Pumping Capacity and Reliability Study on Silicon-Based Cryogenic Micro Pump

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ABSTRACT

As part of a program to develop a cooling system for satellite instrumentation capable of working at cryogenic temperature, we present herein pumping capacity and material reliability study on a silicon-based cryogenic micro pump which will be applied into a future cooling system to satisfy both active and remote cooling requirements.

A test rig for actuating silicon diaphragm, the main functional component of the micro pump, was built by using compressive gas actuation. A Dewar was utilized to cool the diaphragm down to cryogenic temperature. The deflection of silicon diaphragms was measured using both WYKO and ZYGO interferometer. As a result, pumping capacity was derived. The maximum deflection of the silicon diaphragm was found to vary linearly with differential pressure, and the pumping capacity decreased at the cryogenic temperature. Additionally, micro-Raman spectroscopy was employed for stress mapping. As expected, the diaphragm edge centers are most vulnerable to fracture. Finally, a cryogenic fatigue test was conducted. The diaphragm suffered no damage during 10^6 cycles for ~10 days, thereby demonstrating the viability of the silicon-based system for space applications.

Keywords: micro pump, pumping capacity, silicon reliability

1. INTRODUCTION

Satellite instrumentation suffers from lack of heat dissipation [1-3]. Heat is basically generated by the electronic systems, and if exposed, by radiation absorption as well. Therefore, the heat sensitive instrumentation needs an active cooling system, other than natural gas flow over devices or passive atmospheric heat exchanger, in order to maintain at an acceptable operating temperature [4, 5].

Several solutions have been employed. NASA has applied a capillary pumped loop (CPL), utilizing a turbo pump for cooling infrared cameras on the Hubble telescope [6]. Another current option is the heat pipe technology [7], which has been used extensively on space-based missions.

Fulfilling the active cooling requirement, however, these current options are not compatible with remote cooling without some sort of additional pump loop. Some satellite instrumentations require as many degrees of freedom as possible, in order to move and rotate smoothly. A silicon-based micro pump array is desirable due to the cost associated with weight and volume in space based applications. The concept shown in Figure 1a will serve in our proposed cooling system, connecting with a long coiled tubing to provide the flexibility so as to transfer the cryogen from a cryocooler to the instrumentation.

The cryogenic micro pump consists of multiple silicon wafers, making up the diaphragm (Figure 1b). It is expected that the pumping capacity depends on the deformation of the diaphragm, and the system viability associates with diaphragm fracture and fatigue.

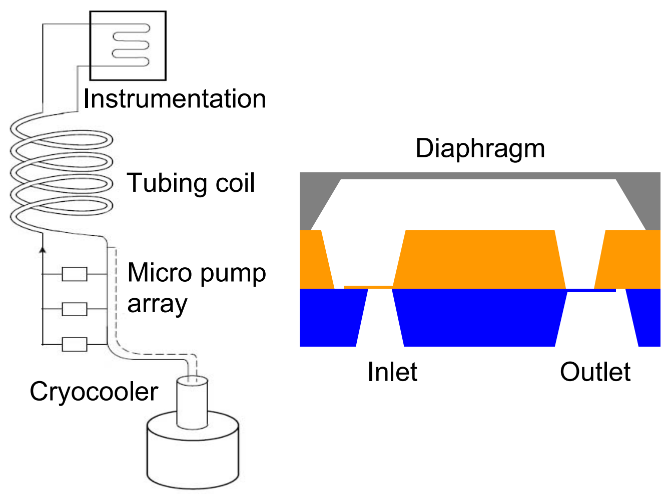

Figure 1: *Schematics of cooling transport loop using micro pump array (a) and silicon-based micro pump design (b).*

2. EXPRIMENTAL SETUP

The realization of the pumping capacity requires some sort of actuation mechanism to deform the silicon diaphragm. These actuation approaches include piezo disc [8], differential pressure [9], electrostatic [10], thermopneumatic [11], and etc. Unfortunately, most of them are either incompatible with the cryogenic operation requirements or too complicated to be integrated with the system. In this work, differential pressure actuation was utilized due to its simplicity and cost efficiency.

2.1 Pumping rig

The compressive gas was first desiccated to avoid gas pipe blockage due to ice formation. Then the gas was led through a solenoid valve to adjust the differential pressure. An optional three-way valve was used for fast switching in the dynamic deflection measurement. The silicon diaphragm was clamped in a two-part sample holder using bolts. The upper part has an opening in the center to allow the interferometer measurement. The compressive gas reaches the backside of diaphragm through the chamber of the lower part for actuation.

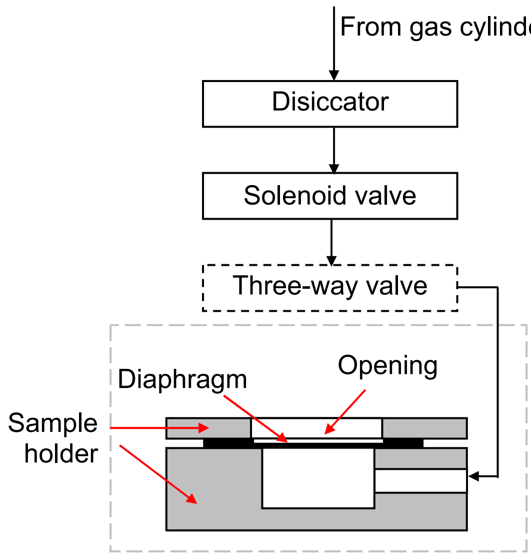

***Figure 2**: Pumping rig for diaphragm actuation.*

2.2 Cryogenic Dewar

In order to achieve a space-based operation environment, a Dewar test rig was designed and further utilized for cooling the silicon-based diaphragm to cryogenic temperature (Figure 3). As shown in the figure, the sample holder was first mounted on the cold finger and then aligned to the quartz window. Prior to each measurement, cryogen (liquid nitrogen) was fed into the inner layer, and the dewar was pumped to vacuum in order to reduce the heat transfer and to keep the temperature in a narrow range.

In this work, long coil tubing was winded onto the inner layer to cool the compressive gas to cryogenic temperature before it reached the sample holder. With such configuration the gas volume change with temperature was minimized.

3. EXPERIMENT AND RESULTS

3.1 Diaphragm preparation

Square-shape diaphragms were fabricated on 4", single crystalline silicon wafers using standard microfabrication process (Figure 4). An array of indicators was designed along with the diaphragm to indicate the etch depth. The thickness of then diaphragm was measured using Fourier Transform Infrared spectroscopy; the lateral dimension of the diaphragm was examined using a microscope with accurate grids.

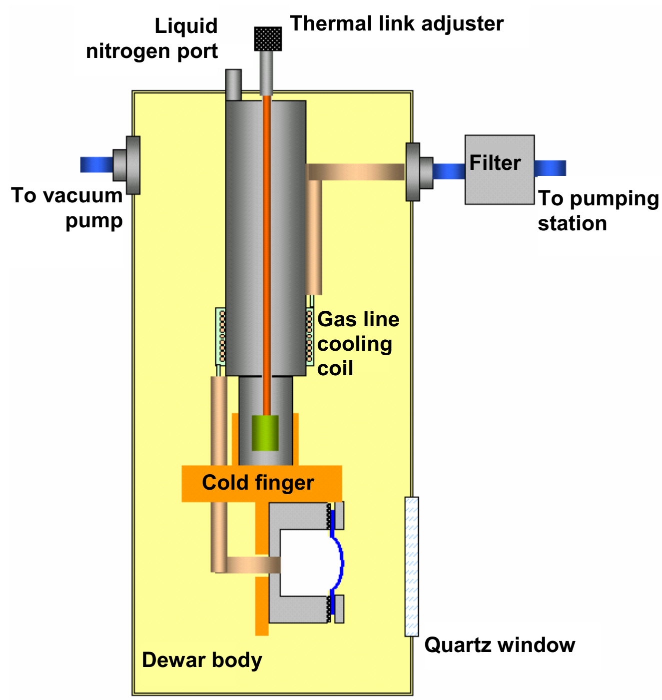

***Figure 3:** Schematic of Cryogenic Dewar Setup.*

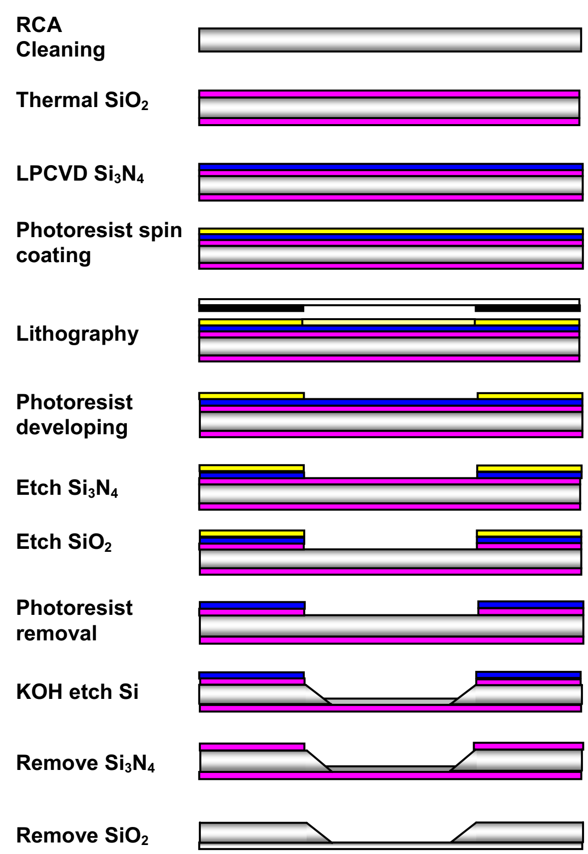

***Figure 4:** Fabrication process for silicon diaphragm.*

3.2 Deflection mapping

It is expected that the pumping capacity depends on the actuation frequency and volume stroke of silicon diaphragm during single cycle. The volume stroke can be obtained by integrating the deflection over the diaphragm region.

In order to measure deflection distribution, WYKO interferometer was applied. Matching with theoretical analysis, this result indicates a linear relationship with the maximum deflection and differential pressure. Figure 5 shows deflection mapping of a 6.3 mm x 6.3 mm diaphragm achieved at room temperature. The thickness is about 110 μm. The maximum deflection was found to be 30.1μm under 40 psi differential pressure. The measured deflection profile has a fairly good agreement with our FEM simulation.

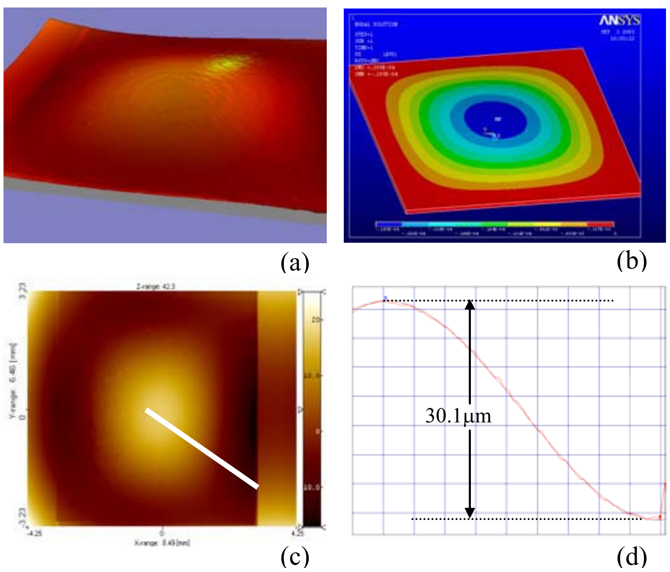

***Figure 5**: (a) 3-D deflection profile obtained from WYKO interferometer under 40 psi differential pressure; (b) 3-D deflection profile obtained from finite element simulation (The calculated maximum deflection is 29.5 μm at 40 psi); (c)-(d) Deflection mapping and profile obtained from the WYKO interferometer (The measured maximum deflection is 30.1 μm).*

Smaller deflection was observed at decreased temperature. For example, the maximum deflection of a diaphragm was 25 μm at room temperature, and 18 μm at 77 K. Given the lateral dimension of the diaphragm (6.3 mm x 6.3 mm), it can be derived that during a single cycle the diaphragm can transfer ~0.36 mm^3 liquid cryogen under 40 psi differential pressure at room temperature, while this value would drop down to ~0.24 mm^3 at 77 K. In other words, the volume change at 77 K would be about two thirds as that at 293 K, with the same actuation condition.

Moreover, in order to investigate the influence of actuation frequency, ZYGO interferometer measurement was subsequently conducted for dynamic deflection observation. The diaphragm was actuated at different frequency, and the deflection was recorded. The results showed that decreasing deflection associates with increasing frequency, which is probably due to the gas resistance in the tubing pipes.

3.3 Stress distribution

To transfer cryogen for cooling, a large volume stroke with high stresses is desired. Therefore, a closer examination of the stress distribution in the diaphragm was conducted to predict the possible diaphragm failure and longevity working viability.

Micro-Raman was employed for stress mapping; stress distribution was also estimated using FEM simulation. Since the thickness of the silicon diaphragm is much smaller than its lateral dimension, the X-axis (Y-axis) stress was found much higher than the out-of-plane stress (Z-axis) and in-plane shear stress. As such, stress distribution within a diaphragm region can be regarded as a biaxial case, and the in-plane stress can be linearly interpreted from the Raman shift, if measured.

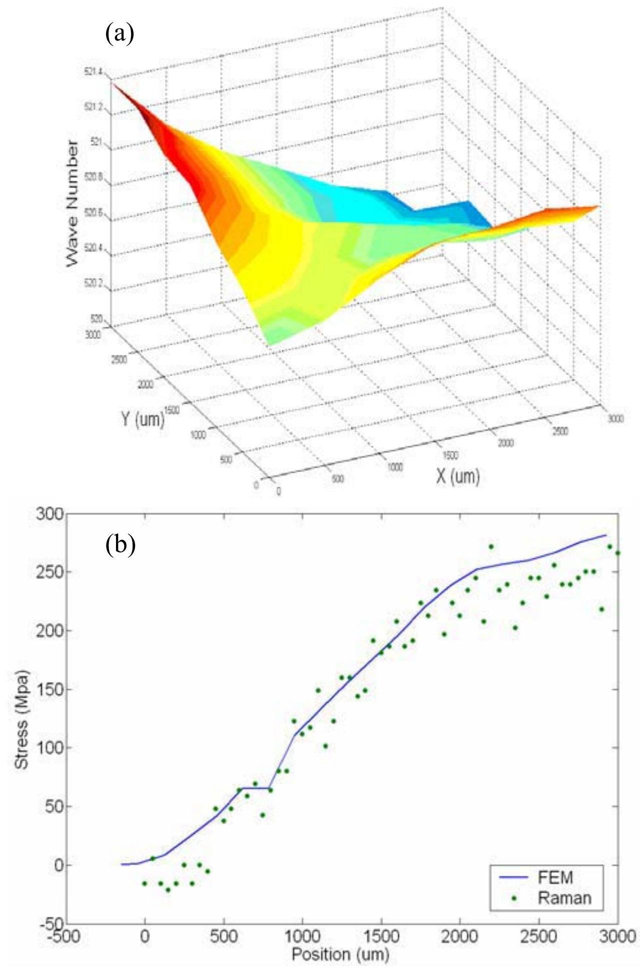

***Figure 6:** (a) Raman shift mapping within a quarter region of the diaphragm. (b) Comparison of stress achieved from Micro Raman spectroscopy and simulation analysis.*

Raman shift distribution within a quarter region of the diaphragm was achieved (Figure 6a). The negative shift occurs in the diaphragm center, indicating tensile stress, while the positive shift occurs in the edge centers of the diaphragm, indicating compressive stress. Moreover, a line scanning was carried out from diaphragm edge to the edge centers, and Figure 6b shows a good match with the FEM simulation. As expected, the edge centers (red region) suffered the maximum stress, and will be most vulnerable for diaphragm failure.

3.4 Fatigue testing

There is no fatigue observed in single crystalline silicon diaphragm at room temperature, while little information was found at cryogenic temperature. Therefore, to investigate the long-term reliability of micro pump at cryogenic temperature, fatigue testing was carried out. Figure 7 shows the setup for longevity tests. The silicon diaphragm was clamped in the sample holder, and then immersed into the liquid nitrogen. Compressive gas was induced to actuate the diaphragm. Preliminary results show that there is no crack observed in the diaphragm after 1.8×10^6 cycles (about 10 days). Efforts are currently underway to evaluate intensively the viability of silicon-based micro pumps for space missions.

Figure 7: *Preliminary fatigue test setup for cryogenic temperature operations.*

4. CONCLUSIONS

This paper presented pumping capacity and reliability studies of a silicon-based cryogenic micro pump for space applications. Fabricated using standard processes, a square-shape diaphragm served as the major functional component of the micro pump. A linear relationship between the differential pressure and maximum deflection of the diaphragm was found. The volume stroke of the diaphragm during single cycle at cryogenic temperature (77 K) is about two thirds as that at room temperature (about 293 K). Moreover, the pumping capacity during single cycle was found to decrease with increasing actuation frequency.

The stress distribution was further examined using micro-Raman interferometer. It was observed that the tensile stress concentrates in the diaphragm center while the compressive stress concentrates in the edge centers of the diaphragm. Accordingly, the edge center regions are most susceptible to the future system failure. Finally, silicon-based diaphragms survived a cryogenic operation for more than 10 days (after 1.8×10^6 cycles), thereby preliminarily demonstrating the viability of silicon-based micro pumps for space missions.

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