
Case Study: Power MEMS

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Thanks to the MIT microengine team, past and present, for many of these materials. Thanks also to A. Forte, J. Yoon, and T. Lyszczarz of Lincoln Laboratory.

Outline

- > **Brief overview of power MEMS**
- > **MIT microengine**
 - **What to make it from, and how?**
 - **High speed rotation**
 - **Combustion**
 - **Motors and generators**
 - **Putting it all together**

Motivation for power MEMS

- > **MEMS are well established for many sensing and actuation applications (accelerometers, pressure sensors, fine positioning of small components...)**

- > **Many useful macroscale systems have high power requirements and typically use macro-scale, non-MEMS solutions**
 - **Electric power generation**
 - **Propulsion**
 - **Cooling**
 - **Lasers**

- > **When the performance of high power macro-scale systems limits the system performance, look for solutions wherever they may be!**
 - **Sometimes scaling favors MEMS...**
 - **... and sometimes it doesn't.**

What to expect today

- > **No commercial case study today**
 - **Consider portable power... your laptop still uses batteries!**
 - **But, the market is there for a truly improved system-level solution**

- > **What we hope to get out of this**
 - **Contrast with the common temptation to focus on some parts of a design and assume that a solution exists for the remaining parts**
 - **This is a failure often seen in packaging**
 - **But, power MEMS tend to push against all limits at the same time: thermal limits, strength of materials, breakdown voltages, thermal**
 - **See examples in which these were (or weren't) successfully considered**
 - **Working within fabrication limits**

Options for electric power generation

> Macroscale heat engines

- A clear win when you can find a wall to plug into, because you have dense energy storage in combustible fuels and efficient generation in large scale systems

> Batteries

- The usual portable power solution, but they can be cumbersome for high power/long usage applications

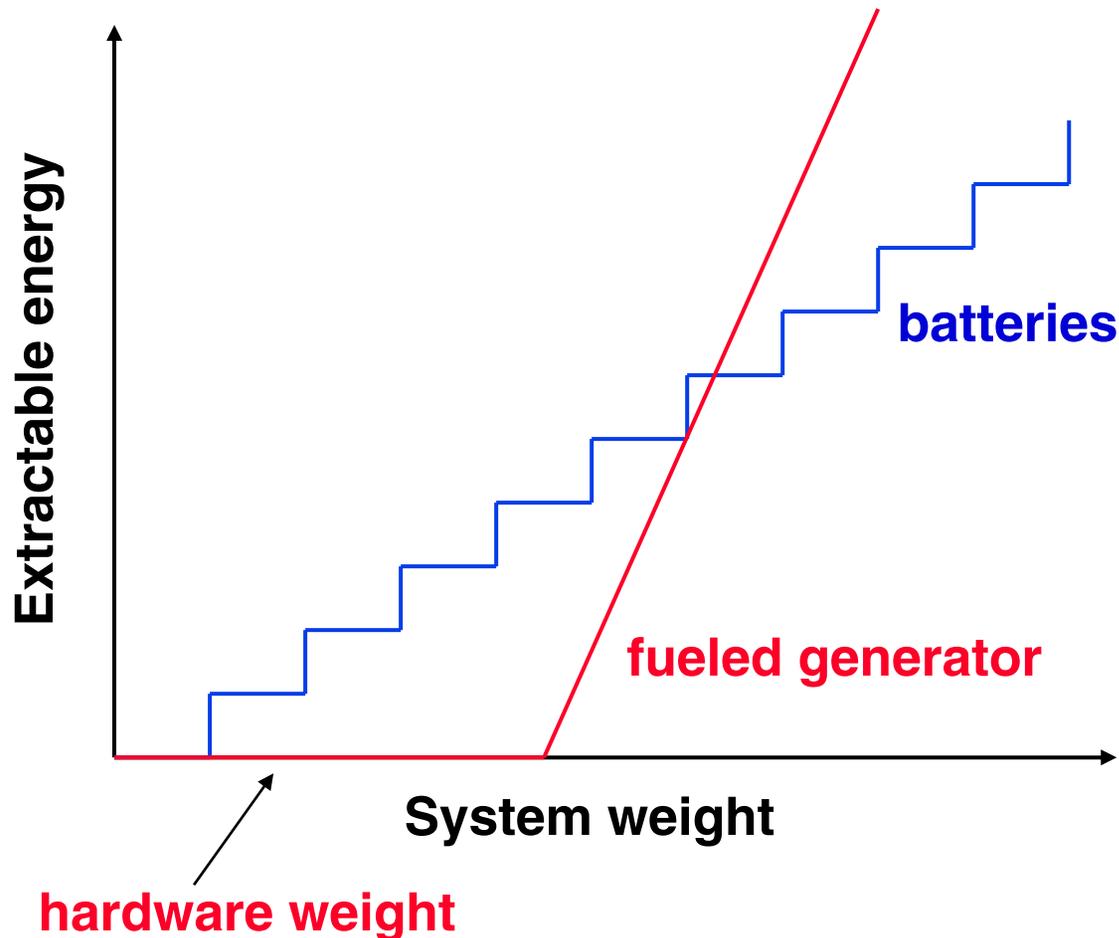
> Fuel cells

- Hydrogen + oxygen = water + electricity
- One concern: size of total system required to make it work

> Power MEMS

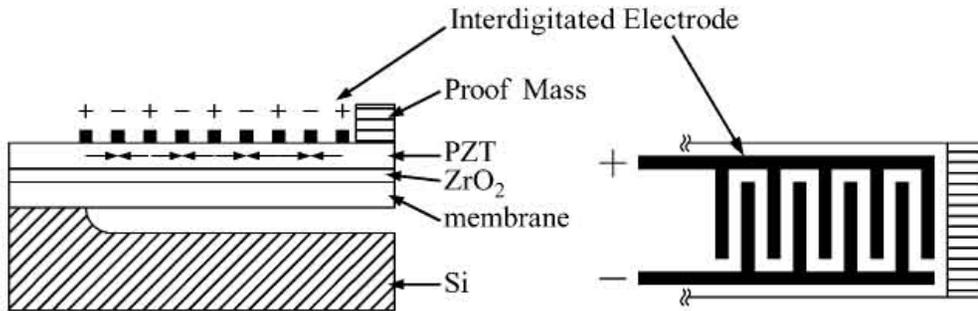
- Fuel burning systems: miniature heat engines of various types, micro fuel cells, thermally driven systems (i.e. thermoelectric)
- Energy harvesters: vibrations and other motions, waste heat can provide low levels of power

Portable power metrics



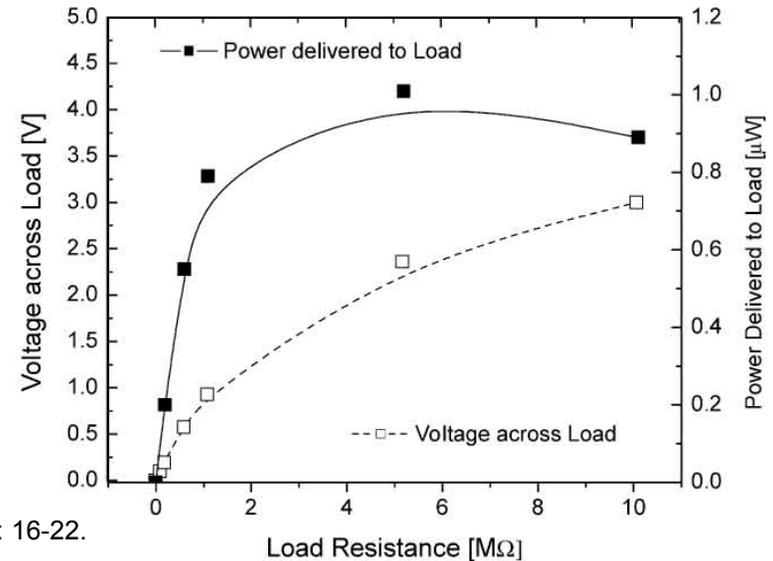
Other metric: power level vs. system weight

Piezoelectric energy harvester



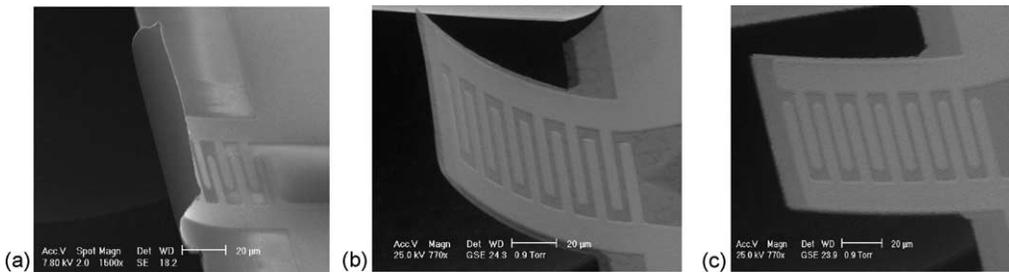
Piezoelectric cantilever converts strain energy to electric energy.

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1 μW power output

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Fabrication and stress control are not trivial!

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MEMS fuel processor

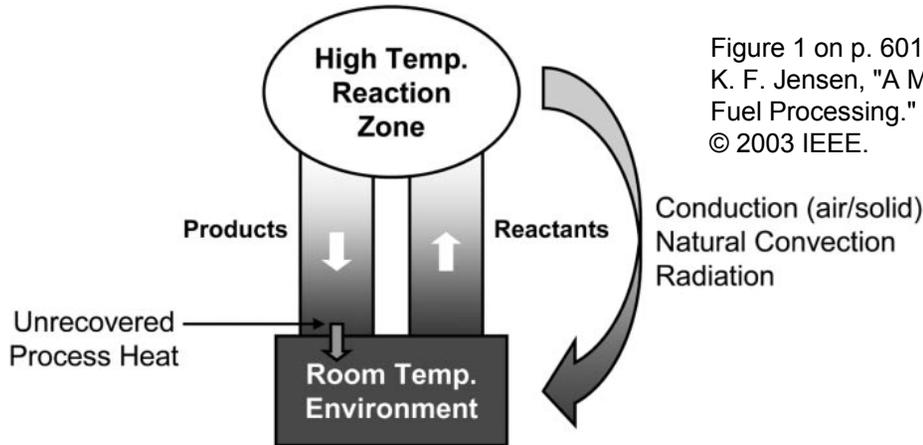
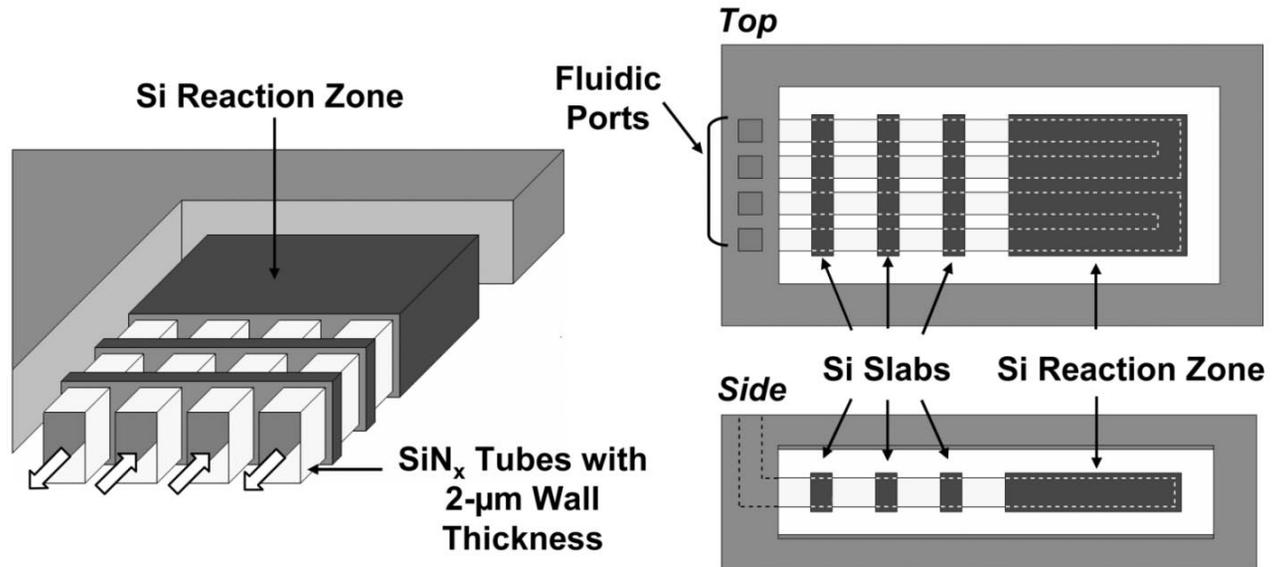


Figure 1 on p. 601 in Arana, L.R., S. B. Schaevitz, A. J. Franz, M. A. Schmidt, and K. F. Jensen, "A Microfabricated Suspended-tube Chemical Reactor for Thermally Efficient Fuel Processing." *Journal of Microelectromechanical Systems* 12, no. 5 (2003): 600-612. © 2003 IEEE.

Figure 2 on p. 602 in Arana, L. R., S. B. Schaevitz, A. J. Franz, M. A. Schmidt, and K. F. Jensen, "A Microfabricated Suspended-tube Chemical Reactor for Thermally Efficient Fuel Processing." *Journal of Microelectromechanical Systems* 12, no. 5 (2003): 600-612. © 2003 IEEE.



MEMS fuel processor

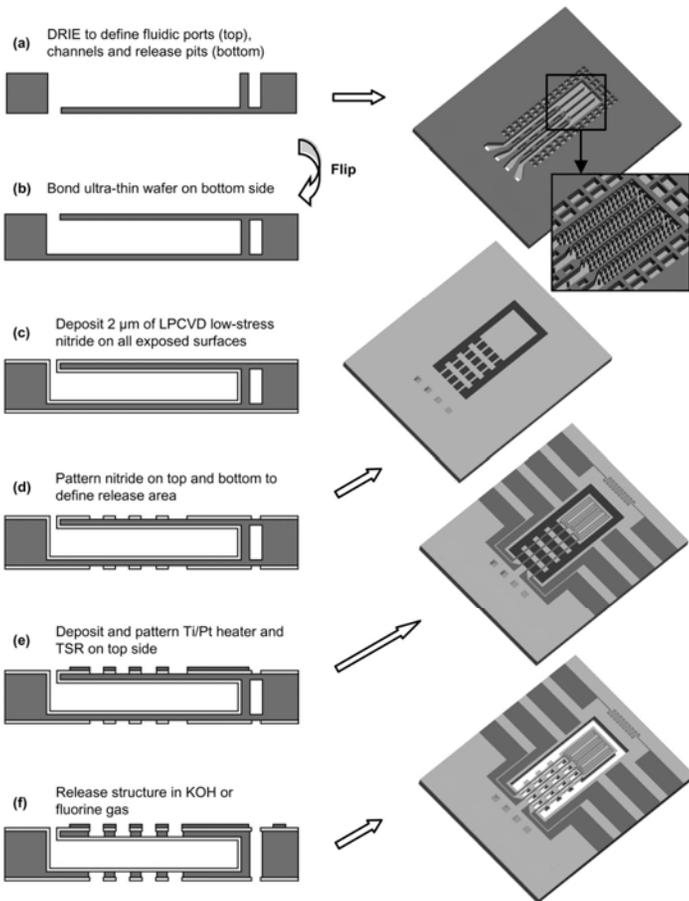


Figure 4 on p. 605 in Arana, L. R., S. B. Schaevitz, A. J. Franz, M. A. Schmidt, and K. F. Jensen. "A Microfabricated Suspended-tube Chemical Reactor for Thermally Efficient Fuel Processing." *Journal of Microelectromechanical Systems* 12, no. 5 (2003): 600-612. © 2003 IEEE.

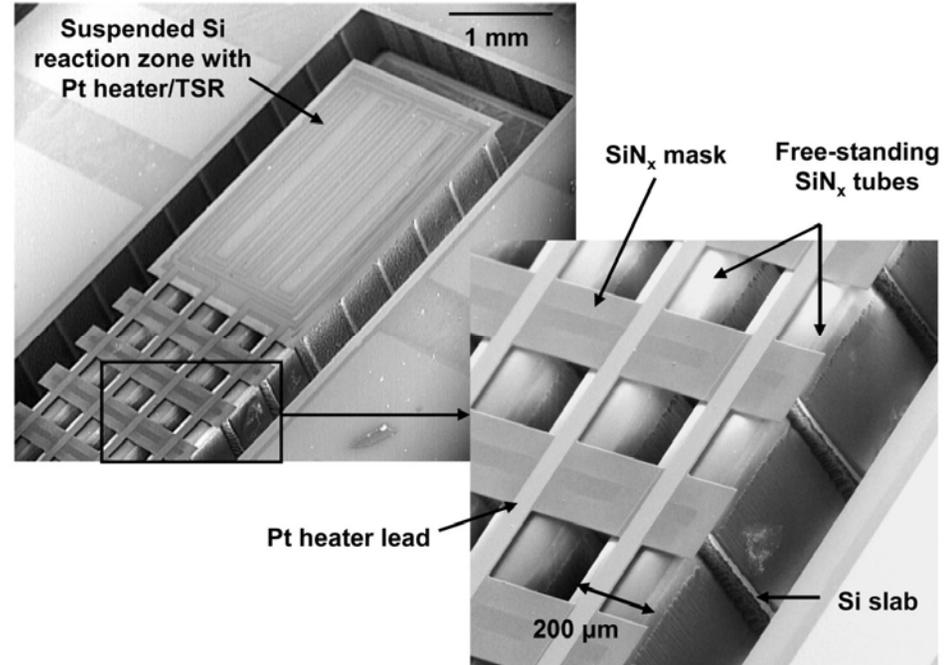


Figure 5 on p. 606 in Arana, L. R., S. B. Schaevitz, A. J. Franz, M. A. Schmidt, and K. F. Jensen, "A Microfabricated Suspended-tube Chemical Reactor for Thermally Efficient Fuel Processing." *Journal of Microelectromechanical Systems* 12, no. 5 (2003): 600-612. © 2003 IEEE.

Outline

- > **Overview of power MEMS**
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 - **High speed rotation**
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 - **Putting it all together**

Detailed case study: MIT microengine project

- > **Goal: an electric generator driven by a miniature gas turbine engine, with overall performance exceeding that of the best batteries**
- > **Unlikely to compete favorably with macroscale gas turbines – lower efficiency**
- > **But, hydrocarbon fuels have high energy density (of order 13,000 W-hr/kg), so even a lower efficiency may outperform batteries (up to ~200 W-hr/kg for rechargeables) on overall energy density**
- > **Other consideration: hardware size**
- > **Similar considerations for all fuel-burning power generators**

Micro gas turbine engine

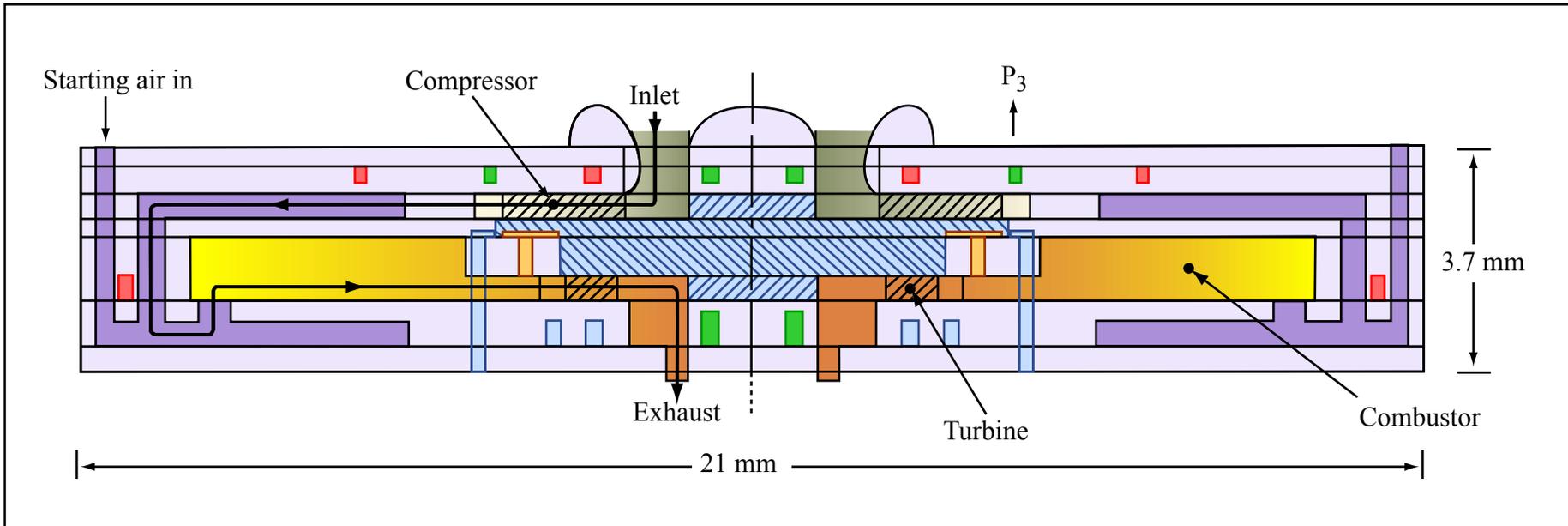


Image by MIT OpenCourseWare.

Thrust = 11 g

Fuel burn = 16 g/hr

Engine weight = 2 grams

Turbine inlet temp = 1600°K (2421°F)

Rotor speed = 1.2×10^6 RPM

Exhaust gas temp = 970°C

Portable compact power sources

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> Approach

- Simple cycle gas turbine
- Direct drive generator (1.2M RPM)
- MEMS fabrication

> Near-term performance goals

- 5% efficiency (chemical to electrical)
- 1-10 watts output

What to make the microengine from?

> Considerations:

- **Combustion and high temperature**
- **Stresses from high rotational speed**
- **Need for highly-controlled feature geometries**

> Candidate materials:

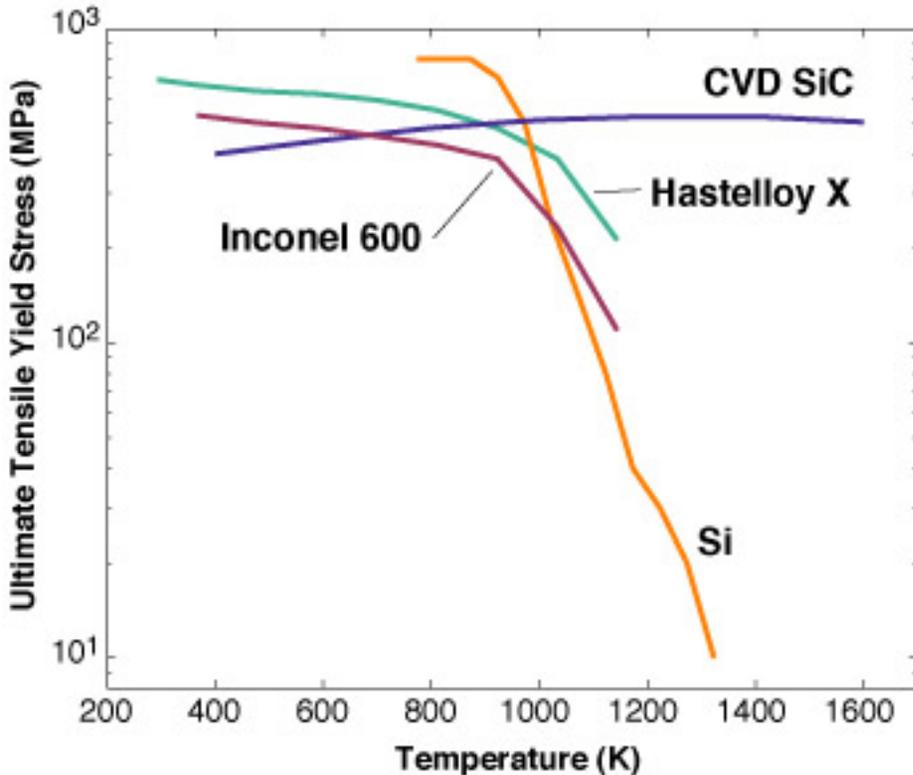
- **Nothing from the polymer family**
- **Conventionally-machined but tiny metal parts (known to be okay from high T/strength point of view, not limited to 2D patterns, possibly easier to machine, likely harder to assemble)**
- **Single crystal silicon (high T OK, readily micromachined, strength?)**
- **Other microfabrication-compatible materials, such as silicon carbide (better high T performance, not so easy to micromachine)**

Design choice: micromachined structure

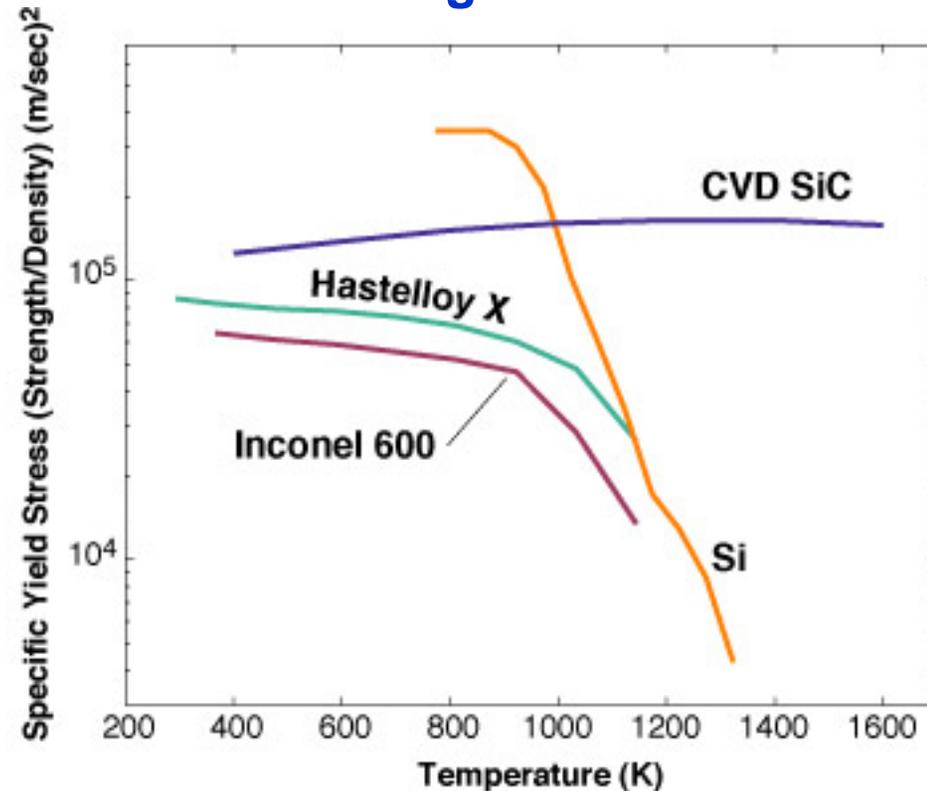
- > **Silicon has deep reactive ion etching (DRIE)**
- > **DRIE exists for silicon carbide as well, but it is slower and does not give as good a profile**
- > **Conclusion: to start out, we are stuck with silicon or nothing. So can silicon do the job?**
 - **Good news: single crystal silicon has close to zero defects, so it will have few points of inherent weakness**
 - **More good news: silicon is lightweight, so it will have less tendency to tear itself apart than a heavier material would**
 - **Bad news: silicon is brittle, so if something bad happens, it will likely involve catastrophic failure**
- > **Parallel approach chosen: demonstrate engine in silicon, measure silicon's properties, and look into silicon carbide technology**

Microfabricated vs. conventional materials for high temperature structures

Static Structure



Rotating Structure

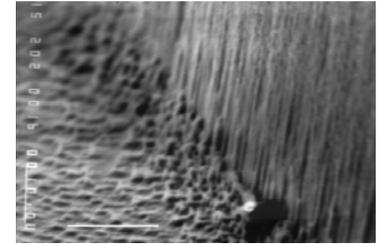


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Other structural concerns

> Factors affecting the strength of micromachined silicon devices:

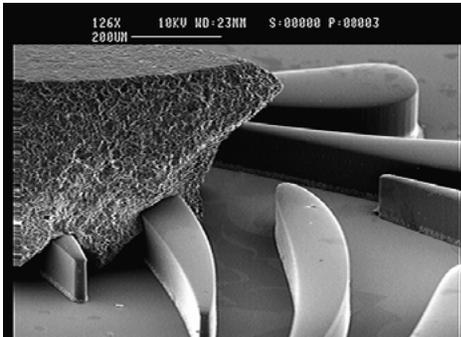
- Surface finish of etched surfaces (etch defects can initiate fracture)
- Strength of wafer bonds
- Deep etch profiles: does base have a fillet radius or a notched undercut?



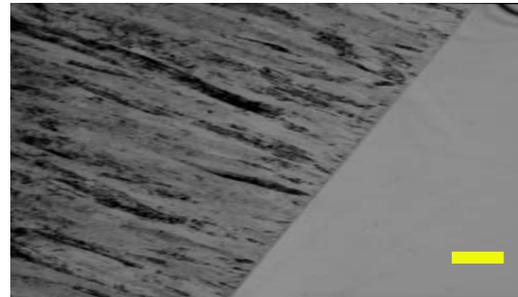
Fillet radius roughness control

Courtesy of S. Mark Spearing and company. Used with permission.

> Manufacturability and performance of silicon carbide structures

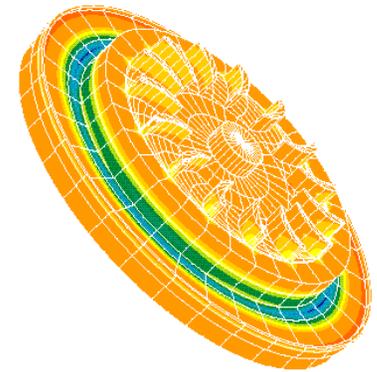


CVD SiC Moulding



TEM of CVD SiC/Si

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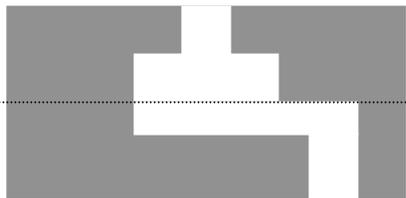
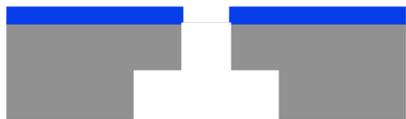


Rotor FEM

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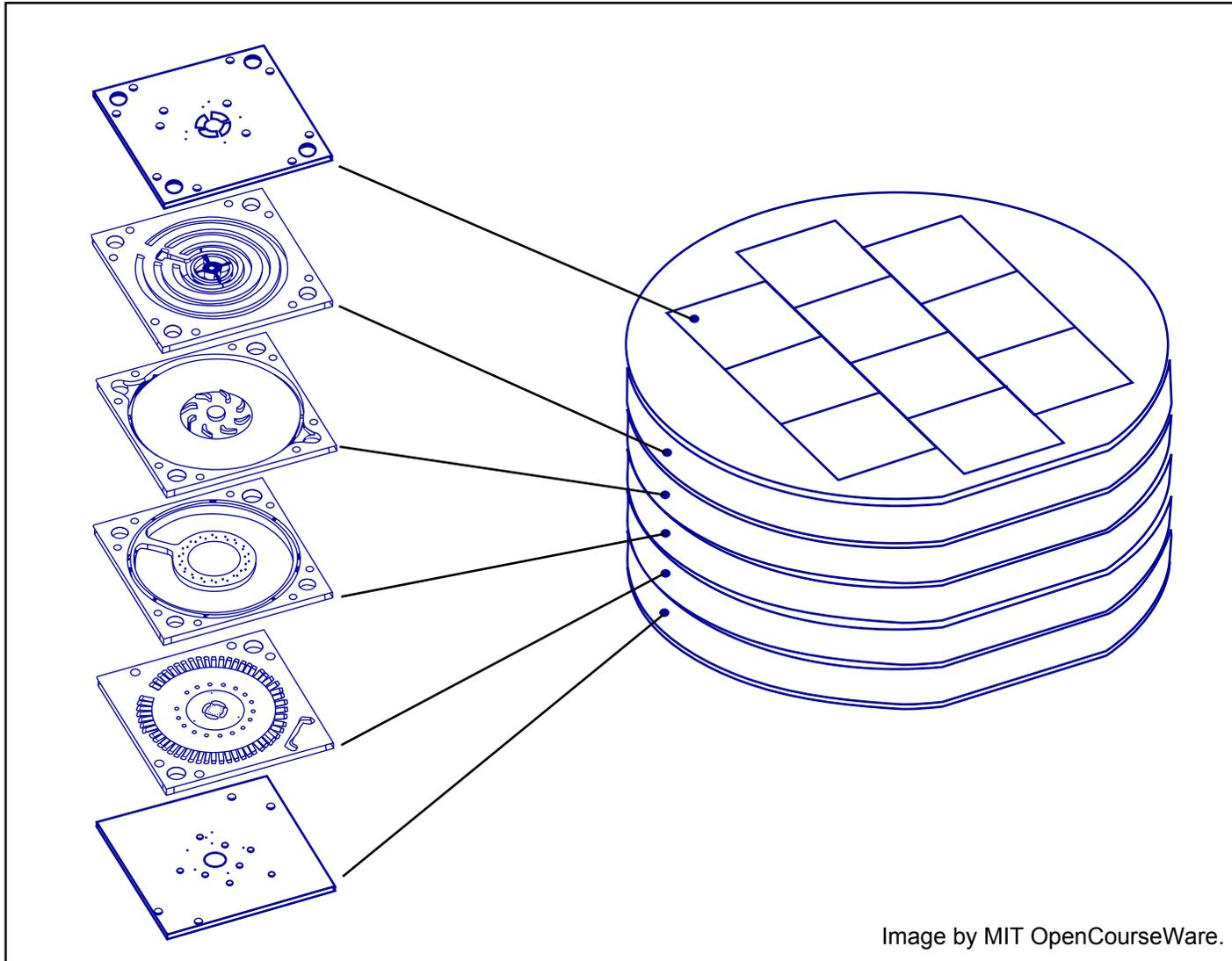
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Fabrication approach: DRIE and wafer bonding



- 1. Pattern front side of Si wafer using photolithography**
- 2. Etch deep, straight-walled etch with an anisotropic deep reactive ion etcher**
- 3. Pattern back side of wafer, aligning to front side features**
- 4. Deep reactive ion etch the back side of wafer**
- 5. Align and fusion bond first patterned wafer to a second patterned wafer**

Patterning of six-wafer engine stack



Pros and cons of fabrication approach

- > **To first order, in plane complexity is “free”**
 - **Just use a more complicated mask**
- > **DRIE can produce high aspect ratio features (30:1) and etch through wafers**

BUT

- > **Deep reactive ion etching produces extruded 2D rather than true 3D**
 - **Limits design, for example turbomachinery design**
- > **Vertical thickness and vertical complexity mean adding more wafers to the stack**
 - **More processing, more wafer bonding**
- > **Pushing technologies to limits: attrition**

Microengines

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Cross-sectioned microengine

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3-D cutaway of a micromachined microengine. Photograph by Jonathan Protz.

MIT microturbine

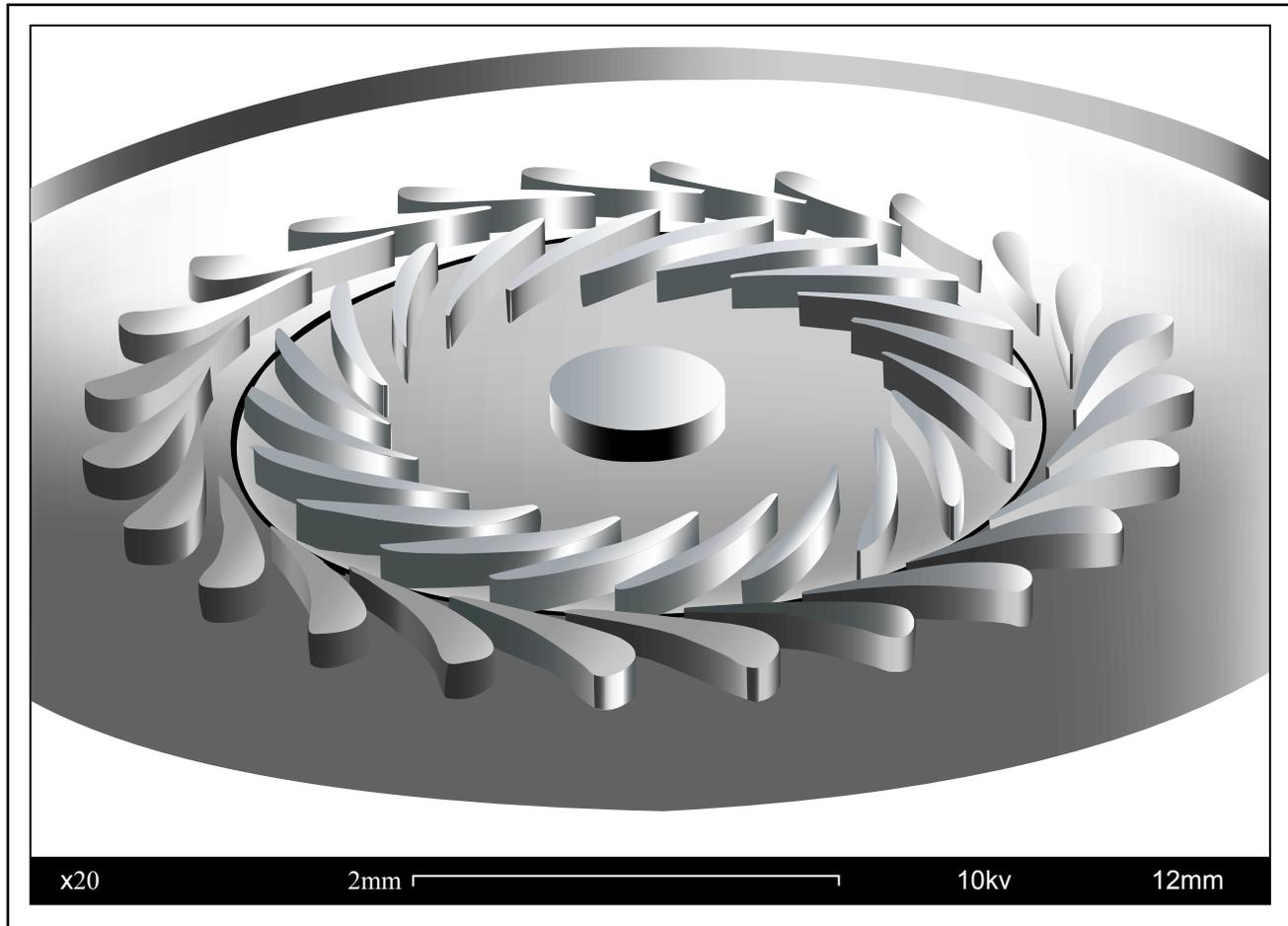


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C.C. Lin

Development approach

- > **System is too complex to develop as a whole**
- > **Split off subsystems and technologies**
 - **Bearings, turbomachinery, high speed rotation**
 - **Combustion**
 - **Packaging for high temperature and pressure**
 - **Materials properties**
 - **Electromechanics: motors and generators**
- > **Approach each through a combination of modeling and creation of stand-alone subsystem test devices**

Micromachined gas bearings

- > **Engine rotor must spin > 1 Mrpm**
- > **Rotation supported on micromachined gas bearings**
 - **Pressurized air is injected into narrow gaps between rotating and stationary components**
 - **As rotor approaches wall, pressure increases and returns rotor to center**
- > **Thrust bearings**
 - **Provide axial support to prevent up-and-down motion of rotor disk**
- > **Journal bearing**
 - **Provides in-plane support to prevent rotor from crashing sideways into housing**

Micro-bearing test device

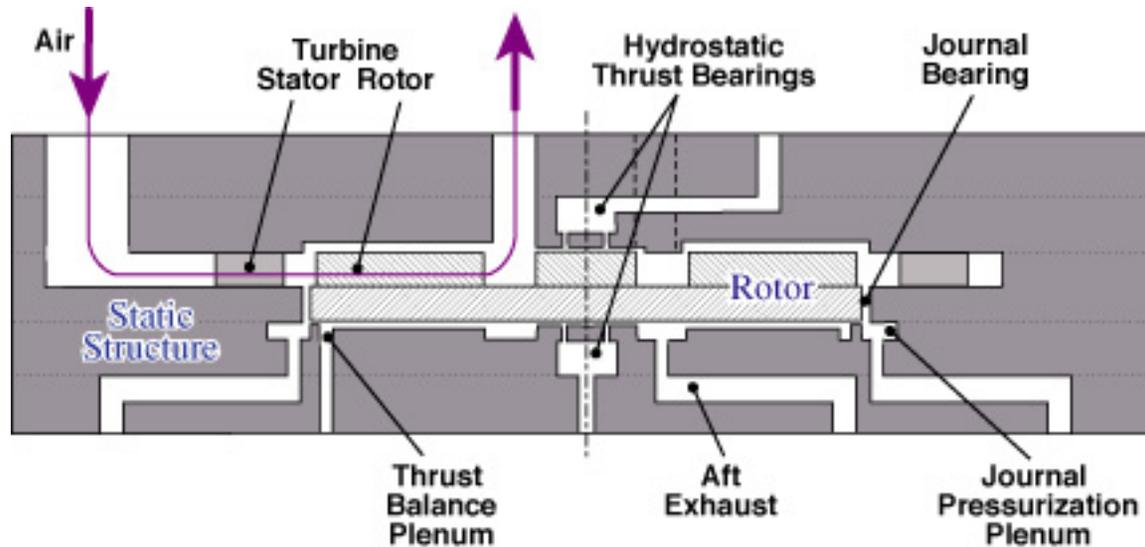


Figure 8 on p. 162 in Wong, Chee Wei, Xin Zhang, S. A. Jacobson, and A. H. Epstein. "A Self-acting Gas Thrust Bearing for High-speed Microrotors." *Journal of Microelectromechanical Systems* 13, no. 2 (April 2004): 158-164. © 2004 IEEE.

Micro vs. conventional gas bearings

- > **Gas bearings are used in macro devices**
 - **Same concept as microdevice, very effective**

- > **Aspect ratio of rotor is different**
 - **Macro: long, cylindrical rotor**
 - **Micro: flat disk with very little outer edge area on which to carry load**

- > **Balancing scheme**
 - **Macro rotors are tested and balanced iteratively**
 - **How to balance a micromachined rotor? Difficult to build it evenly, difficult to adjust balance later.**

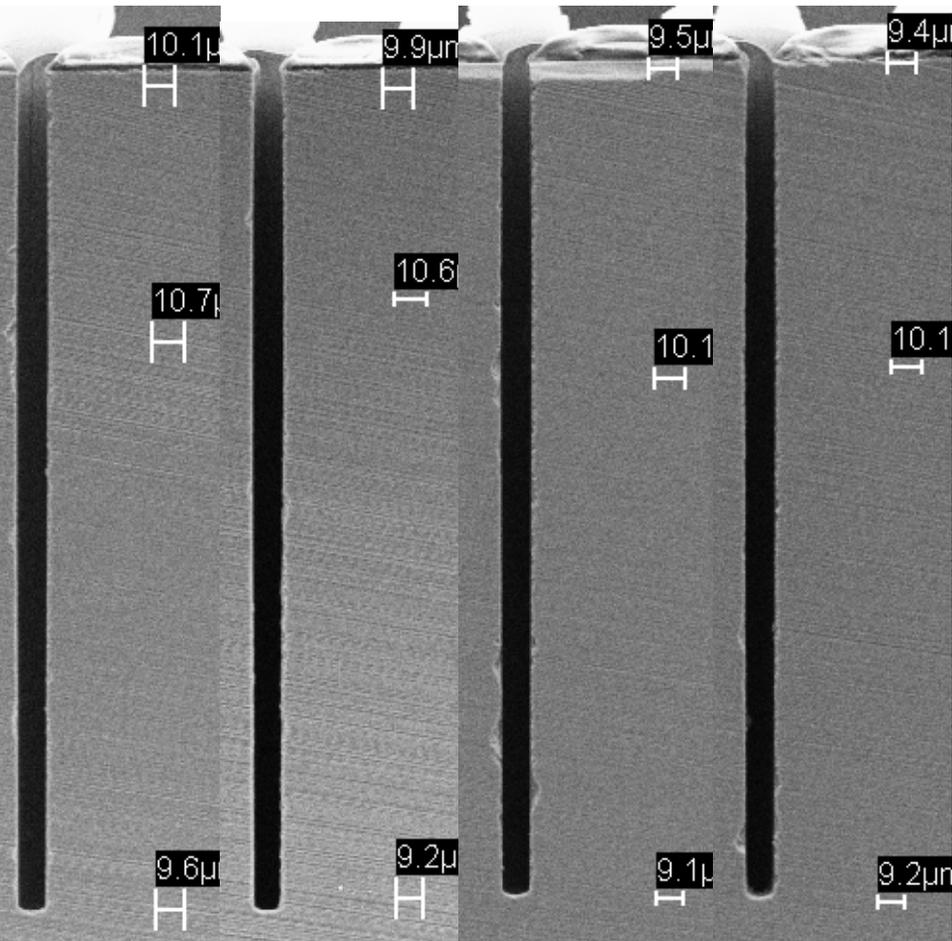
- > **Bottom line for micro: precision, precision**

300 μm long journal bearing

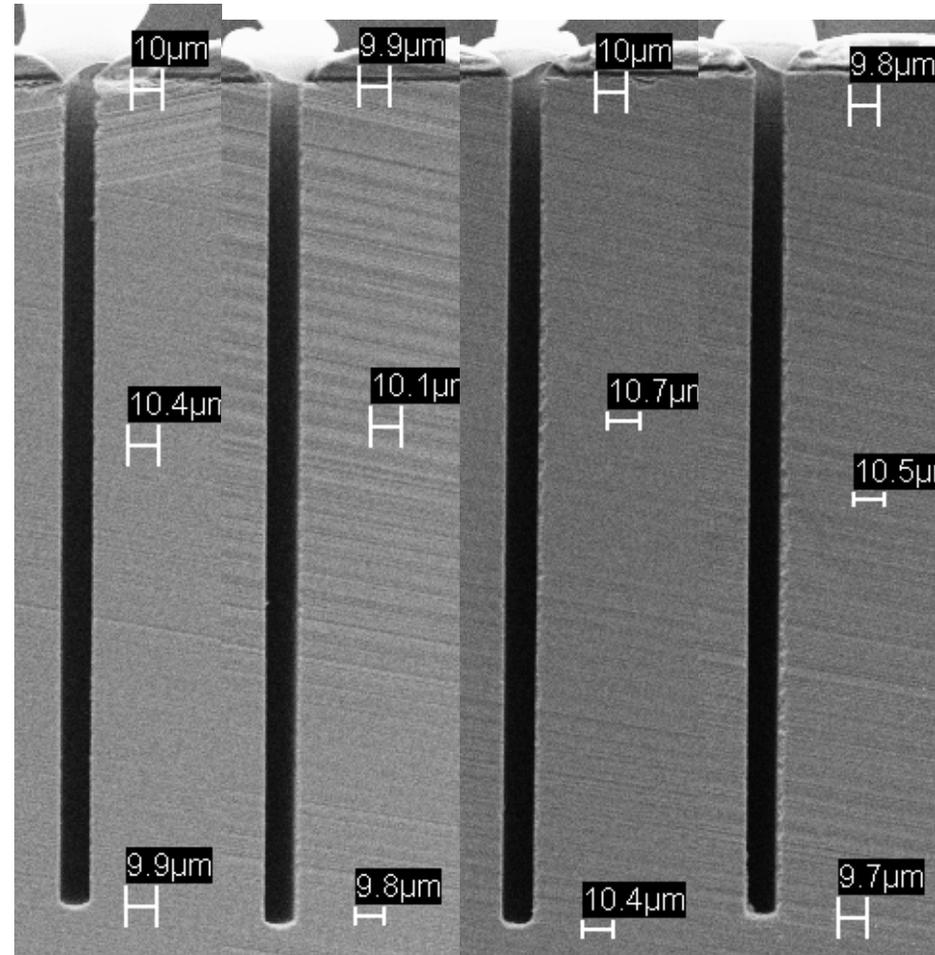
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300 micrometer long journal bearing.

Journal Bearing Quality Control: Wafer to Wafer

Wafer #1



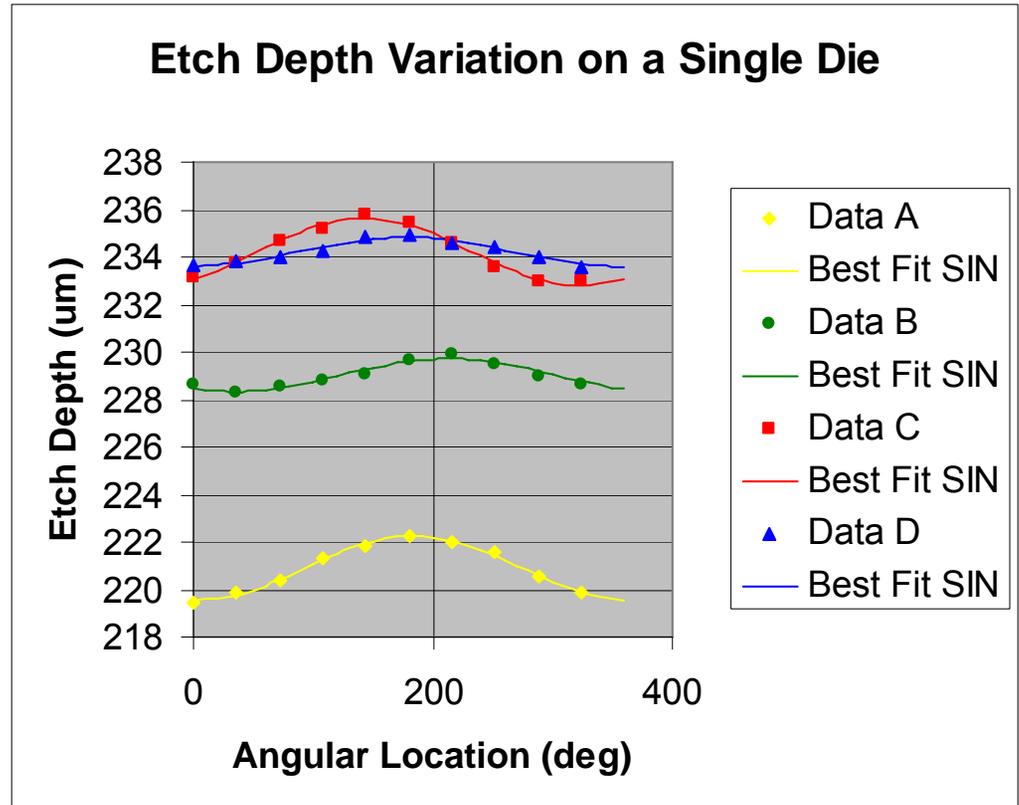
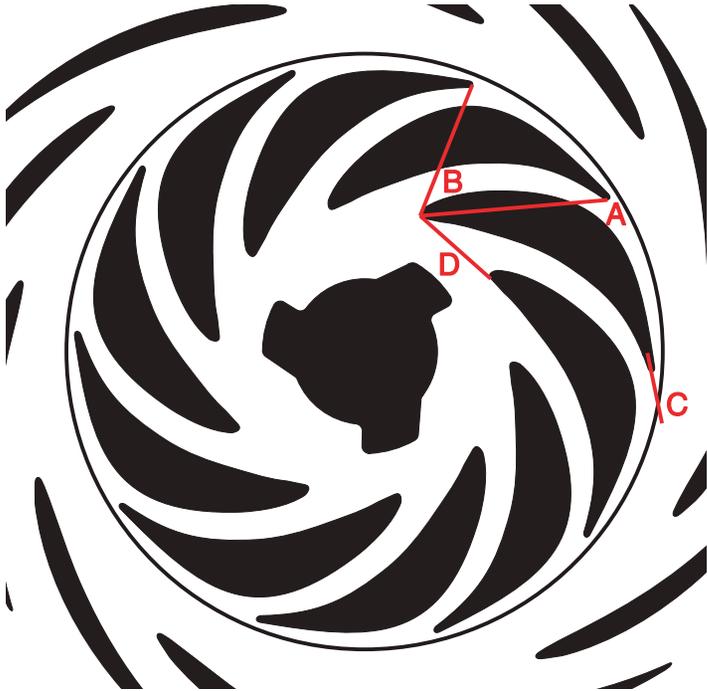
Wafer #2



Courtesy of Hanqing Li, et al. Used with permission.

Rotor balance drives fabrication requirements

-Compressor Etch Uniformity Measurements-



Courtesy of Chiang Juay Teo. Used with permission.

Micro air bearing testing

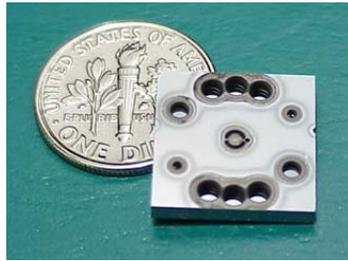


Figure 1 on p. 142 in Frechette, L. G., S. A. Jacobson, K. S. Breuer, F. F. Ehrich, R. Ghodssi, R. Khanna, Chee Wei Wong, Xin Zhang, M. A. Schmidt, and A. H. Epstein. "High-speed Microfabricated Silicon Turbomachinery and Fluid Film Bearings" *Journal of Microelectromechanical Systems* 14, no. 1 (February 2005): 141-152. © 2005 IEEE.

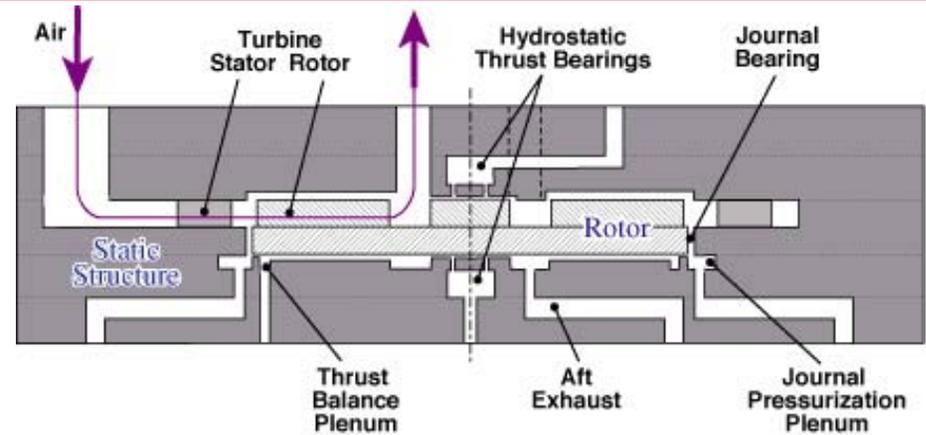
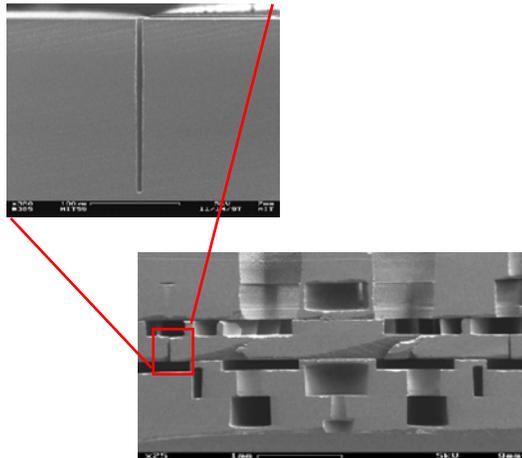


Figure 8 on p. 162 in Wong, Chee Wei, Xin Zhang, S. A. Jacobson, and A. H. Epstein. "A Self-acting Gas Thrust Bearing for High-speed Microrotors." *Journal of Microelectromechanical Systems* 13, no. 2 (April 2004): 158-164. © 2004 IEEE.



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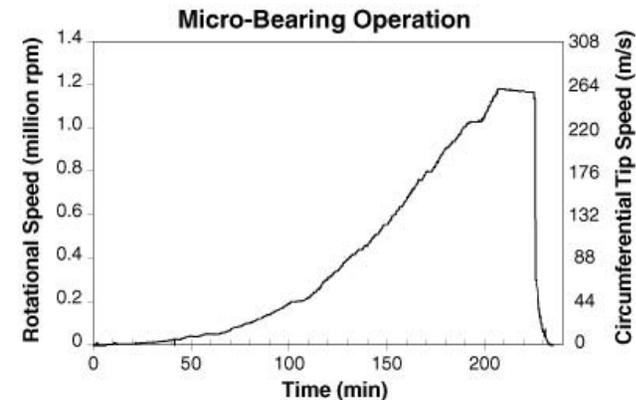


Figure 10 on p. 148 in Frechette, L. G., S. A. Jacobson, K. S. Breuer, F. F. Ehrich, R. Ghodssi, R. Khanna, Chee Wei Wong, Xin Zhang, M. A. Schmidt, and A. H. Epstein. "High-speed Microfabricated Silicon Turbomachinery and Fluid Film Bearings" *Journal of Microelectromechanical Systems* 14, no. 1 (February 2005): 141-152. © 2005 IEEE.

Combustion in microengine

> Requirements

- Sustain a flame in a microcombustor at the design mass flow rates
- Make sure that the reactants have enough time to burn in combustor
- Make sure that the structure can survive the high temperatures and (for rotating components) the high stress

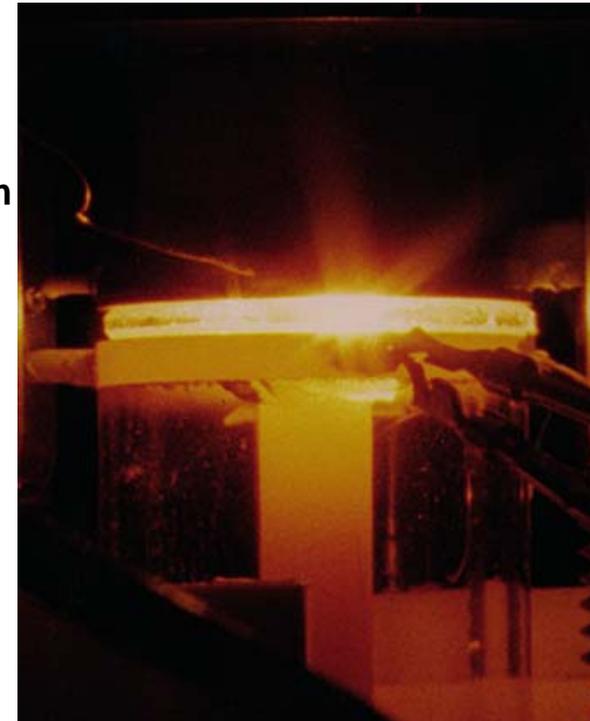
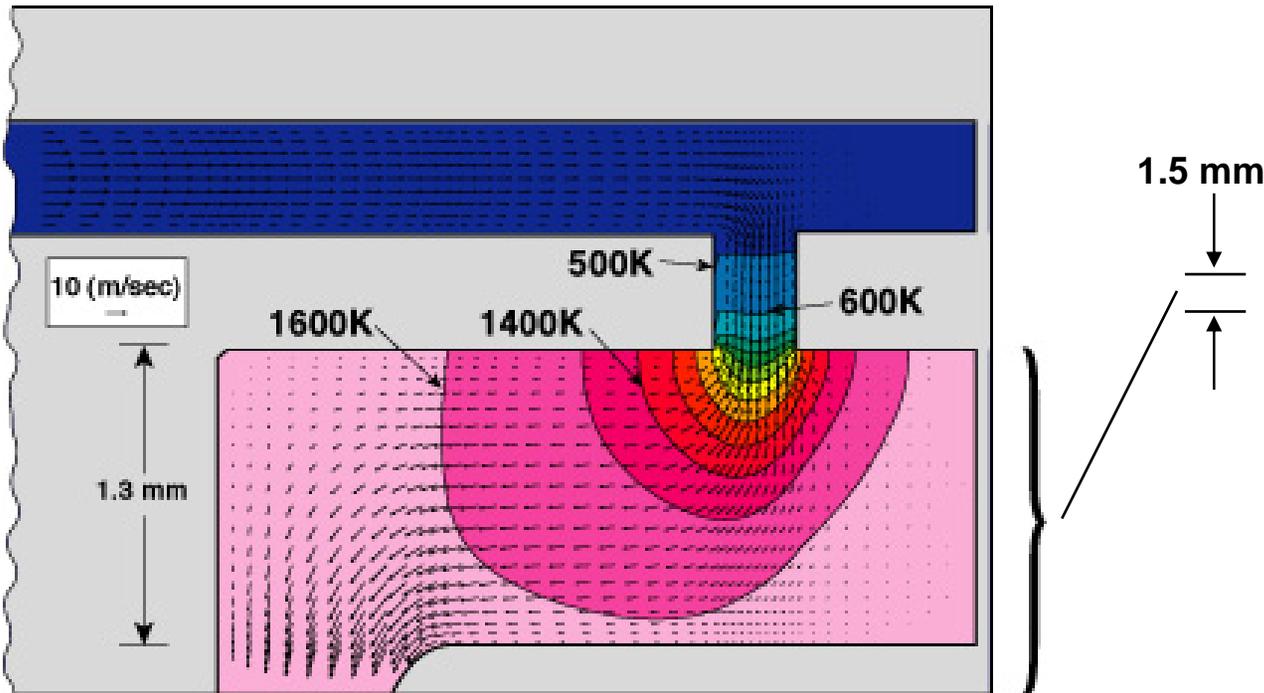
> Reactant mixing times can scale with size and geometry

> Necessary reaction times are independent of scale

- Tradeoffs among high flow rate (short residence time), reaction times for different fuels, and complexity (design of combustion chamber, use of catalysts)

> Burn hydrogen first, then more difficult hydrocarbons

200 Watt microcombustor



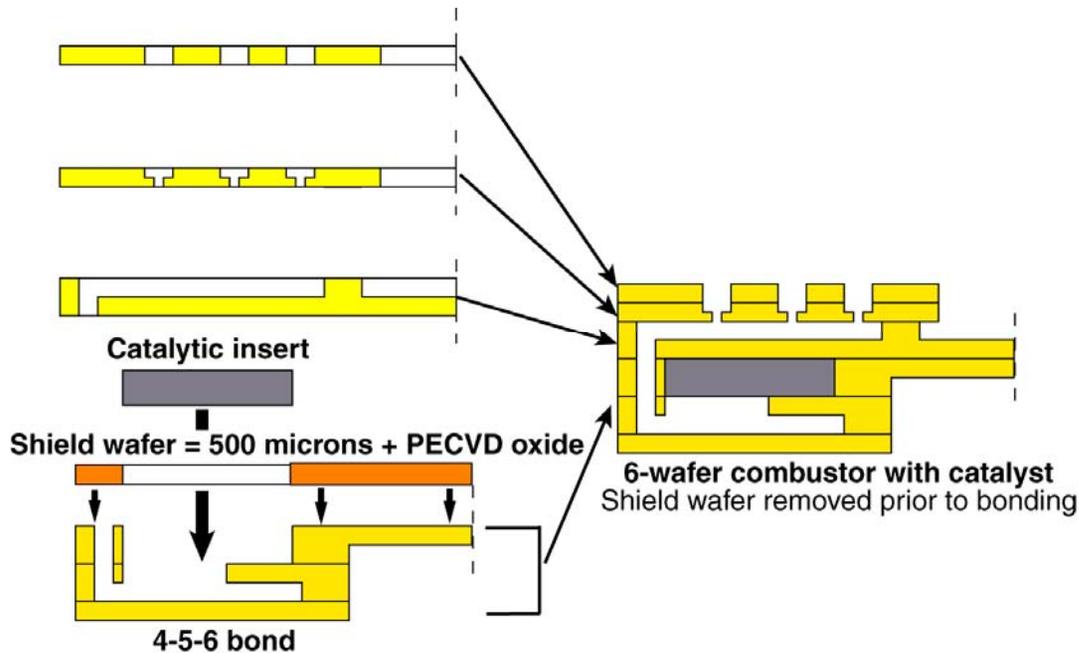
Operation at 1600°K

Courtesy of Amit Mehra and Ian Waitz, et al.
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Numerical Simulation Results

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Catalytic microcombustor



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Combustion with catalyst permits high mass flow rate hydrocarbon combustion but complicates fabrication.

Electric motors and generators

- > **Thoroughly used and understood at the macro scale**
 - **Optimized for macro performance, cost, etc.**
- > **Some different concerns at the microscale guide type of machine chosen**
 - **Materials and process compatibility: for example, reconciling metals or magnetic materials with high T in wafer bonding**
 - **The most convenient structural material (Si) conducts**
 - **The less control required the better, since instrumenting MEMS is difficult**
 - **Change of geometry: for microsystems, easier to put active area on planar surface than on outside of a cylinder**
- > **Potential for Watt-scale outputs**

Magnetic induction machine



Courtesy of Hur Koser, and Jeffrey Lang, et al. Used with permission.

**Conceptually, it's like the motor in your refrigerator.
Uses thick, electroplated structures (copper and magnetic materials).**

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C. Livermore: 6.777J/2.372J Spring 2007, Lecture 22 - 36

Pros and cons of the magnetic machine

> Pros

- Well understood at the macro scale
- High power (multiple Watts) possible
- Large gaps between moving parts minimizes viscous losses

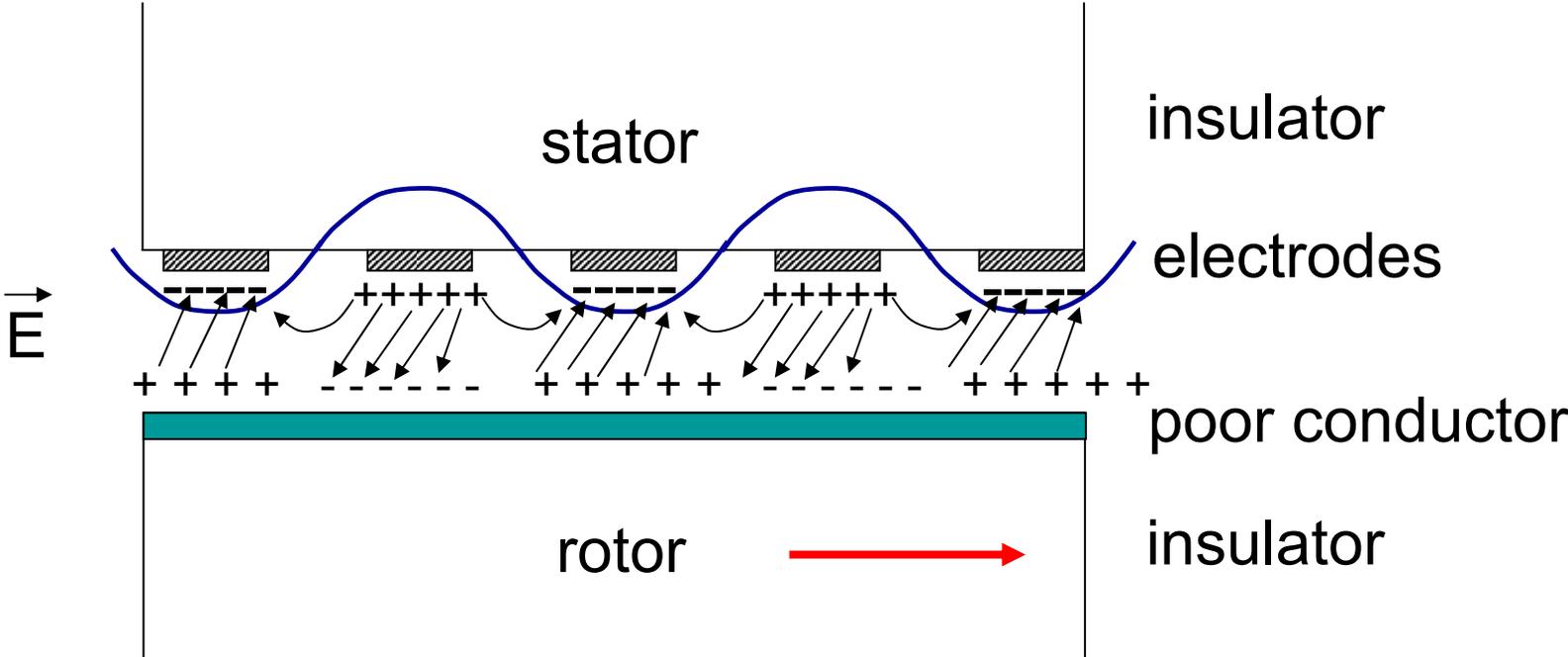
> Cons

- Challenges of microfabrication with magnetic materials
- Magnetic materials heavier and less uniform than silicon: problems with high speed rotation
- Many magnetic materials don't like high temperatures: engine operation? wafer bond anneals?

> Status

- MEMS magnetic generators demonstrated at low speeds, with macroscale bearings: Watts of power produced

Electric induction motor schematic



speed of stator excitation →

speed of rotor film conduction →

rotor speed →

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How to implement the electric induction machine?

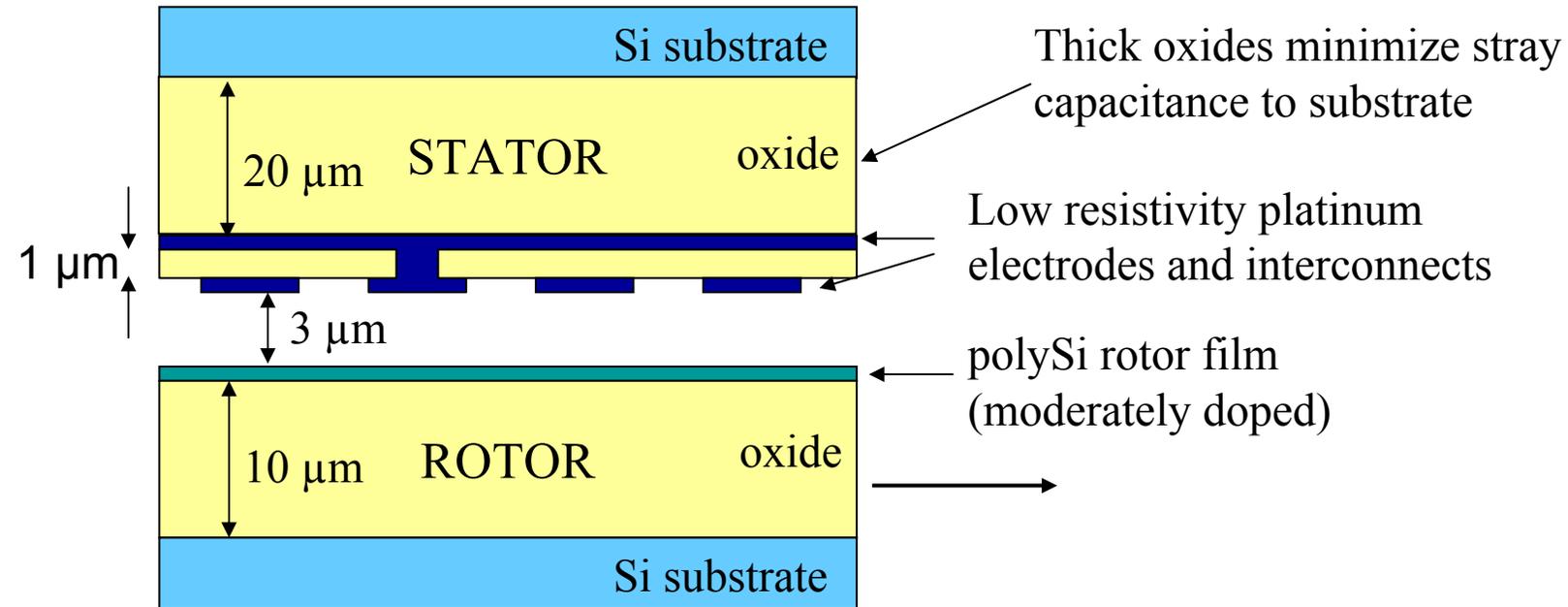
> Requirements

- **Connect electrodes into phases, and connect phases to external leads**
- **Low resistance electrodes and interconnections to minimize power losses**
- **Low stray capacitance to minimize power losses (insulator beneath electrodes and leads)**
- **Bearings that can support high speed rotation (tight tolerances, no leaks!)**
- **Tolerate high temperatures in fabrication and, ultimately, in engine operation**
- **Final structure must be wafer-bondable**

> Contradictions

- **Metals have low resistivity but don't like high temperatures**
- **Need silicon micromachining to make good bearings, but silicon conducts and contributes to stray capacitance problem**

A more realistic picture of the motor/generator



Device diameter = 4.0 mm

786 electrodes grouped in 6 phases

Electrode voltage = 300 V peak

Electrical frequency = 1.5 MHz

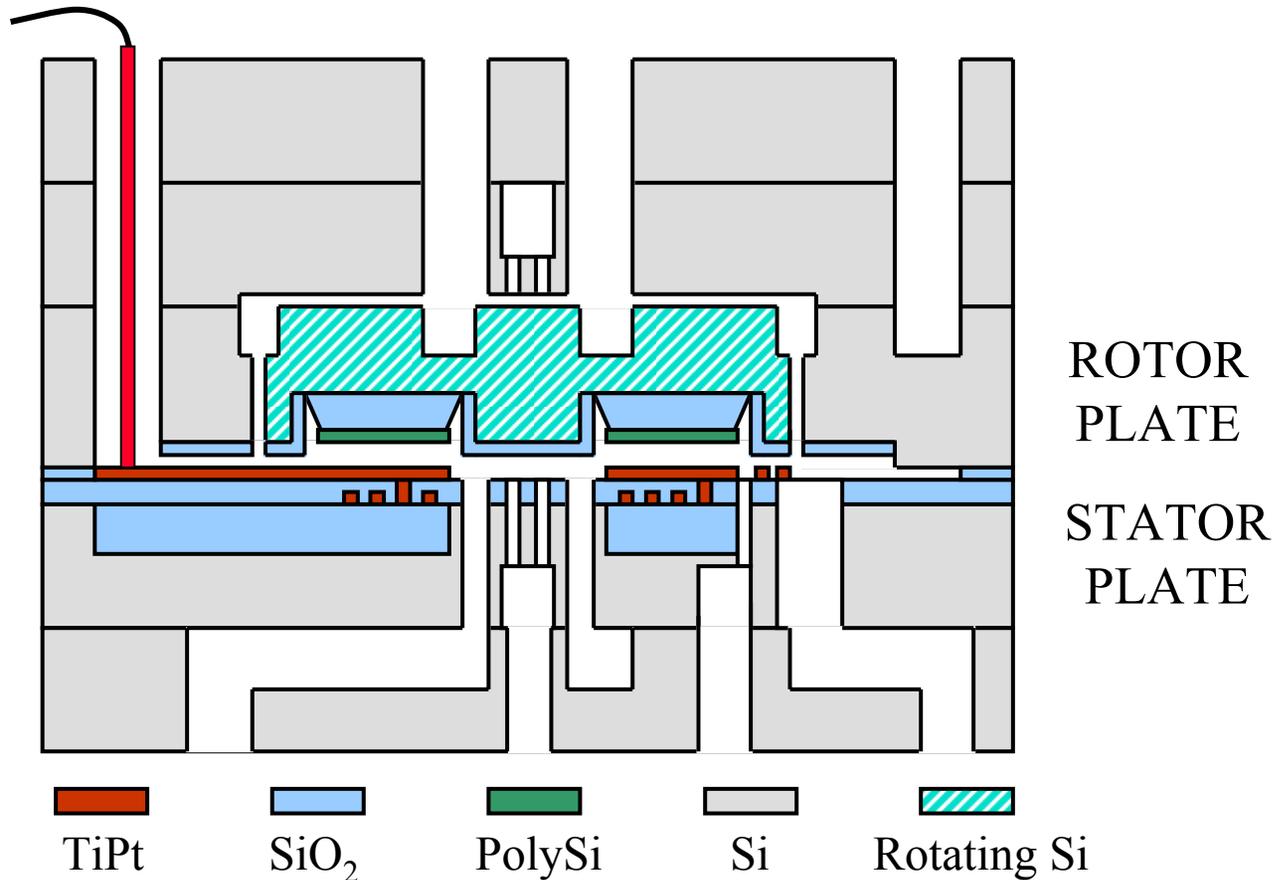
Mechanical frequency = 1 Mrpm

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Major challenge: wafer bonding

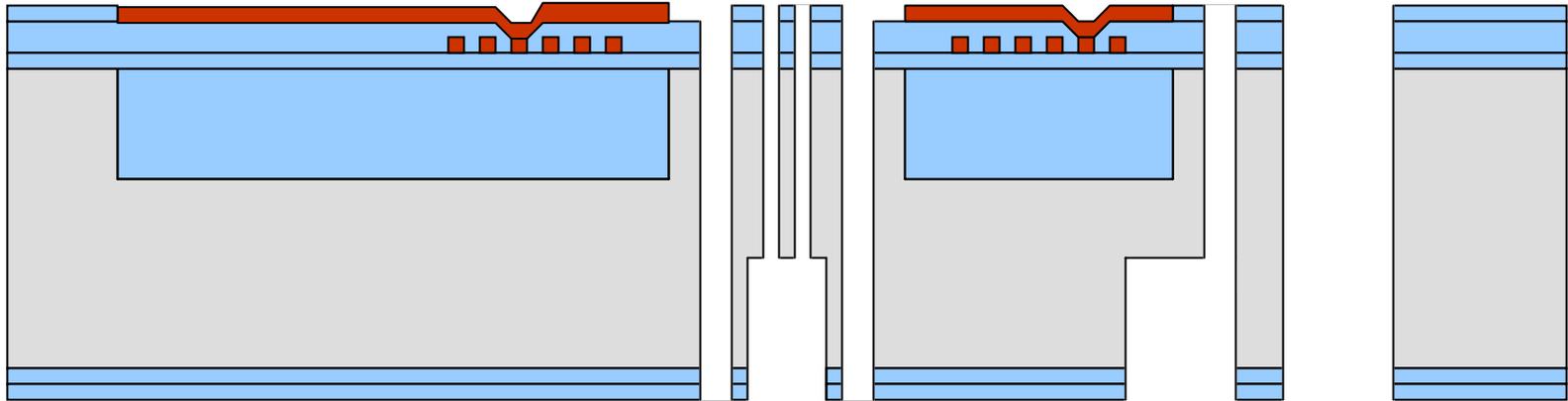
- > **Thick oxides minimize capacitance to substrate, but they create wafer bow that complicates or prevents wafer bonding**
- > **Wafer bonding works best with pristine silicon surfaces**
 - **Preferred: coat surfaces to protect during processing, then uncover at the very end**
 - **This case: need to wafer bond surfaces that are covered with thin films (film roughness, build up of dirt?)**
 - **Approach: polishing**
- > **Metal electrodes and leads**
 - **Typical bond anneal temperature > 1000 C**
 - **Thin films of platinum agglomerate by about 800 C**
 - **Compromise: 700 C for 21 hours**
 - **Also, wafers need to be clean in order to bond, but metals (Ti) etch in typical cleaning chemistries**
 - **Compromise between cleanliness and preservation of features: nanostrip to remove organics instead of RCA or piranha**

Motor/generator schematic cross-section



300 V, 1.5 MHz excitation

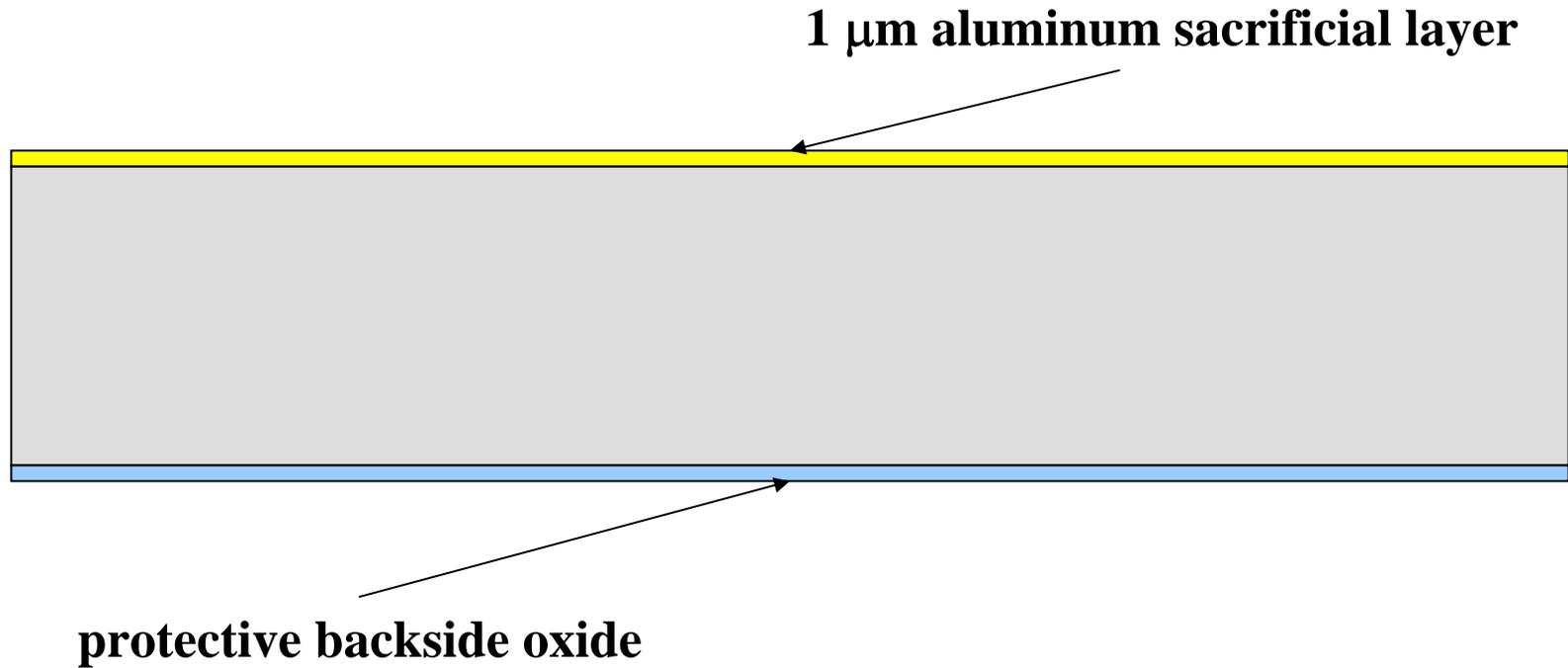
Stator



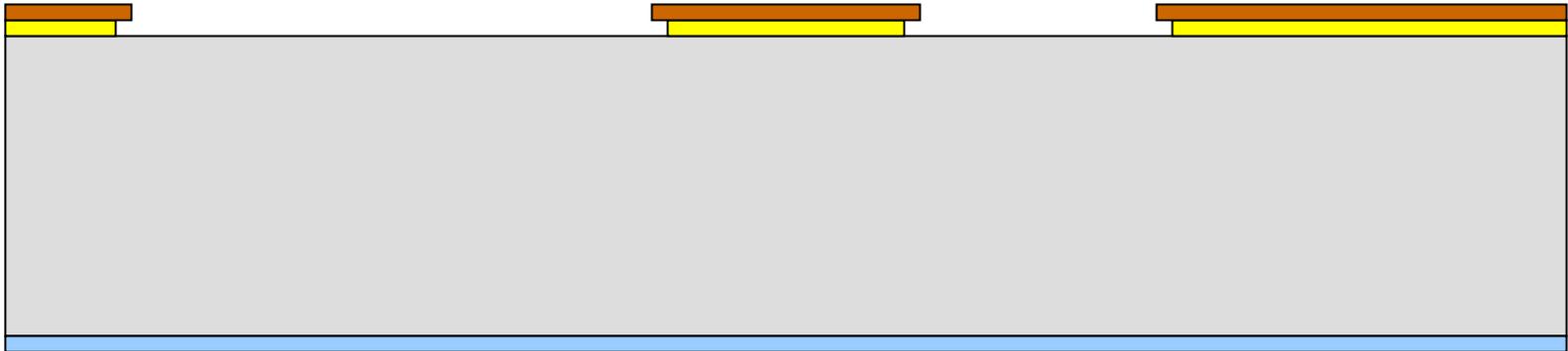
Parts the stator:

Electrodes and interconnections are 0.3 μm thick platinum, deposited over an adhesion layer of titanium. Thick oxide (20 μm thick) minimizes capacitance between electrodes and substrate.

Stator

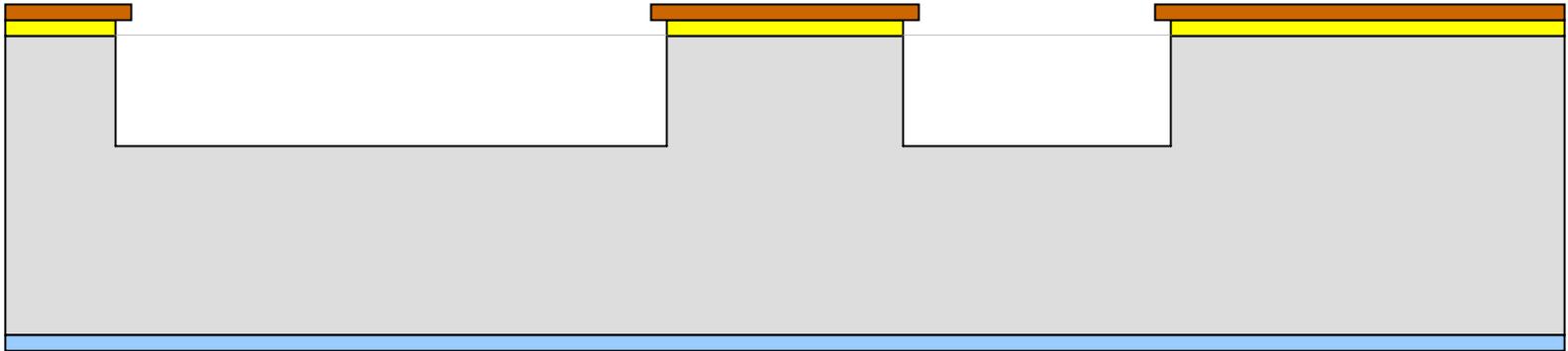


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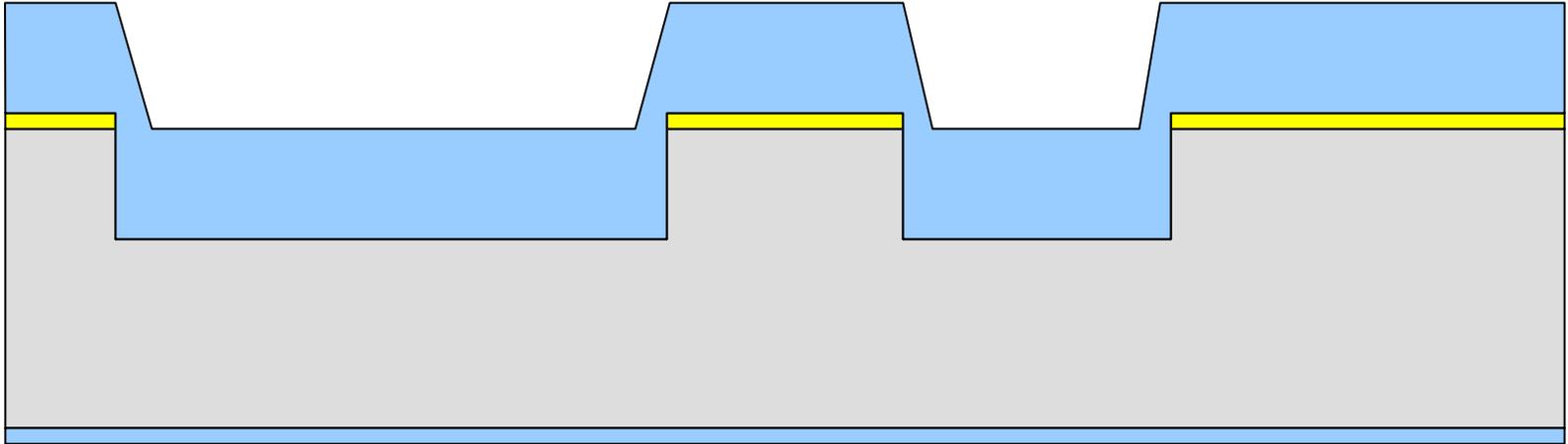
**Remove aluminum where pits will be.
Leave resist mask.**

Stator



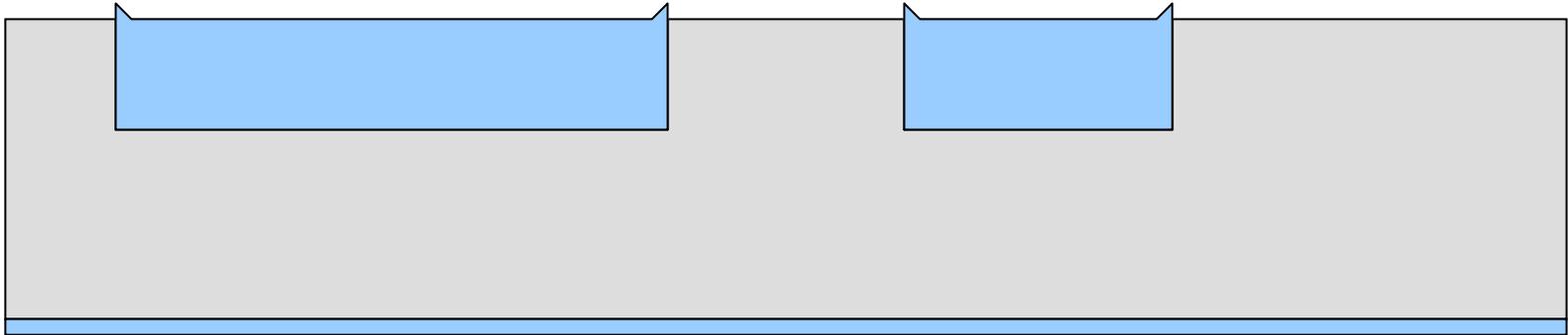
Etch 20 μm deep pits in substrate.

Stator



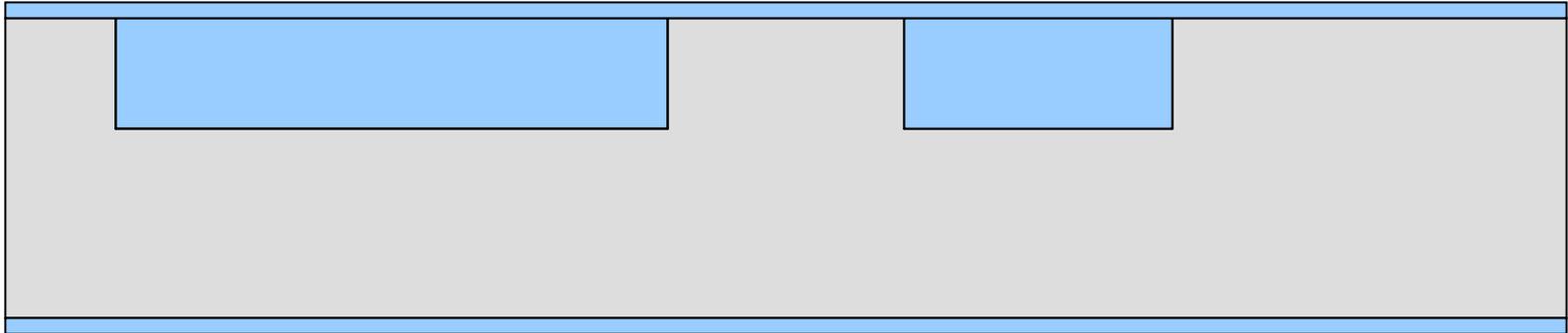
Fill pits with 20 μm PECVD TEOS oxide.

Stator



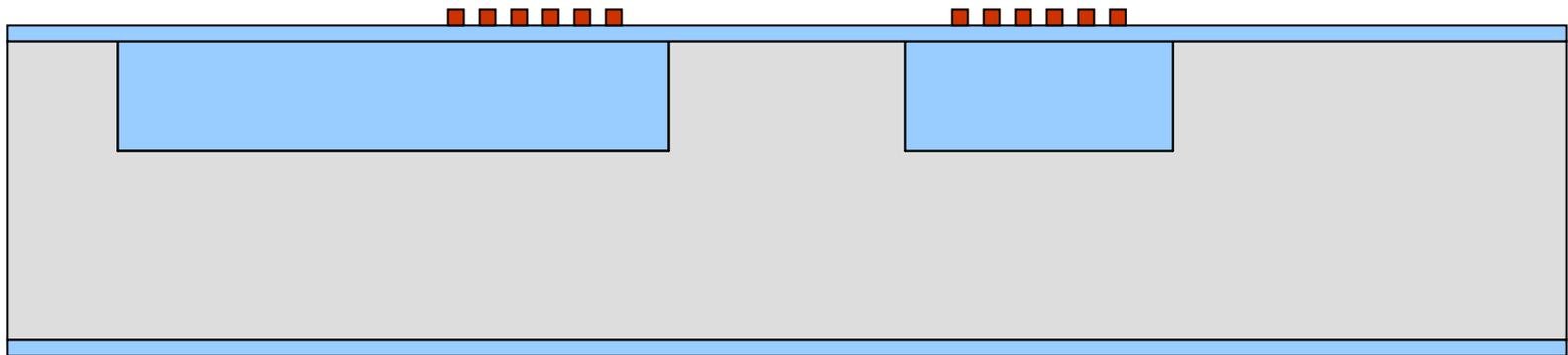
Lift off field oxide by etching Al (HCl for a week).

Stator



Remove spikes: deposit thin oxide and CMP.

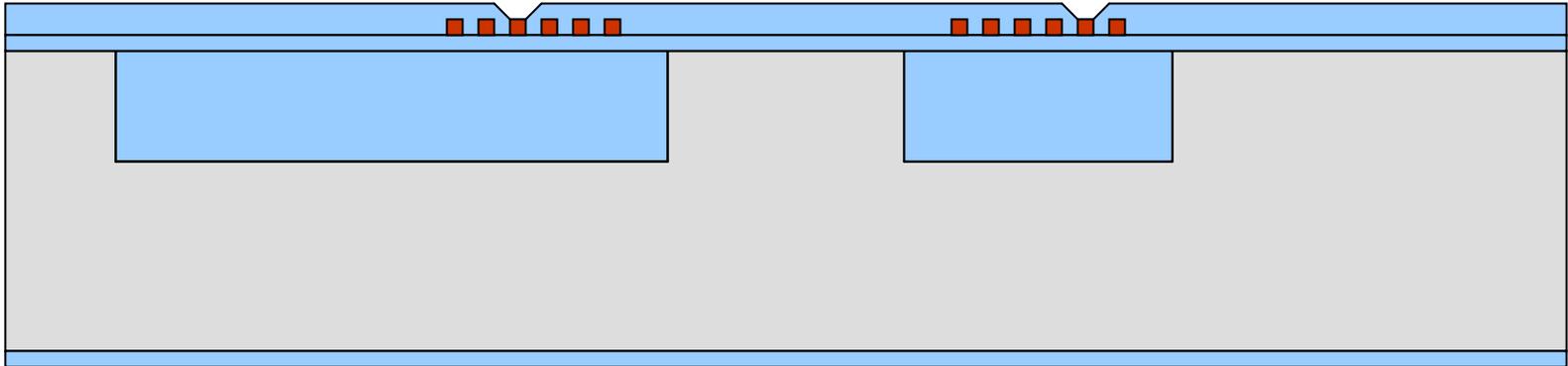
Stator



Deposit interconnect rings (Pt on Ti) with an image reversal liftoff process.

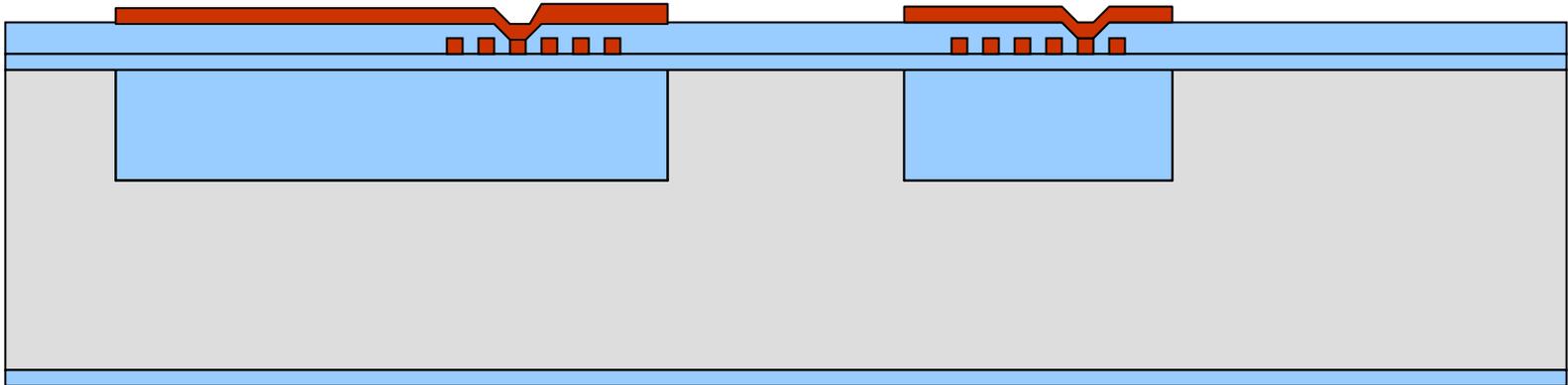
Rings will group stator electrodes into six phases.

Stator



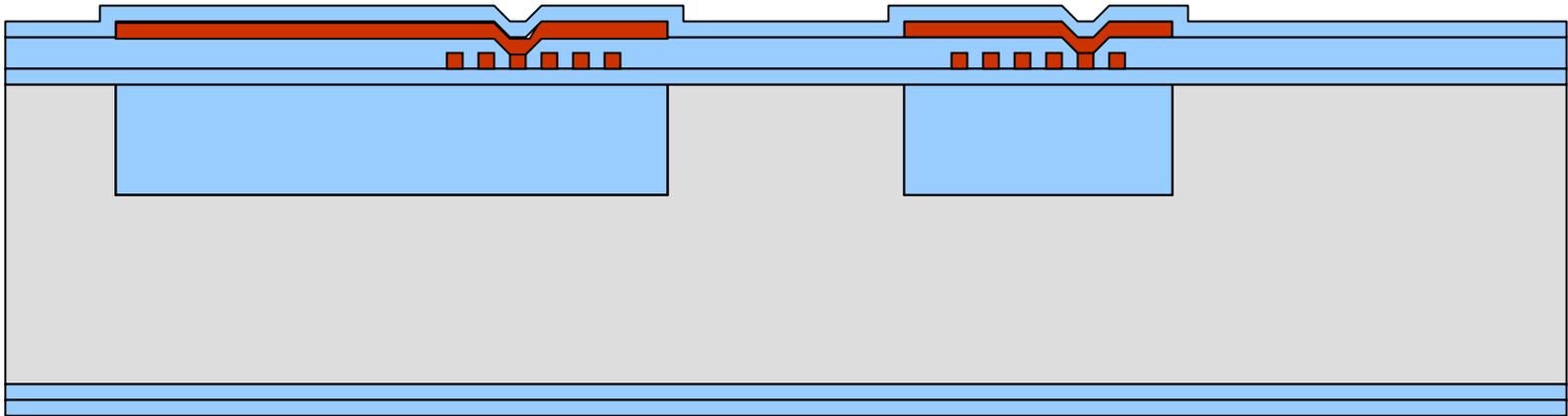
**Deposit interlayer dielectric (PECVD TEOS oxide).
Etch via contact holes.**

Stator



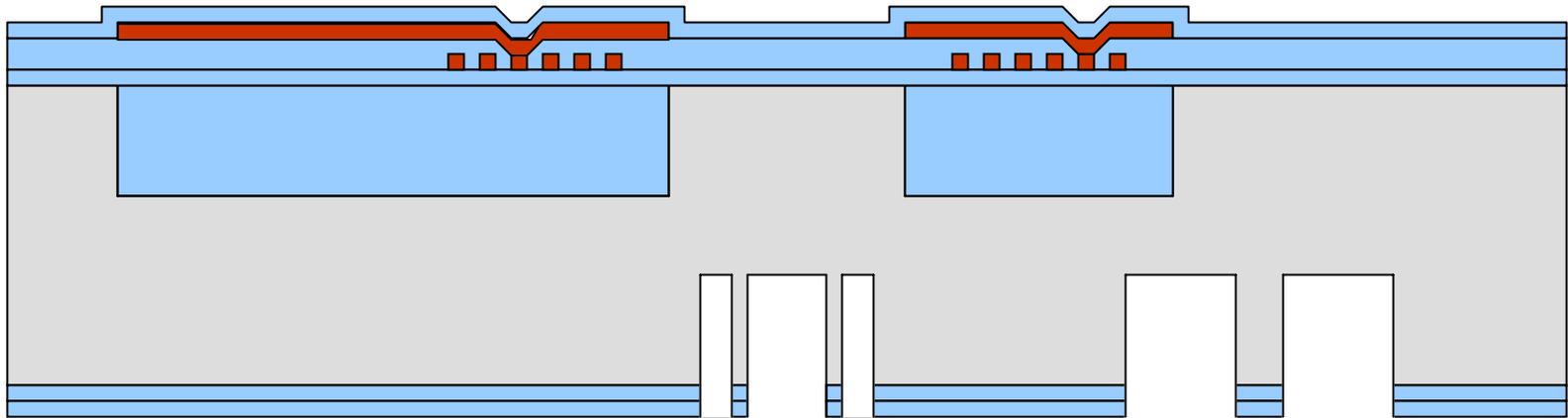
Deposit electrodes (Pt on Ti) with an image reversal liftoff process.

Stator



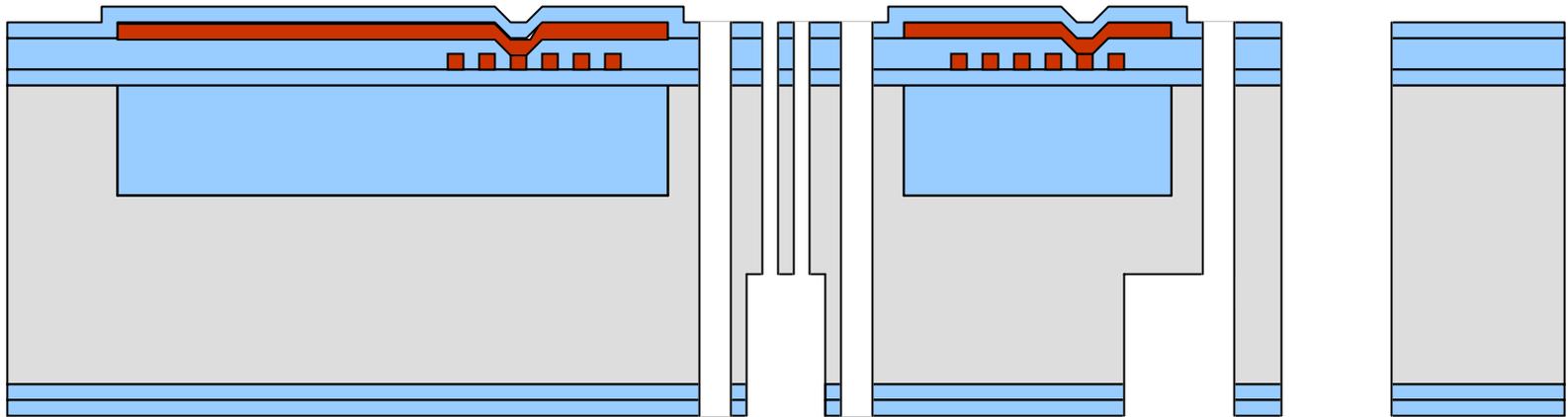
**Deposit PECVD TEOS bonding oxide on both sides.
CMP oxide until surface is bondable.
Anneal to outgas hydrogen from PECVD oxide! (Otherwise, gas
bubbles will split wafers apart during bonding.)**

Stator



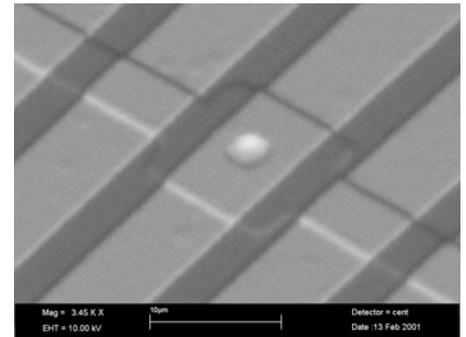
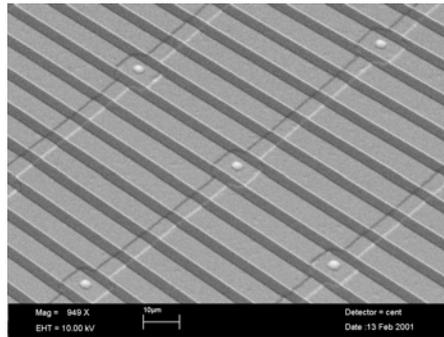
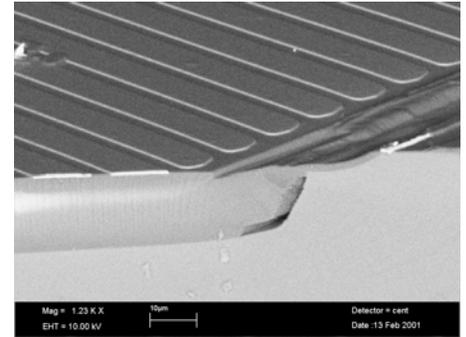
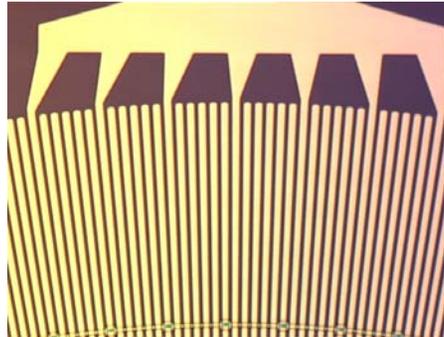
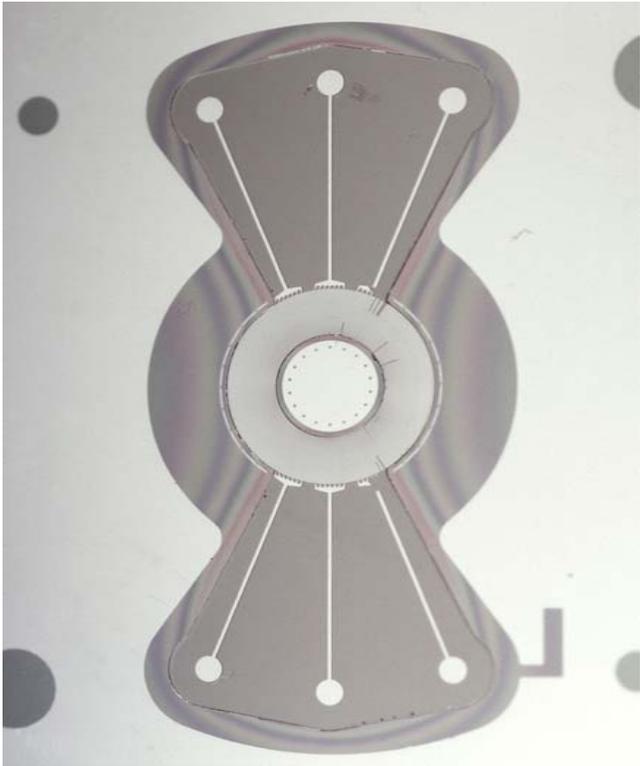
Etch plena: 575 um deep.

Stator



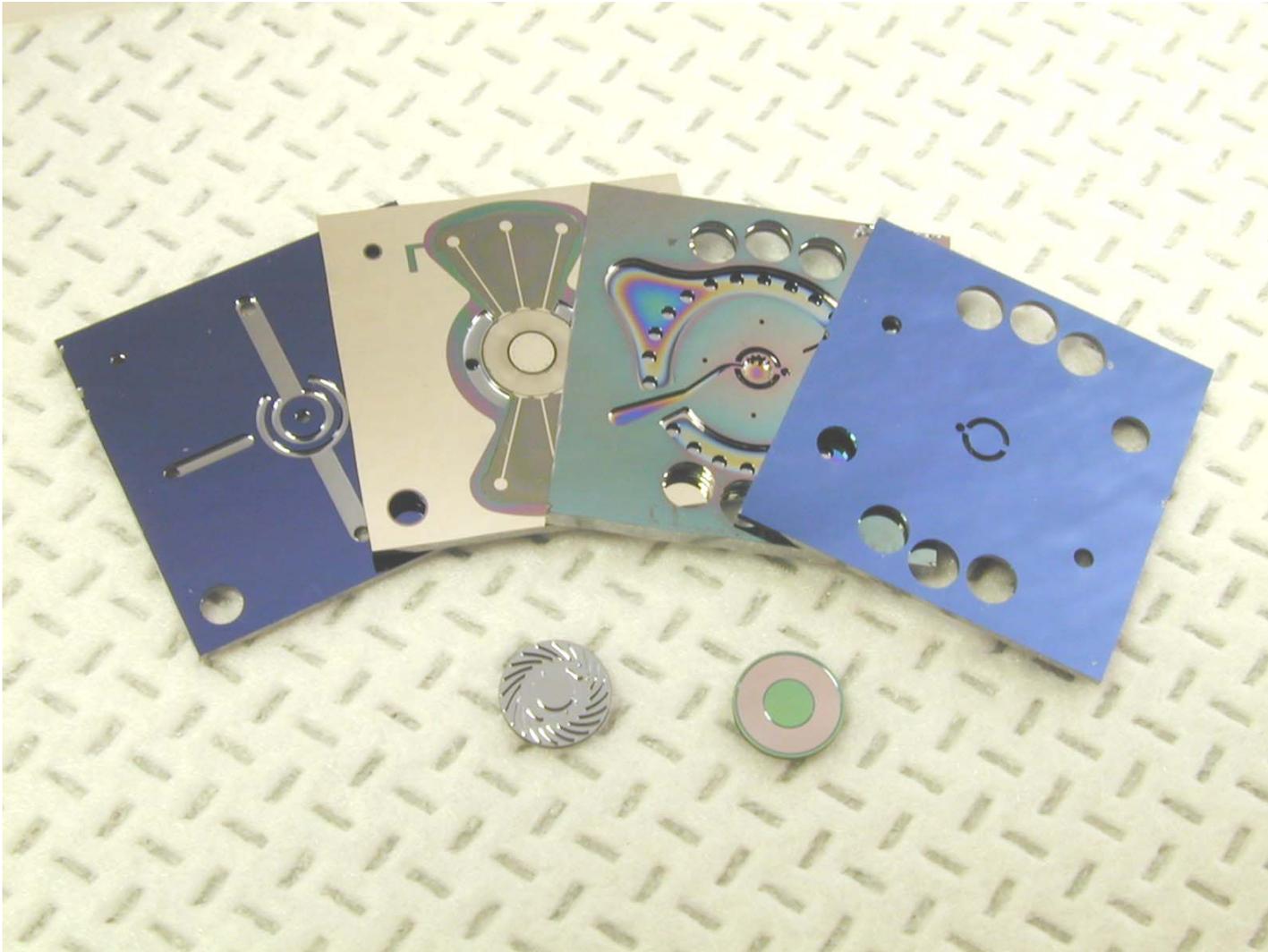
Etch nozzles: 100 um deep.

Electric stator



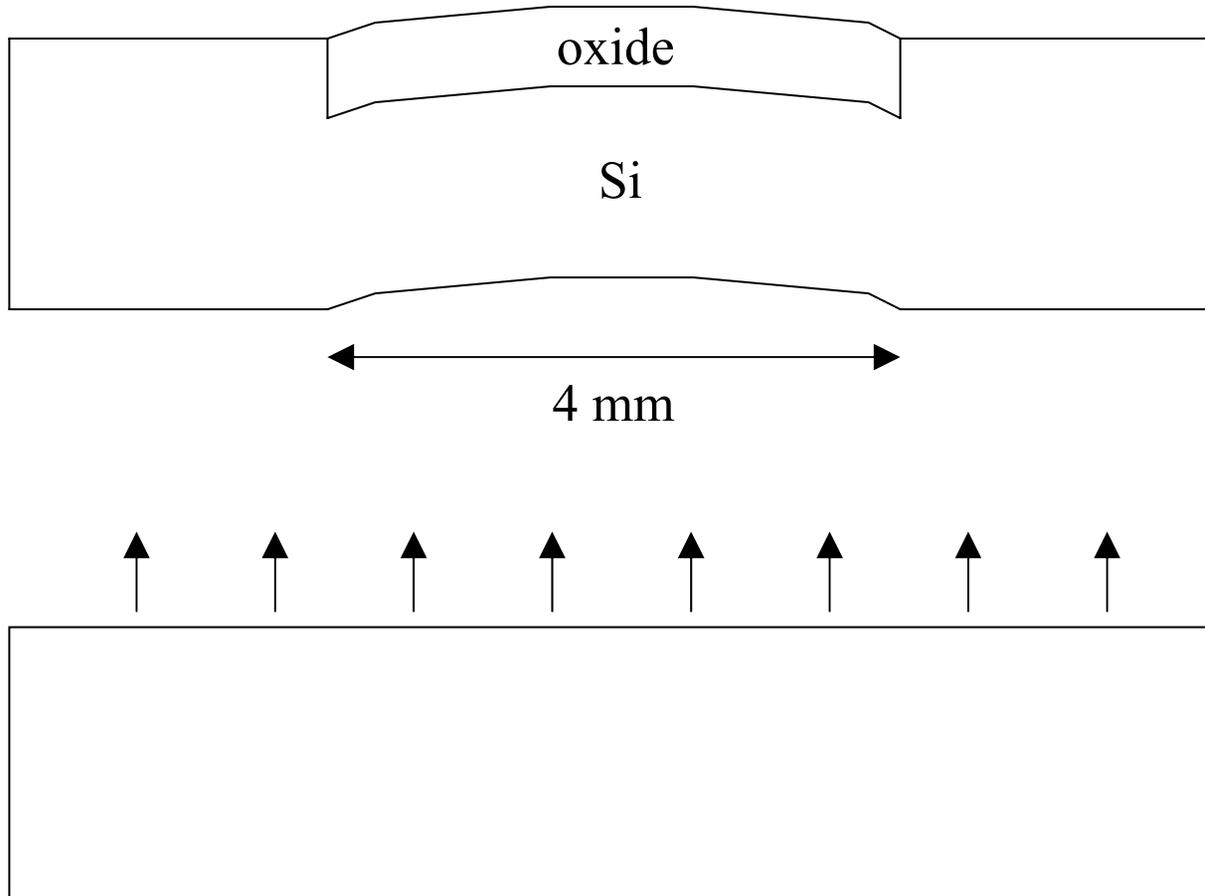
Stator withstands electrode-to-electrode voltages of $300 V_{ac}$ across $4 \mu m$ gaps – defect free lithography and smooth features.

Wafer levels: motor/generator



Cite as: Carol Livermore, course materials for 6.777J / 2.372J Design and Fabrication of Microelectromechanical Devices, Spring 2007. MIT OpenCourseWare (<http://ocw.mit.edu/>), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

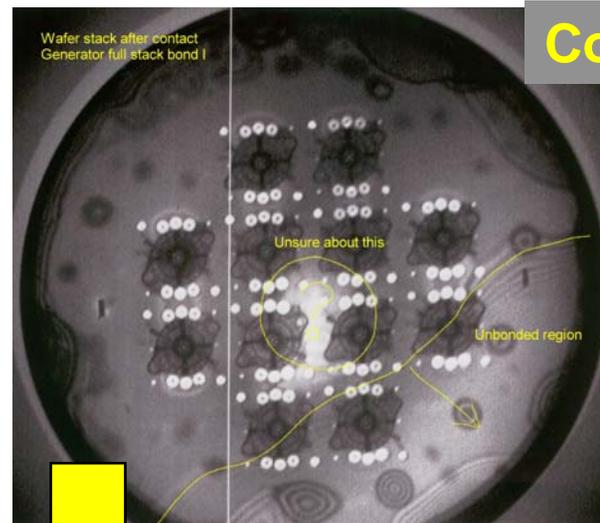
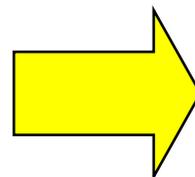
Bonding in the presence of local bow



On some “bubbles” it bonds; in others, it doesn’t.

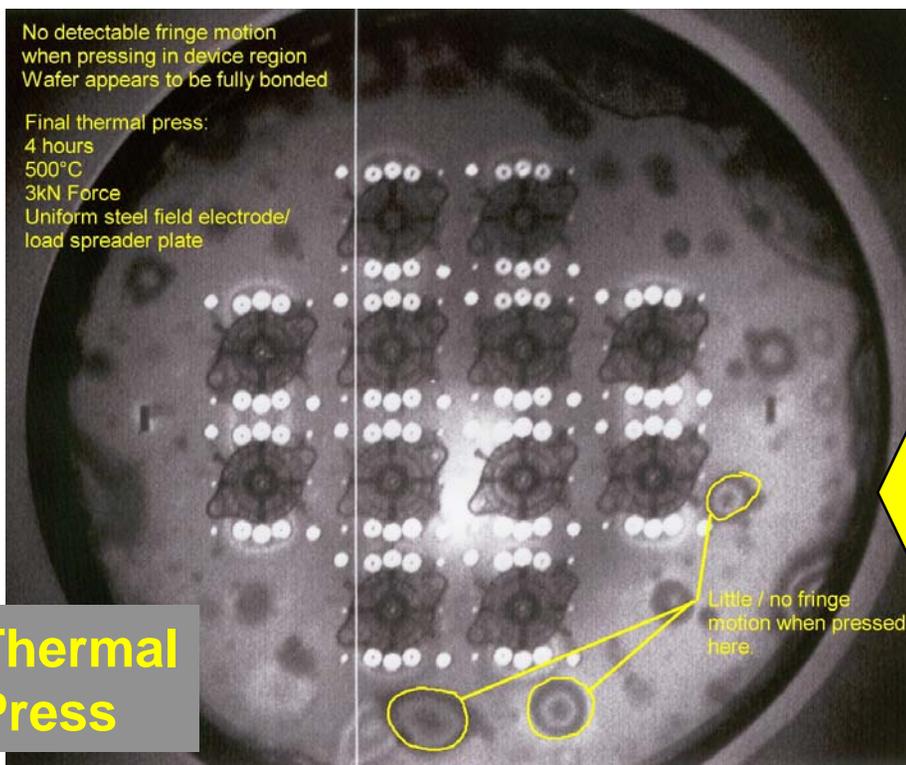
Generator Fabrication: Stack assembly

- After contact: ~ **5/12** die yield
- After long press: ~ **7/12** die yield
- After thermal press, 4h, 500C, 3kN, uniform steel field electrode: **12/12** die bonded



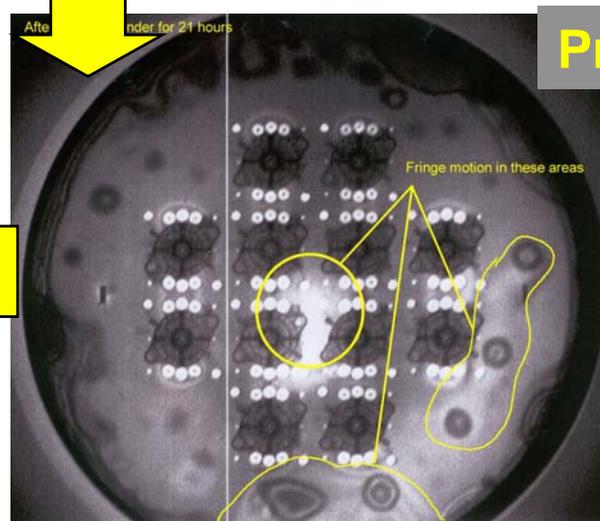
Contact

Courtesy Of Lodewyk Steyn, et al. Used with permission.



Thermal Press

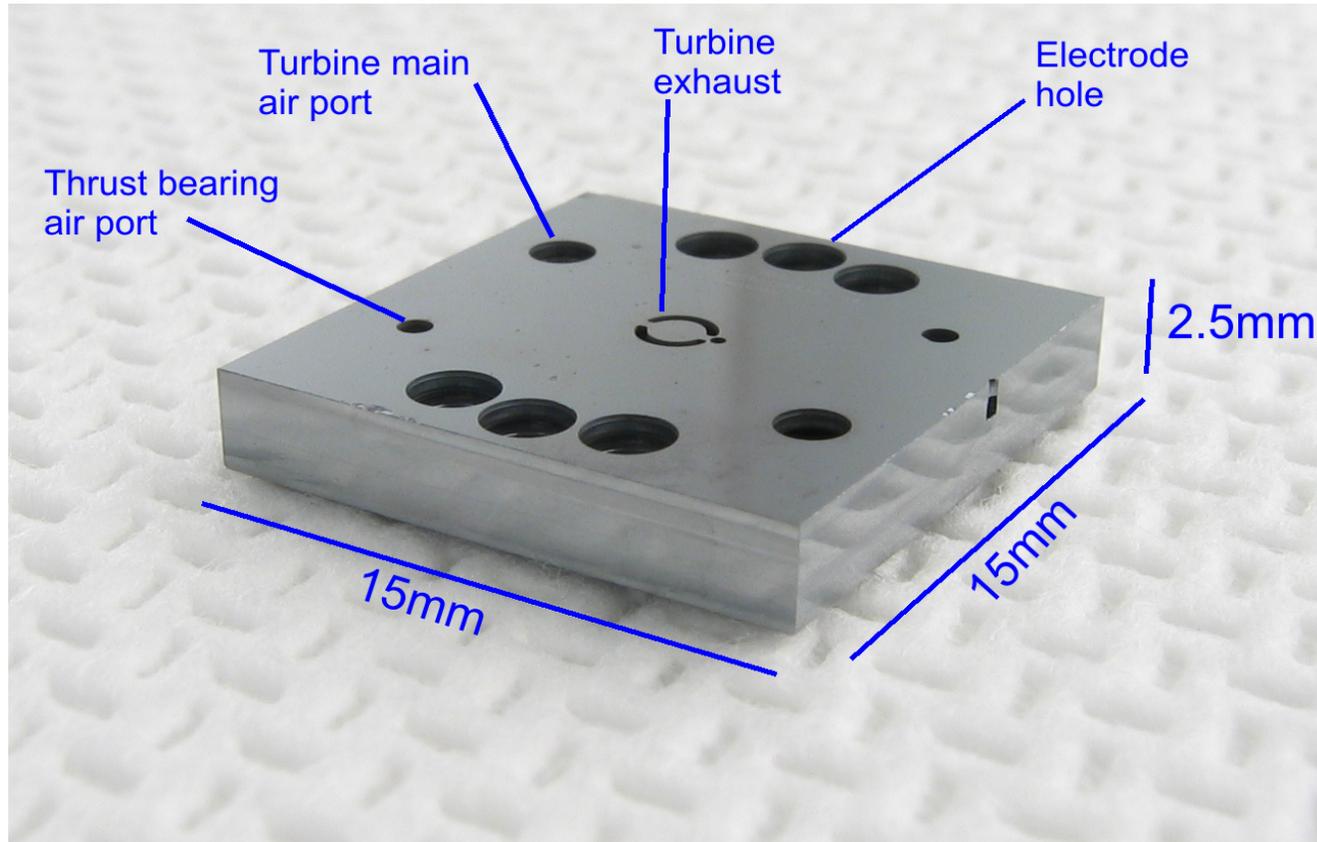
Courtesy of Lodewyk Steyn, et al. Used with permission.



Press

Courtesy Of Lodewyk Steyn, et al. Used with permission.

Bonded generator die



Courtesy of Lodewyk Steyn, et al. Used with permission.

The payoff for all of this care

- > **The motors and generators work**
- > **Generators spin at up to 850,000 rpm and source net power to a load (Lodewyk Steyn's Ph.D. thesis)**
- > **Why this was possible:**
 - **Careful design, including all strays both inside device and out and taking into account what is fabricatable**
 - **Careful fabrication: meeting multiple hard-to-achieve specs at once**
 - **Careful models and test**

Putting it all together

- > **Microengine successes: careful design and detail-oriented, consistent fabrication process development can meet exacting specifications, and work.**
- > **Challenge: attrition! Maybe you can achieve ten miracles, but what is your yield at achieving them all at the same time?**
- > **Which approaches will be commercially successful?**
 - **Alternatives to batteries are desperately needed**
 - **Solutions must meet the requirements adequately and offer an advantage: size, convenience, cost?**
 - **Consider everything: all of the system components (“balance of plant”, external electronics, any necessary fuels, etc.) when making comparisons**