Materials Considerations in Microthruster Design

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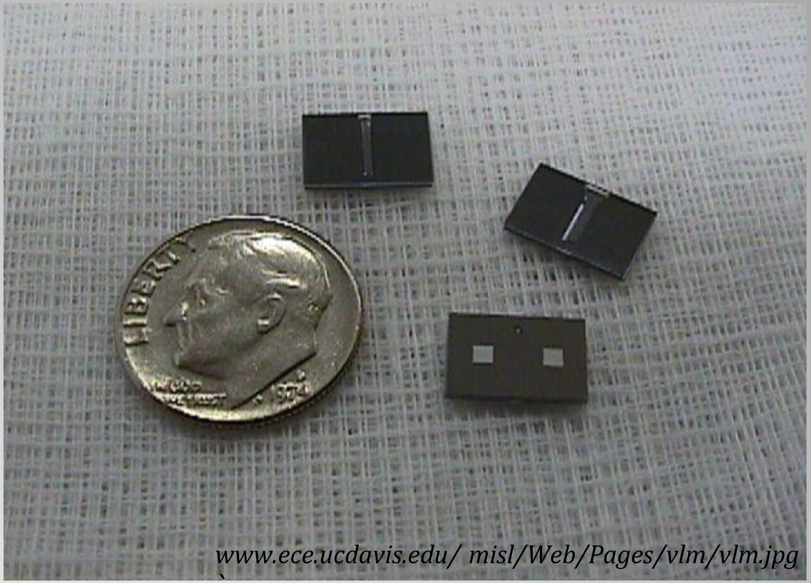
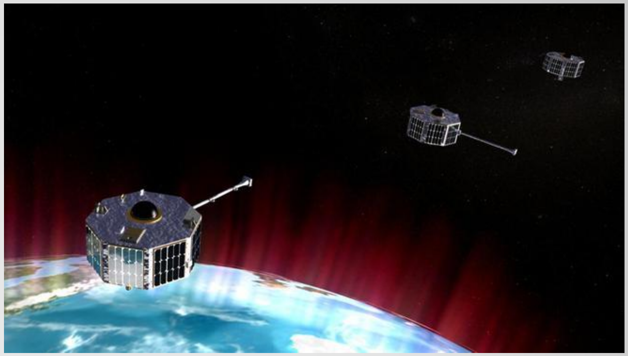


www.ece.ucdavis.edu/ misl/Web/Pages/vlm/vlm.jpg

Introduction

Advantages of Small-scale Spacecraft:

- Using a constellation of vehicles and distributing the payloads and tasks can greatly reduce the mission risk by distributing the failure potential
- Reduces the launch mass, which can significantly reduce mission costs and increase mission rates (*Mueller, 1997*)
- Achieves a high thrust-to-weight ratio



http://www.wired.com/wiredscience/2008/08/microspacecraft/

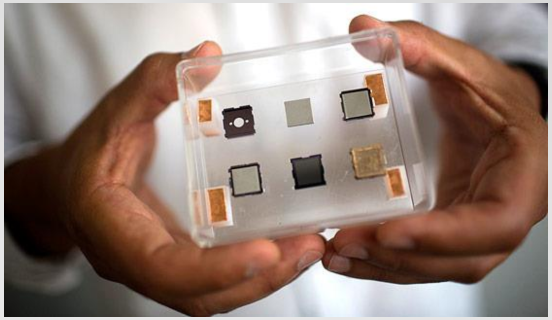
Why microthrusters?

"Small-scale spacecraft"

- "microsatellites" (having a mass of 10-100-kg)
- "nanosatellites" (1-10-kg)

Thrust values can range from micro-Newtons to Newtons

D= 0.001m



http://www.engadget.com/2012/08/18/mit-microthrusters-for-cubesats/

How small is "small-scale"?

- However, on the microscale, the game changes…
  - Fluid dynamics
    - Increased subsonic boundary layer effects
    - Heat transfer effects
  - Material properties
    - Strength
    - Thermal conductivity

Major Microscale Design Issues


http://history.nasa.gov/ap11ann/kippsphotos/saturn5.html

Macro- and Microthruster Perfomance

- In conventional (macroscale) rockets, performance is often evaluated in terms of thrust (F_T) and specific impulse (I_{sp}).

- A thruster's function is to provide a force to which there will be an equal and opposite reaction to move a spacecraft, causing a change in velocity (ΔV) . This ΔV, then, requires a given thrust acting over a given time (Δt). It is related to spacecraft mass and the thruster's exit velocity (u_e) as follows:

$$\Delta V = u_e \ln\left(\frac{M_o}{M_o - M_p}\right)$$

(M_o and M_p are the total spacecraft mass and the propellant mass, respectively.)

- ΔV is directly proportional to u_e, which is increased as M_p is decreased. (*Tsiolkovsky, 1903*)

Macroscale Performance

Macroscale Performance (cont’d)

The exit velocity of the gas (u_e) is related to the operating conditions of the thruster and the propellant properties, such as:

- chamber temperatures (T_c)
- gas temperature (T_g)
- chamber pressure (p_c)
- exit pressure (p_e)
- specific heat ratio (γ)

Given these values, u_e can be determined and used to calculate the thrust (F_T) and specific impulse (I_{sp}):

$$\boldsymbol{u_e} = \sqrt{\frac{2\gamma(\frac{R_u}{MW})T_c}{\gamma-1}\left[1-\left(\frac{p_e}{p_c}\right)^{\gamma-1/\gamma}\right]}$$

$$\boldsymbol{I_{sp}} = \frac{F_T}{\dot{m}g}$$

$$\boldsymbol{F_T} = \dot{m}\mathbf{u_e} + (p_e - p_a)A_e$$

Produces gains in thrust-to-weight ratio (F_T/W).

- Flow and performance parameters will scale differently with the length scale (D), but the overall result is that F_T/W is inversely proportional to D.
  - Rocket: $D = 1\text{m} \rightarrow F_T/W \approx 50$
  - Microrocket: $D = 1\text{mm} \rightarrow F_T/W \approx 50{,}000$.

As the system scale decreases, the surface-to-volume ratio increases, which reduces the thermal mass of the flow and leads to heat transfer effects.

Microthruster Scaling Effects

Scaling Effects (cont'd)

However, as the scale is reduced, viscosity and surface effects increase. Frictional losses are determined by the Reynolds number:

$$\boldsymbol{Re = \frac{\rho_t u_t D_t}{\mu_t} = \frac{\dot{m}}{\mu h_o}}$$

(t subscript denotes throat conditions at the nozzle; h_o is the nozzle height in an extruded nozzle)

Characteristic length scales on the order of microns to millimeters result in corresponding Reynolds numbers of 1 – 1000 within the nozzles. (*Bayt, 1999; Jerman, 2011*)

For an ideal nozzle, $p_e = p_a$, the thrust equation can be reduced to:

$$F_T = \dot{m} u_e$$

At conventional scales, the expansion ratio (A_e/A_t) generally determines the exit velocity, but with the increased influence of viscous effects at smaller scales, it will decrease with the Reynolds number.

Thrust can be related to the Reynolds number by the following:

$$F_T \propto Re\, h_o \mu_t u_e$$

Scaling Effects (cont'd)

One study on scaling and performance of microthrusters (Bruno, et al., 2003) developed the following relationship between Reynolds Number and Thrust:

$$F_T = \frac{\pi}{2}\frac{\mu_o}{{T_o}^{2/3}}{T_g}^{7/6}Re_D D\sqrt{\frac{2\gamma}{\gamma-1}\frac{R_u}{MW}\left[1-\left(\frac{p_e}{p_o}\right)^{(\gamma-1)/\gamma}\right]}$$

Notes:
viscosity, μ, a function of temperature, was replaced by $\mu \sim \mu_o\,(T_g/T_o)^{2/3}$

$\left[1-\left(\frac{p_e}{p_o}\right)^{(\gamma-1)/\gamma}\right]$ is denoted as the ***thermodynamic efficiency term***

Scaling Effects (cont'd)

To account for increased viscous losses at these scales, the following correction factor was used:

$$\eta_\mu = 2 \cdot\ 10^{-5}(Re\ - 100) + 0.8$$

(This offers a simplified way to account for viscous losses that would otherwise require much more complex numerical 2-D calculations.)(*Bruno, et al., 2003*)

Scaling Effects (cont'd)

Micro-thruster Scaling Effects

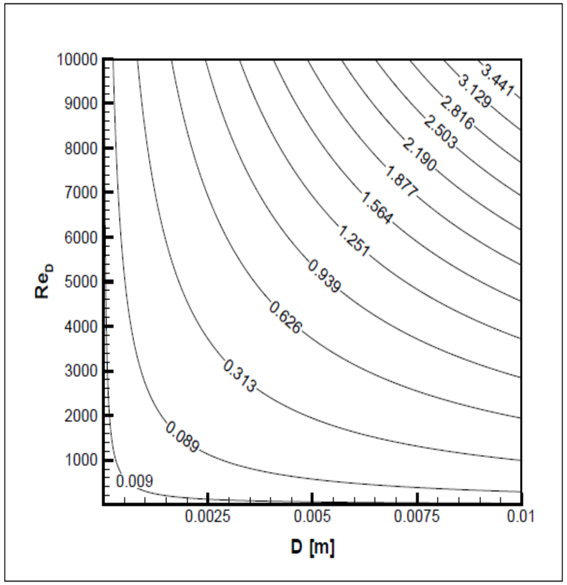


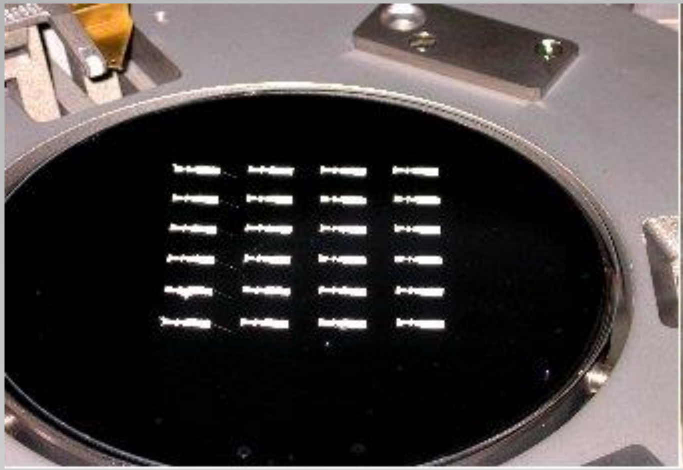
Figure 1: Effective thrust (in N) map as function of the thruster size and chamber Reynolds number.

(*Bruno, et al., 2003*)

To maintain a desired thrust, then, the Reynolds number must be increased as scale decreases.

Further, it must be increased much more at small scales than at large scales.

Possible ways to increase *Re* are to increase the chamber pressure (p_c), chamber temperature (T_o *or* T_c) or gas temperature (T_g).



Design Considerations and Material Selection

Improving geometry

Increase T_g

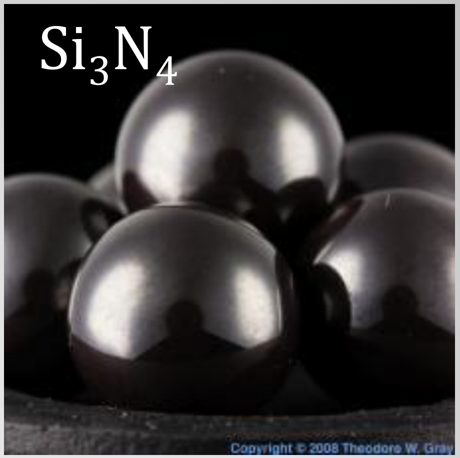
Increase heat loss

Materials

Fabrication Methods

Improving performance?

- Si is the most widely used microfabrication material
- Si compounds can offer more strength



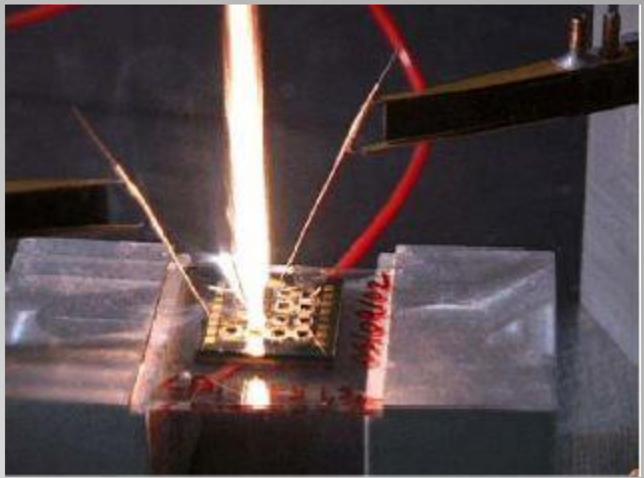
http://periodictable.com/Elements/014/pictures.html

Potential Materials

Material	Density (g/cm^3)	Melting/Breakdown Point (K)	Thermal Conductivity (W/mK^{-1}) (at 300K)	Young's Modulus (GPa)	Fracture Strength (MPa)
Si	2.33	1683 (melting)	149	150	7000*
SiC	3.1	2830 (breakdown)	350	450 435	3440 2090
Si_3N_4	3.29	2173 (breakdown)	--	310	700

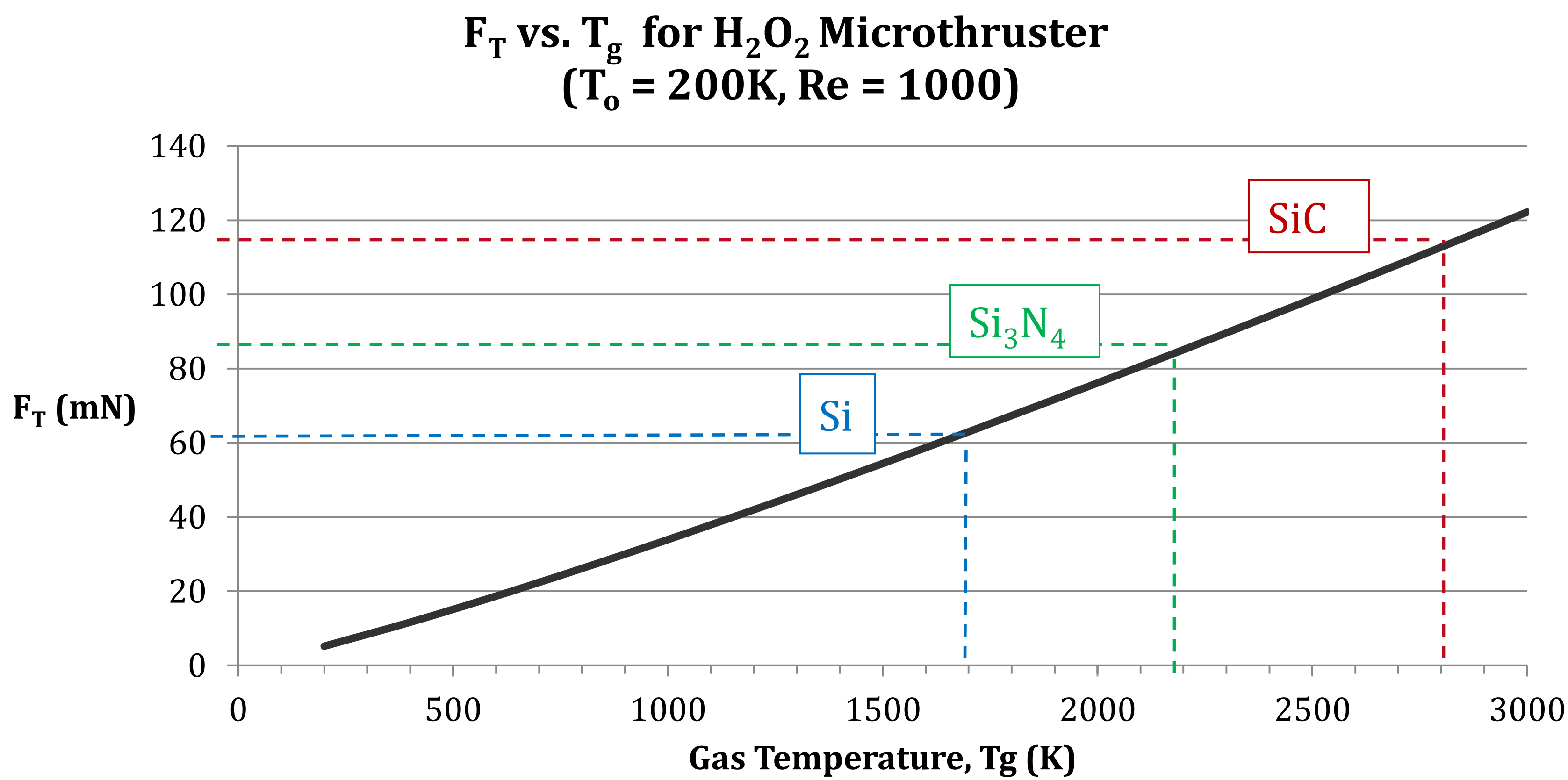
*can be less at the corners of anisotropic etches with stress concentration factors up to 33. (*Sooriakumar, et al. 1995*)

Comparison of Material Properties

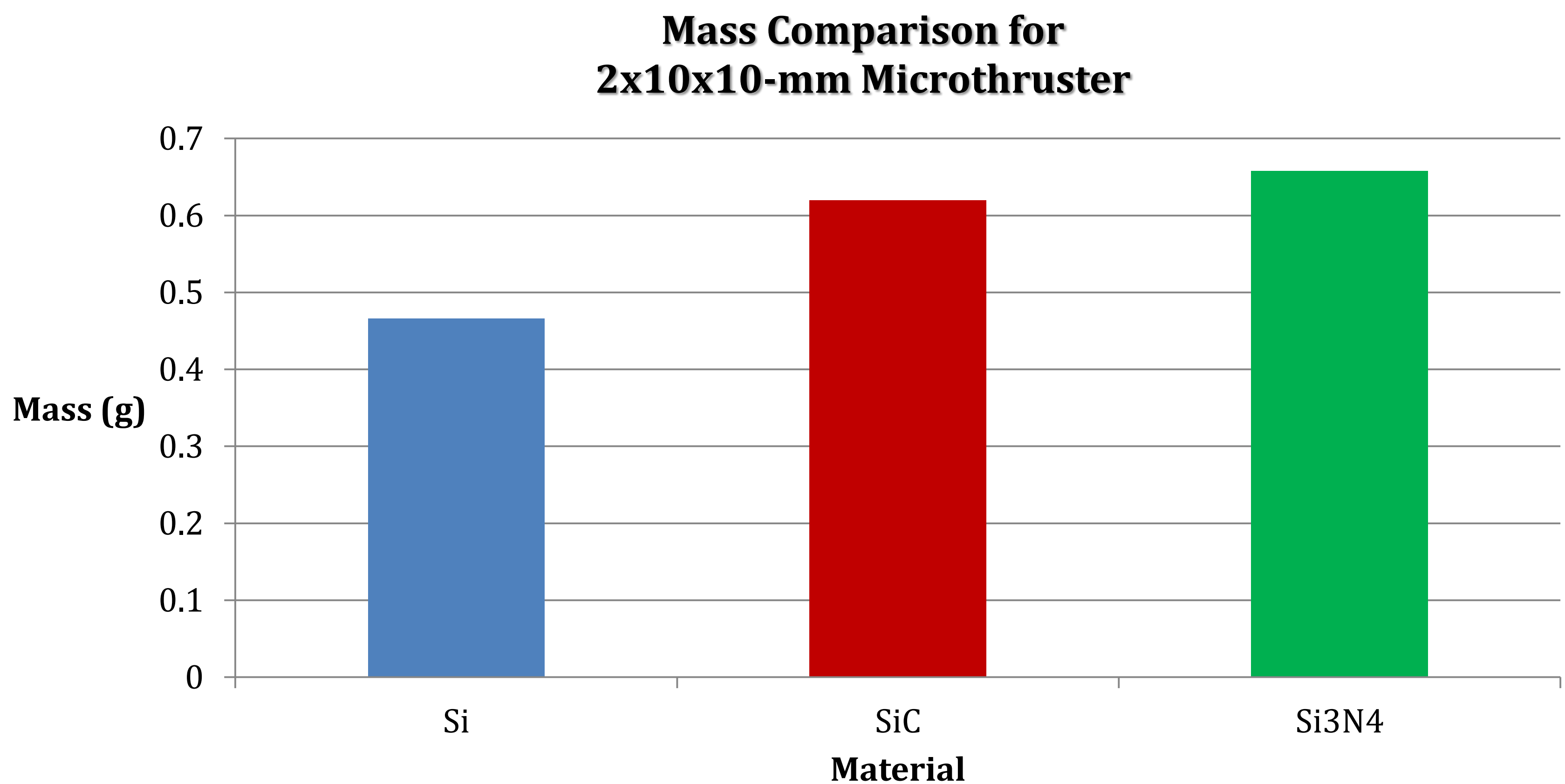


http://simulation.uni-freiburg.de/downloads/benchmark/Thruster%20(38847)

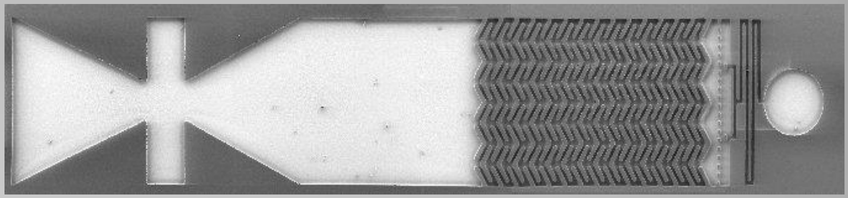
Temperature and Mass Considerations



Temperature Considerations



Mass Considerations



http://www.bo.imm.cnr.it/site/node/245

Fabrication and Mechanical Considerations

- Current manufacturing techniques can result in high dislocation densities can lower the strength (*Stark, 1999*)

- Chemically resistant and therefore unsuitable for wet-etch techniques.

- Can be etched electrochemically or by plasma processes, such as deep reactive ion etching (DRIE). (*Osiander, et al., 2006*)
  - Electrochemical processes provide higher etch rates than plasma processes, but…
    - Etch directionality can be poor
    - Should be limited to highly-directional (anisotropic) etch techniques to assure vertical sidewalls in fabricated structures. (*Gad-El-Hak, 2002*)

- Alternative method of creating precision molds by using DRIE on Si.
  - Polycrystalline SiC is then deposited on the molds via chemical vapor deposition (CVD); Si molds subsequently removed by a wet etching
  - Although this method can create devices without the complications of direct etching, the molded polycrystalline SiC does not exhibit the same mechanical robustness as single-crystal SiC.

Fabrication and Mechanical Considerations - SiC

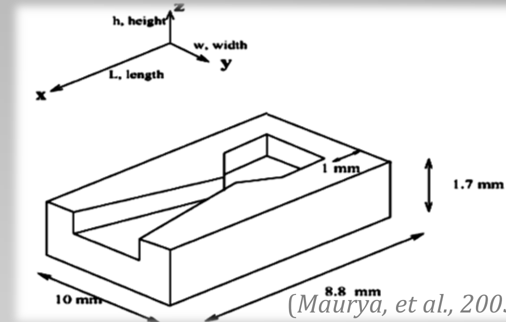
- high mechanical strength

- does not react well with many etching solutions and can be more difficult to use in fabrication.

- strength is dependent on the Si-to-N ratio.
    - high residual stresses that are found in stoichiometric Si_3N_4 limit its use to thin films. However, increasing the Si-to-N ratio can create a "low-stress" nitride, but this will also decrease the etch rate. (*Ghodssi & Lin, 2011*)

Fabrication and Mechanical Considerations – Si_3N_4

Side-exit Microthruster



(*Maurya, et al., 2005*)

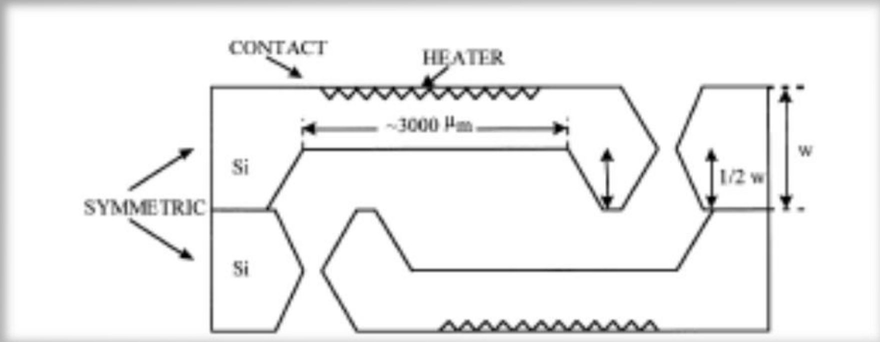
Wet-Etching
least desirable method, particularly with silicon (anisotropic)

Reactive Ion Etching (RIE, DRIE)
can provide etching depths on the order of 10 μm and 100 μm, respectively, while allowing for better control of the geometry

Focused Ion Beams (FIB) Milling
Provides an attractive alternative to these etching methods, as it allows the pattern to be precisely milled out on the substrate.

Main concern: nozzle must be fabricated with precision to obtain the proper geometry, especially smooth nozzle walls.

Fabrication and Mechanical Considerations – Etching Methods



(*Mukerjee, et al., 2000*)

- Easier and less expensive than other methods, and can be done in bulk
- Multiple nozzles can be etched simultaneously on a chip to produce an array

However, anisotropic etching on Si can be problematic…

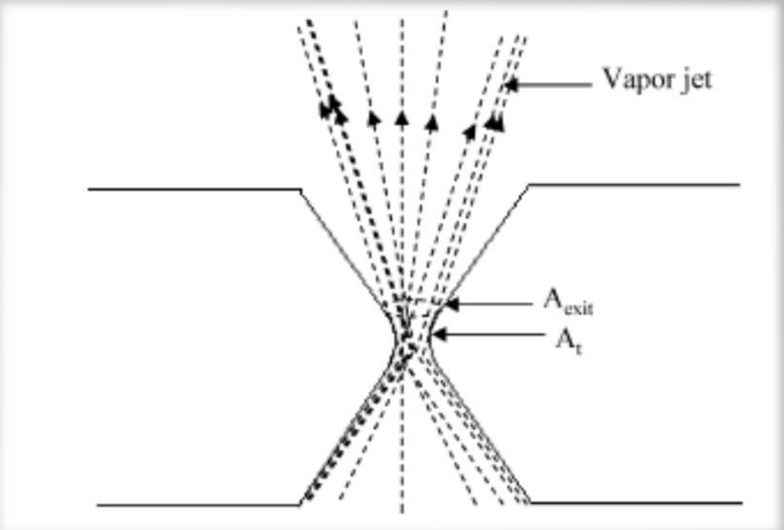
- Etching takes place along the <1 1 1> crystallographic planes of the material, which are fixed at angles of 54.74 degrees relative to the surface.

- This fixes the nozzle angles, which may diminish performance if the side walls are too diverging to match the contour of the emerging vapor jet. (*Maurya, 2005*)

Fabrication Methods and Nozzle Orientation

Fabrication Methods and Nozzle Orientation (cont'd)

- An ideal nozzle will have A_e/A_t to produce the desired thrust, and the nozzle profile will match the contour of the vapor jet.
- However, nozzles formed by anisotropic wet etching of Si can be too divergent to accomplish the latter.
- This can lead to transverse velocity components in the flow, which can diminish the thrust.
- Further, the effective length of the nozzle may be less, decreasing the effective A_e.



(Maurya, et al., 2005)

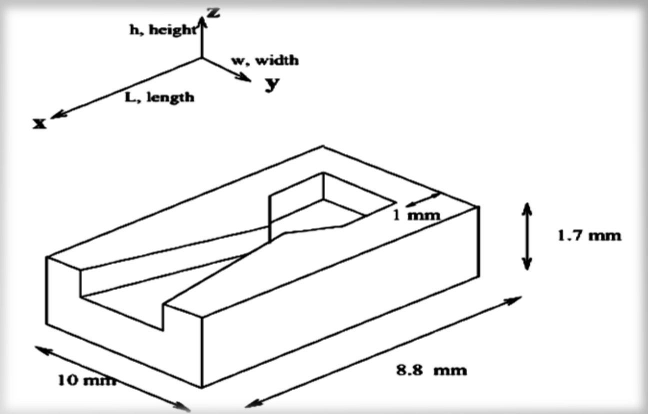
Fabrication Methods and Nozzle Orientation (cont'd)

A bell-shaped nozzle profile is used to provide optimal flow alignment to minimize thrust losses on the macroscale, but two particular challenges emerge on the microscale:

- insufficient geometrical precision in fabrication methods
- inapplicability of inviscid flow theory on the microscale.

On the microscale, viscous boundary layer effects become increasingly significant and cannot be ignored, and the contour becomes dependent on the Reynolds number of the nozzle flow. (*Louisos, et al, 2008*)

Therefore, the linear (conical) nozzle is presently the preferred configuration.



Nozzle Geometry Considerations

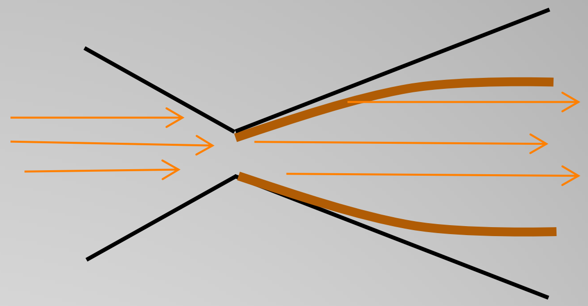
Flows in the microthrusters will differ from the 2-dimensional axisymmetric flows seen on the macroscale:

- Thrust losses produced by the boundary layer formed in the nozzle on the microscale are not insignificant, and the diverging angle must be adjusted accordingly.
- Microthruster nozzles will have a rectangular rather than circular cross-section.
- Boundary layers will also form on the flat-plate

http://www.uvm.edu/~cems/gfx/Louisos2.jpg

Thrusters on the microscale will have Re<1000.

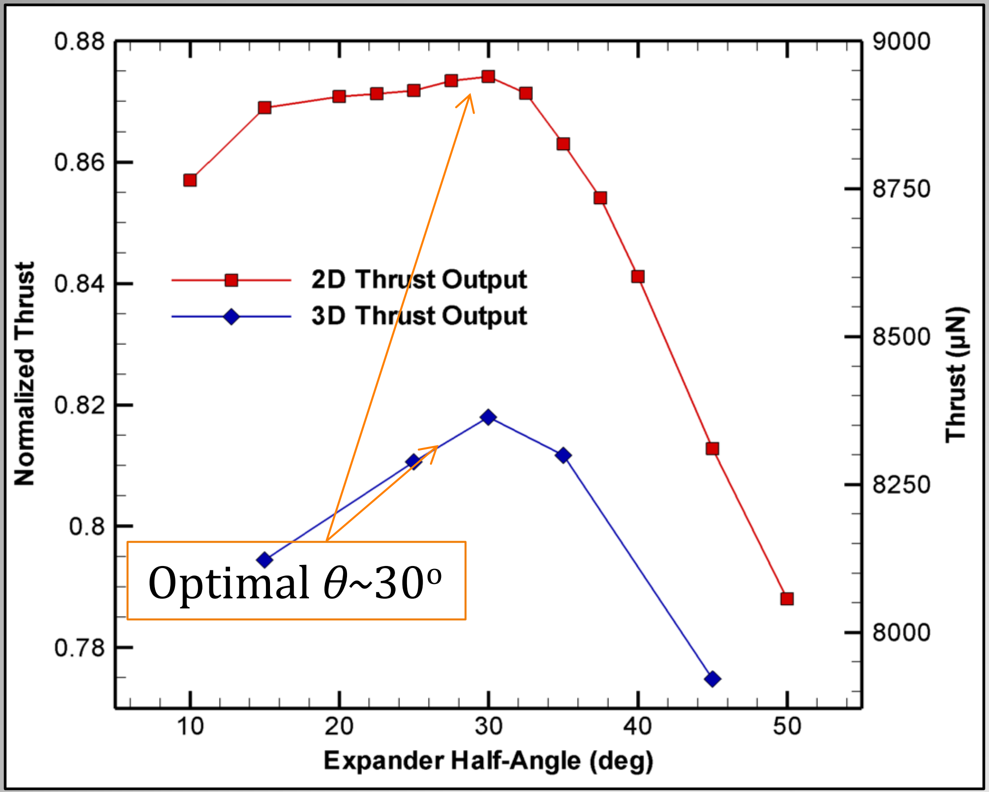
A subsonic viscous boundary layer thickens axially along the nozzle, which leads to a decrease in effective cross-section of the nozzle and reduced performance.



On the macroscale, a typical conical nozzle may have an optimal divergence angle of 15-degrees, but on the microscale this can be increased to compensate for the boundary-layer effects.

However, widening this angle can introduce unwanted transverse velocities, which can diminish thrust.

Viscous Boundary Layer and Geometric Losses



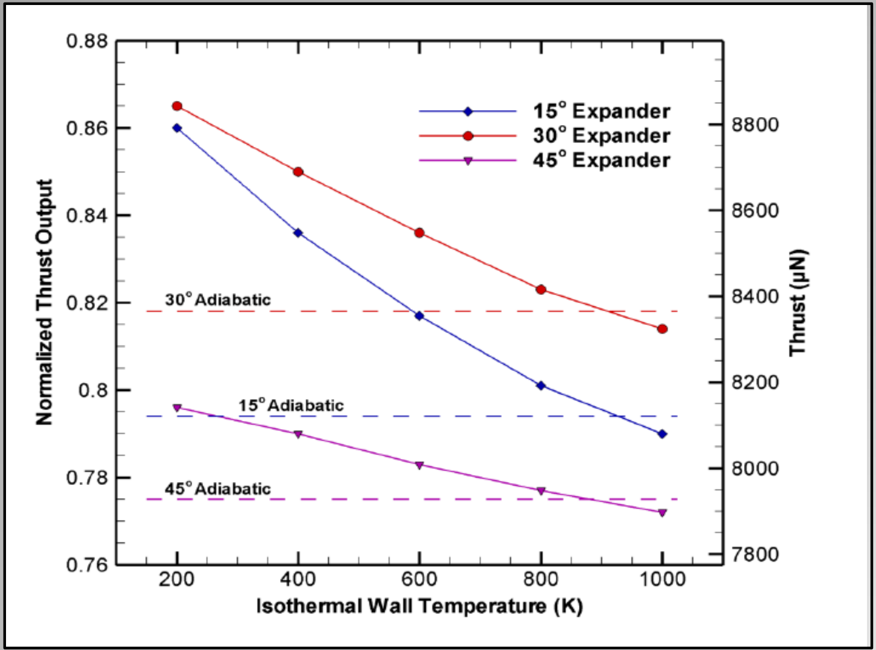
Microthruster Simulation Showing Comparison of 2D and 3D Flow
(*Louisos and Hitt, 2007*)

This leads to a performance tradeoff between the geometric effects and the boundary layer effects.
(*See Louisos and Hitt, 2005*)

- 3D effects (boundary layers forming on the flat-plate walls to constrict the flow) lead to only a slight reduction in performance (about 5%)
- optimal performance at an expander half-angle of 30 degrees is more pronounced for 3D flow

Viscous Boundary Layer and Geometric Losses

Effect of Heat Loss



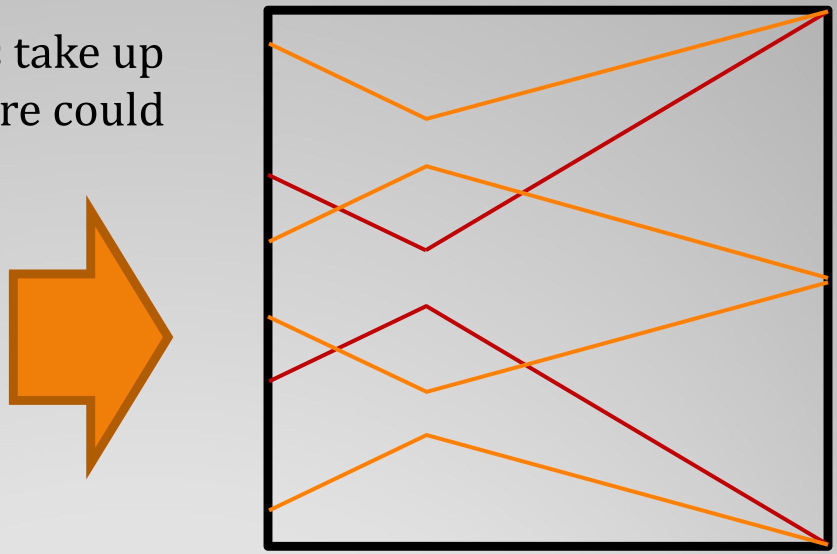
3D Microthruster Simulation
with Isothermal Walls
(*Louisos and Hitt, 2007*)

Can improve thruster performance by reducing viscous effects.
→Removing heat from the flow increases the supersonic flow speed, and the boundary-layer thickness decreases.

As a result, the nozzle expander angle can get closer to the non-axial-flow-minimizing 15-degrees seen on the macroscale.

Expanders with smaller angles take up less space on a chip so that more could be etched on a chip.

Two microthrusters with 15-degree expansions could be placed in the space of one 30-degree expansion microthruster.



A pair of 15-degree expansion microthrusters could produce almost twice as much thrust as a single 30-degree expansion microthruster in the same space.

(e.g., a 30-degree expansion nozzle could have a thrust of 8950 μN, while a 15-degree configuration could have a thrust of 8850 μN)

Heat Loss and Fabrication

Material	k (W/m K)
Si	149
SiC	120
Si_3N_4	---

However, it is important to note that thermal conductivity can decrease significantly at higher temperatures and at the microscale.

Therefore, at least with these materials, selection is irrelevant with regard to improving thruster performance.

Heat Loss and Materials

- Not all conventional approaches to thruster design apply on the microscale, especially with respect to performance and nozzle design.

- Materials must be able to withstand the extreme environment of space and high operating temperatures, and provide strength and reliability, while minimizing system mass.

- On the microscale, viscous effects dominate propellant flow, particularly in the nozzle portion. It appears that current micro-fabrication techniques are sufficient to produce a substantially linear-profile, planar nozzle that will perform comparably to a more complex bell-shaped, conical nozzle.

- Although performance could be improved by increasing heat loss from the flow to decrease the subsonic boundary layer thickness, the scale and operating temperatures of these devices limits the role of material selection in this regard.

Summary and Conclusions

THANK YOU!

End of Presentation **(references follow)**

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