EE C247B – ME C218
Introduction to MEMS Design
Spring 2018

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Module 16: Sensing Non-Idealities & Integration

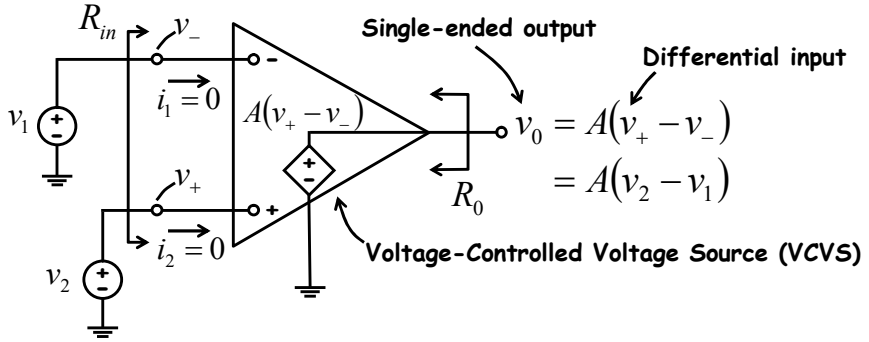
Lecture Outline

- Reading: Senturia Chpt. 14, 15
- Lecture Topics:
  - Ideal Op Amps
  - Op Amp Non-Idealities
  - MEMS-Transistor Integration
    - Mixed
    - MEMS-First
    - MEMS-Last
  - Op Amp Non-Idealities (cont.)

Ideal Operational Amplifiers

Ideal Op Amp

- **Equivalent Circuit of an Ideal Op Amp:**



- **Properties of Ideal Op Amps:**

1. $R_{in} = \infty$ ⟶ 4. $i_+ = i_- = 0$
2. $R_0 = 0$
3. $A = \infty$ ⟶ 5. $v_+ = v_-$, assuming $v_0 = \text{finite}$ **Why?**

Ideal Op Amp (cont)

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Why? Because for

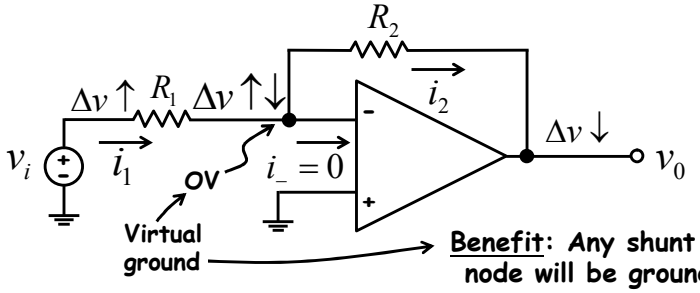
$$\infty(v_+ - v_-) = v_0 = \text{finite}$$

$$\therefore \underbrace{v_+ - v_-}_{\frac{v_0}{\infty}} = 0 \rightarrow v_+ = v_-$$

$\Rightarrow$ virtual short circuit (virtual ground)

- **Big assumption!** $(v_0 = \text{finite})$
- **How can we assume this? We can assume this only when there is an appropriate negative feedback path!**

Inverting Amplifier



Benefit: Any shunt C at this node will be grounded out.

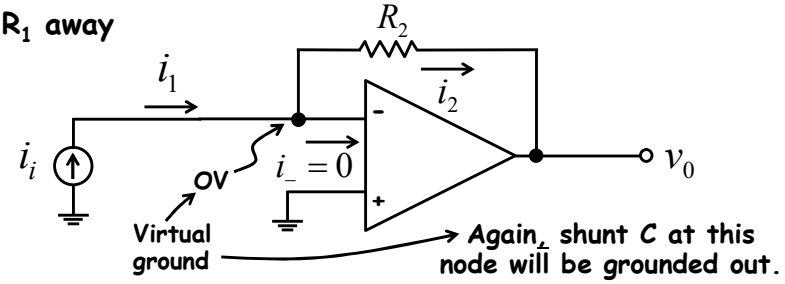
1. **Verify that there is negative FB.**
2. $\therefore v_0 = \text{finite} \rightarrow v_+ = v_- \rightarrow$ **node attached to (-) terminal is virtual ground.**
3. $i_- = 0 \;\therefore\; i_1 = i_2$

NOTE: Gain dependent only on R_1 & R_2 (external components), not on the op amp gain.

$$\left.\begin{aligned} i_1 &= \frac{v_i - 0}{R_1} = \frac{v_i}{R_1} = i_2 \\ v_0 &= 0 - i_2 R_2 = -i_2 R_2 \end{aligned}\right\} \Rightarrow v_0 = -\left(\frac{v_i}{R_1}\right) R_2 = -\frac{R_2}{R_1} v_i \;\therefore\; \boxed{\frac{v_0}{v_i} = -\frac{R_2}{R_1}}$$

Transresistance Amplifier

- Take R_1 away

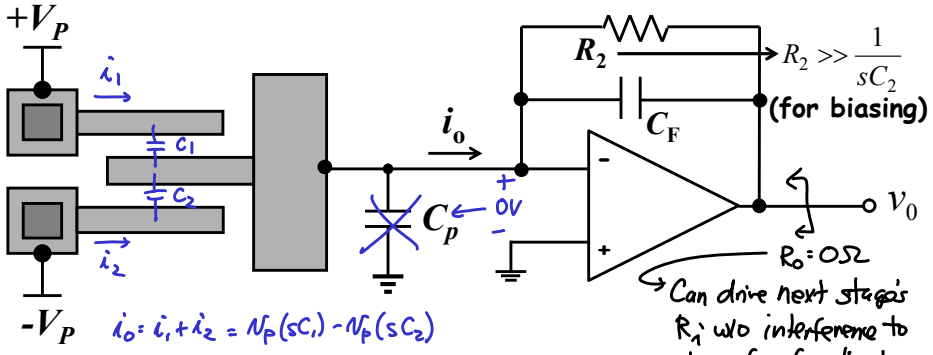


1. Verify that there is neg. FB → yes, since same FB as inverting amplifier
2. Thus, v_o = finite → $v_+ = v_-$ → (-) terminal is virtual ground
3. i_- = 0 → $i_1 = i_2$

$$v_0 = -i_2 R_2 = -i_i R_2 \Rightarrow \boxed{\frac{v_0}{i_i} = -R_2}$$

An inverting amplifier is just a transresistance amplifier with an R_1 to convert voltage to current!

Integrator-Based Diff. Position Sensing



$i_o = i_1 + i_2 = V_p(sC_1) - V_p(sC_2)$

$= V_p s(C_1 - C_2)$

$\therefore V_o = -i_o\left(\frac{1}{sC_F}\right) = -V_p\left(\frac{C_1 - C_2}{C_F}\right)$

$\boxed{\frac{V_o}{V_p} = -\frac{C_1 - C_2}{C_F}}$ ⇒ A seemingly perfect differential sensor/amplifier output! . . . but only when the op amp is ideal . . .

Non-Ideal Operational Amplifiers

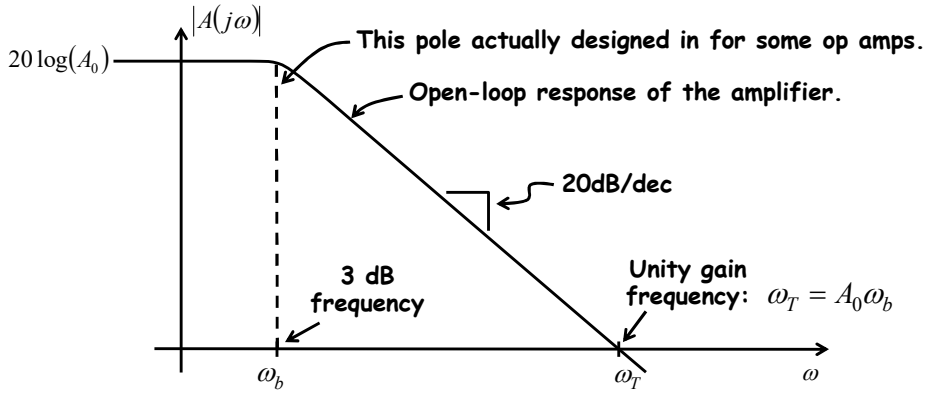
Actual Op Amps Are Not Ideal

- Actual op amps, of course, are not ideal; rather, they …
  - Generate noise
  - Have finite gain, A_o
  - Have finite bandwidth, ω_b
  - Have finite input resistance, R_i
  - Have finite input capacitance, C_i
  - Have finite output resistance, R_o
  - Have an offset voltage V_{OS} between their (+) and (-) terminals
  - Have input bias currents
  - Have an offset I_{OS} between the bias currents into the (+) and (-) terminals
  - Have finite slew rate
  - Have finite output swing (governed by the supply voltage used, -L to +L)
- And what's worse: All of the above can be temperature (or otherwise environmentally) dependent!

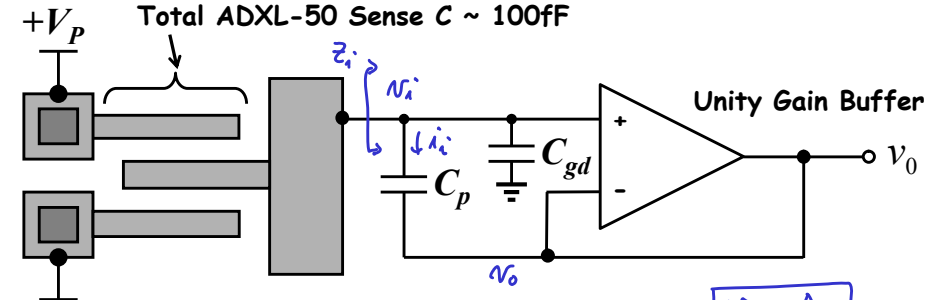
Finite Op Amp Gain and Bandwidth

- For an ideal op amp: $A = \infty$
- In reality, the gain is given by: $A(s) = \dfrac{A_0}{1 + \dfrac{s}{\omega_b}}$ ← Finite Gain; ← Finite Bandwidth
- For $\omega >> \omega_b$:

$$A(s) \approx \frac{A_0}{(s/\omega_b)} = \frac{A_0\omega_b}{s} = \frac{\omega_T}{s}$$ → Integrator w/ time const. $1/\omega_T$



Effect of Finite Op Amp Gain



$v_0 = A_0(v_+ - v_-) = A_0(v_i - v_0) \rightarrow v_0(1+A_0) = A_0 v_i \rightarrow \dfrac{v_0}{v_i} = \dfrac{A_0}{1+A_0}$

Get $Z_i = \dfrac{v_i}{i_i}$: $\quad i_i = (v_i - v_0)sC_p = v_i\left(1 - \dfrac{A_0}{1+A_0}\right)sC_p = v_i \dfrac{1}{1+A_0} sC_p$

$\therefore \dfrac{v_i}{i_i} = Z_i = \dfrac{1}{s\left[\dfrac{C_p}{1+A_0}\right]}$ → $C_{eff} = \dfrac{C_p}{1+A_0}$ ← No longer zero!

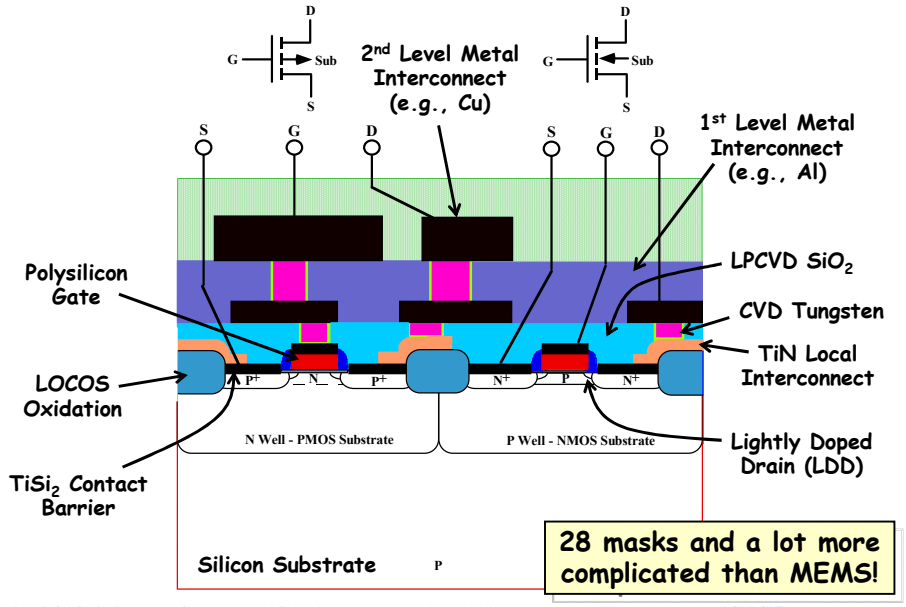
Ex: $A_0 = 100$, $C_p = 2pF$
$\Rightarrow C_{eff} = \dfrac{2p}{101} = 20fF$
↳ Not negligible compared w/ ADXL-50 $C_{tot} \sim 100fF$!

Integration of MEMS and Transistors

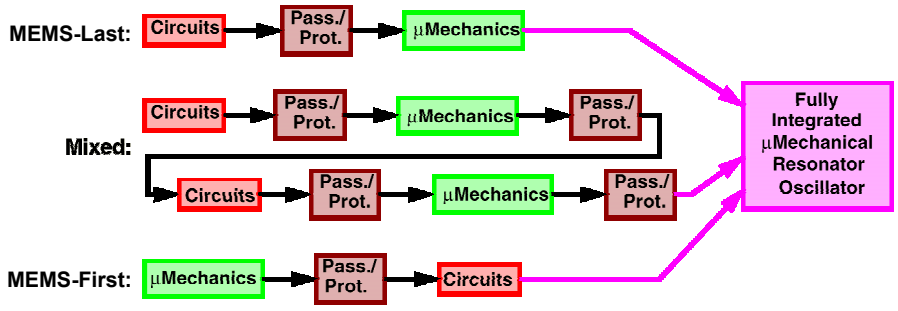
Integrate or Not?

- Benefits:
  - Lower parasitic capacitance and resistance → improved sensitivity and resolution, higher operation frequency
  - Better reliability
  - Reduced size → lower cost?
  - Reduced packaging complexity → integration is a form of packaging → lower cost?
  - Higher integration density supports greater functionality
- Challenges:
  - Temperature ceilings imposed by the transistors or MEMS
  - Protecting one process from the other
  - Surface topography of MEMS
  - Material incompatibilities
  - Multiplication of yield losses (versus non-integrated)
  - Acceptance by transistor foundries

250 nm CMOS Cross-Section



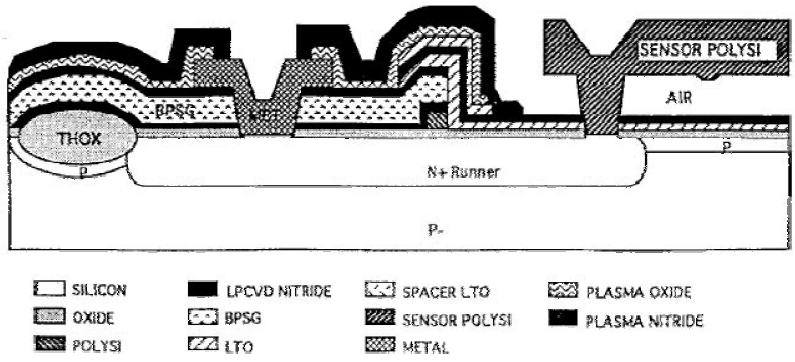
Merged MEMS/Transistor Technologies (Process Philosophy)



- Mixed:
  - problem: multiple passivation/protection steps ⇒ large number of masks required
  - problem: custom process for each product
- MEMS-first or MEMS-last:
  - adv.: modularity ⇒ flexibility ⇒ less development time
  - adv.: low pass./protection complexity ⇒ fewer masks

Analog Devices BiMEMS Process

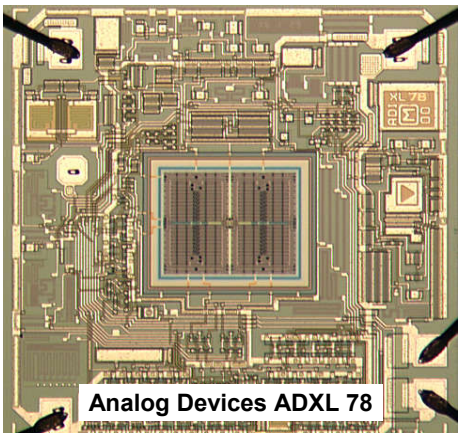
- Interleaved MEMS and 4 μm BiMOS processes (28 masks)
- Diffused n+ runners used to interconnect MEMS & CMOS
- Relatively deep junctions allow for MEMS poly stress anneal
- Used to manufacture the ADXL-50 accelerometer and Analog Devices family of accelerometers

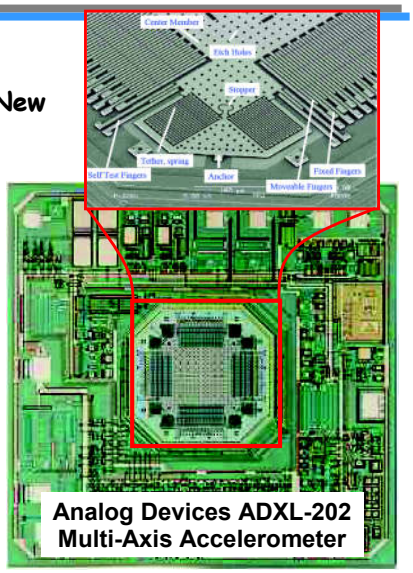


Analog Devices BiMEMS Process (cont)

- Examples:

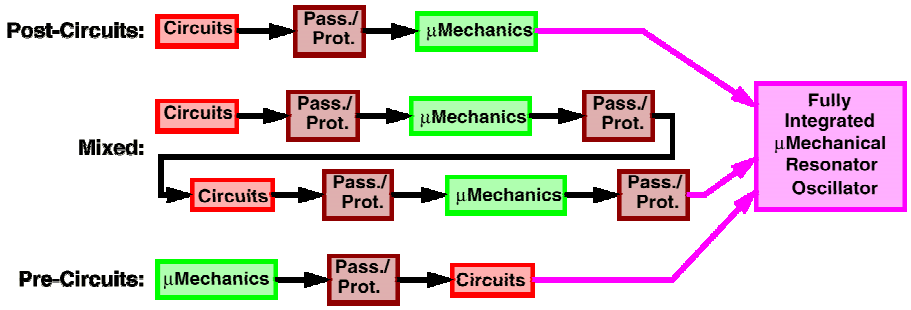
Old ⟶ New





- Can you list the advances in the process from old to new?

Merged MEMS/Transistor Technologies (Process Philosophy)



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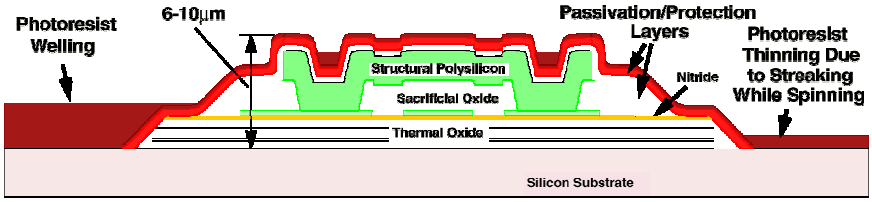
MEMS-First Integration

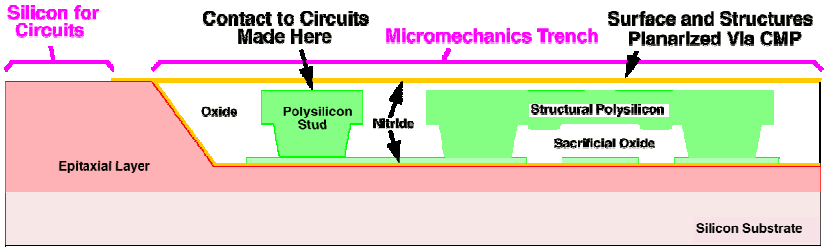
- Modular technology minimizes product updating effort
  - Module 1: micromachining process (planar technology)
  - Module 2: transistor process (planar IC technology)
- Adv.: (ideally) no changes needed to the transistor process
- Adv.: high temperature ceiling for some MEMS materials
- Challenges:
  - Reducing topography after MEMS processing so transistors can be processed
  - Maximizing the set of permissible MEMS materials; the materials must be able to withstand transistor processing temperatures
  - Getting transistor foundries to accept pre-processed wafers

MEMS-First Integration

- Problem: μstructural topography interferes with lithography
  - difficult to apply photoresist for submicron circuits



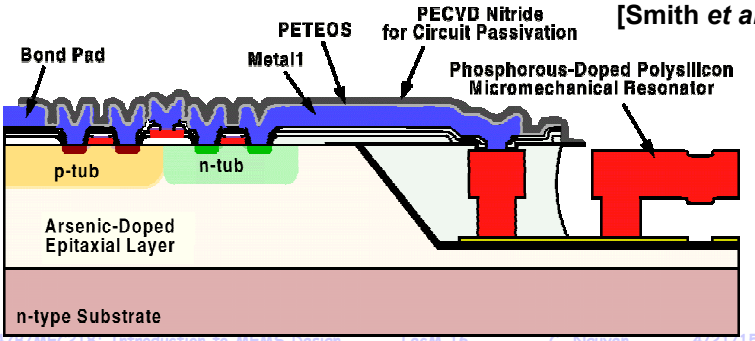
- Soln.: build μmechanics in a trench, then planarize before circuit processing [Smith *et al*, IEDM'95]



MEMS-First Ex: Sandia's iMEMS

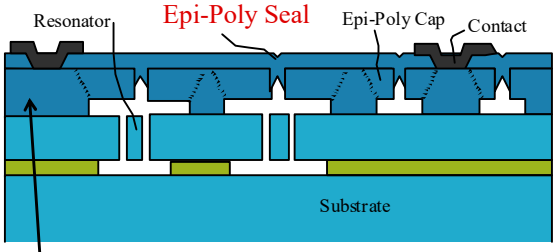
- Used to demonstrate functional fully integrated oscillators
- Issues:
  - lithography and etching may be difficult in trench → may limit dimensions (not good for RF MEMS)
  - μmechanical material must stand up to IC temperatures (>1000°C) → problem for some metal materials
  - might be contamination issues for foundry IC's

[Smith *et al*, IEDM'95]

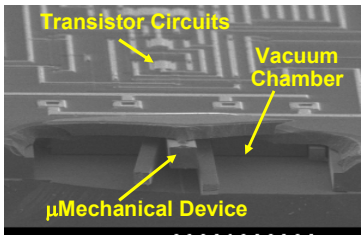


Bosch/Stanford MEMS-First Process

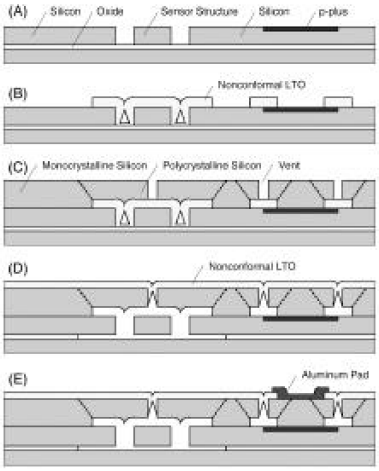
- Single-crystal silicon microstructures sealed under epi-poly encapsulation covers
- Many masking steps needed, but very stable structures



Epi-silicon for CMOS



[Kim, Kenny Trans'05]



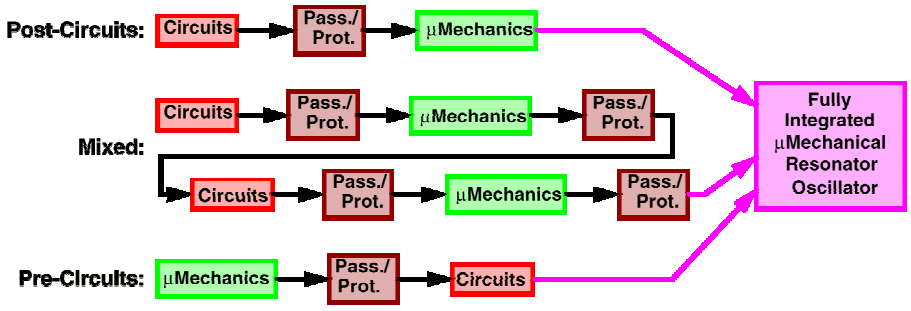
Problems With MEMS-First

- Many masking steps needed, plus CMP required → cost can grow if you're not careful
- Processes using trenches sacrifice lithographic resolution in microstructures
- MEMS must withstand transistor processing temperatures
  - ↳ Precludes the use of structural materials with low temperature req'mts: metals, polymers, etc.
- Exotic MEMS (e.g., ZnO) that can contaminate transistors during their processing are not permissible
  - ↳ thus, not truly modular
- Foundry acceptance not guaranteed and might be rare

Foundry Acceptance of MEMS-First?

- Is a CMP'ed silicon surface sufficiently pure for fabrication of aggressively scaled transistors? How about if an oxide is grown over the CMP'ed surface and removed via a wet etch to yield a "pristine" surface?
- Is epi silicon grown as part of a sealing process sufficiently pure for fabrication of aggressively scaled transistors?
- CMOS is many times more difficult to run than MEMS
  - Feature sizes on the nm scale for billions of devices
  - Contamination a big issue: many foundries may not accept pre-processed wafers for contamination reasons
  - Many foundries will not accept any pre-processed wafers, MEMS or not → just can't guarantee working transistor circuits with unknowns in starting silicon

Merged MEMS/Transistor Technologies (Process Philosophy)



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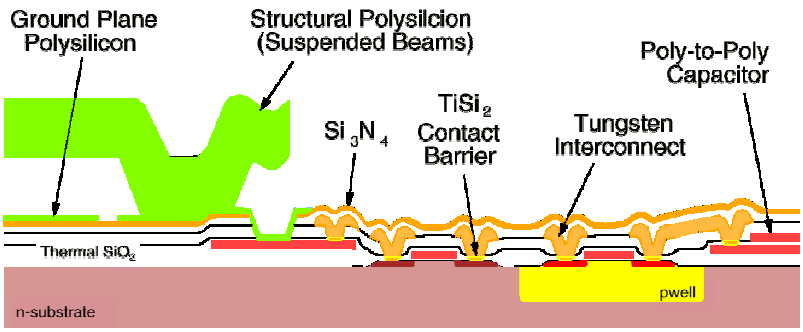
MEMS-Last Integration

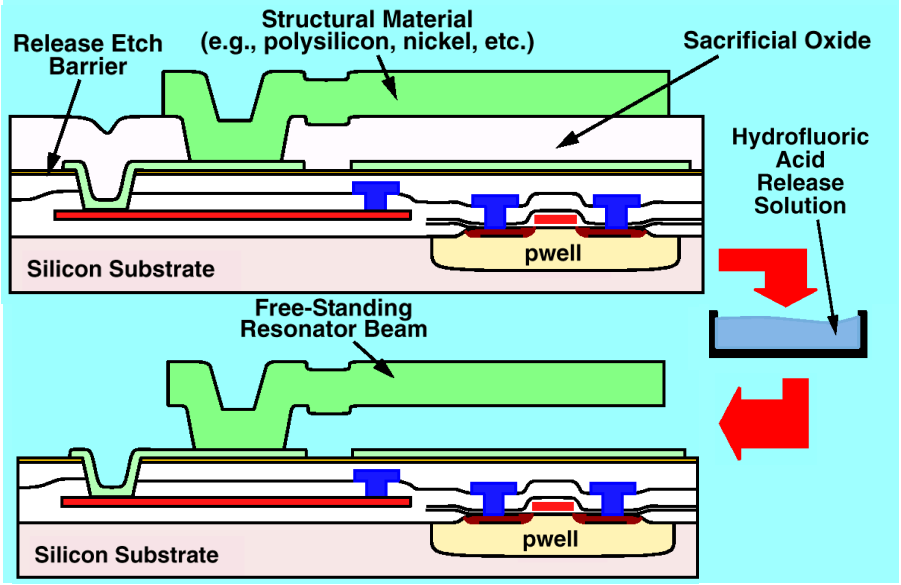
- Modular technology minimizes product updating effort
  - Module 1: transistor process (planar IC technology)
  - Module 2: micromachining process (planar technology)
- Adv.: foundry friendly
  - Virtually any foundry can be used → can use the lowest cost transistor circuits (big advantage)
- Adv.: topography after circuit fabrication is quite small, especially given the use of CMP to planarize the metallization layers
- Issue: limited thermal budget limits the set of usable structural materials
  - Metallization goes bad if temperature gets too high
  - Aluminum grows hillocks and spikes junctions if T>500°C
  - Copper diffusion can be an issue at high temperature
  - Low-k dielectrics used around metals may soon lower the temperature ceiling to only 320°C

Berkeley Polysilicon MICS Process

- Uses surface-micromachinedpolysilicon microstructures with silicon nitride layer between transistors & MEMS
  - Polysilicon dep. T~600°C; nitride dep. T~835°C
  - 1100°C RTA stress anneal for 1 min.
  - metal and junctions must withstand temperatures ~835°C
  - tungsten metallization used with $TiSi_2$ contact barriers
  - *in situ* doped structural polySi; rapid thermal annealing



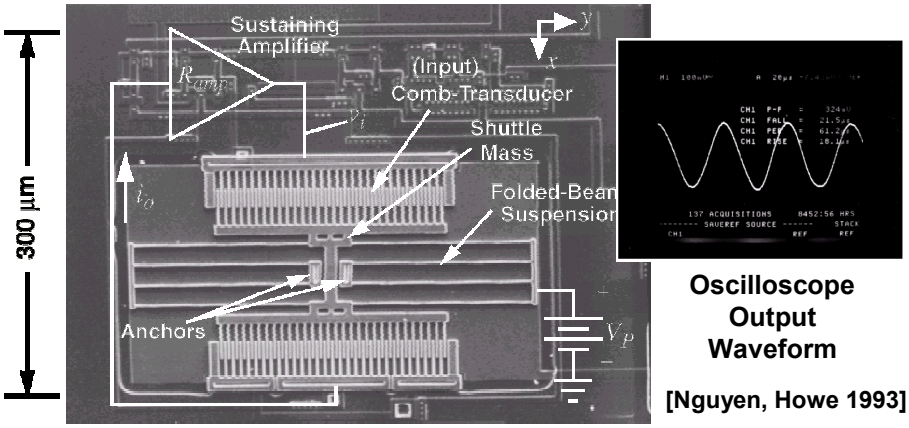
Surface Micromachining



- 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)



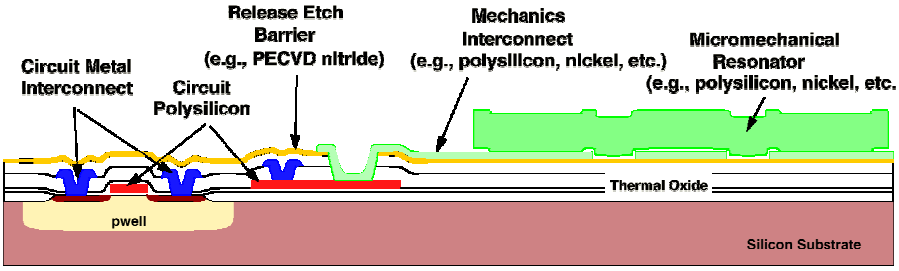
Oscilloscope Output Waveform

[Nguyen, Howe 1993]

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

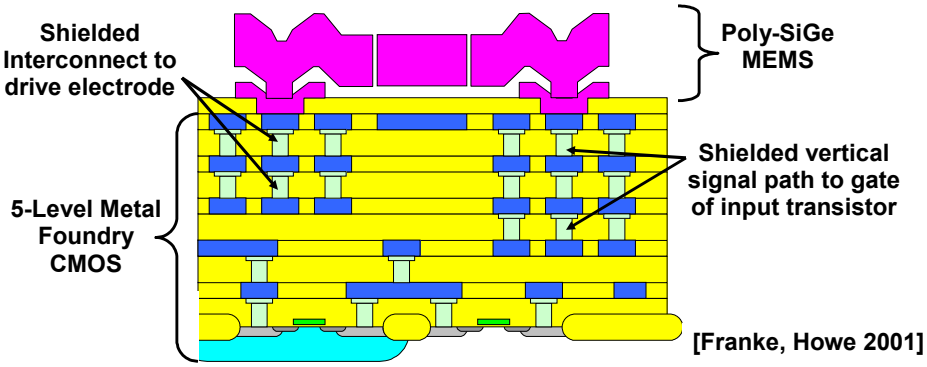
Usable MEMS-Last Integration

- Problem: tungsten is not an accepted primary interconnect metal
- Challenge: retain conventional metallization
  - minimize post-CMOS processing temperatures
  - explore alternative structural materials (e.g., plated nickel, SiGe [Franke, Howe *et al*, MEMS'99])
  - Limited set of usable structural materials → not the best situation, but workable



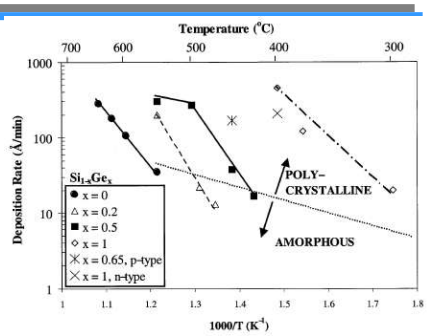
Poly-SiGe MICS Process

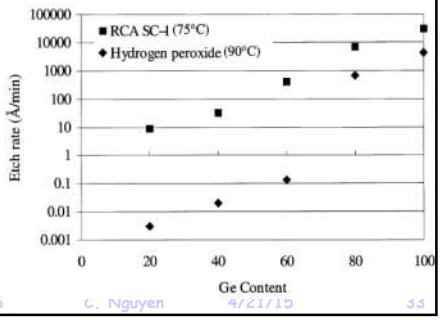
- MICS = "Modular Integration of Circuits and Structures"
- MEMS-last process, where SiGe micromechanics are planar processed directly above conventional foundry circuits
  - enabled by lower deposition temperature of SiGe ~450°C
  - *Adv.*: alleviates contamination issues of pre-circuit processes, allowing a wider choice of IC technologies



Polysilicon Germanium

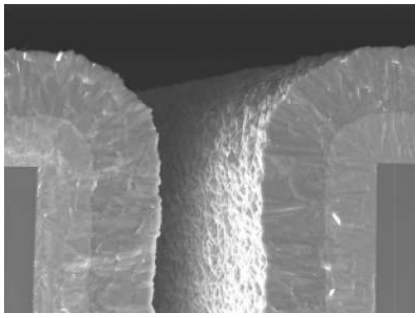
- Deposition
  - LPCVD thermal decomposition of GeH_4 and SiH_4 or Si_2H_6
  - Rate >50 Å/min, T < 475°C, P = 300-600 mT
  - At higher [Ge]: rate ↑, T ↓
  - In-situ doping, ion implantation
- Dry Etching
  - Similar to poly-Si, use F, Cl, and Br^- containing plasmas
  - Rate ~0.4 μm/min
- Wet Etching
  - H_2O_2 @ 90°C: can get 4 orders of magnitude selectivity between >80% and <60% Ge content
  - Good release etchant

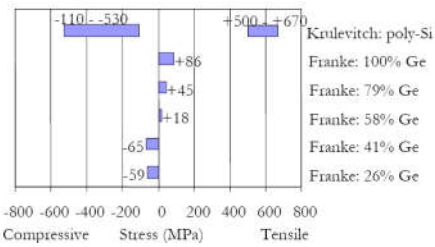




Poly-SiGe Mechanical Properties

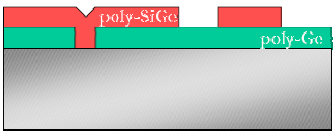
- Conformal deposition
- Low as-deposited stress (when its done right)
- Young's modulus ~ 146 GPa (for poly-$Si_{0.35}Ge_{0.65}$)
- Density ~4280 kg/m^3
- Acoustic velocity ~5840 m/s (25% lower than polysilicon)
  - Harder to achieve high frequency devices
- Fracture strain 1.7% (compared to 1.5% for MUMPS polySi)
- Q=30,000 for n-type poly-Ge in vacuum

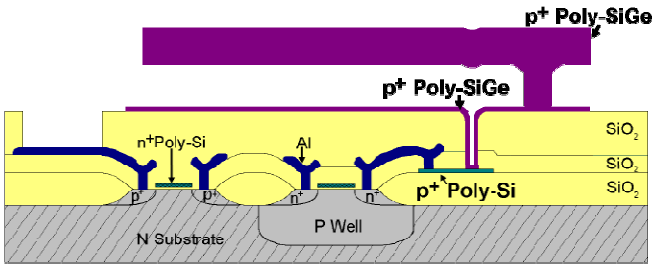




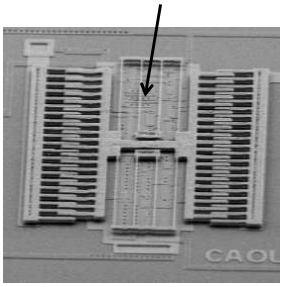
UCB Poly-SiGe MICS Process

- 2 μm standard CMOS process w/ Al metallization
- P-type poly-$Si_{0.35}Ge_{0.65}$ structural material; poly-Ge sacrificial material
- Process:
  - Passivate CMOS w/ LTO @ 400°C
  - Open vias to interconnect runners
  - Deposit & pattern ground plane
  - RTA anneal to lower resistivity (550°C, 30s)



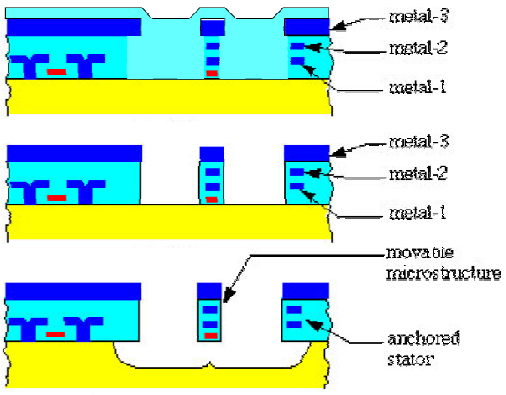


Transistor Circuits

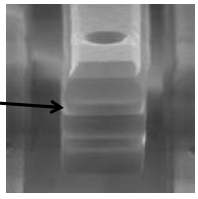


ASIMPS Ckt/MEMS Integration Process

- MEMS constructed from metal/insulator laminates of foundry CMOS
- Top metal layer used as etch mask for CHF_3/O_2 oxide etch
- Structures released via a final SF_6 isotropic dry etch
- Independent electrostatic actuation possible due to multiple insulated metal layers
- Stress issues can be tricky
  - Must design defensively against warping



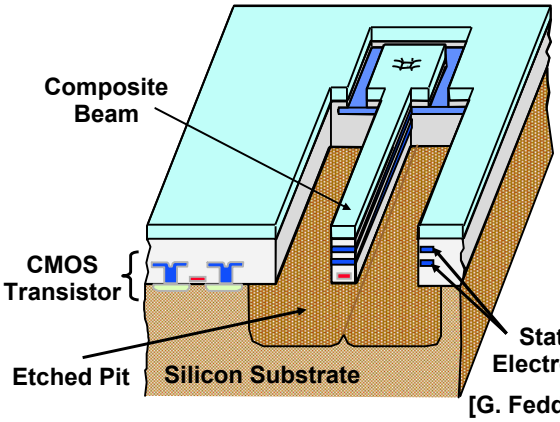
Metal/insulator stack



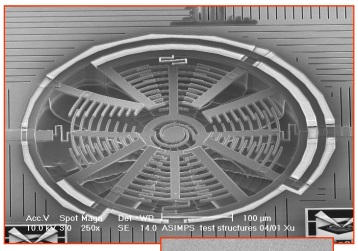
[G. Fedder, CMU]

ASIMPS Ckt/MEMS Integration Process

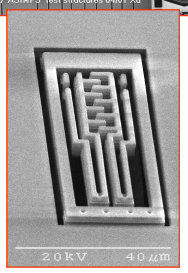
- Direct integration of Al/oxide MEMS structure with silicon CMOS or SiGe BiCMOS circuits
- Multiple electrodes within structures
- Derivatives for bulk silicon structures



[G. Fedder, CMU]



Gyro Resonator



Uncooled IR Detector Element

Actual Op Amps Are Not Ideal

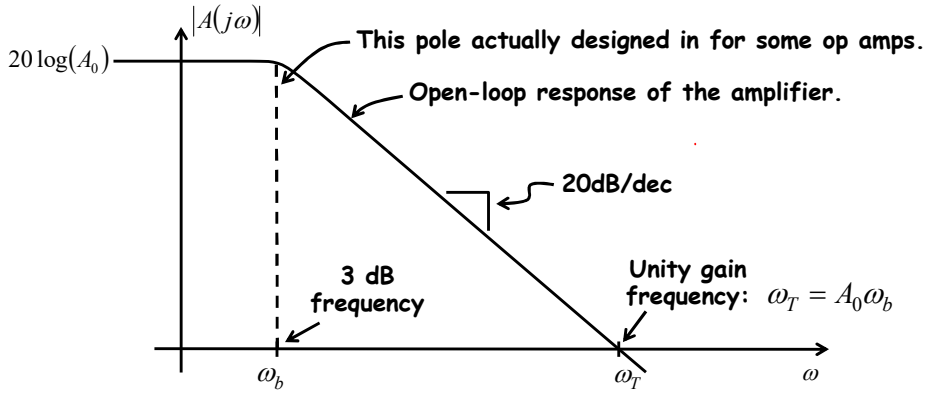
- Actual op amps, of course, are not ideal; rather, they …
  - Generate noise
  - Have finite gain, A_o
  - Have finite bandwidth, ω_b
  - Have finite input resistance, R_i
  - Have finite input capacitance, C_i
  - Have finite output resistance, R_o
  - Have an offset voltage V_{OS} between their (+) and (-) terminals
  - Have input bias currents
  - Have an offset I_{OS} between the bias currents into the (+) and (-) terminals
  - Have finite slew rate
  - Have finite output swing (governed by the supply voltage used, -L to +L)
- And what's worse: All of the above can be temperature (or otherwise environmentally) dependent!

Finite Op Amp Gain and Bandwidth

- For an ideal op amp: $A = \infty$
- In reality, the gain is given by: $A(s) = \dfrac{A_0}{1 + \dfrac{s}{\omega_b}}$ ← Finite Gain; ← Finite Bandwidth
- For $\omega >> \omega_b$:

$$A(s) \approx \frac{A_0}{(s/\omega_b)} = \frac{A_0\omega_b}{s} = \frac{\omega_T}{s}$$

→ Integrator w/ time const. $1/\omega_T$

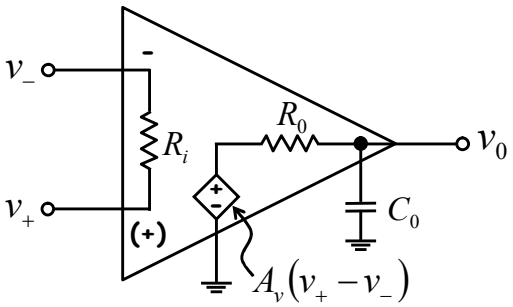


Op Amp Non-Idealities

Op Amp Non-Idealities → R_i & R_0

Input resistance R_i and Output Resistance R_0:

With finite R_i and R_0, and finite gain and BW, the op amp equivalent circuit becomes:



⇒ Basically reduces down to a voltage-amplifier model

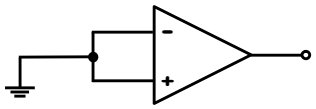
⇒ Add an output C0 to model a single pole response, where

$$w_b = \frac{1}{R_0 C_0}$$

Back to Op Amp Non-Idealities

Input Offset Voltage V_{OS}

Input Offset Voltage, V_{OS}:

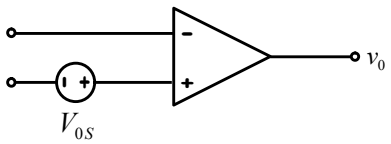


$$v_0 = A(v_+ - v_-)$$

Ideal case: $v_0 = 0$

Reality: $v_0 \neq 0$ (usually, $v_0 = L^+$ or L^- : it rails out!)

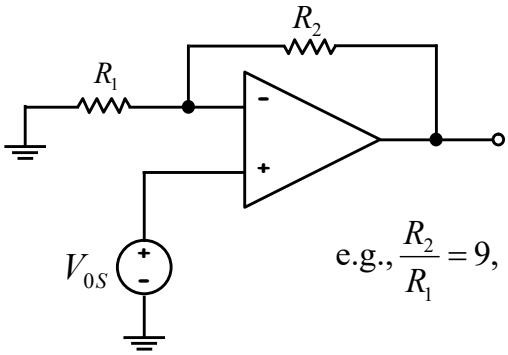
Why? Internal mismatches within the op amp → cause a dc offset. Model this with an equivalent input offset voltage V_{OS}.



Typically, V_{OS} = 1mV – 5mV

Effect of V_{0S} on Op Amp Circuits

Example: Non-Inverting Amplifier



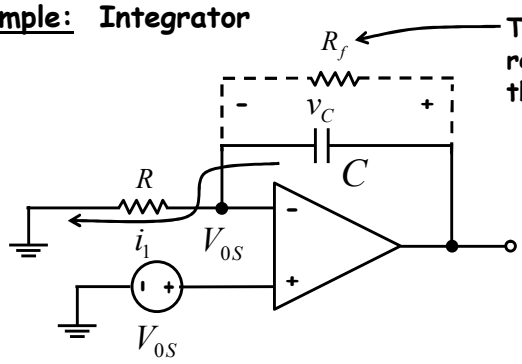
$$V_0 = V_{0S}\left(1+\frac{R_2}{R_1}\right)$$

$$\text{e.g., } \frac{R_2}{R_1}=9,\quad V_{0S}=5mV \rightarrow V_0 = 50mV$$

(not so bad …)

Effect of V_{0S} on Op Amp Circuits (cont.)

Example: Integrator



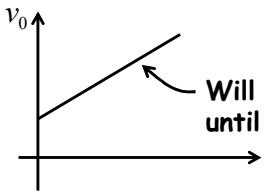
To fix this, place a resistor in shunt with the C → then:

$$v_0 = V_{0S}\left(1+\frac{R_f}{R}\right)$$

$$v_0 = V_{0S}+\frac{1}{C}\int_0^t i_1 dt$$

$$= V_{0S}+\frac{1}{C}\int_0^t \frac{V_{0S}}{R}dt$$

$$= V_{0S}\left(1+\frac{t}{RC}\right)+v_C\big|_{t=0}$$



Will continue to increase until op amp saturates