Ultracompact Microthruster for Pico/Nanosat Attitude and Thermal Control based on Film-Evaporation Effect

Tony Cofer, Bill O’Neill, Steve Heister, Alina Alexeenko
School of Aeronautics and Astronautics, Purdue University

In collaboration with
Khary Parker, Eric Cardiff, NASA GSFC, Propulsion Branch
Carl Kotecki, Manuel Balvin, Larry Hess, NASA GSFC Detectors Branch

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Film-evaporation MEMS tunable array (FEMTA) technology is designed for low-power (< 1 W), µNewton propulsion and thermal control of picosats in < 2 cm³.
Thermal Inkjet Principle

Inkjet Printer Cartridge

http://ytec3d.com/hp45-inkjet-printhead/

Cartridge Nozzle Array

https://www.microengineeringsolutions.com/mes_service/micro-machining/
How FEMTA Works

- Silicon microfabrication produces 2D slot nozzles with embedded microheaters
- Both thrust and evaporative cooling created by low power (10mW-1 W) heaters
- Microscale thermal valving without any moving parts
- High storage density green propellant
FEMTA for PicoSat Applications

12 FEMTA units for 3-axis control on a 1 U cubesat

10 x 10 FEMTA thruster array

140 nm-thick, 10 µm wide Pt heater

2 µm thick Si$_x$O$_y$ insulator

50 nm-thick Au conductor

FEMTA thruster

200 µm
Fabrication time is 4 to 14 days depending on tool availability

A 100 mm diameter wafer delivers 56 dies of 1 cm² area each

Throat widths 5 to 8 microns wide, aspect ratios of ~ 2, 4, 6 and 8 have been produced
Gen1 FEMTA: Aspect Ratio, AR8

Cross Section

Nichrome Heaters

Main challenges: lithography on inclined surface; <10µm nozzle etching uniformity
Nozzle Inlet & Throat

Gen 3 FEMTA Units Built with Throat Aspect Ratios (AR) of 2-8

Key Solutions:
- Increased wafer thickness from 200 to 525 µm
- Gen3 DRI etch vs Gen1 wet etch
- Platinum heater instead of nichrome
## Heater Microfabrication Yield

### Gen 1: May 2014

- **Nichrome heaters**:
  - Resistance in ohms:
    - 258
    - 212
    - 223
    - 335
    - 439
    - 223
    - 222
    - 236
    - 420
    - 245
    - 223
    - 189
    - 124
    - 186
    - 185
    - 188
    - 269
    - 253
    - 315
    - 272
    - 220
- **Yield**:
  - 2%
  - 40%
  - 13%
  - 45%

### Gen 3: April 2015

#### Vanadium heaters
- Resistance in kilo-ohms:
  - 100%

### 4” wafer: 52 devices

- **Functional**
- **High Impedance**
- **Infinite Resistance**

### Comments
- Gen 3: April 2015:
  - 100% functional yield

### Gen 1: May 2014:
- 2% functional yield
- 45% high impedance
- 13% infinite resistance

### Table

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### Graphs
- **Nichrome heaters**
- **Vanadium heaters**
MicroNewton Thrust Stand Test Setup

- Thrust stand mounted in a 4.2 m³ vacuum chamber
- Backpressure ~ $10^{-6}$ Torr
- LVDT resol’n: 30 nm
- Thrust stand calibrated from 8 – 768 µN

- Measurement Uncertainty
  - ±7.2% @ 8.7 µN
  - ±3.5% @ 32.7 µN
  - ±1% @ 72.2 µN
Thrust Data for FEMTA Gen3 AR~2 Nozzles

- Thrust levels higher than expected
- Delay before firing
- Erratic behavior shuts off prematurely
- Unwanted impulse bits in other tests

Short nozzles exhibit capillary instability that increases with applied power
Vapor mean free path is comparable to nozzle length
• Thrust and cooling verified for the first time
• Cooling to input power ratio ~ 12:1 (18:1 is theoretical)
• Observed undemanded thrust outside applied power interval – “burp” of fluid occur after power is turned off

50 mW input – total impulse 2.2 mN·s – mass usage 11 mg – Isp 21 seconds – estimated cooling power 733 mW
Gen3: Thrust and Mass Flow Measurements

- Average mass flow rate 23 µg/s
- Mass flow obtained by integrating pressure change over total pulse time
- Calibrated with nitrogen and converted to water vapor using molecular mass and Bayerd-Alpert gauge constants

Gen 3, AR4: 75 mW input power
Thrust and Input Power Histories of Gen 3 FEMTA Units AR=4

3800 Pa < Internal pressure < 4200 Pa

- Thrust response within 200 millisec of power application
- Linear power to thrust ratio ~ 230 µN/W

Average thrust = 34.6 µN
Average thrust = 15.6 µN
FEMTA Gen3: Propulsive and Cooling Performance Summary

- **Thrust mode, high AR:**
  - Highly repeatable, controllable
  - Isp up to 90 sec
  - 230 microNewton/Watt
- **Cooling mode, low AR:**
  - 12:1 cooling power, Isp~30 sec

AR4: 10 pulses for each input power

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**Graphs:**

1. **Average Thrust (μN) vs. Applied Power (mW):**
   - Linear relationship
   - Maximum thrust near 70 μN

2. **Isp (seconds) vs. Applied Power (mW):**
   - Isp varies with power
   - AR = 4 and AR = 2 curves
   - Isentropic Conv Nozzle and Isentropic Conv/Div Nozzle

3. **Thrust/Power (μN/W) vs. Applied Power (mW):**
   - Logarithmic scale
   - AR = 4 and AR = 2 comparison
   - Power efficiency at different applied powers
FEMTA Gen4: Current Work

Bimorph Shutters

* Image by Carl Kotecki at GSFC

RTD Integration for Thermal Feedback

- 3 µm-wide strips separated from main Pt heater using FIB
- Expect to pin meniscus on RTD so that temperature can be determined by resistance change
Zero G Propellant Delivery System

- Current system gravity fed – won’t work in zero G environment
- Elastic bladder or else collapsible hydrophilic membrane to provide feed pressure
- Either connectors for control ribbon cable or solder lugs for printed circuit board mounting
• Prof. Dmitrios Peroulis, Michael Sinani – MEMS fab
• Prof. Andrew Ketsdever – thrust stand design
• Israel Borges Sebastiao, Bill O’Neill, Andrew Weaver – modeling
• Andrew Strongrich – vacuum lab
• Carl Kotecki, Manuel Balvin, Larry Hess, David Franz, Khary Parker, and Eric Cardiff at Goddard SFC

• NASA SmallSat Technology Partnership:
  • Andrew Petro, Program Manager
  • Greg Dorais, PM/Technical Monitor # NNX13AR02A
  • Elwood Agasid, PM/Technical Monitor # NNX15AW40A
\[ \Delta S_{\text{gen}} = (S_2 - S_1)_{\text{liquid}} + (S_2 - S_1)_{\text{gas}} \]

\[ (S_2 - S_1)_{\text{liquid}} = s^0_{\text{liquid}} \Delta T_{\text{liquid}} \cdot m_{\text{liquid}} = -23 \, J \]

Where \( s^0_{\text{liquid}} = 3886 \, \frac{J}{kg \cdot K} \) is the specific entropy change for liquid water. The entropy change for the gas has two parts; the change of the liquid to FEMTA firing temperature and the change from liquid to gas, and is given by

\[ (S_2 - S_1)_{\text{gas}} = m_{\text{gas}} \left( s^0_{\text{liquid}} \Delta T_{\text{gas}} + \Delta v_{\text{vap}} s^0_{\text{vap}} T \right) = 43 \, J \]

Assuming the phase change occurred at \( T = 323 \, ^\circ K \) which is \( \Delta T_{\text{gas}} = 30 \, ^\circ K \), and \( \Delta v_{\text{vap}} s^0_{\text{vap}} = 2.1 \, \frac{MJ}{kg \cdot K} \) is the specific entropy change of vaporization, then \( \Delta S_{\text{gen}} = +20 \, \text{Joules} \).
Flow Characteristics

Based on firing temperature 50 C or 323 K

Assume sonic flow $M = 1 \quad v = \sqrt{\gamma RT} = 445 \text{ m/s}$

Vapor pressure = 12 kPa – sonic pressure = 6.4 kPa

Assume ideal gas - density at throat = \( \frac{P}{RT} = 0.043 \text{ kg/m}^3 \)

Characteristic length = gap size = $L = 8$ microns

Reynolds number = \( \frac{\rho v L}{\mu} \) = 13.6

Knudsen number = \( \frac{M}{Re} \sqrt{\frac{\gamma \pi}{2}} = 0.1 \)

Mean Free Path = $kn \cdot L \sim 0.8$ microns
Maximum Expected
Performance for 10 x 2500 micron Throat

Assuming $T_0 = 50$ C

\[
\dot{m} = \frac{P_0 A^*}{\sqrt{T_0}} \sqrt{\frac{y}{R}} \left(\frac{2}{y+1}\right)^{\frac{y+1}{y-1}}
\]

\[
\text{power} = \dot{m}c_p\Delta T
\]

\[
P = \dot{m}h_v - \text{power}
\]

\[
I_{sp} = \frac{\sqrt{2RT_0(y+1)}}{\gamma g}
\]

\[
F = \dot{m}g \cdot I_{sp} = 392 \mu N \text{ Thrust}
\]

= 540 $\mu$g/s mass flow

= 67.7 mW input power

= 1.15 W cooling power

= 74 seconds