MEMS Pressure-sensor Arrays for Passive Underwater Navigation

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MEMS pressure sensors have had broad applications in fields such as mining, medicine, automobiles, and manufacturing. Another application to be explored is in underwater vehicular navigation. Objects within a flow generate pressure variations that characterize the objects’ shape and size. Sensing these pressure variations allows the unique identification and location of obstacles for navigation (Figure 1). This concept is inspired by existing biological systems. Fish have such a sensory lateral line, which they use to monitor all aspects of their hydrodynamic environment, including obstacles [2,5].

We propose to develop low-power sensors that passively measure dynamic and static pressure fields with sufficient resolution to detect objects generating the disturbance. We will also develop processing schemes that use the information from the sensors to identify objects in the flow environment. These sensors and processing software emulate the capabilities of the lateral line in fish. While active acoustic means can be used for object detection, the process is power-intensive, and depends strongly on the acoustic environment. A simpler alternative is to use a passive system that can resolve the pressure signature of obstacles. The system consist of arrays of hundreds or thousands of piezoresistive pressure sensors fabricated on etched silicon and Pyrex wafers [1,3,4,6] with diameters around 1 mm; the sensors are arranged over a flat or curved surface in various configurations, such as a single line, a patch consisting of several parallel lines (Figure 2), or specialized forms to fit the hull shape of a vehicle or its fins. The sensors will be packaged close together at distances of a few millimeters apart in order to resolve pressure and flow features near the array spacing, which in turn can be used to identify the overall features of the flow.

REFERENCES
An Integrated Multiwatt Permanent Magnet Turbine Generator

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There is a need for compact, high-performance power sources that can outperform the energy density of modern batteries for use in portable electronics, autonomous sensors, robotics, and other applications. Previous research efforts on a micro-scale, axial-flux, permanent-magnet turbine generator [1-2] culminated in a spinning rotor test stand that delivered 8 W DC output power through a diode bridge rectifier with an overall generator system efficiency of 26.6%. In these experiments, the generator rotor was mounted via a steel shaft to an air-driven, ball-bearing supported spindle and spun to the desired operational speed.

Current research efforts aim to fully integrate the permanent-magnet (PM) generator design into the silicon micro-turbine engine fabrication process and create devices that can deliver 10 W DC output power when driven by compressed air. The integrated generator will couple energy from the compressed air to the rotor through microfabricated turbine blades attached to the backside of the rotor. One important challenge in this integration process is the structural integrity of the magnetic rotor spinning at a tip speed near 300 m/s, or equivalently 450 krpm.

Based on power requirements, a 300-µm thick circular NdFeB PM with an inner radius of 2.5 mm and an outer radius of 5 mm must be embedded into the silicon rotor on top of a 150 µm FeCoV back iron. FEA analysis shows that the maximum principle stress at 450 krpm in the silicon rotor, 900-µm thick and 12 mm in diameter, with bonded annular PM and back iron pieces, will be approximately 180 MPa through the entire structure. This stress is well below the tensile strength of silicon and FeCoV. However, because the PM is brittle and has a typical tensile strength around 83 MPa, it is unclear whether the material will fracture. Tests are currently underway to characterize the reference strength and Weibull modulus of the PM, and from these results, a working rotor design will be proposed.

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**Figure 1:** Conceptual schematic of the fully integrated surface-wound permanent magnet turbine generator. The bottom two wafers constitute the stator and coil winding of the generator while wafers 3, 4, and 5 form the magnetic rotor. A center-fed journal-bearing design is shown in the schematic, but an axial-fed design is also possible.

**Figure 2:** An FEA simulation for the magnetic rotor structure spinning at 450 krpm. Because of the fully-bonded boundary conditions, most of the load is carried by the silicon hub. The maximum principal stresses in the silicon, PM, and back iron are 176.7 MPa, 188.0 MPa, and 184.5 Mpa, respectively.

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**REFERENCES**


A low contact resistance MEMS-relay featuring highly parallel and planar oblique contacts has been fabricated and is currently being tested. The contacts are etched in silicon using a potassium hydroxide (KOH) solution. An offset between the wafer-top and the wafer-bottom KOH masks produces the oblique contact geometry schematically shown in Figure 1A.

In contrast, many prior art MEMS devices [1-3] have rough, non-complementary contacts. As these surfaces touch, they do so in a small number of high points, as shown in Figure 1B, which significantly reduces the effective contact area and leads to a high contact resistance and a low current carrying capacity. Additionally, vertical contacts are prone to poor metallization, which further affects the device’s contact resistance. Our MEMS-relay, shown in Figure 2, is composed of a compliant mechanism (B), a pair each of engaging (C) and disengaging (D) rolling-point “Zipper” actuators [4-5], and a pair of planar and parallel contacts (E). The relay is fabricated by a combination of deep reactive ion etching (DRIE) and KOH etching. Nested masks are used to pattern both wafer-through etches. Low stress silicon nitride ($\text{Si}_3\text{N}_4$), which will later be used as a KOH mask, is patterned initially on both sides of the device wafer. A silicon oxide film is deposited on the KOH mask. The compliant mechanism and actuators are then etched through DRIE and a second $\text{Si}_3\text{N}_4$ film is deposited. The second $\text{Si}_3\text{N}_4$ film is patterned using a “shadow” (through-etched) wafer as a mask. The oxide is selectively etched to reveal the buried nitride mask. The contacts are etched in KOH solution. Both $\text{Si}_3\text{N}_4$ and oxide films are stripped and a thermal oxide, which insulates both the electrostatic actuators and the relay contacts from the rest of the device, is grown. Gold is evaporated over both sides of the insulated contacts and the device wafer is anodically bonded to a Pyrex handle wafer. Experimental pull-in and drop-out voltages of 70 V and 40 V, respectively, agree with the model. Contact travel of 50 µm prevents arcing as the load circuit is switched on and off. A contact resistance of 50 mΩ was demonstrated by our group using an externally actuated structure as a proof of concept for the contact design [4]. Our group continues to develop these MEMS relays for power applications.

![Figure 1](image1.png)  ▲ Figure 1: Schematic cross section of oblique planar parallel contacts (A), schematic cross section of prior art (B).

![Figure 2](image2.png)  ▲ Figure 2: Device as fabricated (A), SEM contact cross section A-A of oblique contacts as shown in Figure 2A (B). The die saw causes the rough edge of the static contact in (B).

REFERENCES