4. Process Integration: Case Studies

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- Surface Machined vs Bulk Silicon MEMS
- Overview of Sacrificial Layer Technology
- Integration with CMOS
- Case Study #1: Pressure Sensor
- Case Study #2: FCantilevered Microgripper

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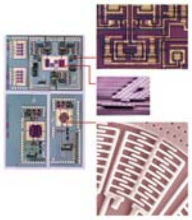
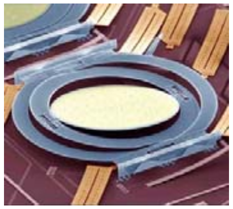
"Surface Machined" MEMS



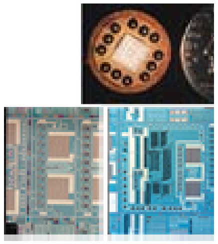
Sandia

Integrated Accelerometers



Lucent

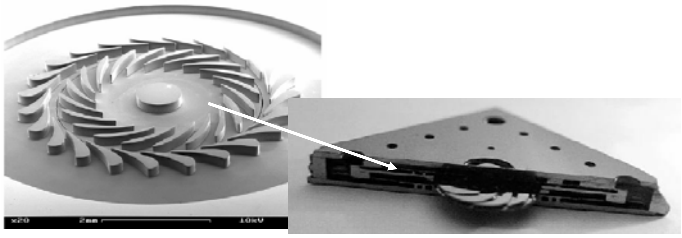
Optomechanical Systems

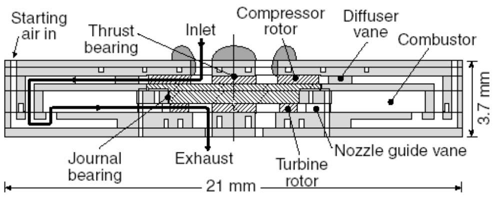


Sandia

Integrated Sensors

“Bulk Silicon MEMS”





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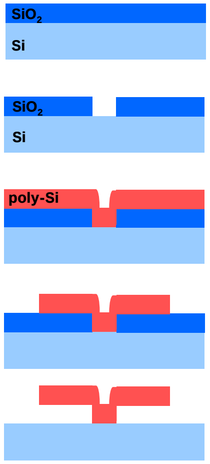
Example of Sacrificial Layer Technique



Starting material: thermal SiO2 on Si

Definition of anchor point using optical lithography

Deposition of conformal poly-Si using LPCVD

Machining of device edges using optical lithography

Release of devices through wet etch of sacrificial layer

Materials Wish list

- Free of residual stresses
- Mutually compatible deposition and machining processes
- Physical and chemical properties must fit the desired application
- Good mechanical stability and adhesion to surface

Common Material Sets in Sacrificial Layer Tech.

- i) Poly-Si and Silicon Dioxide
  - Both are common in IC manufacturing
  - Poly-Si possess excellent mechanical properties and can be easily doped
  - Silicon dioxide can be grown by either themal oxidation or by CVD over a wide range of temperatures (200 - 1200 ^{o}C)

Common Material Sets in Sacrificial Layer Tech.

- ii) Polyimide and Aluminum
  - Polyimide possesses small elastic modulus, about 50 times less the one of Poly-Si
  - Polyimide can withstand large strains prior to fracture
  - Both materials can be prepared at relatively low temperatures

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Common Material Sets in Sacrificial Layer Tech.

- iii) Silicon Nitride/Poly-Si and Tungsten/SiO$_2$
  - In first case, SiN is used as mechanical material while Poly-Si serves as sacrificial layer
  - KOH can be used to dissolve the Poly-Si
  - In second case, tungsten is deposited by CVD, with oxide as the sacrificial material. HF is used to dissolve sacrificial layer

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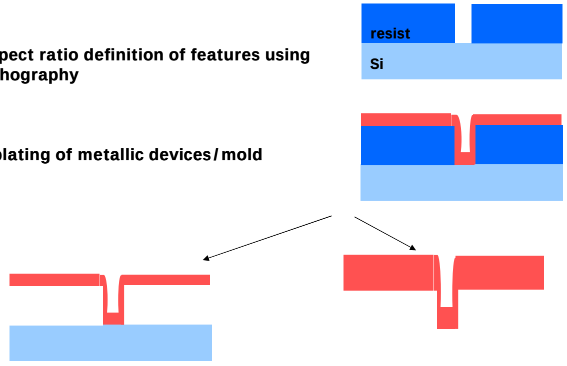
Common Material Sets in Sacrificial Layer Tech.

- v) Electroplated Nickel and Photoresist (eg LIGA Process)



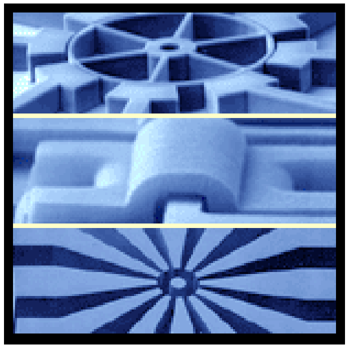
High-aspect ratio definition of features using x-ray lithography

Electroplating of metallic devices/mold

Finished high-aspect ratio device

Mold for cost-effective replication

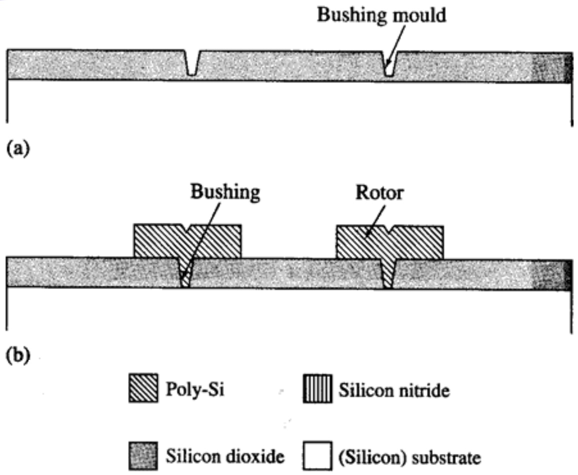
Typical Sidewalls Obtained with LIGA



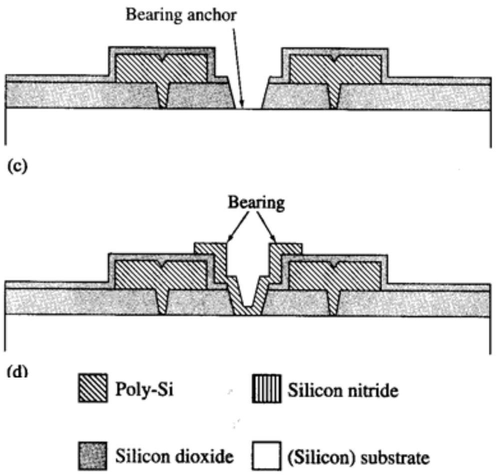
Example

- **Fabricate a disk-shaped rotor made of Poly-Si that is free to rotate around a pin**

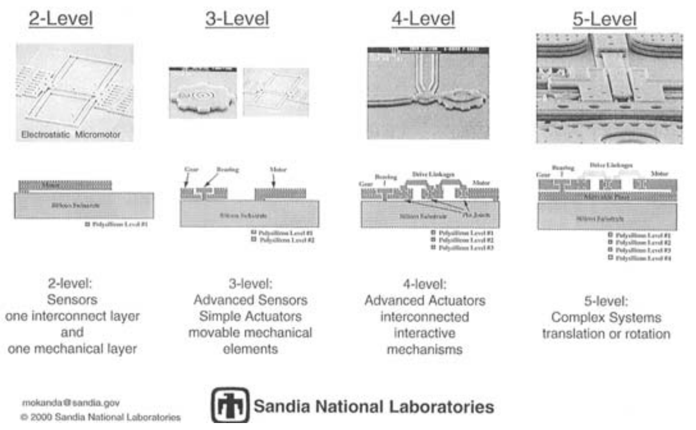
Example (ctnd.)



Example (ctnd.)



Muti-Level Devices



2-Level

3-Level

4-Level

5-Level

2-level:
Sensors
one interconnect layer
and
one mechanical layer

3-level:
Advanced Sensors
Simple Actuators
movable mechanical
elements

4-level:
Advanced Actuators
interconnected
interactive
mechanisms

5-level:
Complex Systems
translation or rotation

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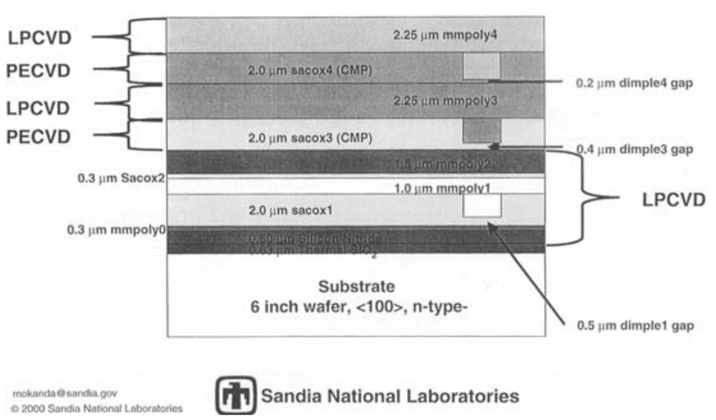
Sandia 5-level SUMMIT Technology



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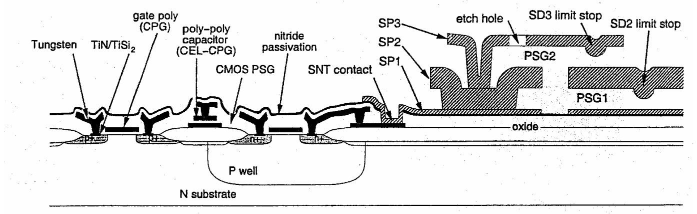
Integration with CMOS



How to integrate thick poly-Si MEMS with CMOS ?

Integration with CMOS (ctnd.)

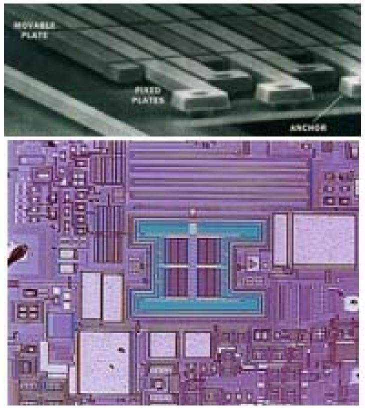
Integration of MEMS with CMOS devices must consider following :

- Compatibilty with IC fabrication process
- Fabrication approach
- Cost
- Time
- Packaging

Three possible approaches:

- Embedded
- CMOS last
- CMOS first

Embedded Approach: Analog Device Accelerometer



- "Embedded" approach integrates the MEMS and CMOS process flow into a dedicated and re-optimized multi-level process
- Requires tremendous investment of efforts and resources that have been justified only in a handful of high-volume "success stories".
- The Analog Devices airbag deployment sensor is one such example

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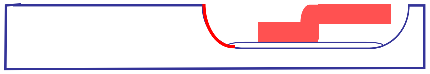
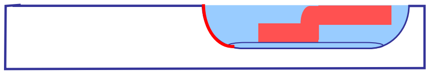
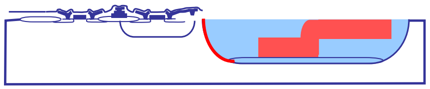
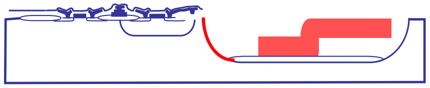
Sandia Approach: CMOS Last

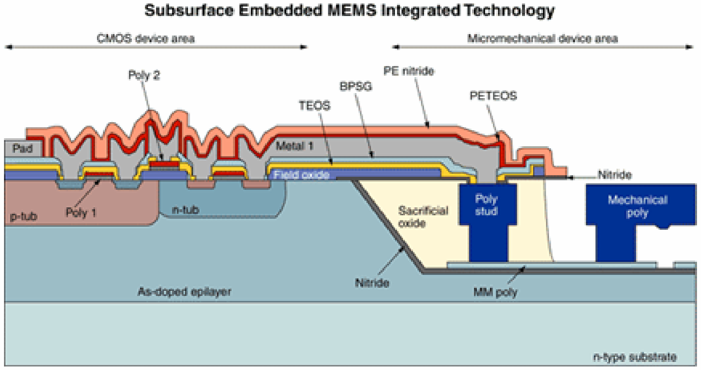

Machining of MEMS in tubs


Burial and planarization of surface

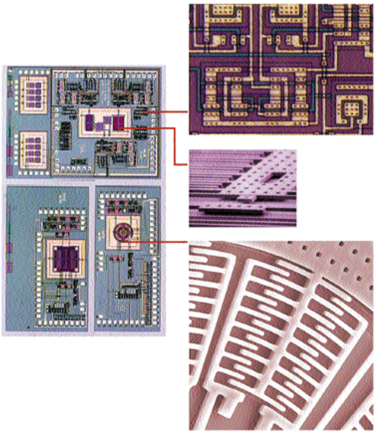

Fabrication of CMOS


Release of MEMS

Sandia Approach: CMOS Last (ctnd.)

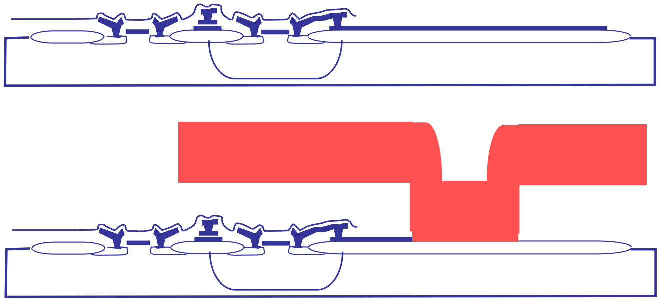

Subsurface Embedded MEMS Integrated Technology

Sandia Approach: CMOS Last (ctnd.)



Six-degrees of freedom accelerometer with integrated IC

CMOS First



Problem with poly-Si: high-temperature anneal incompatible with aluminum interconnect

Approach will rather use standard CMOS layers as MEMS materials

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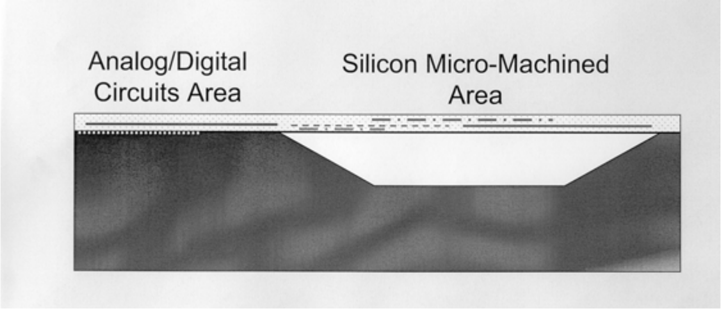
CMOS First (ctnd.)



Approach will rather use standard CMOS layers as MEMS materials

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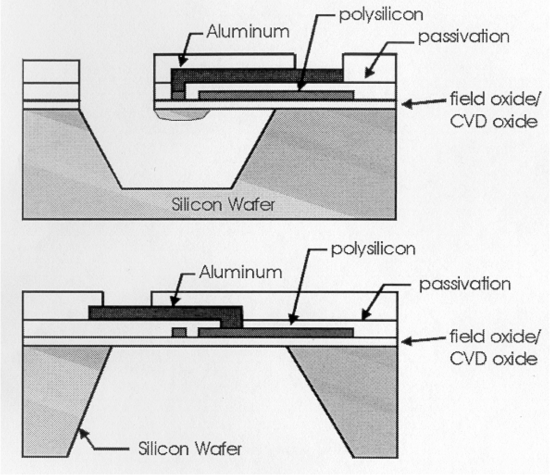
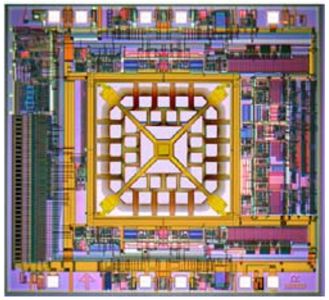
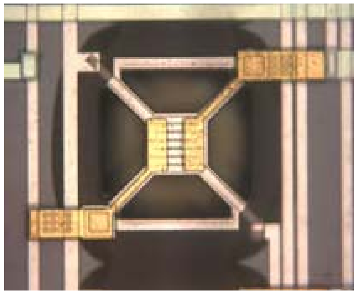
CMOS First: Example



CMOS First: Examples



Dual axis accelerometer (MEMSIC)



Microhotplate gas sensor (NIST)

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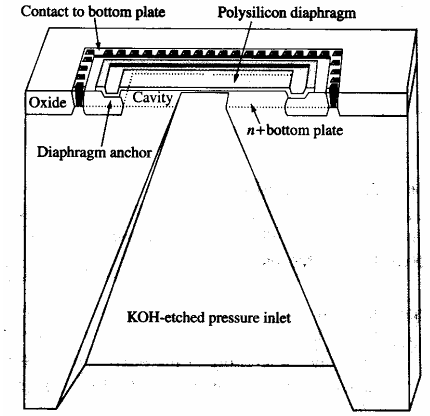
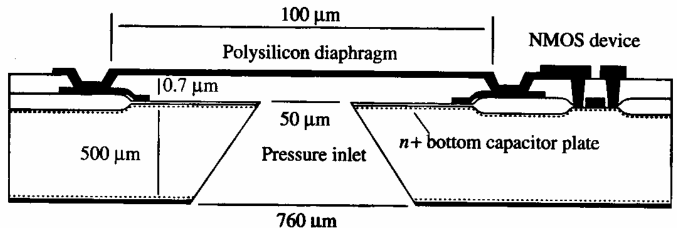
Fabrication of Pressure Sensor



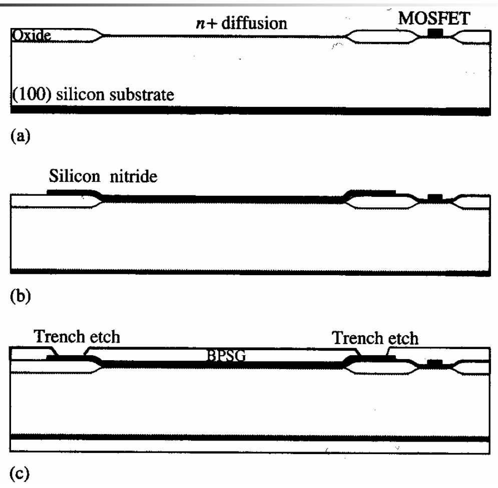
We will fabricate a pressure sensor consisting of a top plate separated by a small air gap, and a bottom plate with inlet for pressurized gas. The gas pressure moves the top plate upward, increasing the gap, and hence decreasing the capacitance.

Fabrication of Pressure Sensor (ctnd.)

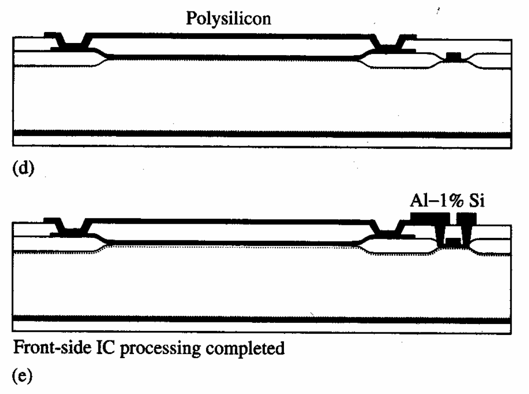


A closer view....

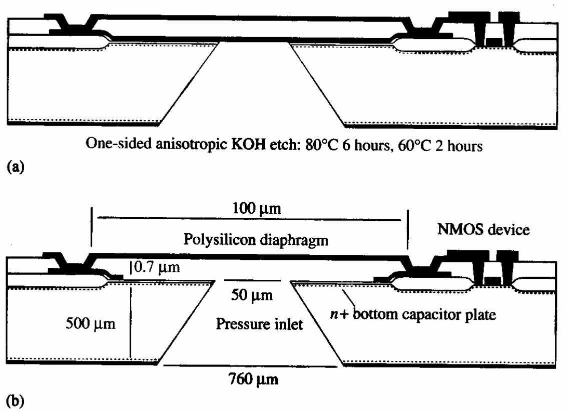
Fabrication of Pressure Sensor (ctnd.)



Fabrication of Pressure Sensor (ctnd.)



Fabrication of Pressure Sensor (ctnd.)



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Fabrication of Cantilevered Microgripper

- Fabricate a poly-Si microgripper that overhangs from a support cantilever beam that itself protrudes from a silicon die, which serves as support for the gripper structure.
- The cantilever is approximately 12 um thick, 500 um long, and tapered from a 400 um width at the base to 100 um at the end.
- This support cantilever accurately locates the overhanging poly-Si microgripper and provides a thin extender for the unit
- The poly-Si microgripper is 2.5 um thick, and 400 um long. It consists of a closure driver and two drive arms that connect to arms that extend to the gripper jaws.
- The beam width for the drive is 10 um to provide relative rigidity. When a voltage is applied between the closure driver and drive arms, the drive arms move and close the gripper jaws.

Fabrication of Cantilevered Microgripper (ctnd.)

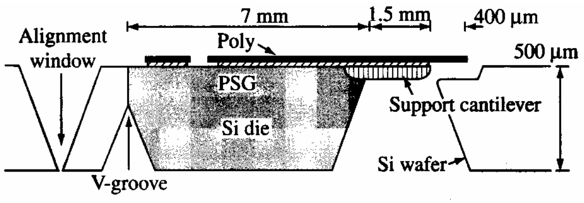
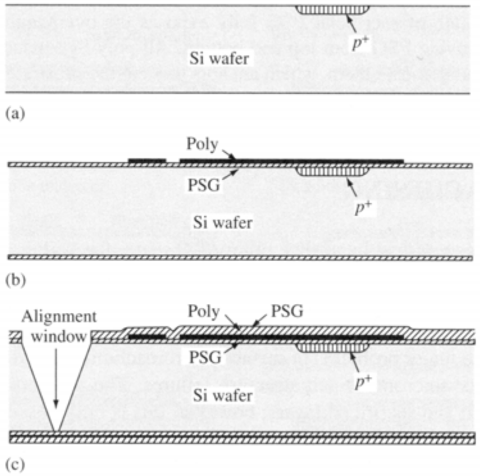


Figure 6.22 Cross-sectional view of a microgripper (Kim *et al.* 1992)

Fabrication of Cantilevered Microgripper (ctnd.)



Fabrication of Cantilevered Microgripper (ctnd.)