Microfabrication of a Silicon Turbopump with Embedded Thermal Isolation for a Rankine MEMS Heat Engine

Amrid Amnache and Luc G. Fréchette
Université de Sherbrooke, CNRS UMI-LN2, Interdisciplinary Institute for Technological Innovation (3IT), 3000 boul. Université, Sherbrooke, Québec, Canada J1K 0A5

Amrid.amnache@usherbrooke.ca

Abstract. This paper presents the fabrication of a silicon MEMS microturbopump with embedded thick thermal isolation, covering the key building blocks to incorporate thermally insulated zones in a multiple wafer stack, and the resulting device. Thermal insulation is a roadblock for the implementation of heat engines at the MEMS scale. To implement the Rankine cycle on a chip, insulation is required to prevent boiling of water in the pump while the turbine is exposed to high temperature vapour flows. To prevent heat from conducting through the silicon rotor, thick glass insulation was embedded into the rotor structure using glass molding and planarization. This composite rotor approach allows us to leverage the capabilities of silicon DRIE, while creating over 100 micron thick glass insulation between the turbine and the pump. Also, in-plane thermal insulation is required between the central pump zone and the surrounding fluid film bearings, fed with steam. This was accomplished by etching deep trenches in silicon to form an array of thin walls, followed by a thermal oxidation step that consumes the silicon walls and closes the trenches to form a deep monolithic oxide zone. These techniques were successfully implemented for the fabrication of a complete MEMS turbopump, which consists of a stack of 4 silicon wafers and one glass wafer, and a total of 18 lithography/etch steps.

1. Need for thermal insulation in micro heat engines
Micro heat engines implemented using MEMS technologies have been proposed as compact sources for electric power or propulsion [1]. The approach combines the high performance and power density of thermodynamic heat engines common at large scale, such as turbines, with the microscale fabrication and integration capabilities brought from the semiconductor manufacturing sector. The envisioned applications range from micro air vehicles powered by chip-scale gas turbines to waste heat recovery from the exhaust of vehicles or factories using arrays of steam power-plants-on-a-chip [2]. Initially inspired by the MIT Microengine project [3], extensive efforts have been undertaking worldwide to tackle the many challenges that emerge when attempting to miniaturize a turbine at the chip scale.

To date, most of the core components required have been demonstrated. However, the engines demonstrated to date have mostly been fabricated in silicon, allowing significant conductive heat transfer between the hot and cold parts of the device. Although this may be a feature to prevent overheating in devices with combustion (>1000°C), in most cases, thermal insulation is required. In the Rankine steam microturbine as illustrated in Figure 1, for example, an embedded liquid pump must be insulated from the surrounding hot components to prevent boiling of the liquid in the pump [4]. Unfortunately, highly conductive Si etched by deep reactive ion etching (DRIE) is typically used to
fabricate the rotor, since it allows the bearing and blade fabrication at the required micron-scale tolerance and high aspect ratios, while demonstrating high mechanical strength [5].

This paper presents the fabrication of a microturbopump designed to implement the Rankine cycle, which includes two strategies for thermal insulation: 1) an out-of-plane thick insulating glass layer embedded in the rotor to prevent heat conduction from the turbine to the pump, and 2) an in-plane thick array of oxidized trenches to insulate the pump from the steam bearing flows. These two strategies are presented in the following sections, followed by the fabrication of a device with these insulating features.

Figure 1 Schematic cross section of a Rankine microturbine. 1. Turbine 2. Pump 3. Seal 4. Thrust bearing 5. Journal bearing

2. Glass molding for thick out-of-plane thermal insulation
To properly insulate the pump from the hot turbine flows, a thick layer of glass or oxide would be required, on the order of 100 microns. Deposition of such thick layers would not be viable, so a glass molding techniques was developed instead. The approach consists of heating the glass above its softening point, and applying a load (pressure) to deform the glass.

In this case, the glass will be molded into a Si cavity previously etched in the rotor. This technique has been studied to create vias through glass substrates [6] as well as high aspect ratio glass structures [7]. The fabrication process flow is represented in Fig. 2. It start with a DRIE of 200 μm deep (Fig.2a). A glass wafer (thicker than the cavity depth) is then anodically bonded to the Si wafer, covering the previously etched cavities (Fig. 2b). The bonding is done under vacuum to remove gases from the cavities (4×10⁻⁵ mbars). The wafer pair is then heated to a temperature of 800°C at ambient pressure, so that the pressure difference between the cavity and ambient will tend to drive the glass into the cavity (Fig. 2c). This molding approach has been shown to entirely fill the cavity, leaving no voids [7]. It however leaves a thick glass layer covering the entire wafer surface, which would preclude subsequent DRIE to cut out the rotor and form the journal bearing around its periphery. A sequence of lapping and polishing steps are therefore done to remove the excess glass and recover the original Si wafer surface (Fig. 2d). The glass that deformed into the cavity remains, forming a thick insulating zone within the Si wafer. Figure 3 shows a scanning electron microscopy of a cross section of a released rotor.

3. Deep trench oxidation for lateral thermal insulation
To prevent overheating (boiling) of the liquid in the pump zone (noted as cold zone in Fig. 1), lateral thermal insulation is also required, since the bearings that surround the pump are fed with hot steam. The insulation must also ensure hermeticity and mechanical strength to support the high internal pressures created by the pump (10’s of bars). The strategy proposed here consists of forming a thick oxide layer in the silicon wafer that surrounds the pump zone. The approach consists of etching an array of trenches by DRIE, leaving only thin walls between the trenches. The wafer is then oxidized until the entire (or most) of the thin wall thickness is consumed and converted into SiO₂. The trench widths were chosen such that the oxide growth fills the trench, leading to a thick monolithic oxide layer as shown in Fig. 3. To complete the thermal insulation, a deep trench is then etched from the wafer backside until the refilled trench array is reached.
4. Micro heat engine implementation and conclusion

This section presents the fabrication of a complete microturbopump device that includes the above insulating features. The device implements the core rotating components of a Rankine steam power-plant-on-a-chip with both a liquid viscous micropump and a steam microturbine (Fig. 1). It is fabricated from 5 wafers, etched and bonded to form a bottom stack and a top stack. The process requires a total of 18 lithographic masks, 11 RIE and 14 DRIE steps. Results are presented in Fig 5, showing top and bottom view of the fabricated microturbine layers (a), top view of a Si/glass rotor (b), turbine blades (c) and bottom view of a rotor showing the embedded molded glass (d).

This confirms that the proposed insulating strategies can be implemented and integrated with a Si MEMS process flow to create a microturbopump. Complete devices have been fabricated, allowing testing to be conducted to evaluate the thermal performance of the insulating features and demonstrate the device operation.

References

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