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**EE C247B - ME C218**  
**Introduction to MEMS Design**  
**Spring 2019**

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**Module 16: Sensing Ckt. Non-Idealities & Integration**

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**Lecture Outline**

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

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## Ideal Operational Amplifiers

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## Ideal Op Amp

- Equivalent Circuit of an Ideal Op Amp:**

Single-ended output

Differential input

Voltage-Controlled Voltage Source (VCVS)

- Properties of Ideal Op Amps:**

- $R_{in} = \infty$
- $R_0 = 0$
- $A = \infty$
- $i_+ = i_- = 0$
- $v_+ = v_-$ , assuming  $v_0 = \text{finite}$     **Why?**

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## Ideal Op Amp (cont)

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**• Properties of Ideal Op Amps:**

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

**Why? Because for**

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

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

$\frac{v_0}{\infty} \Rightarrow$  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!**

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## Inverting Amplifier

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**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.

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

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**Transresistance Amplifier**

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• Take  $R_1$  away

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

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

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

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**Non-Ideal Operational Amplifiers**

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### Integrator-Based Diff. Position Sensing

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$i_0 = i_1 + i_2 = N_p(sC_1) - N_p(sC_2)$   
 $= V_p s(C_1 - C_2)$   
 $\therefore V_0 = -i_0 \left(\frac{1}{sC_F}\right) = -N_p \left(\frac{C_1 - C_2}{C_F}\right)$

$\frac{V_0}{V_p} = -\frac{C_1 - C_2}{C_F} \Rightarrow$  A seemingly perfect differential sensor/amplifier output! ... but only when the op amp is ideal...

$R_2 \gg \frac{1}{sC_2}$  (for biasing)  
 $R_0 = 0\Omega$   
 Can drive next stages  $R_1$  w/o interference to transfer function!

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### Actual Op Amps Are Not Ideal

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- Actual op amps, of course, are not ideal; rather, they ...
  - ↗ Generate noise
  - ↗ Have finite gain,  $A_0$
  - ↗ Have finite bandwidth,  $\omega_b$
  - ↗ 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!

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### Finite Op Amp Gain and Bandwidth

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

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

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### Op Amp Non-Idealities

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Op Amp Non-Idealities →  $R_i$  &  $R_o$

Input resistance  $R_i$  and Output Resistance  $R_o$ :

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

⇒ Basically reduces down to a voltage-amplifier model

⇒ Add an output  $C_0$  to model a single pole response, where

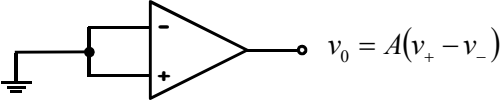
$$\omega_b = \frac{1}{R_o C_0}$$

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## Input Offset Voltage $V_{OS}$

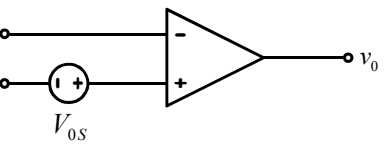
Input Offset Voltage,  $V_{OS}$ :



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

**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  $V_{OS}$ .**



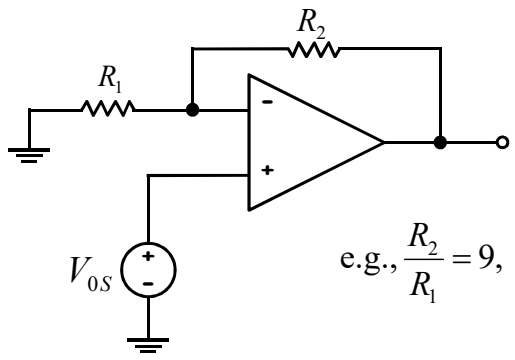
Typically,  $V_{OS} = 1\text{mV} - 5\text{mV}$

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## Effect of $V_{OS}$ on Op Amp Circuits

Example: Non-Inverting Amplifier



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

e.g.,  $\frac{R_2}{R_1} = 9$ ,  $V_{OS} = 5\text{mV} \rightarrow V_0 = 50\text{mV}$   
 (not so bad ...)

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### Effect of $V_{OS}$ on Op Amp Circuits (cont.)

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**Example: Integrator**

To fix this, place a resistor in shunt with the  $C \rightarrow$  then:

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

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

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

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

Will continue to increase until op amp saturates

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### Integrator-Based Diff. Position Sensing

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$R_2 \gg \frac{1}{sC_2}$  (for biasing)

$R_0 = 0\Omega$

Can drive next stage's  $R_1$  w/o interference to transfer function!

$$i_0 = i_1 + i_2 = N_P(sC_1) - N_P(sC_2)$$

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$$\therefore v_0 = -i_0 \left( \frac{1}{sC_F} \right) = -N_P \left( \frac{C_1 - C_2}{C_F} \right)$$

$\frac{v_0}{V_P} = - \frac{C_1 - C_2}{C_F}$

$\Rightarrow$  A seemingly perfect differential sensor/amplifier output! ... but only when the op amp is ideal...

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**Effect of Finite Op Amp Gain**

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Total ADXL-50 Sense C ~ 100fF

Unity Gain Buffer

$V_0$

$-V_P$

$$V_0 = A_o(V_i - V_o) = A_o(N_i - V_0) \rightarrow V_0(1 + A_o) = A_o N_i \rightarrow \frac{V_0}{N_i} = \frac{A_o}{1 + A_o}$$

$$\text{Get } Z_i = \frac{V_i}{i_i}: i_i \cdot (N_i - V_0) s C_p = N_i \left(1 - \frac{A_o}{1 + A_o}\right) s C_p = N_i \frac{1}{1 + A_o} s C_p$$

$$\therefore \frac{V_i}{i_i} = Z_i = \frac{1}{s \left[ \frac{C_p}{1 + A_o} \right]} \rightarrow C_{\text{eff}} = \frac{C_p}{1 + A_o}$$

No longer zero!

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

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**Integration of MEMS and Transistors**

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**Integrate or Not?**

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- **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

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**250 nm CMOS Cross-Section**

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Labels in diagram: D, G, Sub, S, 2<sup>nd</sup> Level Metal Interconnect (e.g., Cu), 1<sup>st</sup> Level Metal Interconnect (e.g., Al), LPCVD SiO<sub>2</sub>, CVD Tungsten, TiN Local Interconnect, Lightly Doped Drain (LDD), Polysilicon Gate, LOCOS Oxidation, TiSi<sub>2</sub> Contact Barrier, N Well - PMOS Substrate, P Well - NMOS Substrate, Silicon Substrate, P.

28 masks and a lot more complicated than MEMS!

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**Merged MEMS/Transistor Technologies (Process Philosophy)**

The diagram shows three process flows converging on a central pink box labeled "Fully Integrated μMechanical Resonator Oscillator":

- MEMS-Last:** Circuits → Pass./Prot. → μMechanics
- Mixed:** Circuits → Pass./Prot. → μMechanics → Pass./Prot. → Circuits → Pass./Prot. → μMechanics → Pass./Prot.
- MEMS-First:** μMechanics → Pass./Prot. → Circuits

• **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

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**Analog Devices BiMEMS Process**

The cross-sectional diagram shows the following layers from top to bottom:

- SENSOR POLYSI
- AIR
- P
- N+ Runner
- P-

Other features include THOX, BPSG, and various interconnects.

SILICON	LPCVD NITRIDE	SPACER LTO	PLASMA OXIDE
OXIDE	BPSG	SENSOR POLYSI	PLASMA NITRIDE
POLYSI	LTO	METAL	

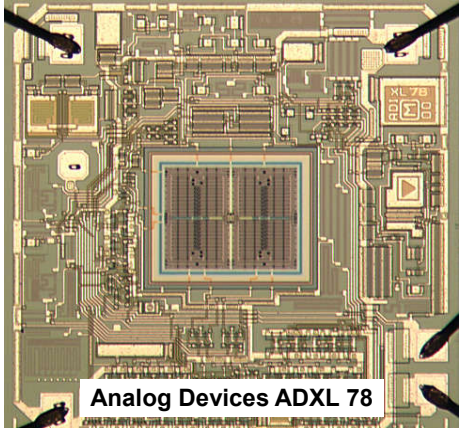
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**Analog Devices BiMEMS Process (cont)**

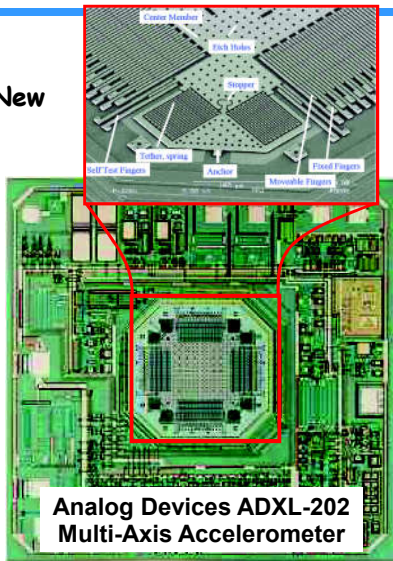
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- Examples:
 

Old
→
New



Analog Devices ADXL 78

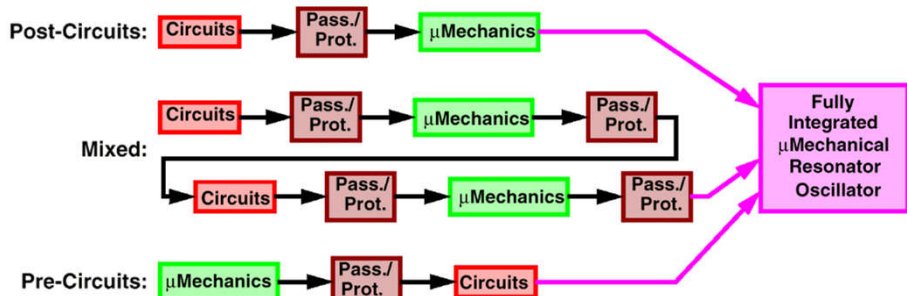


Analog Devices ADXL-202  
Multi-Axis Accelerometer
- Can you list the advances in the process from old to new?

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**Merged MEMS/Transistor Technologies (Process Philosophy)**

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```

    graph LR
        subgraph Post_Circuits [Post-Circuits]
            C1[Circuits] --> P1[Pass./Prot.]
            P1 --> M1[μMechanics]
        end
        subgraph Mixed [Mixed]
            C2[Circuits] --> P2[Pass./Prot.]
            P2 --> M2[μMechanics]
            M2 --> P3[Pass./Prot.]
        end
        subgraph Pre_Circuits [Pre-Circuits]
            M3[μMechanics] --> P4[Pass./Prot.]
            P4 --> C3[Circuits]
        end
        M1 --> IO[Fully Integrated μMechanical Resonator Oscillator]
        P3 --> IO
        C3 --> IO
    
```

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

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**MEMS-First Integration**

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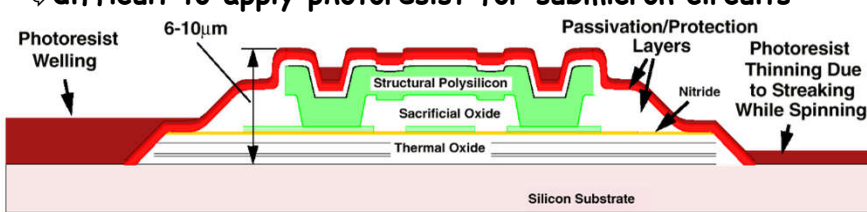
- Modular technology minimizes product updating effort
  - ↳ **Module 1**: micromachining process (planar technology)
  - ↳ **Module 2**: transistor process (planar IC technology)
- **Adv.**: (ideally) no changes needed to the transistor process
- **Adv.**: high temperature ceiling for some MEMS materials
- **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

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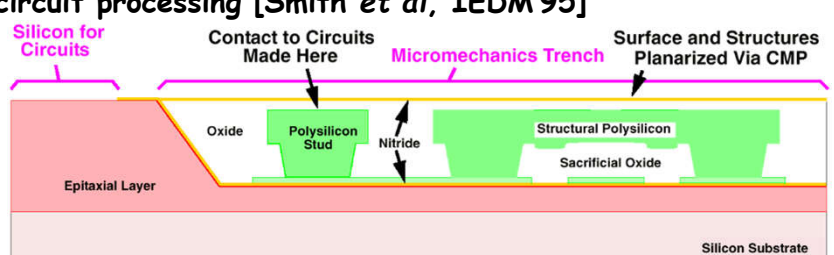
**MEMS-First Integration**

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- **Problem**:  $\mu$ structural topography interferes with lithography
  - ↳ difficult to apply photoresist for submicron circuits



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



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**MEMS-First Ex: Sandia's iMEMS**

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- Used to demonstrate functional fully integrated oscillators
- Issues:**
  - lithography and etching may be difficult in trench  $\Rightarrow$  may limit dimensions (not good for RF MEMS)
  - $\mu$ mechanical material must stand up to IC temperatures ( $>1000^{\circ}\text{C}$ )  $\Rightarrow$  problem for some metal materials
  - might be contamination issues for foundry IC's

[Smith et al, IEDM'95]

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**Bosch/Stanford MEMS-First Process**

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

Resonator, Epi-Poly Seal, Epi-Poly Cap, Contact, Substrate, Transistor Circuits, Vacuum Chamber,  $\mu$ Mechanical Device, Epi-silicon for CMOS

[Kim, Kenny Trans'05]

(A) Silicon, Oxide, Sensor Structure, Silicon, p-plus  
 (B) Nonconformal LTO  
 (C) Monocrystalline Silicon, Polycrystalline Silicon, Vent  
 (D) Nonconformal LTO  
 (E) Aluminum Pad


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## 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

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## 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

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## Merged MEMS/Transistor Technologies (Process Philosophy)

```

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        end
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        end
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        P3 --> FIO
        C3 --> FIO
    
```

- **Mixed:**
  - ↪ **problem:** multiple passivation/protection steps  $\Rightarrow$  large number of masks required
  - ↪ **problem:** custom process for each product
- **MEMS-first or MEMS-last:**
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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  $\rightarrow$  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  $T > 500^\circ\text{C}$
  - ↪ Copper diffusion can be an issue at high temperature
  - ↪ Low-k dielectrics used around metals may soon lower the temperature ceiling to only  $320^\circ\text{C}$

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### Berkeley Polysilicon MICS Process

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- Uses surface-micromachined polysilicon microstructures with silicon nitride layer between transistors & MEMS
  - ↳ Polysilicon dep.  $T \sim 600^\circ\text{C}$ ; nitride dep.  $T \sim 835^\circ\text{C}$
  - ↳  $1100^\circ\text{C}$  RTA stress anneal for 1 min.
  - ↳ metal and junctions must withstand temperatures  $\sim 835^\circ\text{C}$
  - ↳ tungsten metallization used with  $\text{TiSi}_2$  contact barriers
  - ↳ *in situ* doped structural polySi; rapid thermal annealing

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### Surface Micromachining

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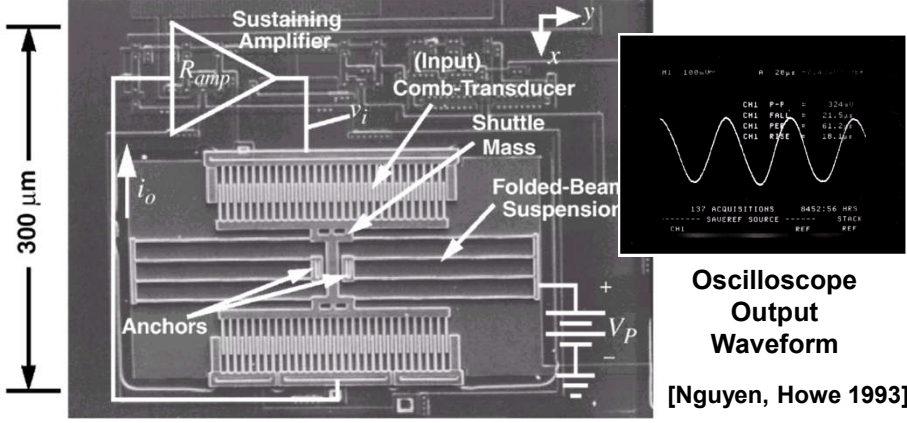
- Fabrication steps compatible with planar IC processing

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### Single-Chip Ckt/MEMS Integration

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



Oscilloscope Output Waveform

[Nguyen, Howe 1993]

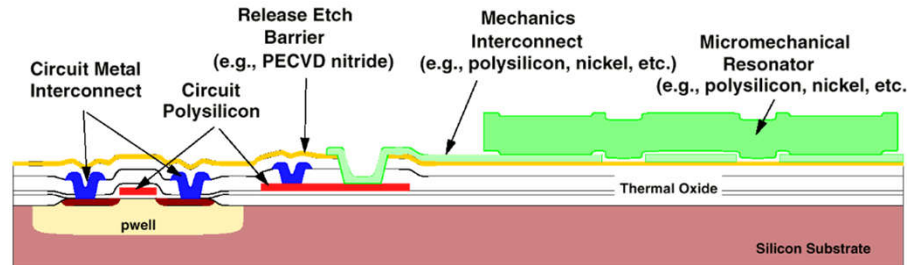
- To allow the use of >600°C processing temperatures, tungsten (instead of aluminum) is used for metallization

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### Usable MEMS-Last Integration

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- **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



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### Poly-SiGe MICS Process

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- 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

[Franke, Howe 2001]

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### Polysilicon Germanium

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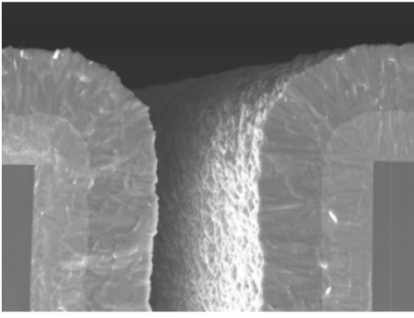
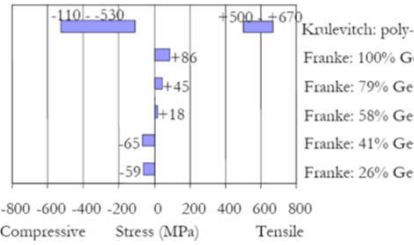
- Deposition
  - ↳ LPCVD thermal decomposition of  $GeH_4$  and  $SiH_4$  or  $Si_2H_6$
  - ↳ Rate  $>50 \text{ \AA}/\text{min}$ ,  $T < 475^\circ\text{C}$ ,  $P = 300\text{-}600 \text{ mT}$
  - ↳ At higher [Ge]: rate  $\uparrow$ ,  $T \downarrow$
  - ↳ In-situ doping, ion implantation
- Dry Etching
  - ↳ Similar to poly-Si, use F, Cl, and  $Br^-$  containing plasmas
  - ↳ Rate  $\sim 0.4 \text{ \mu m}/\text{min}$
- Wet Etching
  - ↳  $H_2O_2$  @  $90^\circ\text{C}$ : can get 4 orders of magnitude selectivity between  $>80\%$  and  $<60\%$  Ge content
  - ↳ Good release etchant

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### Poly-SiGe Mechanical Properties

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- Conformal deposition
- Low as-deposited stress (when its done right)
- Young's modulus ~ 146 GPa (for poly-Si<sub>0.35</sub>Ge<sub>0.65</sub>)
- Density ~4280 kg/m<sup>3</sup>
- 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

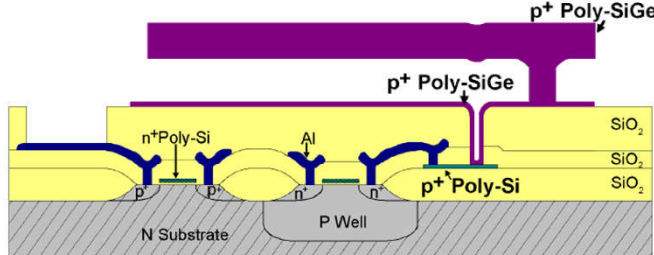
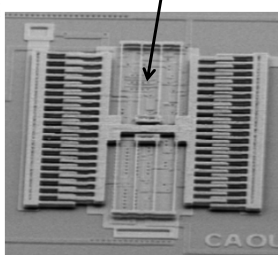
Composition	Stress (MPa)
Kruevitch: poly-Si	-110
Franko: 100% Ge	-530
Franko: 79% Ge	+86
Franko: 58% Ge	+45
Franko: 41% Ge	+18
Franko: 26% Ge	-65
Other	-59
Other	+500
Other	+670

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### UCB Poly-SiGe MICS Process

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- 2 μm standard CMOS process w/ Al metallization
- P-type poly-Si<sub>0.35</sub>Ge<sub>0.65</sub> 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)

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**ASIMPS Ckt/MEMS Integration Process**  
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- MEMS constructed from metal/insulator laminates of foundry CMOS
- Top metal layer used as etch mask for  $\text{CHF}_3/\text{O}_2$  oxide etch
- Structures released via a final  $\text{SF}_6$  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]

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

Composite Beam

CMOS Transistor

Etched Pit

Silicon Substrate

Stator Electrodes

[G. Fedder, CMU]

Gyro Resonator

Uncooled IR Detector Element

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**Effect of Finite Op Amp Gain**

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Total ADXL-50 Sense C ~ 100fF

$V_0 = A_0(V_i - V_o) = A_0(N_i - V_0) \rightarrow V_0(1 + A_0) = A_0 N_i \rightarrow \boxed{\frac{V_0}{N_i} = \frac{A_0}{1 + A_0}}$

Get  $Z_i = \frac{V_i}{i_i}$ :  $i_i \cdot (N_i - V_0) s C_p = N_i \left(1 - \frac{A_0}{1 + A_0}\right) s C_p = N_i \frac{1}{1 + A_0} s C_p$

$\therefore \frac{V_i}{i_i} = Z_i = \frac{1}{s \left[ \frac{C_p}{1 + A_0} \right]} \rightarrow \boxed{C_{eff} = \frac{C_p}{1 + A_0}}$

No longer zero!

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

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