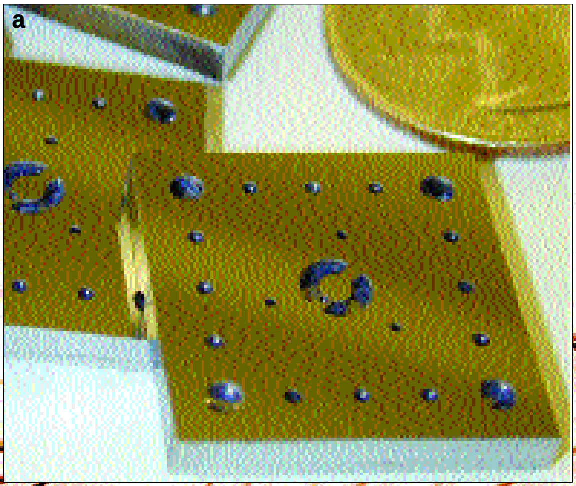
by Carol Livermore

Here Come the Microengines



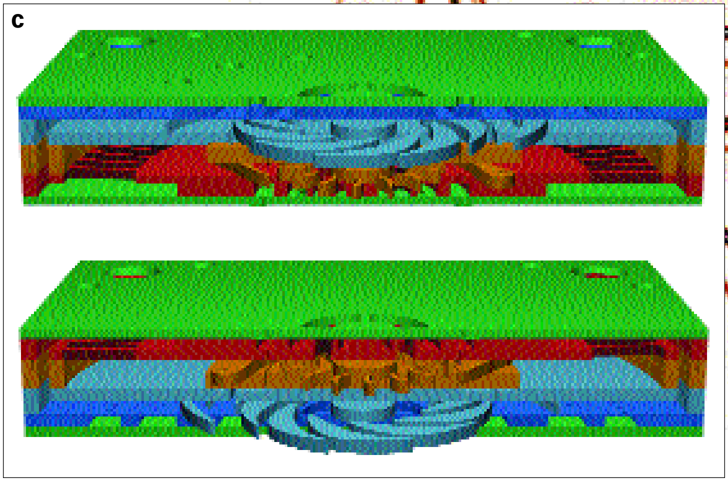
Ravi Khanna

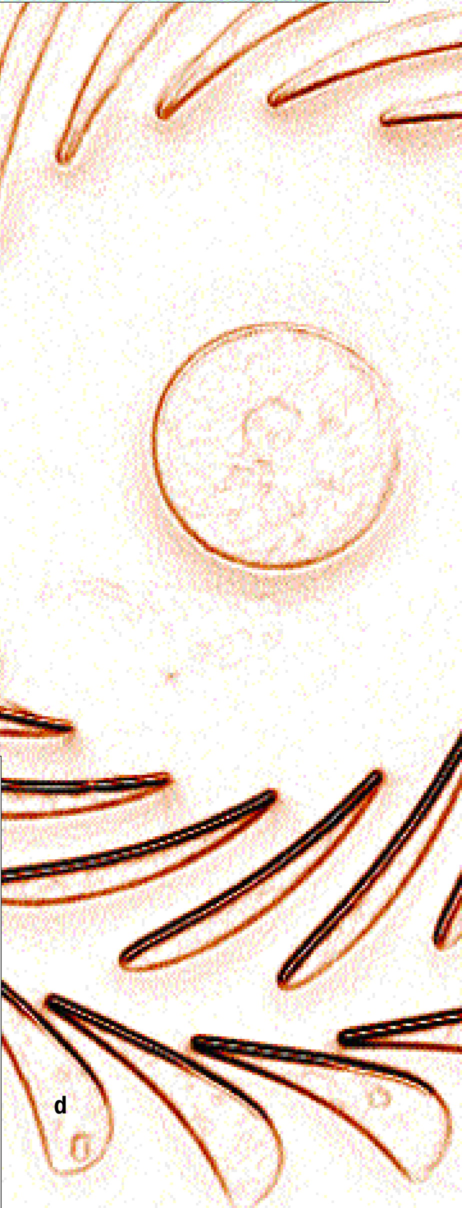
Anyone who has used a laptop computer can appreciate lightweight, long-lasting, portable power sources. We usually look to batteries for our portable power applications because they are effective and readily available. Unfortunately, batteries also store relatively little energy for their weight. Now, imagine that you could harness the greater energy stored in a hydrocarbon fuel, which can have nearly 100 times the energy density of today's best batteries, to run your portable electronics longer or free you from carrying excess weight.

A team at the Massachusetts Institute of Technology (MIT) is developing an alternative portable power source to do just that—a micro gas-turbine engine built on silicon chips (Figure 1). First proposed by MIT professors Alan Epstein and Stephen Senturia in the mid-1990s, a hydrogen-fueled microengine has the potential to output about 10 W of electrical power or 10 g of thrust. A system engineered to burn hydrocarbons could offer several times as much power as one using hydrogen. Measuring just 2 cm on a side and about 3 mm thick, the microengine contains only one moving part, a rotating disk 8 mm in diameter and about 1 mm thick (Figure 2).

Performance is the primary driver for building a micro gas-turbine engine. It burns an energy-dense fuel, and its compact structure is engineered to harness the released power. A microengine could be used to drive a microelectrical generator and output electrical power. This microgenerator has the potential to outperform the best batteries. Alternatively, the microengine might be configured as a turbojet, producing propulsive thrust to power microairplanes. Another device in the microengine family is a micromotor-driven compressor or blower, which is designed to convert electrical power into a portable source of air pressurization. The compressor could be used for chip cooling, air sampling, or pressurizing compact fuel cells. The MIT microengine project is also developing a microrocket engine for microlaunch vehicles or maintaining satellite orbits.

Technology is the secondary driver behind the microengine. Advances in silicon microfabrication for microelectromechanical systems (MEMS) have made it conceivable





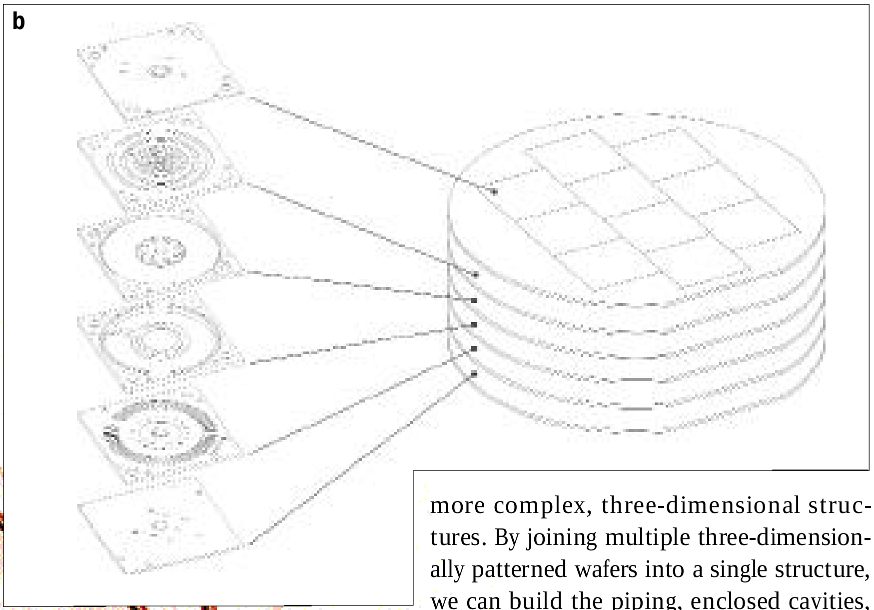
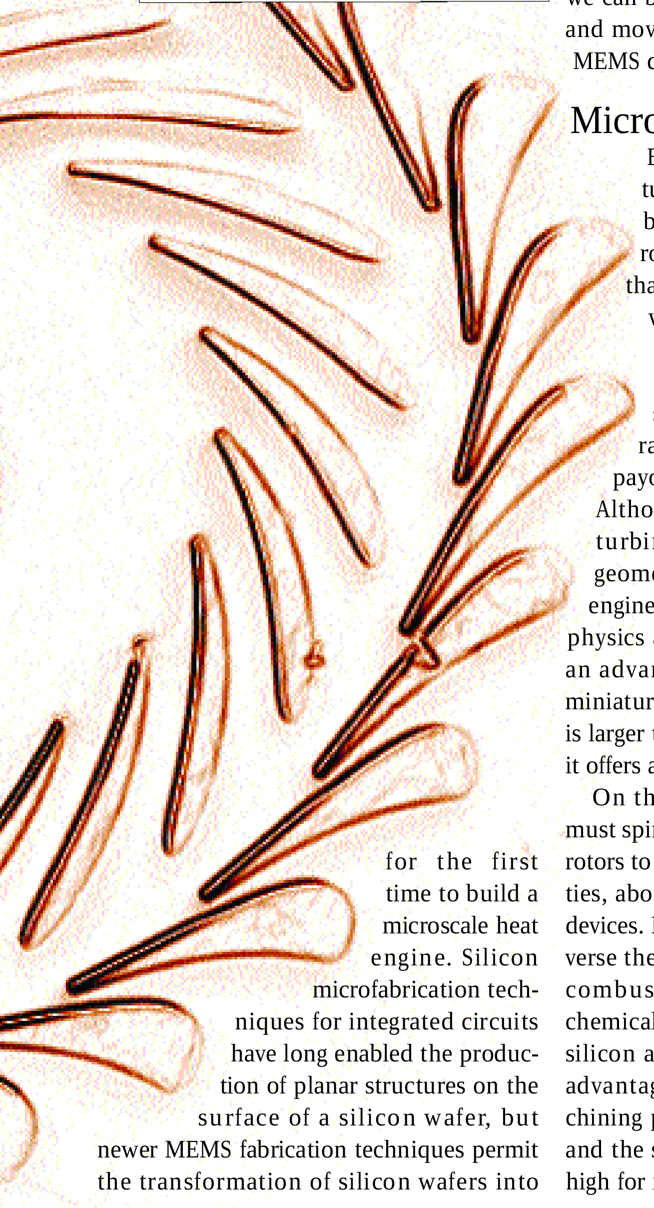


Figure 1. This microengine, measuring 2 cm on a side and 3 mm thick (see quarter in (a) for comparison), is manufactured by stacking six units cut from silicon wafers (b), and it contains only one moving part, the compressor / turbine (d) rotor. The schematic cross-sectional cutaways in (c) show the six stacked wafers distingushed by color, with two views from opposite sides.



for the first time to build a microscale heat engine. Silicon microfabrication techniques for integrated circuits have long enabled the production of planar structures on the surface of a silicon wafer, but newer MEMS fabrication techniques permit the transformation of silicon wafers into more complex, three-dimensional structures. By joining multiple three-dimensionally patterned wafers into a single structure, we can build the piping, enclosed cavities, and movable parts required for a complex MEMS device such as the microengine.

Micro vs macro

Both macro- and microscale gas turbines extract energy from a combustible fuel and use high-speed rotating turbomachinery to transfer that energy between the rotor and the working fluid. This demands speeds at the rotor's outer edge that exceed the speed of sound, high-strength materials, large mass-flow rates, and careful engineering; the payoff is a high power-to-weight ratio. Although the thermodynamics of a gas turbine are independent of scale, the geometry and operations of the microengine are affected by the scaling of both physics and micromachining. This can be an advantage. For example, because the miniature engine's surface-to-volume ratio is larger than that of a macroscale machine, it offers a higher power-to-weight ratio.

On the other hand, microscale rotors must spin at a higher speed than macroscale rotors to achieve the same peripheral velocities, about 1.2 million rpm for the current devices. In addition, fuel and air rapidly traverse the short length of the microengine's combustor, leaving roughly 0.5 ms for chemical reactions to occur. The choice of silicon as a structural material is both an advantage and a disadvantage. Micromachining patterns silicon exceptionally well, and the strength of single-crystal silicon is high for its density because it is lightweight and generally free of flaws. However, silicon is brittle and prone to crack.

The microengine is designed as a turboshaft or turbojet engine, and its structure has two major elements: a static silicon structure and a spinning silicon rotor disk that houses a compressor on the disk's upper face and a turbine on the lower face. Air enters through an inlet port in the static structure and is compressed as it flows through the blades on the spinning rotor disk. The air then mixes with fuel and is routed to a ringlike combustion chamber that wraps around the rotor disk. After the fuel–air mixture burns, the hot gases exit the combustor through the turbine blades, spinning the rotor. The exhaust exits through a nozzle at the back of the static structure.

The microengines are currently fueled with hydrogen; it burns easily and can stay within the thermal limits of the silicon structure. Future engine designs will use high-temperature materials to broaden these thermal limits, which will permit hydrocarbon combustion. Some future engine designs will integrate a generator onto the compressor side of the rotor disk to convert the mechanical power of the spinning rotor into electrical power; other configurations will use the exhaust stream to produce propulsive thrust.

Six-wafer stack

If the microengine's thermodynamic cycle is familiar, its layout is not. This reflects the engine's construction, in which six silicon wafers are etched to form three-dimensional structures and are then bonded together to form the completed devices. The thickness of the engine is set by the thickness of the six silicon wafers, while the

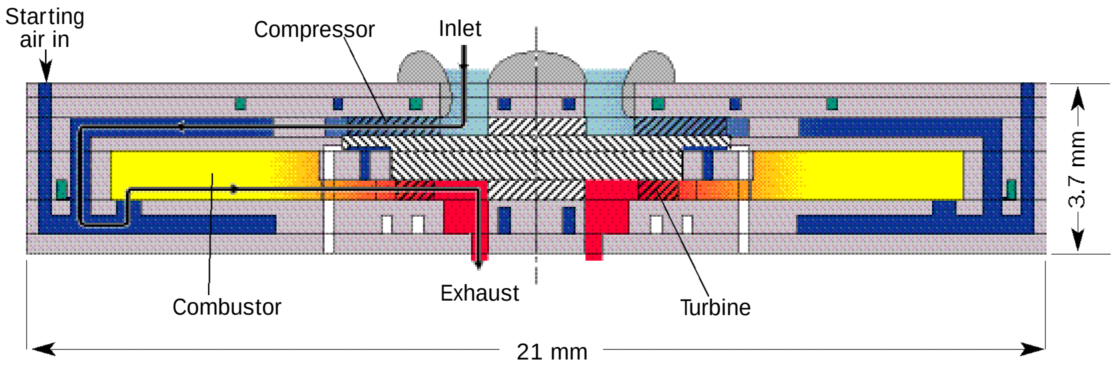


Figure 2. After the microengine is primed with compressed air, fuel and air are fed in, mixed, compressed, and ignited in the combustor to drive the turbine, which is axially conjoined with the compressor.

lateral dimensions are chosen to accommodate the size of the turbomachinery and combustion chamber. The resulting microengine has a squat aspect ratio (height-to-width ratio) that does not resemble a conventional gas-turbine engine. The difference is more than skin deep; space in the microengine is configured differently, which creates new design considerations.

The techniques for patterning each wafer constrain the engine's design even further. Engine structures are defined by transferring planar patterns to the surface of a silicon wafer using conventional photolithography and extending them into the third dimension with deep reactive ion etching (DRIE). One benefit of this approach is that complex in-plane patterns can be readily achieved by adding more features to the lithographic mask. Similarly, multiple engines can be fabricated in parallel by duplicating engine features across the surface of each of the six constituent wafers and assembling them.

One drawback of this approach is the inability to build true three-dimensional structures. The DRIE process simply etches a two-dimensional shape downward, like a straight-walled tower. Turbomachinery would ideally have a carefully optimized three-dimensional shape, and the blades' two-dimensional profile limits their functionality. A second fabrication challenge lies in achieving micrometer-scale precision in deep-etched features that extend over hundreds of micrometers or even millimeters. Achieving vertical complexity is also difficult because it requires the addition of more wafers to the engine's bonded stack.

The MIT microengine team has taken a multipronged approach to bringing the promise of the microengine to reality. First, there is an ongoing effort to optimize and demonstrate the overall microengine system. Complete engines and turbochargers have been fabricated and will continue to be built to reflect the most recent designs. These devices include turbomachinery and combustion systems but do not contain electrical generators. Fabricated devices are under test with the goal of combining high-speed rotation and combustion in a single device.

In parallel with the work on the overall device, the microengine's subsystems have been separated out for individual study and demonstration. The microengine's components have been modeled, and stand-alone test devices fabricated and characterized in the relatively uncomplicated environment outside the engine. The lessons learned with the test devices have helped identify an approach to designing, fabricating, and operating high-power engines.

Bearing development

The development of bearings to enable high-speed rotation at the microscale is an example of the unusual designs and challenging fabrication that go into a successful demonstration of a microengine component. Although microfabricated mechanical bearings have been demonstrated for low-speed rotating MEMS devices, frictional wear makes them inappropriate for any of MIT's high-speed microengines. Gas bearings are sometimes used at the macroscale, but they typically support longer cylindrical rotors at lower rpm's. In the end, microscale gas bearings were designed to supply the microengine with both axial support (thrust bearings) and in-plane rotor support (journal bearings).

The designs go beyond simple extensions of macroscale bearings; the journal bearing in particular must operate in a previously unexplored area of bearing design. Most of the bearings are hydrostatic gas bearings, in which the rotor is supported against a film of externally pressurized air in a narrow gap between the rotating and stationary components. Hydrodynamic bearings, in which the pressurized film is generated by the rotor's motion, have also been tested.

Micromachined bearing-test devices have achieved stable rotation at speeds of more than 1.3 million rpm. Stability is a key requirement for the bearing system. The microbearings must support the rotor from rest to the design speed, and if the rotor's motion becomes unstable, it can crash into its housing, stop spinning, and be damaged or destroyed. The test devices have spun at high speed for hours without loss of stability; operating times have been limited by the experimental setup rather than by physics.

The stand-alone microbearing test devices consist of a 4-mm-diameter rotor disk spun in a static silicon housing by a set of turbine blades on one face of the disk. The design and fabrication of the journal bearing were major obstacles to developing a working set of bearings. As designed, the journal bearing is a long, narrow trench etched between the rotor and its housing. Films of pressurized air are injected into the trench to center the rotor inside the housing. The design calls for longer, narrower bearings to provide as much rotor support and damping as possible, but fabrication capabilities limit the aspect ratio of the straight-walled etched trench, necessitating a shorter, wider design.

This tension between design requirements and the limits of fabrication technology is business as usual for the microengine project, which pushes the limits of understanding on both fronts. With careful design, compromise is possible; the microbearing test device finds a mutually acceptable solution in a 300-µm-long journal bearing about 12 µm in width.

Sustaining combustion

Microscale combustion is a second microengine core technology that has been demonstrated. To sustain combustion in the microengine, the reactants must remain in the combustor long enough to react, and the temperature of the silicon must not exceed its structural limits. Reaction and residence times are affected by the choice of fuel, the fuel-to-air ratio, the size and geometry of the combustion chamber, and the gas-flow rate through the combustor.

Experiments on microfabricated standalone combustion test devices, which mimic the geometry of the microengine, have demonstrated that if the combustor burns hydrogen, the reaction times are short enough to permit sustained combustion at design mass-flow rates. In addition, if the hydrogen fuel is mixed with sufficient air, the temperature remains within the limits of the silicon structures. Both the silicon structure and its external fluid connections survive long exposures to high temperatures well. New combustor designs are being developed to permit combustion of hotter- and slower-burning hydrocarbons.

The micromotor–generator also illustrates the qualitative differences between designing power systems for the macroscale and the microscale. Unlike conventional motors or generators, the microengine's motor–generator is based on electrostatic induction. An electrostatic-induction machine performs mechanical–electrical power conversion by exploiting the interaction between charges on a fixed stator and the charges that they induce on a nearby spinning rotor.

Why use electrostatic induction instead of demonstrated macroscale alternatives, such as magnetic induction? Power densities in electrostatic devices are greater at the microscale than at the macroscale because larger electric fields can be sustained across smaller gaps than across larger ones. Induction machines are attractive because they do not require mechanical contact between the rapidly spinning rotor and the static structures. In addition, the low thermal isolation among microengine components means that the device is too hot for magnetic materials.

Tests of several microfabricated standalone electrostatic-induction motors have demonstrated they work, and the push is on to produce higher-power motors and functioning electrical generators. The motors can spin rotors on their air bearings; motors have also actuated torque metrology devices to obtain an accurate characterization of the electrostatic induction mechanism. Torques of up to 2.0 µN m have been measured.

Six years ago, it was not clear if microengines could be built. The intervening time has seen tremendous growth in our ability to understand, design, and build MEMS devices with useful power-handling capabilities. As more core technologies for the microengine are developed and demonstrated, it seems a matter of time before the microengine becomes a real contributor to the portable-power applications of the future.

For further reading

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BIOGRAPHY

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