NanoSensor Fabrication – An Overview of Some of the Practical Issues Involved

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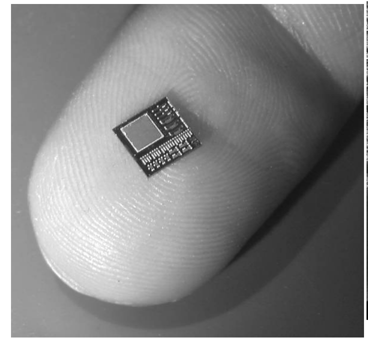
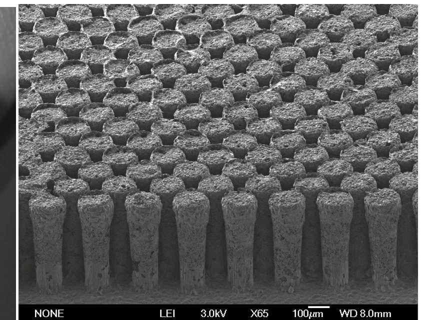
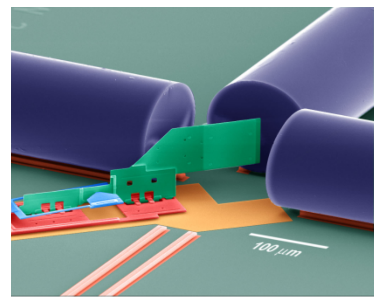
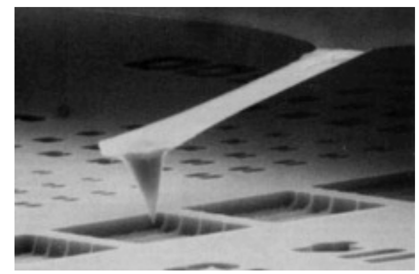
Nanosensors: A New Breakthrough Technology

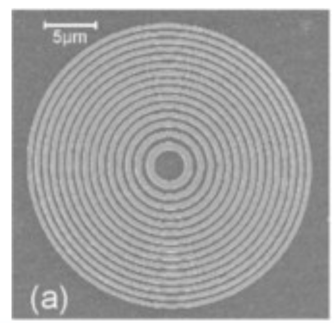
- Hallmark of Nanosensors is the capability of diverse sensing capabilities and multifunctional materials at the nano-scale, potentially merged with integrated circuit electronics
- Ultimately, can combine the capabilities of perception and computation
  - Sensors perceive environment
  - Electronics process sensory information and make decisions

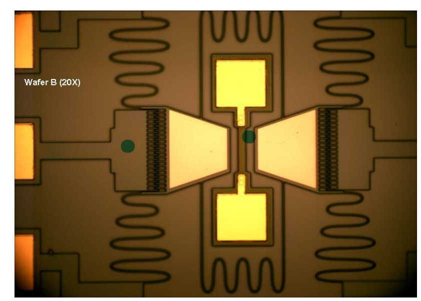






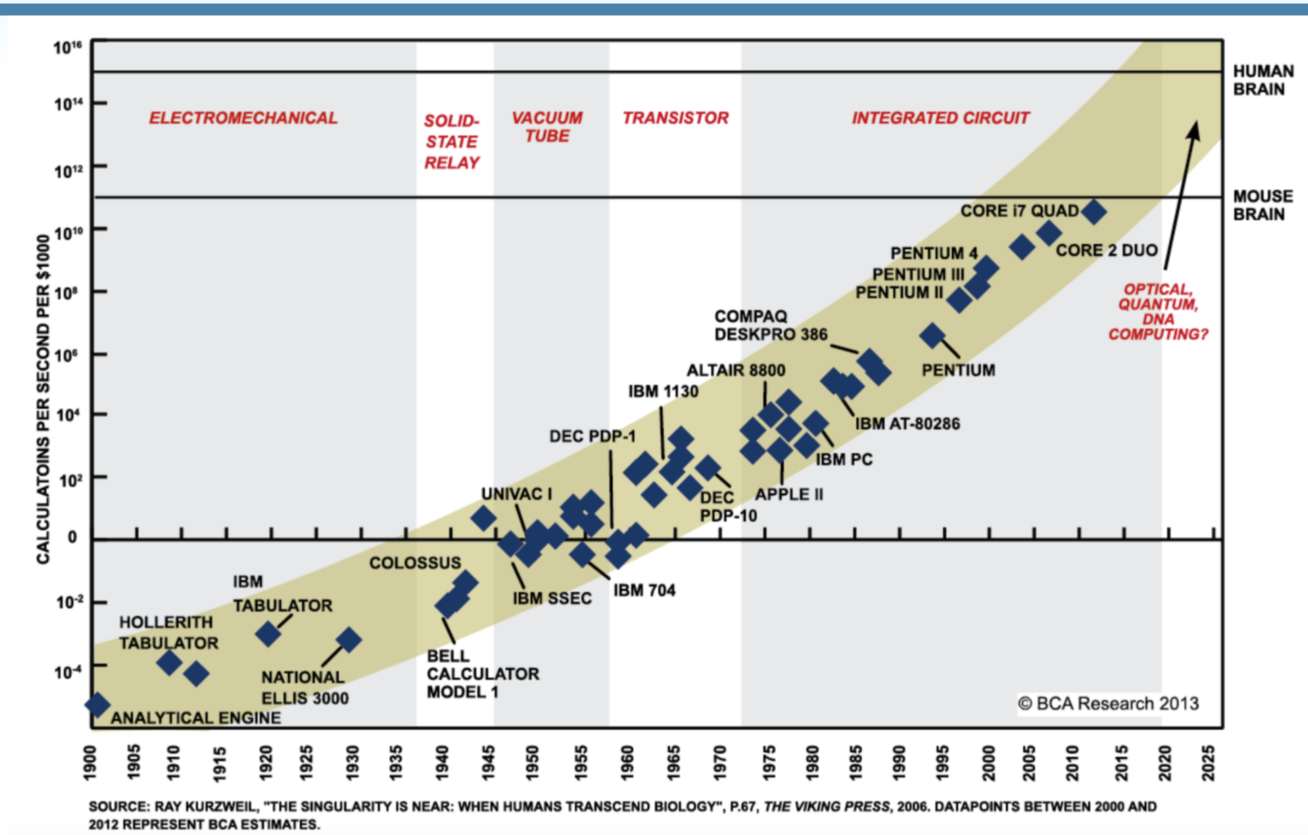






Enables revolutionary new system applications!

Integrated Circuits: Metrics



Until the present time the integrated circuits industry has measured its progress by the number and size of the transistors that can be packed onto a single substrate.

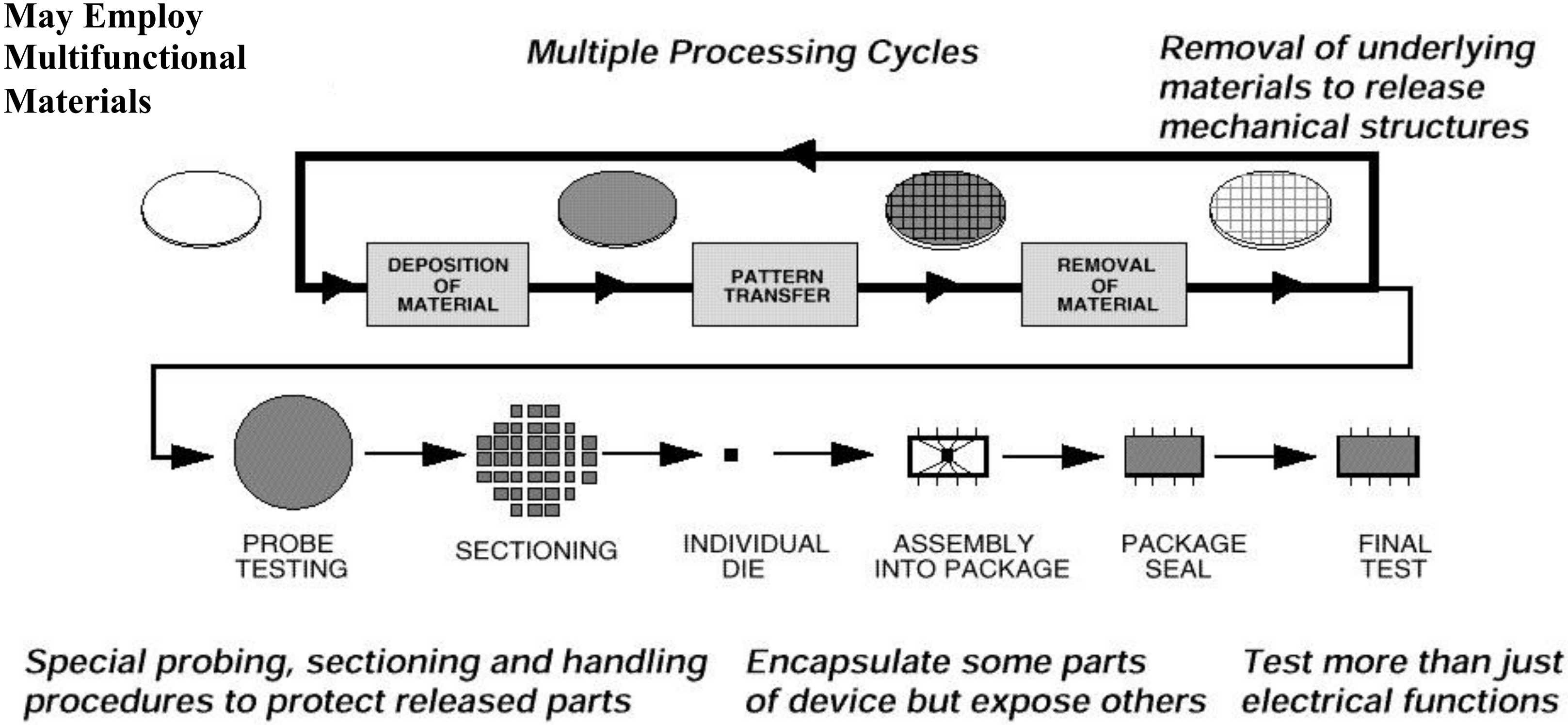
In the future, the important metrics will be: how capable a chip is; how well it can understand and influence its environment; and how it can assist or enlighten its user.

Don’t forget the Internet of Things (IoT)!

Nanosensor Fabrication Commonly Uses Semiconductor Processing Technologies

Typical Nanosensor Fabrication Process

May Employ Multifunctional Materials



How are Nanosensors made?

- Nanosensor processes combine IC-type processes with highly specialized nanotechnology processes

Nanosensor Processes

IC Processes

Oxidation
CVD
Photolithography
Plasma Etching
Sputtering
Ion Implantation
Etc.

Nanotechnology Processes

Exotic Material Depositions
Exotic Material Etches
High-Aspect Ratio Etches
Wafer Bonding
Deep Reactive Ion Etching
Nanomolding
Etc.

Differences between Integrated Circuits and Nanosensors:

- Integrated Circuits have three basic components types - transistors, resistors and capacitors which are wired up differently to form circuits and systems.

- Nanosensors have a much larger number of device types – bio-sensors, chemical sensors, mechanical sensors, etc. - and the list goes on and on.

- Integrated Circuits have standardized to a few process technologies - CMOS, Memory, BiCMOS, etc. The materials and their thickness are fixed. The ordering of the processing steps is fixed.

- Nanosensor process sequences vary greatly for different device types – little to no standardization of process technologies and almost always the ordering of the process steps is completely customized.

The Differences of Nanosensor Fabrication (Cont):

- Integrated Circuits have a standard set of materials and processing techniques which are employed to make devices and circuits.

- Nanosensors uses an extremely diverse set of materials and processing techniques.

- Integrated Circuits foundries are one-stop shopping - i.e., everything needed is under one roof.

- Nanosensor fabrication core competencies in commercial foundries limited to what is useful for IC manufacturing. The design and process freedom is constrained.

The Differences of Nanosensor Fabrication (Cont):

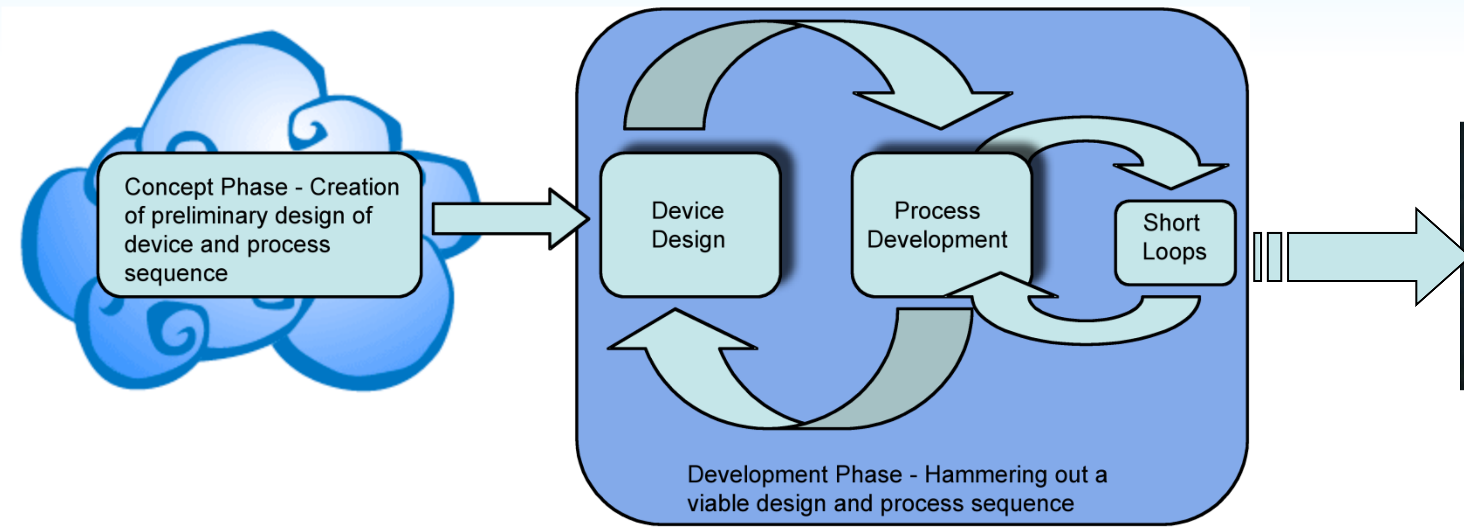
- Integrated Circuit foundries are relatively easy to access and industry has well-treaded pathways for getting ICs made.

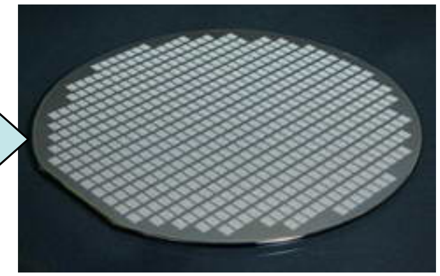
- Access to Nanosensor fabrication resources can be very difficult and expensive. Need very detailed technical knowledge to make good decisions.

- Integrated Circuit industry is a capital-intensive, high-volume business - either dedicated in-house foundry or out-sourced foundry model work well depending on circumstances .

- Many Nanosensor markets are comparatively small (low volume manufacturing), but are still capital intensive. Dedicated in-house Nanosensor fabrication resources may not be economically justifiable.

Typical Development Cycle





Semiconductor Wafer
With Manufactured Devices

Concept Phase
Typically < 6 Months

Development Phase
Typically > 8 Years

Transition to Production
Typically > 1 Year

- •Has proven to be nearly impossible to use a process technology developed for one custom semiconductor device for the production of any another custom semiconductor device.
- •Therefore , every device type has required the development of a new and customized process technology - this is very costly and takes enormous time.
- •Currently <u>process sequences</u> are re-invented for each custom semiconductor device development effort.

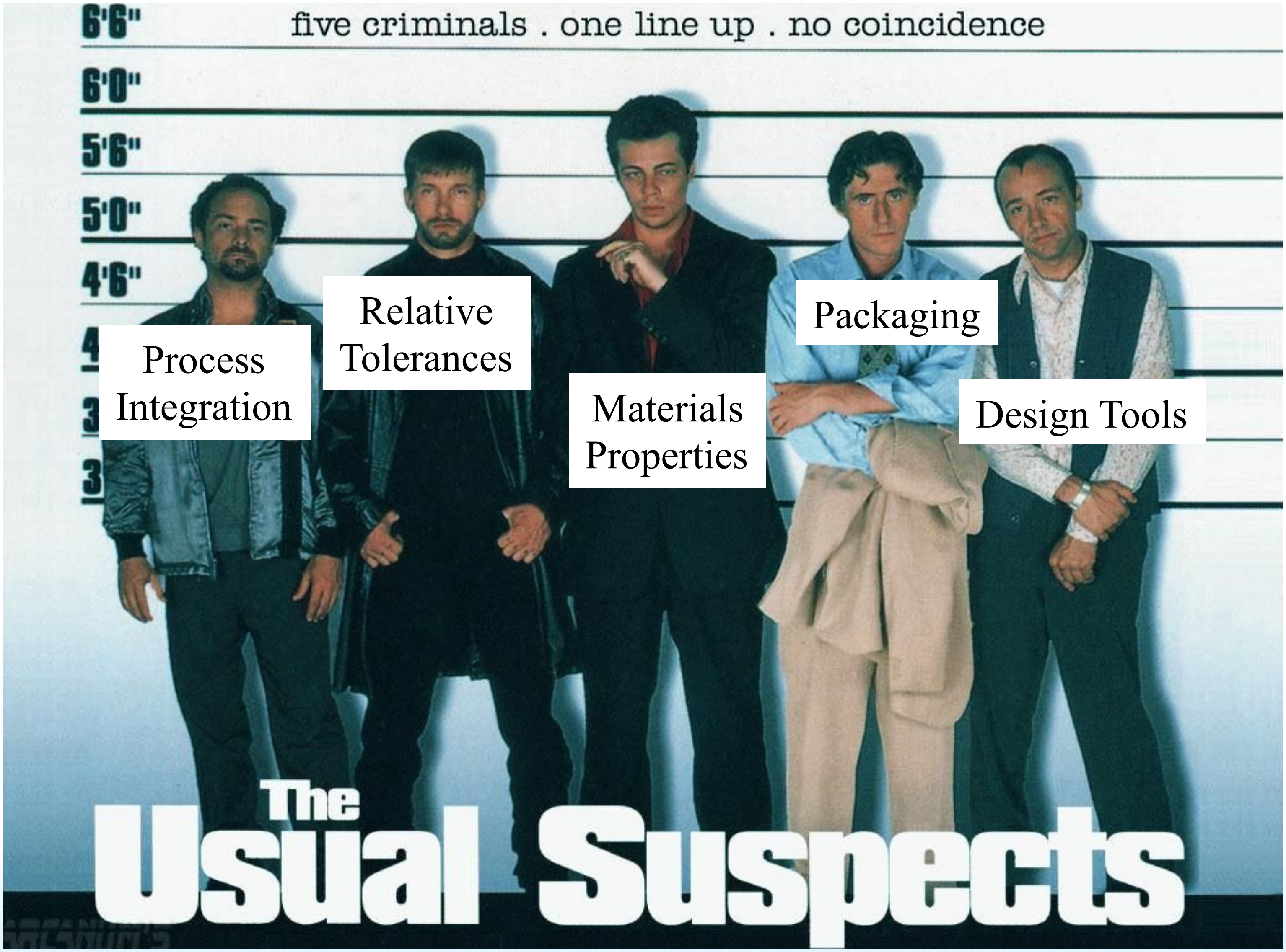
Real World Examples

Development time & costs for several examples of custom devices made using semiconductor manufacturing methods:

MEMS Device	Company	Application Area	Integrated with Microelectronics	Estimated Time to Develop	Estimated Cost to Develop
iMEMS Inertial Sensor	Analog Devices	Automotive Crash Airbags	Yes	12+	$500M
Digital Light Processor	Texas Instruments	Displays	Yes	15+	$1B
Thermal InkJet	Xerox	Printers	Initially No	12+	>$300M*
SiSonic Microphones	Knowles	Acoustics	No	12+	>$50M
FBAR	Avago	Communication Filters	No	12+	unknown
Oscillators	SiTime	Timing	No	10+	>$65M
Microbolometer	Honeywell	Infrared Focal Plane Array	Yes	15+	>$200M
Gyroscope	Honeywell**	Inertial Sensing	No	12+	unknown
Sensory Silicon™	Akustica	Acoustics	Yes	7+	unknown
mirasol® Displays	Qualcomm	Displays	No	12+	unknown

- Current situation eliminates interest in developing custom semiconductor devices for small volume markets.
- Development costs and times are prohibitive for many applications.
- Even for large volume markets, the return-on-investments (ROIs) are not attractive.

Important Manufacturing-Related Issues



Current Method of Manufacturing Process Development

Develop complex custom process sequence from tens to hundreds of individual manufacturing process steps.

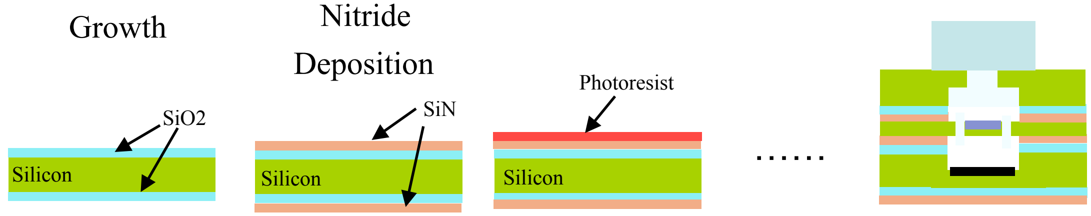
Process Step #1 | Process Step #2 | Process Step #3 | …… | Process Step #100

Thermal Oxide Growth

LPCVD Silicon Nitride Deposition

Photo 1

Release



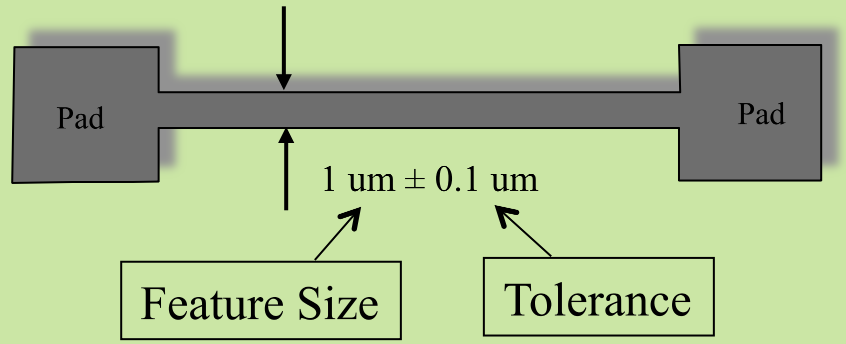
Completed Device

Current method of developing manufacturing process sequences - Assemble a "customized and ordered set" of individual processing steps (i.e., thermal oxide growth, LPCVD SiN deposition, photo 1, etc).

Extremely difficult to get all the individual processing steps to work together - typically need many cycles to solve process integration issues (i.e., develop a process sequence) and get working devices.

Current Precision of Semiconductor Device Manufacturing

Example: Metal Interconnect



Attributes:

•Very common element in most semiconductor devices.

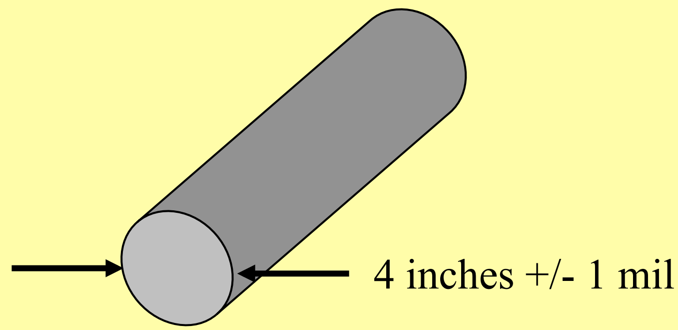
•Fabricated using essentially highest precision semiconductor manufacturing capability available.

$$\text{Relative Tolerance (Precision)} = \frac{0.1\ \text{um}}{1.0\ \text{um}} = 10\%$$

Compare to Conventional Manufacturing

Example: Cylindrical Steel Shaft

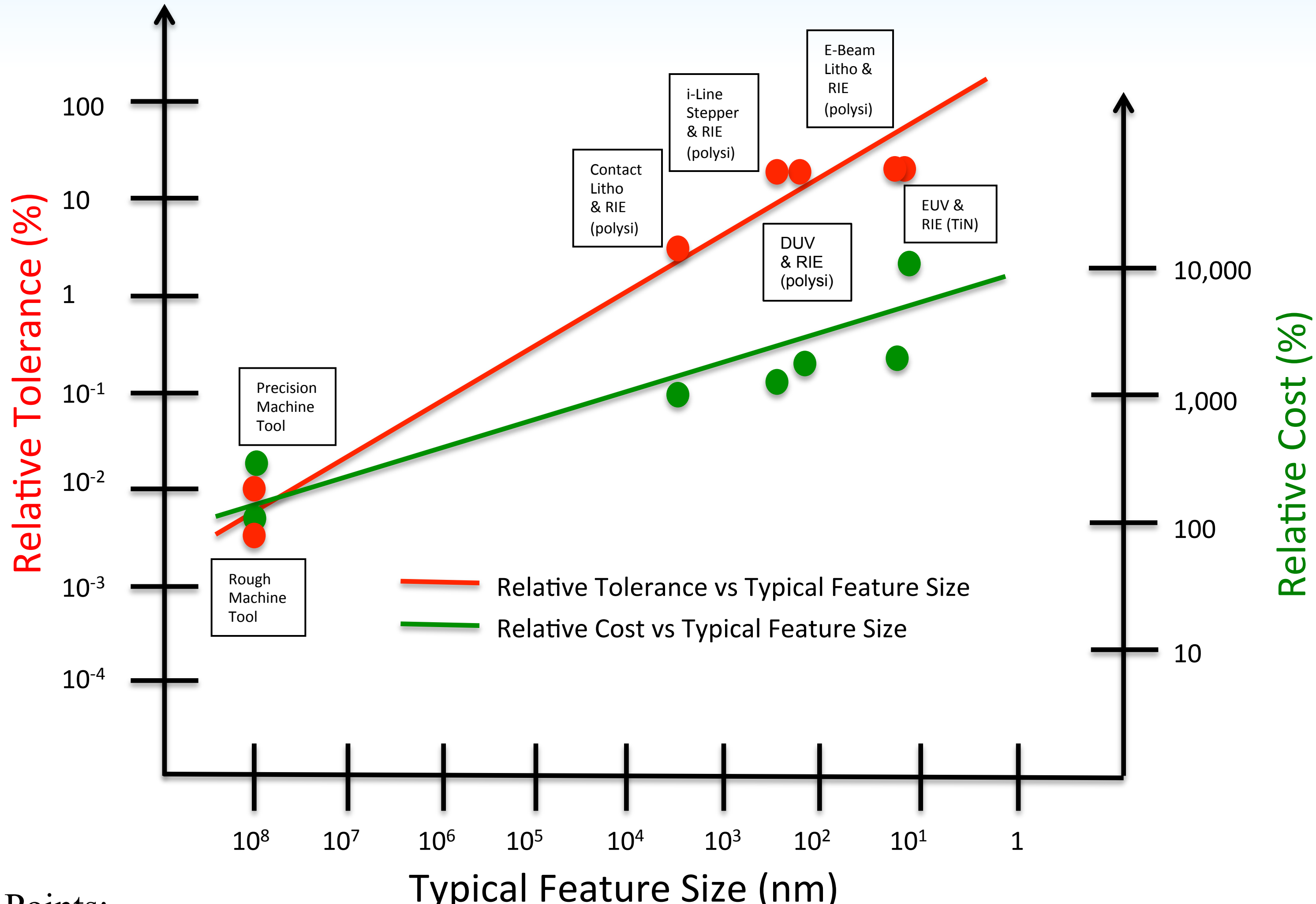
Macroscale Manufacturing Machine Tool



$$\text{Relative Tolerance} = \frac{25.4 \times 10^{-6}\ \text{m}}{100 \times 10^{-3}\ \text{m}} \times 100\% = 0.0254\ \%$$

Semiconductor manufacturing has a relative tolerance > 390% worse!!

Comparison of Manufacturing Precision



Key Points:

- Relative tolerances tend to degrade as feature sizes decrease;
- Current technologies used to make features in semiconductor materials have much worse relative tolerances than macro-scale machine tools; and
- However, relative cost of low volumes of samples increases rapidly as feature sizes decrease.

Poor Precision Combined with Device Physics

Lack of Precision Often Has a Higher Power Effect on Device Physics

- Total effect of precision related to device's physics:
  - (Digital). Least sensitive to variation - CMOS
  - 1st power (Linear). Analog Electronics, Inductors
  - 2nd power
  - 3rd power
  - 4th power

  2nd–4th power: Capacitors, Filters, Resonators, Gyroscopes, Etc.; Microfluidics, Pressure Transducers

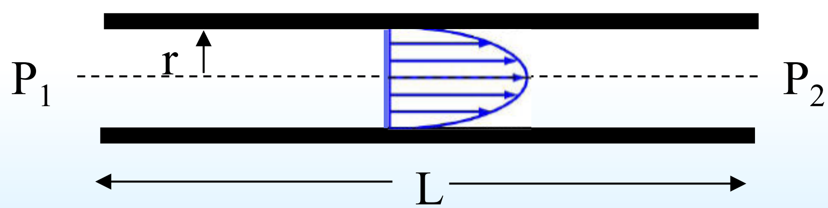
  Most Custom Semiconductor Devices Involve Higher Power Physics
- Impact of precision is on performance and yield

Example: Volumetric Flow Rate, Q, in Small Fluid Channel:

$$Q = \frac{\pi r^4 \Delta P}{8uL}$$

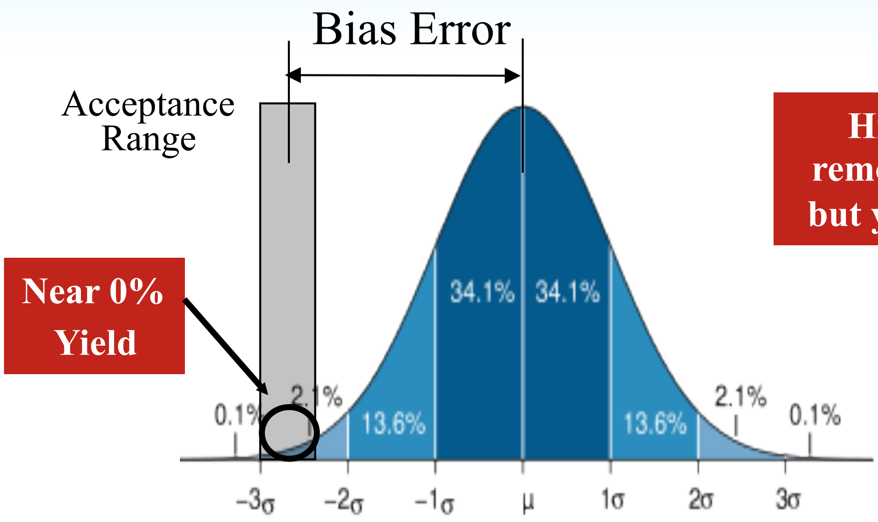
Flow rate is dependent on microchannel radius, r, to fourth power

Therefore, if the relative tolerance of radius is +/- 10%, then the effect on flow rate is +/- 40%!

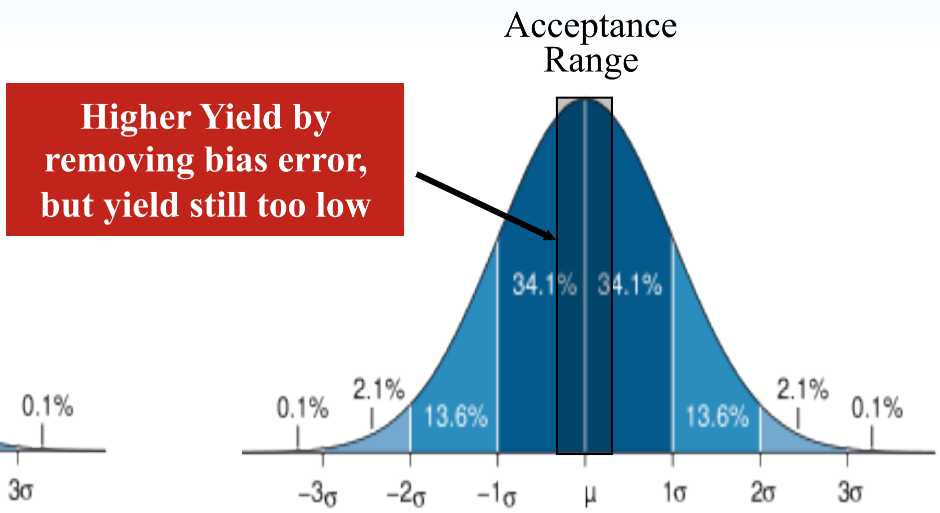


Small Dimension Fluid Conduit

Resultant Manufacturing Yields

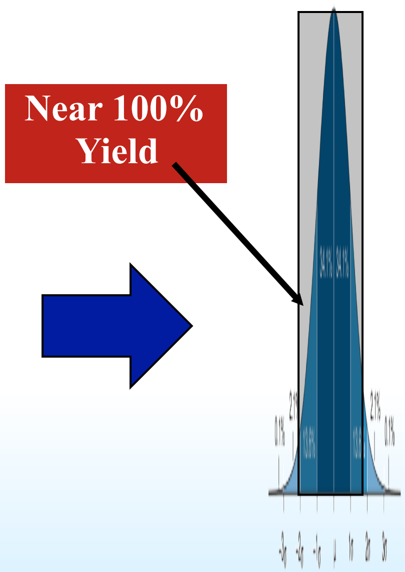


Manufacturing yield given by overlap of manufacturing function and acceptance function.



Manufacturing yield improved by removing bias error.

However, high yields can only be obtained by tightening the spread in the tolerances – requires much greater precision in manufacturing.



Nanofabricated devices typically have large spreads in the distributions due to large relative tolerances in manufacturing, a bias error, but often require tight acceptance ranges for high performance.

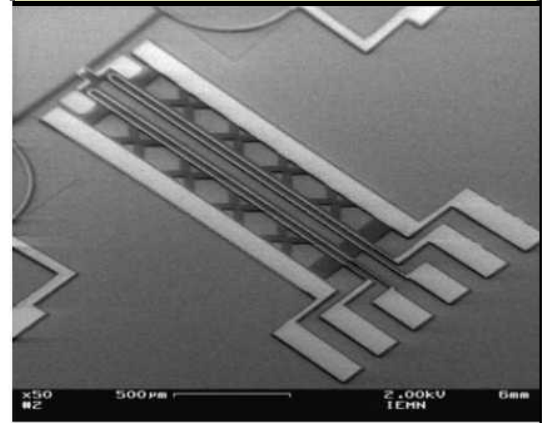
Typically, relative tolerances increase as critical dimensions get smaller.

Material Properties of Thin Films

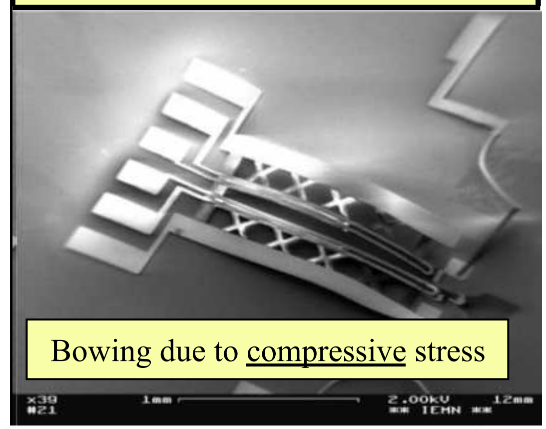
Uncontrolled thin film stress affects ALL properties of the thin film:

Affected properties	Examples of properties that may deviate from expected values due to thin film stress affects
Electrical	resistivity, dielectric strength, piezoelectric response
Optical	index of refraction, scattering defect density, transmittance
Mechanical	hardness, bowing, elastic modulus, specific weight
Chemical	activity, diffusion length, specific internal surface area
Acoustic	acoustical absorption, speed of sound
Magnetic	permeability, Curie point, shape of hysteresis
Thermal	thermal conductivity, emissivity, Seebeck coefficient

Prior to Release



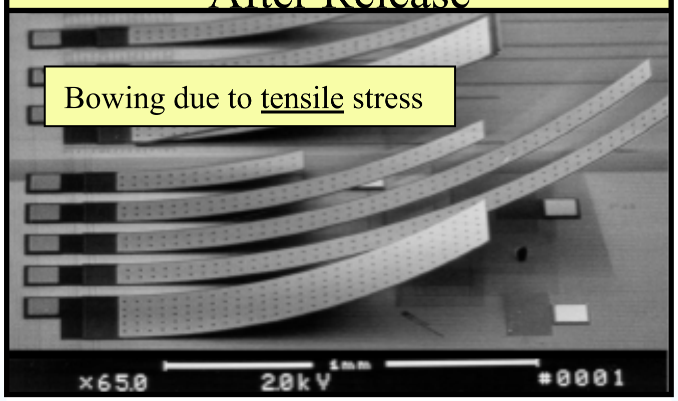
After Release



http://matthieu.lagouge.free.fr/phd_project/extractor.html

The state of the thin films has a huge effect on the device behavior!

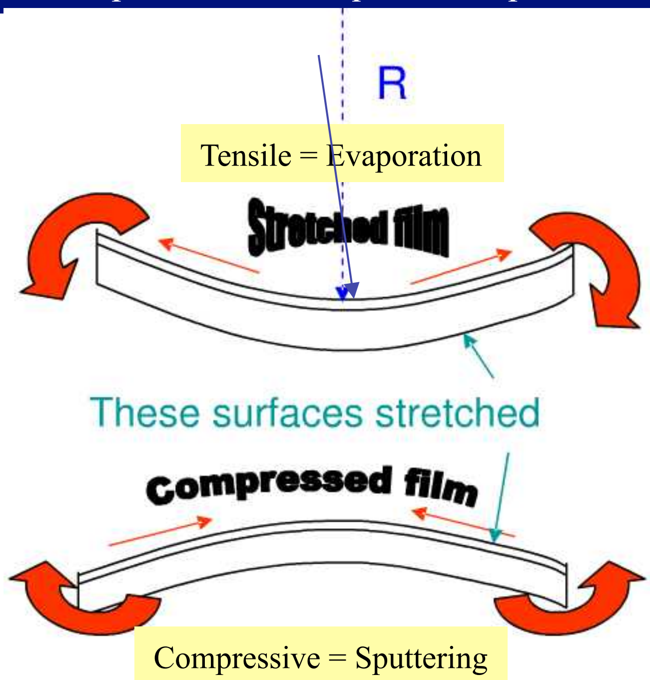
After Release



Thin Film Deposition: All material properties are dependent on thin film stress.
Currently, very difficult to deposit thin films with controlled material properties.
Control of thin film stress gives control of thin film material properties and device behavior.

Consequences of Uncontrolled Thin Film Stress

Currently the Nature of Stress is Largely Dependent on Deposition Technique & Temperature

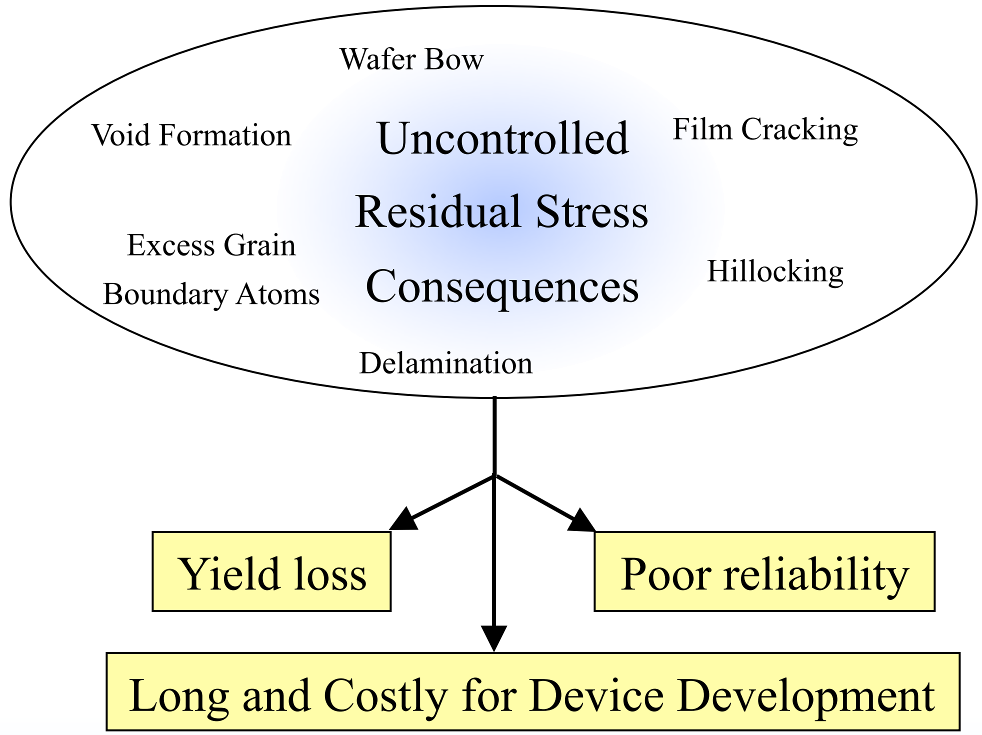


With any thin film, deposition parameters are interconnected and determine the resulting device properties

Open-Loop Process Development

Current Approach to Thin Film Deposition – Thin film stress deposition technology is currently completely an open-loop process.

End Result – Runaway external and residual (intrinsic) film stress bows wafers, induces cracks, forms voids, causes hillock formation and film lifting, which leads to yield loss and poor reliability issues.



Currently in Thin Film Deposition: State of the art is open-loop stress management.
Open-Loop = Uncontrolled Material Properties.
Low Yield, Poor Reliability, and Long and Costly Development.

Recommendations:

1. Keep the device design and manufacturing process as simple as possible.
2. Consult early with industry fabrication experts on developing manufacturable processes.
3. Stick to existing already developed process steps and process technologies to extent possible.
   - Avoid new and exotic processes and techniques, if possible.
4. Determine if resolution and relative tolerances of tools and processes can provide required yield numbers.
   - You may need to employ fabrication experts to help with this task.
   - You may also need to perform some fabrication experiments.
5. Determine how variations in material properties will impact yield.
6. Design packaging as early as possible.
7. May need to use combination of methods to develop models. Models must be validated with some amount of experimental data.
8. Expect to perform multiple iterations in process development and multiple design changes.
9. Embed test structures in layout to determine material properties.
10. Exercise care in selecting fabricators. Changing foundries is very costly.

Your idea may be great, but will not matter if it cannot be made.

Overview of MNX

The MNX is:

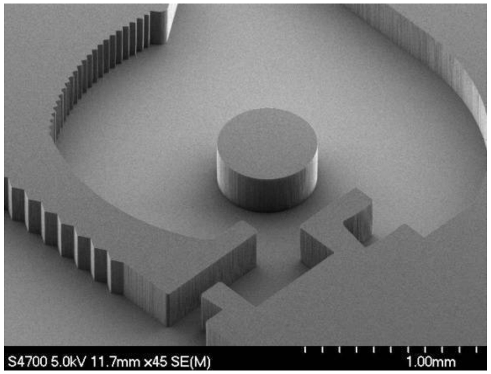
•An implementation and manufacturing service (providing design, process development, prototype fabrication, and production) that has been operating since 1999.

•Provides enormous diversity of process capabilities that allows maximum design and processing freedom - important for obtaining highest performance devices.

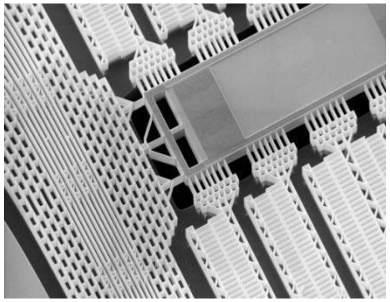
See: http://www.mems-exchange.org

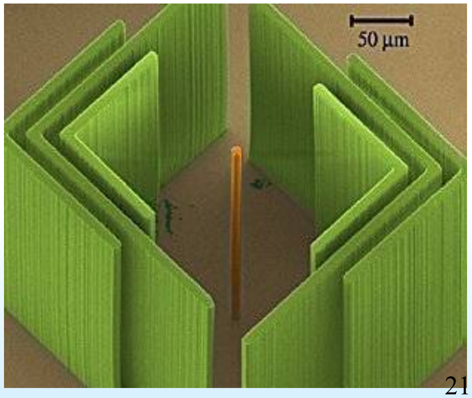
•A full-service organization staffed with design and fabrication experts combined with the most comprehensive and diverse set of state-of-the-art fabrication capabilities to enable customers to get their devices made in the most efficient and expedient method possible.

Some MNX Stats:



- Over 4000 process steps available as well as several process modules and process technologies. Most comprehensive and diverse set of process offerings in industry for MEMS and related technologies.
- Over 600 processing tools (i.e., equipment tools) currently in inventory.
- Hundreds of material types available.
- Number of process runs submitted to MNX and completed to date: 2885.
- Number of Business Accounts : 1,075
- Extensive experience with every type of fabrication technology.
- Huge diversity of application space including: RF; inertial; acoustics; magnetic; microfluidic; electromagnetic; etc.





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