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A Micro Turbine Fabricated with Pre-bonded Wafer to Enhance DRIE Uniformity

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Abstract

This paper presents the development of a silicon-based micro turbine, which is one of the important components of our micro gas turbine engine. The key challenges to develop a successful high-speed turbine are the fabrication of profiles of blades and guide vans with good uniformity and high aspect ratio air journal bearing. To enhance DRIE uniformity for a well balanced rotor, pre-bonded wafers with 1.5 µm thick SiO_2 embedded layer are used. High-aspect-ratio air journal bearing has also been realized by fabricating rotors and stators separately on the same wafer. The turbine device has been assembled and rotated by compressed air. Experimental results show that the performance of micro turbine has been improved.

Keywords: Micro turbine, pre-bonded wafer, DIRE uniformity, air bearing.

1 INTRODUCTION

Due to the increasing demands for high-density power source, the development of micro engine and high-speed rotating machinery is quite attractive. In order to achieve high power densities, micro rotating machinery must spin at high rotating speeds, which motivates the use of air bearings [1-3]. Rotors supported by air bearings instead of solid contact are more susceptible to the influence of microfabrication errors, thus fabrication precision as well as the design of micro air bearings are of great importance to the successful development of micro rotating machinery with air bearings.

This paper presents our silicon-based micro air-driven turbine with air-bearings, which is a part of the project for the development of micro gas turbine engine [4]. To enhance the uniformity of deep reactive ion etching (DRIE) for well balanced rotors and stators, pre-bonded wafers with 1.5 µm thick SiO_2 embedded layer are used. The intermediate layer is expected to terminate further etching in depth. High-aspect-ratio air journal bearing has been realized by fabricating rotors and stators separately on the same wafer to skip the direct fabrication of the narrow and deep circular trench, which is a critical challenge to standard DRIE process. The improvements due to the use of the new fabrication recipes are demonstrated by the measurements of etched surface profile and performance evaluation of micro turbines.

2 DESIGN OF MICRO TURBINE DEVICE

Figure 1 shows the schematic cross section of the designed device for micro air-driven turbine, which consists of three layers of silicon wafers and two layers of acrylic plates for tubing and assembling. An exploded view of the turbine device excluding the top acrylic plate is shown in figure 2. There are three flow paths inside the bottom acrylic plate, which are for the compressed and purified air feeding to journal air bearing, thrust air bearing and stator blades respectively. Silicon wafers of 400 µm thick were used for the fabrication of the 1st and the 3rd wafers. The rotor and the stator were fabricated on the 2nd wafer with a thickness of 760 µm. The rotor has 17 blades with outer and inner diameters of 8.4 mm and 4.4 mm respectively. The stator has 23 guide vanes, and the outer and inner diameters of the guide vanes are 10.5 mm and 8.5 mm. The height of rotor blades and stator vanes is half the thickness of the silicon wafer.

A shallow pan of 10 µm deep was provided for forming thrust bearings in the center of both the 1st wafer and the 3rd wafer. Eight holes with a diameter of 0.24 mm are equally distributed on a circle of 6 mm diameter to provide compressed air for the hydrostatic thrust bearing. The journal bearing is defined by the radial clearance between rotor outer sidewall and stator inner sidewall. A clearance with a width of 10 µm and depth of 200 µm (aspect ratio is as high as 20) and its verticality requirements are far beyond standard DRIE processing capability. In this work, we designed the rotors and the stators in the different zones on the same wafer to skip the direct etching of the clearance. A journal bearing with a radial clearance of 10µm can be expected after the etched rotor and stator are assembled into the turbine device.

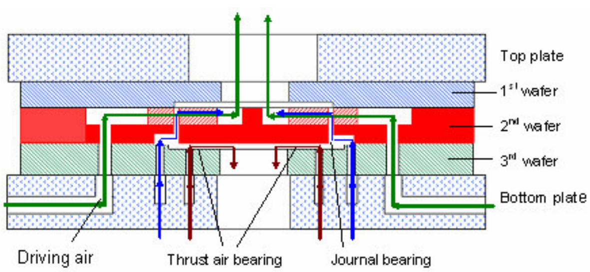
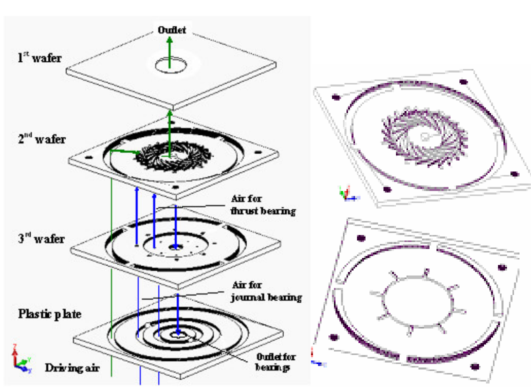


Figure 1 Schematic cross-sectional view of micro turbine device.



(a) (b)

Figure 2 The exploded view. (a) Micro turbine device; (b) Top-side and backside view of the 2nd wafer.

3 FABRICATION AND DIRE UNIFORMITY

The etch variation occurs during DRIE process. The DIRE non-uniformity [5] causes the difference of etched blade heights and even the mismatch of mass center and geometry center of rotors, which both increase the possibility of rotor collision with the surrounding wall. Figure 3 shows the etching rate variation across the wafers with rotor patterns and stator patterns respectively, where the rotor wafer has 5×5 rotor dies; the stator wafer 3×3 stator dies; the sampling points are distributed along the diagonal direction. The different etching rate across the wafer will cause the non-uniformity of etched rotors both locally and globally. To solve the issue, pre-bonded wafers with 1.5 µm thick SiO_2 embedded layer are used. The use of the intermediate SiO_2 layer is expected to stop the further etching and thus to obtain the uniform etching depth from the wafer surface to the intermediate layer. Figures 4(a) and (b) show the topographical maps of the floor of etched rotors using a pre-bonded wafer and a standard wafer, respectively. A comparison of the two contour maps illustrates the improvement of uniformity in DRIE etching depth The etching uniformity especially at the gulf between blades has been greatly improved. Therefore, the use of pre-bonded wafers is an effective measure to reduce the non-uniformity of DRIE.

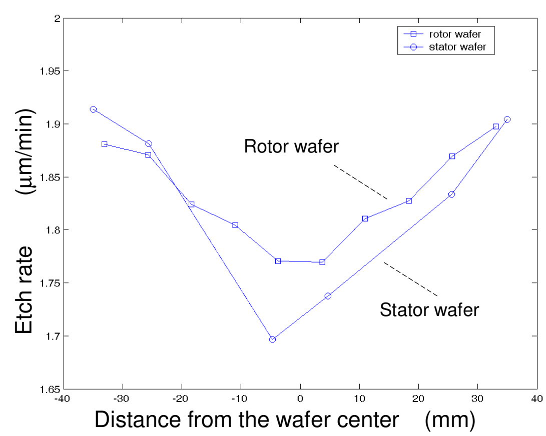
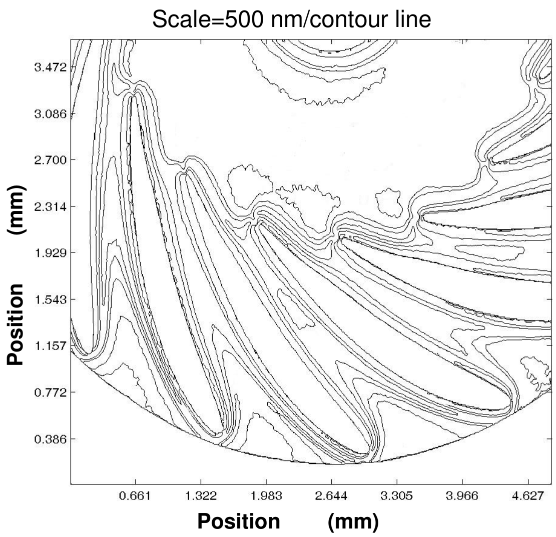
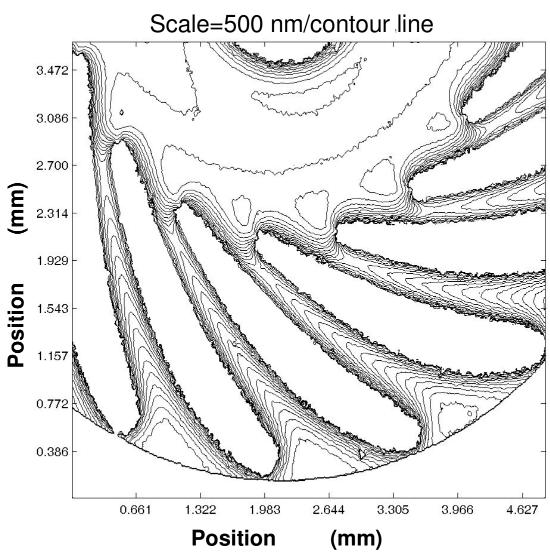


Figure 3 Variations of Etching rate across the wafer

As discussed in the previous section, the direct fabrication of a high aspect ratio clearance between the rotor outer sidewall and stator inner sidewall is a critical challenge. To skip the direct etching of the high aspect ratio clearance, we previously designed the rotor pattern and the stator pattern on separate wafers. This, however, caused the difference of etched depth between rotors and stators due to the two separate etching processes or the thickness difference of two wafers. By designing rotors and stators in the separate zones of the same wafer, we not only skipped the direct etching of the narrow trench but also avoided the possibility of fabricating rotors and stators on wafers with different thickness. Figure 5 shows the dimension of the radial clearance between a rotor and a stator, which agreed well with the designed value.



(a) A rotor fabricated using the pre-bonded wafer



(b) A rotor fabricated using a standard wafer

Figure 4 DRIE variations of micro rotors

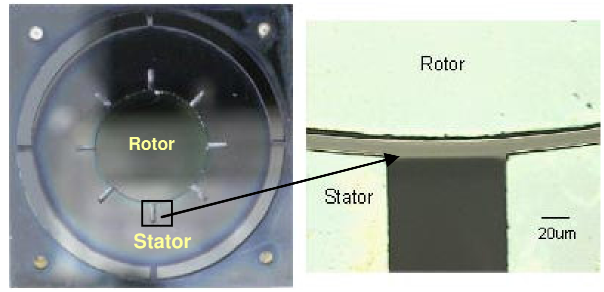


Figure 5 Clearance between the rotor and stator

4 PERFORMANCE EVALUATION

The performance of micro turbine can be evaluated by the measurements of rotational speed. To measure the rotation speed, the micro turbine is assembled in an acrylic package, and then the package is connected to a gas distribution system, which consists of the compressed and purified air source, pressure transducers, valve regulators and mass flow meters. An optical fiber sensor was used to monitor the rotation of micro air-driven turbine. Figure 6 shows the experimental setup. A color zone was marked on the rotor for the fiber sensor to measure the rotational speed of the rotor by sensing the periodic change of reflectivity. Figure 7 demonstrates the real time output signal of the optical fiber sensor, which could be acquired into a computer for signal processing using Fast Fourier Transform (FFT) to calculate the rotational speed.

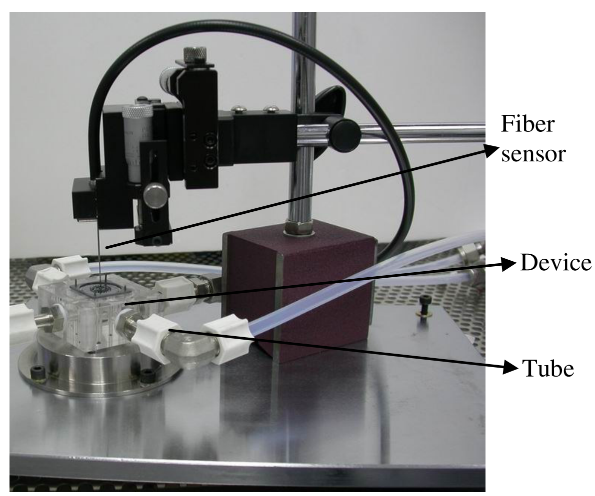


Figure 6 Setup for rotational speed measurements of micro air-driven turbine.

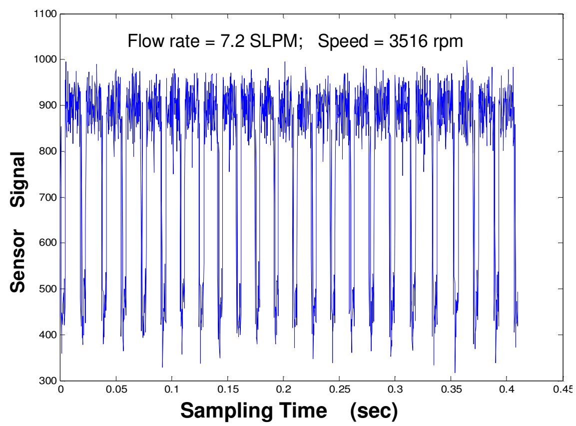


Figure 7 Output signal of the fiber sensor. The signal was then automatically processed to obtain rotational speed.

To compare the performance of micro air-driven turbine fabricated from pre-bonded wafer and that fabricated from conventional standard wafer, rotational speed measurements of two corresponding sets of micro turbines were conducted. Figure 8 shows a comparison of the performance of two micro turbines. The rotational speeds of these two turbines were measured at the same air inflow rate of 5.0 SLPM (standard liter per minute). The comparison illustrates that (1) the micro turbine fabricated from pre-bonded wafer (Turbine 1) has a better rotating stability than Turbine 2 fabricated from standard silicon wafer; (2) stable operation and high rotational speed of micro turbine can be achieved by precision fabrication. A further examination of Turbine 2 demonstrated that the width of the fabricated radial clearance was near to 20 μm, which led to unstable operation of air bearings.

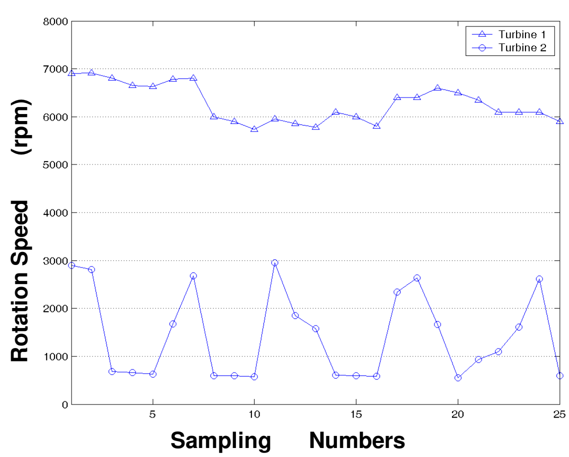


Figure 8 Comparison of measured rotation speeds

5 CONCLUSION

We demonstrated our developed micro air-driven turbines. The etching variation during DRIE process was discussed and the measure of DRIE on pre-bonded wafers was presented to reduce or eliminate the etching non-uniformity. The micro air-driven turbine with a pair of rotor and stator fabricated on a pre-bonded wafer showed better performance than that using common DRIE process. Therefore, precise fabrication is essential for the stable and high-speed operation of micro rotating machinery.

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