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Design, Fabrication and Test of MEMS Propulsion with Solid Propellant

4th Round Table on Micro/Nano Technologies for Space
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Outline

- Micro Propulsion System Overview
- Structure Design
- Fabrication
- Propellant Research and Casting
- Modeling and Analysis
- Thruster Performance Prediction

Future Space System Require Micro Propulsion System

- **Future Space System and Requirement**
  - New Space System: Microspacecraft constellation, Formation Flying
  - Requirement for Propulsion Subsystem: Low mass, accurate impulse bit, integration, facility
- **Several Micro Propulsion Implementation**
  - Gas Thruster
  - Chemical Thruster: Solid propellant, Bi-propellant
  - EP: FEEP, PPT's(μ PPT), Colloid Thruster

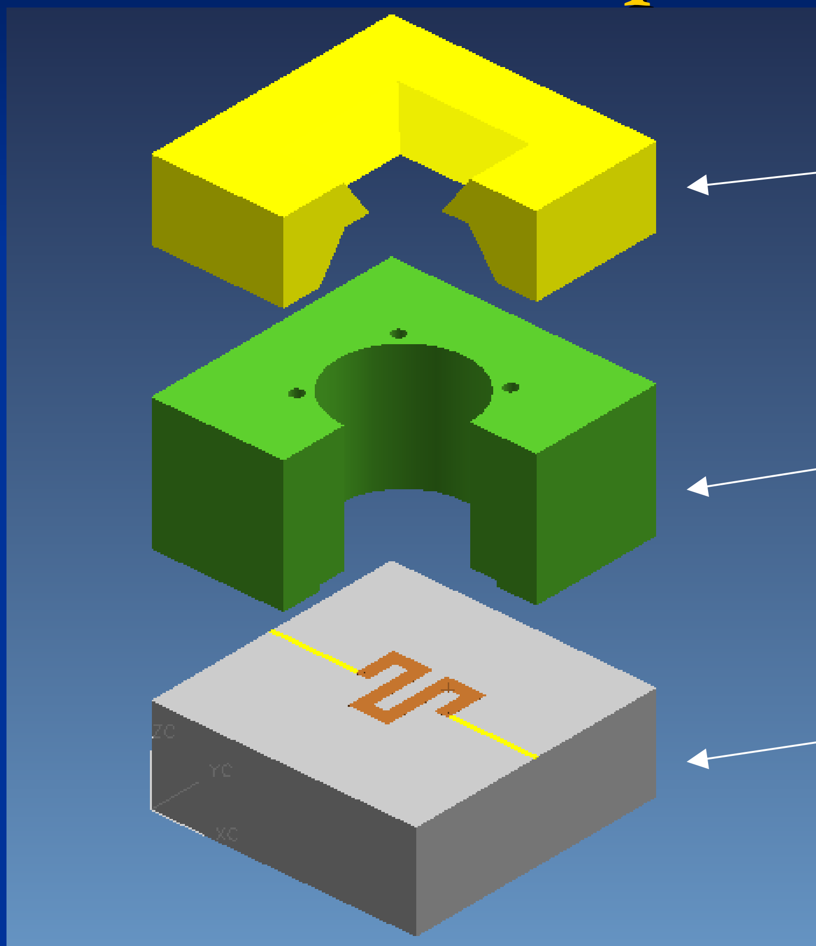
Several Micro Propulsion System

Propulsion System Type	Gas Thruster (Snap-1)	PPT's (DAWGSTAR PPT, AFRL μ PPT)	FEEP (Cesium)	MEMS (Chemical)	MEMS (Electrical, Especially colloid)
Thruster Operation	Continuous	Pulsed	Continuous	Pulsed	Pulsed
Thrust Range	45mN@0° C, 120mN@40° C	10~1e3 μ N	0.1~1200 μ N	1~1e5 μ N	>1e5 μ N
Specific Impulse	>60s	500~1500s	7000~11000 s	100~300	1000~2000s

Advantages of MEMS Propulsion with Solid Propellant

- **Small:** Mass, volume are Small enough
- **Integration:** Integrated all parts in one chip
- **Adjustable Thrust:** The thrust force of each unit generated may be set by geometrical and dimensional considerations of the nozzle and chamber .
- **Addressable:** Several different units ignited together can generate various thrust force.
- **Reliability:** no moving parts

Structure of MEMS Propulsion Unit



Top Layer-convergence and divergency nozzle on top

Middle Layer-combustion chamber with four exhaust holes

Bottom Layer-Pt resistor as ignitor

Exploded View

Fabrication Process of Prototype

- Bottom Layer, Ignitor-Deposit Pt &Au orderly on the Prex7740, Pattern to realize the ignitor resistor, the electrical pads and the electrical supply lines.
- Middle Layer-ICP etch P-type (100) wafer to form the combustion chamber.
- Top Layer-KOH etch (100) wafer on both side to form the nozzle.

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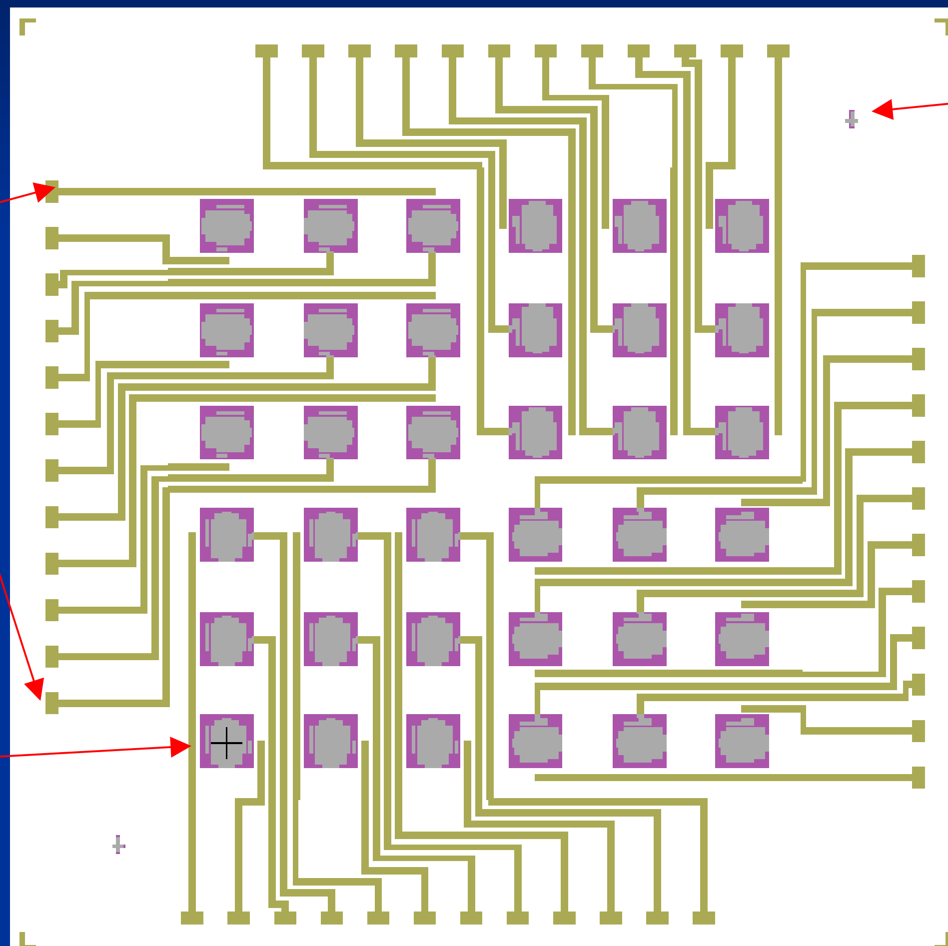
Top View of Bottom Layer

Bond Pad

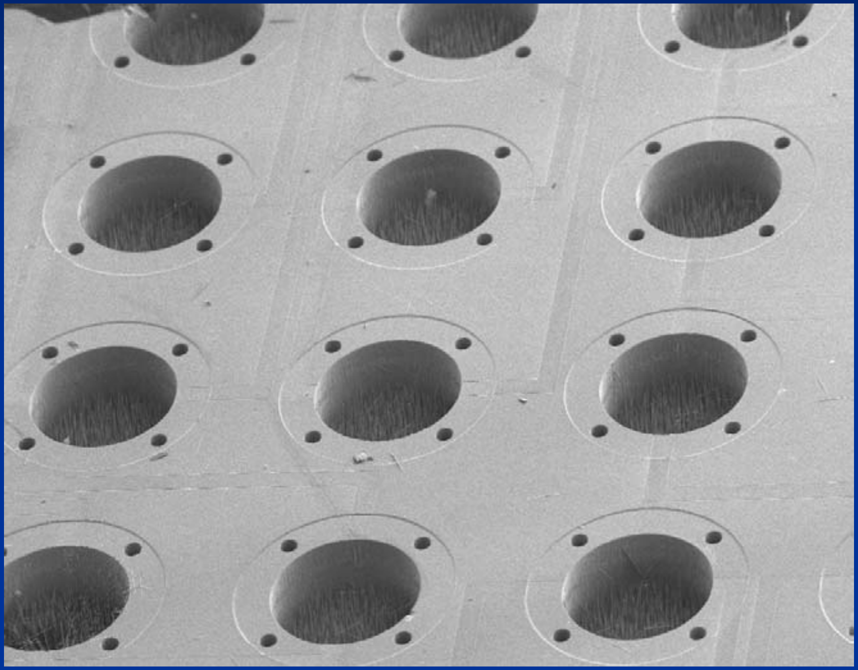
Alignment Cross Hole

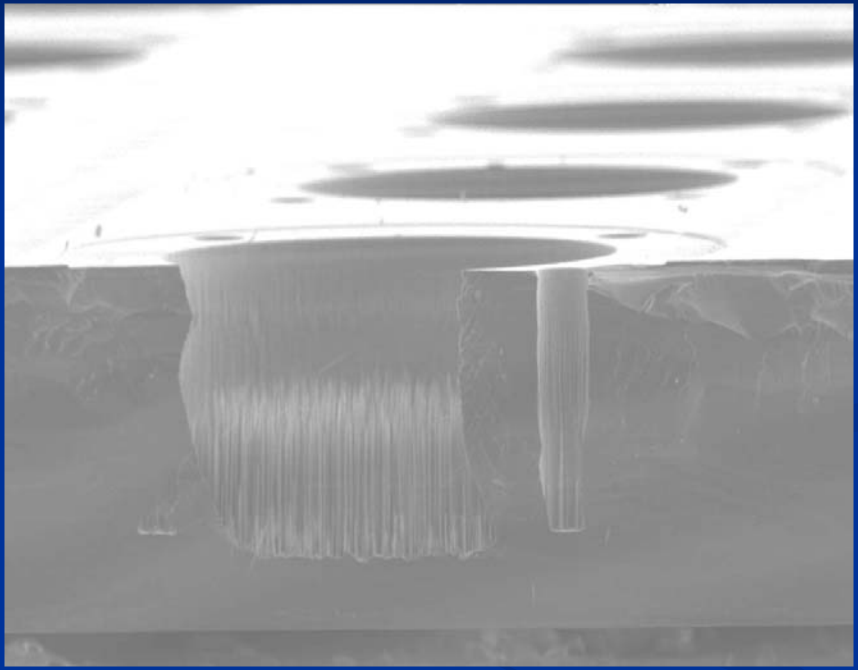


36 ignitors in a 6*6 arrays

9mm square

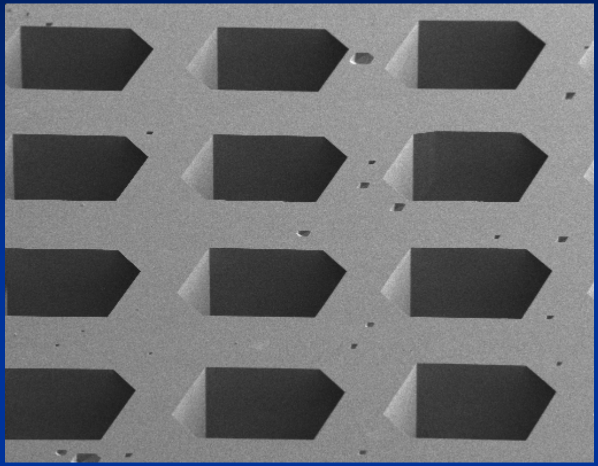
SEM of The Thruster Structure

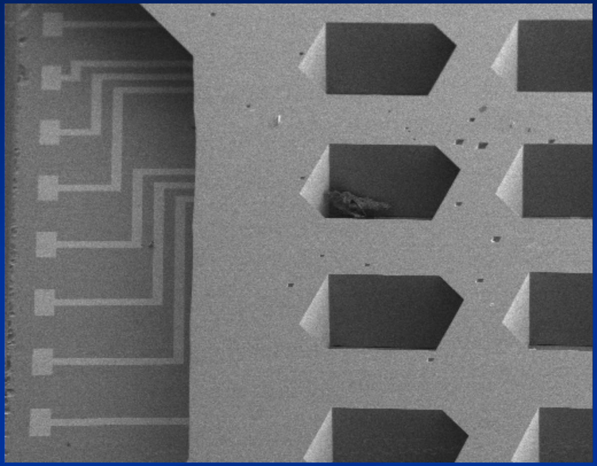


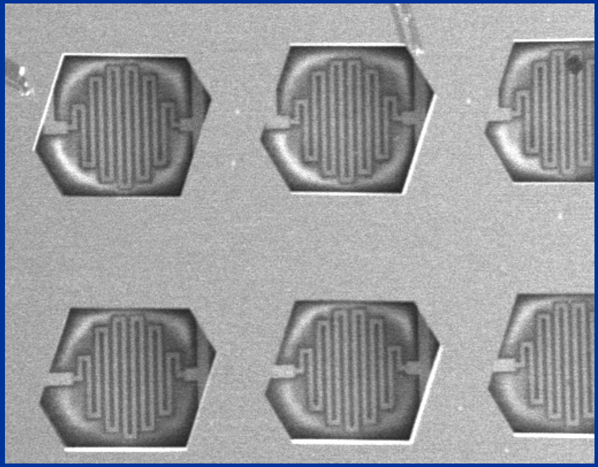


SEM (Scanning electron microscope**) of ICP (**Inductively Coupled Plasma**) Etching Chamber with Four Exhaust Holes**

SEM of The Thruster Structure

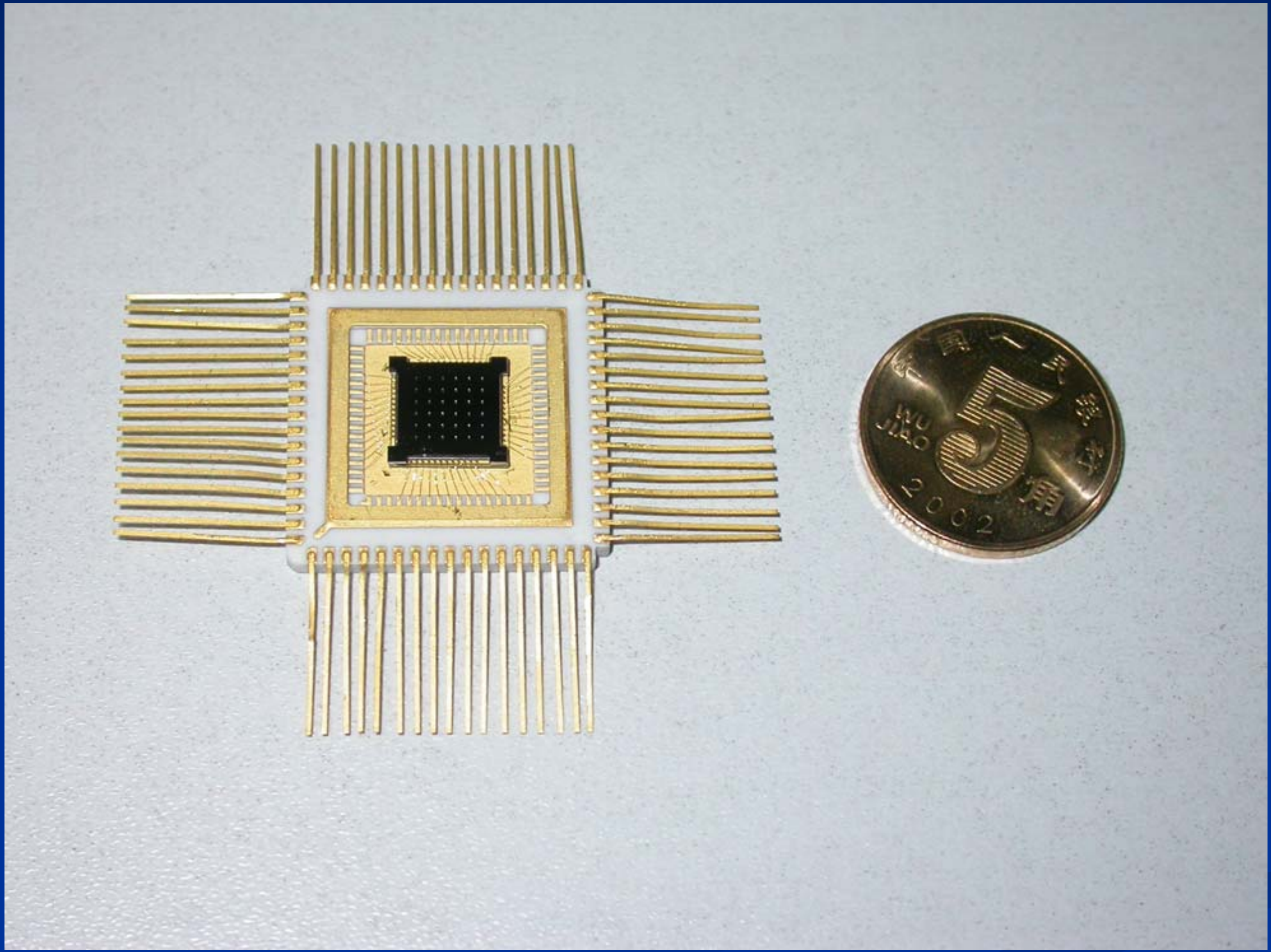




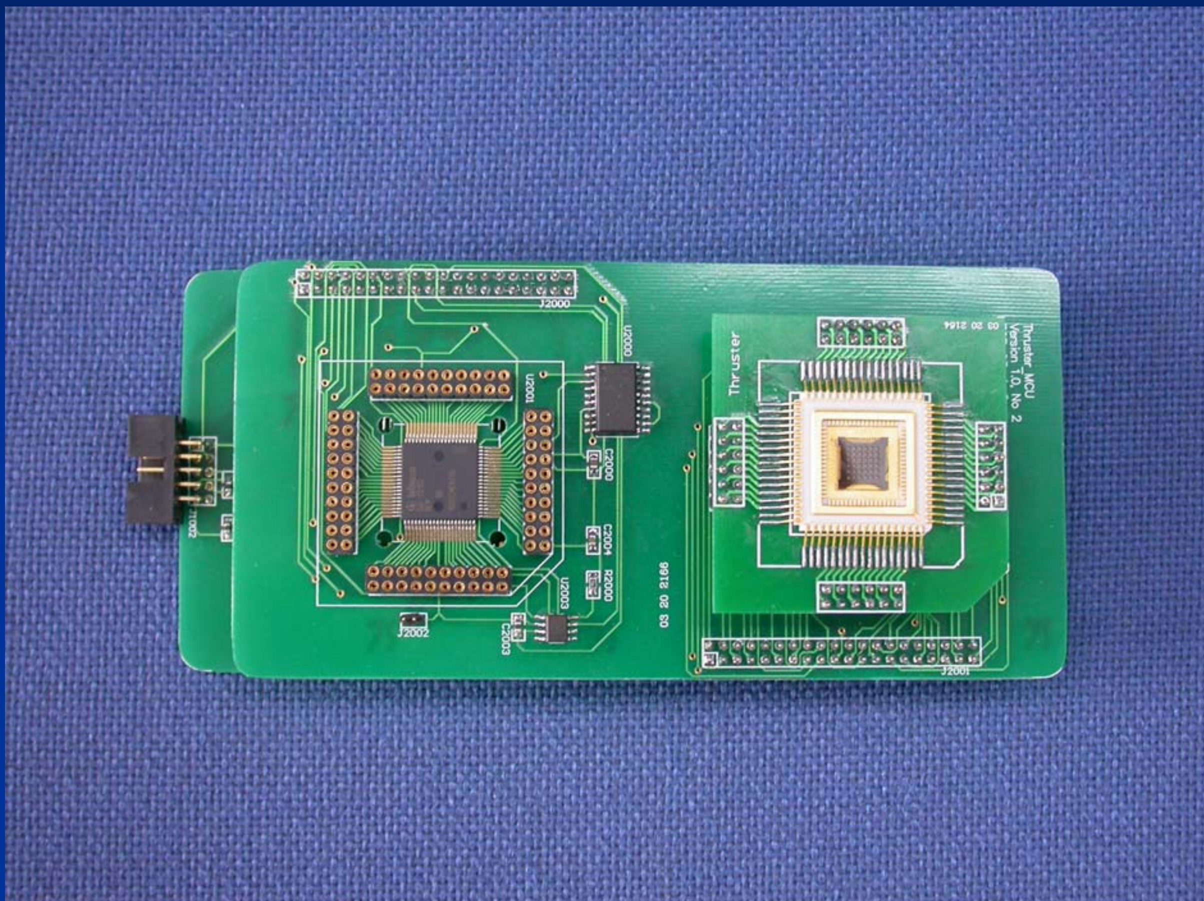


SEM of KOH Wet Etching Chamber with Four Exhaust Holes, Bond Pads, Ignitors

Assembled Thruster Prototype



Micro Propulsion Subsystem Module



Command from OBC transmit to the micro-propulsion module through the RS232 or CAN bus.

Design and Fabrication Issues Discussion

- **Nozzle array**
  - Quasi-laval binary geometry
  - No diaphragm, eliminate the energy expense with rupture
  - How to ensure the adequate pressure? Nozzle geometry? Suitable ratio of At to Ac
  - Next Stage: Thermal isolation - Surface thermal oxide layer
- **Chamber**
  - With exhaust holes around, hope to improve the combustion performance
  - Next Stage:
    - Adiabatic film, coating thermal oxide
    - Reduce Volume, increase arrays
- **Ignitor array**
  - Now: Pt resistor on the Prex7740, oxidation resistance, but low density of integration
  - Nest Stage: Addressing and driving circuit on the SOI wafer, cavity on the back side for thermal isolation
- **Bonding Approach**
  - Bottom layer and middle layer: anodic bonding before propellant filled
  - Top layer: glue in the less of 100° C after propellant filled
  - Next Stage: Si – Au (or Al) - Si Bonding, not require any glue

Principle of The Propellant Choice

- Low energy threshold for igniting: require lead styphnate
- Withstand high transient pressure for bonding
- Solid propellant, easy storage
- No leaking
- Fluidity in certain condition, easy to cast

A-Type Propellant Performance Specification

- A-type Propellant: HTPB/AP

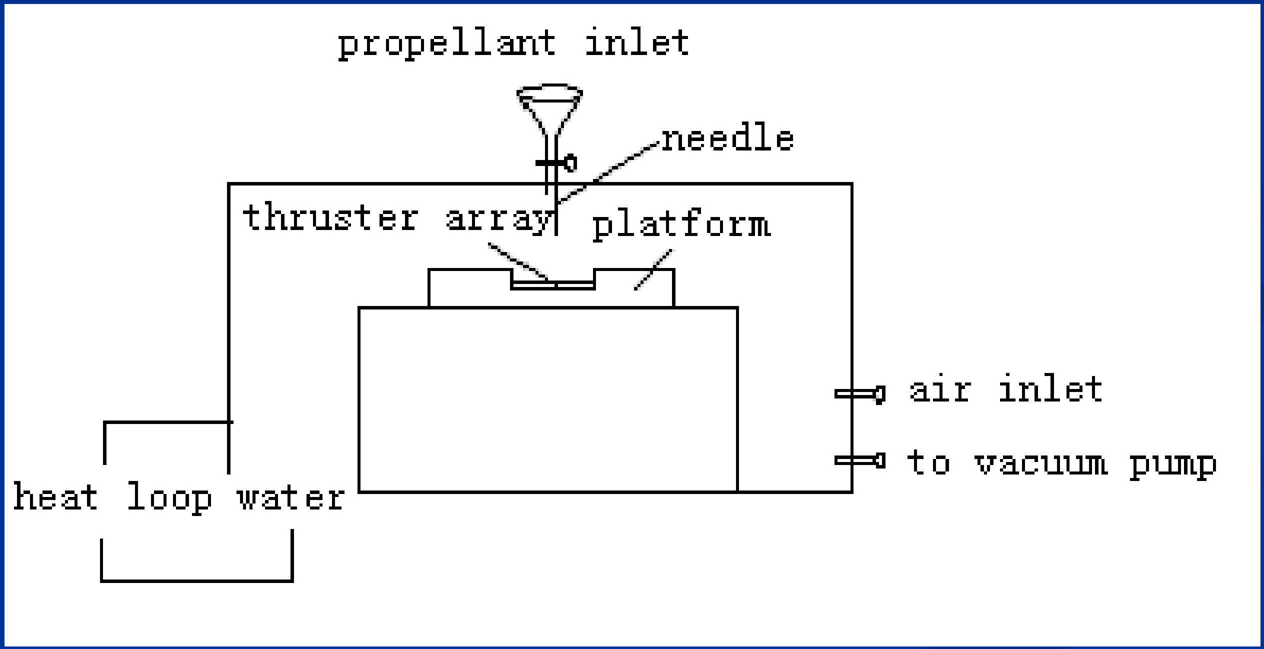
Item		Value
Characteristic Rate C (m/s)		1379.4
Flame Temperature Te (K)		2046
Density (g/cm3)		1.625
Specific Heat Cp		1.5
Combustion Rate (mm/s)	Pre exponential factor a	5.52
	Exponential coefficient n	0.45
Thermal Capacity ratio γ		1.25
Mean Molecular Weight Mg (g/mol)		21.08
Mole Ng (mol/Kg)		47.43

B-Type Propellant Performance Specification

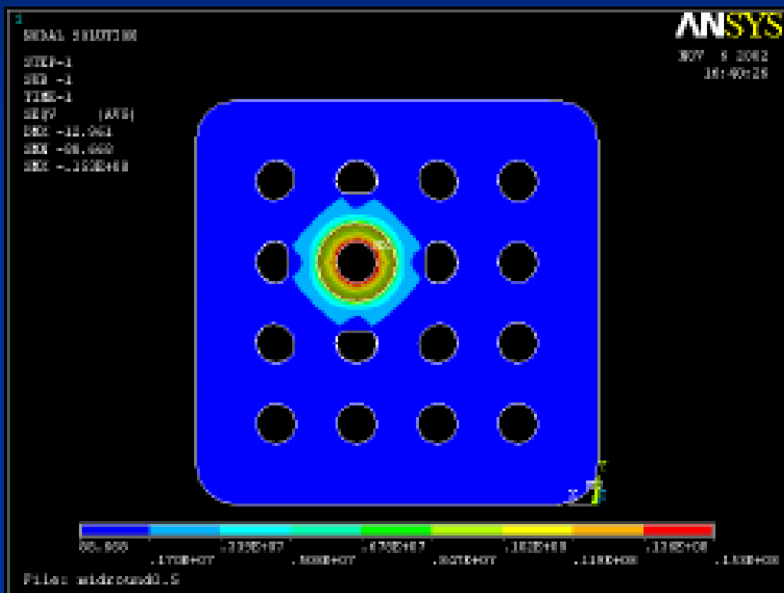
- B-type Propellant: HTPB/AP/Mg

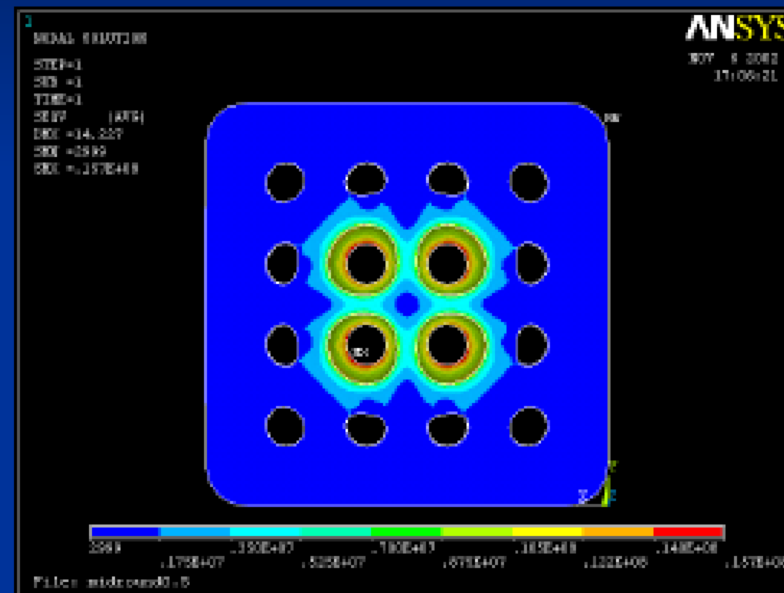
Item		Value
Characteristic Rate C (m/s)		1427.4
Flame Temperature Tc (K)		2223
Density (g/cm3)		1.614
Specific Heat Cp		1.53
Combustion Rate (mm/s)	Pre exponential factor a	5.63
	Exponential coefficient n	0.45
Thermal Capacity ratio γ		1.25
Mean Molecular Weight Mg (g/mol)		19.51
Mole Ng (mol/Kg)		47.54

Schematic of the System to Fill Chamber with Propellant



Stress Distribution at Different Operating Mode





500 μ m diameter chamber VonMises stress distribution under single unit firing and four neighbour units firing

Ultimate Stress and Strain List

- **Maximal stress and strain under different working pressure**

Result \ Pressure	Type	0.7(MPa)	2(MPa)	5(MPa)	10(MPa)	20(MPa)
VonMises (Pa) MAX (Absolute Value)	Single	0.12632E+07	0.36091E+07	0.90228E+07	0.18046E+08	0.36091E+08
	Four	0.13379E+07	0.38225E+07	0.95561E+07	0.19112E+08	0.38225E+08
Strain (μm) MAX (Absolute Value)	Single	2.1133	6.0380	15.095	30.190	60.380
	Four	2.4485	6.9956	17.489	34.978	69.956

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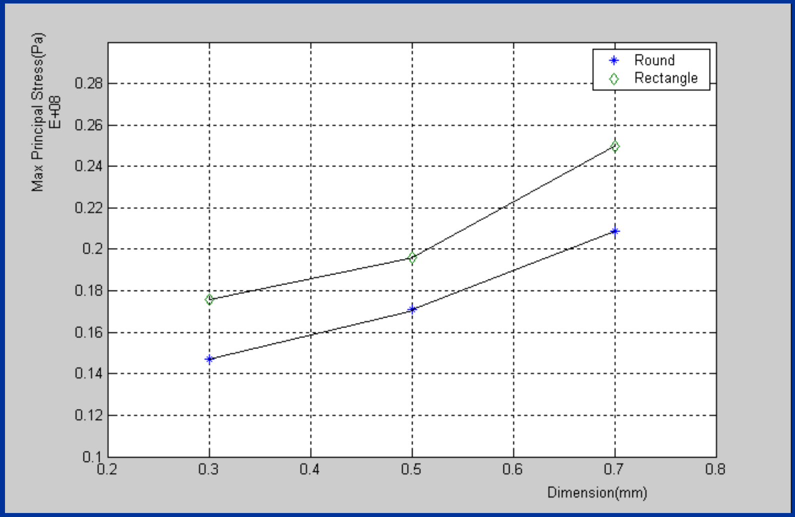
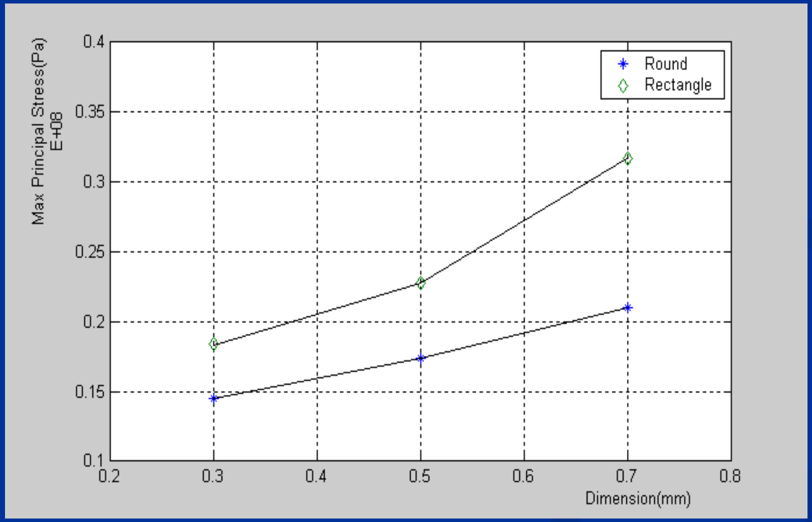
Graph of Relation between Ultimate Stress and Chamber Diameter

- Utmost Stress Relative to Chamber Diameter



Single Chamber Working State



Four Chambers Working State

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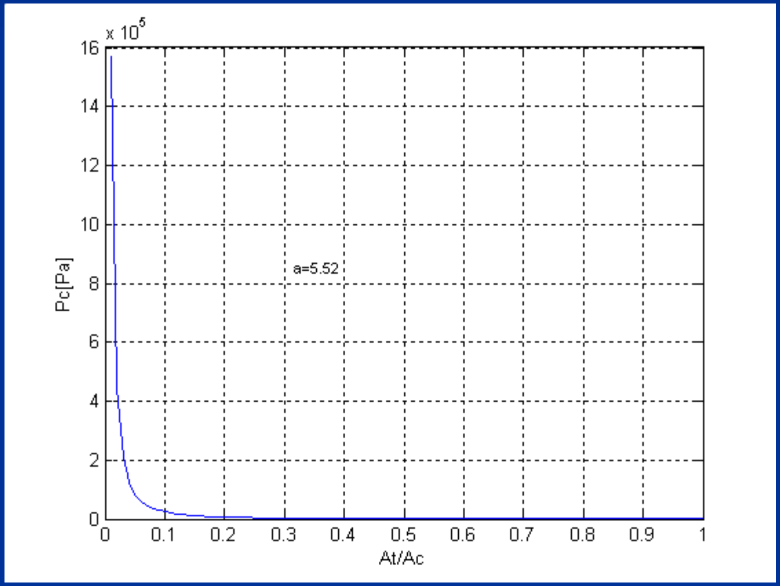
Thrusts Performance Prediction

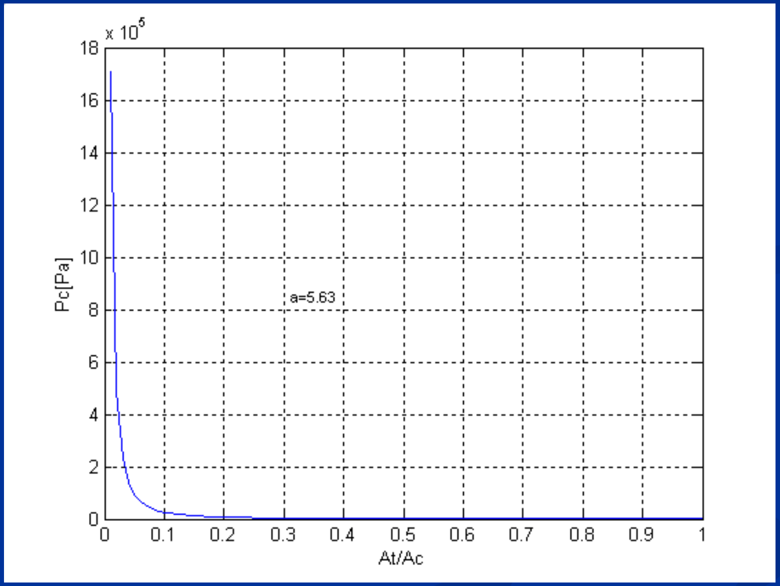
- **Basic thermodynamic principles are used, taking the following considerations**
  - The propellant chemical reaction products are homogeneous.
  - All the species of the working fluid are gaseous.
  - The combustion gases follow the ideal gas law.
  - The propellant flow is steady and constant.
  - The chamber and nozzle wall is adiabatic.
  - The nozzle is Laval geometry.
  - The gases velocity, pressure, temperature and density are uniform across the section.
  - Boundary layer effects are neglected.
  - There is no shock waves and discontinuities in the nozzle flow.

Chamber Pressure Calculation

- Functional relation between pressure Pc in the chamber and the throat-to-chamber section ratio At/Ac



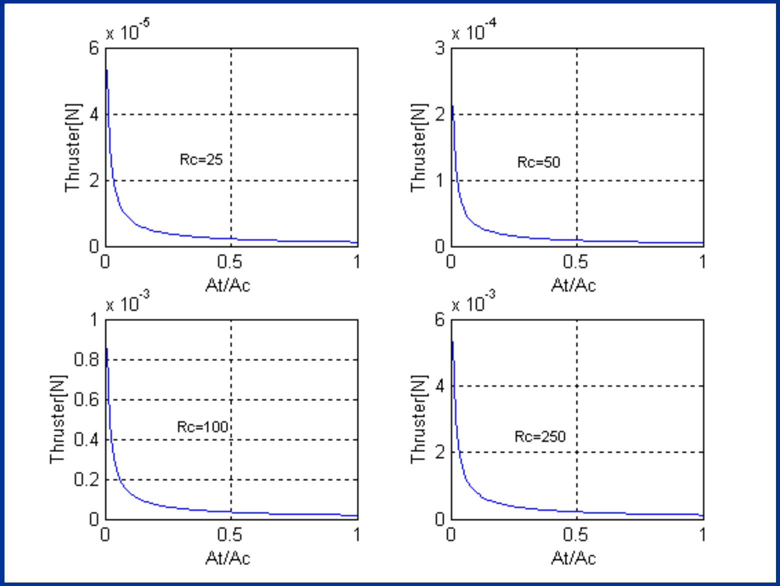
A-type propellant



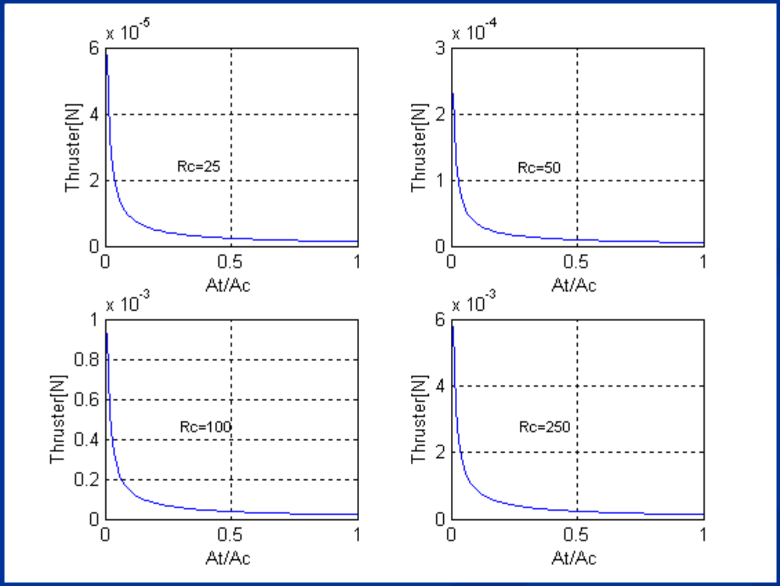
B-type propellant

Thrusts Performance Calculation

- Functional relation between thruster F in the chamber and the throat-to-chamber section ratio At/Ac



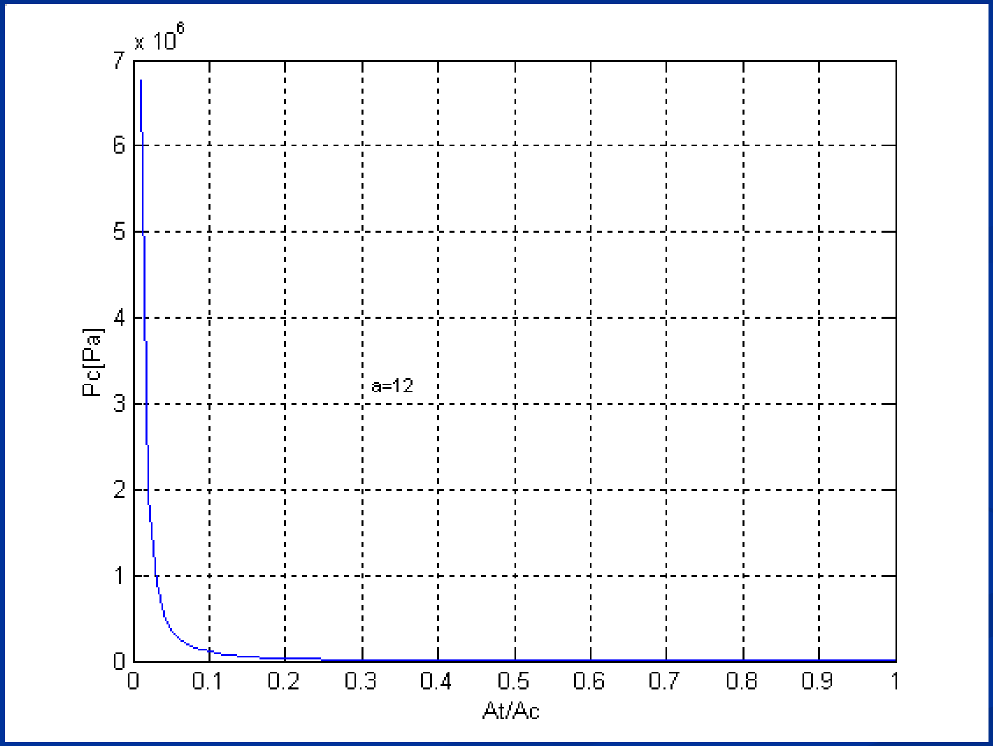
A-type propellant



B-type propellant

Chamber Pressure Calculation with Increasing Combustion Rate

- Increasing the pre exponential factor a and the ratio Ac/At help to increase the pressure Pc



Conclusion

- MEMS solid propellant propulsion is a better option.
- Real thrust force and special impulse is lower than the theoretical value.
- Increasing the combustion rate and the throat-to-chamber section ratio is a efficient way to enlarge the thrust force.
- Increasing the combustion rate will improve the thruster firing performance, and ensure the combustion sufficiently.
- In order to increase the special impulse, thermal isolation of chamber and nozzle must be adopt.
- Under the micro scale condition, the boundary layer effect, thermal transfer and the propellant combustion mechanics need be further studied on.

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Thank You!

Any Comments or Suggestions Will be Highly Appreciated!