Packaging

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

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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!

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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**

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A diversity of devices to package

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Motorola accelerometer.

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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?

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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**

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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**

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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?

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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

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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

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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?

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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

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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?

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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

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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)**

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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

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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

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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…?**

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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

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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**

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Vacuum sealing by anodic bonding

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

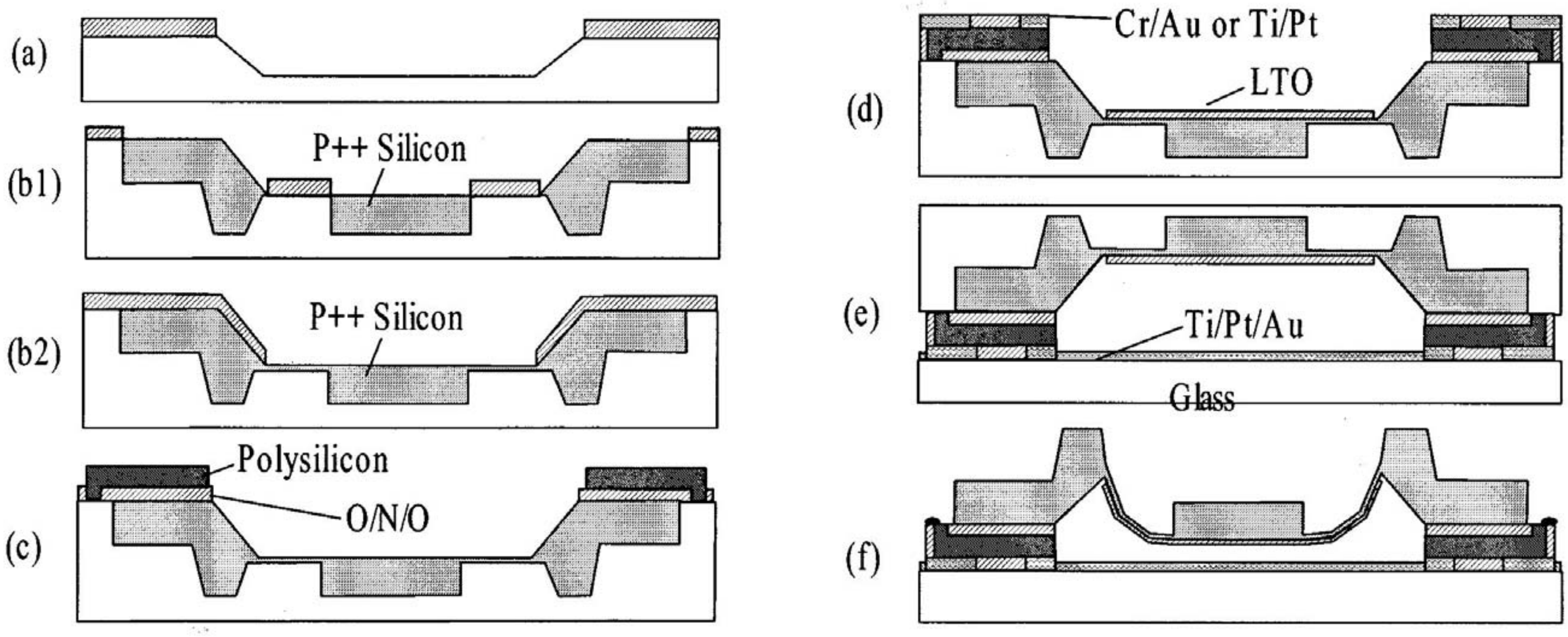

Figure 4 on p. 582 in: Chavan, A. V., and K. D. Wise. "Batch-Processed, Vacuum-Sealed Capacitive Pressure Sensors."
Journal of Microelectromechanical Systems 10, no. 4 (December 2001): 580-588. © 2001 IEEE.

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Vacuum sealing by fusion bonding

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

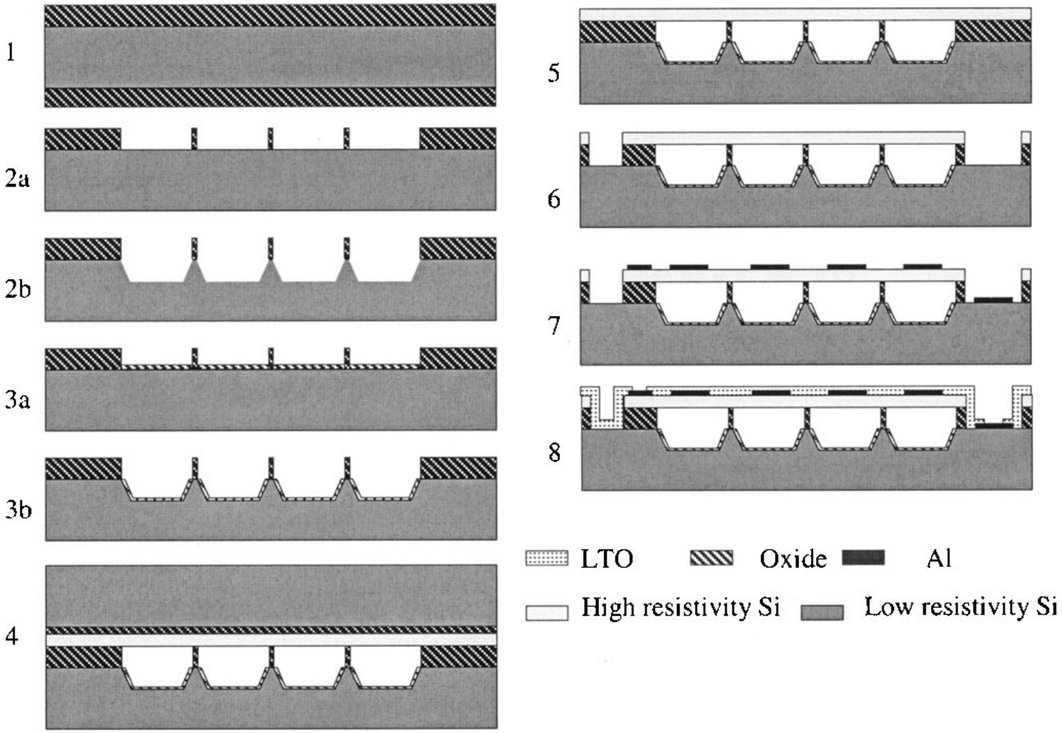

Figure 1 on p. 130 in Huang, Y., A. S. Ergun, E. Haeggstrom, M. H. Badi, and B. T. Khuri-Yakub. "Fabricating Capacitive Micromachined Ultrasonic Transducers with Wafer-bonding Technology." *Journal of Microelectromechanical Systems* 12, no. 2 (April 2003): 128-137. © 2003 IEEE.

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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

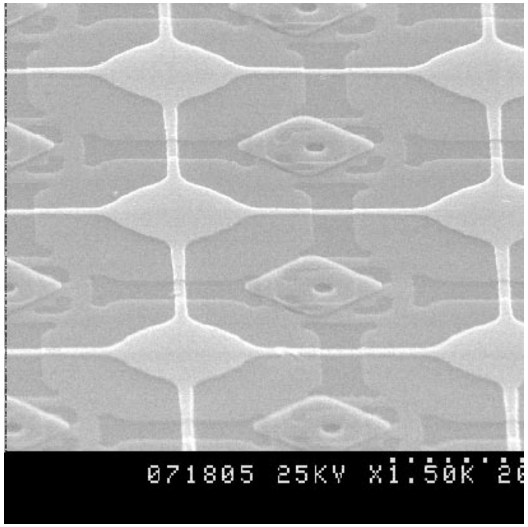

Figure 16 on p. 106 in Jin, X., I. Ladabaum, F. L. Degertekin, S. Calmes, and B. T. Khuri-Yakub. "Fabrication and Characterization of Surface Micromachined Capacitive Ultrasonic Immersion Transducers.“ *Journal of Microelectromechanical Systems* 8, no. 1 (March 1999): 100-114. © 1999 IEEE.

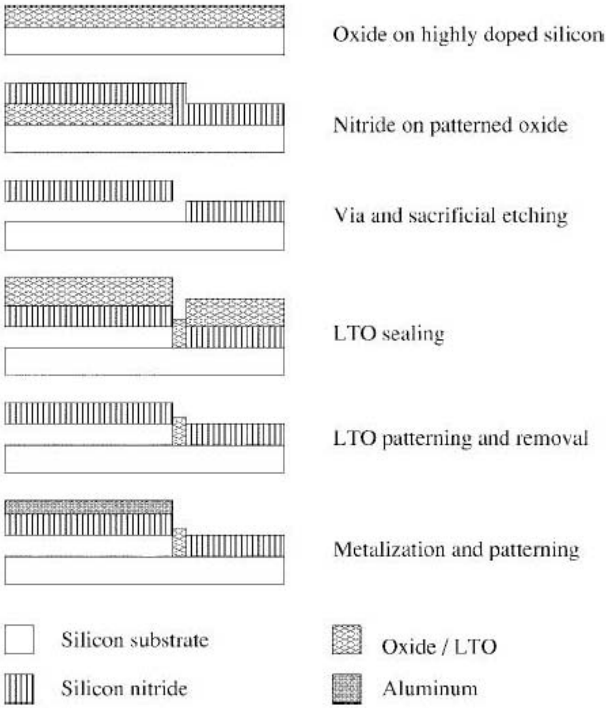

Figure 2 on p. 101 in Jin, X., I. Ladabaum, F. L. Degertekin, S. Calmes, and B. T. Khuri-Yakub. "Fabrication and Characterization of Surface Micromachined Capacitive Ultrasonic Immersion Transducers." *Journal of Microelectromechanical Systems* 8, no. 1 (March 1999): 100-114. © 1999 IEEE.

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Resonator with thin film vacuum packaging

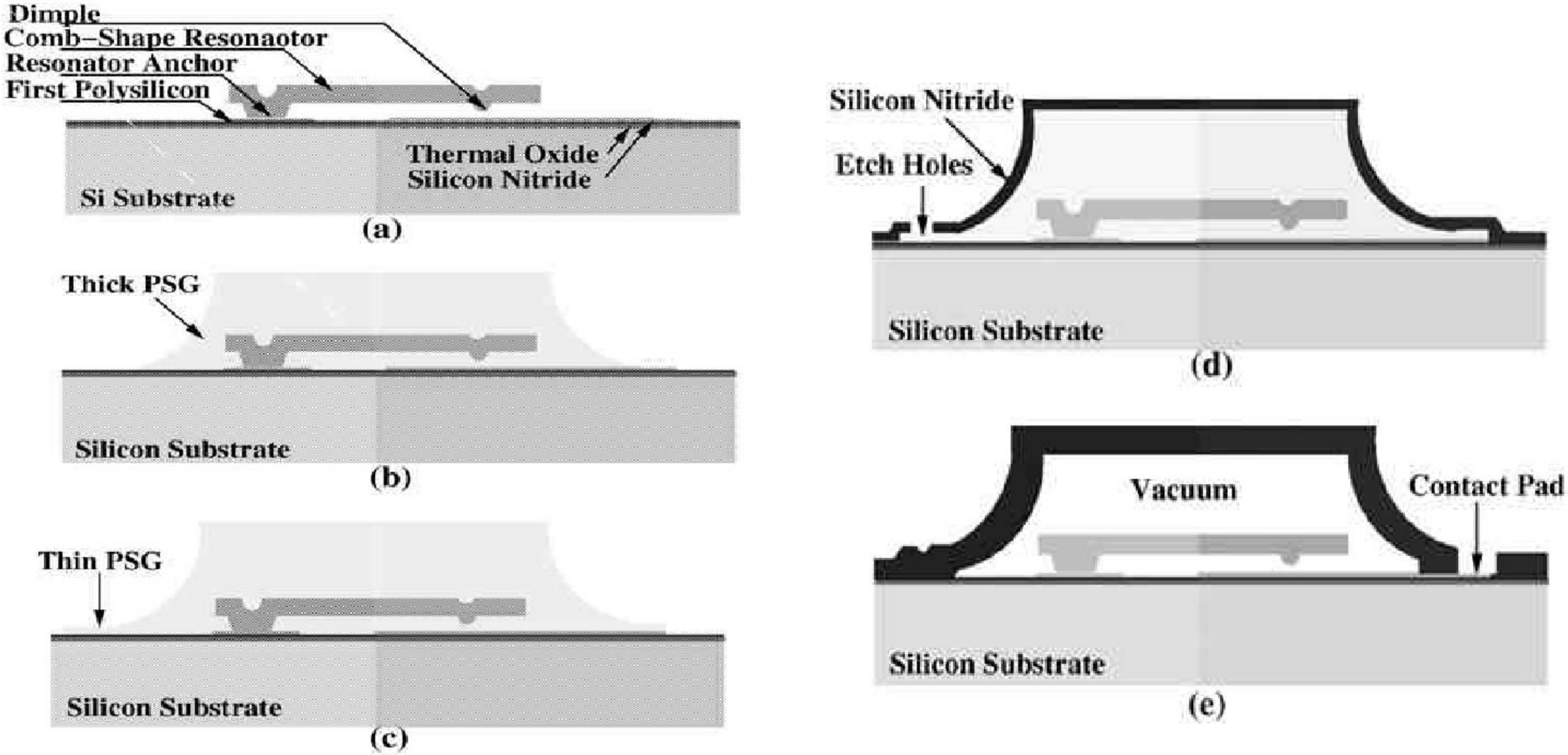

Figure 10 on p. 290 in Lin, L., R. T. Howe, and A. P. Pisano. "Microelectromechanical Filters for Signal Processing." *Journal of Microelectromechanical Systems* 7, no. 3 (September 1998): 286-294. © 1998 IEEE.

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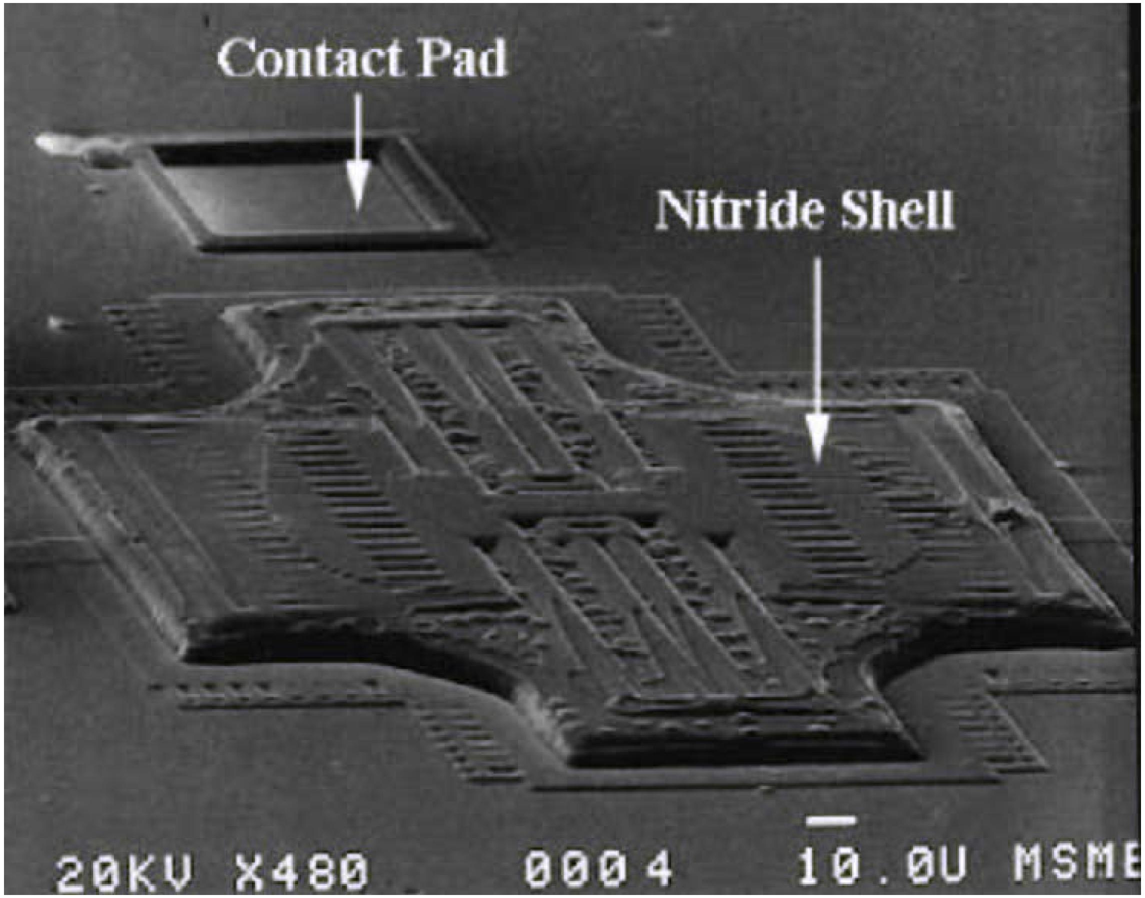

Figure 11 on p. 291 in Lin, L., R. T. Howe, and A. P. Pisano. "Microelectromechanical Filters for Signal Processing." *Journal of Microelectromechanical Systems* 7, no. 3 (September 1998): 286-294. © 1998 IEEE.

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.

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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

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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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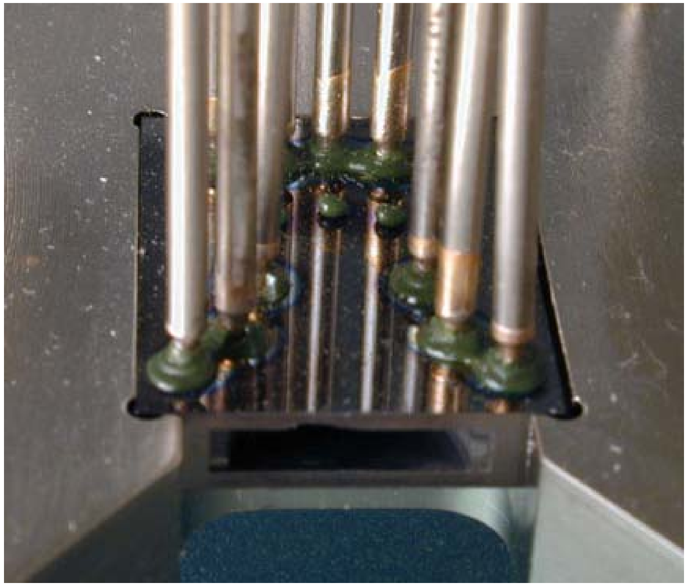
Lab-scale packaging: micro rocket

- **"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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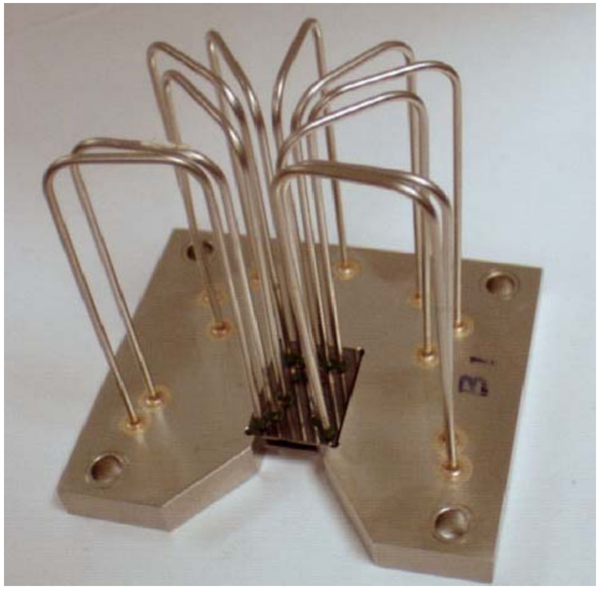

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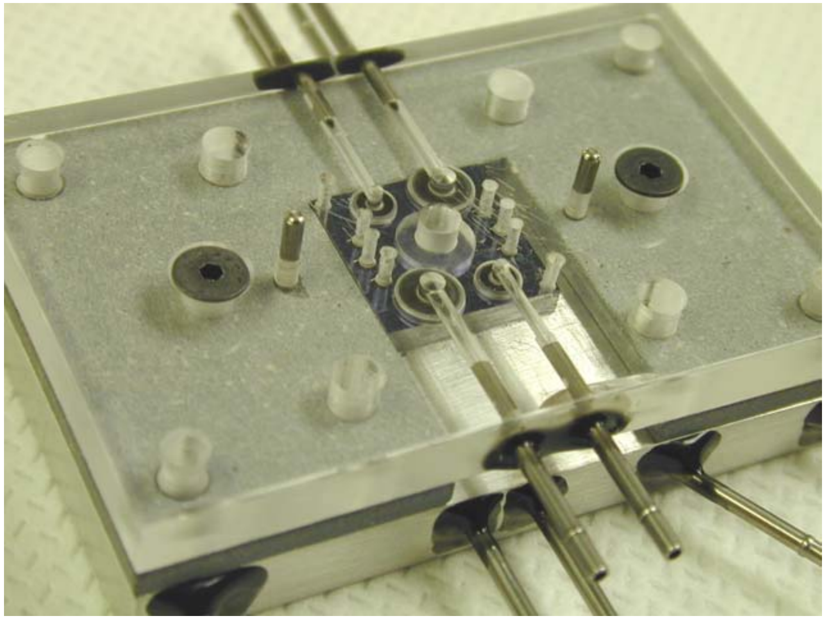
Lab-scale packaging: micro turbine

- 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?



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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.

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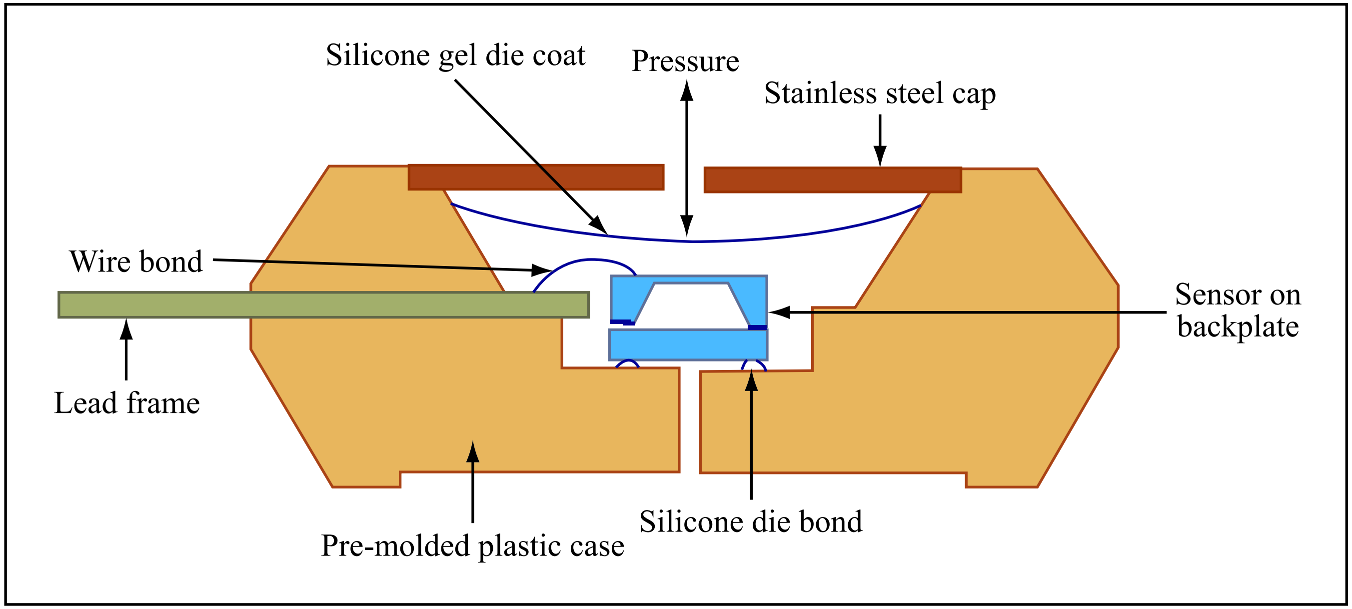
Device and Package Concept

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



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

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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….

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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**

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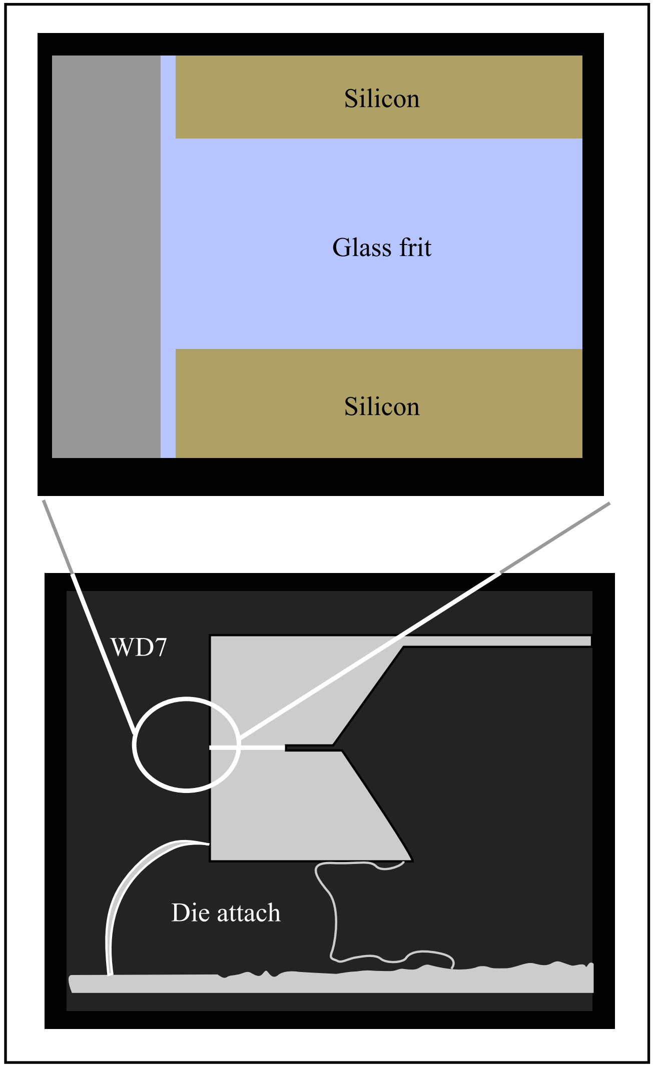
Wafer-level packaging

- 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

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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

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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

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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

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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.

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