Fabrication and Optimization of a Tesla Valve

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As devices are getting smaller and smaller, the need for miniaturized components has increased. In the world or microfluidics, the control and manipulation of fluids on a microscopic scale, components like valves that allow flow in one direction only and that can handle micro size volumes of fluids are needed. For this we can turn to the Tesla valve. This experiment explores the fabrication and optimization of these valves.

I. INTRODUCTION

Tesla valves were invented by Nicola Tesla in the 1920's, but only recently has the technological world been interested in them. As microfluidics become more widely used the need for smaller and smaller microfluidic components has increased. The Tesla value is a microfluidic tubular conduit designed to allow the free flow of a fluid in one direction but impede the flow in the opposite direction without the need for any moving parts (Figure 1). This design makes it resistant to wear and fatigue. They also can be built very small on the microscopic level.

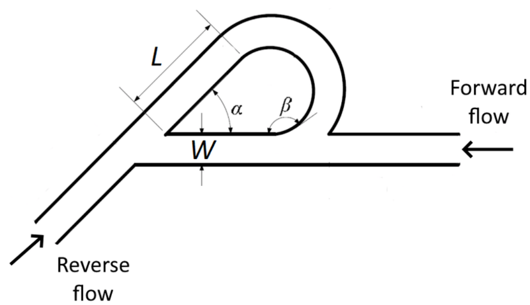


FIG. 1. The basic scheme of Tesla valve design indicates different dimensions and parameters: valve width, W, length of the straight segment of the valve channel, L, valve side-channel leaving angle, α, and valve side-channel return angle, β (REF. 1).

Microfluidics is the manipulation and control of fluids in microscopic structures measuring in the submillimeter range and usually only deal with very small volumes of fluids (can be in microlitres). Microfluidics is being used in Lab-on-Chip technology: very small chips that can provide an array of testing and analysing procedures. These chips can include such Point of Care procedures like pregnancy testing and glucose biosensors. Microfluidics is also used in drug administration, pH control and cell analysis. The Lab-on-Chips can be fabricated easily and at low cost, so these chips have become very popular recently. Therefore, there is an increasing need for miniaturized components like check valves. This is where the Tesla valve can be advantageous.

How these valves work is quite simple. When used in the forward flow direction, the flow does not get much resistance, so the flow is not impeded. When the valve is used in the reverse flow direction, the unique design of the valve loop causes turbulence within the channels causing the flow to be impeded. When the flow reaches the valve side leaving channel, at the Y split, the flow is split up and most of the fluid tends to go straight rather than change directions at the Y split going down the main channel. The flow is then redirected via the loop and the flow re-enters the main channel at the valve side return junction. The fluid coming in from the valve side return meets with the fluid in the main channel. Since the fluids are not going in the same direction, turbulence results and causes the flow to slow down or halt all together (Figure 2).

The effectiveness of a Tesla valve depends on its ability to impede flow in the reverse direction. This is what is known as it's diodicity. Diodicity (Di) can be calculated using the change in pressure, the pressure drop (ΔP), in the reverse flow direction versus the forward flow direction given that the pressure drops are measure with the same flow rate (Q):

$$Di = \left(\frac{\Delta P_{reverse}}{\Delta P_{forward}} \right)_Q \tag{1}$$

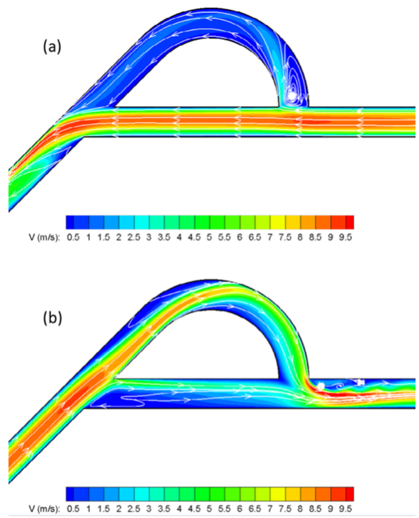


FIG. 2. Tesla valve simulation: forward and reverse flow velocities (REF. 2).

In order to have a more effective Tesla valve, its diodicity should be high. This means that the turbulence caused in the channels must be increased to impede the flow in the reverse direction. This turbulence is caused by how the Tesla valve is designed and built. There are many different ways that a Tesla valve can be built but there is no formula to predict how changes in the valve's dimensions will effect the valve's diodicity. One way to create an optimal Tesla valve is by trial and error.

In this experiment, multiple Tesla valve designs will be created each with only one parameter changed to their dimension. These Tesla valves will be fabricated and tested for their effectiveness. The intent of the is experiment is to discover what dimensions of the Tesla valve produces optimal performance with the highest diodicity.

II. THE EXPERIMENT

The procedure for this experiment will involve many stages each with their own procedures with the goal of producing an optimized Tesla valve. There is a design stage where the valves are designed, and chip designs are made where the valves will be situated on a chip. These chip designs are photographed where the film negative will be used in the masking stage of the soft-lithography fabrication process. The chips will be fabricated using soft lithography (Figure 3). The final chips with Tesla valve embedded will be tested and their effectiveness will be measured.

To create an optimally performing Tesla valve, different versions of a Tesla valve would have to be tested. Tesla valves have many parts with dimensions that can be changed. To keep the scope of this experiment feasible, the valve-side leaving angle, α, and the valve side return angle, β, (Figure 1) were chosen to be the only parameters that were intentionally manipulated.

Three values of α and three values of β were chosen to manipulate a Tesla valve's diodicity. The α angles consisted of 15°, 30°and 45°. The β angles consisted of 90°, 120°, and 150°. The valves were designed so that each valve with a certain α angle would have a version with the 3 different β angles (Figure 4(a)). This gave rise to 9 permutations of the valves. As a control, a "valve" with no valve parts (no the leaving, loop and return channels) was created for each α angle so just the contribution of the α angle to the valve's effectiveness could be measured. This created a set of 4 valve designs for each α angle, 12 in total. All Tesla valve designs had a channel width, (W),(Figure 1) of 85 μm.

Each α angle set was put on one chip design (Figure 4(b)). These chip designs would be the actual layout of the Tesla valves when the chips are fabricated. These chip designs were to be photographed with film where the negative of the photograph will be used in the masking stage of the fabrication process. Since the film negative would be the actual size of the valves. A scale factor was needed.

The film was 35 mm high definition black and white film. The negatives have a dimension of 36 x 24 mm, 3:2 ratio. The chip designs were designed with the paper size of A4 (297 x 210 mm) in mind since a 3:2 image would fit best on it. The chip designs had a 288 x 192 mm dimension so all designs had a scale up factor of 8:1. The width of the Tesla valves were to be 85 μm, this meant that the printed version of the valves would have channels of 0.68 mm (8 x 85 μm). Each chip design was printed to be photographed (Figure 5).

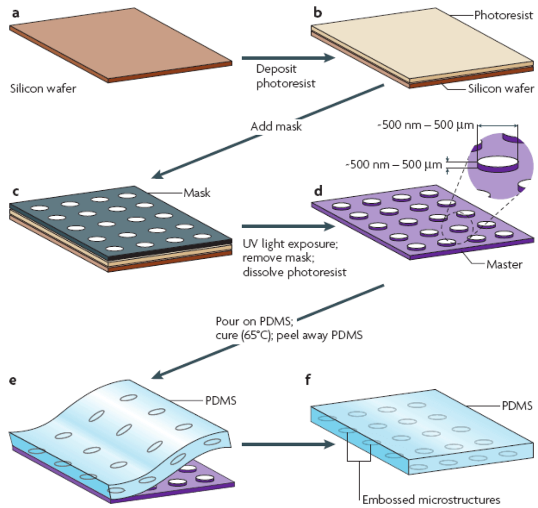
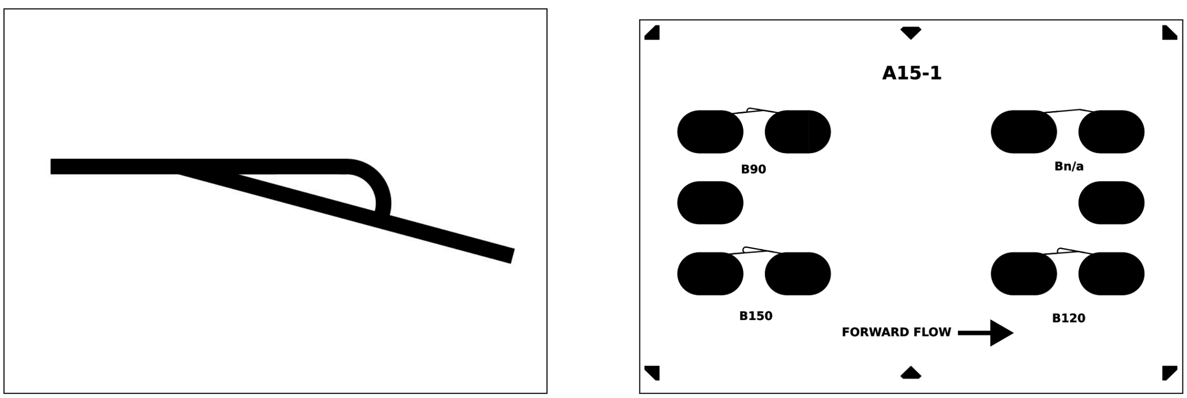


FIG. 3. The soft lithography technique to fabricate the Tesla valve chips (REF. 3)



(a) A single Tesla valve design with α angle of 15°and β angle of 90°

(b) Printed chip design A15-1

FIG. 4. Tesla valve designs

The negatives of these chip design are to be used in the masking stage of fabrication, so the negatives would need to have high contrast. The black portions needed to be as black as possible not to let light through and the transparent portions must be as clear as possible to let as much light through as possible. An experiment to create film negative with the optimal contrast was developed. Multiple photographs were taken, using a Nikon FM10 35 mm camera, of one chip design changing the aperture and exposure settings in a controlled environment (Figure 6). The settings that produced optimal contrast was a zoom of 70, aperture of 4.5 and exposure valve of 15. The chip designs were photographed using these settings. Multiple photos of each design were taken and filled a whole roll of film.

To produce a working Tesla value, soft lithography was used to fabricate the chip designs. First an SU-8 mold of the chip design was then created. A clean blank silicon wafer was centered a spin coater. This mold will produce the thickness of the Tesla valves, giving the valve height to the 2-dimensional design. The channels of the Tesla valves were designed to be 85 μm so the height of the channels had to be around the same value, giving them a square cross section. The target height was 100 μm, so the SU-8 needed to be the same thickness.

About a teaspoon of the SU-8 was put onto the center of the wafer and allowed to slightly dissipate over the surface. The SU-8 is very thick and sticky, so it is very slow moving. The spin coater will spin the wafer with the SU-8 to spread out the SU-8 to give it a uniform thickness. To get a desired thickness, the spin coater is programmed with two stages of angular speeds, times and angular accelerations. Stage 1 consisted of an angular speed of 500 rpm for 10 s with an angular acceleration of 50 rpm/s. Stage 2 consisted of an angular speed of 1000 rpm for 30 s with an angular acceleration of 150 rpm/s. The wafer with the SU-8 was pun at stage 1 and stage 2 consecutively.

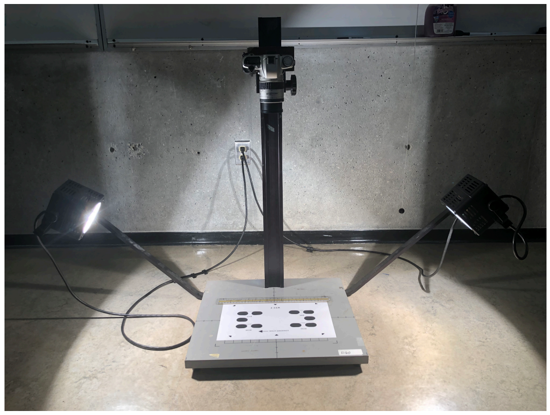


FIG. 5. Apparatus used to photograph printed chip designs.

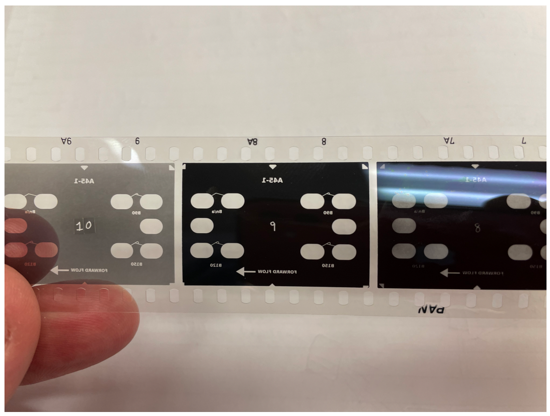


FIG. 6. Sample of the film that was used for exposure testing.

Once the silicon wafer was coated with SU-8, the wafer and SU-8 was baked on a hot plate. It was baked at 65°C for 3 mins, increased to 95°C at 7.5°C/min (approximately 4 mins) then allowed to bake for 9 mins at 95°C. While it was heating, some of the lighting was turned off as the heating process activated the SU-8's photo-sensitivity. The heat was shut off and the wafer was allowed to cool naturally. Once cooled it was transferred to a metal petri dish and its lid was secured to block as much light as possible since the SU-8 is now ready for the ultraviolet (UV) light exposure.

A negative with the best contrast of each chip design was cut from the film strip (Figure 7). A duplicated of the A15 chip was also cut since 4 chip designs could fit the wafer. Film negatives were placed over the SU-8 and arranged so they didn't overlap but fit within the confines of silicon wafer. They negatives were placed inside curve down. This is the side that the actual film image is on and makes sure the at the masking images is as close to the SU-8 as possible creating cleaner structures. A quartz plate was cleaned of dust and put over the film masking to make sure the film lay flat and close to the SU-8 surface as possible. The silicon wafer was put on a tray in the UV chamber and was exposed to UV light at 100% for 10s. After exposure, the masking film was removed, and the wafer was transferred to the metal petri dish and covered with the lid.

Once the SU-8 had been exposed to UV another bake was carried out. The wafer was removed from the metal petri dish and the SU-8 was baked at 65°C for 2 mins, increased to 95°C at 7.5°C/min (approximately 4 mins) then allowed to bake for 7 mins at 95°C. It was transferred immediately to the metal petri dish after the bake to allowed to cool naturally (approximately 15 mins).

When the wafer and SU-8 had cooled to room temperature, the SU-8 was used to develop it. The wafer was put into a crystallizer dish and covered with SU-8 developer just enough to cover the SU-8. The dish was agitated and allowed to wash over the SU-8 for 7 mins. The wafer and developed SU-8 was rinse with IPA for 10s on both sides of the wafer and allowed to air dry. The SU-8 developer washed away the parts of the SU-8 that was not exposed to the UV light and the chip design were now visible. The SU-8 mold was now complete (Figure 8).

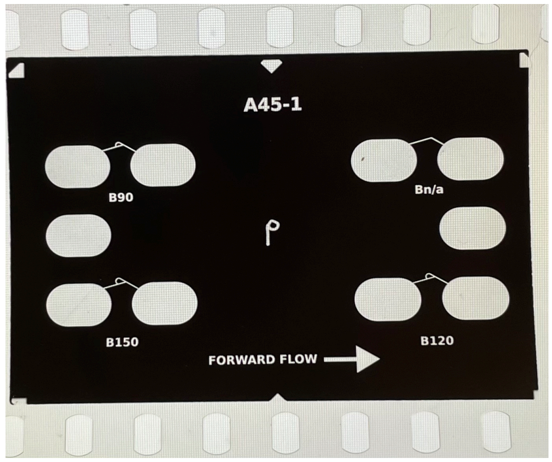


FIG. 7. Black and white film negative used as masking.

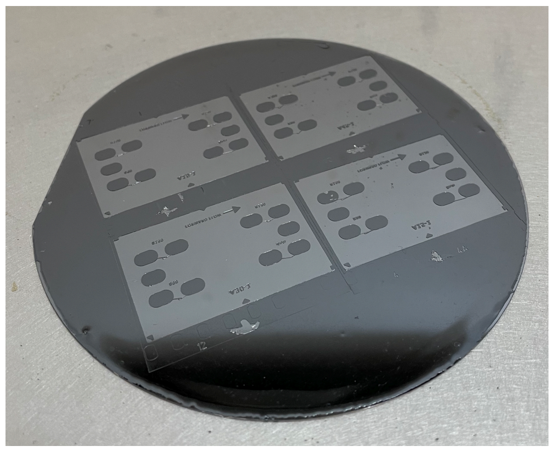


FIG. 8. Finished SU-8 mold on a silicon wafer.

PDMS replication is the next stage to fabricating the tesla valves. Sylgard 184 Silicon Elastomer PDMS (polydimethylsiloxane) was measured out at 72.1 g and mixed with the 7.2 g of curing agent (10:1 ratio). It was mixed thoroughly with a glass rod. The mixture was degassed in a vacuum chamber to rid the mixture of bubbles, for approximately 40 mins.

The SU-8 mold was sprayed with compressed air to rid the surface of any dust particles. The degassed PDMS was poured over the SU-8 mold in the metal petri dish. The petri dish with its contents were put into the vacuum chamber again and allowed to degas again for approximately 25 mins. While it was degassing, another volume of PDMS was prepped. After the PDMS in the mold was finished, the new PDMS was degassed as well and poured over a blank silicon wafer in the petri dish lid and allowed to degas once more. This blank PDMS will serve as a lid for the PDMS chip. Both the PDMS in the mold and the bank PDMS were baked in an oven at 100°C for 30 mins.

The PDMS is now a very clear rubber-like material. Each PDMS chip was cut out with a scalpel. A lid the same size as the chip was also cut from the blank PDMS. Only one PDMS chip was removed at a time to prevent dust contamination of the surface that will be bonded with the lid. The chip was laid embossed side up and a piercing device was used to punch holes through the areas designated for inlet/outlets. Once the chip was pierced, a PDMS lid was removed. The chip and lip were laid on a glass shelf with bonding surfaces facing up. The glass shelf was inserted into a plasma cleaner.

The plasma cleaner door is closed, and the vacuum pump is turned on. Once the chamber reached 0.500 torr, the plasma cleaner was turned on high for 2 mins. The plasma was turned off and the chamber pressure was slowly increased to atmospheric pressure. The surfaces of the PDMS need to be bonded within 2 mins after exposed to the plasma, so the PDMS chip and lid were removed and using a reverse peel away technique, bonded the lid to the chip. A glass petri dish was put onto the lid and uniform pressure was applied to help the bonding process. Each of the other chips were bonded the same way and all chips were baked again in the oven at 80°C for 1 hour. The PDMS chips were then complete (Figure 9). A scanning electron microscope was used to get close up images of the fabricated Tesla valves (Figure 10(a))and a cross section of the depth of the channels (Figure 10(b)).

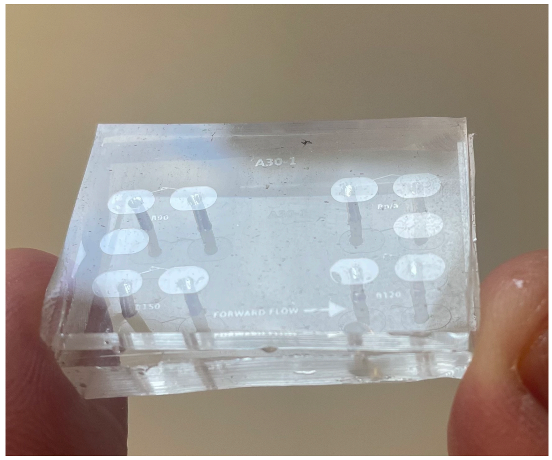
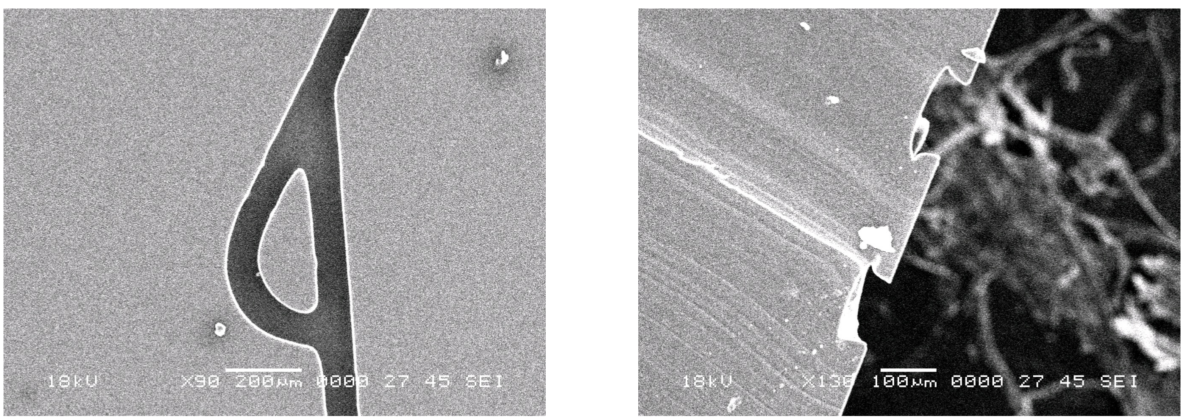


FIG. 9. PDMS chip containing Tesla valves.



(a) Tesla valve

(b) Cross section of Tesla valve showing channel height

FIG. 10. Scanning electron microscope images of A15B90 Tesla valve in PDMS

The Tesla valves were tested using a testing apparatus designed for this experiment. An Epsimed Syringe Pump, model KL-602, was used as way to deliver a specific flow rate. A 1.6 mm ID hose was attached to the end of the syringe. The hose led to a hose tee that branched off, with one hose branch leading to a pressure sensor and the other branch leading to the inlet of the PDMS chip. The pressure sensor was a Honeywell ABP2 series sensor with a gauge pressure range of 0 - 60 psi (413 kPa) with an I^2C bus. The sensor was connected to a Trinket M0 microcontroller, and a Circuit Python program was written to retrieve and convert the senor date to a pressure reading.

Before the chips were tested, and testing process had a test run. The syringe was filled with deionized water and any air trapped was purged. The syringe was set up in the syringe pump. The hose was attached to the end. An input and outlet was attached to a PDMS chip. The pump was turned on at a slow rate of 10 mL/hr. At first no water was moving. This was due to a large amount of air being trapped in the hose. This problem was corrected by purging the air before hooking up to the PDMS. This way the only air in the testing system would be the small amount in the PDMS chip. Once water was observed leaving the outlet tube, testing and measurements could begin.

The chip that was tested was the A15-1 chip where all Tesla valves had an α angle of 15°. The lines were purged of air. The inlet and outlet hose leads were installed in the forward flow configuration. The outlet lead was a short piece of hose allowed to drain into a petri dish. The pump was turned on a specific flow rate. The computer would take pressure readings once the pressure increase would start to level off. Once it leveled off a pressure measurement would be recorded for that flow rate and the pump would be set to the next higher flow rate. The pressure measurements would continue to be recorded with correlating flow rates. Once all measurements were made for the forward flow rate, the outlet and inlet leads were switched, and the flow was applied in the reverse direction and measurements were taken and recorded the same way as the forward flow.

Some precautions were taken during the fabrications process. The application of SU-8 on the silicon wafer must be done in a fan hood as there are toxic fumes that come from the SU-8. The SU-8 should be handled using gloves and goggles and lab coat should be worn. SU-8 must be cleaned using acetone so that would also be best under a fan hood.

Other precautions taken were mostly to prevent dust from contaminating the fabrication and testing process. The SU-8 and PDMS was continually covered when possible. When the PDMS chips were tested with the deionized water, the water lid was secured after each water draw with the syringe.

III. RESULTS

The first trial of testing and measurements were conducted on the Tesla valve with an α angle of 15°and a β angle of 90°contained in the A15-1 chip. The testing resulted in an increase in reverse flow pressure drop (Figure 12) and a final diodicity of 1.08 at a flow rate of 170 ml/hr (Figure 11). This was a first trial of testing to test out the testing and measurement procedure.

First Trial: Tesla Valve Pressure Responses to Forward and Reverse Flow rates (pressures in kPa)

Tesla Valve			FORWARD Flow rate (ml/hr)				
Chip	α	β	50	100	150	160	170
A15-1	15	90	30.1	63.0	96.8	104.7	109.3

Tesla Valve			REVERSE Flow rate (ml/hr)				
Chip	α	β	50	100	150	160	170
A15-1	15	90	32.0	65.0	102.4	111.4	118.5

First Trial: Tesla Valve Diodicity

Tesla Valve			Flow rate (ml/hr)				
Chip	α	β	50	100	150	160	170
A15-1	15	90	1.06	1.03	1.06	1.06	1.08

FIG. 11. First trial pressure drops in Tesla valve A15B90

The next trial of testing involved the same PDMS chip. Tested 3 α 15°Tesla valves: one with no leaving, loop or return channel, one with a β angle of 90 and one with a β angle of 120 (Figure 13).

IV. DISCUSSION

The valves that were fabricated in chip A15-1 did not perform as expected. The reverse flow pressure drops should have been significantly higher than that of the forward flow pressures but they were not (Figure 14). Therefore, the data collected on the Tesla valves fabricated in this experiment is inconclusive.

There are a few reasons why these Tesla valves did not perform as expected. In a simulation of a Tesla valve in "A numerical investigation of flows of nanofluids through a micro Tesla valve" (REF. 2), the range of flow rates and resulting pressures were much higher than what was tested in this experiment. In the simulation, significant pressure differences between forward and reverse flow rates began around 3 ml/min (180 mL/hr). In this experiment, the fabricated Tesla valves could only be tested at a maximum of 120 - 170 mL/hr before the syringe pump occlusion sensor would cause a pause in fluid flow. This occlusion sensor of the pump, due to its medical nature, was designed to detect a blockage in intravenous lines by sensing a high pressure. The highest pressure setting that this could be set at was 150 kPa. Therefore, testing the Tesla valves at the flow rates needed was not possible.

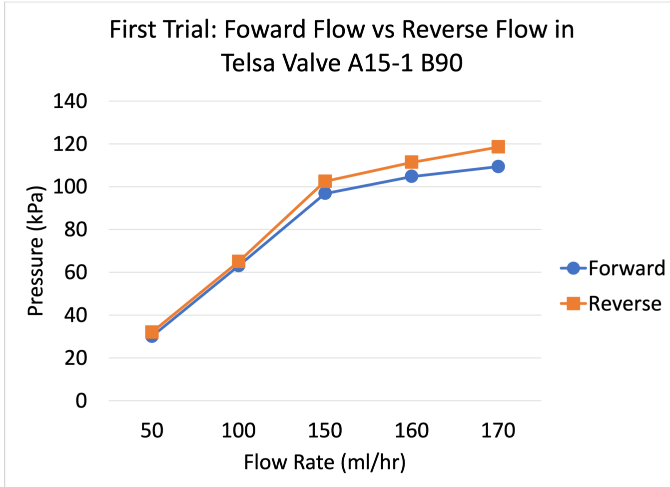


FIG. 12. First trial and measurement testing of Tesla valve A15B90

Second Trial: Tesla Valve Pressure Responses to Forward and Reverse Flow rates (pressures in kPa)

Tesla Valve			FORWARD Flow rate (ml/hr)									
Chip	α	β	25	50	75	100	110	120	130	140	150	160
A15-1	15	n/a	10.8	20.5	30.3	44.5	52.6	57.2	64.2	69.0	72.9	79.4
A15-1	15	90	15.9	29.0	46.3	62.0	70.2	77.5	83.9	92.6	N/A	N/A
A15-1	15	120	17.4	34.4	53.6	76.5	85.2	93.2	102.1	N/A	N/A	N/A

Tesla Valve			REVERSE Flow rate (ml/hr)									
Chip	α	β	25	50	75	100	110	120	130	140	150	160
A15-1	15	n/a	15.8	30.4	45.8	62.6	70.7	78.1	85.9	94.0	100.7	107.4
A15-1	15	90	15.7	30.9	47.3	63.8	72.5	79.1	N/A	N/A	N/A	N/A
A15-1	15	120	15.9	32.9	49.4	70.3	77.3	85.4	93.6	102.8	108.2	N/A

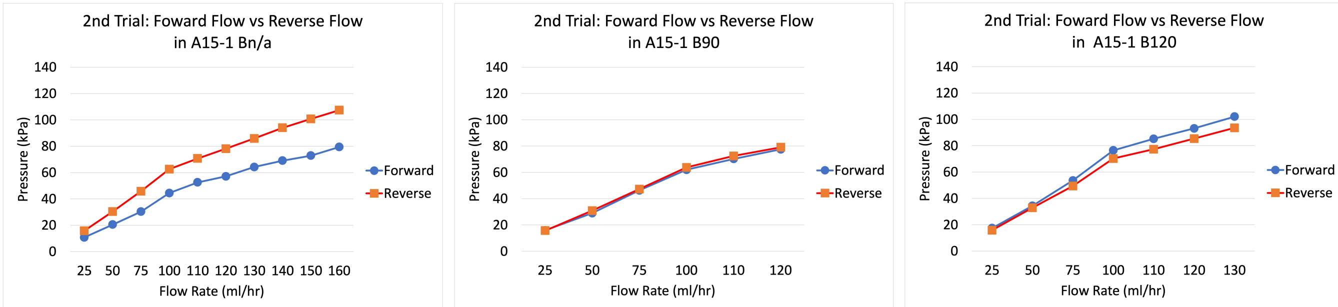
Second Trial: Tesla Valve Diodicity

Tesla Valve			REVERSE Flow rate (ml/hr)									
Chip	α	β	25	50	75	100	110	120	130	140	150	160
A15-1	15	n/a	1.47	1.48	1.51	1.41	1.34	1.37	1.34	1.36	1.38	1.35
A15-1	15	90	0.99	1.07	1.02	1.03	1.03	1.02	N/A	N/A	N/A	N/A
A15-1	15	120	0.91	0.96	0.92	0.92	0.91	0.92	0.92	N/A	N/A	N/A

FIG. 13. Second trial pressure drops in Tesla valves A15Bn/a, A15B90 and A15B120

When testing the Tesla valves, they responded with higher pressures than expected. The high pressures were the reason why the pump's occlusion sensor preventing testing at higher flow rates. In the simulation mentioned above pressures were measured around 45-50 kPa at the 2 mL/min (120 mL/hr) whereas in this experiment the pressures at that same flow rate had a range of 60-90 kPa. This could have been due to the different size of the channels of the valves in the simulation (100 x 100 μm) vs the channels of the valves fabricated in this experiment (approximately 85 x 50 μm). Another reason for the higher pressure could be due to contaminates. At a microscopic level the introduction of a small piece of lint or dust could impede flow very easily.

Going further this experiment could be carried out successfully by improving on a few of the procedures. The syringe pump the main drawback in this experiment. A syringe pump that could create flow rates up to 400 mL/hr and allowed to exceed pressures of 150 kPa would be needed. The spin coating procedure of the SU-8 must be altered to provide the proper desired thickness of SU-8 which determines the height of the Tesla valve channels. Also, the testing phase of the Tesla valves could have been improved if more steps were taken to reduce contaminates such as preforming the testing in a clean room.



(a) Tesla valve with no leaving or return channel with α at 15° (b) Tesla valve with α at 15°and β at 90° (c) Tesla valve with α at 15°and β at 120°

FIG. 14. Pressure to flow rate responses of 3 Tesla valves, second trial.

V. CONCLUSION

The intent of this experiment was to optimize a Tesla valve. The Tesla valves produced in this experiment did not show higher pressures in reverse flow rates when compared to the pressure of the forward flow rates. Since the Tesla valves did not respond as predicted, obtaining an optimized Tesla valve was not possible in this experiment. The fabrication process was successful in producing accurate dimensions of the 2-dimensional design, however the height of the channels of the Tesla valves were not produced as intended.

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