ISSCC 2012 Tutorial

Getting In Touch with MEMS: The Electromechanical Interface

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Overview

These slides accompany the 2012 ISSCC Tutorial, Getting In Touch with MEMS: The Electromechanical Interface.

The tutorial is written for practicing IC engineers and students. No MEMS background is needed.

The goal is to expand the attendee's potential role from circuit designer to system designer. From "Here is the MEMS device, design the interface circuit." into "Here is the problem, define an optimal solution."

Outline

- MEMS Materials, Processes, and Example Applications
- Electrical Interfaces
- Scaling Laws
- Packaging is Critical
- CMOS Integration
- How to Succeed
- References

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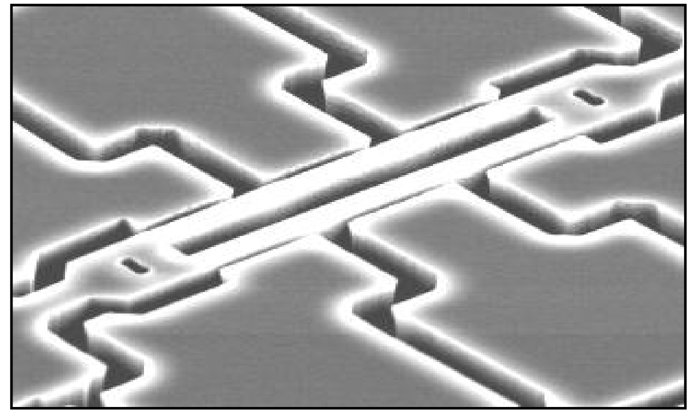
Materials

- Standard Semiconductor Materials
  - Silicon (single crystal and poly).
  - Oxide (thermal and deposited).
  - Nitride.
  - Aluminum.

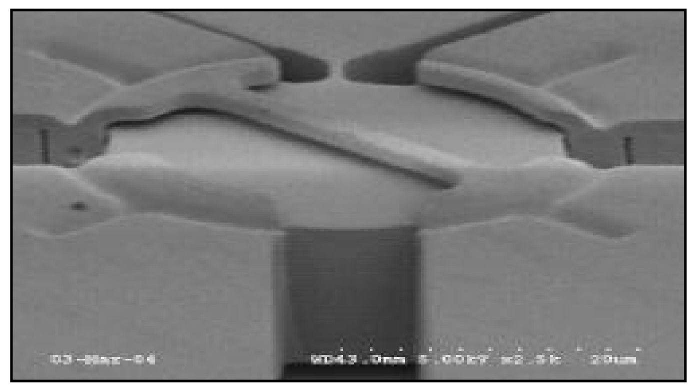
- Unusual Materials
  - Gold, various other metals.
  - Piezoelectrics (AlN mostly).
  - Plastics (e.g. SU-8).
  - And then just about anything else.

Processes

- Early in MEMS many unusual etches were common.
- Now standard fab process are preferred when possible.
- A few special processes
  - Bosch etch.
  - HF vapor etch.
  - Oxide plasma release.
  - Xenon difluoride (XeF_2) release.
- Deep etches are common.



Tuning fork resonator, Bosch 2003

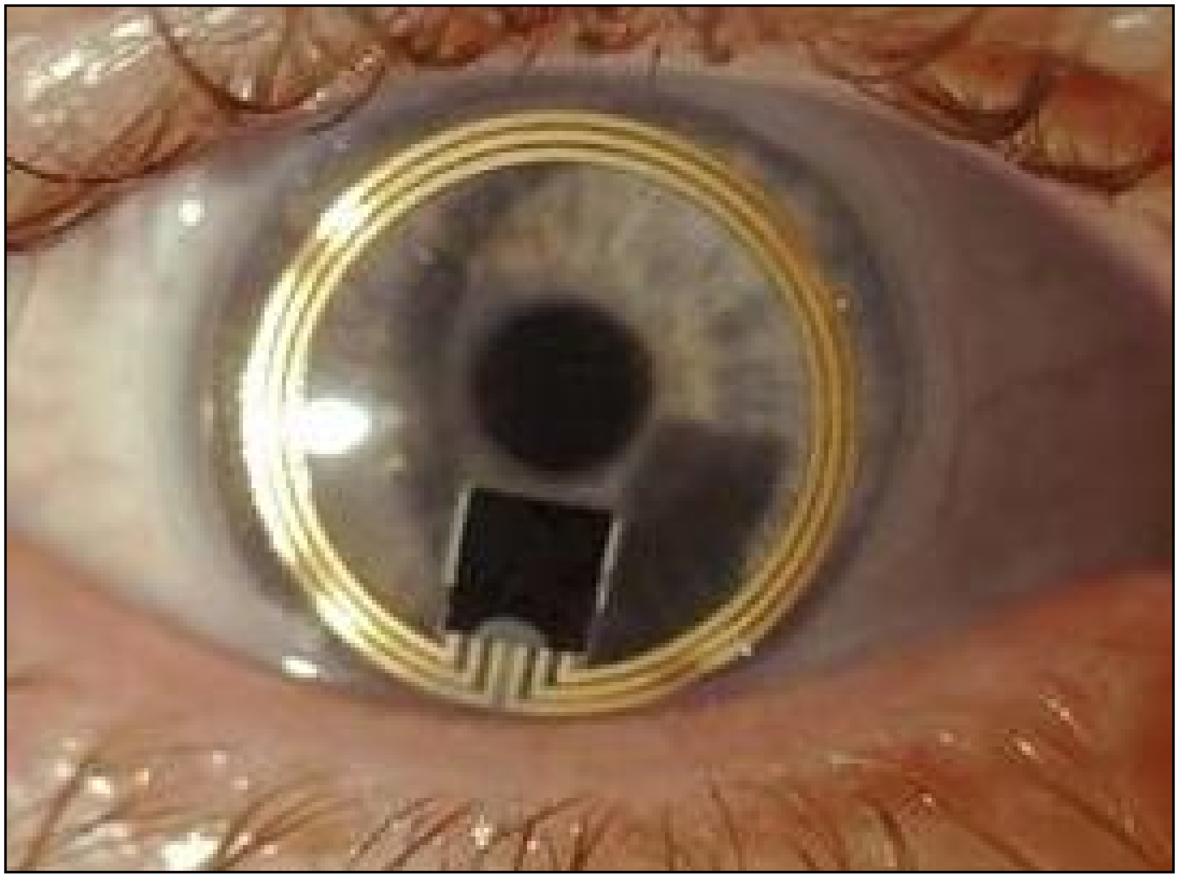


S. Pourkamali, F. Ayazi, 2004

Example Applications

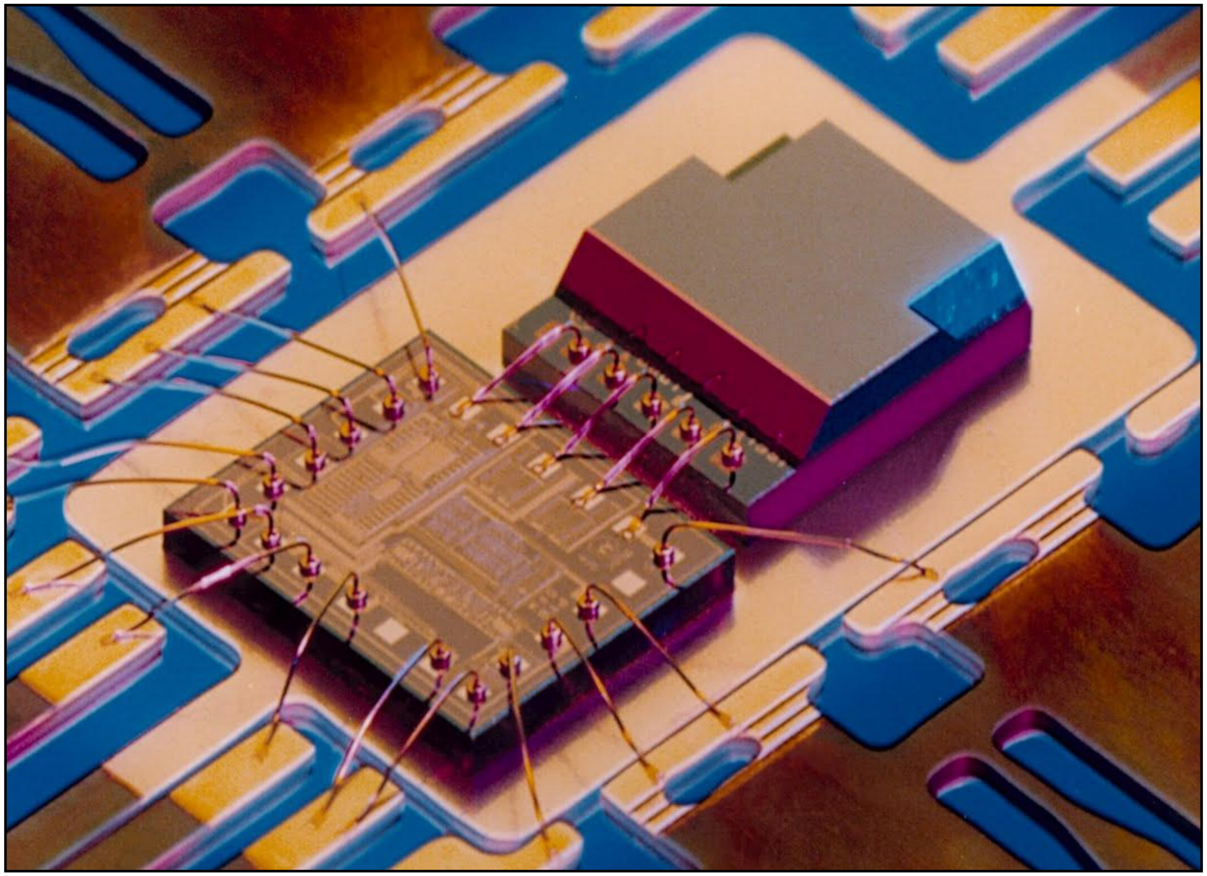
- MEMS will find its way into practically every application.
- Right now, it is strong in
  - Automotive (pressure, acceleration, rotation).
  - Consumer (acceleration, rotation, time).
  - Industrial and Military (pressure, acceleration).
  - Medicinal (pressure, biological sensors).
- Future hot apps will be
  - Medical, for diagnostic tools.
  - Timing, to replace quartz.
  - RF Filters, switches, etc.
  - Inertial, to sense motion of all types.

Pressure Sensors



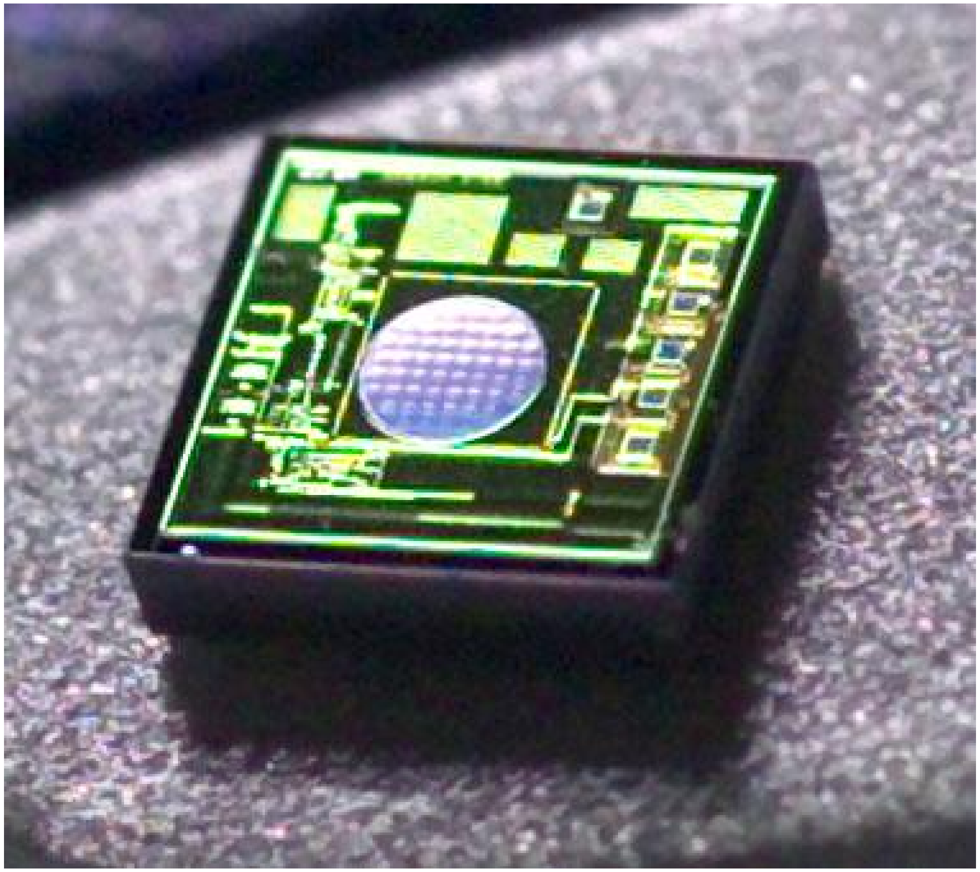
Sensimed intraocular pressure sensor in contact lens

Accelerometers & Gyroscopes



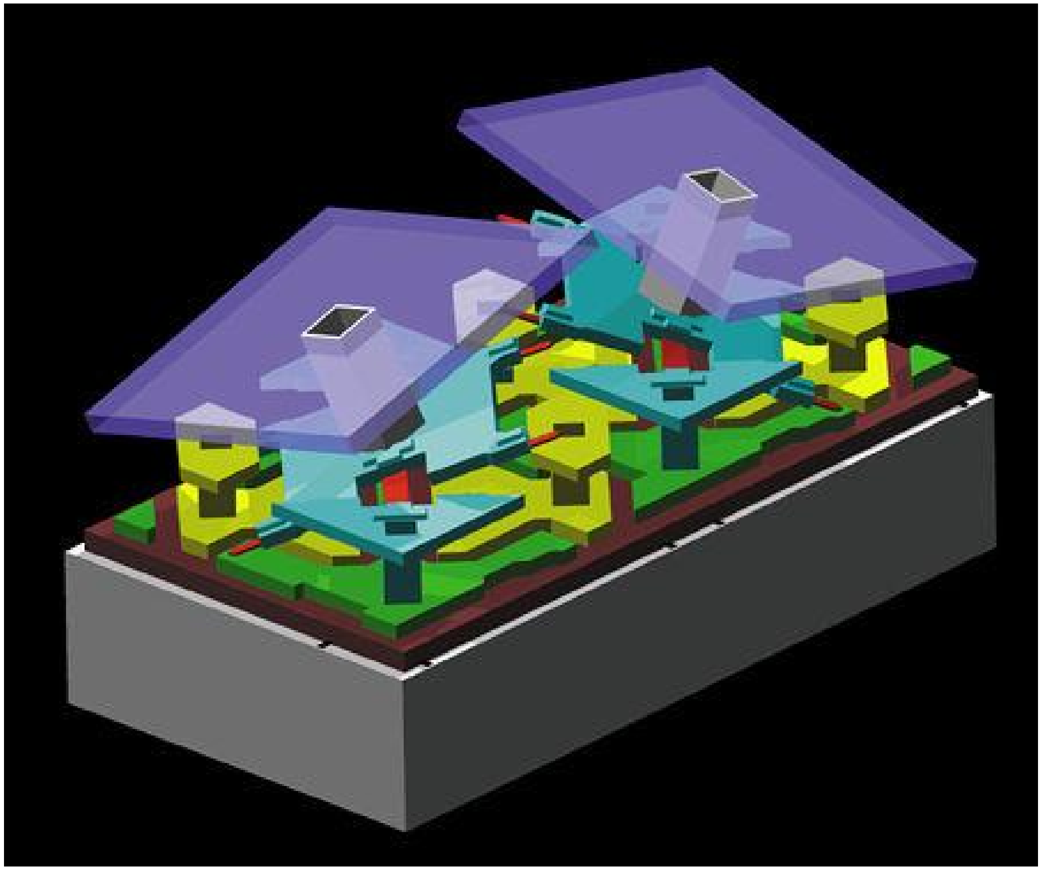
Freescale accelerometer

Microphones



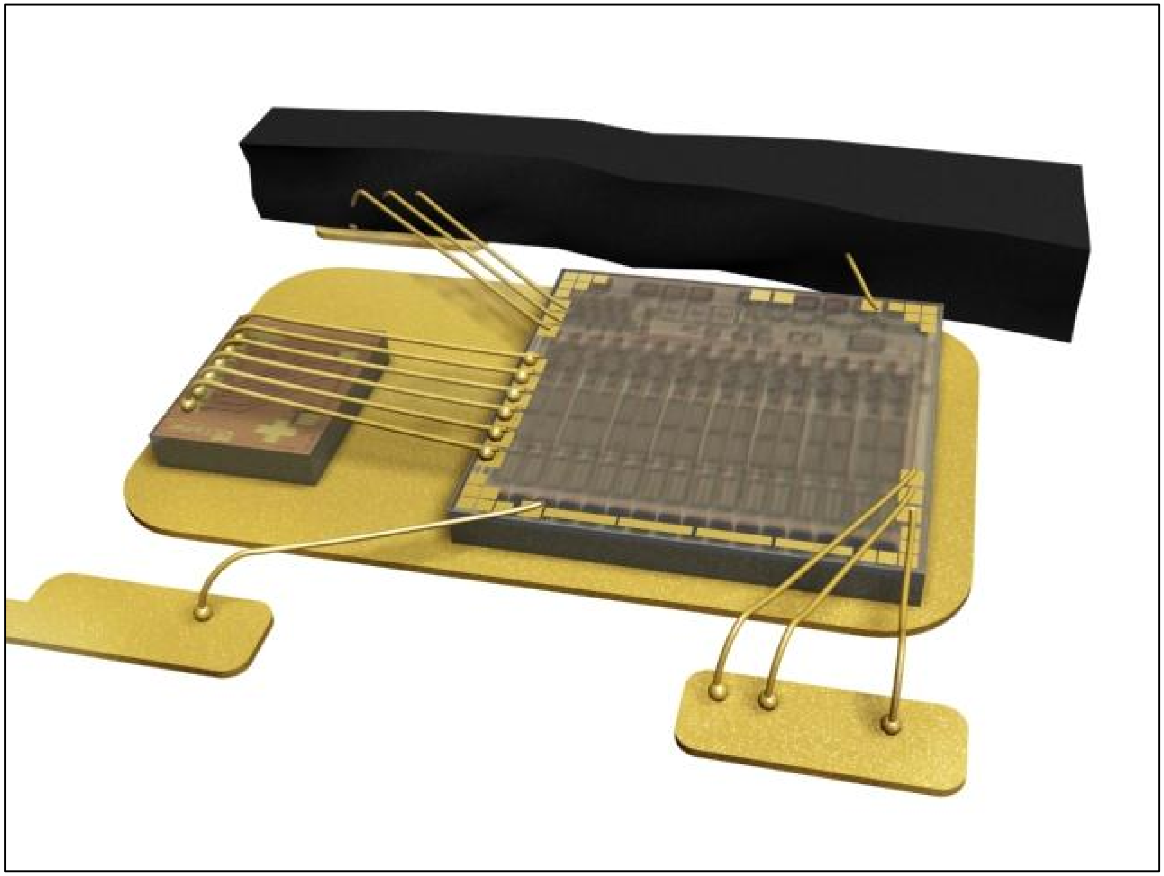
Akustica microphone

Light Modulators & Projectors



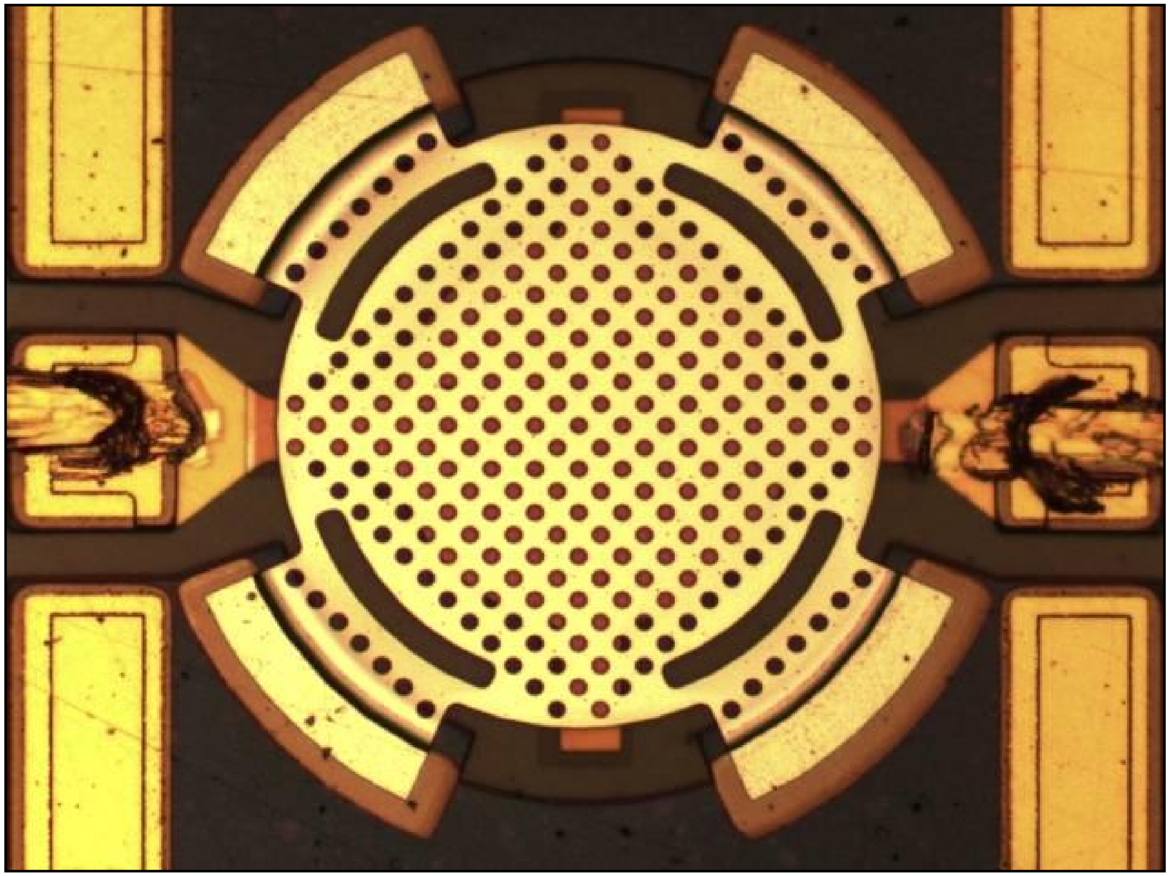
Two pixels in a TI DLP mirror array

Resonators & Oscillators



SiTime oscillator

RF Switches



G. Rebeiz UCSD, RF switch

- MEMS Materials, Processes, and Example Applications
- **Electrical Interfaces**
- Scaling Laws
- Packaging is Critical
- CMOS Integration
- How to Succeed
- References

Capacitive Overview

- Capacitive transduction is used in 90% of MEMS interfaces.
- Good Points:
  - Easy to build, no need for special materials.
  - With the Bosch etch we can make beautiful cap structures.
  - Can move small to large distances.
  - Can move in-plane and out-of-plane.
  - Can sense tiny displacements.
- Bad points:
  - Often will not deliver as much force as desired.
  - Needs bias voltage, sometimes large.
  - Output signals can be very small.

Capacitive Drive

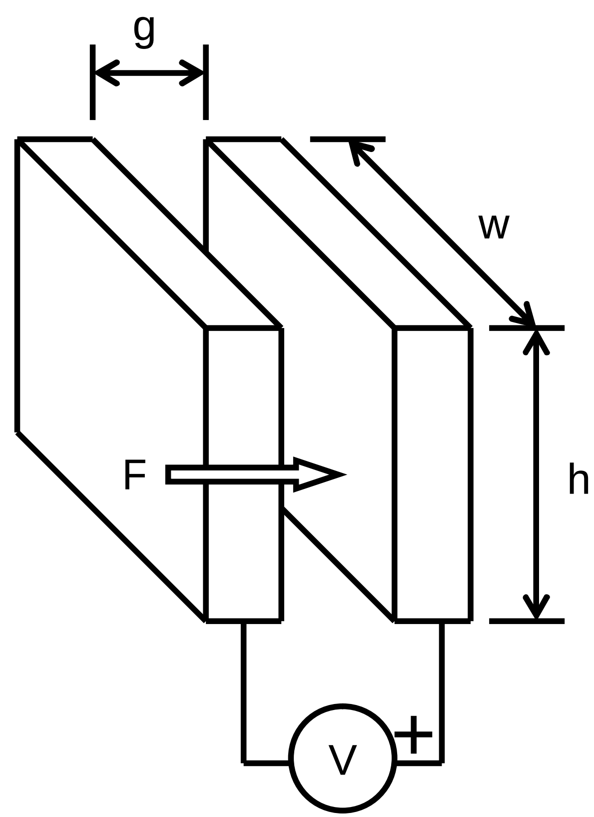
- How does capacitive drive work? Take a parallel plate example:

$$F = \frac{\varepsilon_c wh}{2g^2} V^2$$

- Were F=force, ε_0=permittivity, w=width, h=height, g=capacitive gap, V=voltage.

- The voltage squared gives attractive forces and drive nonlinearity.

- The gap squared gives displacement nonlinearity.



Capacitive Drive

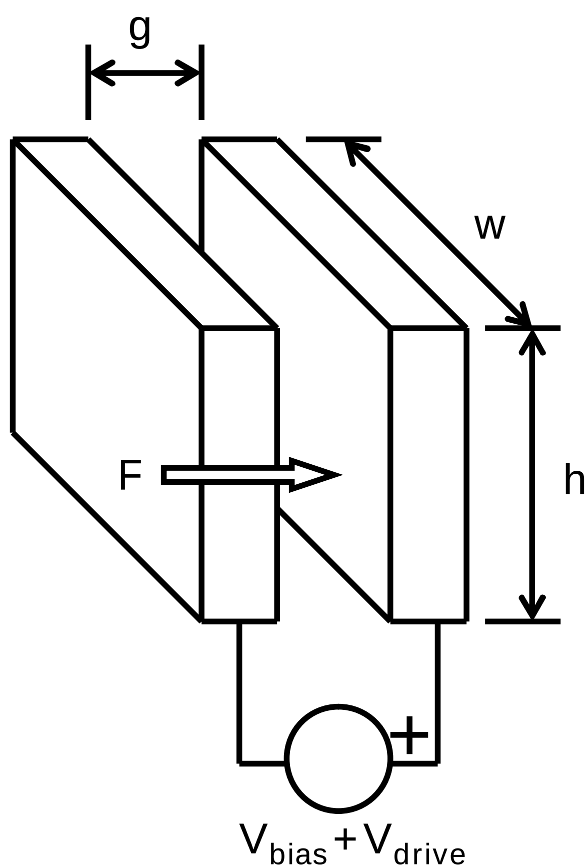
- Want bipolar force?
- We can offset the attraction (pull more and pull less) with DC bias and AC drive.

$$F = \frac{\varepsilon_c wh}{2g^2}(V_{bias} + V_{drive})^2$$

- Set $V_{bias} >> V_{drive}$ and we get a bipolar offset drive.

$$F_{offset} \approx \frac{\varepsilon_c wh}{g^2} V_{bias} V_{drive}$$

- As bias is increased and drive is decreased the linearity improves.



Capacitive Drive

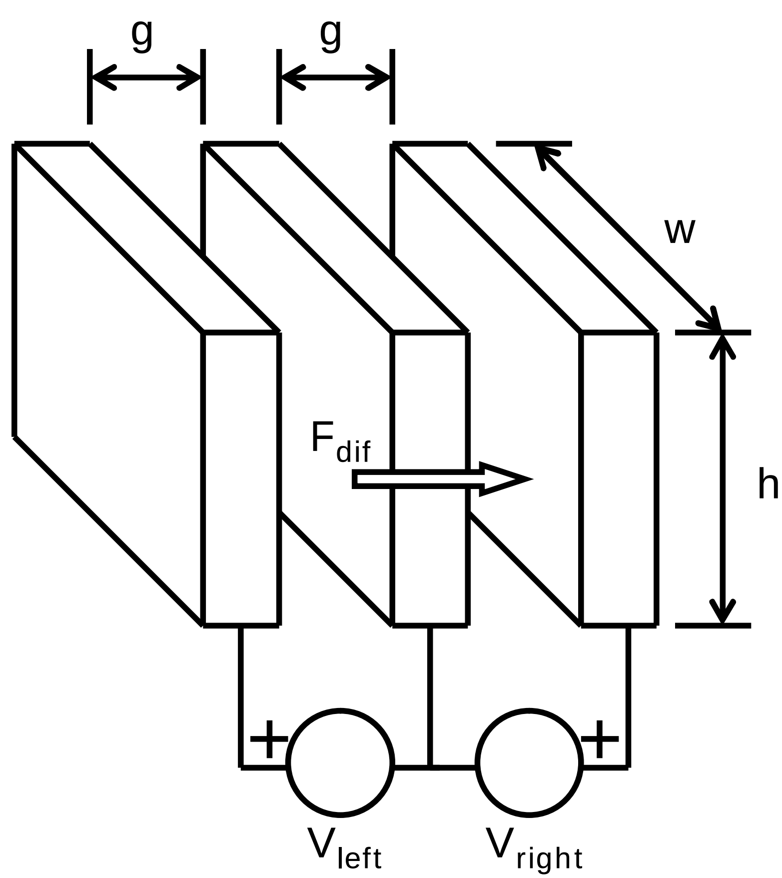
- Second option for bipolar is differential (pull one way, pull the other),

$$F_{dif} = \frac{\varepsilon_c wh}{2g^2}\left(V_{left}^2 - V_{right}^2\right)$$

- Offset and differential can be combined,

$$F_{dif} \approx \frac{\varepsilon_c wh}{g^2} V_{bias}\left(V_{right} - V_{left}\right)$$

- Typical bias and drive are 5V and 0.5V.

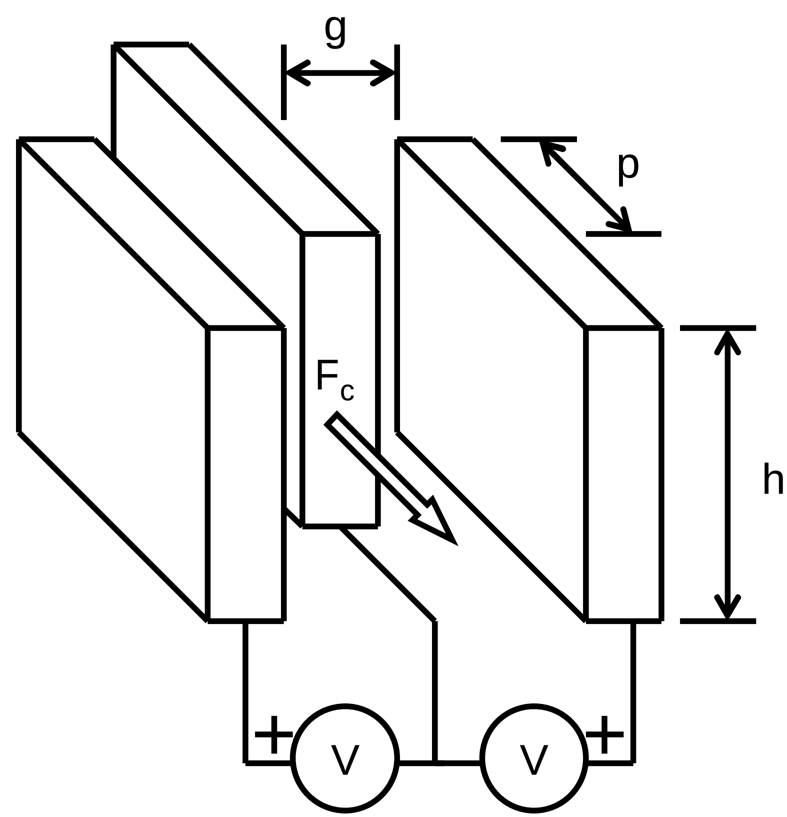


Capacitive Drive

- Interdigitated fingers (combs) can move further and are more linear.

$$F_{dif} = N\frac{\varepsilon_c h}{g}V^2$$

- *N* is the number of fingers.
- Since p does not effect F_c it is linear in displacement.
- Pairs of fingers can be used differentially to linearize V and push-pull.



Capacitive Sense

- For capacitive sensing, we need to think about charge,

$$Q = CV, i = dQ/dt$$

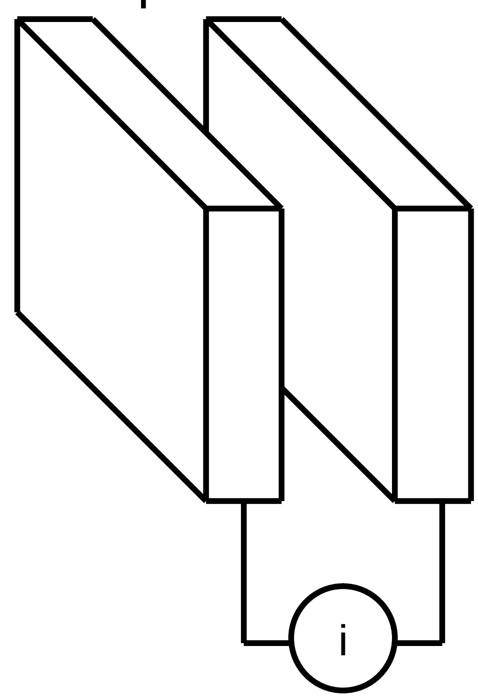
- We all learned that,

$$i = C(dV/dt)$$

- But for MEMS sensing we sometimes care more about,

$$i = V_{dc}(dC/dt)$$

- And we use a bias V_{dc}, often about 5V but can be 100's!



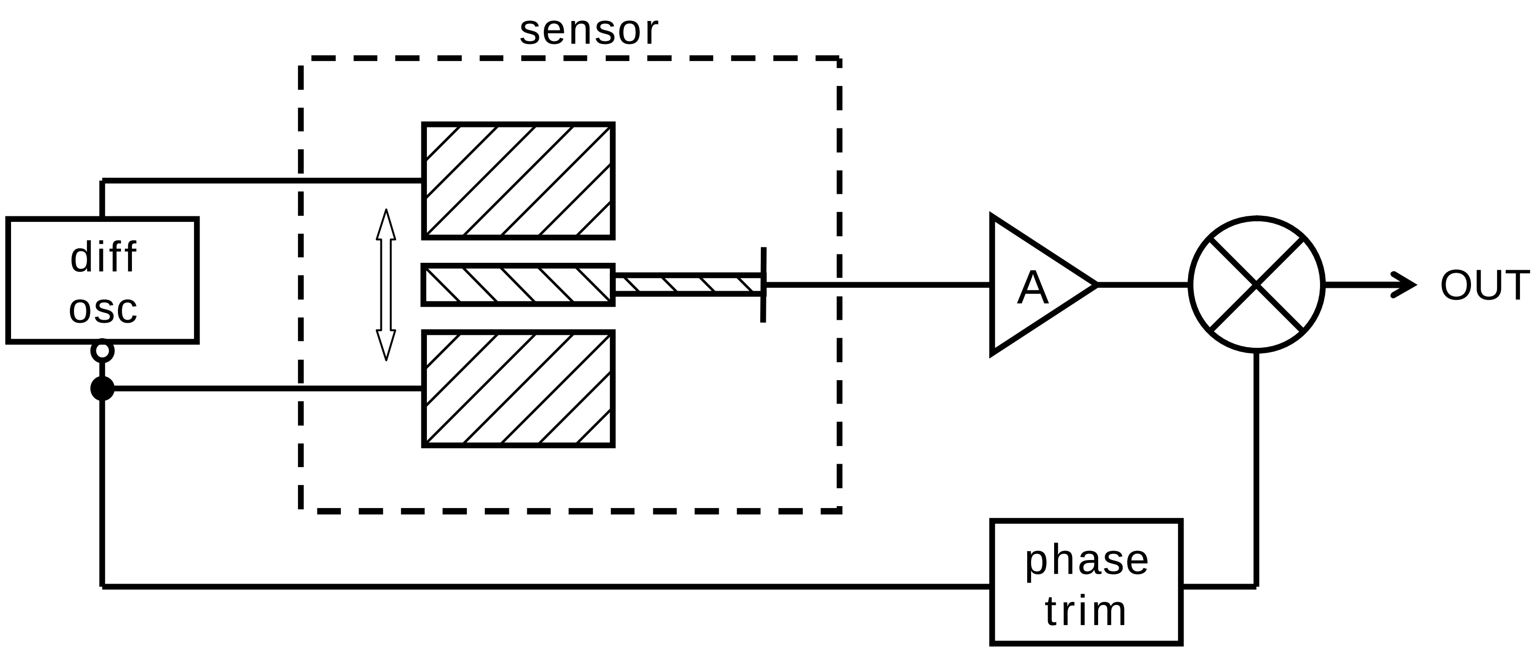
Any structures with dC/dx work. Fingers are common.

Capacitive Sense

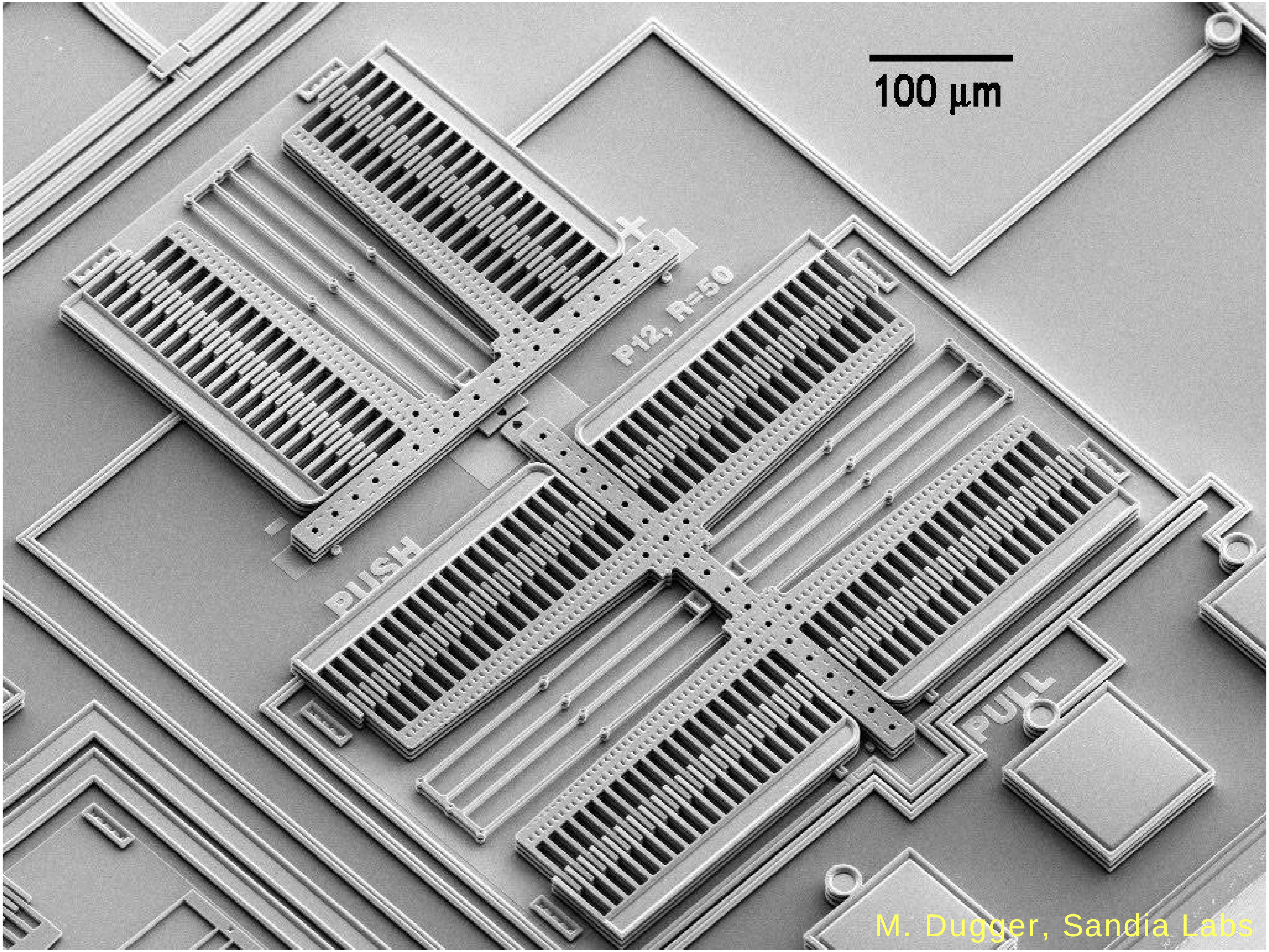
- What you will need to do as an engineer
  - Because capacitances are small, sense currents are small.
  - Design the lowest noise sense amps possible.
  - If noise is not critical then shrink the MEMS.
  - Always push the circuits, always simplify the MEMS.

- Drive Circuits
  - For AC system (gyros, vibrometers, oscillators) we need to sense AC current.
  - For DC systems (accelerometers) we need to modulate a carrier.
  - Clasic accelerometer drives a differential signal on plates and measures current with a lock-in amplifier.

Capacitive Sense



- Differential lock-in sense amp for accelerometers.


100 µm
P12, R=50
PUSH
PULL
M. Dugger, Sandia Labs

Piezoresistive Overview

- Transduces strain to resistance.
- One of the earliest MEMS interfaces and still important.

- Good points:
  - There is mechanical gain, typically about 30x.
  - The common sensor structure is a Wheatstone bridge.
  - Silicon-friendly fabrication, doped resistors work well.

- Bad points:
  - Main problem is temperature sensitivity – moderately doped silicon resistors change about 0.5% per C or more.
  - 1/f noise and drift can be problematic.
  - Only senses, does not drive.

Piezoresistive Sense

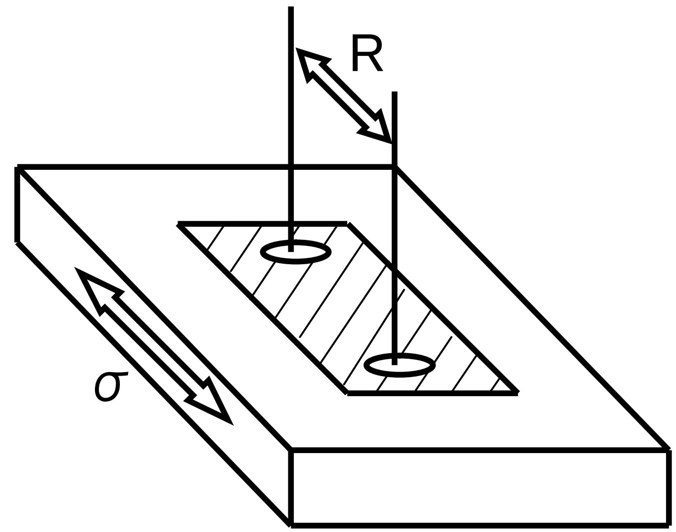
- A simple idea with may coefficients – strain changes resistivity.

$$\frac{\Delta\rho_\omega}{\rho} = \sum_{\lambda=1}^{6} \pi_{\omega\lambda}\sigma_\lambda$$

- $\Delta\rho/\rho$ = change in resistivity, $\pi_{\omega\lambda}$ are piezo coefficients, $\sigma_{\omega\lambda}$ are stress. The $\pi_{\omega\lambda}$ form a sparse 6x6 matrix.

- For specific cases the equation can be simplified to,

$$\frac{\Delta R}{R} = \pi_{effective}\sigma_{axial}$$

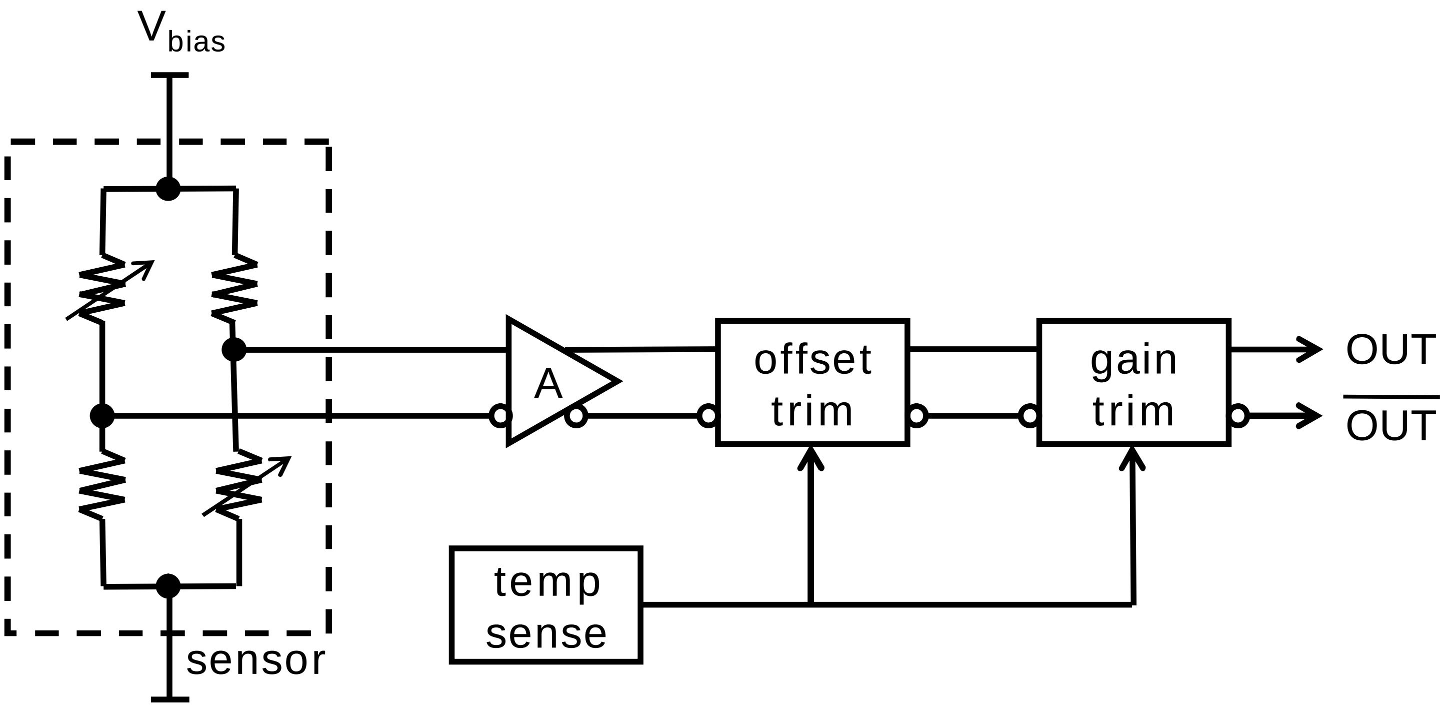


Piezoresistive Sense

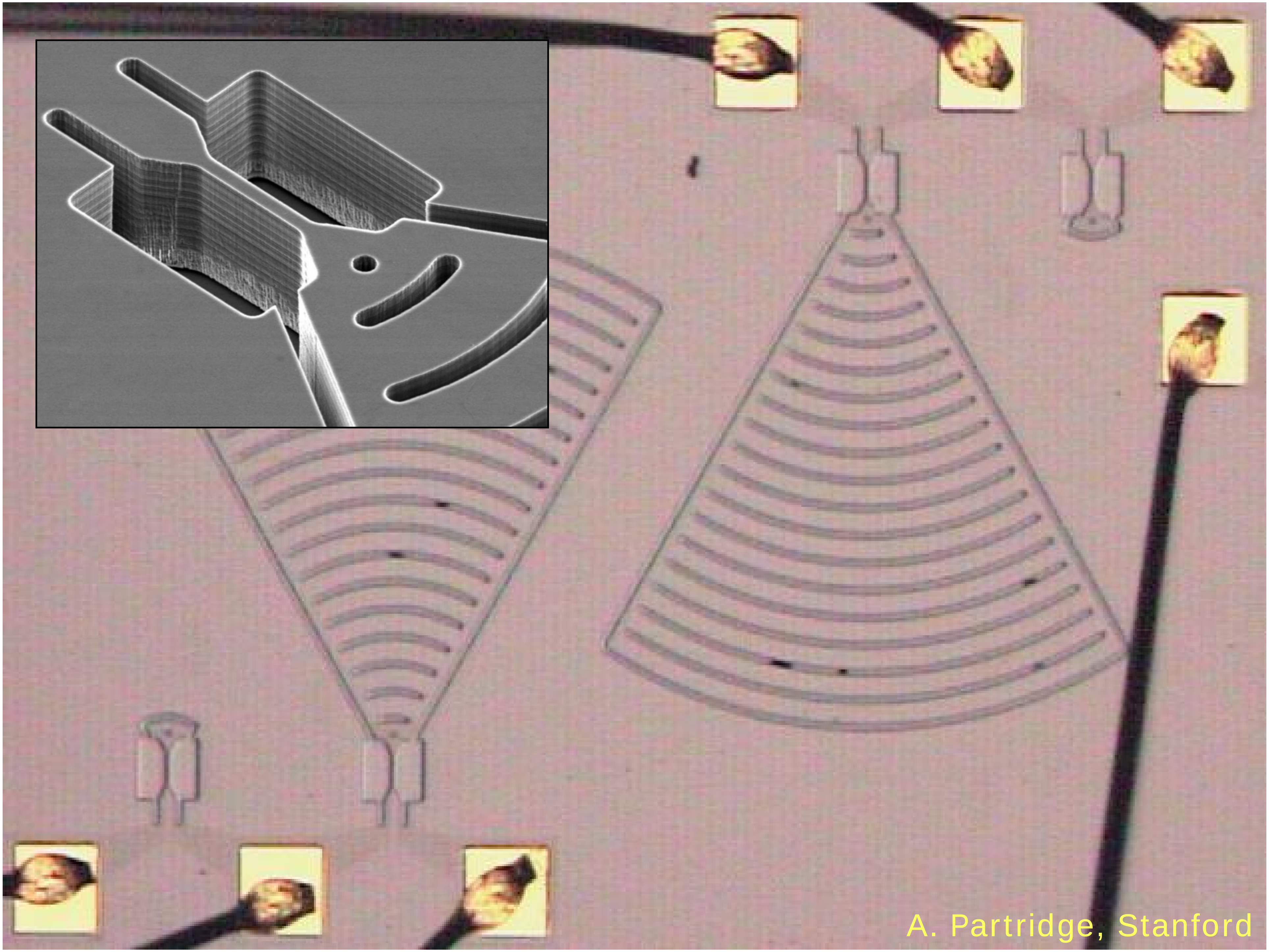
- Typical sense circuits are bridges.
  - This minimizes the temperature sensitivity that can swamp signals.
  - Input offset often vital – use switched caps, diversity, etc.
  - Often must minimize 1/f noise – use switched topologies.
  - Temperature compensation of offset and gain variation is often needed.

- See: A.A. Barlian, W-T. Park, J.R. Mallon Jr., A.J. Rastegar, and B.L. Pruitt, ‘Review: Semiconductor Piezoresistance for Microsystems ”, Proceedings of the IEEE, v.97, n.3, March 2009.

Piezoresistive Sense



- Bridge amp with temperature offset and gain correction


A. Partridge, Stanford

Piezoelectric Overview

- Transduces force to voltage.
- Aluminum Nitride (AlN) is the most common material.

- Good points:
  - Moderately easy to fabricate, available in MEMS foundries.
  - Can provide low impedance and tremendous power handing for RF.
  - Works well at high frequencies.

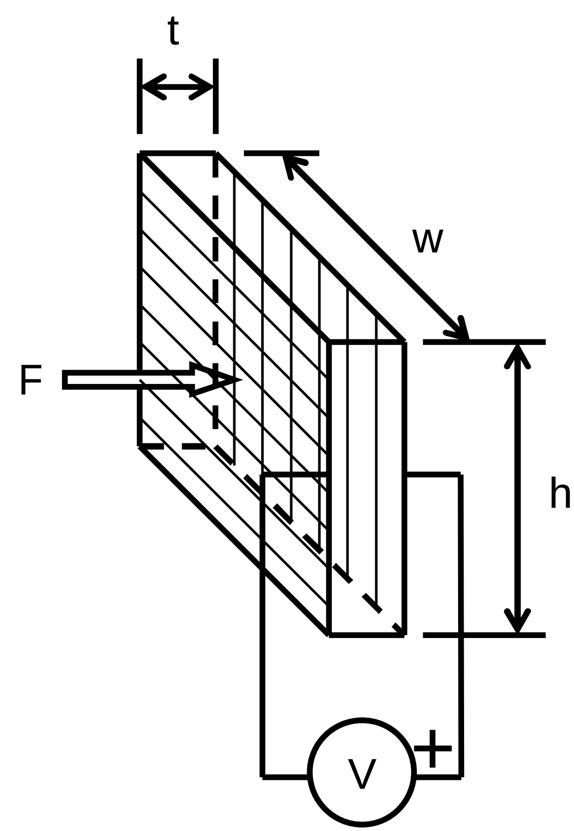
- Bad points:
  - Displacements are tiny, so not generally used for motion.
  - Rather low Q’s when used in resonators.
  - Does not transduce DC signals.

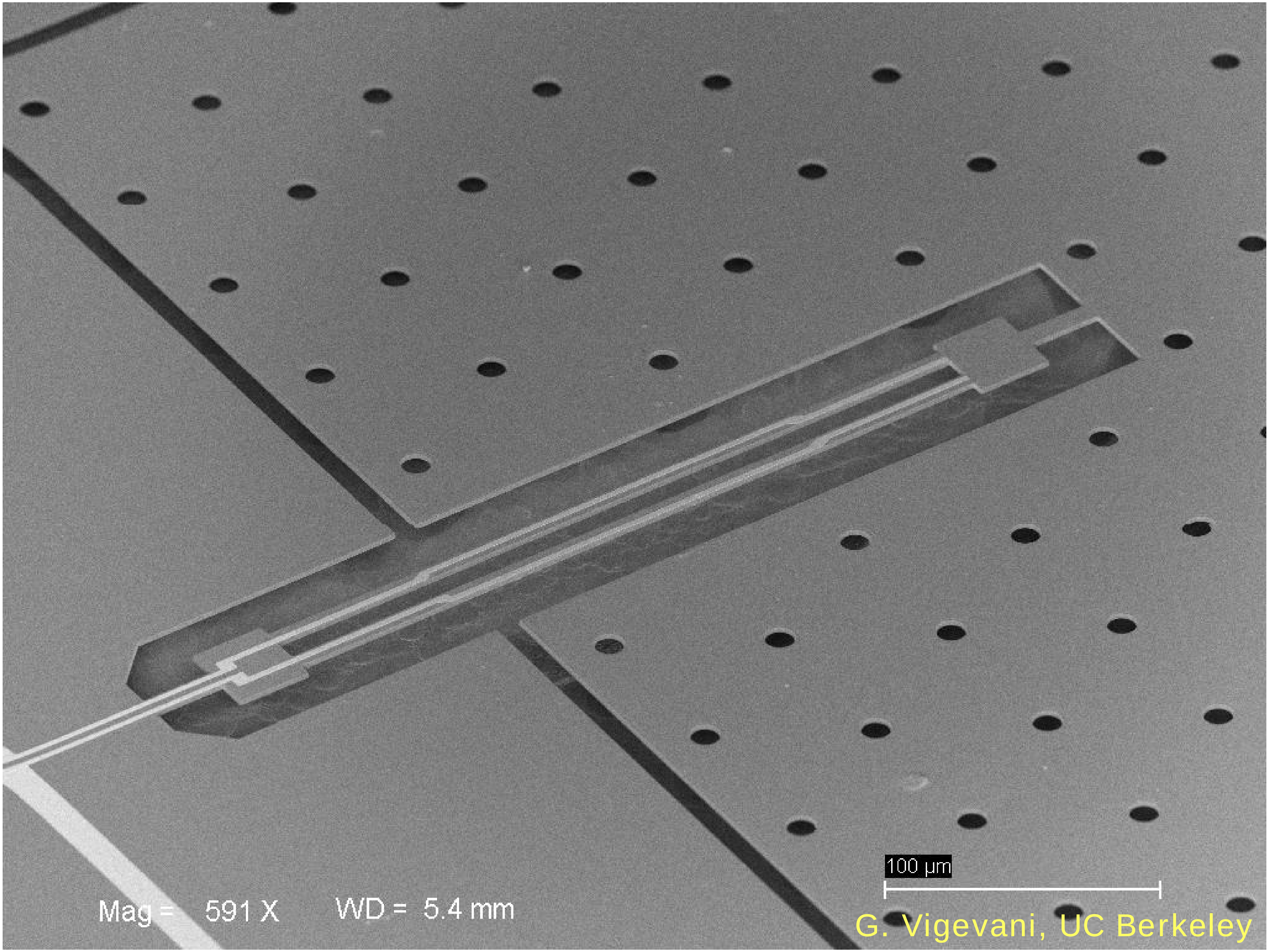
Piezoelectric Drive and Sense

- For sense and drive, think in terms of S21 and S12.
- In the simplest form,

$$V = \bar{d}\,\frac{t}{ewh}\,F$$

- Where t=thickness, e=dielectric permittivity, and d-bar is the piezoelectric charge coefficient (a function of material and orientation).




100 µm
Mag = 591 X
WD = 5.4 mm
G. Vigevani, UC Berkeley

Other Transducers

- Thermal sensors, particularly thermistors, are often used for IR imaging bolometers.
- Chemical sensors of all kinds are used in biology.
- There are lots of optical transducers, and this is an important area for displays. Optical forces can even be used to drive MEMS, but that is rare.
- Magnetic transducers are common in macrosystems but don t work well in micro. They are rare.
- There are endless other ways to transduce signals.

Remember This:

You will usually need to design the lowest noise circuits possible. If the MEMS is producing extra signal then it should be simplified.

- MEMS Materials, Processes, and Example Applications
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Scaling Laws

- Most things scale against us, not for us.

- Mechanical structures
  - Volume and mass: x^3 (simple)
  - Mechanical stiffness: x (extensional)
  - Resonant frequency: $1/x$ (extensional)

- Transducers
  - Piezoresistance: — (no scale)
  - Capacitance: x (voltage to force)
  - Piezoelectrics: x (voltage to force)
  - Magnetics: x^4 (current to dipole torque)
  - Optics: λ (wavelength limits)

Why Does Scaling Matter?

- Most MEMS things get worse when made smaller
  - Mass goes down cubically, so inertial sensing gets tougher.
  - Capacitive and piezoelectric transducers get worse linearly.
  - Magnetic transducers scale terribly.

- A few things get better
  - Circuits can be mounted closer, so C-strays decrease.
  - Resonant frequencies increase.
  - Reliability improves.
  - And (the most important) unit costs decrease.

- Poor scaling is counterintuitive for circuits engineers.

Remember This:

Know how your system scales and leverage things that work for you and not against you.

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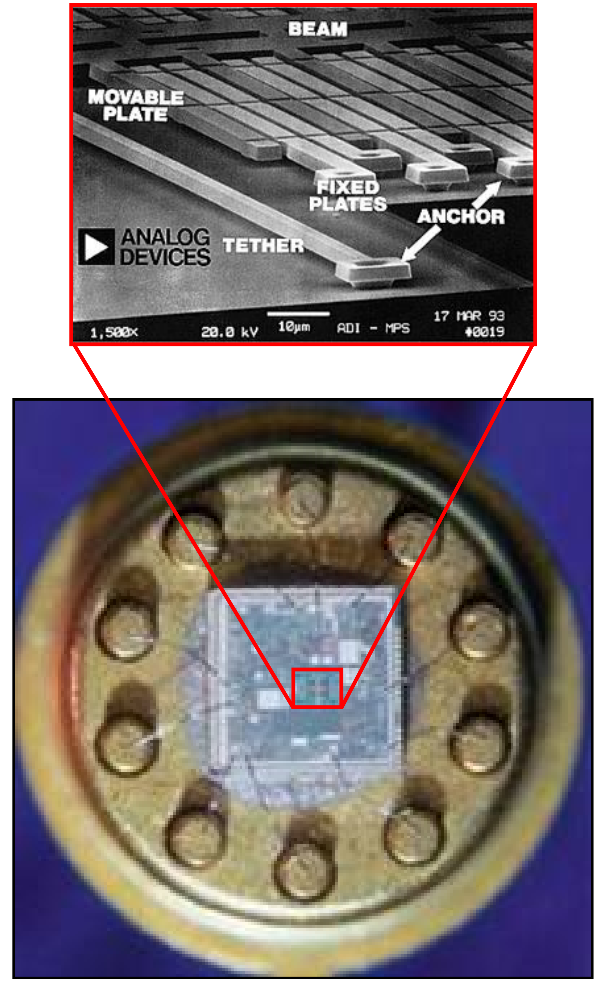
Packaging is Critical

- In circuits we don't think about packaging, except for
  - Size.
  - Lead inductance and resistance.
  - Heat dissipation.
- In MEMS, packaging is the single most important thing after the transducer selection
  - How do we protect the parts in operation?
  - How do we handle the parts in packaging?
  - Can we dice the parts from the wafers?
  - How do we connect to the sense/drive medium?
  - How do we isolate from the environment?
  - A million problems happen here.

Back-end Packaging

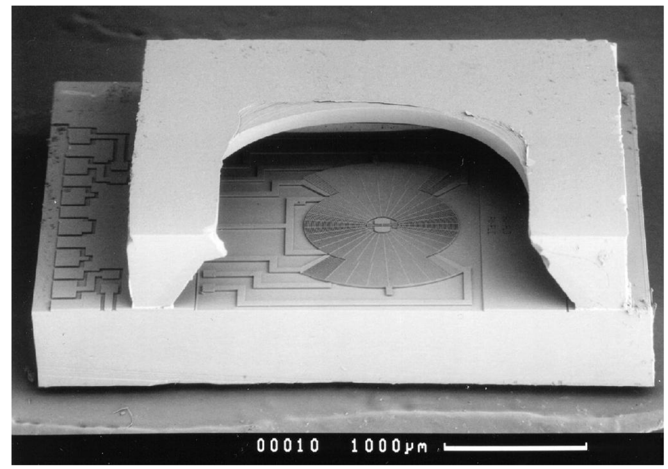
- Sometimes just put the MEMS and CMOS into a package.
- Don t touch it!
- Production complications
  - How to dice?
  - How to pick & place?
  - Need a clean room?
- For some apps, like chemical detectors, it can work well.



ADI ADXL-50 circa 1995

Bonded Covers

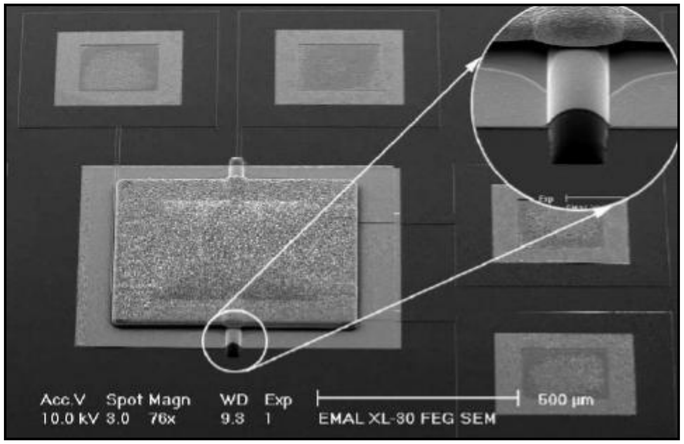
- Wafer bonded covers protect the MEMS elements
  - Can use frit glass to glue the wafers together.
  - These covers can take 80% of the die area.
  - Building the covers can be expensive.
- Much less expensive then handling naked MEMS wafers.
- The dominant technology today.



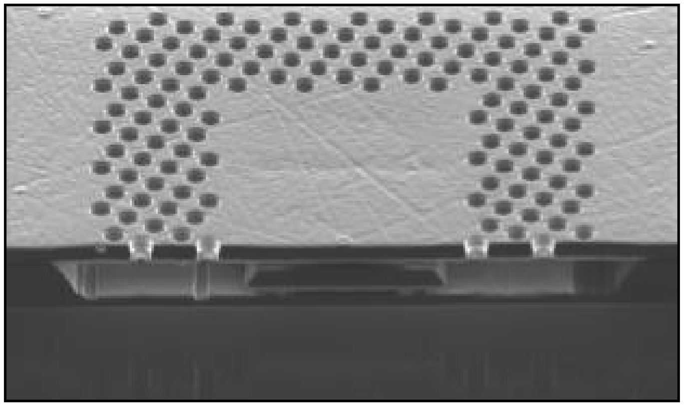
Bosch Gyroscope circa 1999

Deposited Thin Film Covers

- Save space by depositing rather than bonding covers.
- Harder than it looks
  - How to empty it out inside?
  - Thermal mismatches.
  - Contamination.
  - Need strength for plastic.
  - Limits MEMS designs.
- Development is expensive
  - Only makes sense for high-volume applications.

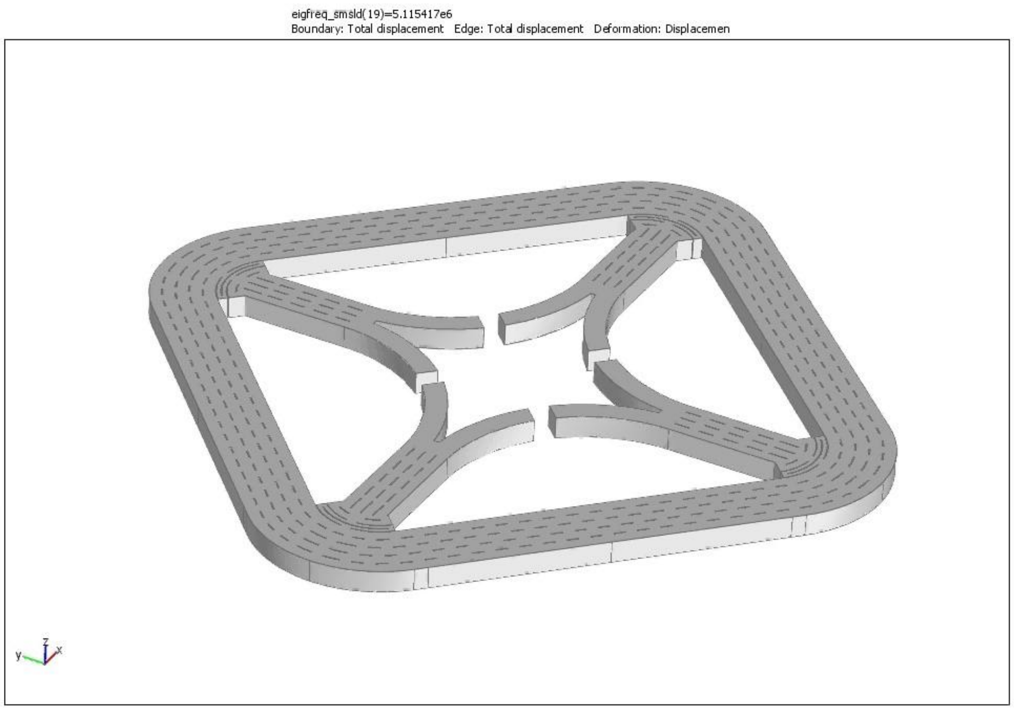


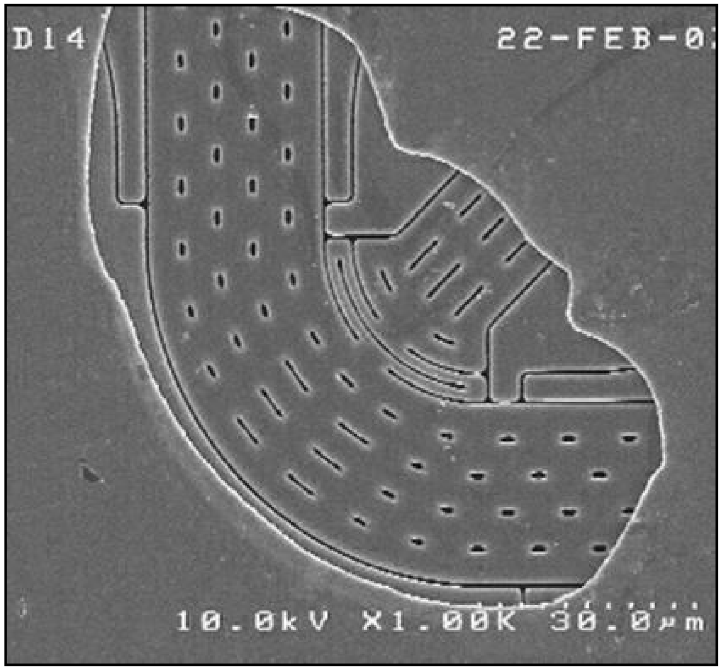
B.H. Stark, JMEMS 2004



J.L. Lund, Hilton Head, 2002

Deposited Encapsulation Example



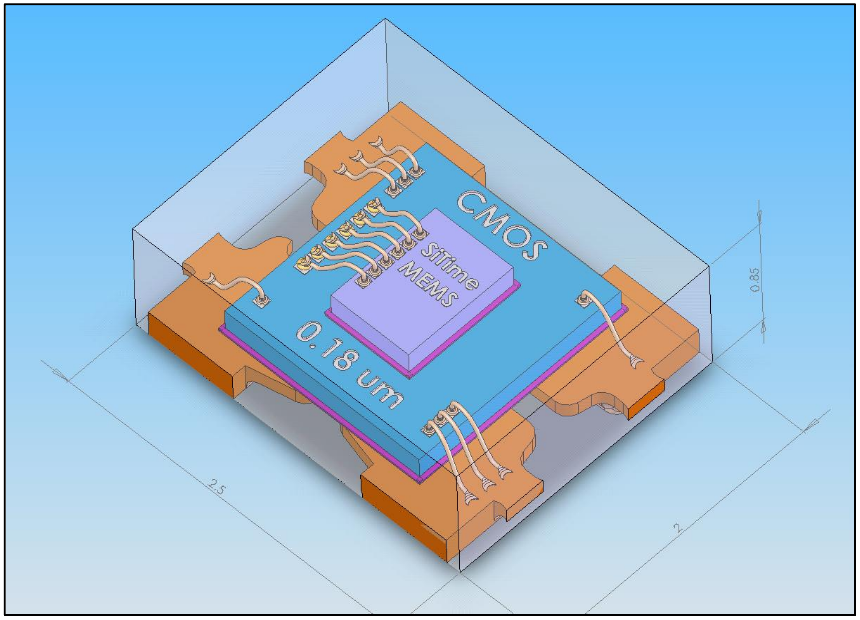


SiTime Resonator

- SiTime (my company) buries resonators under the wafer surface.

Stacked Die in Plastic

- When the MEMS is covered or encapsulated
  - It can be diced like a CMOS wafer.
  - Pick-place, wire bond, mold, etc, all normal.
- A low cost option when it works for the app.
- Applications like optical switches can t use this.



SiTime Oscillator Construction

Remember This:

Design from the outside to the inside,
and do the packaging first.

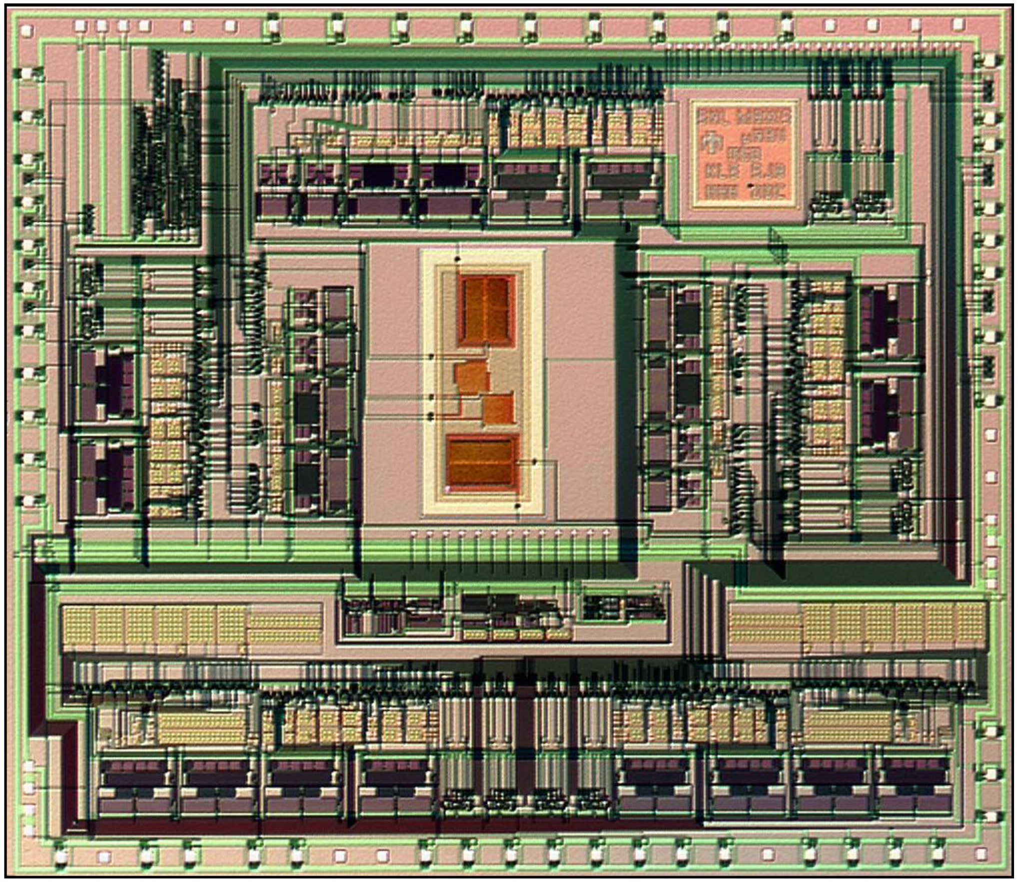
Homogeneous Integration

- Only three ways
  - MEMS on CMOS.
  - MEMS in CMOS.
  - MEMS under CMOS.

- Usually not the best approach
  - Do you have the time and money?
  - Do you feel lucky?

- Just a few of the problems...
  - The MEMS process can change the CMOS behavior.
  - The CMOS process may need to be adjusted.
  - Price leverage of CMOS at risk.
  - MEMS process limitations are severe.
  - Wasted area increases costs for each process.
  - Yield issues multiply (literally).

Homogeneous Example



3-Axis Accelerometer, Sandia

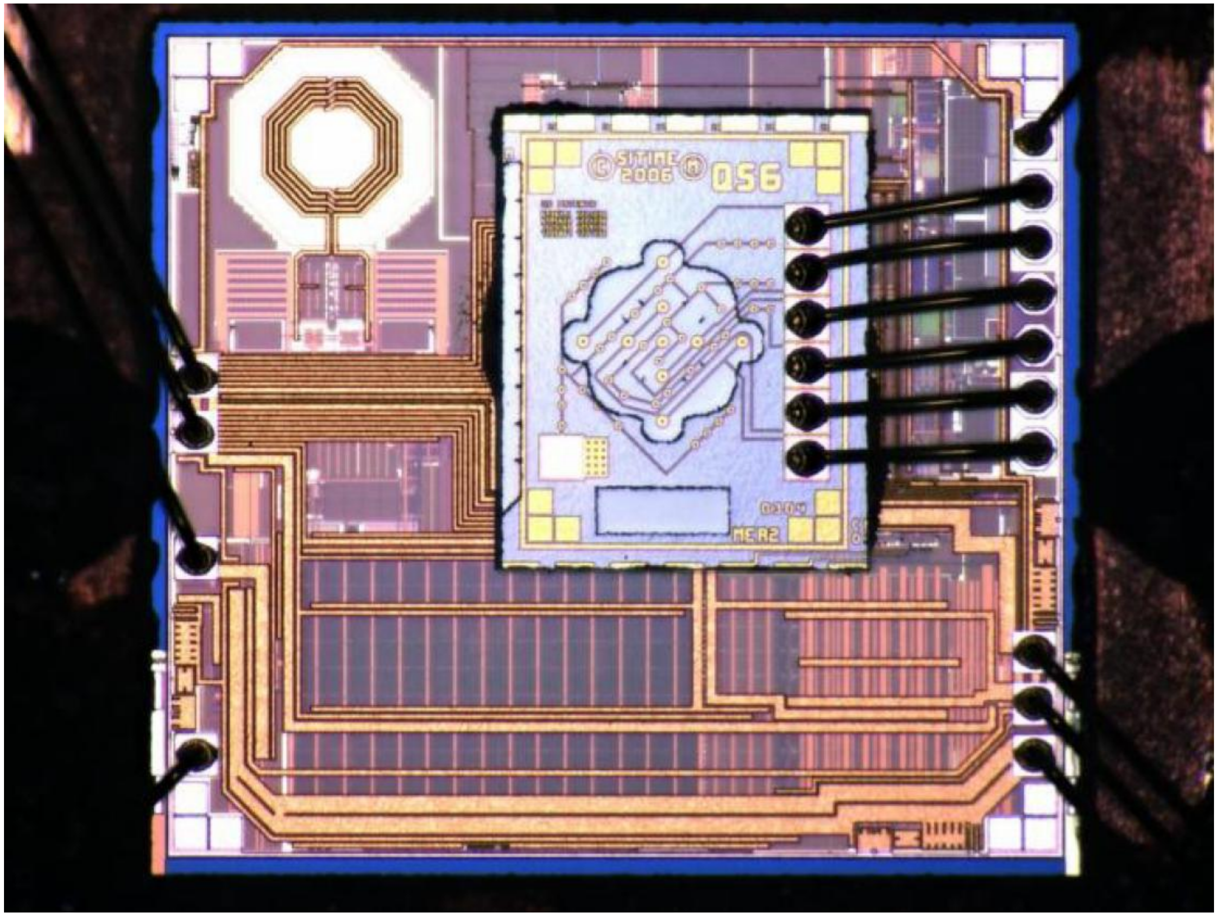
Heterogeneous Integration

- Usually a better approach
  - Build the MEMS and CMOS die into one package.
  - Can be wire bonded or bump bonded.
  - Requires the MEMS be pre-covered for most apps.

- Usually cheaper, faster, and more versatile
  - MEMS+CMOS can be developed in parallel.
  - Fewer material and temperature restrictions on the MEMS.
  - Shorter development times.
  - Many fewer surprises.

- Be prepared to argue against a homogeneous approach
  - It seems obvious, everything is getting integrated right?
  - Actually, heterogeneous integration is very common in RF.

Heterogeneous Example



Oscillator, SiTime

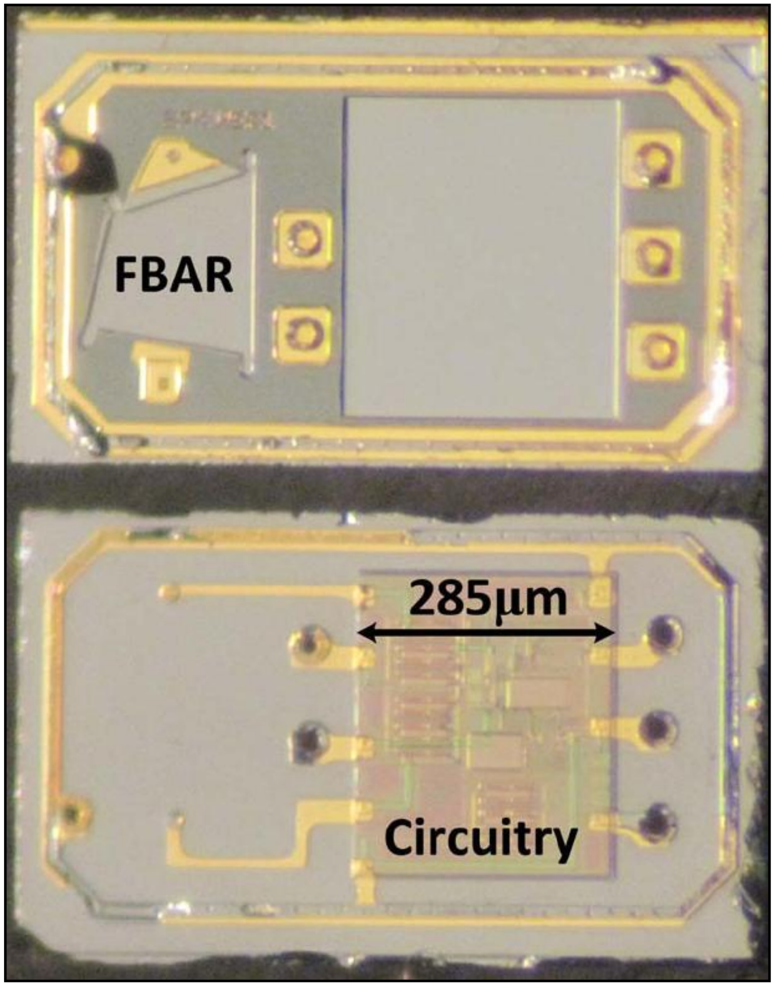
Wafer-scale Integration

- MEMS wafer bonded to CMOS wafer
  - The wafers are bonded face-face at the MEMS fab.
  - Various proprietary metallurgies at MEMS fabs.
  - Common are gold compression and eutectics.

- Has some good points
  - Electrically close – low capacitance.
  - Many interconnects possible.
  - Usually a decent and hermetic lid.
  - Built in parallel, a full wafer at a time.

- Not always a good idea
  - Enforces a 1:1 size constraint on MEMS:CMOS die.
  - Usually wastes space on one or both die.
  - Yield losses multiply.

Wafer-scale Example



MEMS Wafer

Circuits Wafer

Rich Ruby, Avago, IFCS 2011

Remember This:

Never integrate MEMS on, in, or under CMOS without a very compelling reason.

- MEMS Materials, Processes, and Example Applications
- Electrical Interfaces
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Problems to Manage

- You will need to build something early
  - The MEMS components will not be finished when you start your IC design.
  - You will not have solid data for your analysis.
  - If prototypes have been tested, the new parts (the real parts!) will be different.
  - When the MEMS is tested it will show "surprises".

- You will need to make your own circuit models
  - The MEMS components will not modeled for you.
  - At best you will have theory or Matlab code.
  - Spice? Verilog-A? CppSim? You will need to build them yourself.

Problems to Manage

- Specs will change in the middle of development
  - There are three, maybe four things in flux.
  - Circuits, MEMS design, MEMS process, and software.
  - On the applications side, marketing and sales learn too.
  - Rates of flux are higher than you may be used to.

- To improve the chances your circuits work
  - Understand the system in detail.
  - Understand the MEMS as much as possible.
  - Design circuits with as much flexibility as possible.
  - Insist on rapid prototyping cycles with test chips.
  - Don t go for product too early, it can waist design effort.

Important Points

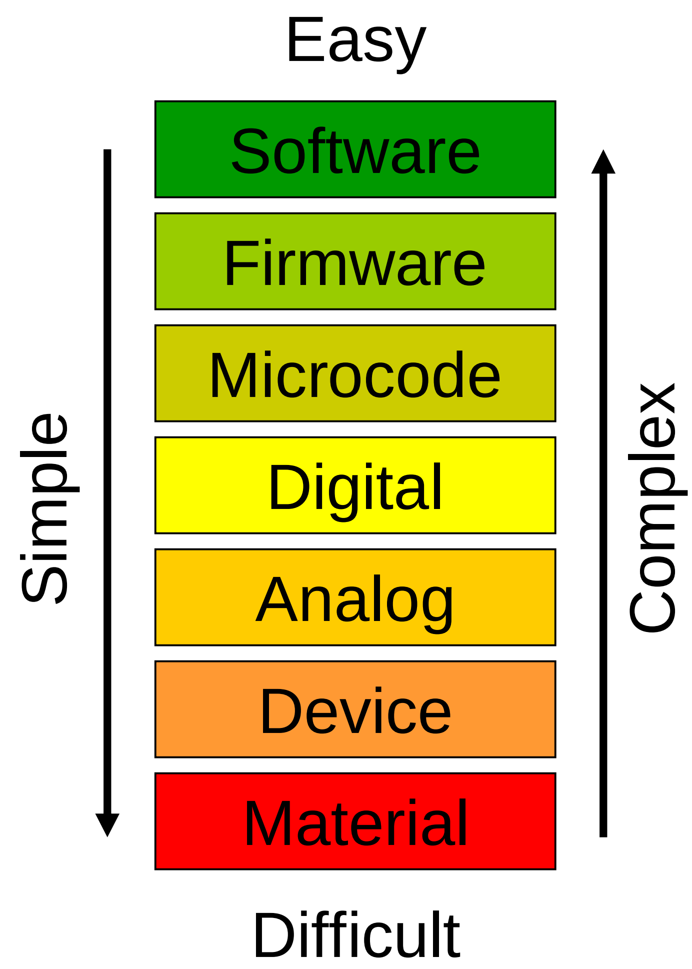
- Be sure you have a MEMS expert on the team
  - Hire one or consult with one, but get one.
  - Amateurs who think they are smart enough are wrong.
- Understand the application drivers
  - How does the scaling work?
  - Does it require integration?
- Consider the packaging carefully
  - Design from the outside to the inside.
- Be sure an IC engineer (you) are involved early
  - System design requires balancing circuit tradeoffs.
  - Does a good circuits person know the details?

Important Points

- Build flexibility in your IC
  - The MEMS will not work as expected, so roll with it.
  - The MEMS will be improved later, and the earlier IC should support that.
- Insist on many small learning cycles
  - Use test chips to prove out the concepts.
  - Don t go into product design too early.
- Take a bigger role than IC designer
  - You must be the guardian of your success.

Aaron's Complexity Paradox

- The "Simple" solutions are difficult.
- The "Complex" solutions are easy.
- Move toward easy solutions whenever possible, this means increasing complexity.
- Embrace complexity to succeed.



Aaron's Complexity Paradox

- For system designers this means
  - Push the problem out of MEMS whenever possible.
  - Don't ever make the MEMS designers do something that one can possibly do elsewhere.

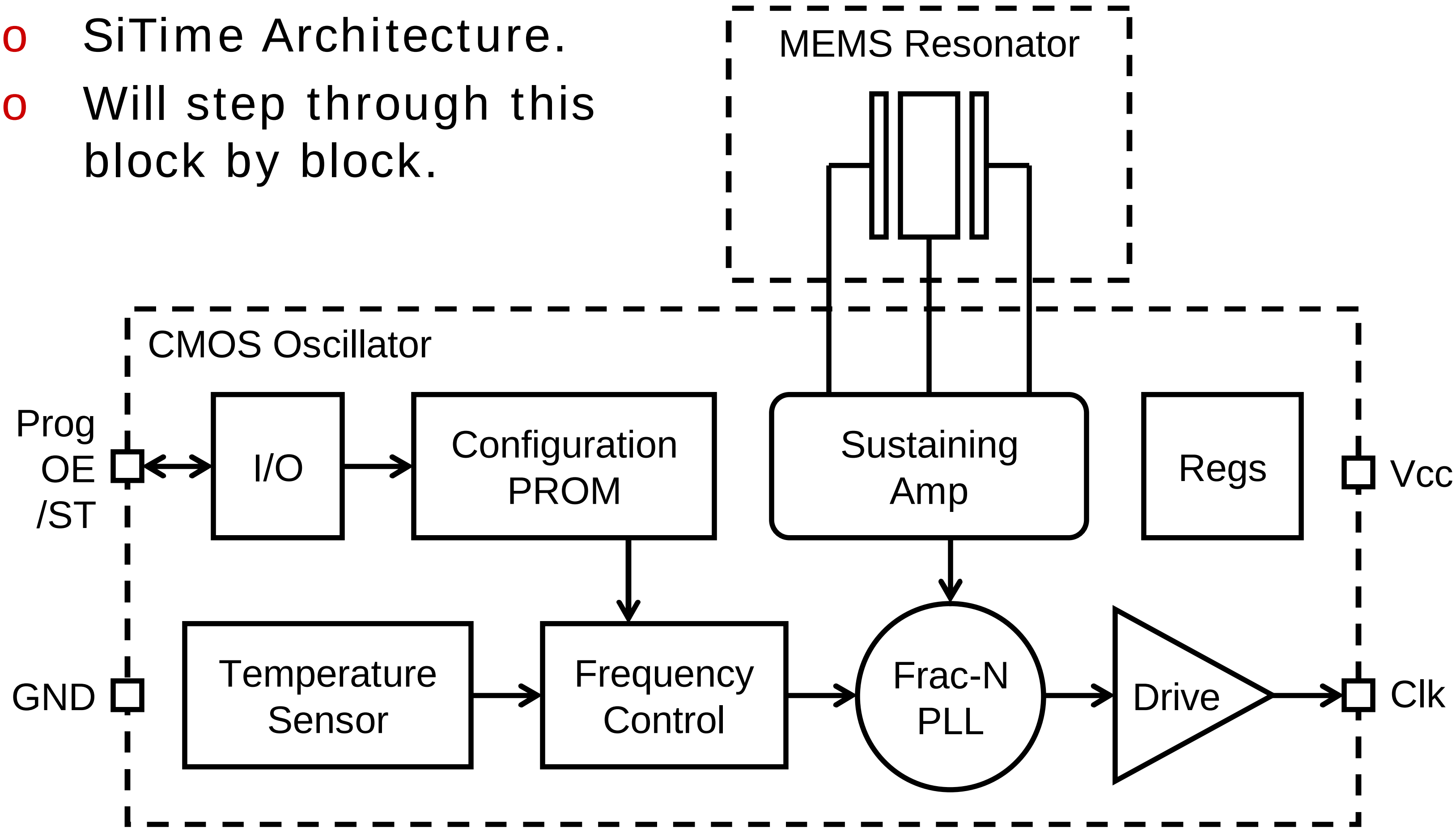
- For IC designers this means
  - You will be (or should be!) asked to push your circuits to the limit to ease the work in MEMS.
  - Working with MEMS will never be easy – you will always need to bring your best game.

Complexity Management Example

- MEMS oscillator researchers (including me!) tried to build frequency-accurate temperature-flat resonators.
  - *That didn't work.*
- Then my colleagues and I moved the complexity into CMOS and managed the frequency with frac-N PLLs.
  - *That worked!*
- *Then all sorts of great things started happening – we could include new functions in that CMOS.*

Complexity Management Example

- SiTime Architecture.
- Will step through this block by block.



Choose the Right Products

- Must have a Starving Market. (Kurt Petersen)
- Must have an Unfair Advantage. (Arno Penzias)

- Why discuss this in a circuits tutorial?
  - Because we engineers and scientists can almost always make our stuff work.
  - But failure happens when people don t want our stuff.
  - Good engineering, when not needed, is wasted effort.

- We don t have time to waste, we are very expensive for our companies.
- And besides, we have better things to do than engineer stuff that people don t need.

Remember This:

We are valued not by what we do, but
by what we do that makes a difference.

Your Work Does Make a Difference

- Technology has fundamentally helped Humanity.
- Engineers make small contributions that are multiplied countless times.
- What you do matters to Billions of people!

Dorothea Lang, ‘Migrant Mother” 1936

Thank You!

Questions?

- MEMS Materials, Processes, and Example Applications
- Electrical Interfaces
- Scaling Laws
- Packaging is Critical
- CMOS Integration
- How to Succeed
- References

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