NOZZLE FABRICATION FOR MICRO PROPULSION OF A MICRO SATELLITE

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Abstract — *To enable formation flying of micro satellites, small sized propulsion systems are required. Our research focuses on the miniaturization of a feeding and thruster system by means of micro system technology (MST). Three fabrication methods have been investigated to make a conical converging-diverging nozzle. These methods are reactive ion etching, femtosecond laser machining (FLM) and a combination of powderblasting and heat treatment. It is shown that the latter two methods are very promising.*
Key Words: *nozzle, thruster, micro propulsion, satellite*

I INTRODUCTION

In a propulsion system, the nozzle is primarily used to increase the velocity of the exhaust. The higher the effective outlet velocity the more thrust is generated with the same amount of expelled mass and therefore efficiency is increased.

These nozzles are required as part of a propulsion system to enable formation flying of micro satellites. For the formation flying of two micro satellites where the distance between the satellites is controlled a nozzle is required delivering a thrust in the order of 1 to 10 mN. The typical shape of a de Laval nozzle is shown in Figure 1. A subsonic flow enters the converging part of the nozzle and becomes supersonic in the throat of the nozzle. The gas is further accelerated in the diverging part of the nozzle till it is expelled though the nozzles exit.

Previously, nozzles have been fabricated by means of micro system technology [1]. These nozzles are fabricated by reactive ion etching which is used to obtain a 2D extruded shape.

We explored three potential technologies to make a conical converging-diverging nozzle. To enable integration with the other parts of the MST thruster and feeding system the nozzle should be made of silicon or glass. Important parameters for the nozzle are profile control and surface roughness. The most important aspects of the nozzle profile are the throat and exit diameter and the half angle (α) of the diverging bell shaped part of the nozzle. The throat area determines the mass flow through the nozzle and the ratio between the throat area and the exit area determines the outlet velocity and outlet pressure of the exhaust flow. To obtain the required thrust the throat diameter should be in between 50 and 300µm, depending on the inlet pressure and expansion ratio. The diverging part of the nozzle has a half angle between 15 and 20°. The converging part of the nozzle is typically 30°, but is not a very important parameter for the performance.

Typically, the radius of curvature (r_t) of the throat is equal to the throat diameter. To prevent flow separation and shock formation in the nozzle the roughness of the sidewall should be minimal especially in the throat. A rough surface widens the viscous boundary layer reducing the generated thrust.

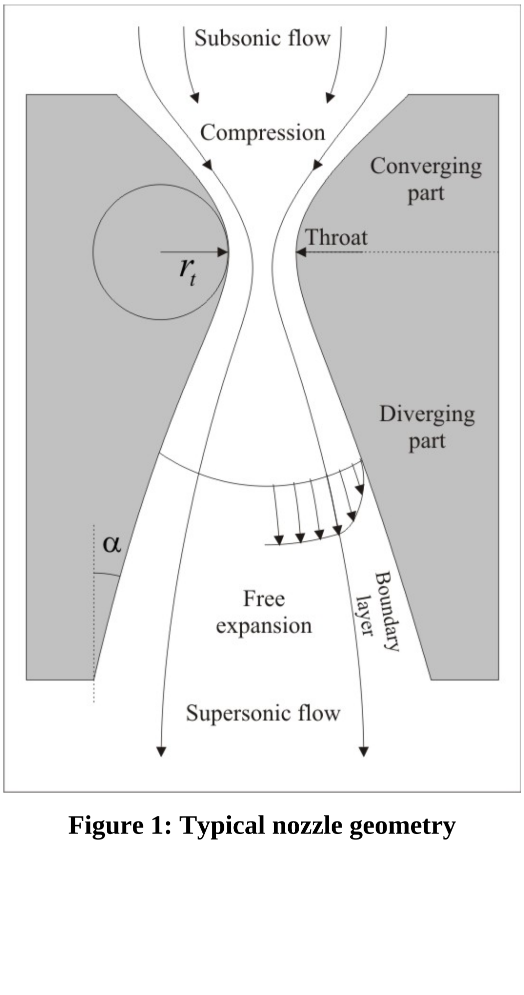

Figure 1: Typical nozzle geometry

II NOZZLE FABRICATION

II.1 DEEP REACTIVE ION ETCHING

The first fabrication method that is explored is deep reactive ion etching (DRIE), where plasma is used that consists of ionic and reactive (radical) species which are important in the etching of silicon [2]. The basic idea for etching the nozzle is to combine an isotropic etch step for the converging part of the nozzle (Figure 2 left), with a negatively tapered etch step (Figure 2 middle) having a diverging angle between 15 and 20°. During both etch steps the same photo-resist mask is used which has 50μm circular features. When both etch steps are preformed for 10 minutes consecutively it results in the shape as shown in Figure 2 (right). The depth of this nozzle shape is 260μm and the throat diameter is 76μm. The angle of the diverging part of the nozzle is approximately 5°. As the critical part is the diverging angle this is studied in the next section.

Figure 2: (left) Isotropic etch, (middle) directional etch, (right) obtained nozzle shape

There are two mechanisms that can cause a negative tapered profile; the ion angular distribution (IAD) and the image force (IF) effect. The plasma glow shown in Figure 3 is a region where the plasma is highly conductive and rich of ions and radicals. In between the plasma glow and the silicon a dark space is present where there is a depletion of electrons which gives it insulating properties. This causes strong electrical fields to develop in the dark space when a bias voltage is introduced, which accelerates ions from the plasma glow straight towards the etching surface.

Because of the collisions of ions with other species and their thermal motion in the plasma glow, ion dispersion will occur (Figure 3). At high pressure the ions encounter many collisions with gas molecules while travelling through the dark space and the IAD broadens to ca. 30°. When ions arrive under an angle with sufficient kinetic energy, they will cause etching of the sidewalls below the mask; i.e. negative tapering. Figure 3 shows the result of a high speed etch recipe based on the Bosch process [3] optimized for a broad IAD and high kinetic energy, meaning high pressure and bias voltage. The larges negative taper that was achieved is about 5° and not enough for the diverging part of the nozzle.

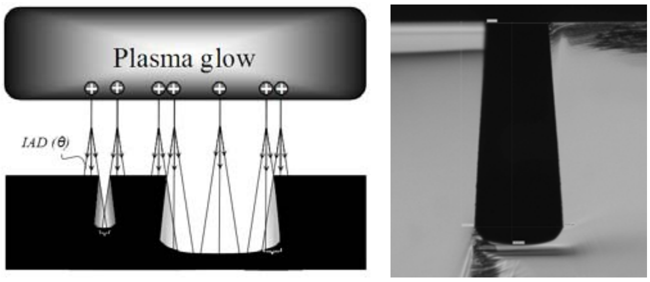

Figure 3: IAD effect: ion angular distribution caused by collision in the dark space.

The image force is the electrostatic attraction of incoming ionic species due to influencing fields, towards the silicon sidewalls as shown in Figure 4. This force is inversely proportional to the square of the distance, so the acceleration toward the sidewall is ever increasing until the particle collapses with the surface causing a negative taper. A high speed etch recipe based on cryogenic SF_6/O_2 is used to show the effect of the IF [4]. This kind of recipe is known for its thin SiO_2 passivation layer which makes it sensitive for the IF when a low bias voltage is used. From the resulting etch profile as shown in Figure 4 one can observe two important effects. The upper part of the profile is insufficiently passivated and therefore the silicon is etched by radicals. There is no process setting found that result in a sufficient negative taper while the upper part of the profile is preserved. Second, the negativity of the taper is ever increasing towards the bottom of the profile. This is an undesired property for the diverging part of the nozzle because it results in flow separation when the angle becomes too large.

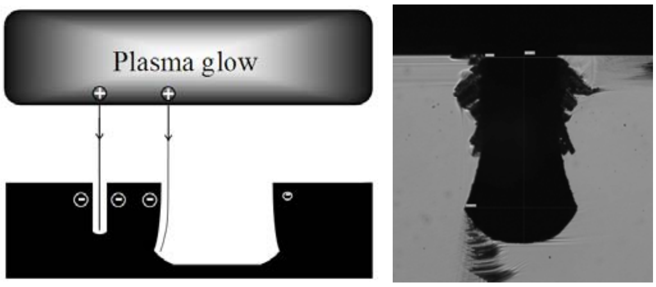

Figure 4: IF effect: image force caused by deflection of ions inside trenches.

II.2 FEMTOSECOND LASER MACHINING

For the second method of fabrication femtosecond laser machining (FLM) is explored, which is considered a promising technology for manufacturing down to the micro-scale. Due to ultra short pulses and high peak intensities a small amount of material is ablated resulting in high accuracy and repeatability ([5],[6]).

To obtain the conical-divergent nozzle shape, the silicon is machined from two sides. The laser beam is focused into a laser beam spot size of 25 µm. The energy density (fluence) in the laser beam spot is 0.81 J/cm^2 (Gaussian distributed). This is substantially above the minimum energy density needed on the surface of the material for ablation to occur, i.e. the ablation threshold. We found that the minimum beam fluence needed for ablation to occur depends on the machining speed and pulse repetition rate. At a machining speed of 80 mm/s and pulse repetition rate of 50 kHz the ablation threshold is determined at 18 J/cm^2. To machine the nozzles, a machining pattern was programmed to manipulate the laser over a circular area. This pattern and the configuration of the laser settings were optimized for sidewall smoothness and machining time.

The slope of the nozzle sidewall is controlled by the pulse power of the laser beam and can be tuned for angles in between 15 and 20°. A cross section of an unfinished hole is shown in Figure 5 (left) where one can see the sloped sidewall. On a sloped sidewall the laser energy irradiates a larger area, as depicted in Figure 5 (right). This reduces the fluence on the surface of the sidewall. At some value of the nozzle half angle the fluence on the surface drops below the ablation threshold and no material is removed. When the fluence on the surface is just below the ablation threshold a very thin melt layer is formed and thereby the nozzle side wall is smoothened.

The location of the nozzle throat is controlled by the diameter and slope of the holes drilled from the two sides. Figure 6 shows a nozzle inlet and outlet of a typical nozzle produced with a throat diameter of 210µm. The figures show that the throat of the nozzle is not exactly aligned in the middle and is slightly elliptical. This is caused by an elliptical energy distribution in the laser spot.

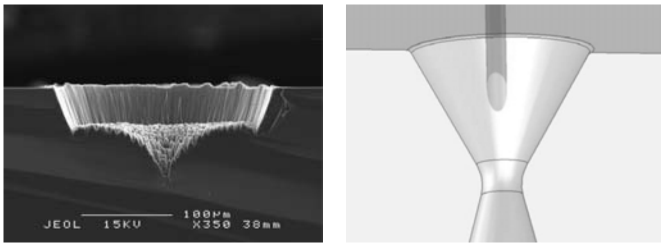

Figure 5: (left) SEM image of unfinished hole, (right) increased irradiated area

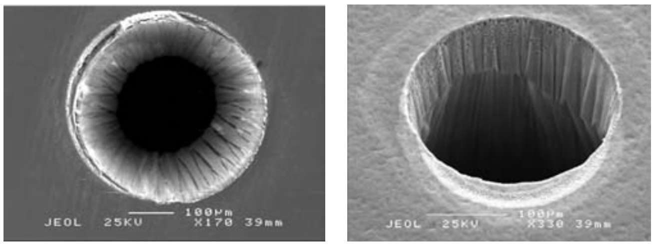

Figure 6: SEM images: (left) nozzle inlet, (right) nozzle outlet

New developments aim at improved control over the three dimensional geometry of drilled holes and nozzles. For this, a new focusing and manipulation technique is in development, which enables machining with a spot diameter of 3µm. 3D shapes can now be determined directly in software instead of using the ablation threshold to control the converging angle.

II.3 POWDER BLASTING AND HEAT TREATMENT

The final fabrication method that is considered consists of a combination of powder blasting and heat treatment. The fabrication scheme is shown in Figure 7. After applying a mask with circular features with a diameter of 400µm, a hole is made through a 500µm thick Pyrex glass wafer by powder blasting [7]. The hole has a positive taper in between 15 and 20°, which is suitable for the diverging part of the nozzle. This angle depends on the initial size of the mask feature and the amount of used powder per area. The novelty of the process lies in the following two steps. First a silicon wafer is bonded to the Pyrex wafer to fix the exit diameter during a consecutive heat treatment. This anodic bonding step is done at a temperature of 450°C. At this temperature the Pyrex glass keeps its shape. Second, a high temperature step is done to round of the corners at the entrance of the nozzle without rounding of the exit of the nozzle [8]. Additionally, this high temperature step improves the smoothness of the nozzle sidewall which is important to prevent flow separation and shock formation in the nozzle [9]. Hereby the final nozzle shape is obtained. In the last step the nozzle exit is opened by etching a hole through the silicon wafer with reactive ion etching.

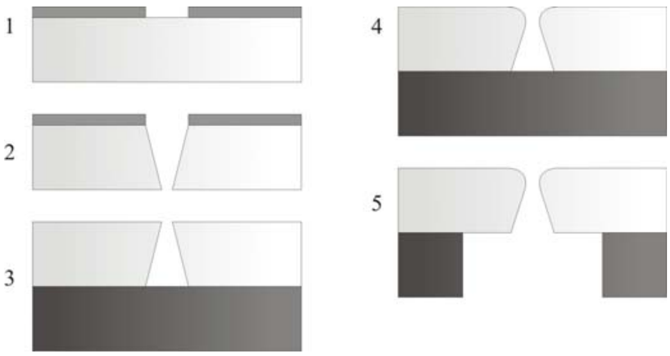

Figure 7: Glass nozzle fabrication scheme

Figure 8 shows a cross-section of the resulting nozzle shape. The throat diameter of this nozzle is 130µm and the radius of curvature and position of the throat are controlled by the heat treatment. The half angle of the nozzle is approximately 20° but can be tuned for smaller angles.

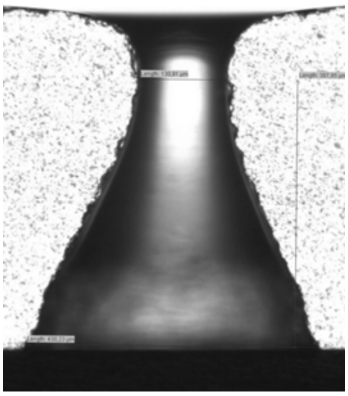

Figure 8: Cross-section of glass nozzle

III DISCUSSION AND CONCLUSION

The resulting nozzles manufactured by the different technologies are compared. Our research shows that the DRIE fabrication method is not suitable for making a conical nozzle. The shape of the directional etch profile can not be tuned by the IAD or IF effect in such a way that the desired half angle of the nozzle is obtained.

FLM is a good method to fabricate nozzles in silicon especially for rapid prototyping. The half angle of the diverging part of the nozzle can be tuned according to the requirements. With this method the radius of curvature of the throat is not controlled, it is a sharp corner which has a negative effect on the performance. The roughness estimated from SEM pictures of the sidewall is in the order of microns. Further improvements of this method will lead to controllable curvatures, a larger freedom of choice for the diverging angles and a smaller roughness. Furthermore machining of other materials like glass, metals or ceramics is possible.

The method of powder blasting in combination with heat treatment results in a very smooth nozzle sidewall which is especially important in the throat [8]. The radius of curvature and the position of the throat are controlled by the temperature step and can be adjusted according to specifications.

It can be concluded that the nozzles manufactured by FLM and by powder blasting in combination with heat treatment are with great potential.

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