Surface Micromachining and Inertial Sensors

Tutorial 2A

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Presentation Outline

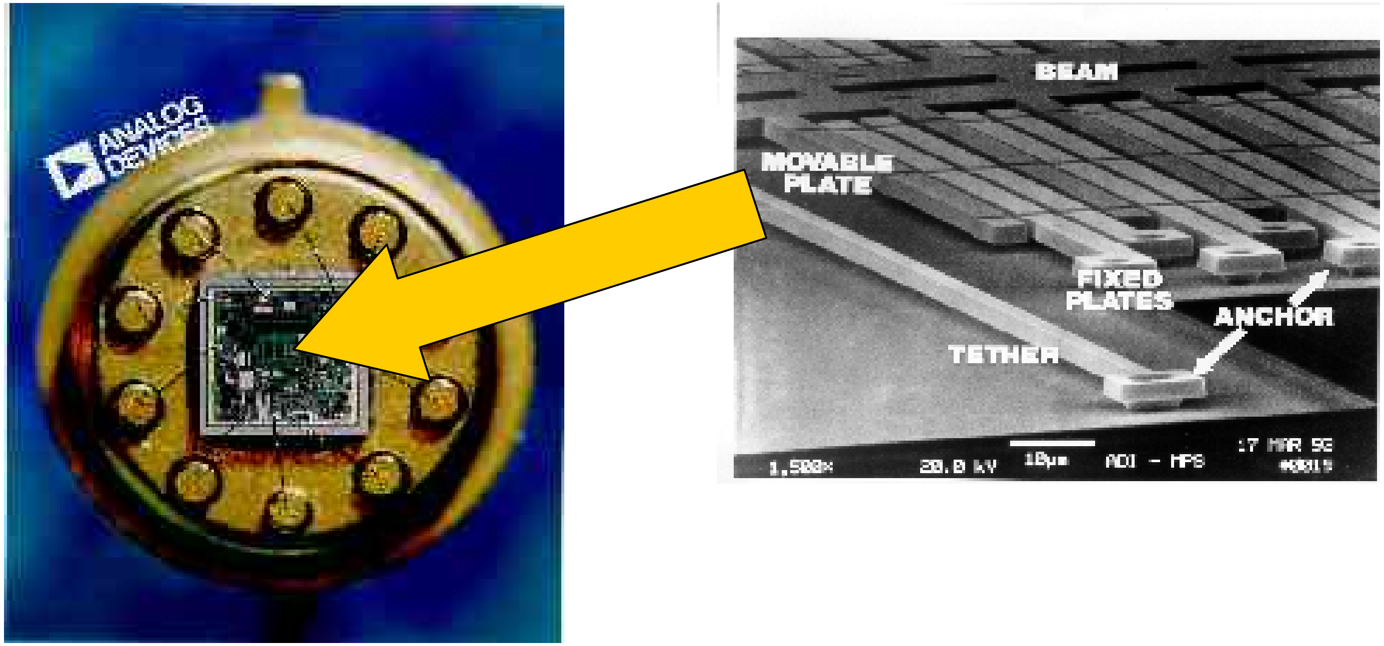
- Technology of MEMS
- Surface Micromachined MEMS
- Processing
- Inertial Sensing
- Conclusions

Introduction

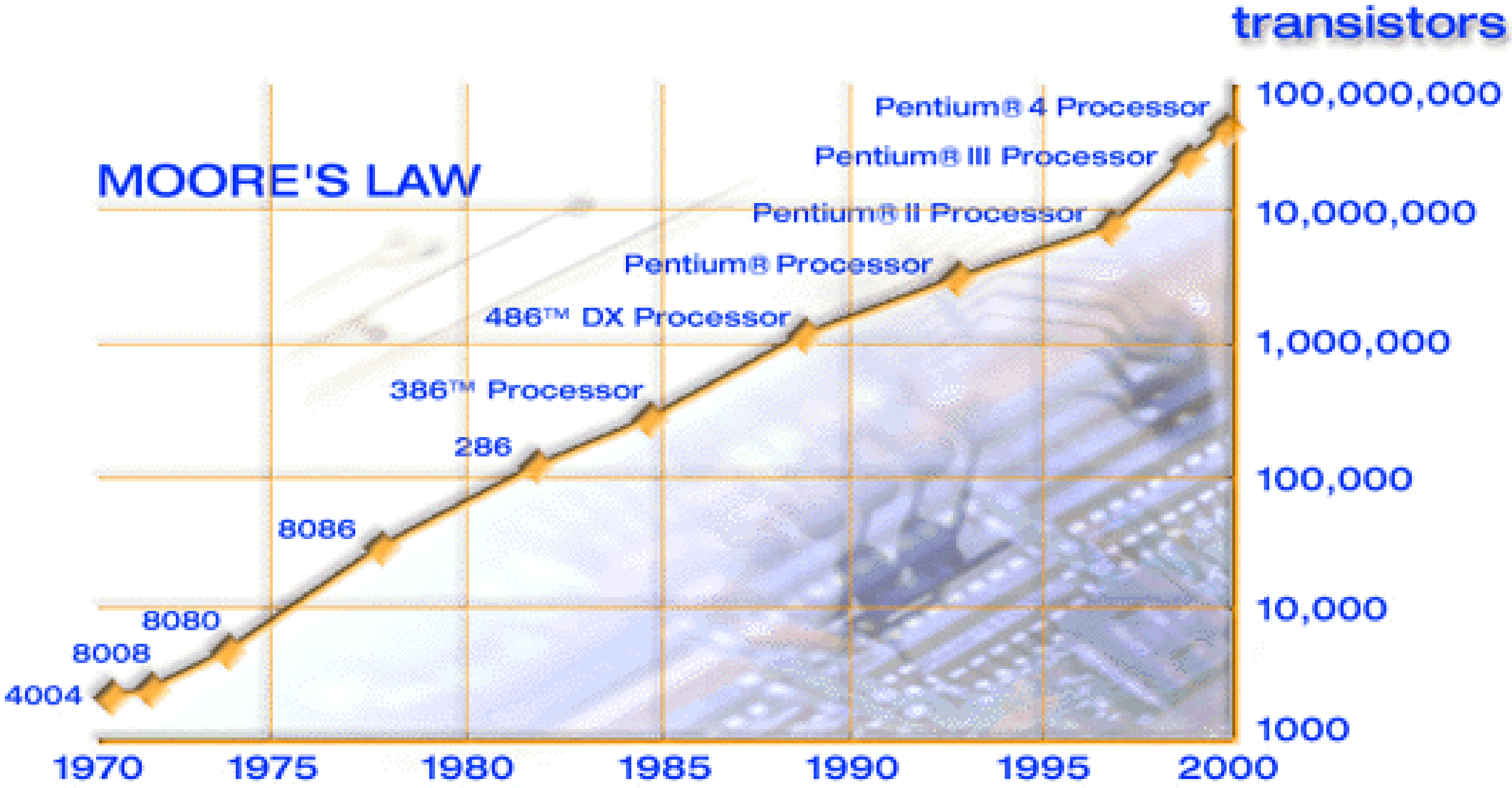
- Micromachining is a subset of Microelectronics
  - Semiconductor Infrastructure
  - Semiconductor Equipment
  - Productivity Parallels Semiconductors

What is MEMS?
(Microsystems Technology, Micro-Mechantronics)

- Micro-Electro-Mechanical-Systems Batch fabricated like IC’s (chips) with mechanical structures



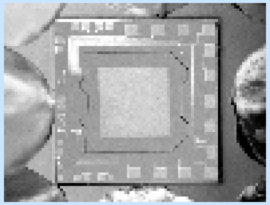
Semiconductor Productivity

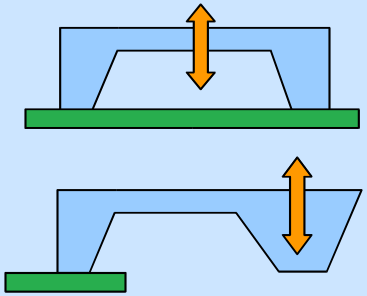


Source: Intel

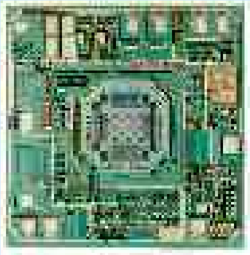
MEMS Technology

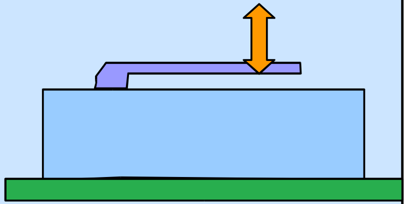
- Bulk Micromachining
  - Pressure Sensors
  - Accelerometers
  - Printing Nozzles



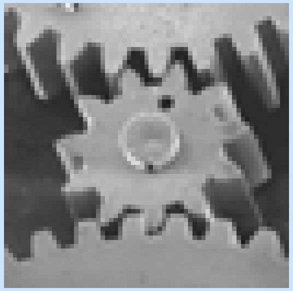


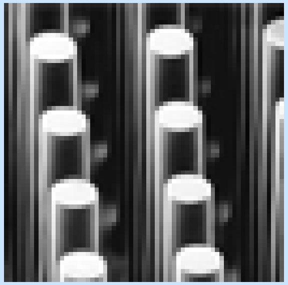
- Surface Micromachining
  - Pressure Sensors
  - Accelerometers
  - Projector Displays





- LIGA
  - Mechanisms

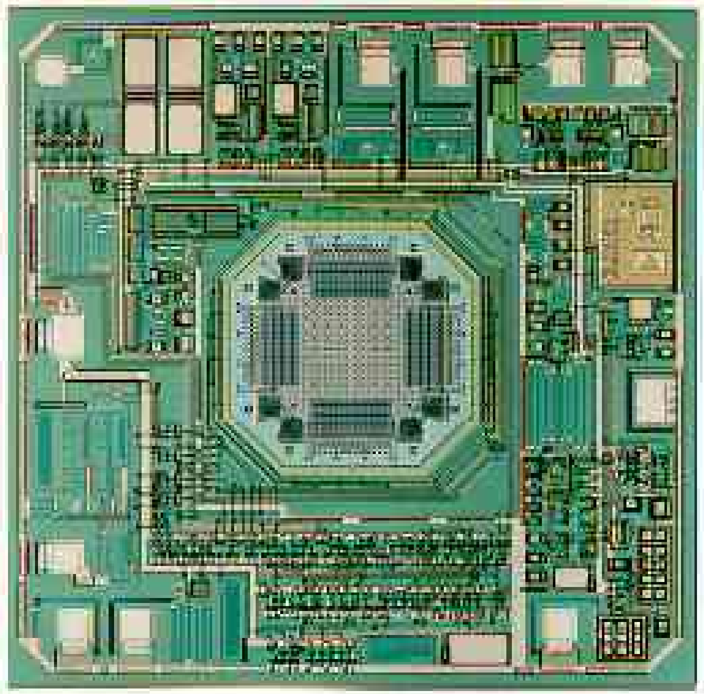




MEMS Sensors Are More Than a Die

- **Packaging**
  - Approximately 33% of the cost
  - Most of the reliabilty issues
  - Difficult to standardize
- **Testing**
  - Approximately 33% of the cost
  - Test tools needed for characterization
  - Special tools needed
  - Requires mechanical and electrical design

Integration at Different Levels



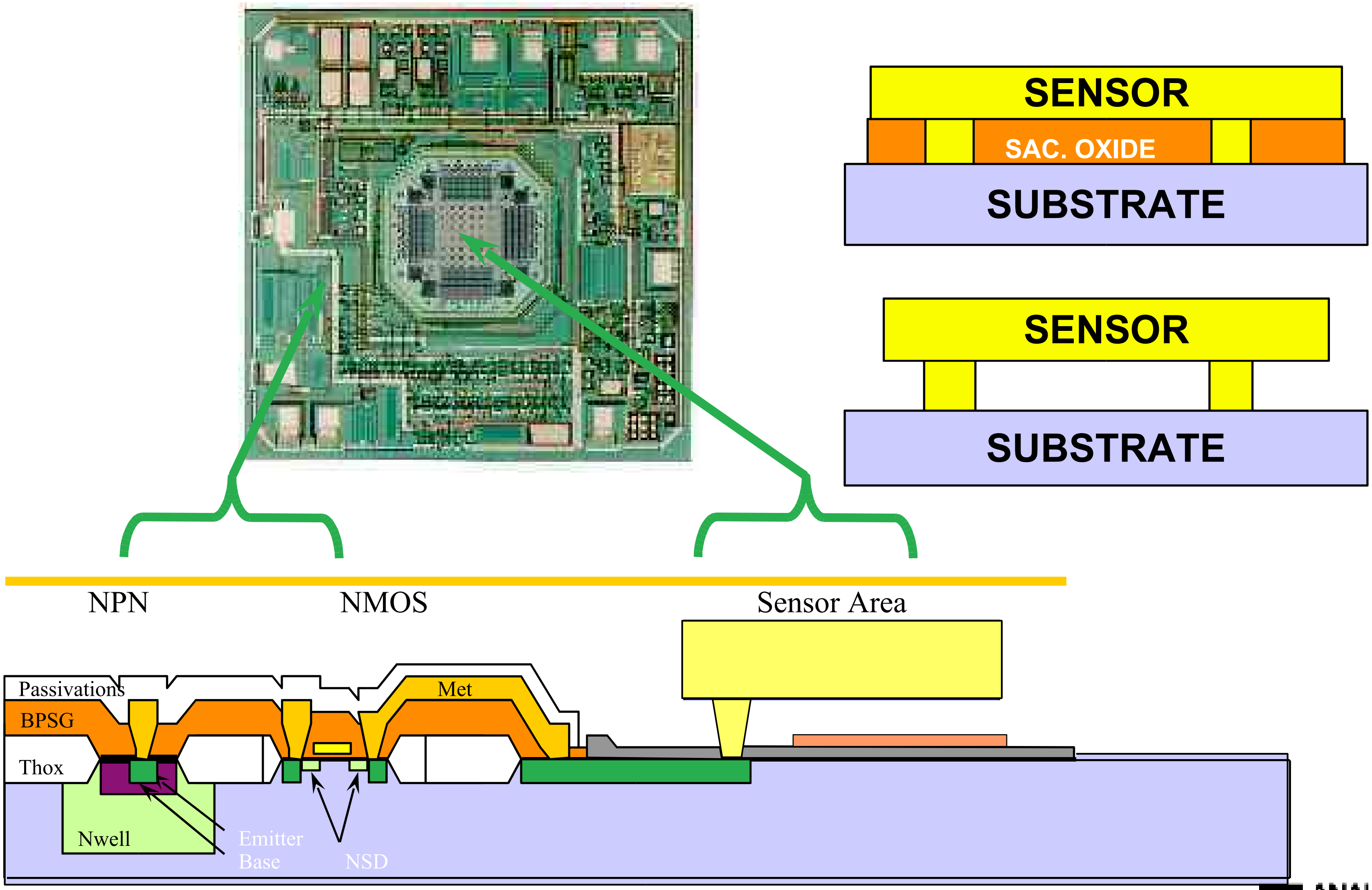
Multi-Chip

Integration in Package

Single Chip

Integration on Chip

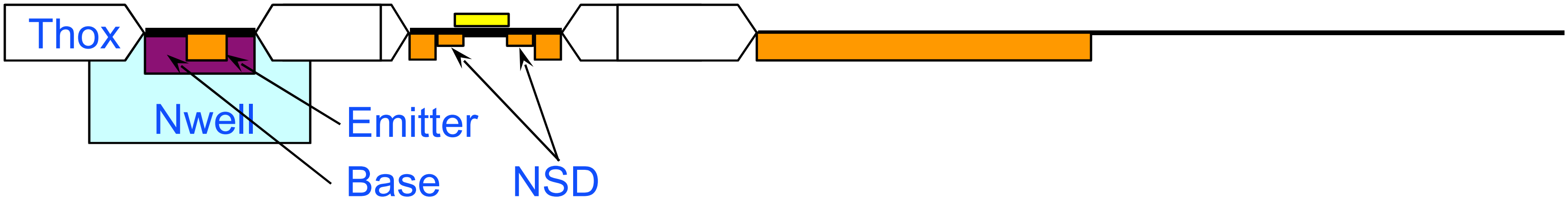
Surface Micromachining *i*MEMS®



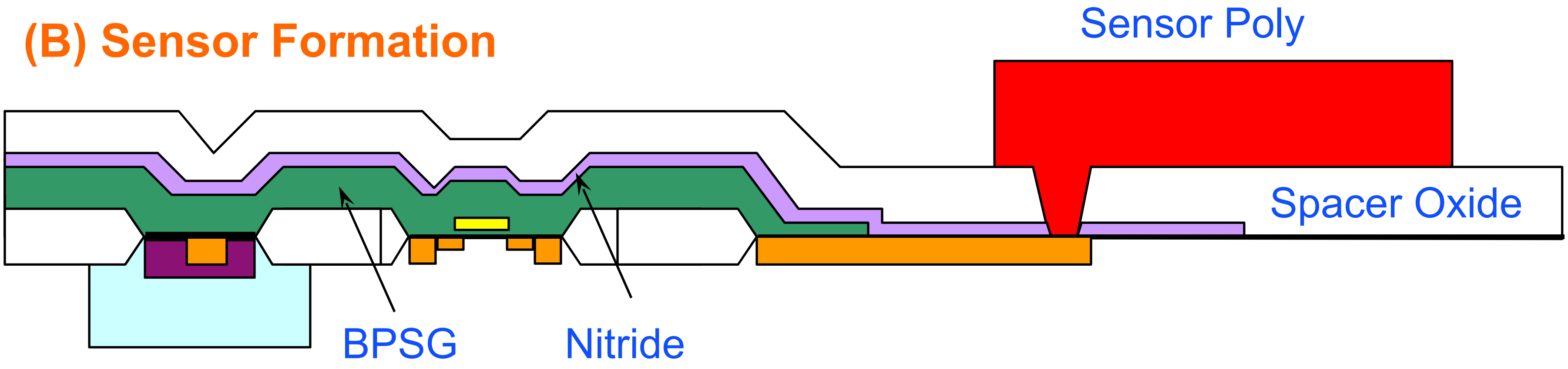
iMEMS Process Flow

NPN **NMOS** **Sensor**

(A) Circuit Formation



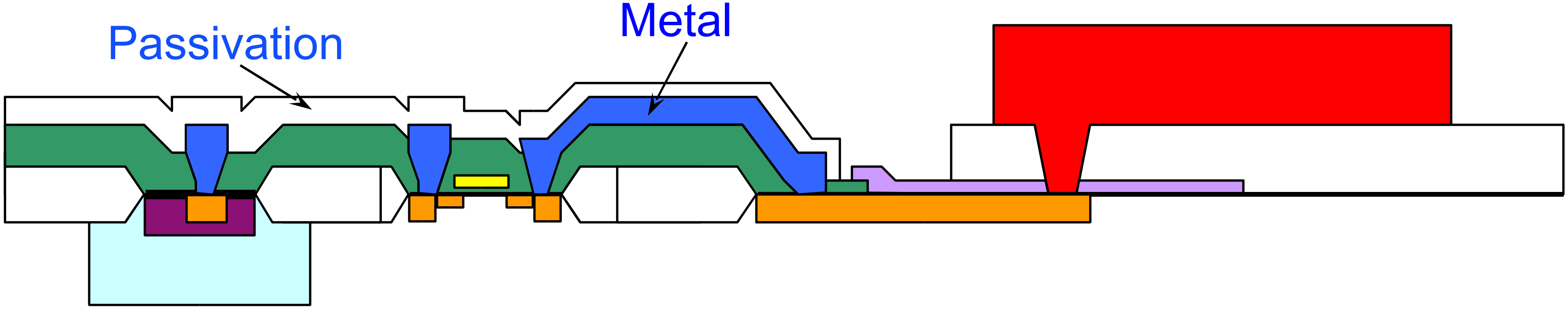
(B) Sensor Formation



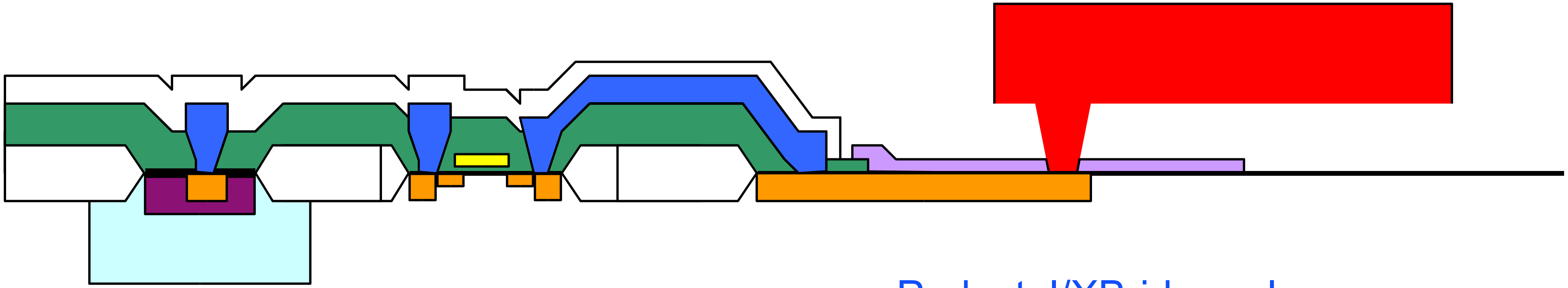
iMEMS Process Flow

NPN **NMOS** **Sensor**

(C) Circuit Completion



(D) Sensor Release



Pedestal/XBridge release process

Process Sequence for *i*MEMS®

BiMOS + MEMS + Thin Film Resistors

- Process Silicon Substrate for CMOS and Bipolar Devices
  - Reserve Area for Mechanical Polysilicon MEMS
- Deposit Mechanical Polysilicon for MEMS
  - High Temperature Anneal of Polysilicon (3hr @ 1100 deg C)
- Process Thin Film Resistors and Metal Interconnect
- Etch Sacrificial Layer
  - Support Polysilicon with photoresist

Analog Devices Micromachined Products

Dedicated Fab >3 million accels per month, < 10 ppm

- QS9000 Compliant Fab, BiCMOS & MEMS

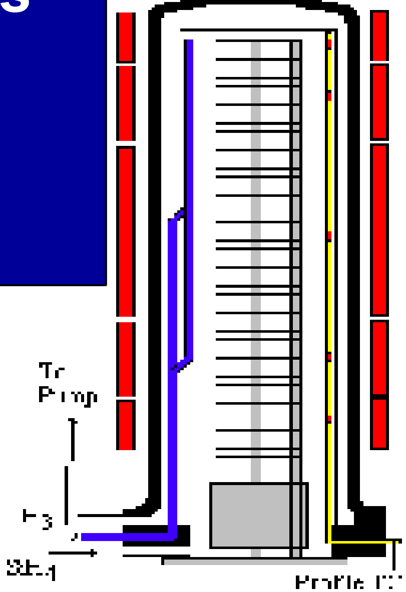
Processing Semiconductor Tools

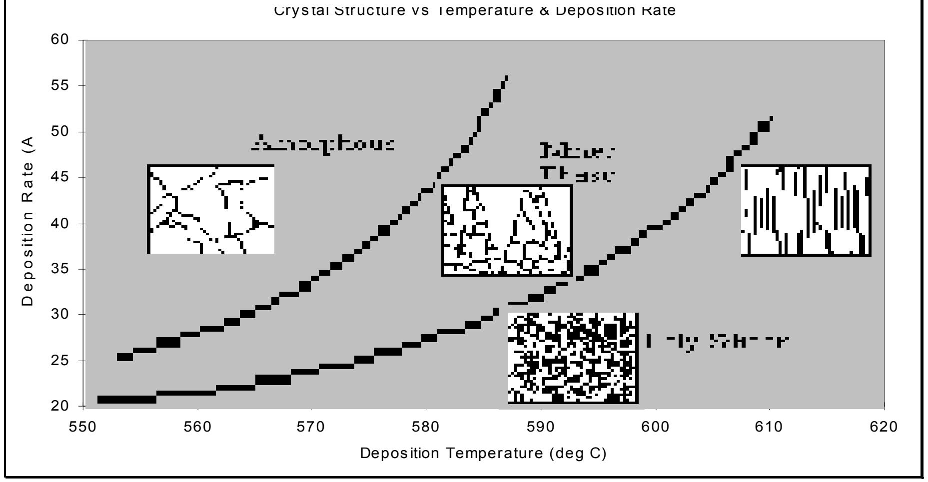
ETCH

Photo Coat/Develop

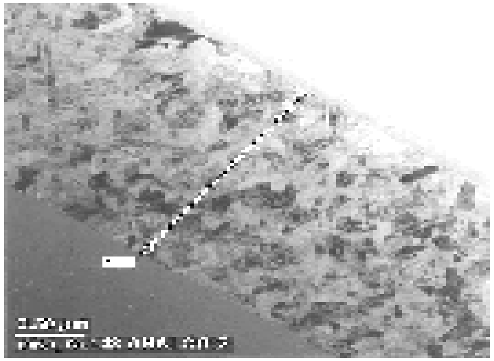
Polysilicon Properties

- Material Properties
- PPM O_2
- Recrystallization





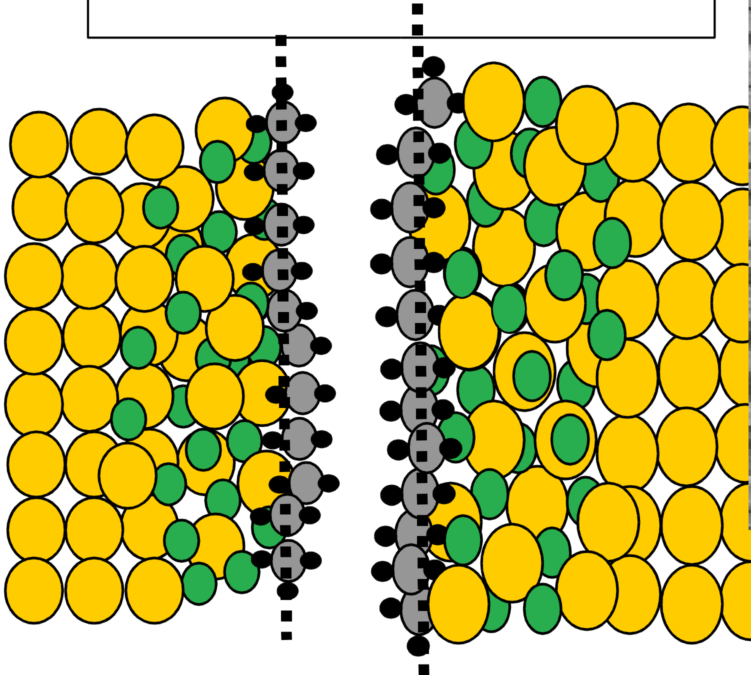
Grain structure for 2um 580 Deg C undoped film with no O2

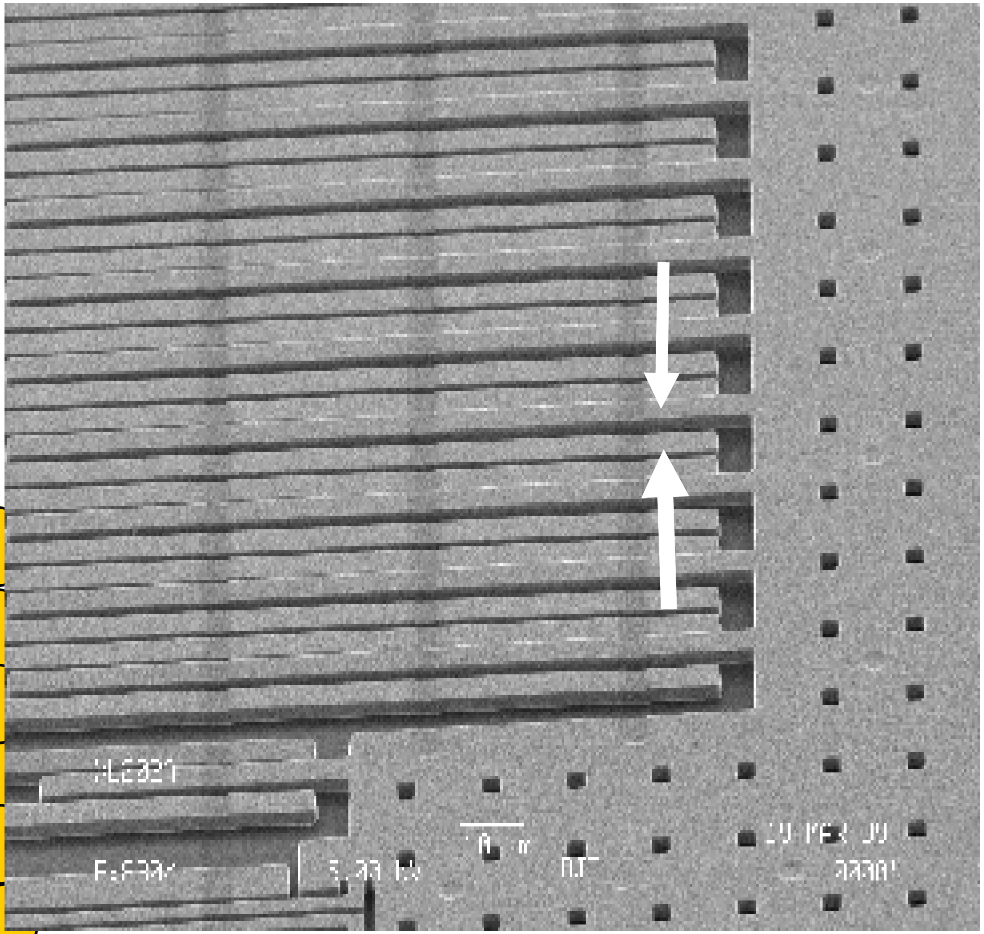


Grain structure for the same deposition conditions but with O2 added to the deposition step using N2O2 mix.

Sub Nanometer Coatings

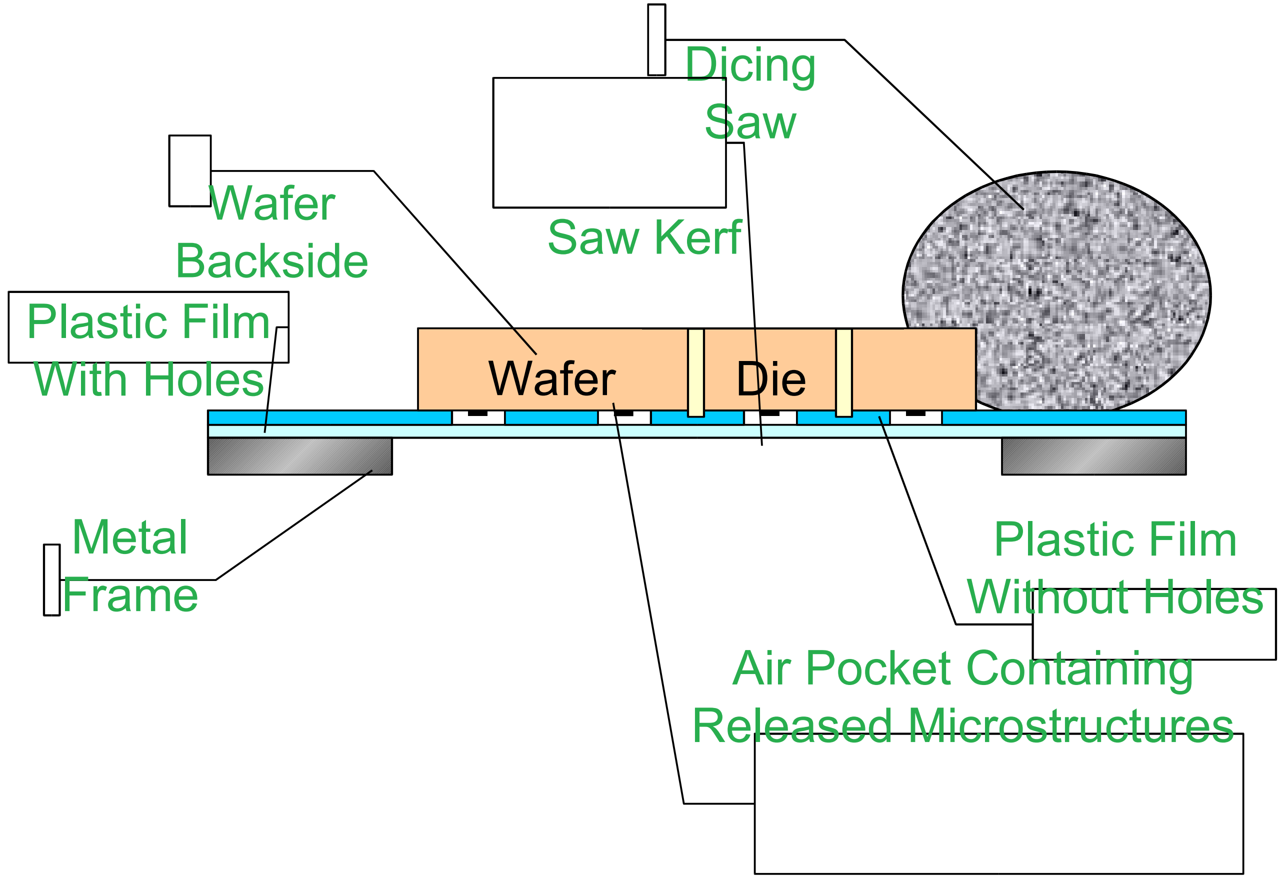
- **0.2 nM coatings eliminate static friction**
- **Vapor deposited at wafer level for reliable films**





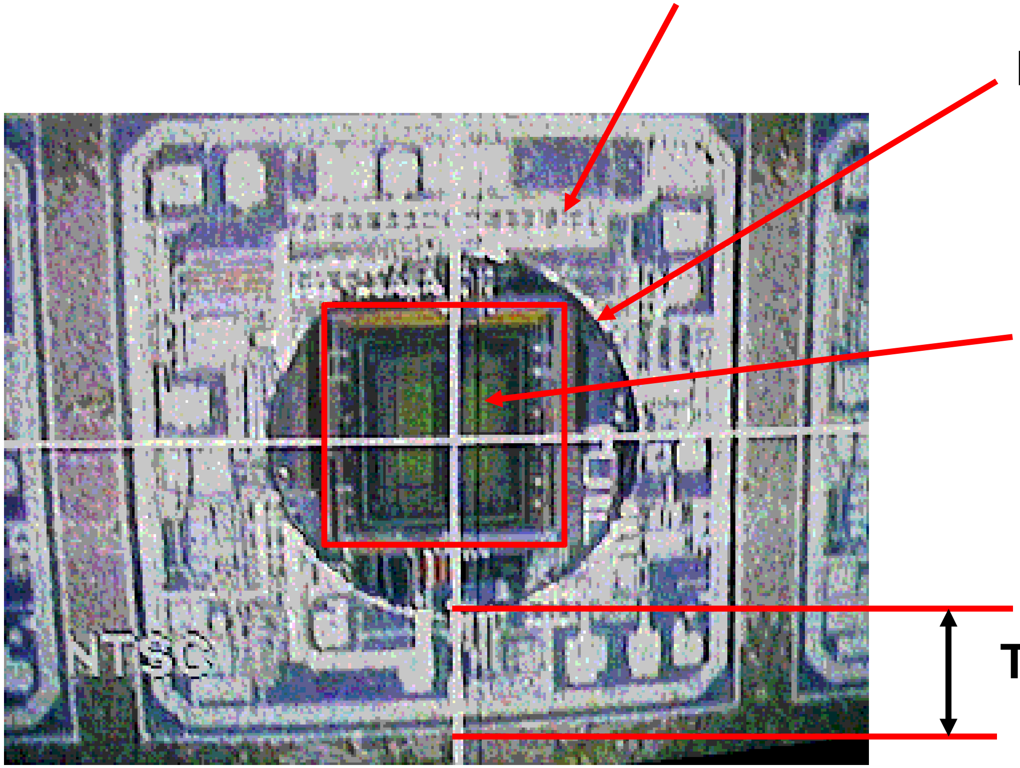
Die Singulation for MEMS

- Protect MEMS devices with a temporary cover
- Up-side-down saw
  - **US Patent 5,362,681 (Analog Devices)**



Dicing Exposed MEMS structures

Backside Saw



PVC tape

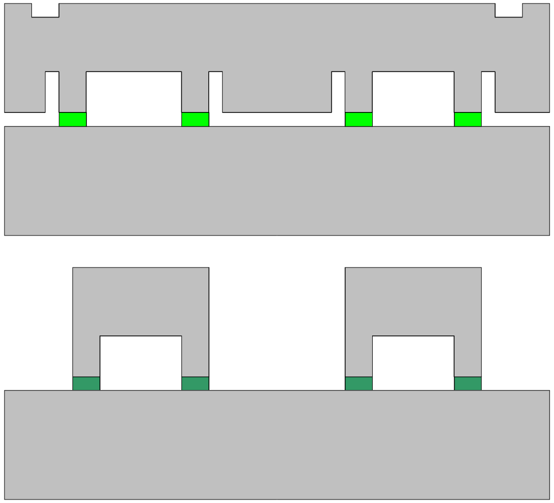
punched hole

MEMs area of Die

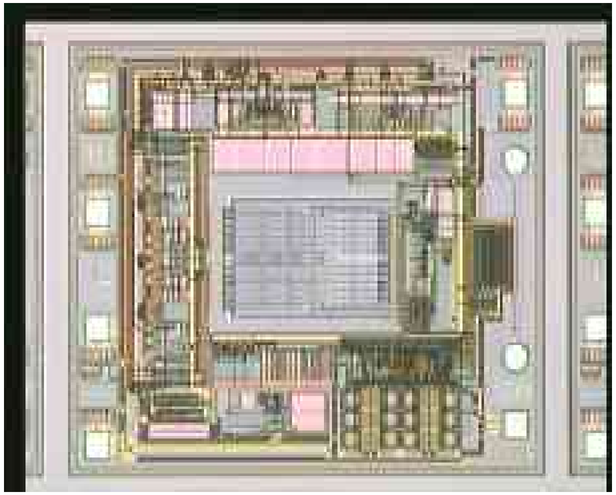
Tape Seal Area

Accelerometer Die

Front-end Process Technology: How has iMEMS evolved?



- **Capping**
  - **Wafer level (4 masks)**
  - **Capabilities**
    - Better control of environment around sensor
      - pressure & gas species
    - Lower die stress
      - die attach choices open
  - **Reliability/Quality**
    - Lower particle levels
  - **Enables lower cost**
    - packaging (i.e., plastic)
    - foundry assembly



Front-end Process Technology: How has iMEMS evolved?

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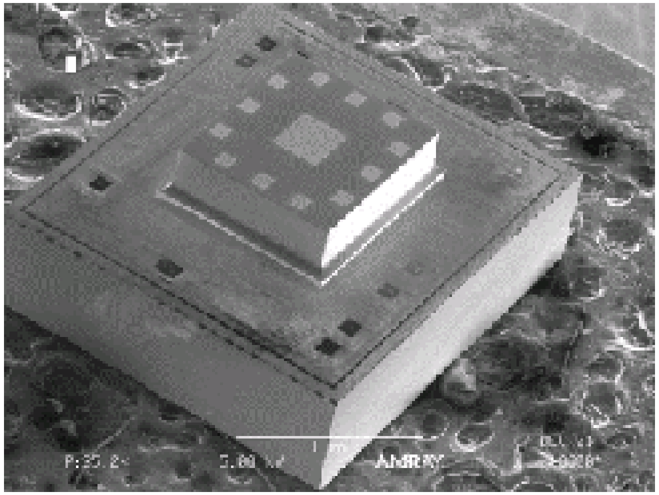
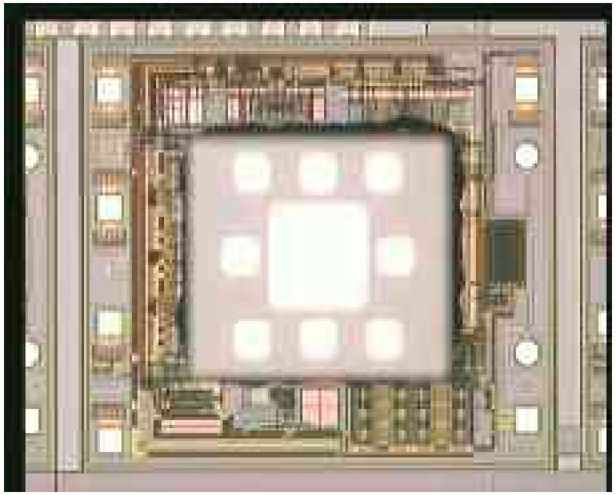
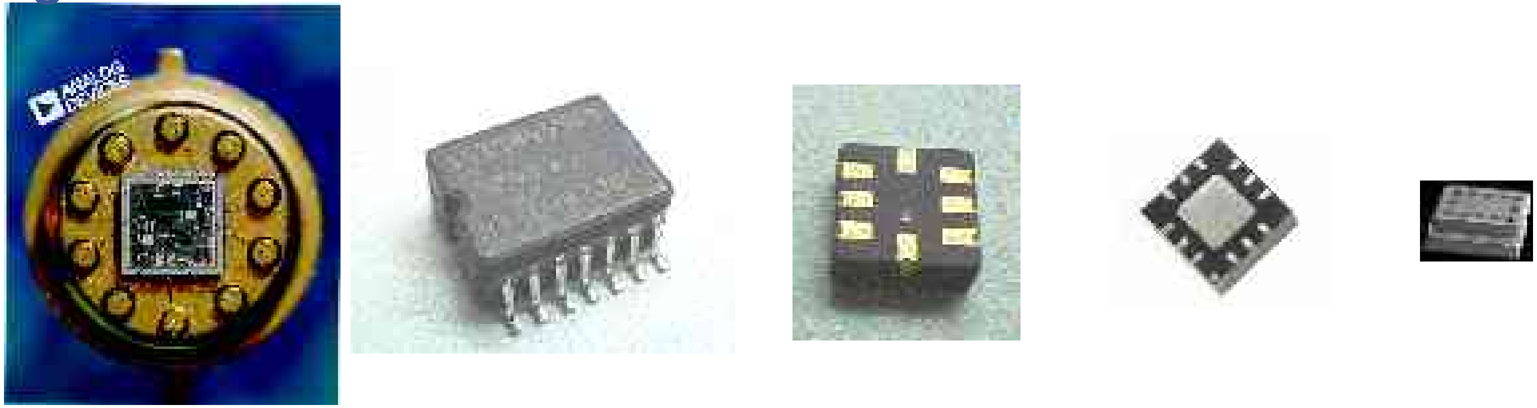




Accelerometer Packaging Trends

Package Evolution



	Header	Cerdip/Cerpak	LCC	QFN	WSP
Xmm	10	10	5	4	2
Ymm	10	10	5	4	2
Zmm	7	5	2	1.45	0.9

Lead Free Packages →

Assembly & Test Operations Subcontractor in Philippines

Dedicated Line in Large Factory
200 people for accelerometers

Tester Development

Issues to Deal With

Testing Machines not Developed
Measurement Standards Inadequate
Dynamic Parameters and Vibration

Solution

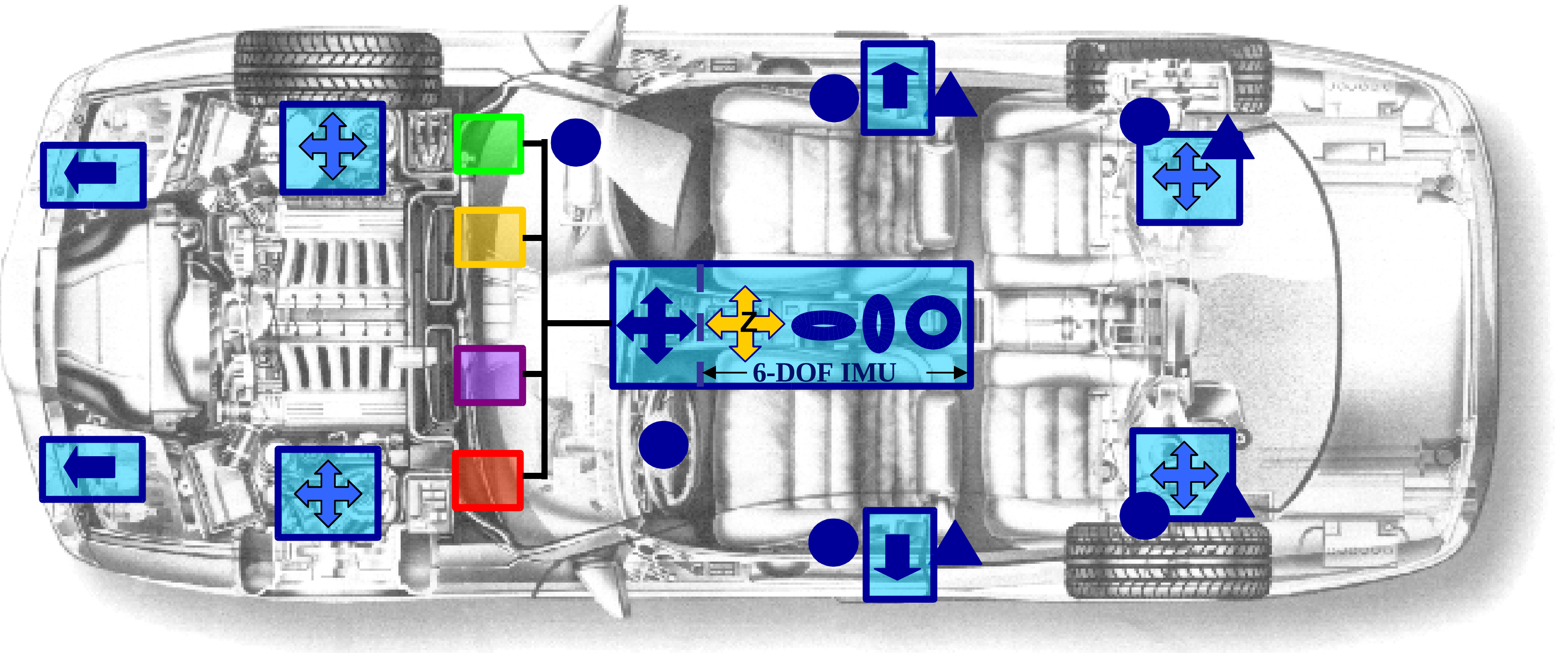
Semiconductor Handler Based Tool
Custom Tooling – Exclusive IP
Serialized Parts – OCR
Transfer to Off-Shore after qualification

Automotive Airbag Sensors
Market Pull

< 1 ppm quality level

< 1 FIT (53 million device hours, MTBF 6.6 X 10^9 hr)

Inertial Sensors in Vehicles



- 🟩 **Crash Detection System**
- 🟨 **Vehicle Dynamic Control System**
- 🟪 **Navigation/Driver Information System**
- 🟥 **Body/Chassis Control System**

- ⬆ **Satellite Sensor**
- ✥ **Dual-axis airbag sensor**
- ✥ **Low *g* chassis control sensor**

- ● **Airbag**
- ▲ **Seatbelt Pretensioner**
- ○ **Gyro**

*i*MEMS® Technology

Accelerometers

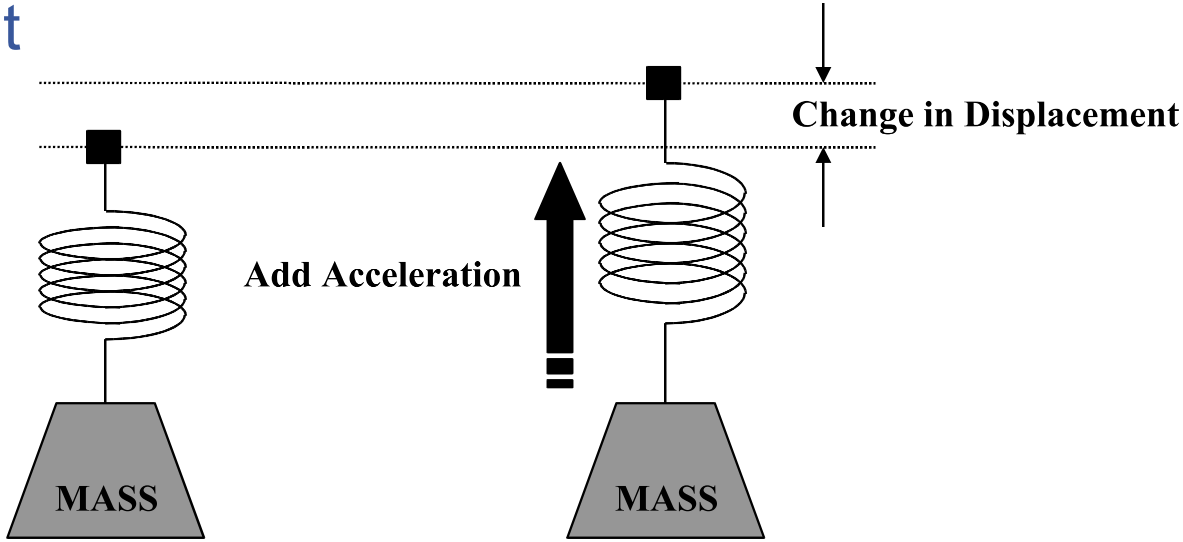
- **What Does an Accelerometer do?**

  MOTION & TILT MEASUREMENT
  - ❑ **Measurement of static gravitational force**
    - **e.g. Tilt and inclination**
  - ❑ **Measurement of dynamic acceleration**
    - **e.g. Vibration and shock measurement**
  - ❑ **Inertial measurement of velocity and position**
    - **Acceleration single integrated for velocity**
    - **Acceleration double integrated for position**

*i*MEMS® Technology

F=MA

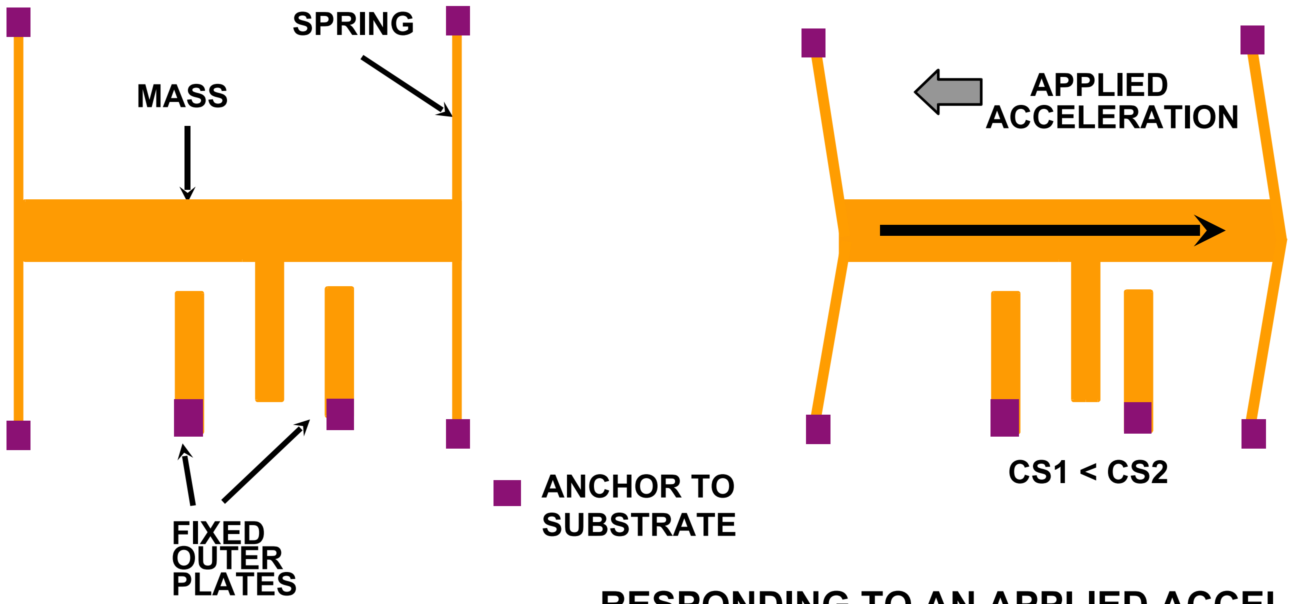
- Acceleration can be measured using a simple mass/spring system.
  - Force = Mass * Acceleration
  - Force = Displacement * Spring Constant
  - So   Displacement = Mass * Acceleration / Spring Constant



*i*MEMS® Technology

Sensor Principle: Differential Capacitive Sensing

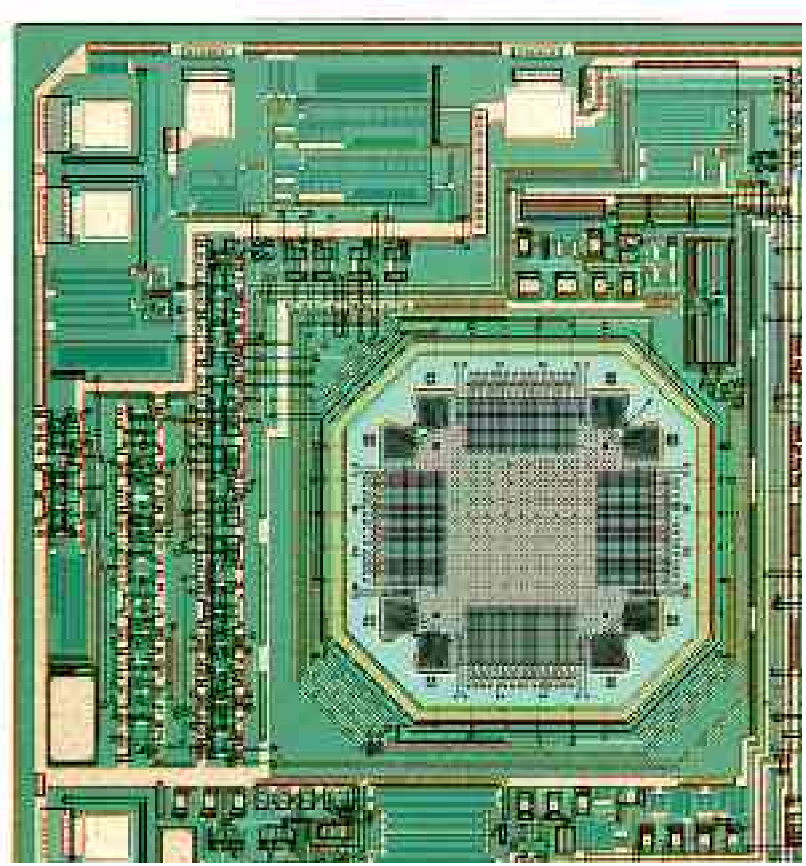
- **Use Silicon to make the spring and mass, and add fingers to make a variable differential capacitor**
- **Measure change in displacement by measuring change in differential capacitance**

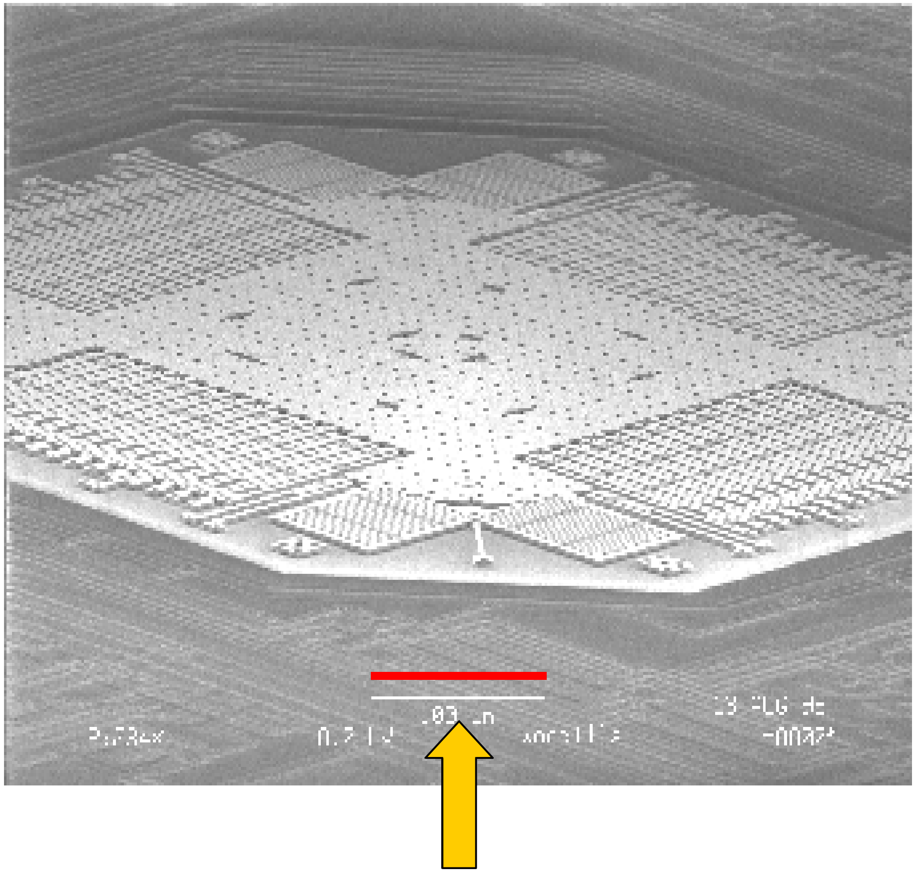


SENSOR AT REST

RESPONDING TO AN APPLIED ACCELERATION (MOVEMENT SHOWN IS GREATLY EXAGGERATED)

Integrated Micromachined Accelerometer

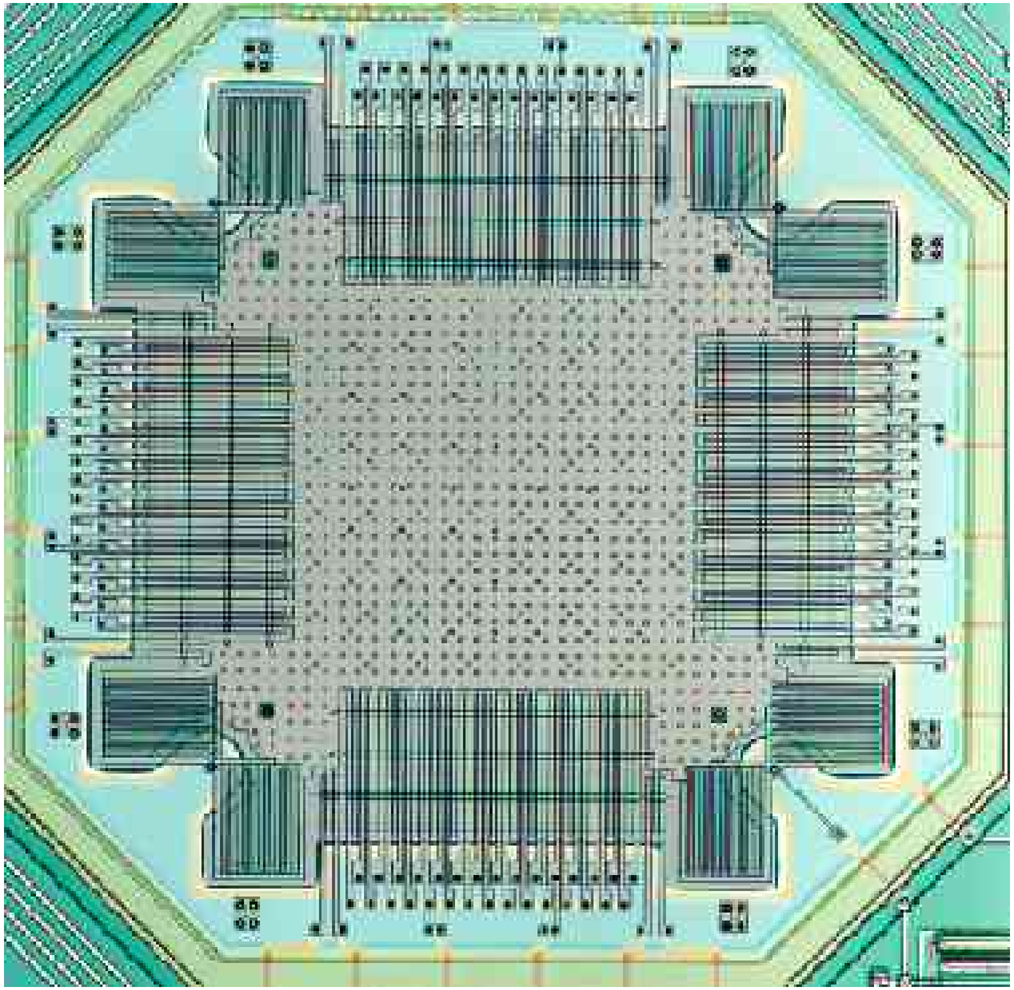




100 microns

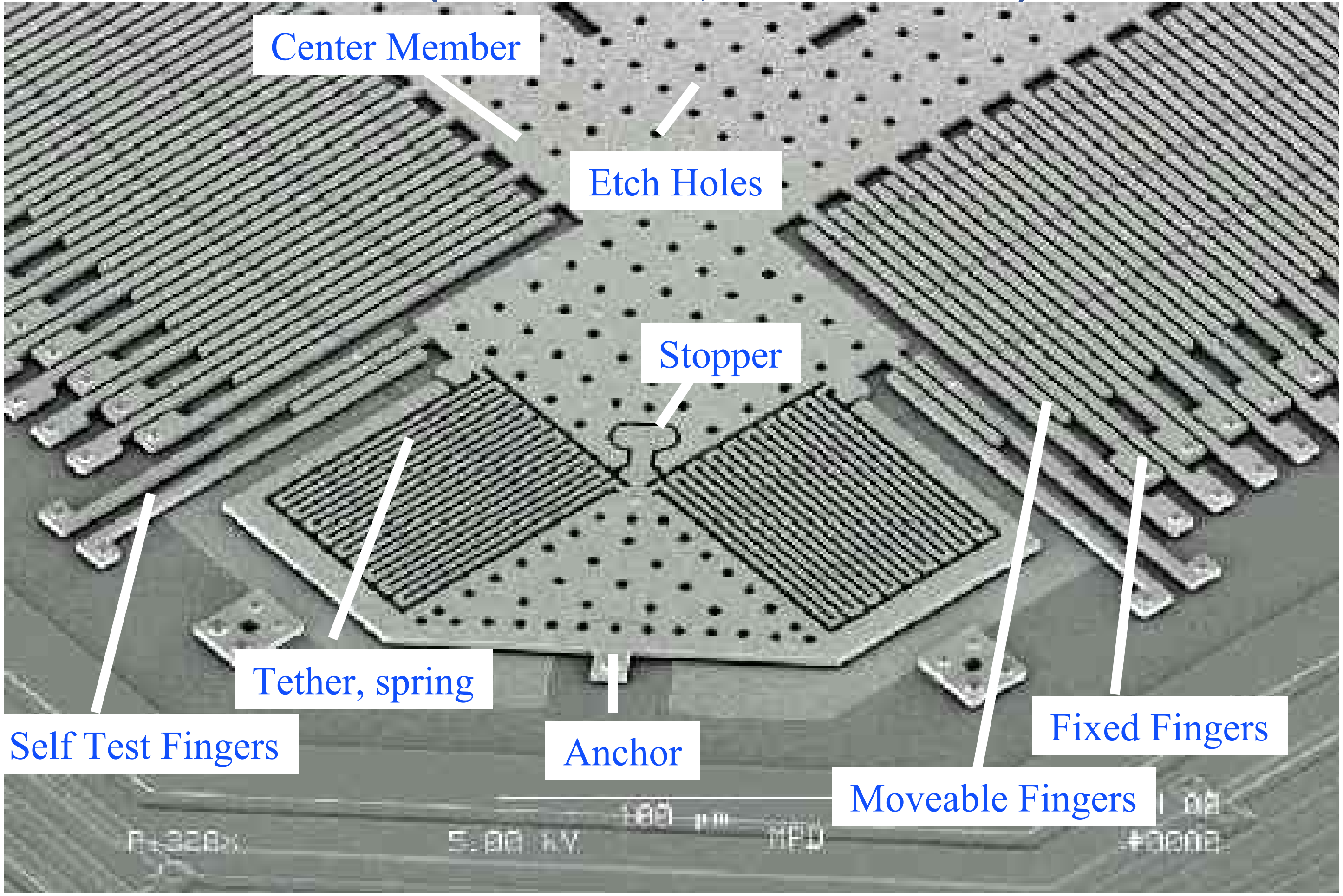
*i*MEMS® Technology

Accelerometer Beam (ADXL202)



*i*MEMS® Technology

Accelerometer beam (ADXL202, one corner)

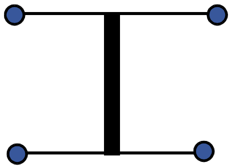


*i*MEMS® Technology

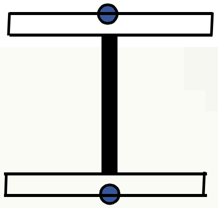
- **Amplifier with adjustable gain (via thin film laser trim)**
  - Zero g offset and sensitivity are laser trimmed at wafer level
  - How do we trim sensitivity without shaking the part?
    - Fn =sqrt (K/M) where K is spring’s displacement vs force
    - We measure the resonant frequency of the beam to learn the mass and spring constant
- **Output filter**
  - Simple R-C filter for low-g products (internal R, external C)
  - 2 pole switched capacitor filter on high-g parts

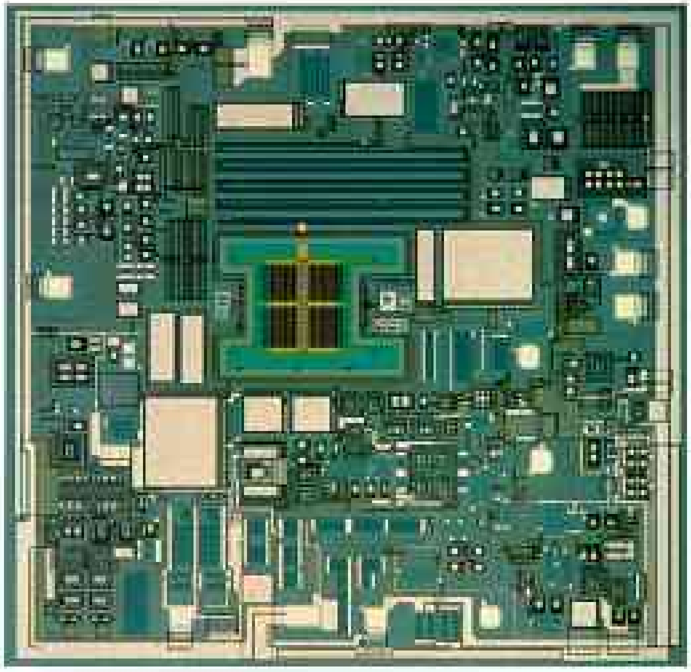
Early Accelerometer Design Evolution

Closed Loop
Tensile Spring

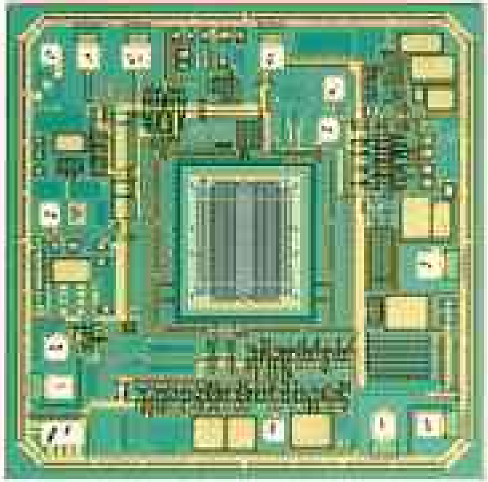


Open Loop
Folded Spring

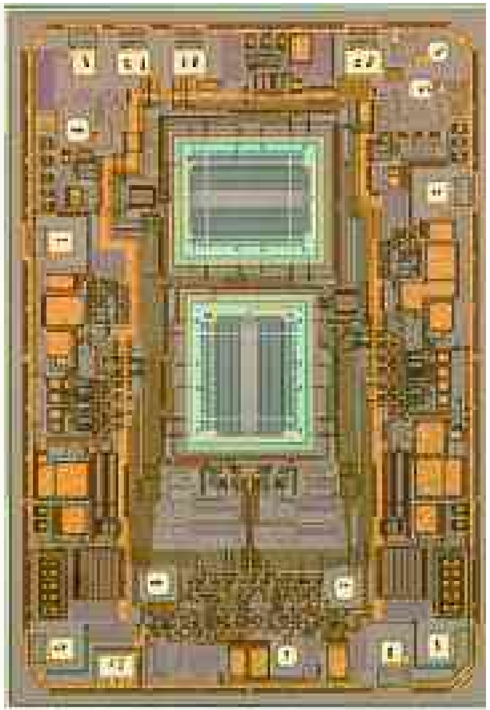




XL50



XL76



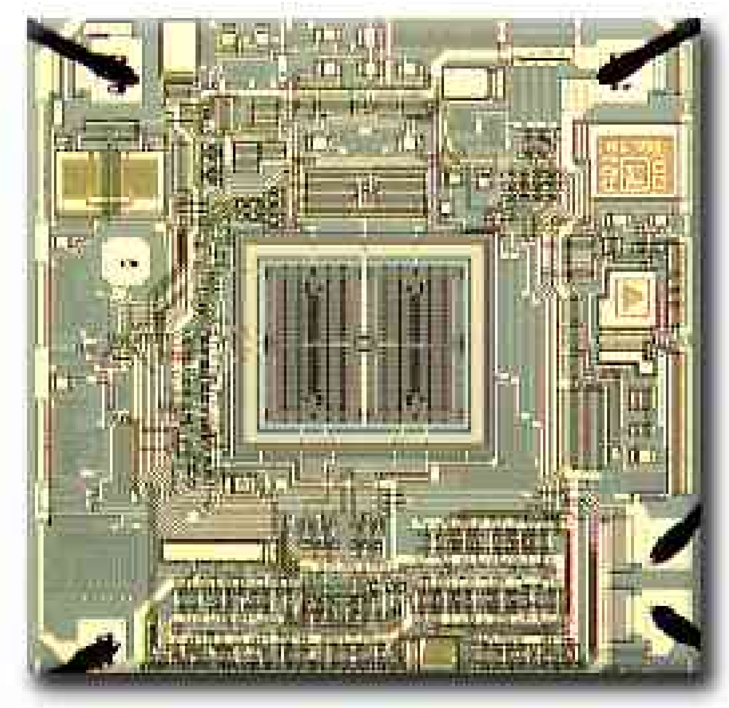
XL276

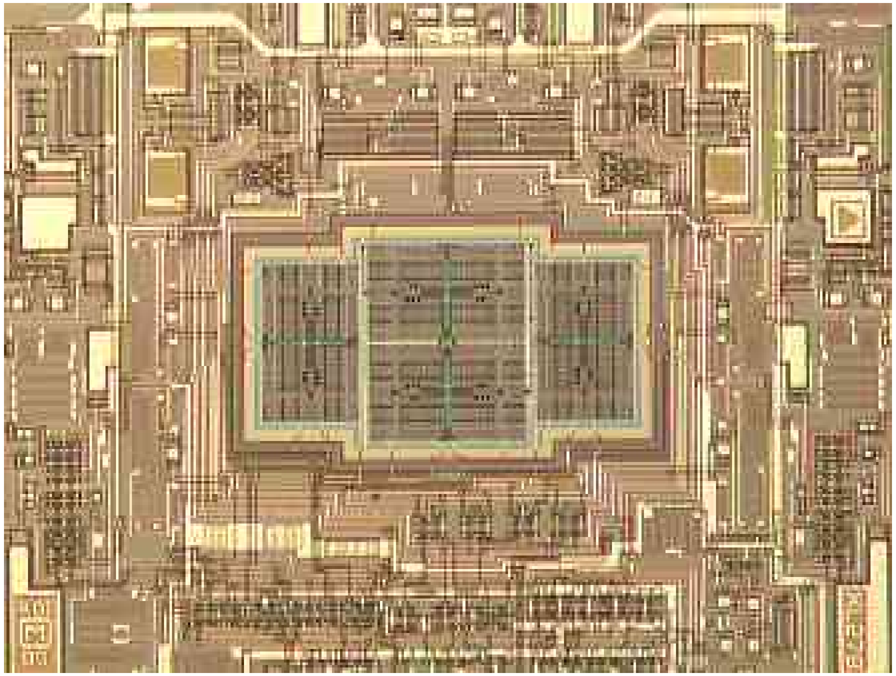
ADXL78 and 278 Full Differential Designs

Mechanical Design Duplicated

Differential Capacitance

Demodulation of Two Channels





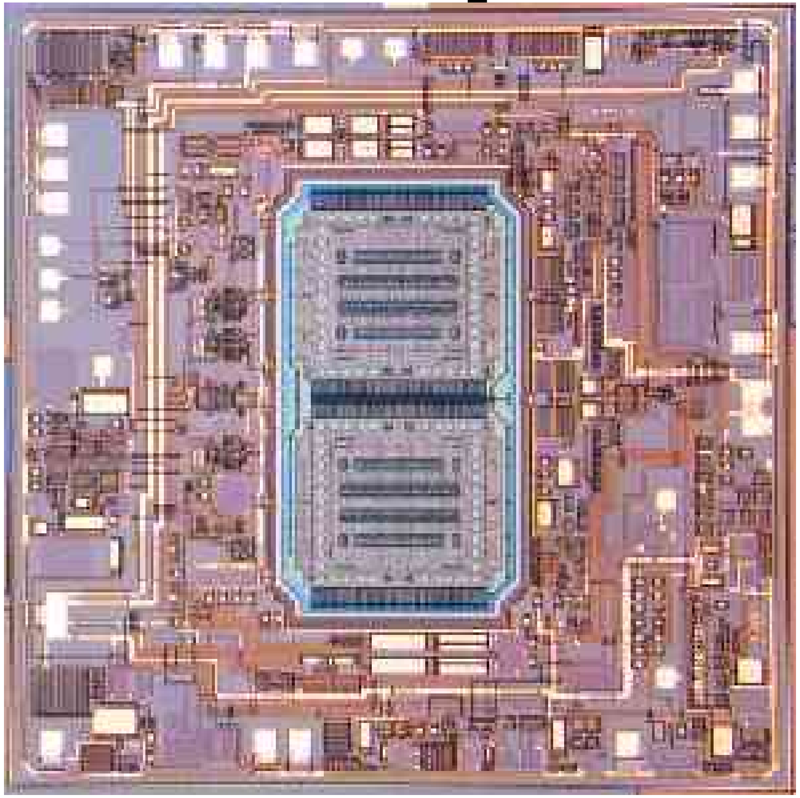
Integrated Micromachined Gyro

Single Chip Rate Sensor

5V Operation
Std Atmosphere
150 deg per second
Self-Test
0.03 deg/sec/sqrt hz
Compensated 5%

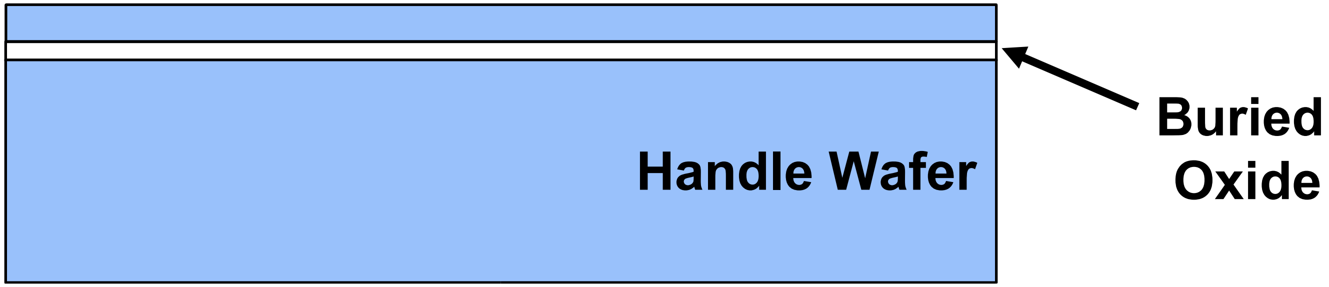
Lessons Learned In Accelerometer Development of Meso Structures Detecting Nano dimensions now applied to sub pico-dimensions

Single Chip

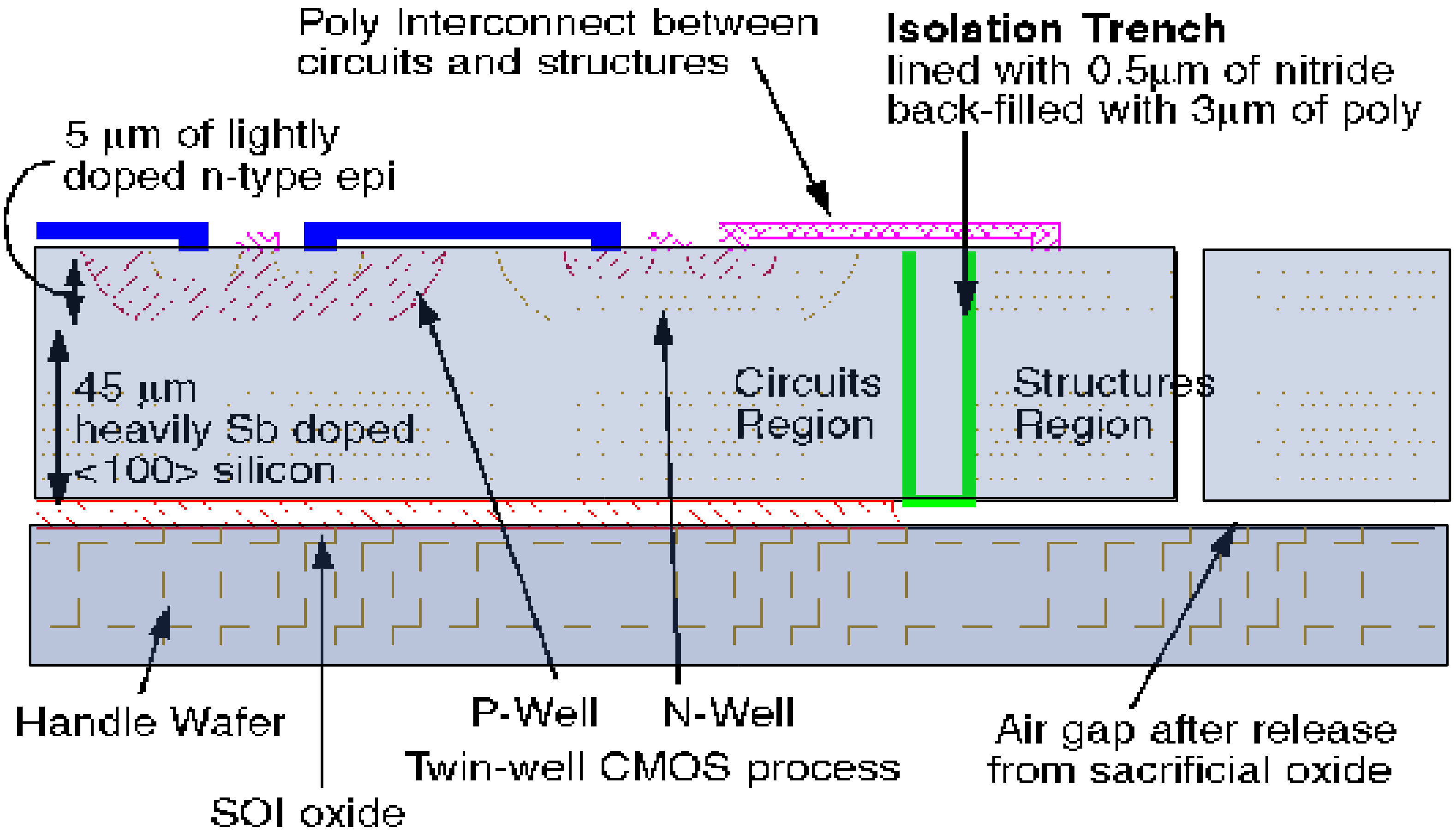


Future Trends

- More Integration of Circuit Functions
  - Communications
  - Calibration and Identification
  - Wireless
- Use of Silicon-on-Insulator
  - Preprocess the Wafer for MEMS
  - Foundry the Semiconductor Process
  - Use DRIE Etching to Access the Buried Oxide
  - More Mass for Inertial Devices



SOI Sensor Configuration



Poly Interconnect between circuits and structures

Isolation Trench
lined with 0.5µm of nitride
back-filled with 3µm of poly

5 µm of lightly doped n-type epi

45 µm
heavily Sb doped
<100> silicon

Circuits Region

Structures Region

Handle Wafer

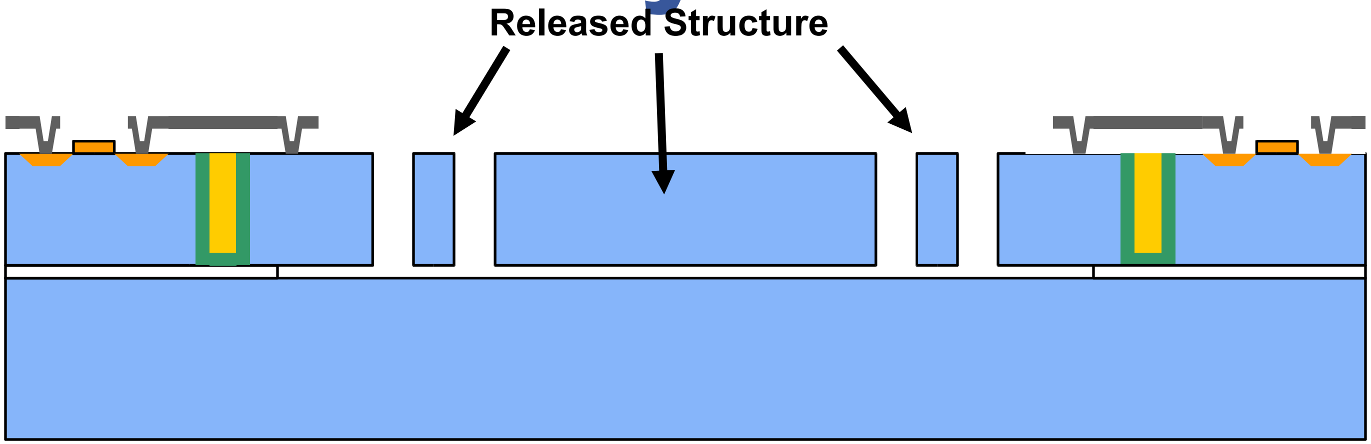
SOI oxide

P-Well N-Well
Twin-well CMOS process

Air gap after release from sacrificial oxide

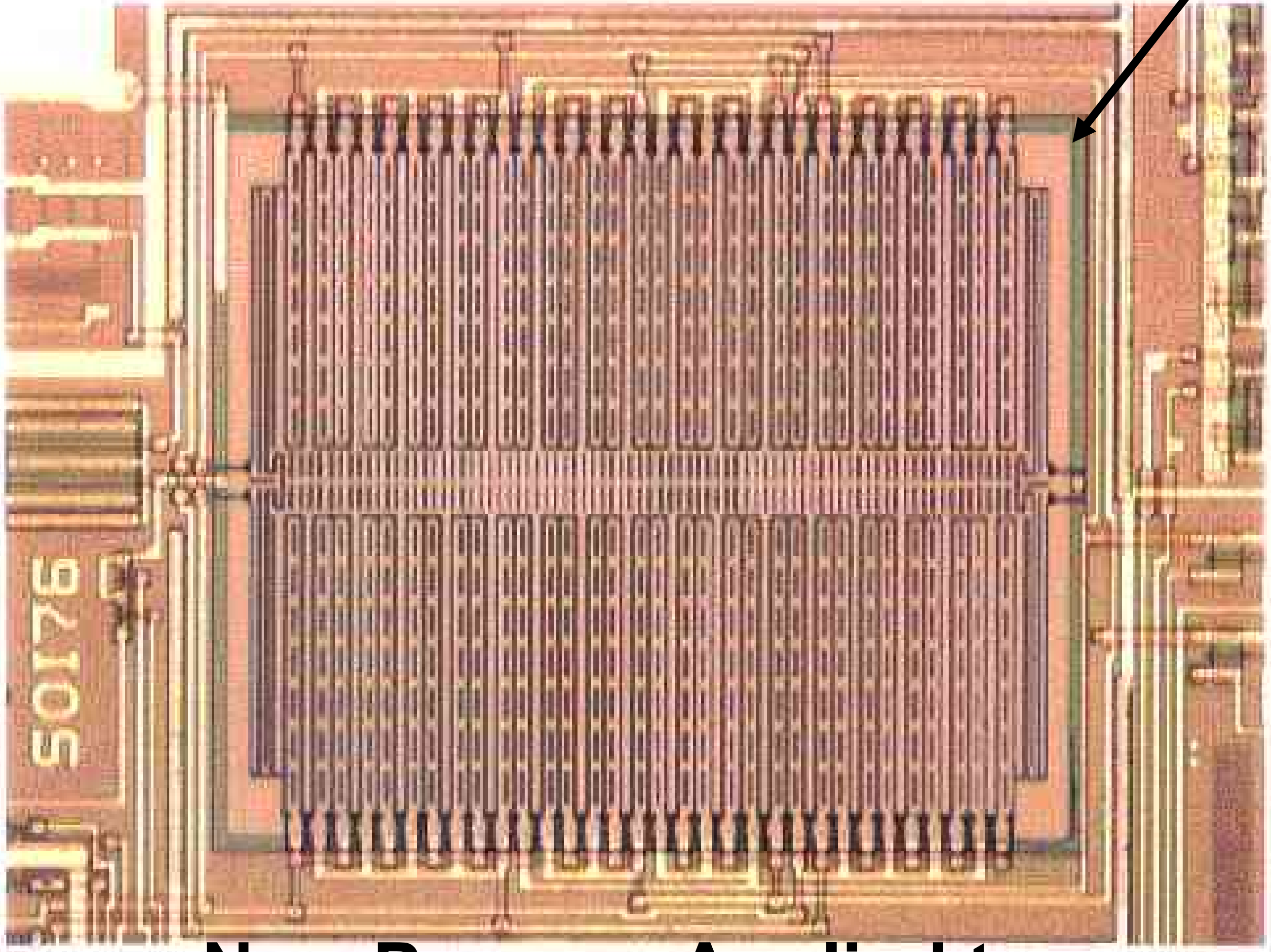
Note: CMP wafer planarization is performed after trench back-fill

Sensor Fabrication Process after foundry of circuits



- Deep Reactive Ion Etch Stop at Buried Oxide
- Etch oxide beneath MEMS structures
- Strip Protective Photoresist

SOI Accelerometer

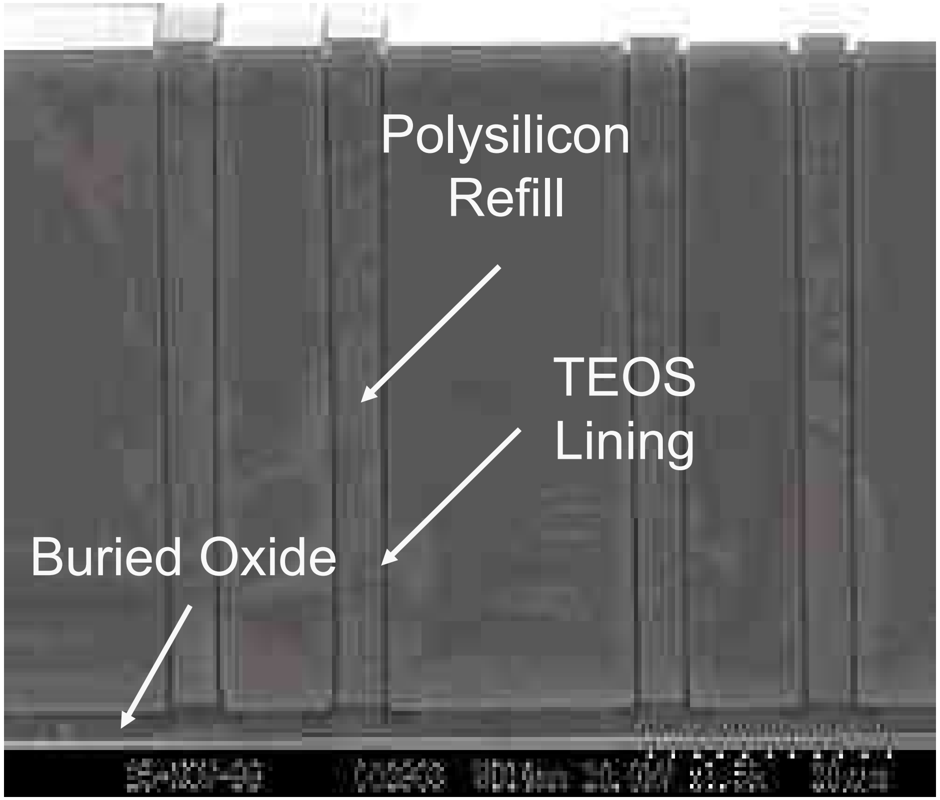


Isolation Trench

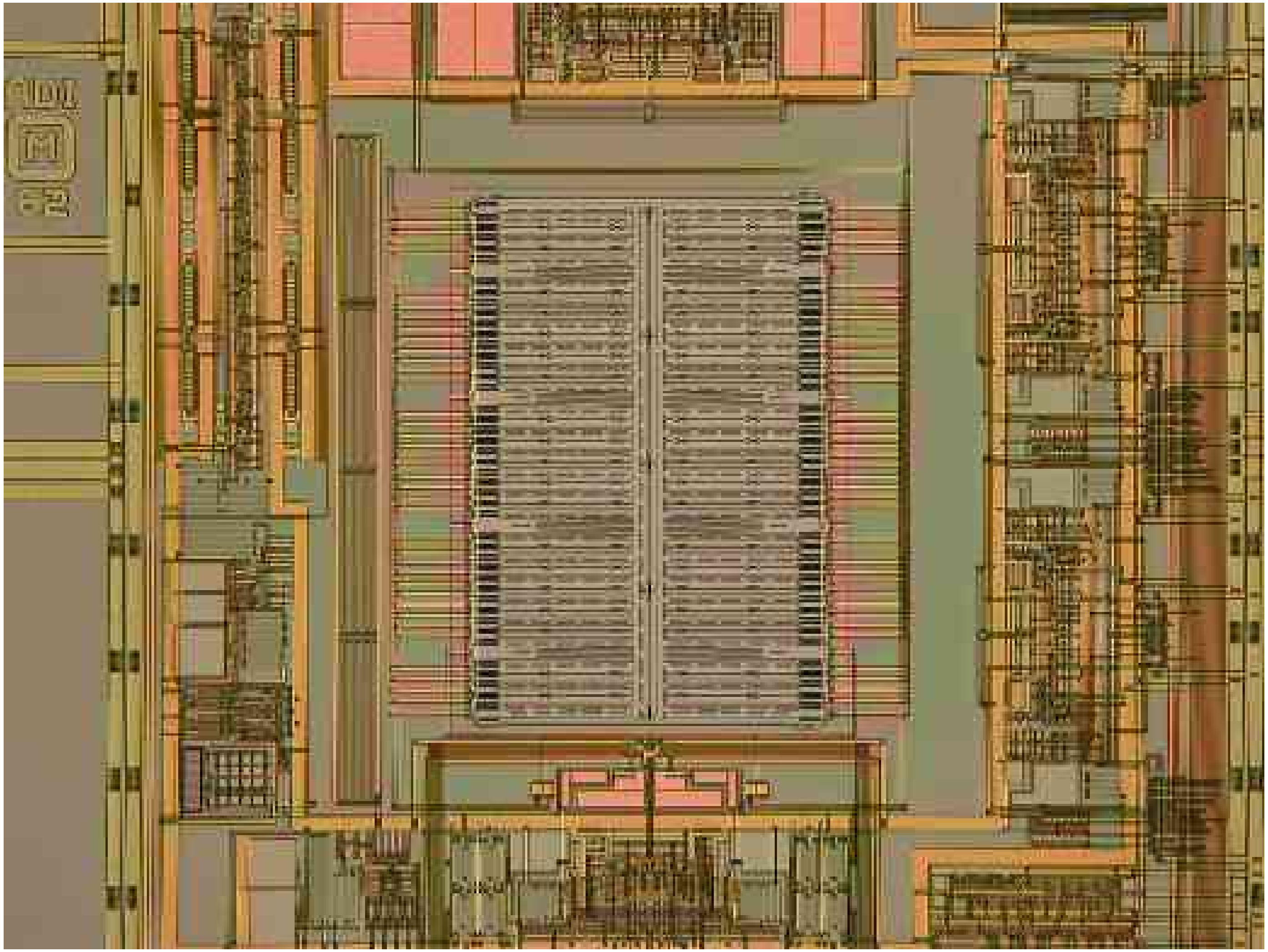
New Process Applied to
High Volume Accelerometer

Trench Isolation for SOI MEMS

- DRIE trench etching, stopping on buried oxide
- Deposit dielectric lining
- Polysilicon refill
- CMP to planarize



Integrated SOI Sensor



Conclusions

- MEMS Technology is based on microelectronics and can have similar economic advantages
- Surface Micromachining builds layers over a sacrifical level
- Inertial MEMS devices are accelerometers and gyroscopes that measure motion
- The trends are to smaller devices with multiple axis of sensing

Questions Please