nguyen MEMS'04]



163-MHz Differential Disk-Array Filter

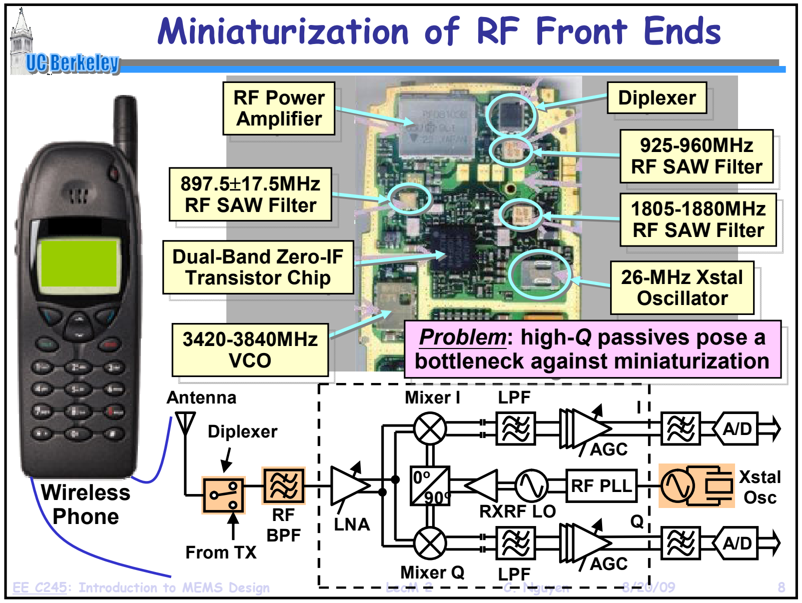
[Li, Nguyen Trans'07]



Linear MEMS in Wireless Comms

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

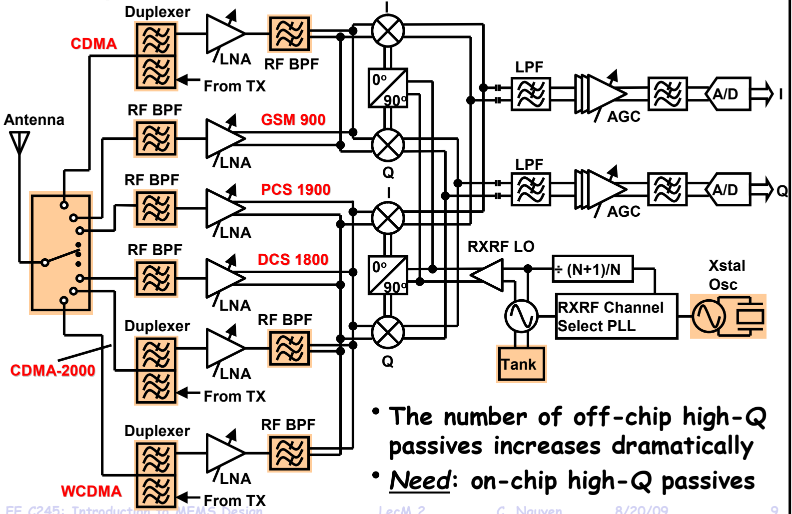
Micromechanical Bandpass Filter



Miniaturization of RF Front Ends

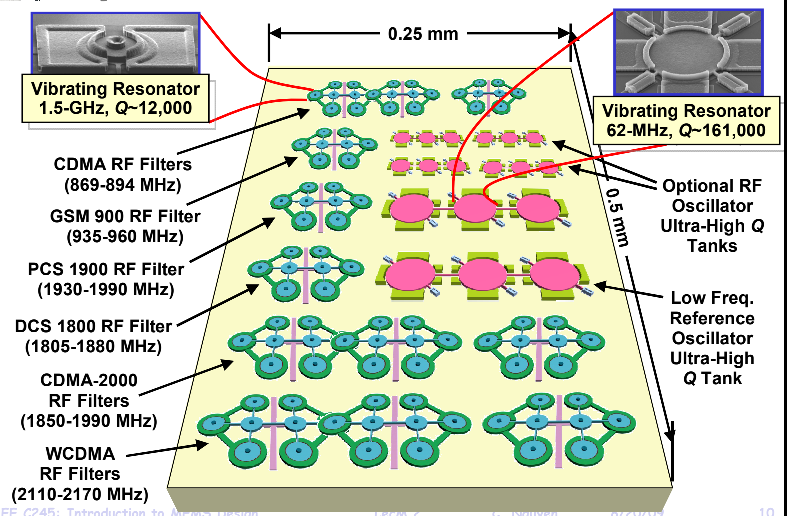
Problem: high-Q passives pose a bottleneck against miniaturization

Multi-Band Wireless Handsets



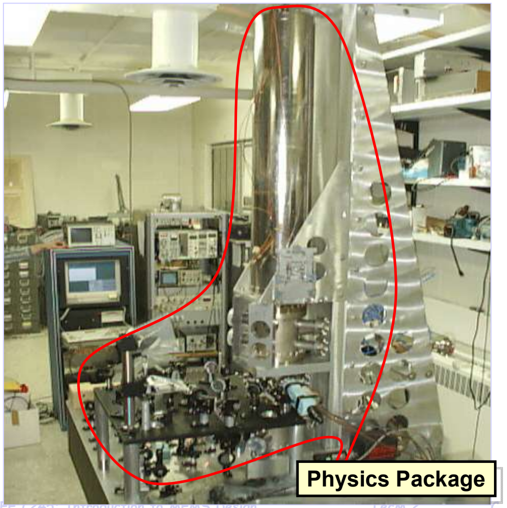
- The number of off-chip high-*Q* passives increases dramatically
- *Need*: on-chip high-*Q* passives

All High-Q Passives on a Single Chip



Chip-Scale Atomic Clocks (CSAC)

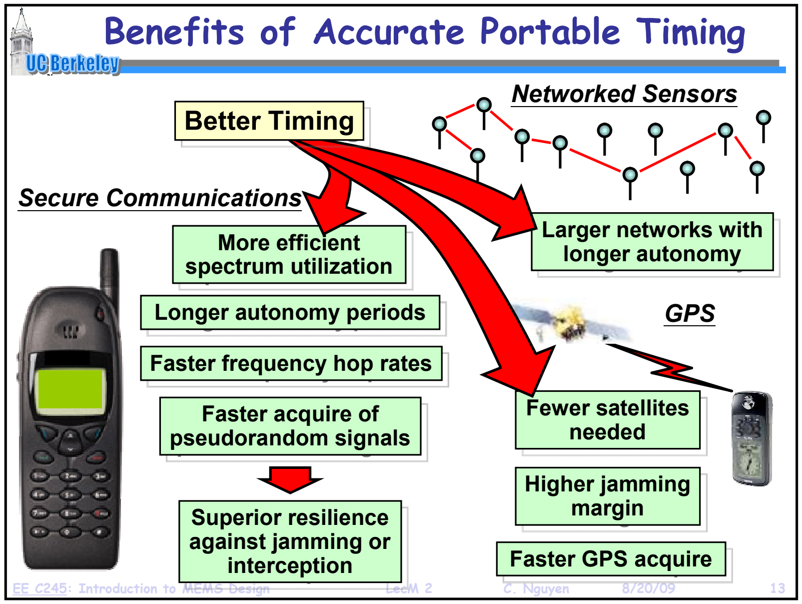
NIST F1 Fountain Atomic Clock



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

After 1 sec ⇨
***Error*: 10^{-15} sec**

Loses 1 sec every 30 million years!



Benefits of Accurate Portable Timing

Better Timing

Secure Communications

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

⇩

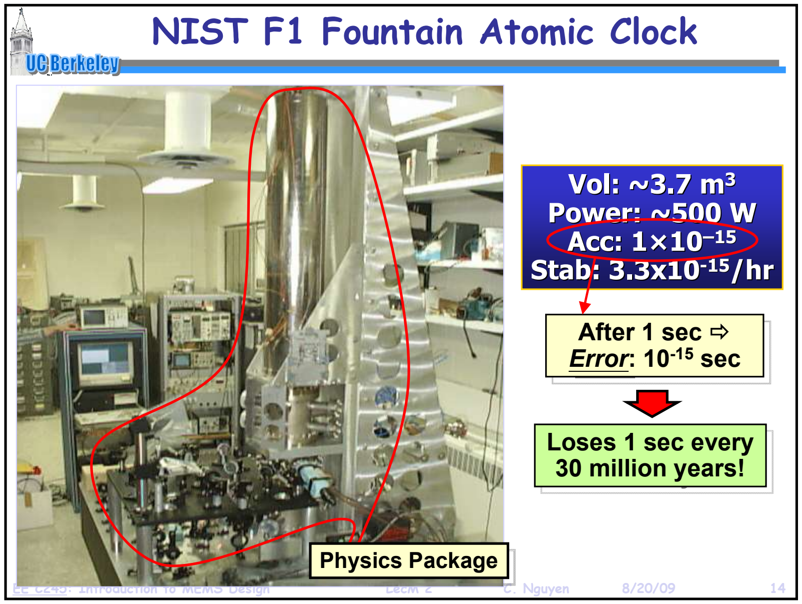
- Superior resilience against jamming or interception

Networked Sensors

- Larger networks with longer autonomy

GPS

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



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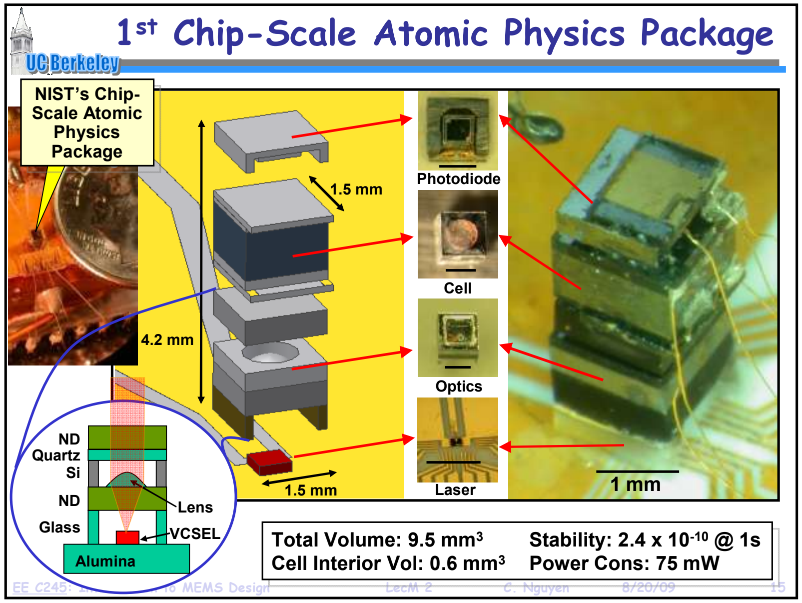
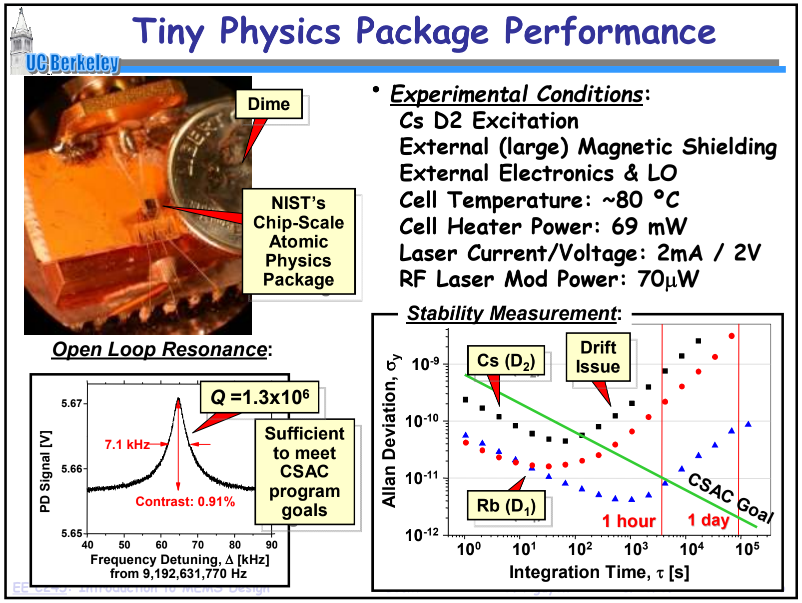


1st Chip-Scale Atomic Physics Package

NIST's Chip-Scale Atomic Physics Package

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



Tiny Physics Package Performance

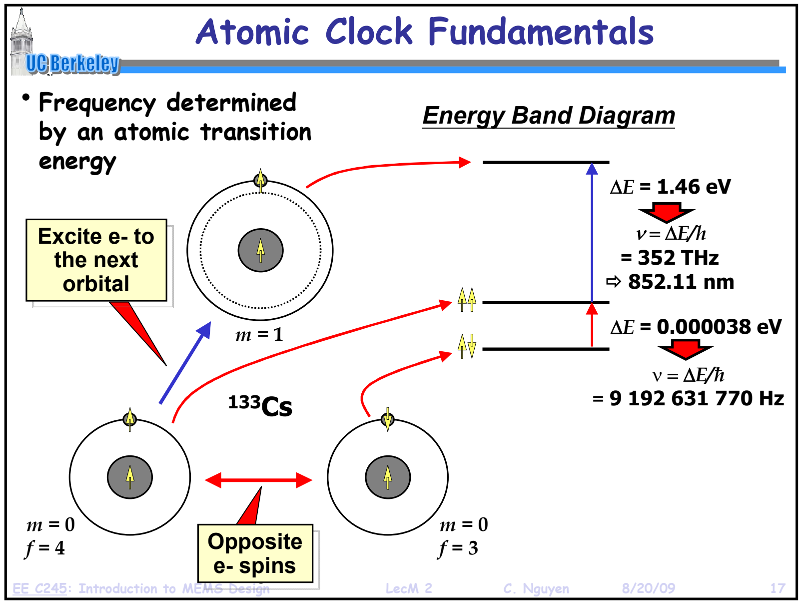
- ***Experimental Conditions***:
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: ~80 °C
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70μW

Open Loop Resonance:

Q =1.3x10^6

Sufficient to meet CSAC program goals

Stability Measurement:



Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

Energy Band Diagram

Excite e- to the next orbital

$m = 1$

^{133}Cs

ΔE = 1.46 eV

$\nu = \Delta E/\hbar$ = 352 THz ⇨ 852.11 nm

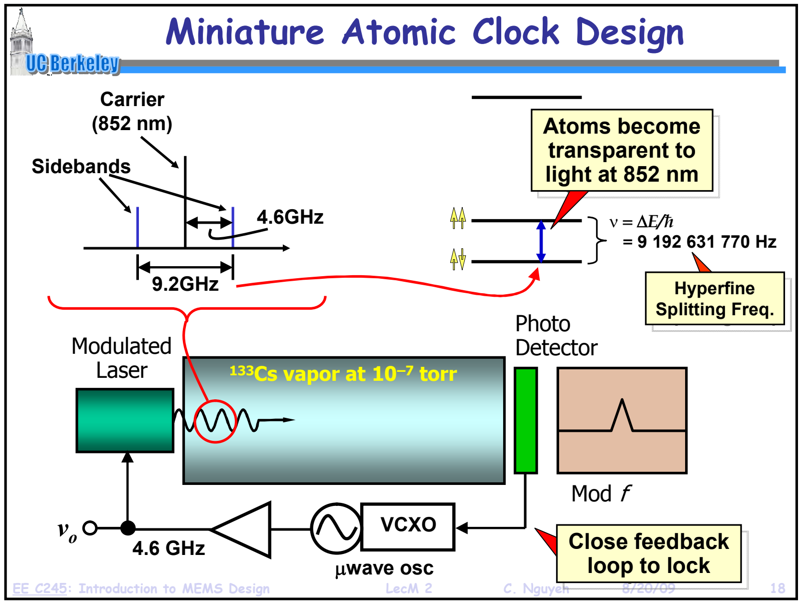
ΔE = 0.000038 eV

$\nu = \Delta E/\hbar$ = 9 192 631 770 Hz

$m = 0$
$f = 4$

Opposite e- spins

$m = 0$
$f = 3$



Miniature Atomic Clock Design

Carrier (852 nm)

Sidebands

4.6GHz

9.2GHz

Atoms become transparent to light at 852 nm

$\nu = \Delta E/\hbar$ = 9 192 631 770 Hz

Hyperfine Splitting Freq.

Modulated Laser

^{133}Cs vapor at 10^{-7} torr

Photo Detector

Mod f

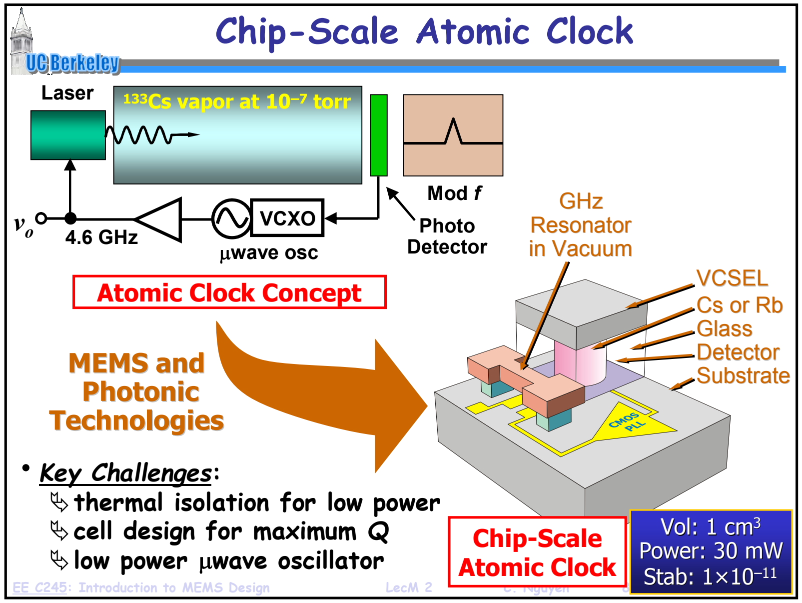
v_o

4.6 GHz

VCXO

μwave osc

Close feedback loop to lock



Chip-Scale Atomic Clock

Laser

^{133}Cs vapor at 10^{-7} torr

Mod f

Photo Detector

v_o

4.6 GHz

VCXO

μwave osc

Atomic Clock Concept

MEMS and Photonic Technologies

GHz Resonator in Vacuum

VCSEL

Cs or Rb

Glass

Detector

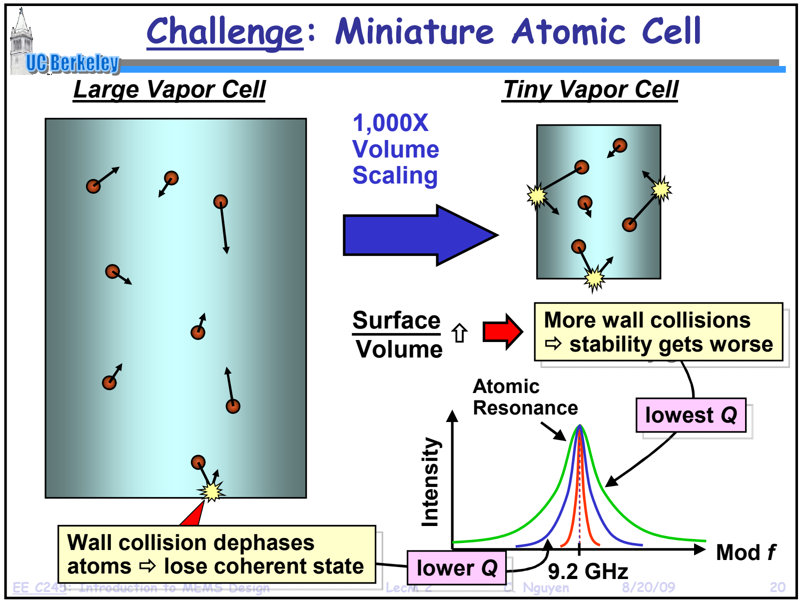
Substrate

CMOS PLL

- *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: 1×10^{-11}



Challenge: Miniature Atomic Cell

Large Vapor Cell

Tiny Vapor Cell

1,000X Volume Scaling

Surface / Volume ⇧ ⇨ More wall collisions ⇨ stability gets worse

Atomic Resonance

lowest Q

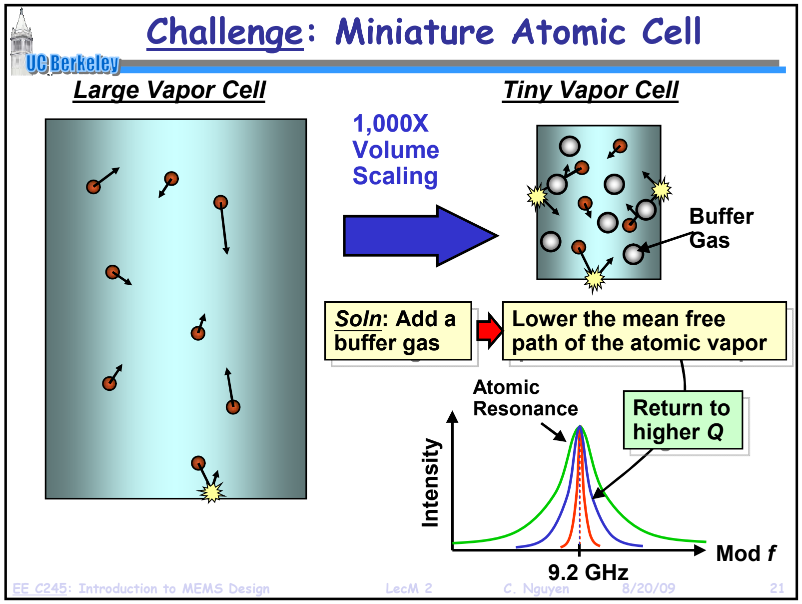
Intensity

Mod f

9.2 GHz

lower Q

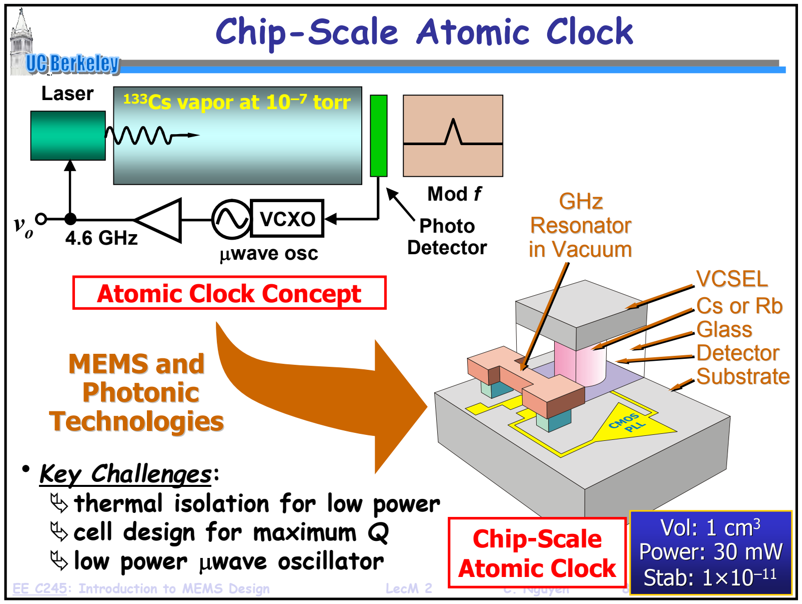
Wall collision dephases atoms ⇨ lose coherent state



Challenge: Miniature Atomic Cell

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

Return to higher *Q*



Chip-Scale Atomic Clock

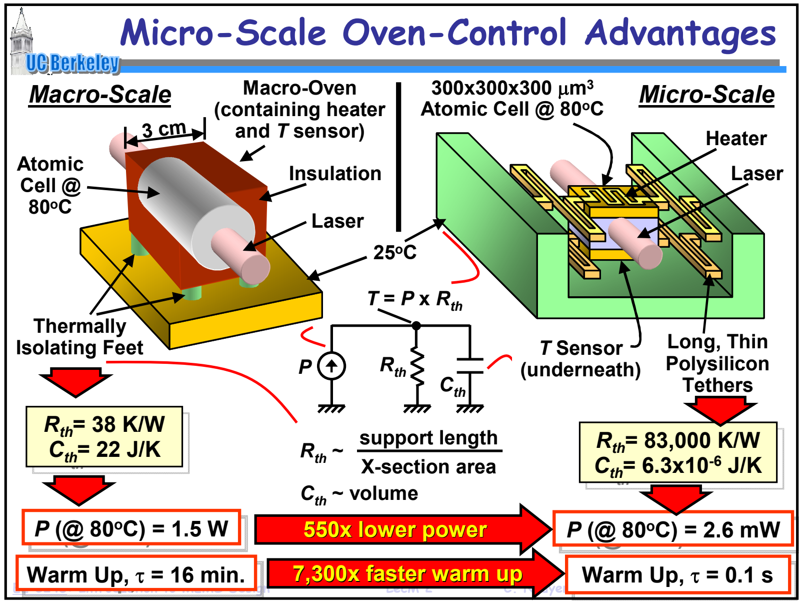
Atomic Clock Concept

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: 1×10^{-11}



Micro-Scale Oven-Control Advantages

$T = P \times R_{th}$

R_{th}= 38 K/W
C_{th}= 22 J/K

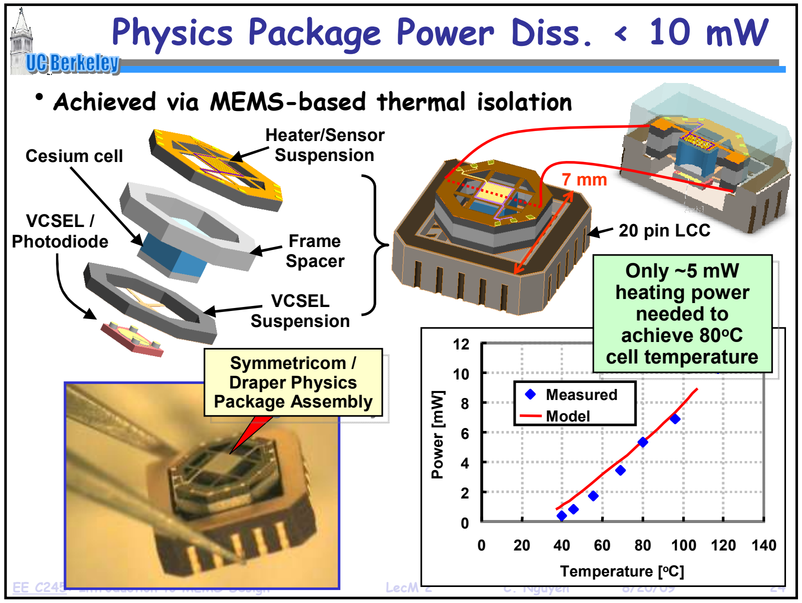
$$R_{th} \sim \frac{\text{support length}}{\text{X-section area}}$$

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

- Achieved via MEMS-based thermal isolation

Symmetricom / Draper Physics Package Assembly

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