EE C247B – ME C218
Introduction to MEMS Design
Spring 2020

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Lecture Module 1: Admin & Overview

Instructor: Prof. Clark T.-C. Nguyen

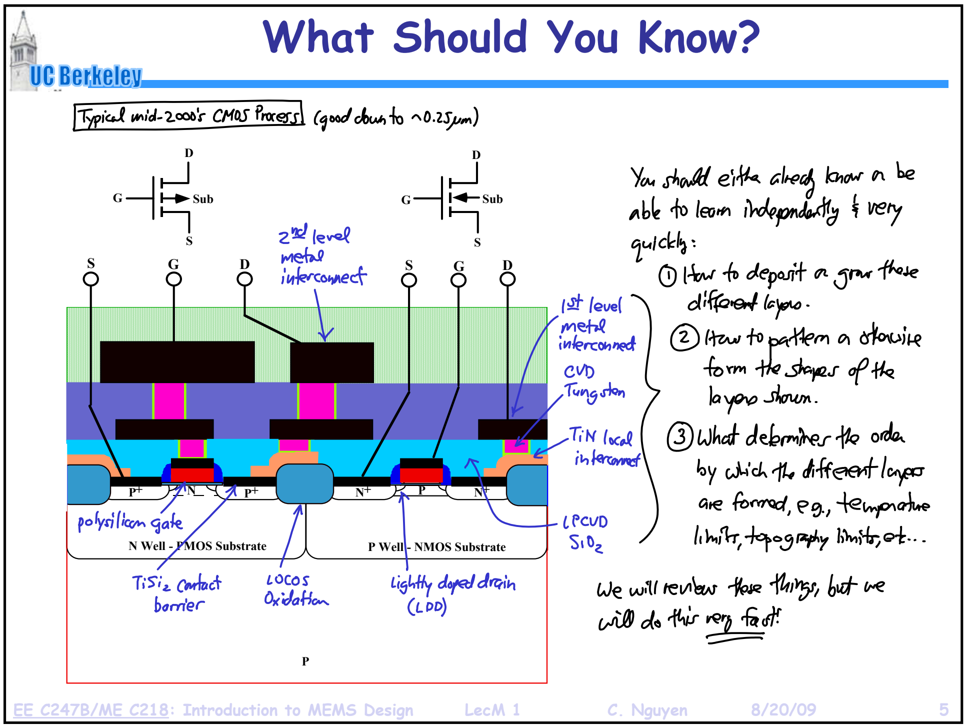
- *Education*: Ph.D., University of California at Berkeley, 1994
- *1995*: joined the faculty of the Dept. of EECS at the University of Michigan
- *2006*: (came back) joined the faculty of the Dept. of EECS at UC Berkeley
- *Research*: exactly the topic of this course, with a heavy emphasis on vibrating RF MEMS
- *Teaching*: (at the UofM) mainly transistor circuit & physics; (UC Berkeley) 140/240A, 143, 243, 245,247B/ME218
- *2001*: founded Discera, the first company to commercialize vibrating RF MEMS technology
- *Mid-2002 to 2005*: DARPA MEMS program manager
  - ran 10 different MEMS-based programs
  - *topics*: power generation, chip-scale atomic clock, gas analyzers, nuclear power sources, navigation-grade gyros, on-chip cooling, micro environmental control

Course Overview

- Goals of the course:
  - Accessible to a broad audience (minimal prerequisites)
  - Design emphasis
    - Exposure to the techniques useful in analytical design of structures, transducers, and process flows
  - Perspective on MEMS research and commercialization circa 2017
- Related courses at UC Berkeley:
  - EE 143: Microfabrication Technology
  - EE 147/247A: Introduction to MEMS
  - ME 119: Introduction to MEMS (mainly fabrication)
  - BioEng 121: Introduction to Micro and Nano Biotechnology and BioMEMS
- Assumed background for EE C247B/ME C218:
  - graduate standing in engineering or physical/bio sciences
  - knowledge of microfabrication technology

Course Overview

- The mechanics of the course are summarized in the course handouts, described in lecture today
  - Course Information Sheet
    - Course description
    - Course mechanics
    - Textbooks
    - Grading policy
  - Syllabus
    - Lecture by lecture timeline w/ associated reading sections
    - Midterm Exam: Thursday, March 22
    - Final Exam: Thursday, May 11, 8-11 a.m. (Group 13)
    - Project due date TBD (but near semester's end)



What Should You Know?

Typical mid-2000's CMOS Process (good down to ~0.25μm)

You should either already know or be able to learn independently & very quickly:

① How to deposit or grow these different layers.

② How to pattern or otherwise form the shapes of the layers shown.

③ What determines the order by which the different layers are formed, e.g., temperature limits, topography limits, etc...

We will review these things, but we will do this very fast!

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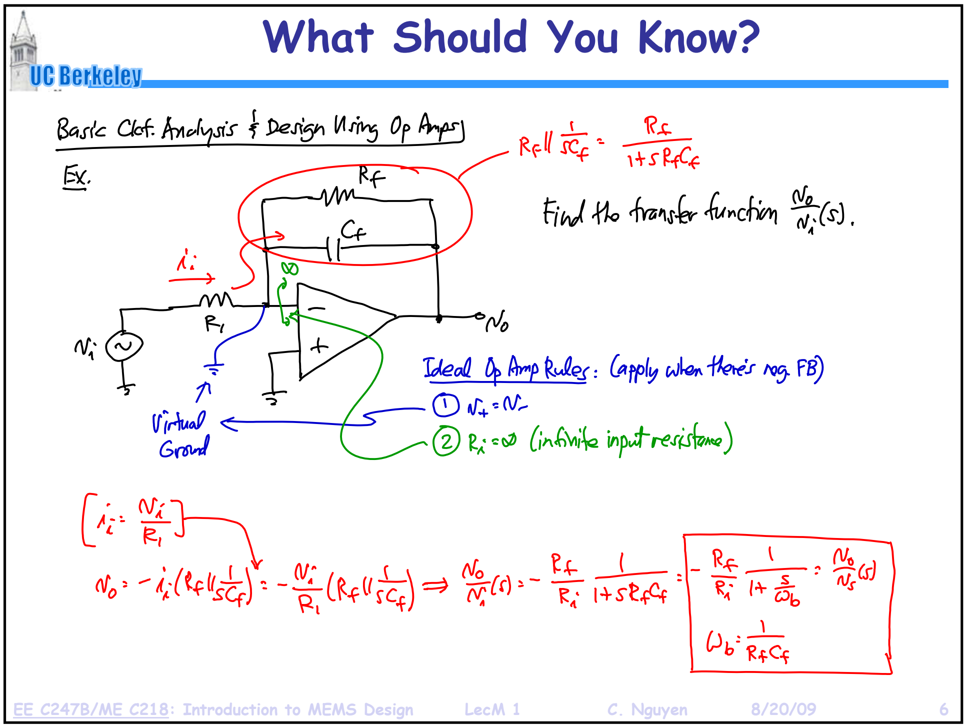

What Should You Know?

Basic Ckt. Analysis & Design Using Op Amps

Ex.

$$R_f \parallel \frac{1}{sC_f} = \frac{R_f}{1+sR_fC_f}$$

Find the transfer function $\frac{v_o}{v_i}(s)$.

Ideal Op Amp Rules: (apply when there's neg. FB)

① $v_+ = v_-$

② $R_i = \infty$ (infinite input resistance)

$$\left[i_i = \frac{v_i}{R_1} \right]$$

$$v_o = -i_i\left(R_f \parallel \frac{1}{sC_f}\right) = -\frac{v_i}{R_1}\left(R_f \parallel \frac{1}{sC_f}\right) \Rightarrow \frac{v_o}{v_i}(s) = -\frac{R_f}{R_1}\frac{1}{1+sR_fC_f} = \boxed{-\frac{R_f}{R_1}\frac{1}{1+\frac{s}{\omega_b}} = \frac{v_o}{v_s}(s) \quad \omega_b = \frac{1}{R_fC_f}}$$

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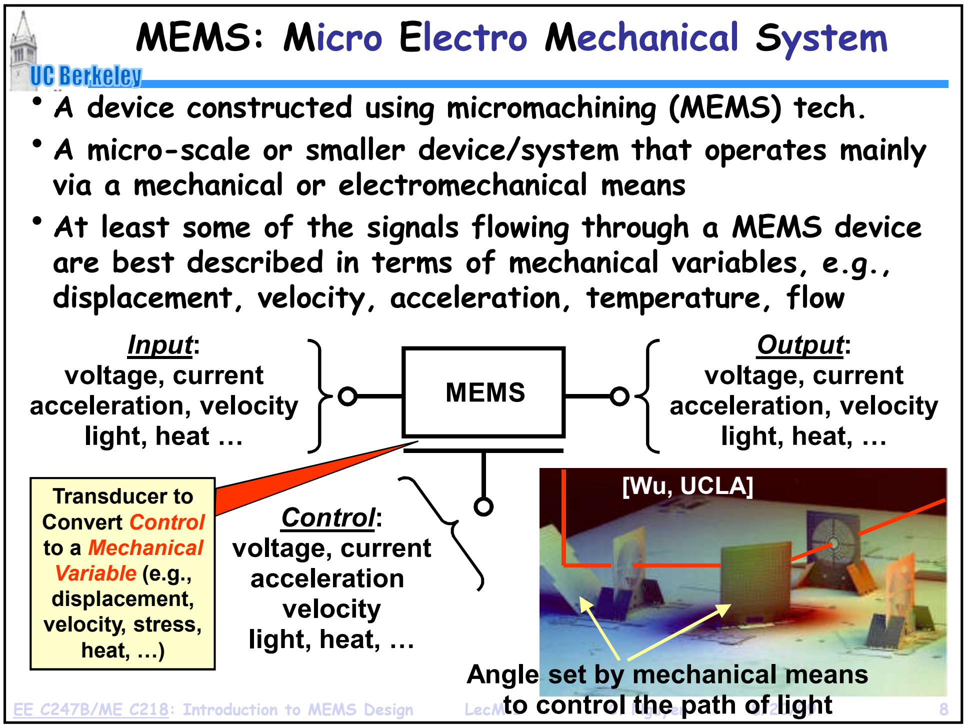
Lecture Outline

- Reading: Senturia, Chapter 1
- Lecture Topics:
  - Definitions for MEMS
  - MEMS roadmap
  - Benefits of Miniaturization



MEMS: Micro Electro Mechanical System

- A device constructed using micromachining (MEMS) tech.
- A micro-scale or smaller device/system that operates mainly via a mechanical or electromechanical means
- At least some of the signals flowing through a MEMS device are best described in terms of mechanical variables, e.g., displacement, velocity, acceleration, temperature, flow

Input:
voltage, current
acceleration, velocity
light, heat …

MEMS

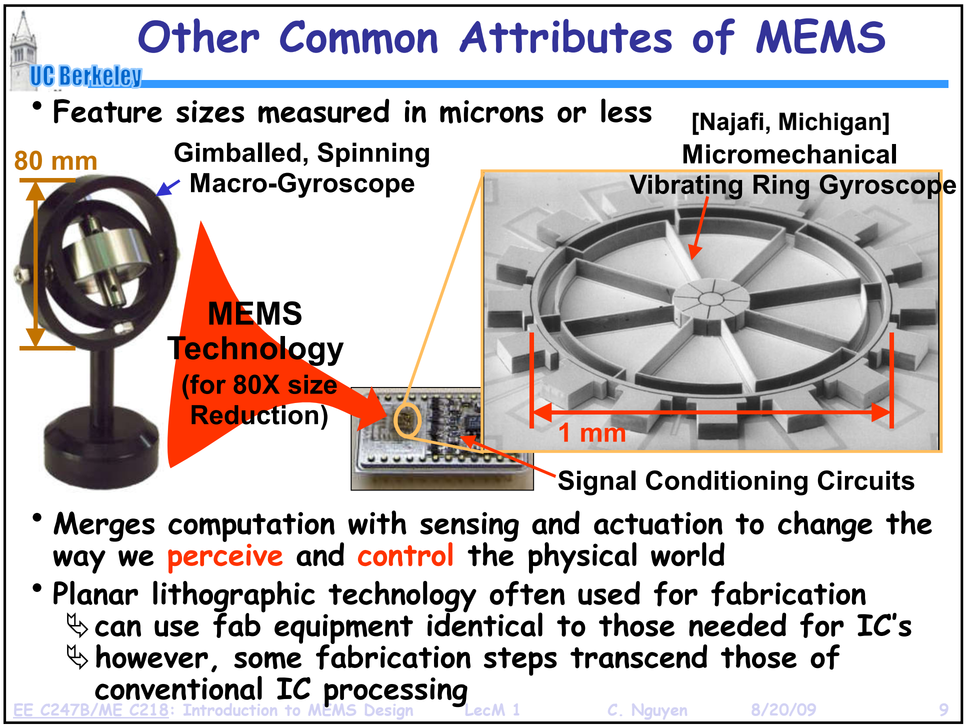
Output:
voltage, current
acceleration, velocity
light, heat, …

Transducer to Convert *Control* to a *Mechanical Variable* (e.g., displacement, velocity, stress, heat, …)

Control:
voltage, current
acceleration
velocity
light, heat, …

[Wu, UCLA]

Angle set by mechanical means to control the path of light



Other Common Attributes of MEMS

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- Feature sizes measured in microns or less

80 mm

Gimballed, Spinning Macro-Gyroscope

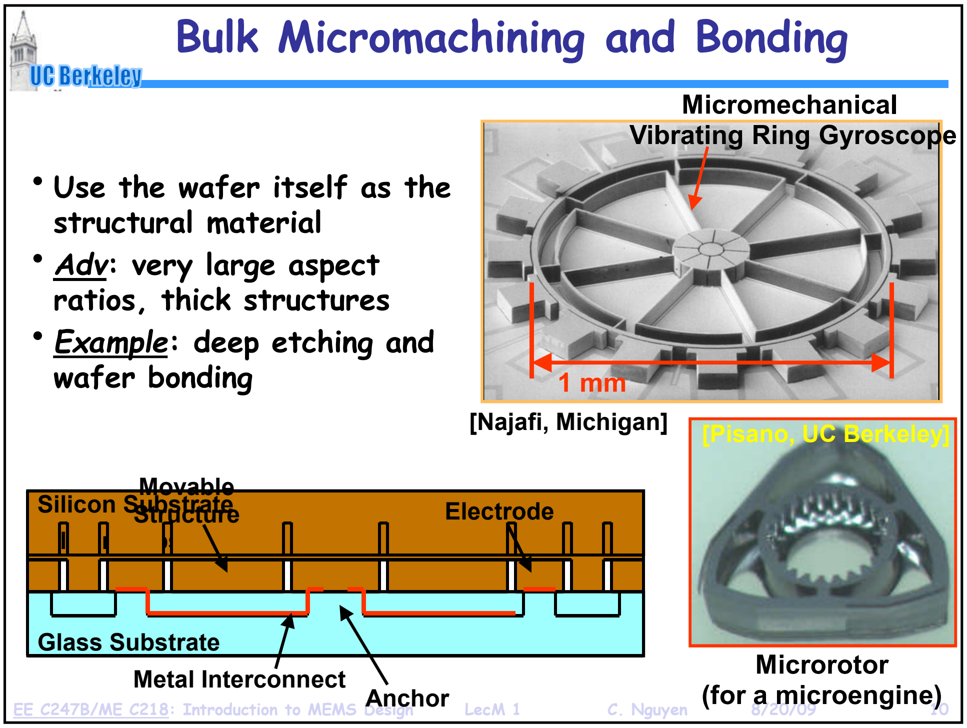
MEMS Technology (for 80X size Reduction)

[Najafi, Michigan] Micromechanical Vibrating Ring Gyroscope

1 mm

Signal Conditioning Circuits

- Merges computation with sensing and actuation to change the way we perceive and control the physical world
- Planar lithographic technology often used for fabrication
  - ↳ can use fab equipment identical to those needed for IC's
  - ↳ however, some fabrication steps transcend those of conventional IC processing



Bulk Micromachining and Bonding

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- Use the wafer itself as the structural material
- *Adv*: very large aspect ratios, thick structures
- *Example*: deep etching and wafer bonding

Micromechanical Vibrating Ring Gyroscope

1 mm

[Najafi, Michigan]

Silicon Substrate

Movable Structure

Electrode

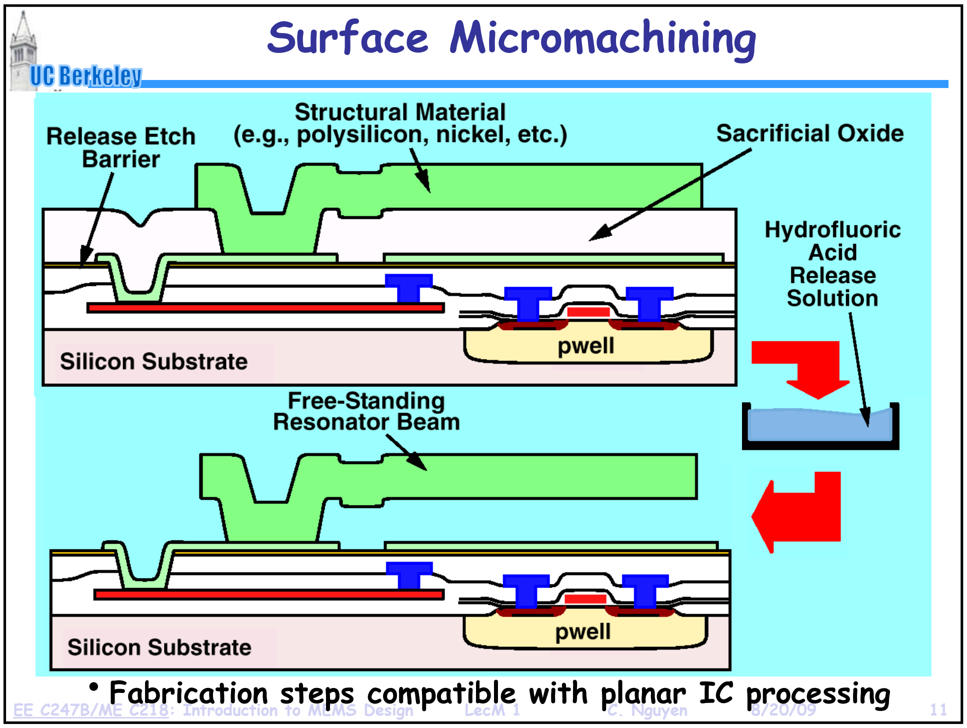
Glass Substrate

Metal Interconnect

Anchor

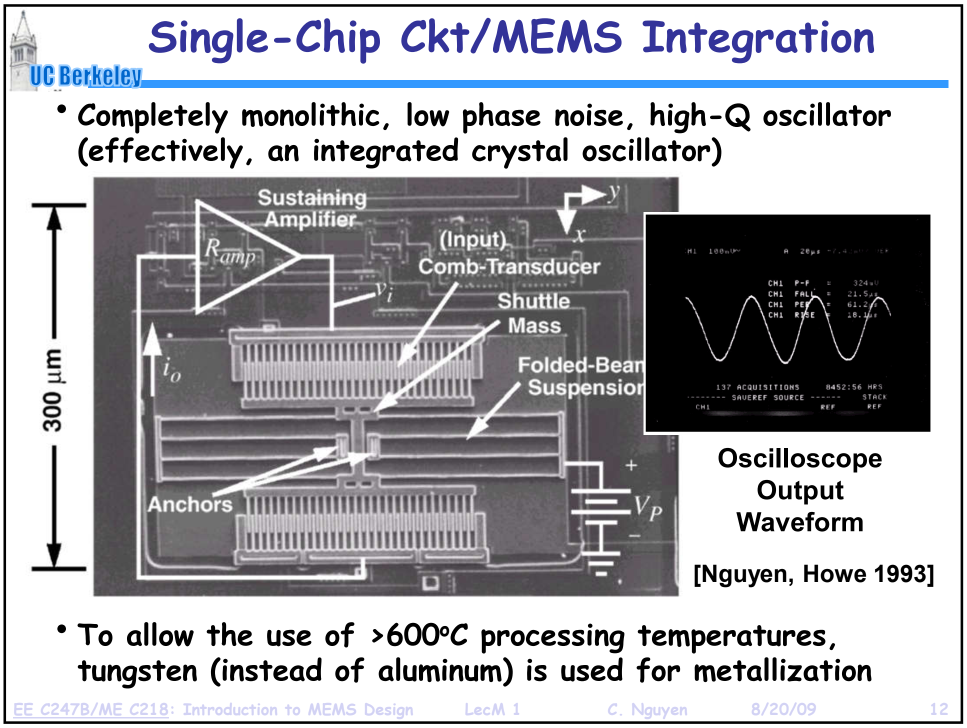
[Pisano, UC Berkeley]

Microrotor (for a microengine)



Surface Micromachining

- Fabrication steps compatible with planar IC processing



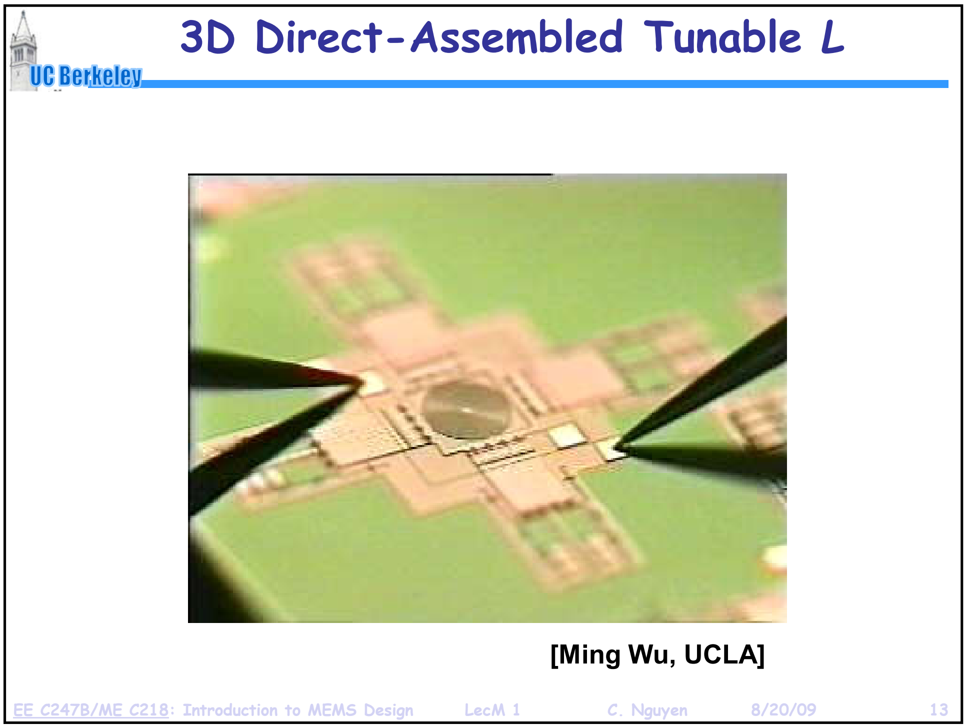
Single-Chip Ckt/MEMS Integration

- Completely monolithic, low phase noise, high-Q oscillator (effectively, an integrated crystal oscillator)

Oscilloscope Output Waveform

[Nguyen, Howe 1993]

- To allow the use of >600°C processing temperatures, tungsten (instead of aluminum) is used for metallization



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3D Direct-Assembled Tunable L

[Ming Wu, UCLA]

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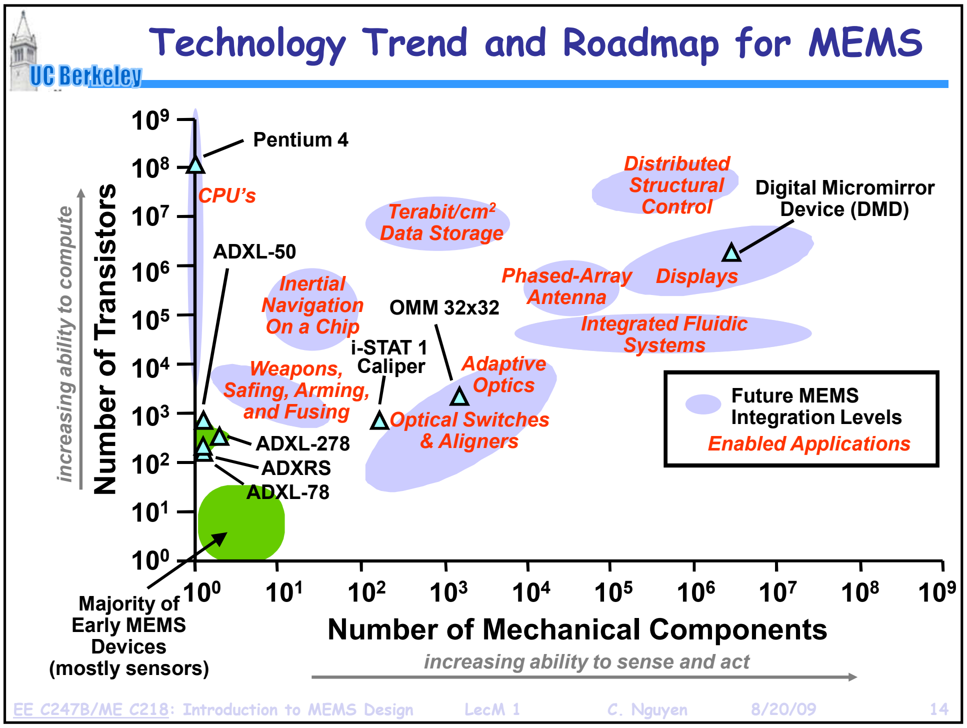

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Technology Trend and Roadmap for MEMS

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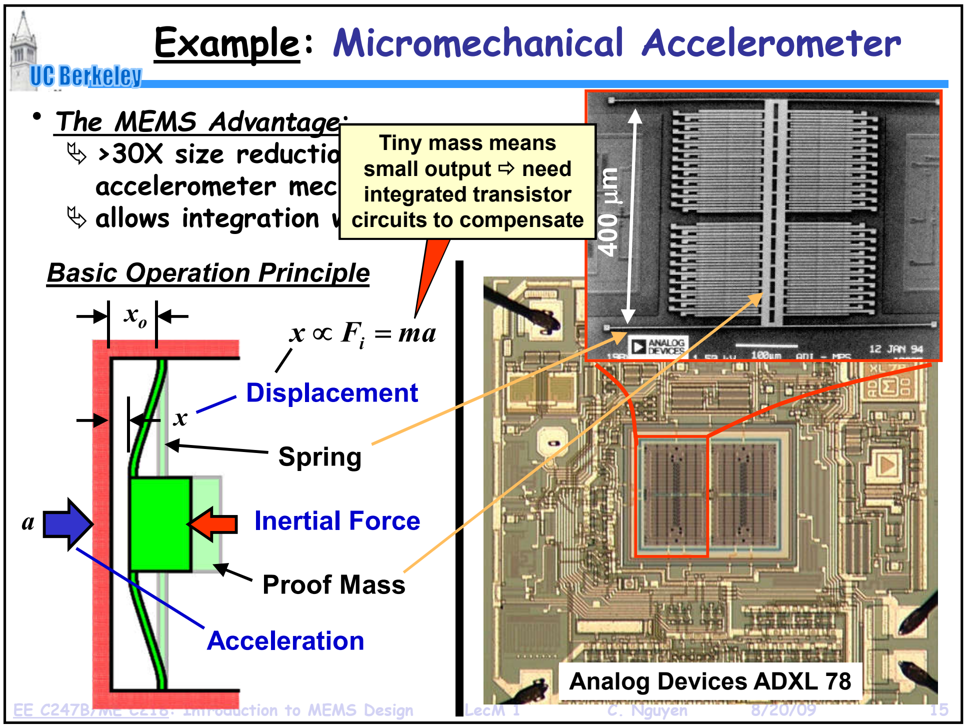

Example: Micromechanical Accelerometer

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- *The MEMS Advantage:*
  - >30X size reductio accelerometer mec
  - allows integration v

Tiny mass means small output ⇨ need integrated transistor circuits to compensate

Basic Operation Principle

x_o

$x \propto F_i = ma$

Displacement

x

Spring

a

Inertial Force

Proof Mass

Acceleration

400 µm

Analog Devices ADXL 78

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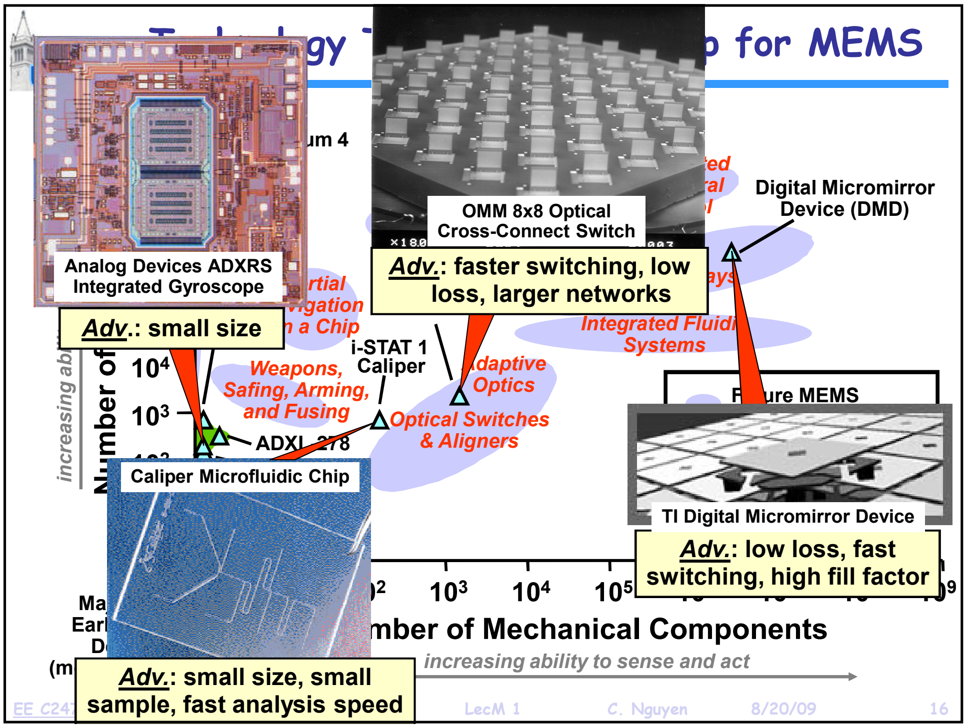

T gy p for MEMS

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Analog Devices ADXRS Integrated Gyroscope

Adv.: small size

OMM 8x8 Optical Cross-Connect Switch

Adv.: faster switching, low loss, larger networks

Digital Micromirror Device (DMD)

ted ral l

ays

rtial igation n a Chip

Integrated Fluidi Systems

i-STAT 1

Caliper

Weapons, Safing, Arming, and Fusing

Adaptive Optics

Optical Switches & Aligners

F ure MEMS

10^4

10^3

ADXL 278

Caliper Microfluidic Chip

TI Digital Micromirror Device

Adv.: low loss, fast switching, high fill factor

increasing abi

Number of

Ma Earl D (m

10^2 10^3 10^4 10^5 10^9

mber of Mechanical Components

increasing ability to sense and act

Adv.: small size, small sample, fast analysis speed

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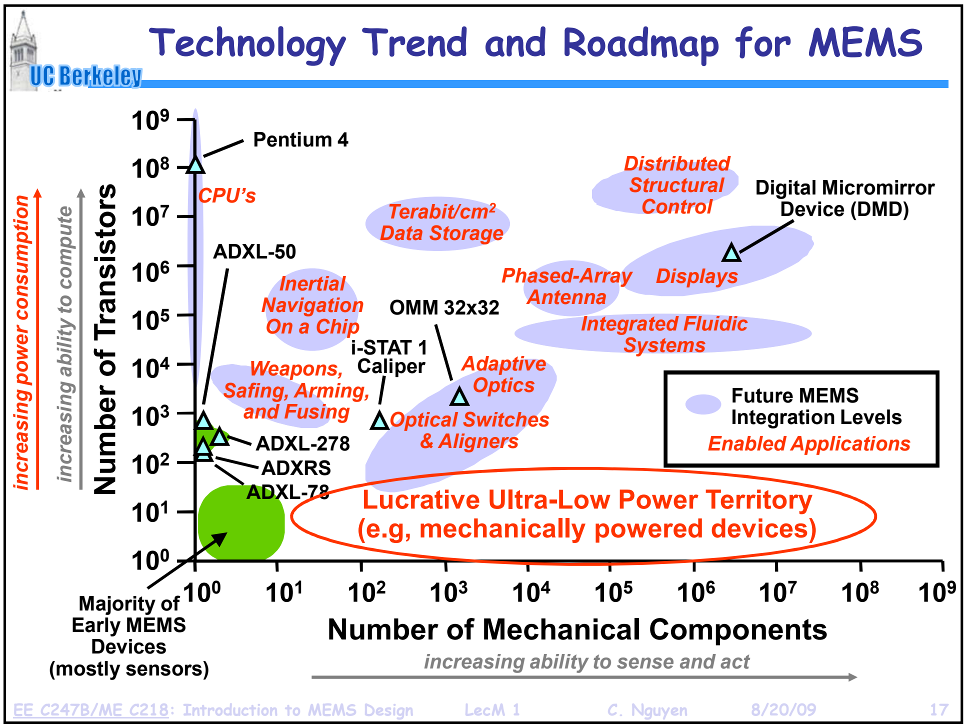
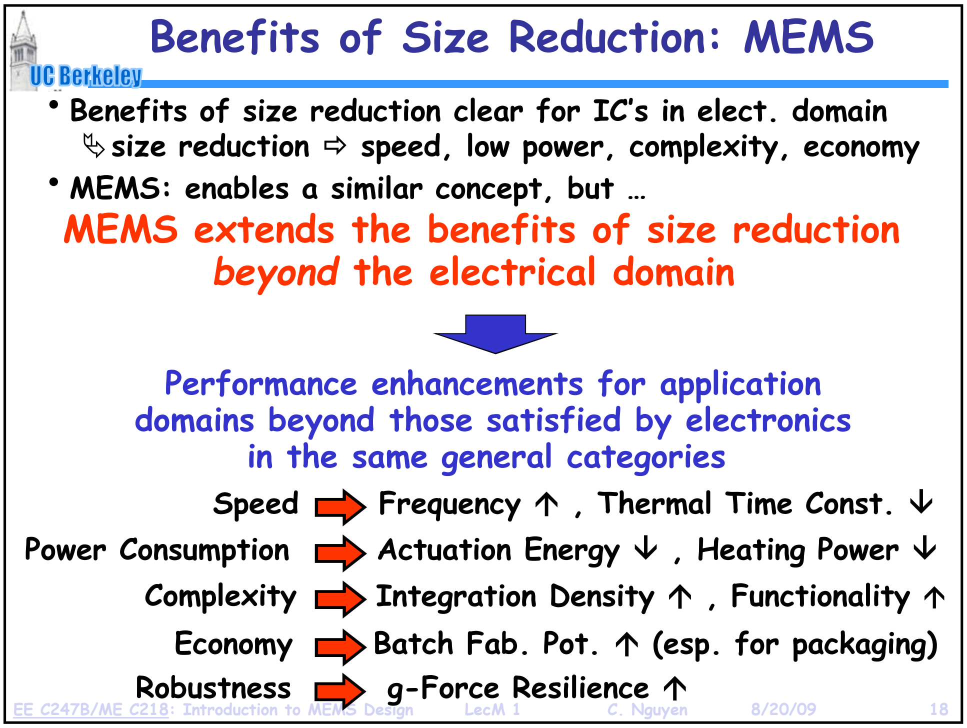


Technology Trend and Roadmap for MEMS



Benefits of Size Reduction: MEMS

- Benefits of size reduction clear for IC's in elect. domain
  - size reduction ⇨ speed, low power, complexity, economy
- MEMS: enables a similar concept, but …

MEMS extends the benefits of size reduction *beyond* the electrical domain

Performance enhancements for application domains beyond those satisfied by electronics in the same general categories

Speed ➡ Frequency ↑ , Thermal Time Const. ↓
Power Consumption ➡ Actuation Energy ↓ , Heating Power ↓
Complexity ➡ Integration Density ↑ , Functionality ↑
Economy ➡ Batch Fab. Pot. ↑ (esp. for packaging)
Robustness ➡ g-Force Resilience ↑