Packaging

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***With thanks to Steve Senturia, from whose lecture notes some of these materials are adapted**

Outline

- Evolution of the packaging dilemma
- How to approach the challenge of getting a working system, including:
  - Packaging
  - Partitioning
  - Test
  - Calibration
- Some common tools and considerations
- Examples

Package requirements

- "Man the gates": let the right things in and out and prevent other things from entering or leaving
- Protect the die
- Make it easy to interface the die with the rest of the world (outer layer of packaging must conform to industry expectations)
- Be as inexpensive as possible
- The details can vary greatly
- Some elements that are often seen:
  - Fabrication/packaging cross-over, with first level packaging occurring at the wafer scale, in the fab
  - Die attach into a package
  - Die encapsulation
  - Making connections
  - The need to plan for calibration and test!

Evolution of the MEMS package challenge

> **MEMS micromachining and packaging began as answers to a practical question: "If I want to take advantage of silicon piezoresistivity to measure pressure, what does the rest of the product look like?"**

> **Subsequent products adapt what they can from the earlier approach and develop specific solutions where they must**
  - **Problem: no universal solutions**
  - **Must solve the details for every device design, and the solutions are almost always different**

> **Enthusiasm for MEMS grows: packaging often neglected with painful results**
  - **High costs (package cost 10x device cost!), devices that must be redesigned**
  - **Devices can't make the jump to market!**

> **Present drive to create more widely-applicable packaging solutions**

A diversity of devices to package

Image removed due to copyright restrictions.
Motorola accelerometer.

Image removed due to copyright restrictions.
Ultrasonic transducer array made by Siemens Corporation.

Image removed due to copyright restrictions.
Hymite/MEMSCAP packaged in-vivo magnetic switch.

Image removed due to copyright restrictions.
Motorola manifold absolute pressure sensor.

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Key Ideas

> **Concurrent design**
  - ***Design the device and the package at the same time***
  - **Often companies have different teams for the two parts…**

> **Partition carefully**
  - **Which functionalities go in the chips, and which functionalities go in the package?**
  - **How many chips will it have?**
  - **Which functionality goes on each chip?**
  - **How will the chips be connected together, and to the package?**
  - **How will the way we partition it affect the way that we have to test it?**

The question of electronics

> **Partitioning electronics and MEMS**

- **Ask yourself honestly if integrating electronic functionality monolithically with the MEMS device is worth it**
- **It is difficult to optimize two different things simultaneously**
- **Separating fab processes into pre-electronics and post-electronics can limit your options severely**
- **Two chips separately are often cheaper than one integrated chip (remember the N_{masks}*A_{device} rule?)**
- **A cute, monolithically integrated device that doesn't work because of unintended interactions between the MEMS function and the electronics is useless**
- **Some successful commercial products are monolithically integrated**

Designing for testability

- If the device is expensive, the package is expensive, and the process of attaching the two is expensive, how much testing should you do before committing a device to a package?
- There is no universal answer to this question, but it must be considered for every device. Do a cost analysis with your best estimates of costs and yields to balance risk and cost.
- The package/test procedure will have a significant impact on the ultimate cost of building the part, and on its economic viability
- Many systems can't be tested at all without some form of packaging

Planning for variations

- Given the many variations possible from fabrication and packaging (both random and systematic), how do you ensure a working device at the end?
- Aim for a perfect as-fabricated device and no shifts from the package?
- Aim for a device that is perfect once it has interacted with the package?
- Admit that you can't control all the factors and simply trim the hardware once it's packaged?
- Admit that you can't control all the factors and simply calibrate whatever you get in the software?
- All of these are expensive… do you want to put a lot of resources into getting the fab just right, or into fixing each and every part after it's made?

Checklist before detailed design

> **You're ready to do the detailed design of the system and all of its components when you have the following:**
  - **Complete specifications for both the chip(s) and the package**
  - **Specifications for all interconnections**
  - **A list of all of the parasitics that you can think of, and some assessment of their effect on the system operation**
  - **Provision for calibration and test**

To do list: the detailed design

> For the MEMS device
  - A process flow
  - A mask set
  - The corresponding device geometry and materials
  - A model supporting predicted performance
  - Specification of the test and calibration method

> For the package
  - Artwork
  - Specification of components and how they are made (or where purchased)
  - Acceptance procedures for packages

> Full assembly
  - The packaging procedure
  - Test, acceptance, and calibration

Outline

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> **How to approach the challenge of getting a working system, including:**

- **Packaging**
- **Partitioning**
- **Test**
- **Calibration**

> **Some common tools and considerations**

> **Examples**

Die separation

- Multiple dies fabricated on the same wafer must be separated in order to be packaged and sold
- Die saw common
- Die saw blades are of order 30 μm to 250 μm thick
- High speed blade rotation, cooled by a flow of water
- Lots of debris, vibrations, and general dirt
- How to protect the device?
  - Release etch after die saw
  - Wafer bonding as first-level packaging, before the die saw step
  - Die saw the device upside down
  - Don’t die saw: etch mostly through and crack chips apart
- Question: do you need to do any testing before you separate the dies?

Die attach

- Whether IC's or MEMS devices, dies must be attached to a package
- Package: application specific
- Solder as adhesive: commonly soft solder (lower melting temperature, about 100 C – 400 C)
- Epoxy as adhesive: cross-link when heated (about 50 –175 C)
- Polyimide or silicone as adhesive
- Adhesive application: dispense through a nozzle, screen print
- Can use "pick and place" tools to position dies on top of adhesive in the package

Plastic packaging

- The integrated circuit standard
- Very inexpensive, pennies per electrical connection pin
- A thermosetting plastic is melted (ballpark 175 C) and injected into a mold
- The plastic cools and hardens
- The least expensive approach:
  - Attach the die to a metal lead frame with an adhesive
  - Injection mold the plastic around it
  - Question: will your device and electrical connections survive this?
  - Question: will encapsulation in plastic impair its functionality?

Plastic packaging

- Second approach: a more flexible, more expensive, gentler approach to plastic packaging
- Injection mold the package around a lead frame before the die is attached
- Attach the die with an adhesive
- Cap the package
- Applications:
  - Fragile devices or electrical connections
  - Achieving connections that are not standard in IC packages, such as fluid connections or optical transparency
  - Special requirements are integrated into the package cap

Ceramic packaging

- Collections of particles are sintered at temperatures ranging from 800 C to 1600 C to form the package (often alumina, Al_2O_3)
- Ceramic packages are often processed as laminates
  - Individual layers can have screen printed electric interconnects, metal film resistors, and even interlayer via connections
  - Anneal the package; braze pins to package
  - Make electrical connection between die and package
  - Cap and seal the package (application-specific)
  - Resistors on the outer layer can be trimmed after the die is packaged
- Durable, potentially well-sealed (hermetic)
- Higher cost (ballpark a few tens of dollars vs. less than a dollar)

Metal packaging

- A solution for harsh environments or relatively quick prototyping
- Can be well-sealed (hermetic)
- Common materials: Kovar or stainless steel
- When features are more important than cost, can simply machine the package with the needed features
- Example: a pressure sensor for environments that silicon cannot tolerate
  - Package a Si pressure sensor in a stainless steel package
  - Cap the package in part with a thin stainless steel diaphragm
  - Fill the gap between Si and steel with oil to transfer the pressure

Making electrical connections

> Techniques adopted from IC packaging

> Wire bonding connects electrical contact pads on die to electrical contact pads in package

- An ultrasonic sewing machine that stitches with wire
- Heat + pressure + ultrasonic energy joins wire to contact pad
- Frequency considerations: ultrasound may excite a resonance
- Thickness of bond pads

> Flip-chip bonding

- Chip turns upside down; solder bumps attach it directly to package
- Heat to flow solder (think about temperature)
- Smaller connections/lower inductance than with wirebonding

Making fluid connections

- Not standardized
- Techniques at the laboratory scale
  - O-ring seals and conventional tubing
  - Glue a tube in a hole (includes more sophisticated approaches)
  - Stick a needle through a polymer structure, and inject through it
- For lab-on-a-chip applications: various proposals for the "world to chip" interface
- For a pressure sensor: protect the membrane with a cap layer and route a hole in the package to the connector of your choice (ie screw thread)
- For your application…?

Packaging in the fab – why do it?

- Your structure will become so fragile when you do the release etch that you will no longer be able to package it
- Your device won't survive die saw unless the fragile parts are encapsulated
- You want to minimize the package size
- You can't afford to have any particulates on your device, so it needs to be encapsulated before it leaves the cleanroom
- It's less expensive in your case
- You expect the quality of the seal to be better in a microscale process such as anodic bonding than in a macroscale process such as gluing
- You want to create a sealed cavity with vacuum inside
- You want to create a sealed cavity with a controlled atmosphere inside

Sealing

- Vacuum operation
  - Device needs to operate at vacuum, or some fixed pressure, without ever being pumped out again
  - Examples: measuring absolute pressure, high Q resonators
  - Typically accomplished in the fabrication process rather than in packaging
  - Approaches: wafer bonding, deposited films as sealants
  - Concern: outgassing
- Isolation from environment
- Hermetic packaging
  - Device doesn't need to operate at vacuum, but if water gets inside, the device will eventually be destroyed

Vacuum sealing by anodic bonding

- Anodic bonding to seal a pressure sensor
- Fabricate on a Si wafer; dissolve it away at the end

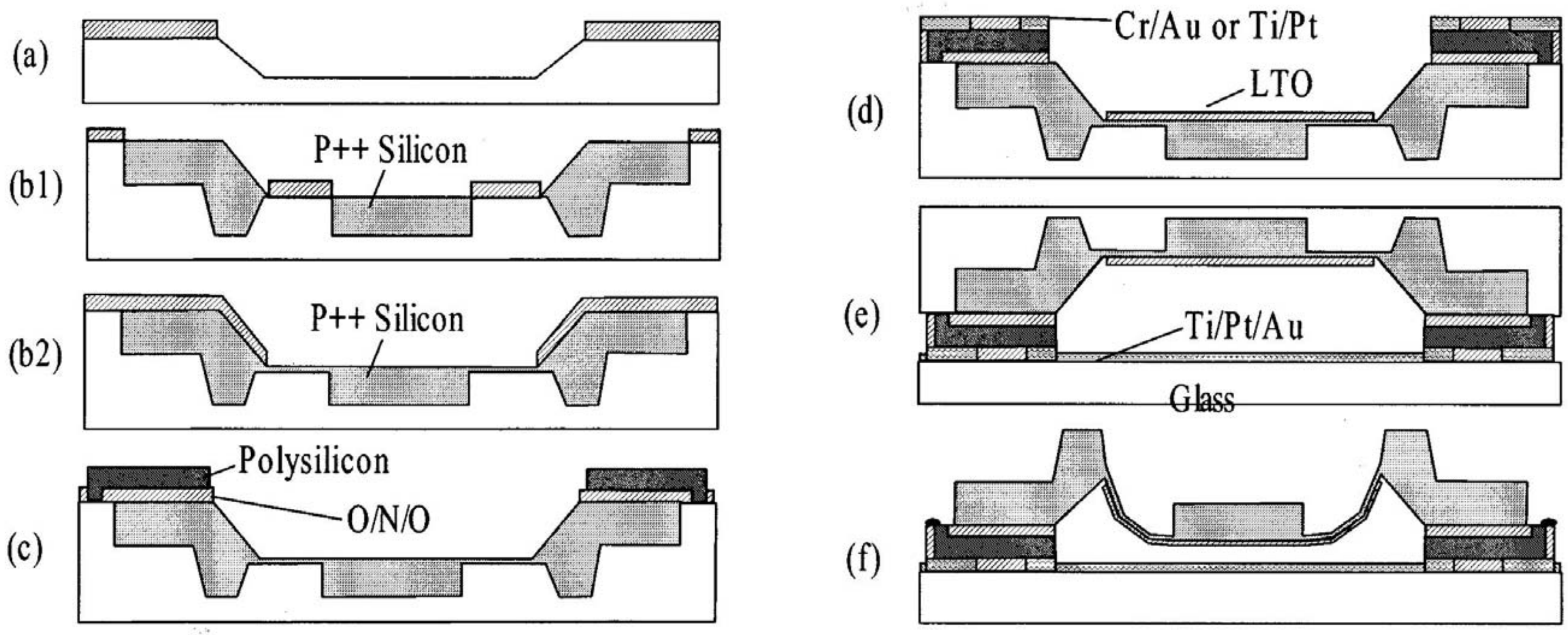

Figure 4 on p. 582 in: Chavan, A. V., and K. D. Wise. "Batch-Processed, Vacuum-Sealed Capacitive Pressure Sensors."
Journal of Microelectromechanical Systems 10, no. 4 (December 2001): 580-588. © 2001 IEEE.

Vacuum sealing by fusion bonding

- An ultrasonic transducer (a microphone, essentially) sealed by silicon fusion bonding
- Contact in vacuum; risk of outgassing on anneal

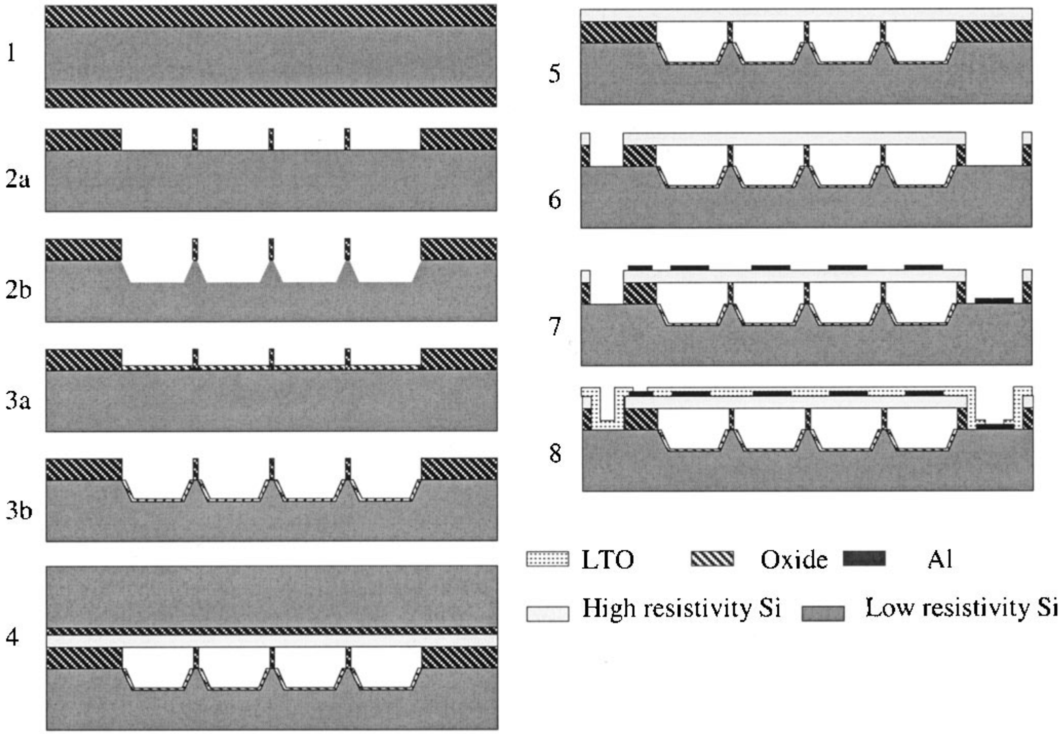

Figure 1 on p. 130 in Huang, Y., A. S. Ergun, E. Haeggstrom, M. H. Badi, and B. T. Khuri-Yakub. "Fabricating Capacitive Micromachined Ultrasonic Transducers with Wafer-bonding Technology." *Journal of Microelectromechanical Systems* 12, no. 2 (April 2003): 128-137. © 2003 IEEE.

Vacuum sealing by film deposition

- An ultrasonic transducer sealed by a deposited film
- Using the stringer effect for a good cause
- Could worry about outgassing

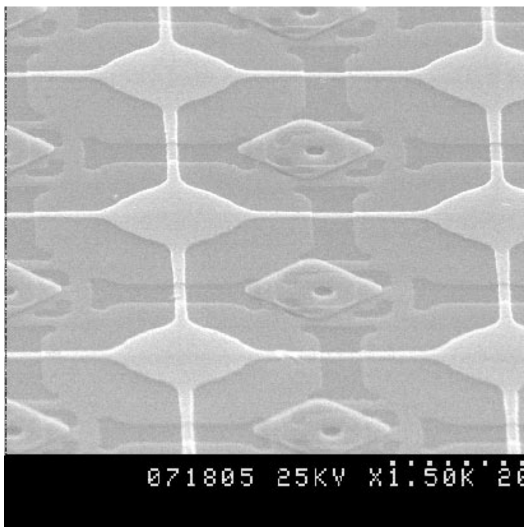

Figure 16 on p. 106 in Jin, X., I. Ladabaum, F. L. Degertekin, S. Calmes, and B. T. Khuri-Yakub. "Fabrication and Characterization of Surface Micromachined Capacitive Ultrasonic Immersion Transducers." *Journal of Microelectromechanical Systems* 8, no. 1 (March 1999): 100-114. © 1999 IEEE.

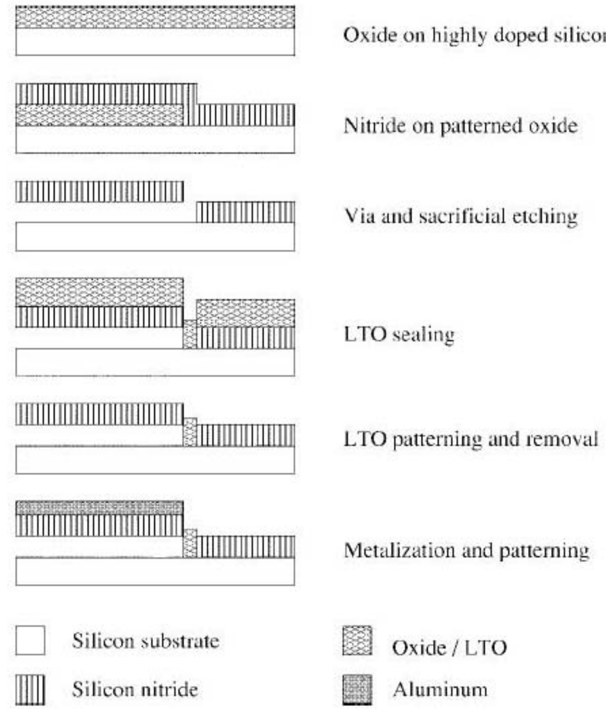

Figure 2 on p. 101 in Jin, X., I. Ladabaum, F. L. Degertekin, S. Calmes, and B. T. Khuri-Yakub. "Fabrication and Characterization of Surface Micromachined Capacitive Ultrasonic Immersion Transducers." *Journal of Microelectromechanical Systems* 8, no. 1 (March 1999): 100-114. © 1999 IEEE.

Resonator with thin film vacuum packaging

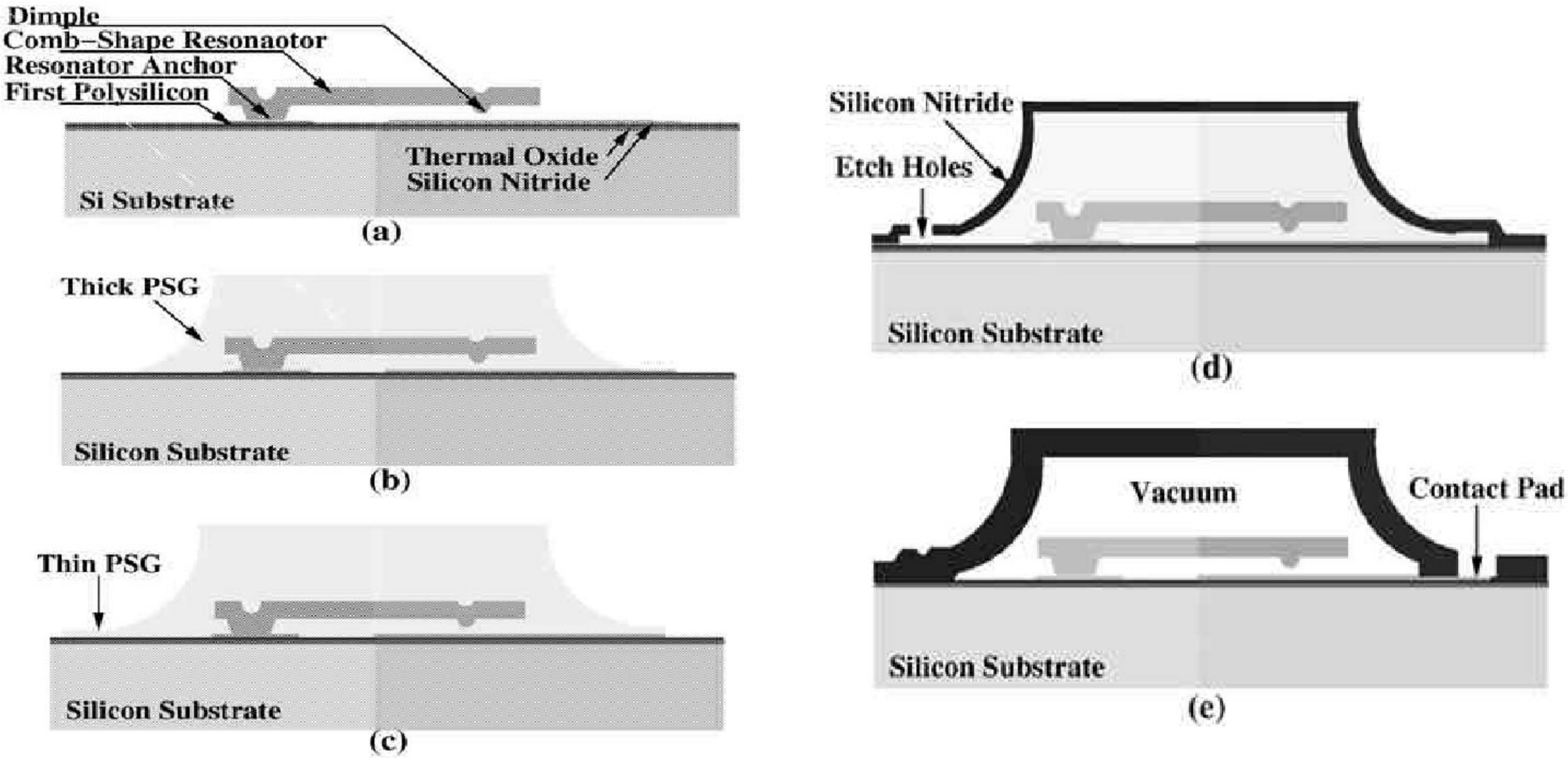

Figure 10 on p. 290 in Lin, L., R. T. Howe, and A. P. Pisano. "Microelectromechanical Filters for Signal Processing." *Journal of Microelectromechanical Systems* 7, no. 3 (September 1998): 286-294. © 1998 IEEE.

Resonator with thin film vacuum packaging

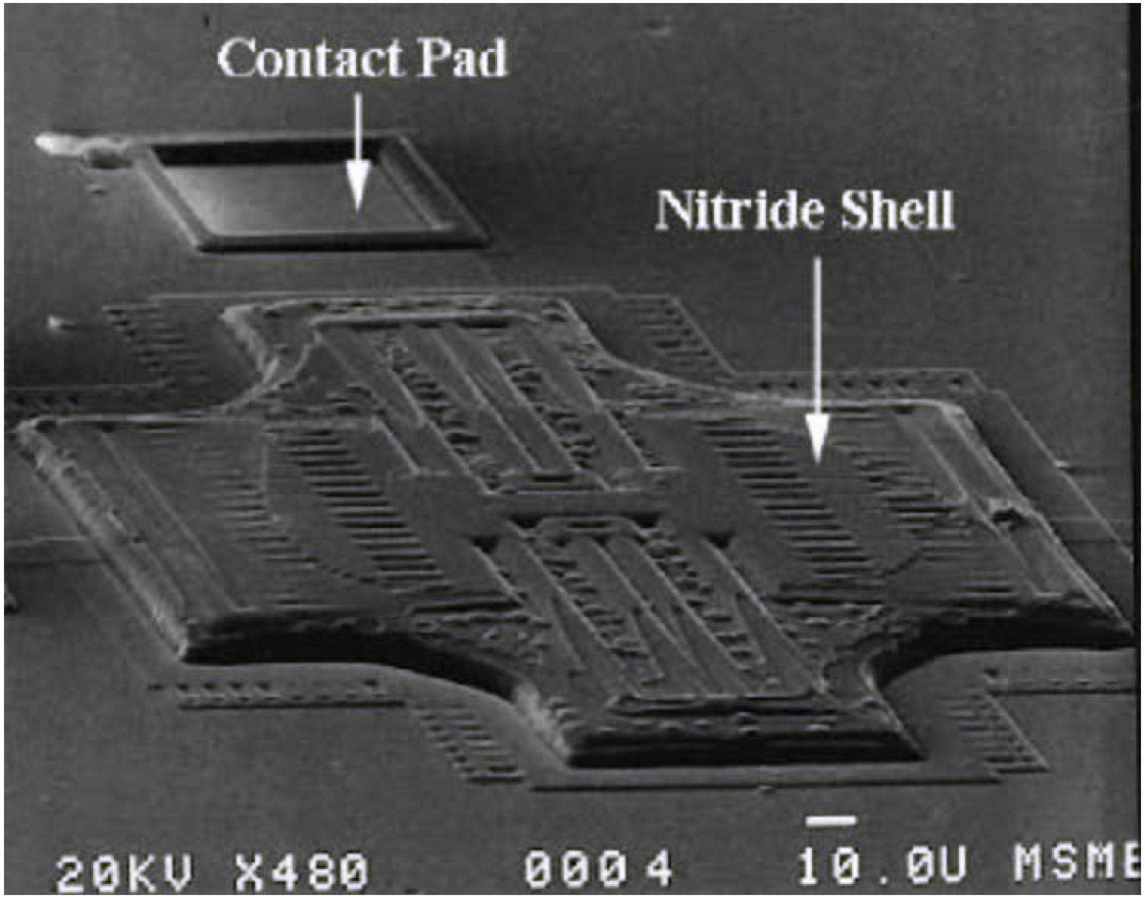

Figure 11 on p. 291 in Lin, L., R. T. Howe, and A. P. Pisano. "Microelectromechanical Filters for Signal Processing." *Journal of Microelectromechanical Systems* 7, no. 3 (September 1998): 286-294. © 1998 IEEE.

Isolation from the environment

> **Example: an automotive pressure sensor**
- **The membrane must be able to feel the pressure**
- **But, the environment is not inert**
- **Solution: coat the business part to protect it while not compromising the functionality**

> **Example: bioMEMS, especially in the body**
- **Biocompatible but functional**

> **Parylene is useful here**
- **Conformal material, deposition near room temperature**
- **Minimal structural impact**
- **Resistant to water, many organic solvents, weak acids/bases, salt, fuel… but it is not invulnerable.**

Hermetic packaging

- Moisture is bad and can lead to corrosion in the most benign of circumstances
- Electronics and MEMS often last much longer and are more reliable if moisture is kept out
- Definition of hermetic: "prevents the diffusion of helium", with a definition for the maximum allowable helium leak rate
  - Perfect hermeticity does not exist in practice
- Working definition of hermetic: "keeps the moisture out"
- Good material choices: silicon, metal, ceramic, thick glass (mm thickness or above)
- Bad material choices: plastics, organic materials
- All connectors must also be hermetically sealed

Permeability chart

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Considerations when selecting packaging

- First, everything that you need to think about in designing the device itself
- Electrical parasitics
- Stress: will your package squeeze your device and change its characteristics?
- Will you be able to calibrate and test your device? When and how? All significant package-induced variations must occur before that point, or else be accounted for in advance.
- Other concerns: fragility, range of temperature operation and CTE, etc.

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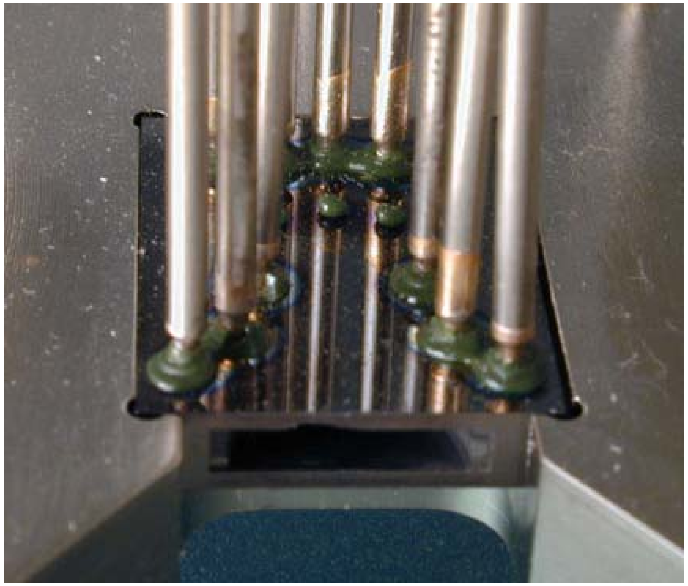
> **Some common tools and considerations**

> **Examples**

Lab-scale packaging: micro rocket

- “If I’m just trying to get a degree, and I don’t plan on selling this device, do I still have to design the package with the device?”
- YES!!! (You want the degree, right?)



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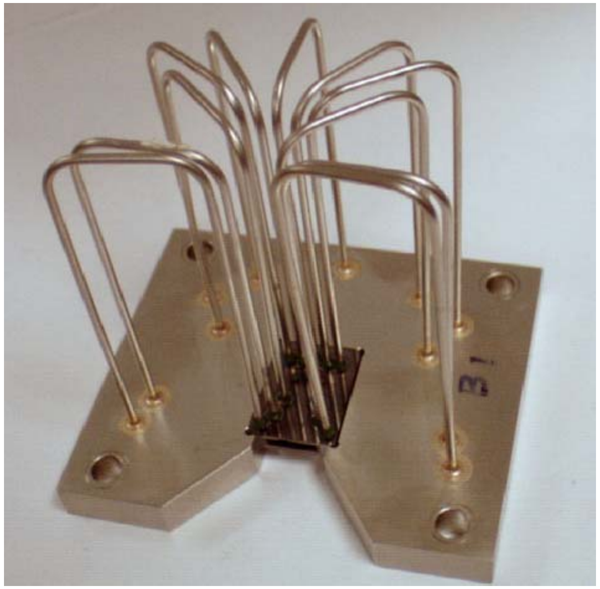

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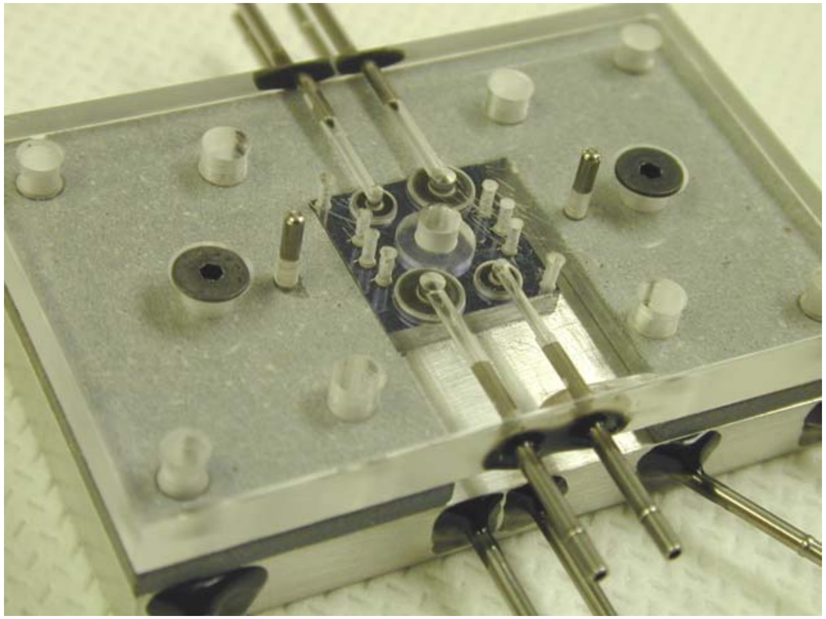
Source: Adam London, MIT.

Lab-scale packaging: micro turbine

- Micro turbine device, with fluidic and electrical connections
- Fluid connections: seal acrylic plate to die via o-rings
- Questions to think about BEFORE sending out the masks: will the pressure distort the die? Is there room for the o-rings?



Pressure Sensor Case Study

- A Motorola manifold-absolute-pressure (MAP) sensor
- Silicon micromachined diaphragm with piezoresistive sensing

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Motorola manifold absolute pressure sensor.

Device and Package Concept

> **Monolithic pressure sensor with circuitry in a custom bipolar process mounted on silicon ($$$) support mounted in plastic package**

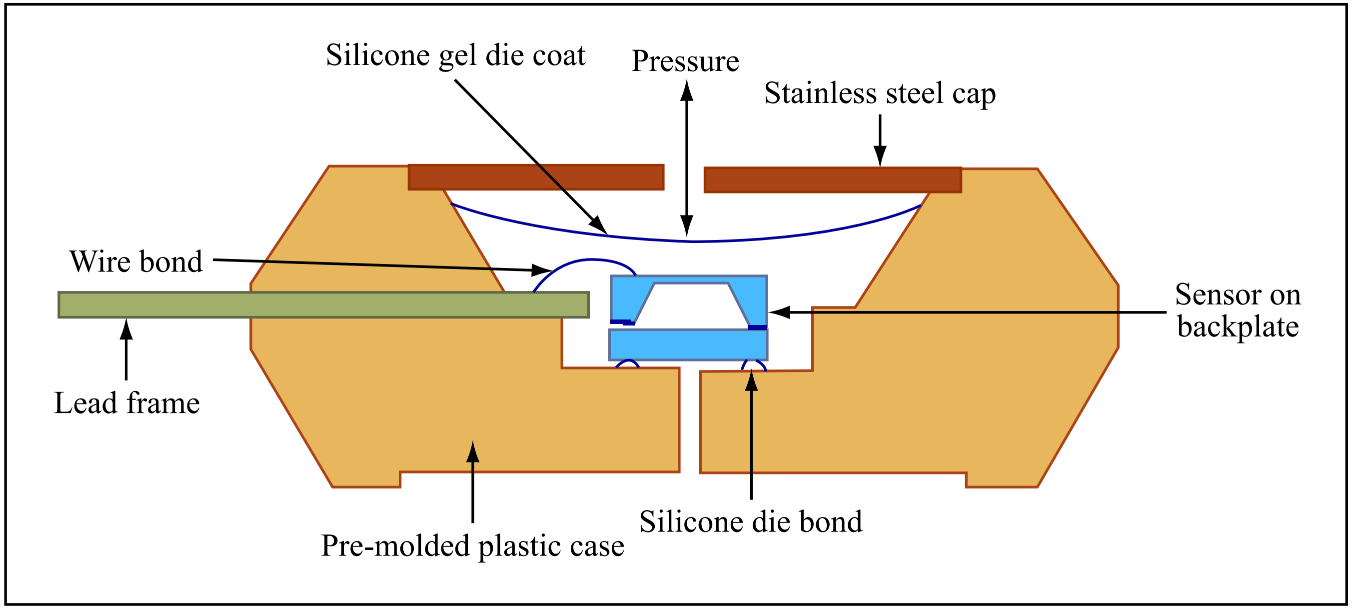


Image by MIT OpenCourseWare.
Adapted from Motorola. *Sensor Device Data/Handbook*. 4th ed. Phoenix, AZ: Motorola, Inc., 1998.

The Arguments for Monolithic

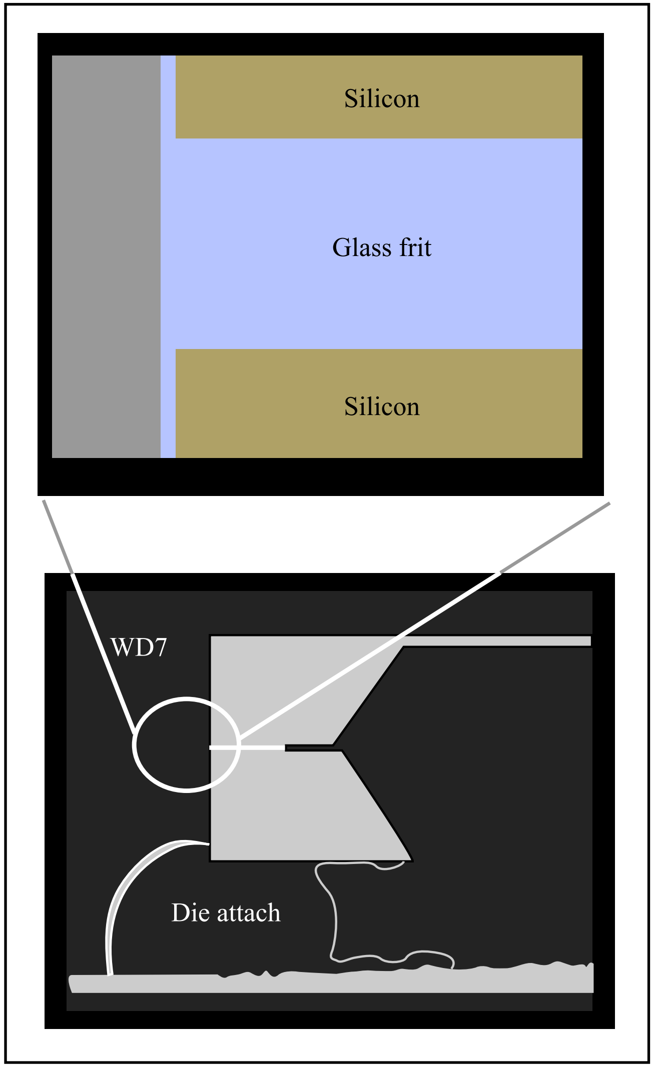
- Smaller overall system
- More reliable interconnect
- Solves a customer's problem:
  - Does away with a circuit board
  - Therefore, may be a cheaper total solution for the customer even if the integrated sensor by itself is more expensive than the hybrid sensor
- It's a business decision….

Define Interfaces

- Electrical interface: how many pins?
  - The sensor needs only three pins
- Mechanical interface: a stainless steel lid on the package
- When to calibrate? Before or after packaging?
  - Things to consider
    - Package-induced stress
    - Gel-seal induced shift in calibration
- The decision: Calibrate after bonding into the package, but before the gel-seal.
  - Cost: EXTRA PINS ON THE PACKAGE

Wafer-level packaging

- Can't use fusion bonding (circuitry can't stand it)
- What about anodic bonding?
- Bonding to silicon backplane using a glass-frit bond (more forgiving of deviations from wafer flatness)
- Firing temperature between 450 and 500 C.
- Must be void free and more pure than standard glass frits



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Details and headaches

- **Package material and molding process: avoiding leaks**
- **Die attach**
  - **Originally used RTV (room-temperature vulcanized) silicone adhesives**
  - **Now use a gel-like silicone or fluorosilicone that requires 150 C cure (rubbery material transfers low stress to the chip)**
  - **Biggest problem: batch to batch variation of the die-attach material**
- **Wire bonding**
  - **With the chip sitting on a gel base, how can you wire bond to it?**
  - **Heat transfer through the gel is poor**
  - **Mechanical support is soft**
  - **Motorola developed custom tooling to apply heat directly to the chip during wire bonding**

More details and headaches

- **Final gel encapsulant**
  - **Must wire bond before trimming, but cannot put final gel coat on until after trimming**
  - **Gel does produce a small shift in response**
  - **Calibration targets must be pre-distorted to anticipate the effect of the gel coat**
  - **Batch to variations in gel materials can then create problems**
- **Next level assembly: keeping customers happy**
  - **Market fragmentation**
  - **Different customers want different next-level assemblies (Ford doesn't want a Chrysler package)**

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Example: a newer capping technology

- **Disclaimer:**
  - **This is not a sales pitch. This particular technology is described here simply because it is well-described in the literature. Flexible packaging techniques are of wide interest.**
- **Concept: bulk-micromachined silicon caps with integrated interconnects, assembled onto dies at the wafer-scale**
- **Electrical connections and hermetic package seal made by flip-chip solder bonding and through-cap interconnects**
- **Small overall package sizes possible**
- **Clean (no particles from ceramic components), CTE matched to minimize damage and package-device interaction**
- **Reference: Elger et al., presented at IMAPS 04, cap technology by Hymite**

Application for this example

> **MEMS switch for in vivo use, to be switched by an external magnetic field**

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Details

- Caps made by standard KOH/electroplating bulk micromachining process
  - SOI substrate, KOH etched from both sides
- Including interconnects in device would lower yield and affect device process flow
- Through-cap interconnects permit flip-chip bonding to device and to outside world with minimal disturbance to device process
- Silicon caps can be cleaned with chips before assembly to minimize unwanted material in sealed-cavity
- Moderately low melting solder with no flux (no organic contamination)
- Pick and place assembly, or wafer to wafer transfer; heat in the pick and place tool to prevent caps from sliding

Bottom line

- **People are actively trying to create and sell techniques like this that can package a greater (though still not infinite) set of MEMS devices with a single process and vendor**
- **This may make the life of the MEMS designer easier, permit smaller packages, and (hopefully some day) smooth the trip to market for some MEMS devices**
- **But there is still no universal solution: what if you need optical access, fluidic access?**
- **And you still have to design the device and the packaging process together, even as the number and convenience of available tools increases**

Where to learn more

- Nadim Maluf, "An Introduction to Microelectromechanical Systems Engineering", Artech House, 2000.
- Handbooks of microelectronics packaging, such as:
  - R.R. Tummala and E.J. Rymaszewski (eds.), Microelectronics Packaging Handbook, Reinhold, 1989.