Nanotechnology-Enabled Microthrusters: Nanoenergetic Materials and MEMS Paradigm

Ivan Puchades¹, Mkhitar Hobosyan², Lynn F. Fuller¹, Felix Liu¹, Sunnykumar Thakur¹,
Karen S. Martirosyan² and Sergey E. Lyshevski¹

¹Department of Electrical and Microelectronic Engineering, Rochester Institute of Technology, Rochester, NY 14623
E-mail: Sergey.Lyshevski@mail.rit.edu

²Department of Physics and Astronomy, University of Texas at Brownsville, Brownsville, TX 78520
E-mail: Karen.Martirosyan@utb.edu

ABSTRACT

We study microthrusters which can be used in various flight and underwater platforms. The MEMS-technology thrusters with Al/I₃O₅ and Al/Bi₂O₃ nanostructured energetic composites increase thrust-to-weight ratio and energy density, thereby ensuring enabling capabilities. The integrated micromachining ensures overall technology compatibility, scalability, simplicity, affordability, robustness, etc. These lead to advantages as compared to conventional solutions. The MEMS-technology microthrusters with solid-fuel are suitable in a wide range of applications, such as payload delivery, stabilization, guidance, navigation and other platforms.

Keywords: MEMS, microthrusters, nanoenergetics

1. INTRODUCTION

It is important to develop and apply new scalable and integrated technologies. We focus on applications of micro and nano technologies in design and developments of integrated microthrusters which use nanoenergetic materials [1-3]. The overall functionality may be ensured using integrated MEMS technology with high-energy-density nanostructured materials encapsulated in silicon-micromachined voids [4]. A scalable and modular system-level solution is achieved by integrating of microstructures, MEMS sensors and energetic materials. Our solution ensures enabling capabilities, such as safety, high stored energy capacity, high specific energy, high energy and gas release rates, optimal burning, etc. The MEMS design and integration of self-assembled nanoenergetic materials imply development of integrated MEMS and nano technologies.

Proof-of-concept MEMS-technology systems have been fabricate [5, 6]. Sensing, diagnostics, control and other attributes must be ensured guaranteeing safety, robustness, monitoring, data acquisition, uncontrolled ignition prevention, etc. Depending on vehicles, missions, requirements and specifications, various physical variables must be directly or indirectly measured. The fabricated devices include integrated ignition capabilities along with temperature and pressure sensors.

Our studies indicate that the synthesized Al/Bi₂O₃ and Al/I₃O₅ nanocomposites ensure energy release and generate transient pressure impulses which are three times higher than traditional nano-thermite reactive mixtures. The peak pressure is generated during the combustion of nanoenergetic mixtures. The bismuth trioxide nanoparticles, synthesized by combustion synthesis generates pressure, ensure pressure three times higher than pressure of commercial Bi₂O₃ nanoparticles [7].

We address and provide systems-level design solutions solving integration, packaging, diagnostics, control and other problems. The net thrust in a wide range (from ~μN to N) can be generated by a single or multi-array thruster cells. It is possible to ensure controlled impulse- and uniform near-continuous-thrust propulsion for micro-air, space and underwater vehicles. Depending on applications, high temperature, high pressure, specified combustion, desired flow rates, optimal energy conversion, effective energy release, and other desired features can be achieved.

2. NANOENERGETIC MATERIALS

The established and demonstrated nanoenergetic thermite composites include mixtures of Al and other metal oxides. Among numerous thermodynamically feasible nanoenergetic mixtures, the most widely studied are Al/Fe₂O₃, Al/MoO₃, Al/WO₃, Al/CuO, Al/Bi₂O₃ and others. The distinguishing features of these compounds are significant enthalpy release and adjustable rate of energy discharge. These features result in a wide range of combustion rates, energy release and ignition sensitivity.

Among common thermite composites, Al/Bi₂O₃ and Al/I₃O₅ mixtures ensure high energy density and generate the highest pressure impulses reaching ~11 MPa. The high pressure during the combustion of Al/Bi₂O₃ and Al/I₃O₅ results because the reaction product (bismuth or iodine) boils at temperature 1560°C and 184°C, respectively [1]. The aforementioned temperatures are lower than the maximum reaction temperature, which is ~2000°C. This causes bismuth or iodine evaporation, with the increase the released gas pressure. The energy release nanoenergetic reactions are

\[ \text{Bi}_2\text{O}_3 + 2\text{Al} = \text{Al}_2\text{O}_3 + 2\text{Bi} + \Delta H \sim 15.2 \text{ kJ/cm}^3 \], \hspace{1cm} (1)

\[ 3\text{I}_2\text{O}_5 + 10\text{Al} = 5\text{Al}_2\text{O}_3 + 6\text{I} + \Delta H \sim 25.7 \text{ kJ/cm}^3 \]. \hspace{1cm} (2)

Aluminium nanoparticles are highly pyrophoric in air, and, they are usually coated with a 4-8 nm thick coating oxide Al₂O₃ shell during their fabrication. The coating reduces the active Al content in a compound, thereby decreasing the ignition sensitivity. In most experiments, we use Al particles with an average size ~100 nm. This powder is not very active in air, and, can be safely mixed with metal oxides in the preparation of thermite reactions mixtures.
3. SELF-ASSEMBLED NANOENERGETIC COMPOSITES

Controlled self-organization is an ability to synthesize robust, well-defined, atomically-self-engineered and self-aggregated structures, composites and mixtures from atoms, molecules and compounds in a pre-defined and controlled synthesis process with external control inputs such as heat, light, mechanical agitation, etc. Once initiated, the self-organized and self-aggregation processes utilize immense number of molecules, organized into integrated nanostructured mixtures, which possess specific performance, attributes and capabilities. In our synthesis, a polymer chain poly(4-vinyl pyridine) binds Bi$_2$O$_3$ or I$_2$O$_5$ with Al nanoparticles. The polymer is a structural link for the nanoparticles assembly process. The Al nanoparticles (~100 nm in diameter with 4 nm of passivation layer) with the nanoparticles assembly process. The Al nanoparticles and uniform exhaust velocity clusters in micromachined micro-chambers ensures high continuous thrust is achieved by Al/Bi$_2$O$_3$ and Al/I$_2$O$_5$. The controlled uniform burning of the propellant produces a controlled thrust for continuous and impulse propulsion of flight vehicles as well as to rocket-propelled supercavitation underwater vehicles.

The net thrust is

\[ F = \dot{m}_e v_e + A_e (P_e - P_a), \]

where \( \dot{m}_e \) is the propellant exhaust gas mass flow which depends on the propellant combustion rate \( \dot{m} \); \( v_e \) is the effective exhaust velocity along the thrust axis; \( v_a \) is the actual exhaust velocity at nozzle exit plane; \( A_e \) is the flow area at the nozzle exit plane; \( P_e \) and \( P_a \) are the static pressure at the nozzle exit plane and ambient pressure.

The total impulse is defined as \( \int F dt \), while the continuous thrust is \( F_t \).

The combustion of self-assembled nanoenergetic clusters in micromachined micro-chambers ensures high and uniform exhaust velocity \( v_e \) and rate \( \dot{m}_e \). The major thruster core and support structures are comprised from silicon-micromachined chamber and nozzle. There are no channels, pumps, valves, propellant tanks, fuel lines, etc. [8]. The designed microthruster is illustrated in Figure 1. The chamber, where the nanoenergetic materials are encapsulated, and nozzle are made from silicon and silicon-competitive materials. The MEMS sensors are used to measure temperature, temperature gradient, pressure and other physical quantities.

Different concepts and designs are considered. The microthruster arrays can be made by using multi-layered silicon, glass and polymer layers, while the middle layer or cavities consist of encapsulated combustible nanoenergetic propellants in a solid form. The polysilicon heaters initiate combustion. Cells can be separately ignited, producing desired thrust and ensuring the thrust-vectoring capabilities. Microthrusters can be controlled and ignited within the desired sequence using ICs. Various sensors can be used in our highly-integrated MEMS platform. The microthruster array may be designed within different micro-chambers configurations and three-dimensional geometry.

4. NANOENERGETIC COMPOSITES AND MEMS

The nanoenergetic materials can be used as explosives, solid-fuel propellants, pyrotechnics, additives for liquid propellants, etc. The spontaneous chemical reaction, as initiated, is driven by a large exothermic change (release of heat) as well as gas release. A very favorable rapid thermodynamic process is achieved by Al/Bi$_2$O$_3$ and Al/I$_2$O$_5$. The controlled uniform burning of the propellant produces a controlled thrust for continuous and impulse propulsion of flight vehicles as well as to rocket-propelled supercavitation underwater vehicles.

The MEMS technology allows one to fabricate structural silicon and silicon-compliant microstructures, semiconducting electronic and sensing devices, etc. The scalability, functionality and other features, pertained to a microelectronic compatibility, are guaranteed. We design structurally and functionally integrated MEMS. Sensing, diagnostics, control and other attributes are ensured. These guarantee safety, robustness, monitoring, data acquisition, uncontrolled ignition prevention, etc. Wireless communication and management systems can be designed. The aforementioned features significantly enable and enhance solutions reported in [8].
Processing, controlling, sensing and signal conditioning ICs comprise an Integrated Electronic Management Module. A proof-of-concept of the studied NanoEnergetic MEMS MicroThruster Platform is fabricated. The technology-, application- and platform-specific designs are performed. We design and tested MEMS system prototypes within different organizations and complexity which define the overall functionality. The solid-fuel high-energy-density propellant should burn in controllable and optimized manner, producing exhaust gases and thrust. The chamber and nozzle dimensions and three-dimensional geometries are designed to ensure the specified pressure and thrust produced from the exhaust gases. Depending on vehicles, missions, requirements and specifications, various three-dimensional chambers and nozzles are fabricated as illustrated in Figure 2. The physical variables must be directly or indirectly measured. In particular, temperature, pressure, velocity and other physical quantities are of interest. The ignition is accomplished by the p+ silicon or aluminum heater.

A bulk MEMS microfabrication process was used to fabricate microthrusters. For the proposed design, there is no need to use a deep reactive ion etch (DRIE) technique which results in the high aspect-ratio nozzle structure or the chamber cavity. We develop a hard-mask process to define the nozzle and chamber geometries using conventional RIE techniques. A wet KOH etch is used to form the chamber. Silicon is used as the structural material, SiO₂ forms insulating layers, doped p+ silicon is aimed for temperature and stress sensing, while aluminum forms interconnections and heater. The fabrication process starts with double-side-polished n-type silicon wafers. A silicon oxide is grown and used as a masking layer for the p+ silicon spin-on-dopant process, which could be the heating element on the membrane, as well as the strain sensor to measure the membrane deflection and pressure. A pad silicon oxide is thermally grown. The silicon nitride is deposited using a low-pressure chemical vapor deposition (LPCVD). The silicon nitride and oxide are patterned on the backside of the wafer by dry SF6 and buffered oxide etch (BOE). Polysilicon is deposited by means of LPCVD to protect the patterned nitride on the backside of the wafer until the bulk silicon etch is performed. A 1 μm oxide layer is deposited, and the contact openings to p+ silicon are etched in a BOE solution. After the contacts are etched, a 1 μm Al layer is deposited, and then patterned to make the electrical connections, function as the ignition heater, and, function as the temperature sensor. 1 μm passivation oxide is deposited on the front of the diaphragm to provide a layer of separation needed for the hard-mask material used to etch the top hole. A 0.5 μm AI hard-mask is deposited and defined with the top-hole pattern. The front of the wafer is protected with Brewer Science’s PROTEK™. The diaphragms are formed by etching from the back of the wafers. The patterned silicon nitride is used as a protection layer during the silicon KOH etching process. The depth of etching is measured until the desired diaphragm thickness is obtained. As desired depth is ensured, the PROTEK™ is removed. A bottom 0.5 μm Al layer is deposited to protect the back of the devices. The wafers are then diced in a conventional dicing saw. The top hole is etched using SF6 RIE. The aluminum hard mask on the front of the wafer, and, the Al on the back of the wafer, are etched away using a commercial wet aluminum etch solution. The final step consists on etching the oxide separation layer in SF6 to expose the aluminum contact pads to the devices. Temperature can be sensed by the Al resistor by measuring the change in resistance during ignition. In fact, the temperature-dependent resistance is given as

\[ R_f(T) = R_0 [1 + \alpha (T - T_0)], \]

where \( R_0 \) and \( T_0 \) are the resistance and temperature at room temperature; \( \alpha \) is the temperature coefficient, \( \alpha_{Al}=3.6 \%/K \).

The pressure in the chamber is estimated by monitoring the change in resistance of the p+ resistor due the piezoresistive effect. The stress \( \sigma \) seen by the resistor at the edge of the diaphragm is

\[ \sigma = 0.3 \rho L^2/h^2, \]

where \( L \) is the length of the diaphragm; \( h \) the thickness; \( \rho \) the pressure.

The change of resistance is a function of the strain. Using the piezoelectric coefficients of the p+ silicon,

\[ R = R_0 [1 + \pi L \sigma_{\text{xx}} + \pi_T (\sigma_{\text{yy}} + \sigma_{\text{zz}})], \]

where \( \sigma_{\text{xx}} \) is the stress in the specified direction; \( \pi_L \) and \( \pi_T \) are the longitudinal and transverse piezoelectric coefficient with respect to the direction of the charge carriers.

Two ignition heaters, which can be used as the temperature sensors, formed by deposited Al and p+ silicon, are on the opposite sides of the nozzle opening as shown in Figures 1 and 2. In the p+ silicon structure, the resistance changes due to both strain and temperature variations. The variations of \( R \) should be correlated taking into the account both factors. The SEM images, reported in Figure 2, show the desired near vertical nozzle sidewall with a slight retrograde shape as per optimal design. This 3D geometry optimizes the thruster performance. The thickness of the diaphragm may vary from 30 to 150 μm. The refinements can be performed to further optimize microthrusters performance. The top and bottom structures are bonded, and, solid fuel is encapsulated.

![Figure 2. Nozzle structures: (a) Top view of nozzle opening; (b) Cross-sectional view of nozzle showing a nearly vertical opening.](image)

6. Microthruster Testing

For testing, the electrical connections are made by wire-bonding the top component to a PCB board as illustrated in Figure 3.
The thrust and force, produced by a single microthruster were measured experimentally. The microthrusters are attached to an analytical balance which is connected to a PC with the recording, data acquisition and processing capabilities. The microthrusters are ignited as illustrated in Figure 3. The measurements are made, thereby guarantying characterization and evaluation.

![Figure 3](image1.png)

Figure 3. (a) Assembled microthruster with wire-bond connections to a PCB board; (b) Testing of a microthruster: Ignition by using a heater; (c) Microthruster before and after ignition test

Figure 4 illustrates the mass change of the microthruster during the combustion process using a sensitive balance. The exhaust gases are directed vertically upward, while a microthruster is exhibit the force on the balance during combustion. There is time delay due to inertia of the balance. However, the maximum force produced by microthruster is measured. The amount of Al/I₅ nanoenergetic material was 4.82 mg. The inner volume of the chamber was 4.2 mm³. Thus, the density of Al/I₅ in the microthruster cavity is 1.15 g/cm³. The packing density significantly affects the thrust and force. The produced force is 7.2 mN, ensuring the quantitative measure 1.5 N/g. The force produced by a single microthruster can be varied by using nanostructured materials with different stored energy, changing the solid-fuel density, varying amount of fuel in the chamber, etc. Changing the chamber size and volume, one refined the weight and density of the encapsulated nanoenergetic compound.

![Figure 4](image2.png)

Figure 4. Evolution of mass change during the solid-fuel combustion

### 6. Conclusions

Departing from conventional solutions, new nanoenergetic materials were designed and synthesized. We reported fundamental, applied, experimental and technological studies for enabling high-energy-density nanostructured materials based on bismuth and iodine oxides. High-yield synthetic reaction and synthesis process were developed to precisely control molecular structure of nanoenergetic materials. These materials can be encapsulated in integrated MEMS which include controlling, sensing, diagnostics and processing capacities by means of microelectronics. We documented transformative developments towards **NanoEnergetic MEMS MicroThruster Platforms**. This solution guarantees sensing, diagnostics, control and functionality. The application-specific thrust impulses, thrust-vectoring and continues thrust can be ensured by microthrusters and their arrays. Various issues should be considered, such as:

- Optimization of three-dimensional chamber and nozzle volumetrics and geometries;
- Controlled combustion propagation and dynamics;
- Uniformity of reaction, burning, heat transfer, pressure, temperature, stress, combustion, flame, etc.;
- Data-intensive analysis, diagnostics, adaptation and optimization.

The system-level design was accomplished. The integration and functionalization of self-assembled nanoenergetic materials was archived by using an integrated MEMS technology. Novel technologies and transformative developments were initiated.

### References


