A MICROMACHINED TITANIUM SPUTTER ION PUMP FOR CAVITY PRESSURE CONTROL

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ABSTRACT

This paper describes a micro-scale sputter ion pump and its use in the controlled reduction of pressure in a large cavity package. The pump is composed of titanium electrodes on a glass substrate which are sputtered away and form the source of Ti ions that react and bind with oxygen and nitrogen. The discharges are powered by DC and pulsed DC high voltage. The duration of applied voltage determines the amount of sputtered titanium and consequently, the pressure reduction inside a cavity. To date, the pressure inside sealed commercial packages of volumes 6.33 cm^3 and 2.2 cm^3, has been reduced by 168 Torr and 126 Torr, respectively.

I. INTRODUCTION

The adsorption or removal of gas from a sealed cavity has been used to lower the pressure in cavities below the pressure obtained when they are sealed. Options that eliminate moving parts are promising from the viewpoints of longevity and field usability. Coatings and pumps have been suggested for use on the microscale in order to evacuate small cavities. Past efforts involving the application of coatings to the inside of sealed cavities include non-evaporable getters (NEGs), thin-film getters (e.g. Nanogetters™), and reactive sealing [1-4]. While these technologies work on both the macroscopic and microscopic scale, they typically require activation temperatures of 200-550°C. Micromachined thermal molecular pumps without moving parts have been proposed and Knudsen pumps have been developed [5-7]. However, these typically require temperatures that are even higher.

Titanium is used as a getter in macroscale capture pumps including titanium sublimation pumps (TSPs) and sputter-ion pumps (SIPs) which operate in high vacuum environments. TSPs function by subliming a hot filament of titanium onto the inner walls of a chamber where it chemisorbs impinging reactive gases. SIPs operate through the creation of a discharge in an externally applied magnetic field. The magnetic field traps electrons which ionize the surrounding gas. Ions are then accelerated towards the cathode, which is typically titanium, and sputter fresh metal ions onto the surrounding walls and anode, where they getter gas molecules. Titanium ions are known to getter nitrogen and oxygen. Heavy non-reactive gases are also confined as they are buried by the deposited material [8, 9].

This paper describes a micro-scale Ti sputter-ion method without moving parts that can remove a relatively large volume of air. The amount of air removed can be controlled through the duration of applied DC voltages that energize the created plasma discharge. This method can also be used in relatively large cavities and has been demonstrated in cavities with volumes of 2.2 and 6.33 cm^3.

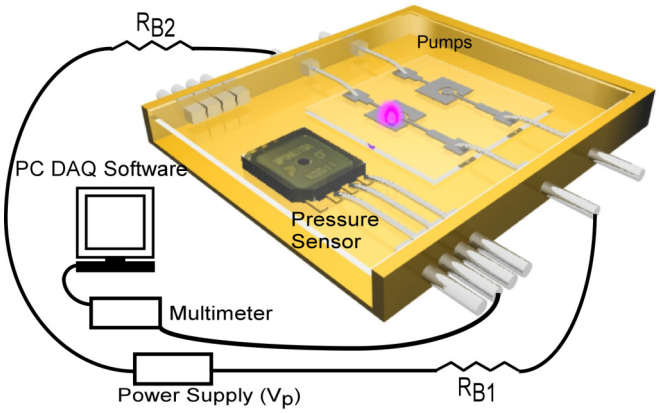

Fig. 1: Schematic of a cavity, pressure sensors, electrode configuration, power, and readout circuitry. R_{B1} and R_{B2} are 1.2 MΩ ballast resistors which limit the current flowing through the arc between electrodes. All electrode pairs have a 50 μm discharge gap.

II. DEVICE CONCEPT AND OPERATION

The microchips that constitute the sputter ion pumps (Fig. 1) have been enclosed in industry-standard packages that are hermetically sealed using solder bonded stainless steal lids. Each microchip pump consists of one or more titanium anode-cathode pair that is patterned on a glass substrate. These electrodes are then powered by leads through the cavity (or perhaps by an adjacent circuit that is co-packaged with them). Past work has shown that discharges between narrowly spaced electrodes can be spatially confined in a very effective manner by controlling the powering scheme [10-12].

The microscale sputter ion pump functions in a manner similar to traditional SIPs in that it uses sputtering of a titanium target but has some differences as well. Macroscale SIPs create a plasma region between the anode and cathode while using external magnets to spatially confine the carriers. In contrast, for micro-scale plasmas magnetic confinement is not essential, and further, these discharges can exits at higher pressures (including atmospheric pressure) as arcs, plasmas or a combination of the two.

These discharges result in sputtering of the titanium from the cathode, and the consequent binding of gas

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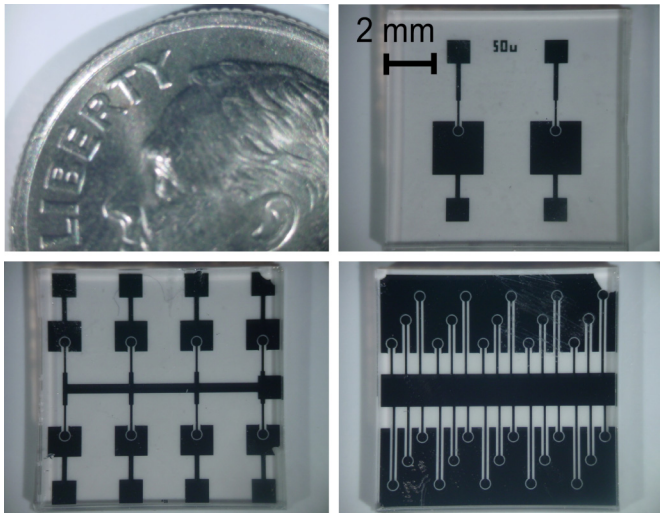

Fig 2: (a–top left): A US dime. (b–top right): Two junction chip. (c–bottom left): Single anode with eight cathode chip. (d–bottom right): Single anode with two cathodes each having fifteen junctions chip.

molecules. Ballast resistors of 1.2 MΩ are placed in series with the electrodes to limit the current and provide control over discharge energy.

Titanium serves with high efficiency as a getter for a number of molecules including CO, CO_2, H_2, N_2, and O_2 [13]. In macroscale titanium SIPs, the resulting film layers have been found to consist of 44% Ti, 40% N, 8% O, and 8% C [9]. Titanium and nitrogen have been shown to be uniformly distributed through the thickness of the deposited layer. This data indicates that one titanium atom is able to getter approximately one atom from the surrounding air environment [14]. However, it is worth noting microscale discharges differ in some ways that can potentially change this [15]. In particular, they are typically localized above the cathode, which can affect the re-deposition pattern of sputtered molecules, and consequently the final distribution of compounds. In addition, micro-discharges have a small population of electrons and ions with extremely high energy, which can also affect the binding of the titanium with gas molecules.

The composition of the exposed pump surfaces affects the pumping behavior and speed. In addition to sputtering titanium, exposed titanium surfaces at any location inside the cavity can adsorb reactive gasses such as nitrogen [16]. The buildup of insulating films such as Ti_xN_y can also lead to a scenario termed the "disappearing-anode effect," which can cause changes in the metal impedance and arcing characteristics. While noteworthy, it is difficult to determine the impact these effects have on performance.

III. DESIGN AND FABRICATION

The primary goal of the pump designs reported in this effort is to maintain controlled, progressive sputtering of the titanium on the cathode for an extended duration of time. In order to accomplish this, the cathode was designed to erode evenly along the boundary of the anode through the use of a circular anode surrounded by the cathode. The circular design provides a uniform electric field over a large width of interaction between the electrodes. In contrast, if there were any sharp corners present, the discharges would be formed at those locations preferentially.

Three different pump designs are used on separate chips, each of 1 cm^2 area, as shown in Fig. 2. The first design, Fig. 2b, is composed of two single anode/cathode junctions and uses separate lead connections for each electrode, should one electrode be destroyed through the application of a large current or a bad connection. The second design, Fig. 2c, is composed of a single composite anode that interacts with 8 separate but identical cathodes. As the anodes are not significantly destroyed by the arc, a common lead to them is sufficient. Each cathode can be sputtered separately or wired together off-chip and sputtered simultaneously. Four times as much titanium is available for sputtering as compared to the previous design. The final design, Fig 2d, has a single anode and two cathodes. Each cathode has fifteen junctions which maximizes the amount of potentially sputtered titanium but allows the user less control compared to the other designs.

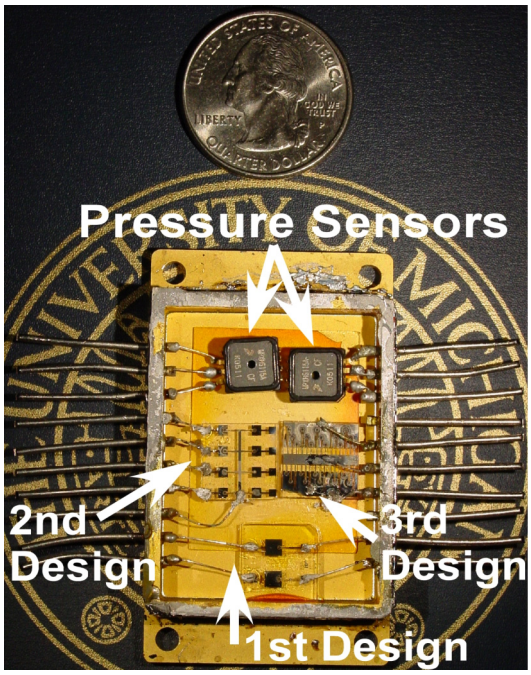

Fig. 3: Package after opening with two pressure sensors and all three pump designs included.

The electrodes were formed by evaporating and patterning a 1 μm thick titanium layer on a glass substrate. The spacing between the anode and cathode is 50 μm on all three chips. The first, second, and third chips have 5.06, 1.82, and 33 mm^2 titanium cathodes respectively. The chips were diced and separated. Wires were bonded to the titanium contacts using a solder with 97% indium and 3% gold.

IV. RESULTS

Industry-standard packages of two different sizes with solder bonded stainless steal lids were used to validate the

performance of the pumps. In the first experiment, the cavity volume was 6.33 cm^3. Figure 3 illustrates the package with a 3.3x4.3 cm^2 interior footprint. One copy was included of each of the three pumps described in Fig. 2, along with reference pressure sensors. The sealing pressure for the package was slightly lower than atmospheric pressure due to heating required to bond the lid. The sputtering was performed by the application of 15 discharges using four different electrode pairs. The pressure was measured by one Freescale MPXH6115A device, but a second copy of it was used to provide confirmation. A multimeter and a computer interface were used to record the pressure sensor output voltage at programmable intervals while the current was also recorded.

Figure 4 illustrates the pressure drops over time with varying discharge durations. The pressure was reduced by 168 Torr from the pressure at which the package was sealed. The figure shows that the pressure sensor correctly measured room pressure when the cavity was opened for inspection. In the second experiment, a single pump was packaged in a 2.2 cm^3 cavity and reduced the pressure by 126 Torr, through the application of extended discharges.

Different pressure responses were observed for pulses of varied duration. Sputtering for short periods, e.g. 10 minutes, resulted in a pressure rise due to an increase in temperature followed by a sharp decline as air was adsorbed. The pressure rose for approximately three of the ten minutes before falling sharply. After discharge extinction the pressure continued to drop for up to twenty minutes and eventually stabilized, holding steady for hours between discharges.

Sputtering for extended durations, e.g. hours, resulted in a steady pressure drop after an initial rise due to temperature. In order to apply pulses for hours, the voltage had to be increased as time progressed. This is because the gap between the electrodes effectively increases as the proximal cathode region is sputtered away.

Figure 5 displays the pressure loss and adsorbed molecules as a function of the electrical energy used for the discharge. The pressure drops quickly when the pump is first turned on and appears to saturate as more titanium is sputtered. The upper trend (red) line on the figure represents pressure drops measured with the pump off, when no energy was being applied to the system. The saturation could be caused by a lack of exposed titanium as it is sputtered away or covered by Ti_xN_y molecules. This saturation is apparent in each of the experiments and may eventually represent a practical limit for the pressure reduction that can be achieved.

Upon opening the cavities, titanium regions of the cathodes had been sputtered away and a film was evident on the substrate and anodes as shown in Fig. 6. Areas of the 1 μm thick titanium were completely removed in the intended manner, demonstrating controlled sputtering. As the titanium is sputtered away from one location, the discharge occurs at a different location and thus sputters the cathode uniformly on all sides of the anode. The distance between the anode and cathode increases with time and when the applied voltage is not enough to bridge the electrodes, the discharge ceases. This leads to the concentric consumption of the cathode, as shown in Fig. 6. The anode regions remained largely intact, showing no indication of sputtering as expected, although some delamination and damage can potential occur due to heating caused by current spikes.

Figure 7 shows the damage occurring on all surfaces of the cathode near the anode as well as the localized plasma

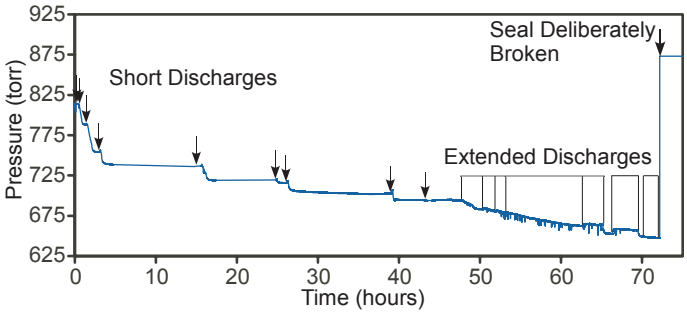

Fig. 4: Pressure drop in the cavity over time. Fifteen consecutive discharges dropped the pressure 168 Torr. The pressure remained stable over periods of ten hours of pump inactivity and returned to room pressure when opened.

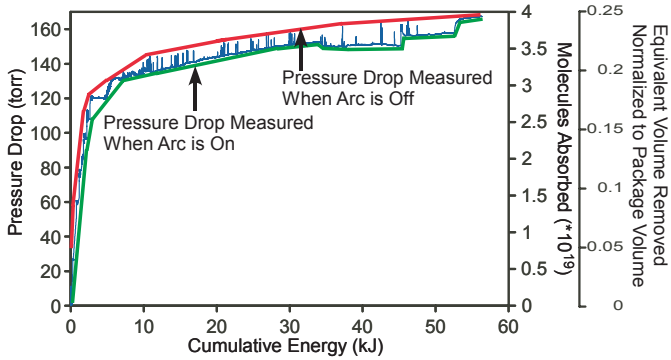

Fig. 5: The pressure drop as a function of the cumulative energy supplied to the discharge. The upper and lower trend lines respectively show the pressure reading when the discharge is interrupted (causing spikes as the pressure stabilizes without an increase in energy) and when the discharge remains on. The corresponding number of gas molecules removed at room temperature, and the fraction of the cavity volume evacuated, are also noted on the right-hand-side Y-axes.

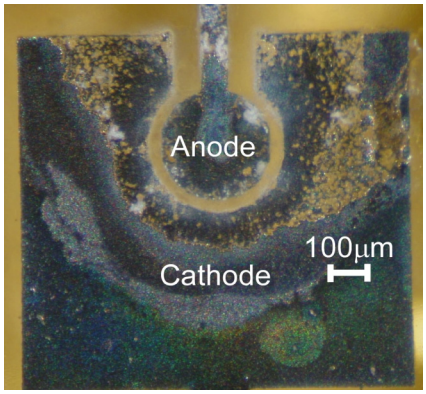

Fig. 6: Remains of the top electrode of the second pump design, illustrating areas of complete titanium sputtering.

region over the cathode. At atmospheric pressure, lower current limits create a single arc discharge as shown in Fig. 7a while larger currents cause multiple discharges as shown in Fig. 7b. Multiple discharges consume the cathode more rapidly.

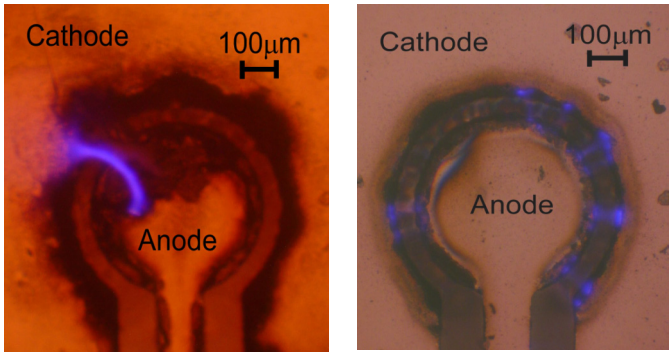

Fig. 7: (a–left) Hybrid discharge and sputtered electrodes. Hybrid discharges such as this occurred when the arcing current was limited to 50 µA. (b–right) Multiple discharges created by high current. Discharges such as this sputtered a majority of the titanium.

V. CONCLUSION

This effort successfully demonstrates a micromachined titanium sputter ion pump which can function at atmospheric pressure. The pump is designed to function in a sealed cavity without heating surrounding devices and provides the user control over the amount of air removed from the inside of the cavity. The number of cathodes used as well as the applied voltage determines this removal rate. The pump has successfully removed 168 Torr from a 6.33 cm^3 cavity and 126 Torr from a 2.2 cm^3 cavity when starting near atmospheric pressure. These characteristics make the pump appealing for experiments requiring pressure control as well as packaging.

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