DESIGN, FABRICATION AND TESTING OF THE P³ MICRO HEAT ENGINE

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ABSTRACT

The development and testing of a micro heat engine is presented. The P³ micro heat engine is an external combustion engine, in which thermal power is converted to mechanical power through the use of a novel thermodynamic cycle that approaches the ideal vapor Carnot cycle. Mechanical power is converted into electrical power through the use of a thin-film piezoelectric membrane generator. This design is well suited to photolithography-based batch fabrication methods, and is unlike any conventionally manufactured macro-scale engine.

INTRODUCTION

There is a pressing need for high energy density micro power generation systems. The energy densities of existing electrochemical batteries are too low (around 1 kJ/g) to sustain the power needs of MEMS devices for long periods [1]. An attractive alternative to batteries are hydrocarbon fuels, currently the most successful means yet developed to transport and store energy compactly. A typical liquid hydrocarbon fuel holds around 50 kJ/g in its chemical bonds [2]. However, the development of a micro-scale device that can efficiently convert this chemical energy into useful electrical power is challenging. Among the micro-scale concepts to generate electrical power using the chemical energy of hydrocarbon fuels now being explored are fuel cells, static heat engines and dynamic heat engines.

On the macro-scale, dynamic heat engines have achieved greater success than either fuel cells or static heat engines. This success is in large part because dynamic heat engines are more fuel flexible than fuel cells and have achieved higher conversion efficiencies than static heat engines. For these reasons, a variety of designs for micro-scale dynamic heat engines have been advanced. These include a gas turbine (Brayton cycle) engine[3,4], a micro rotary internal combustion (Otto cycle) engine[5] and a micro heat engine based combustion driven reciprocating liquid piston (Otto/Diesel cycle)[6]. Each of these dynamic heat engines are internal combustion engines.

Work at WSU has been directed toward the development of a MEMS power system based on a dynamic heat engine that is driven by an external heat source, the P³ micro heat engine [7]. Since micro-manufacturing methods excel at producing many identical copies of two-dimensional structures, the engine design is a modular, two-dimensional architecture. The P³ micro engine produces electrical power by employing a three-part strategy. First, thermal power is conducted into the P³ engine from an external heat source. Second, thermal power is converted to mechanical power through the expansion and compression of a two-phase working fluid by the oscillation of a flexible membrane. Third, mechanical power is converted into electrical power through the use of a thin-film piezoelectric generator.

DESIGN

The design of the P³ micro heat engine is based on a two-dimensional modular architecture. An individual module or unit-cell engine consists of a cavity filled with a saturated, two-phase working fluid, and bounded on the top and bottom by thin membranes. The top membrane of the cavity is a thin film piezoelectric membrane generator.

Heat is alternately conducted in and out of the two-phase working fluid, through the thin membranes capping the cavity at top and bottom. As heat is conducted first into and then out of the working fluid, the quality and volume of the saturated mixture first increases and then decreases. As a consequence, the upper membrane, which is fabricated of a piezoelectric thin film, acts like a piston in a conventional large-scale engine. Instead of sliding in and out, however, the piezoelectric thin film membrane flexes in and out. In this way, the piezoelectric membrane acts alternately as a generator/expander and as an actuator/compressor during the engine cycle. The useful output of a unit cell engine is the electrical power generated by the piezoelectric membrane as it is strained during expansion of the two-phase working fluid, minus the power consumed by the membrane during the compression of the working fluid.

The working cycle of the micro heat engine may be approximated with four ideal processes: (1) compression, (2) isothermal, isobaric high temperature heat addition, (3) expansion and (4) isothermal, isobaric low temperature heat rejection. The capability to expand and compress a saturated two-phase working fluid enables the engine's thermodynamic cycle to approach the ideal Carnot vapor cycle [8].

A power supply can be constructed of a single unit-cell engine or an array of many unit cell engines combined together. This modularity gives great flexibility in the assembling of energy conversion devices. Combined in parallel, the unit cell engines would be driven by the same temperature difference. Combined in series, the unit cell engines would form a cascade so that each unit cell engine would be driven by a fraction of the total temperature difference across the entire cascade.

FABRICATION

A prototype unit-cell heat engine is fabricated of three components: a silicon membrane with thin-film piezoelectric generator, a middle spacer in which the engine cavities are defined, and a silicon membrane with resistance heater. Figure 1 shows a cross-section. A two-phase mixture of the working fluid, Fluorinert, fills the engine cavities. The piezoelectric material used in the thin-film membrane generator is lead zirconate titanate or PZT.

The generator and heater membrane wafers are fabricated from (100) Silicon wafers. First an oxide layer is grown through a dry thermal process. Photolithography is used to define the square

membrane geometries on the back side of the wafers. An anisotropic wet etch in EDP creates square pyramidal cavities in the (100) silicon wafer. Membranes are created in the generator and heater wafers, with membrane thickness controlled with a Boron-doped etch stop. Membranes with thickness from 2.0 to 0.5 microns and side lengths from 2000 to 4000 microns have been fabricated.

The engine cavity is defined through the use of a spacer between the generator and heater wafers. Presently that spacer is fabricated out of semiconductor tape. The diameter of the engine cavity is determined by the size of the hole cut in the tape. The cavity depth is determined by stacking up multiple layers of tape. Since the tape is ~90 microns thick, nominal cavity depths of 90 and 180 microns are used.

The wafer containing the heater membranes is completed, by fabricating gold resistance heaters on the front side of the membranes. In the prototype engine, these heaters are used as a controllable heat source to run the engine. The heaters take the form of a ring with a radius equal to the engine's vapor bubble radius. To fabricate the resistance heaters, gold is sputtered on the wafer, and the ring heater geometry is defined by photolithography.

Thin-film piezoelectric membrane generators are fabricated on the front side of the membranes on the generator wafer. First, a common bottom electrode is formed by sputtering 20 nm of titanium followed by 200 nm of platinum. The wafer is then spin coated with PZT solution in a sol-gel process [9]. Presently, final PZT thin film thickness can be tailored from 0.25 to 2.0 microns. Top electrodes are formed by sputtering 200 nm of gold on top of the PZT thin film. Electrode pads are defined by photolithography. Figure 2 shows a top view of a membrane generator.

The engine is assembled, by sealing a two-phase working fluid into a cavity formed by a semiconductor tape spacer between the heater and generator membranes. The cavity is filled with liquid working fluid from a syringe, and the membrane generator is then aligned face down on the spacer and centered above the resistance heater. A vapor bubble is nucleated in the engine cavity by applying an electric current to the heater. Once the vapor bubble is in place, the assembled engine is clamped together to seal in the two-phase working fluid. Figure 3 shows a top view of a back-lit engine after assembly. The vapor bubble and ring heater are clearly visible in the photograph.

MEMBRANE GENERATOR TESTING

Dynamic testing of membrane generators is performed with a bulge tester designed to generate a cyclic pressure wave to excite the membrane. An interferometer is used to measure membrane deflection. Interferograms of the membrane generators are captured at any position in the membrane oscillation during dynamic testing with a timing circuit that controls the laser pulse and camera shutter [10].

Results of the dynamic testing of a 2.5 micron thick, 1.45 mm square membrane generator are given in Fig 4. In the figure, the bulge tester applies a sinusoidal pressure wave, oscillating between 0 and 13.8 kPa, at the resonant frequency of the membrane, 1300 Hz. This excitation causes the membrane generator to deflect between - 8 microns and +16 microns, and produces an open circuit voltage of 60 mV (peak-to-peak).

Increases in generator output over that seen in Fig. 4 have been achieved by improvements in membrane generator design

Figure 1. Cross-section of P^3 unit cell engine.

Figure 2. Top view of a membrane generator.

Figure 3. Top view of a back-lit engine.

and fabrication [11]. Figure 5 shows a plot of open circuit voltage versus membrane deflection, as produced by a second-generation membrane generator (2.5 mm thick, 2.5 mm square). This improved membrane generator has a resonant frequency of 482 Hz and produces 1.6 V at a deflection of just under 60 microns.

The power produced by a membrane generator can be determined by dissipating the electrical output of a membrane generator through a known resistance. Figure 6 shows power versus load resistance curves acquired at different operating frequencies for a second-generation membrane generator. The maximum power produced by the membrane generator increases by nearly two orders of magnitude from 1 microwatt to nearly 50 microwatts as the driving frequency rises from 100 Hz to 482 Hz (the membrane generator's resonant frequency).

HEAT ENGINE TESTING

Dynamic testing of the micro heat engine is performed by electrically pulsing the engine's resistance heater to periodically heat the two-phase working fluid. A square wave with duty cycle between 1 and 25% is used to power the resistance heater. The engine cycle speed is determined by the frequency of this square-wave heating function. Membrane deflection is measured using the holographic interferometer described in the previous section. Typical results from dynamic tests of the micro heat engine are shown in Figs. 7, 8 and 9.

In Fig. 7 measured membrane deflections are plotted versus time for a micro engine driven at 100 Hz. The generator membrane is seen to deflect between 4 and 12 microns.

Open circuit voltages produced by an engine running at five cycle speeds between 100 and 200 Hz are shown in Fig. 8. In the figure, voltage is plotted against the energy dissipated as heat in the resistance heater during each cycle. Voltages between 10 and 60 millivolts are produced when the engine is driven with heat pulses between 1 and 16 millijoules.

The electrical power produced by the engine can be determined by dissipating the electrical output of the membrane generator through a known resistance. Figure 9 shows power produced versus load resistance for an engine running at 100 Hz. Maximum power produced is 0.6 microwatts. Recall from Fig. 8, that this power is similar in magnitude to the maximum power produced by the membrane generator driven by the bulge tester at 100 Hz. In that figure, the power produced by the membrane generator increased nearly two orders of magnitude as the cycle speed of the membrane generator increased from 100 Hz to its resonant frequency. A similar increase in power production is expected as the cycle speed of the micro engine is increased from 100 Hz to its resonant frequency. For this reason, current efforts are focused on increasing the cycle speed of the micro engine.

CONCLUSIONS

The development of a micro heat engine, has been described. The design, fabrication and testing of the engine and its membrane generator have been discussed. Membrane generators have been shown to be capable of producing open circuit voltages of over 1.5 Volts and a peak power of nearly 50 milliwatts. Prototype micro engines have been run at cycle speeds of 100 to 200 Hz, with membrane deflections on the order of 10 microns. The micro

engines produce an open circuit voltage of 60 millivolts and a peak power of 0.6 milliwatts. Running the micro engines at

Figure 4. Pressure, deflection and PZT membrane generator output voltage versus driver phase angle.

Figure 5. PZT membrane generator output voltage versus membrane deflection.

Figure 6. PZT membrane generator power versus load resistance at driving frequencies of 100, 200, 300 and 482 Hz.

their resonant frequency is expected to significantly increase their output.

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Figure 7. Membrane deflection versus time for a micro engine cycling at 100 Hz.

Figure 9. Membrane generator power versus load resistance for a micro engine cycling at 100 Hz.

Figure 8. Membrane generator output voltage versus energy into engine per cycle.