Team 15

Design of A Compact Pressure Sensor for Multi-Layer Insulation Inside a Vacuum Environment

Design of Manufacturing, Reliability and Economics

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Abstract

The design for manufacturing, economics and reliability for the capacitor pressure sensor is discussed throughout the paper. The design for manufacturing (DFM) discusses the processes necessary to produce the scaled prototype as well as the final prototype. The DFM also discusses the time necessary for developing the prototype. The design for reliability section will discuss modes of failure and the consequences. The design for economics discusses an estimation of the cost of the budget as well as a visual aid.

Design for Manufacturing

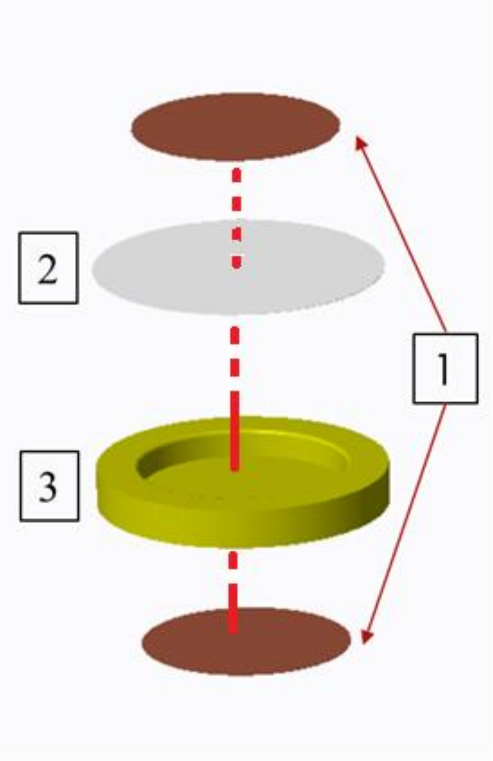

Figure 1 (1) Palladium-Gold sputtered tracts. (2) 0.50 µm thickness Silicone diaphragm. (3) Germanium doped silica base

Figure 1 shows an exploded view of the capacitor pressure sensor. Part 1 in figure 1 is the Palladium- Gold sputtered tracts, part 2 is the silicone diaphragm and part 3 is the silica core or epoxy core for scaled prototype.

I. Necessary Supplies for Scaled Prototype Manufacturing

1. HIPs Filament
2. 3D Printer
3. Fibre Glast 2000 Epoxy resin
4. Fibre Glast 2000 Epoxy cure
5. Stirring stick
6. D-limonene
7. UV10 silicone epoxy by MasterBond
8. Vacuum chamber
9. Moveable platform capable of fitting and operating inside the vacuum chamber
10. UV light
11. Silicone sheet 0.1mm
12. High grit sand paper
13. Low grit sand paper

14. Sputtering Machine
15. Palladium-Gold sputtering material
16. Solder gun
17. Solder material
18. 2- Resisters of known resistance
19. 1- Variable resistance resistor
20. 2- Capacitors of known capacitance
21. Low temperature oven (not necessary)
22. Electric drill (not necessary)
23. Shaft (not necessary)
24. 3D Printed Mixing Propeller (not necessary)
25. Tape (not necessary)
26. Aluminum Foil (not necessary)

II. Steps to Manufacture Scaled Prototype

Using a 3D printer, upload the .obj file of the upper the sensor mold, seen in figure 2, into a 3D printer. Select the necessary options to begin the print.

Figure 2 HIPS bottom mold

Figure 3 HIPS top mold

Once the print has finished, remove the mold and begin to print the lower part of the mold shown in figure 3. The time to print the mold depends on the quality of the 3D printer. Once the molds have been printed, the Fibre Glast 2000 epoxy resin and Fibre Glast 2000 epoxy cure should be mixed in the prescribed directions. After thoroughly mixing the resin, allow 5 to 10 minutes for the bubbles to rise. This step is crucial as any bubbles that form in epoxy will decrease the sensors strength. Once the bubbles have risen, pour the epoxy into the bottom mold slowly to not allow any bubbles to be trapped under the epoxy. If any bubbles have been trapped or remain in the epoxy, then allow it to sit for roughly 2-5 minutes. Place the top part of the mold in to the bottom part slowly. Once the mold is assembled, allow 18-24 hours for the epoxy to cure due to the minimal heat exposer. This step can be accelerated by placing the assembled mold into the oven at a very low temperature (maximum temp allowed is 175°F), but allow the epoxy to cure for 10-15 minutes before placing in the oven. This will prevent any bubbles from forming while inside the oven. The time for the epoxy to cures varies on the temperature of the oven. Once the epoxy has hardened completely, place the mold into the D-limonene bath and allow for the HIPS plastic to dissolve. The time for this process varies vastly. The dissolving process can take up to 13 hours and thus it is recommended to enhance the dissolving rate. This can be done with a few different methods. The method selected by team 15 was to create a circulating current inside the D-Limonene bath. This was achieved by attaching a 3D printed mixing propeller, as shown in figure 3, to a shaft. This shaft was then placed inside of a 12-volt electric drill. The propeller was placed on the surface of the D-Limonene bath, and the electric drill was held in the on position by holding the button with tape as shown in figure 5.

Figure 4 3D printed mixing propeller

Figure 5 Electric drill being used to create a current in bath

This allows for the fluid to circulate decreasing the dissolving time to roughly 3-4 hours. If the circulating current is not created inside the D-limonene bath, then it is highly recommended to constantly check every 20 to 30 minutes, and remove the lose dissolving HIPS from the surface as this will decrease the dissolving time by a couple of hours. It is acceptable to simply allow the HIPS mold to dissolve in the D-limonene bath without assisting it, but the dissolving time could take more than 12 hours. Remove the sensor base from the D-Limonene and begin to sand any uneven or rough edges with the low grit sand paper, then use the high grit sand paper to give the mold a smooth and even finish. Clean any powder that may remain on the sensor after sanding. Cut a 2”x2” square of silicone. Place small moving platform inside the vacuum chamber with the silicone on the platform. Place the sensor base into the vacuum chamber directly underneath the platform. Place the UV10 epoxy on rim of the sensor base. Turn on the vacuum chamber and allow for all the air to be removed. Lower the platform onto the sensor and hold in place. Place the UV lights above the vacuum chamber and allow for the resin to cure. UV10 can take roughly 60 seconds to cure depending on the amount of UV light being used. It is recommended to use a UV light of wavelength 320-365 nm and energy output as low as 20-40 milliwatts/cm^2. If a UV light of different ratings is used the UV epoxy could take several minutes to cure. If a UV light of different ratings is used it is highly recommended to surround the entire structure in Aluminum foil. This will reflect any UV light amplifying the process. Once the resin is set, remove the sensor and trim excess silicone. Using the sputtering machine, sputter the top diaphragm and bottom surfaces using Pallidum-Gold for 15 minutes per surface. The rate of sputtering can be increased to increase the electric conductivity of the sensor. Solder the lead wires to the capacitor, and build a Schering bridge.

III. Time to manufacture scaled prototype

Table 1 Time to manufacture the sensor

Step	3D printing mold	Setting epoxy in mold	Dissolving HIPS mold	Sanding sensor	Attaching diaphragm to sensor	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	**80**	**1440**	**720**	**10**	**15**	**40**	**20**	**30**	**2,355**

The process to manufacturing the sensor was roughly 2,355 minutes (39 hours and 15 minutes) as seen in table 1. The manufacturing process took slightly longer than expected during the setting of the epoxy in the mold and dissolving of the HIPS. This was taken into consideration during the next batches of sensors manufactured. The manufacturing time was then reduced by introducing additions to certain process as previously mentioned in section 2. The mold for the sensor was also redesigned to allow for more surface area in the dissolving process. The reduced manufacturing time can be seen in table 2. The reduced total time to manufacture the sensor is 490 minutes (8 hours and 10 minutes), which was roughly half the time from the initial manufacturing process.

Table 2 Reduced time to manufacture the sensor

Step	3D printing mold	Setting epoxy in mold	Dissolving HIPS mold	Sanding sensor	Attaching diaphragm to sensor	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	**75**	**120**	**180**	**10**	**15**	**40**	**20**	**30**	**490**

IV. Necessary Supplies for Nano-Scaled Prototype Manufacturing

1. Electron Microscope
2. Germanium doped Silica fiber (165 µm diameter)
3. Hydrofluoric Acid (HF)
4. UV10 silicone epoxy by MasterBond
5. Moveable platform capable of fitting and operating inside the vacuum chamber
6. Sputtering Machine
7. Palladium-Gold sputtering material

8. Solder gun
9. Solder material
10. 2- Resisters of known resistance
11. 1- Variable resistance resistor
12. 2- Capacitors of known capacitance
13. UV lights
14. Silicone sheet (0.5µm)
15. Vacuum Chamber

V. Steps to Manufacture Nano- Scaled Prototype

A solid germanium doped silica fiber, roughly 165 µm in diameter, is prepared for an acidic etching solution with hydrofluoric acid. Acid is applied to the face of the silica, and allowed to etch downwards in a parabolic fashion into the germanium doped silica. Special consideration will need to be taken to ensure the cavity diameter created from the etching process is consistent with the diameter requested. A silicone diaphragm is then to be prepared at the correct thickness, 0.50 µm. UV10 polymer is applied to the rim of the silica fiber where the etching occurred. The sensor is then to be placed into a robotic arm that holds the sensor underneath the diaphragm. Once the air pressure is fully lowered below 10^{-2} Pa, the sensor is raised to the diaphragm until contact between the UV10 and diaphragm has occurred. Next, the UV light is turned on to set the UV polymer, and thusly seal the vacuum inside of the sensor. The sensor can now be taken out of the vacuum chamber. The sensor is then taken to a sputtering machine, so that Palladium-Gold tracts can be sputtered on both the hard silica bottom, and the top of the diaphragm on the opposite side. Next, wires need to be adhered to each respective capacitance plate, and the Shearing Bridge is constructed.

VI. Time to manufacture Nano-scaled prototype

The etching process at the beginning will take roughly 15-20 minutes, depending on the depth of the cavity that we would like to create. The etching process could be shortened, if a stronger acid is used\ or a more reactive substrate is chosen. Shaving the silicone diaphragm to the correct thickness is a slow process, and not meant to be accomplished hastily. This is approximated to take roughly 30-45 minutes, depending on the available equipment. The application of UV polymer glue at the Nano-scale is an arduous task, and could take the longest out of most of the steps. This process would have to occur under an electron microscope, and many factors can cause trouble. One big issue is the viscosity of the polymer. On a Nano-scale, viscous fluids need to be controlled slowly, as the misplacement of the sticky polymer could ruin the entire sensor. This is approximated to take roughly 20-30 minutes. Both bringing the vacuum down and setting the UV polymer is one of the easier steps, with the vacuum taking roughly 10 minutes to set to equilibrium, and the UV polymer activation taking 2 minutes to finish. The sputtering of the sensor, due to the small Nano-layers that would be needed, will only take 10 minutes at most to accomplish the desired tracts. The full sensor manufacturing can take roughly 4-5 hours, with very little room for optimization due to the issues faced at the Nano-scale.

All times for the Nano-scaled prototype are a rough estimate due to not being able to build the sensor. The Nano-scaled sensor would have to be outsourced to a third party company to manufacture.

Table 3 Time to manufacture Nano scale Prototype

Step	Etching Silica core	Silicone thickness face cut	Setting UV polymer	Attaching diaphragm to sensor	UV curing	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	20	40	30	10	2	10	40	30	182

VII. Complexity of the design

There are only 3 main components in the manufactured sensor. Those parts consist of the Palladium-Gold sputtering, silicone diaphragm and the silica base (or epoxy for the scaled prototype). The design cannot be simplified as these are the minimum parts necessary to create the sensor. The only section of our design that can be changed would be the Schering Bridge. The addition of a network analyzer to replace the Schering Bridge will allow the pressure to still be read without the complexity or additional parts necessary for the Schering Bridge. The network analyzer would be more useful when conducting experiments in lab, while the Schering Bridge would be more useful in its application in outer space.

Design for Reliability

The prototype should work just as well the first time as it does the 10,000 time. This is because there are not many moving parts with this sensor since it is mostly electrical. The far more probable chance of failure is if the senor breaks from damage incurred during the lift off or flight. The main reliability concern is if the seal breaks within the sensors measuring cavity. If this problem did occur, it could only be fixed at a lab able to reseal the seal under a vacuum chamber.

Design for Economics

The total budget set aside for this project was in the range of $500 – 700, but these funds weren't physically allocated to Team 15. It is expected out-of-pocket costs spent on the project will be reimbursed. Taking $500 as the minimum for the expected allocated budget, the total cost of the project was roughly $160. Thus, 32% of the total budget was exhausted. Figure 6 lists the costs of each component of the system.

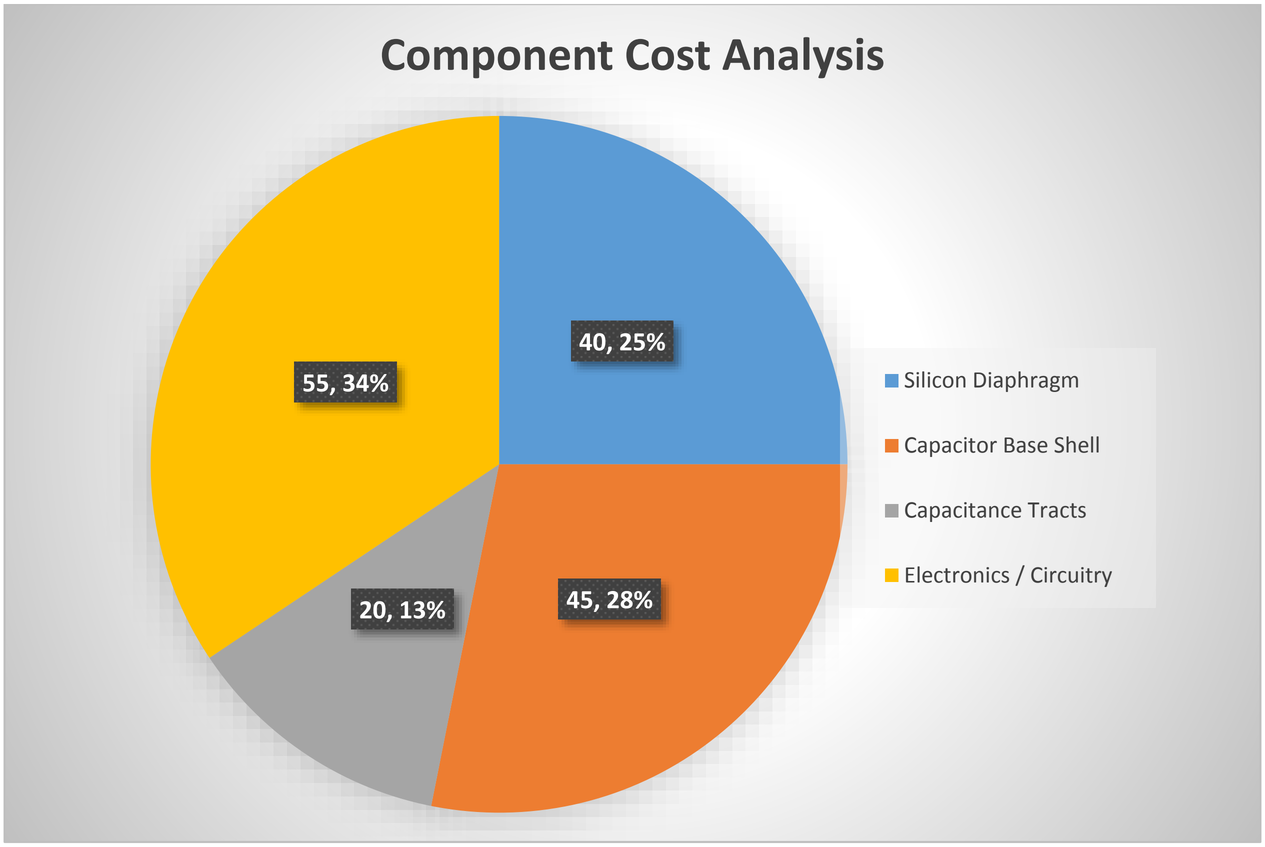

Figure 6 A pie chart depicting the breakdown of funds spent on the project as a number and a total percentage

Approximately 25% of the $160 was spent on purchasing sheets of silicon for the top diaphragm. 28% was spent on purchasing moderately cheap epoxies that were used to create the capacitor base shell. By far, the cheapest component of the system was the capacitance tracts, which were only $20 but this figure is a rough estimate. The costliest part of the system was the circuitry which comprised a significant chunk of the budget as expected since electronics are always the priciest component of any system. $340 or 68% of the $500 were unused. Since the price of the capacitance tracts is an estimate, a good price range for the pressure sensor is expected to be $145 – 160. To further reduce this cost, cheaper epoxies could have been used to produce the capacitance base shell, cheaper electronics could have been integrated into the system, or a different material could have been used for the diaphragm although silicon offers good flexibility and a measurable deflection at low pressures.

It is difficult to compare the original, Nano scale pressure sensor to other competitors on the market since most pressure sensors aren’t built to be accommodated into the interstitial space (0.42mm) between the Multi-Layer Insulation. However, comparing the scaled-up prototype to other competitors’ pressure sensors doesn’t prove to be a challenge. Figure 7 illustrates this comparison.

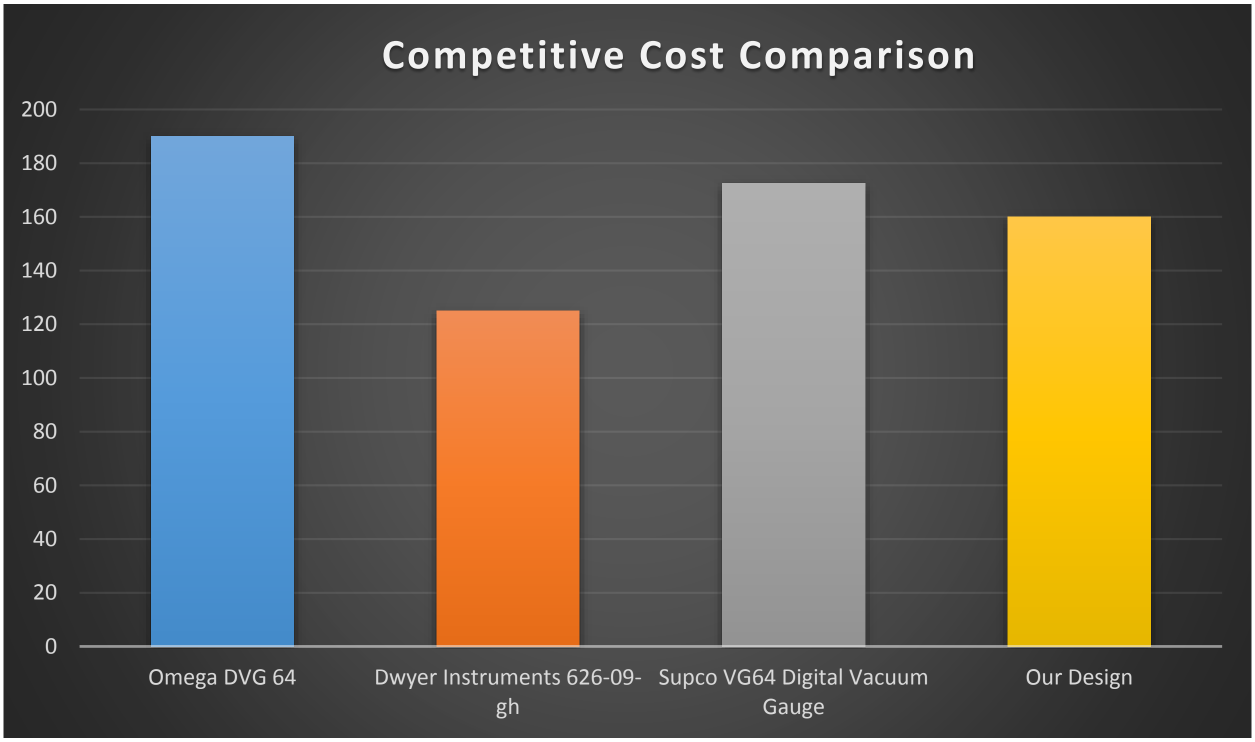

Figure 7 Bar graph comparing competitor’s pressure sensors

Our specific design wasn’t the cheapest, but was relatively cheap when compared to other competitors. The Dwyer Instruments 626-09-g-h-p1-e4-s1 pressure transducer, with a reading range of 0 to 50psig, outperformed our design in cost, but doesn’t offer advantages that our sensor does like scalability and minimal power consumption[1]. The Vacuum Gauges, the Omega DVG 64 and the Supco VG64, were pricier than our capacitive pressure sensor and also offer good reading ranges from roughly 0 to 12 Torr [2].

References

[1] "Pressure Transducer, 0 to 50 PSI." *Everything You Need to Clean, Build or Fix*. N.p., n.d. Web. 07 Apr. 2017.

[2] "Providing the Finest Test Equipment Solutions since 1992." *ROBOT WARNING - at the Test Equipment Depot*. N.p., n.d. Web. 07 Apr. 2017.

Appendix

Key Part	Potential Failure Mode	Potential Failure Effects	Severity	Potential Causes	Occurance	Current Control	Key Part	Potential Failure Mode
Palladium Gold Sputtered Capacitance Plate	Doping Surafce Wears Off	Renders Sensor Inoperable	10	Wore Down by the Sun	1	Check Sensor Every Three Months	9	5
[redacted]	Surface Breaks	Renders Sensor Inoperable	10	Damage by Collision or Enviromental Effects	1	Check Sensor Every Three Months	8	5
Silicone Diaphram	Diaphram Ruptures	Renders Sensor Inoperable	10	In a High Pressure Eniviroment	1	Ensure Control of the Pressure of the Enviroment	6	5
Silica Capacitor Plate	Plate Cracks	Renders Sensor Inoperable	10	Enviroment	1	Check Sensor Every Three Months	9	5
Integrated Circuit	Circuit Breaks or Cracks	Cannot View Measurement	9	Outgassing	3	Check Several Times Before Launch that Circuit Has Been Expelled of All Gas	10	8
[redacted]	Circuit Malfunctions	Cannot View Measurement	9	Coponent Breaks	2	Test Circuit Before Launch	9	3