COMBUSTION TESTS IN THE 6-WAFER STATIC STRUCTURE OF A MICRO GAS TURBINE ENGINE

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ABSTRACT

As part of a program to develop button-sized micro heat engines, we present the design, fabrication and initial testing of the first engine static structure micromachined from silicon. Comprising the non-rotating components of a micro gas turbine engine, the device measures 2.1 cm $\times$ 2.1 cm $\times$ 0.38 cm, and is aligned-fusion bonded from 6 silicon wafers. Fabricated through the use of Deep Reactive Ion Etching (DRIE), the structure required anisotropic dry etching through a total thickness of 3,800 μm. Complete with a set of fuel plenums, pressure ports, fuel injectors and compressor and turbine static airfoils, the device is the first demonstration of the hot flow path of a multi-level micro gas turbine engine. The 0.195 cm^3 combustion chamber has been shown to sustain stable hydrogen-air combustion with exit gas temperatures up to 1725K. Combined with high temperature testing that showed no visible degradation after 6 hours of operation, these results establish the viability of using microfabricated silicon structures for an emerging class of high power density micro heat engine applications.

INTRODUCTION

Recent advances in the field of silicon microfabrication technology have led to the realization of miniature combustion systems for applications in chemical process development [1]&[2], energy transfer [3]-[5], and portable power generation [6]. Measuring of the order of a few cubic centimeters in volume, such systems are characterized by their large power densities and surface area-to-volume ratios that make them particularly appealing for applications requiring enhanced heat transfer or high energy per unit volume. In particular, Epstein *et al.* have recently reported their applications for portable power generation and micro air vehicle propulsion [7]. A Brayton-cycle based microengine would be part of a new generation of centimeter-scale power-MEMS (Microelectromechanical Systems) that would contain all the functional components of a large-scale gas turbine engine, yet be about one millionth of its volume. Combined with the benefits of the cube-square law and the higher strength-to-density of silicon[1], the power density of a microengine could be made to exceed that of a conventional large-scale engine [8], thereby allowing it to provide over 10 times the power density of the best batteries available today.

As part of the MIT microengine program, Epstein *et al.* [7] and Groshenry [9] have completed the preliminary design feasibility study for a device capable of producing 10-50 Watts of electrical power while consuming 7 grams of jet fuel per hour. The detailed design and operation of the device is presented in Ref. [7]. Since such a microengine will require a high temperature combustion chamber to convert the chemical energy of a fuel into fluid thermal energy, it is necessary to develop viable combustion strategies that are compatible with the overall fabrication and system constraints of the engine. The design challenges for a hydrogen combustor for this engine have been presented by Waitz *et al.* [10], along with a demonstration of premixed hydrogen-air combustor in a 0.13 cm^3 macrofabricated steel combustor. Stable hydrogen combustion in a microfabricated silicon combustor was first demonstrated by Mehra and Waitz [11], who showed that it was possible to attain exit gas temperatures in excess of 1800K without compromising the structural integrity of the 0.066 cm^3 combustion chamber. The heating rates obtained by the silicon microcombustor were sufficient to obtain positive work output from the microengine thermodynamic cycle, and suggested that the performance of a silicon microcombustor would be satisfactory for heat engine applications. Consequently, efforts were undertaken to integrate the silicon combustor with the rest of the engine.

This paper reports the results of those integration efforts by presenting the design, fabrication and operation of a hydrogen combustor in its final engine configuration. The static structure reported in this paper is intended to complement a rotating microturbine test rig [12], and comprises all the non-rotating functional components of the microengine. Since it is consistent with the structural and thermal constraints of the final geometry, it is the first demonstration of the hot flow path of a 6-wafer multi-level microengine. Designed on the basis of a multi-disciplinary approach that accounted for all the aerodynamic, chemical, mechanical and materials fabrication aspects of the engine, this device is fully compatible with the fabrication sequence and geometrical constraints of a completed engine. It contains static turbomachinery airfoils and a combustor recirculation jacket that allows the compressor discharge air to cool the outer walls of the hot chamber, and also has internal plumbing and diagnostic ports for external igniters and sensors.

It should be noted that although the static structure contains the main functional components of a conventional gas turbine engine, it is by no means a scaled-down version of a large-scale engine. In fact, since the physics influencing the design of the components changes with scale, much of the component design and optimization is quite different from that in conventional engines. This places these micro-scale devices in a unique operating space and mandates new design considerations that are specifically based on the system trade-offs of this new regime. We therefore begin with a brief overview of the primary design challenges that arise from the unique functional requirements and constraints of a microcombustion environment.

OVERVIEW OF MICROCOMBUSTION

Since microengines are targeted for portable power generation and micropropulsion applications, the power density of the energy conversion unit is a primary figure of merit. Because these low-volume microengines are able to transfer the

[1] Since the power output of an engine scales with mass flow, and hence the area, and the weight scales with volume, the power density of a device linearly increases as its size is reduced (component efficiencies being equal).

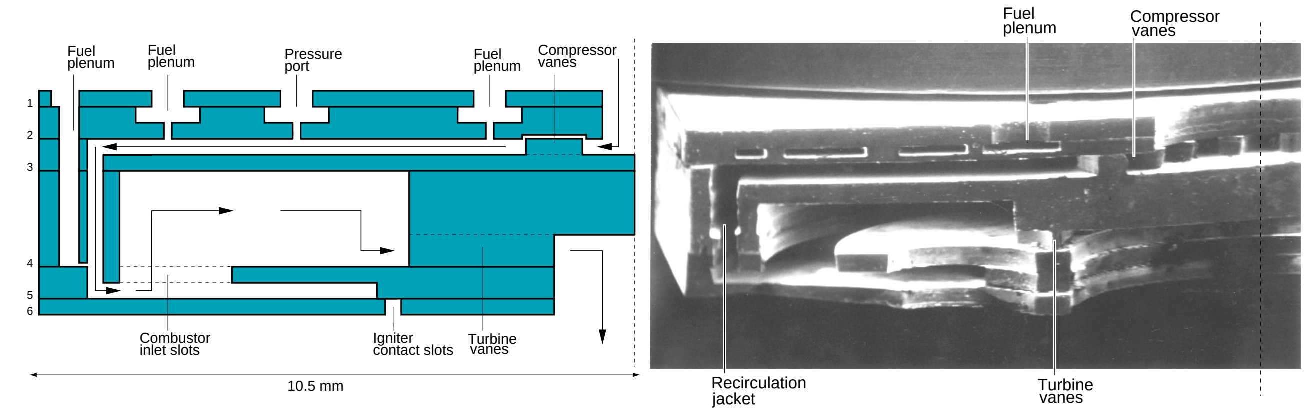

Fig. 1. Schematic and SEM cross-section of half of the axisymmetric 6-wafer static structure. (Note: The dies on the wafer had two types of combustor inlet holes - one type had slots as shown in Figure 2, the other had an annular opening as shown above.)

chemical energy of a fuel into a fluid at high mass flow rates, they have very high power densities and are particularly appealing at these scales. In fact, the power density of these silicon microcombustors is at least an order of magnitude higher than any other power-MEMS device [13]. The realization of these power densities however, requires effective completion of the combustion process within a small volume, and is therefore limited by the chemical reaction time constraints of the fuel. Consequently, tailoring the fluid flow to stabilize the flame and allow effective mixing of the cold reactants with the hot products is critical to getting the fuel to completely react within a short time, and is therefore a fundamental challenge for the design of these systems.

The chemical kinetics constraint is also exacerbated by the enhanced heat transfer effects that result from the large surface area-to-volume ratio of these devices. Not only does this high heat loss make it impossible to achieve conventional combustor efficiencies in excess of 99.9%, it also increases chemical reaction times by lowering the temperature of the flame stabilization zones. The coupling between the fluid dynamics, heat transfer and chemical kinetics is much more pronounced for these small systems, and is therefore a critical element of the design process.

The design space is further complicated by the addition of a third factor - the material and fabrication constraints. While silicon microfabrication is instrumental to achieving the economy and high tolerances necessary to make a microengine viable, it is still largely limited to rudimentary 3-D geometries. Furthermore, while creep constraints in the stressed rotor limit wall temperatures to 900K [14], chemical kinetics demand higher temperatures to achieve stable and efficient combustion. The system trade-offs therefore mandate careful operation in a narrow window where the heat loss is not so high so as to quench the reactions or drastically reduce combustor efficiency, but high enough to cool the silicon walls and allow the attainment of the desired exit gas temperatures within the material constraints of the silicon[2].

Given these constraints, the design of a microcombustor requires careful trade-offs between power output, cycle parameters, physical dimensions, and material and manufacturing capabilities. We illustrate some of these design considerations in the following sections by using the static structure as a working example.

[2]One might add that the design and operation of such microsystems is also complicated by the difficulty in instrumenting the small experimental rigs. The inapplicability of conventional diagnostics mandates the development of "on-chip" sensors for temperature, pressure, etc.; efforts are currently underway to incorporate these transducers in future devices.

THE ENGINE STATIC STRUCTURE

The static structure was developed with the following intent:
1. To demonstrate an ability to deep etch, wafer bond and diesaw 6 wafers for all the static systems of a microengine.
2. To evaluate the structural integrity of silicon in the thermal environment of the engine configuration.
3. To serve as a test bed for the identification of the combustion stability boundaries for hydrogen and hydrocarbon fuels, and to evaluate the effectiveness of the recirculation jacket, the viability of different fuels, fuel injector holes, etc.

The first two of these objectives have already been achieved and will be the main focus of this paper. The third is currently being worked on and will be reported later.

Design

Since the static structure was primarily intended to integrate a working hydrogen microcombustor with the remaining non-rotating components of the engine, it has the same basic geometry as the 3-wafer combustor described in Ref. [11]. A schematic of the static structure is shown in Figure 1 alongside an SEM of the bonded structure. Detailed views of the pre-bonded wafers are also shown in Figure 2. As highlighted on the pictures, air enters the device axially and makes a right angle turn into the compressor. In the absence of a rotating impeller, stationary compressor vanes are used to provide the requisite exit flow angle into the combustor. Fuel is injected axially through multiple fuel injector holes[3], and mixes with the air as it flows through the combustor recirculation jacket. This recirculation jacket was designed with the dual purpose of insulating the outer walls of the device while cooling the hot walls of the chamber with compressor discharge air. The flow then enters the combustor through axial inlet slots, burns in the 0.195 cm^3 annular-shaped volume, and finally exhausts through turbine static vanes that are designed to maintain an elevated operating pressure in the combustor by choking the flow. (In the engine configuration, the flow would also pass through the turbine rotor for power extraction prior to being exhausted.)

The key features of this design are described below:
Overall size and geometry: Based on the mass flow and design pressure ratio of the engine, the combustion chamber was re-scaled to 0.195 cm^3 to maintain the same flow residence time as that in the already demonstrated hydrogen

[3]Multiple fuel injectors were designed to evaluate the trade-off between duct burning and fuel-air mixing. If the fuel is injected too close to the combustion chamber, there might not be enough mixing length. If it is injected too far upstream, the mixture might burn in the duct and compromise the insulation of the outer walls.

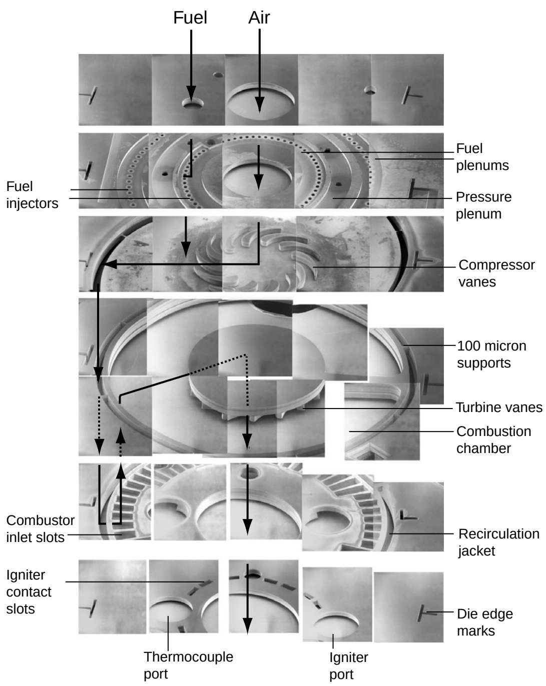

Fig. 2. A composite of 35 SEMs of the individual wafers prior to bonding showing the detailed fluid flow path. (Note: This particular die has the slotted openings into the combustion chamber.)

combustor [11]. The maximum die size was also limited to 2.1 cm to accommodate at least 10 dies on a 4" wafer.

Design of the fuel injectors: To identify the optimal location for fuel injection, the static structure was designed to have 3 fuel injection schemes - 2 axial and 1 radial (see Figure 1). By varying the diameter and spacing of the injector holes, half of the dies were optimized for hydrogen injection, the other half for hydrocarbons. In all cases, the injectors were designed using semi-empirical models for jet penetration and lateral spreading [15], their final number and diameters ranging from 60-90 and 120-224 μm, respectively.

Design of the flame holders: The combustor inlet holes were designed on the basis of chemical kinetics and Computational Fluid Dynamics (CFD) calculations so that the resulting fluid recirculation zones could sustain a stable flame over the widest range of mass flows and heat loss. The final mask set included 2 configurations - an annular opening supported by two bridges, and a set of axial inlet slots. These configurations are shown in Figures 1 and 2, respectively.

Design of the recirculation jacket: Previous experimental testing of the 3-wafer microcombustor showed that although ambient heat loss reduced combustor efficiency to approximately 75%, it was instrumental to the survival of the silicon at high temperatures [11]. In an effort to improve combustor efficiency within the material constraints of silicon, a 400 μm wide recirculation jacket was designed to wrap the compressor discharge air around the combustion chamber. This "recuperator" was designed with the dual intention of recovering the lost energy of the combustor to preheat the combustion gases, while allowing the flow to cool the hot walls of the chamber and enable the silicon to survive at the high temperatures necessary for stable combustion. It also insulated the combustor from the outer walls to reduce the temperature and heat loss from the packaged device. To reduce the thermal path between the chamber and the outer walls, the chamber was supported by eight 100 μm wide supports that were circumferentially distributed.

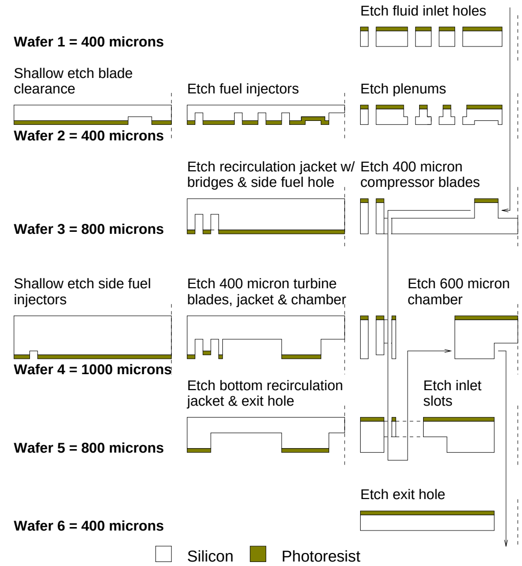

Fig. 3. Fabrication process for the static structure. (Note: Wafer thicknesses were chosen in accordance with the strength and thermal stress predictions for the device [14].)

Fabrication

The fabrication of the 6-wafer static structure required 15 masks, including one that contained wafer-level global alignment marks. A combination of 2 shallow reactive ion etches and 12 dry anisotropic deep reactive ion etches were used to define the various components. The overall process is illustrated via wafer-level cross-sections in Figure 3. The key fabrication steps are summarized as follows:

Photolithography: Except for the shallow etches, all steps used 10 μm of positive photoresist as a mask [12] & [13]. The wafers were patterned using double-sided infrared alignment.

Shallow etches: Wafers 2 and 4 were shallow-etched 5 μm to define the compressor blade tip clearance and side fuel injectors. The tip clearance was required to prevent the compressor blades from thermally shorting the combustor to the outer walls of the device; the side fuel injectors were designed to connect the outer fuel plenum to the recirculation jacket and to introduce the fuel at the combustor entrance.

Deep reactive ion etches: A multiplexed inductively-coupled plasma of SF_6 etchant and C_4F_8 passivating polymer was employed to anisotropically dry-etch the high aspect ratio fluid paths of the static structure. The performance of the etcher was optimized by characterizing the recipes over a wide parameter space [16], thereby allowing the fabrication of high tolerance and high aspect ratio structures such as the 400 μm high compressor and turbine airfoils, and the 1000 μm deep combustion chamber that was supported by the 100 μm bridges.

Aligned wafer bonding: After individual processing, the bonding was completed in 3 stages using an Electronic Visions bonder (3 2-wafer bonds followed by a 2-stack to a 2-stack and a 4-stack to a 2-stack bond.) Each bond required an RCA clean and a 1 hour anneal in an 1100°C ambient. Following the bonding, the 3.8 mm thick stack was diesawed to obtain five bonded dies out of a possible ten[4].

[4]IR inspection of the wafers showed poor bonding of the 2-stack to the 4-stack due to contamination of the wafer surfaces during bonding stages. Consequently, several dies separated at the 2-4 bond line during diesaw. For future work, the bonding will be completed in a single step to minimize contamination and improve overall device yield.

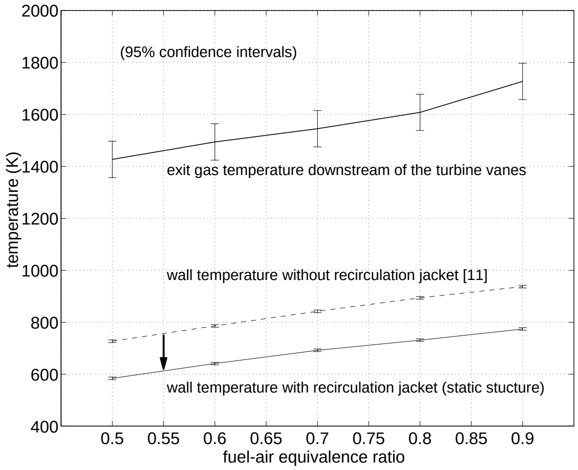

Fig. 4. Experimental results for the static structure. (Note: The exit gas temperature for the previous 3-stack microcombustor [11] is not plotted because it was measured upstream of the turbine static vanes, and is therefore not directly comparable. Additional analyses and measurements are currently being carried out to assess the heat loss through the vanes, and to allow a back-to-back comparison of the exit gas temperatures from the two devices.)

Experimental Results

Preliminary testing of the static structure was completed by closing the fuel ports and introducing premixed hydrogen and air through the inlet at atmospheric operating conditions. Similar to the experimental setup presented in Ref. [11], an invar jig was designed to interface the macrofluidic connections into the microdevice and to house wall and gas temperature thermocouples. An externally heated platinum wire was used to ignite the mixture; type K, 250 μm diameter thermocouples were used to measure temperature.

The combustor exit gas and silicon wall temperature measurements for the atmospheric tests are shown in Figure 4 along with the wall temperatures measured in the 3-stack microcombustor [11]. At identical mass flows and fuel-air ratios ($\dot{m}_{air}$=0.045 gm/sec[5]), the results show that it is possible to achieve turbine rotor inlet temperatures in the static structure that are sufficient to close a micro gas turbine cycle, yet simultaneously reduce the outer wall temperatures by approximately 200K. This suggests that the recirculation jacket is successful in insulating the outer walls from the hot combustion chamber. Additional testing is currently underway to measure the gas temperature upstream of the turbine vanes, and thus quantify the increase in combustor efficiency.

The static structure was operated at high temperatures for 6 hours and showed no visible degradation. This suggests that even though the combustion temperature was of the order of 1800K, the compressor discharge air was able to cool the walls of the chamber and allow the silicon to survive. (Note: In the 3-stack microcombustor [11], the walls were being cooled by the heat loss to the ambient.) While these results are still preliminary and additional elevated pressure testing is still needed to validate the stability boundaries and structural constraints for non-premixed hydrogen and hydrocarbon combustion, they suggest that it is possible to successfully operate a silicon static structure in a realistic engine-like configuration. Efforts are currently underway to continue the testing and to integrate the device with the rotating components of the engine geometry.

[5] The design mass flow of the engine is 0.36 gm/sec at an operating pressure ratio of 3; 0.045 gm/sec corresponds to approximately 40% of the static structure design mass flow at scaled atmospheric conditions.

SUMMARY AND CONCLUSIONS

In an attempt to integrate a hydrogen combustor with the other non-rotating components of a micro gas turbine engine, we have completed the design, fabrication and initial testing of a 6-wafer static structure for the engine. The 2.1 cm × 2.1 cm × 0.38 cm device was largely fabricated using DRIE and aligned wafer bonding, and is the first demonstration of the completed hot flow path of a 6-wafer multi-level microengine. Preliminary hydrogen-air combustion tests have demonstrated exit gas temperatures up to 1725K without any visible degradation after 6 hours of operation. The incorporation of a recirculation jacket to cool the combustor walls with compressor discharge air and to insulate the outer walls of the package also achieved a 200K reduction in outer wall temperature over the previously reported microcombustor [11]. While much additional testing is still needed to understand the combustion phenomenon at this scale, the results thus far demonstrate the viable fabrication and operation of a silicon static structure for an emerging class of high power density micro heat engines.

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References

[1] Benson, R. S., Ponton, J. W., *"Process Miniaturization-A Route to Total Environmental Acceptability"*, Trans IChemE 71 A, pp. 160-168, 1993.
[2] Lerou, J. J., Ng, K. M., *"Chemical Reaction Engineering: A multiscale approach to a multiobjective task"*, Chemical Engineering Science 51, pp. 1595-1614, 1996.
[3] Hagendorf *et al.*, *"A Pt/Al_2O_3 Coated Microstructured Reactor/Heat Exchanger for the Controlled H_2/O_2-Reaction in the Explosion Regime"*, Process Miniaturization: 2nd International Conference on Microreaction Technology, Topical Conference Reprints, 1998.
[4] Brooks *et al.*, *"Integrated Microchannel Combustor/Evaporator Development"*, Process Miniaturization: 2nd International Conference on Microreaction Technology, Topical Conference Reprints, 1998.
[5] Tonkovich *et al.*, *"Microchannel Chemical Reactors for Fuel Processing"*, Process Miniaturization: 2nd International Conference on Microreaction Technology, Topical Conference Reprints, 1998.
[6] Epstein *et al.*, *"Power MEMS and Microengines"*, presented at the IEEE Conference on Solid State Sensors and Actuators, Chicago, 1997.
[7] Epstein *et al.*, *"Micro-Heat Engines, Gas Turbines, and Rocket Engines"*, presented at the 28th AIAA Fluid Dynamics Conference and the 4th AIAA Shear Flow Control Conference, Snowmass Village, 1997.
[8] Epstein, A. H., Senturia, S. D., *"Macro Power from Micro Machinery"*, Science, Volume 276, p.1211, May 23, 1997.
[9] Groshenry, C., *"Preliminary Study of a Micro-Gas Turbine Engine"*, S.M. Thesis, Massachusetts Institute of Technology, 1995.
[10] Waitz *et al.*, *"Combustors for Micro-Gas Turbine Engines"*, Proceedings of the ASME Aerospace Division, AD-Vol. 52, 1996.
[11] Mehra, A., Waitz, I. A., *"Development of a Hydrogen Combustor for a Microfabricated Gas Turbine Engine"*, presented at the Solid-State Sensor and Actuator Workshop at Hilton Head, 1998.
[12] Lin *et al.*, *"Fabrication and Characterization of a Micro Turbine/Bearing Rig"*, presented at MEMS'99, Orlando, 1999.
[13] Mehra *et al.*, *"Microfabrication of High Temperature Silicon Devices Using Wafer Bonding and Deep Reactive Ion Etching"*, to be published in the IEEE/ASME Journal of Microelectromechanical Systems, June 1999, Volume 8, Number 3.
[14] Chen, K-S., *"Materials Characterization and Structural Design of Ceramic Micro Turbomachinery"*, Ph.D. Thesis, Massachusetts Institute of Technology, 1999.
[15] Schetz, J. A., *"Injection and Mixing in Turbulent Flow"*, AIAA Prog. in Aeronautics and Astronautics, Vol. 68, 1980.
[16] Ayón *et al.*, *"Characterization of a Time Multiplexed Inductively Coupled Plasma Etcher"*, Journal of the Electrochemical Society, Vol. 146, No. 1, January 1999.