Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 470–471

A-9-3 (Invited)

Micro Power Generation Programs at DARPA

William C. Tang

Program Manager, Microsystems Technology Office, Defense Advanced Research Projects Agency
3701 North Fairfax Drive, Arlington, VA 22203, USA
Phone: +1-703-696-2254 Fax: +1-703-696-2206 E-mail: wtang@darpa.mil

1. Introduction

Since 1992, the US Defense Advanced Research Projects Agency (DARPA) has been funding research and development in Micro-Electro-Mechanical Systems (MEMS). The use of MEMS technology for sensing and actuation has demonstrated size reduction, mass reduction, power reduction, performance enhancements, new sensing concepts, and new functionality in autonomous and semi-autonomous systems and platforms. However, these standalone systems currently rely on batteries as power supplies. Micro power generators (MPG) with significantly higher energy densities than batteries will be the key components in ultimate miniaturization and integration of standalone, self-contained, wireless micro sensors and micro actuators that can be deployed remotely and operated autonomously. The DARPA MPG program was recently established to demonstrate the capability to generate power at the micro scale with MEMS technology.

2. Program Goals

The MPG program aims at generating power at the micro scale to enable standalone micro sensors and micro actuators with wireless communication function to realize new autonomously operated systems [1]. Hydrocarbon fuels offer attractive alternatives as power sources due to their superior energy densities. For example, the energy densities of propane, methane, gasoline, and diesel are at least 50 to 100 times higher than the best lithium-ion batteries (Fig 1). With a modest energy conversion efficiency of 10% from chemical energy to electricity, the resulting power generator will still be five-to-ten times smaller than a comparable battery.

Specific demonstration goals of the MPG program include:

- Feasibility and practical limits in converting chemical energy into electrical energy on the micro-scale;
- Significant advantage (>10X) in energy density over state-of-the-art battery;
- Capabilities in fuel processing, energy conversion to electricity, thermal and exhaust management;
- Integration of various power-generation components with micro sensors and micro actuators; and
- Standalone remotely distributed micro sensors and actuators with built-in power supply and wireless communication.

Microfabrication techniques used to create micro power generators include deep reactive-ion etching (DRIE), laser milling, wafer bonding, stereo lithography, thin-film deposition, and heterogeneous integration. Novel materials suitable for combustion and fuel cells include alumina, SiC, Si, Pt, PdH, polymer membranes, etc. Micro power generation techniques include thermoelectric converters, micro combustion engines, micro fuel cells, and micro fuel reformers. The key research focus is on innovative MEMS solutions that allow system optimization on several major factors affecting the overall efficiency and utility of the final MPG devices. Examples of optimization factors include (1) the power requirement of the associated sensor, actuator, and/or electronic circuits, which typically range from tens of microwatts for sensor operations to less than a few hundred milliwatts for wireless data transmission; (2) thermal management if conversion of thermal energy is involved; (3) intake and exhaust managements if fluid or solid transports are required; (4) material compatibility and robustness if high-temperature and high-contact mechanical loads and/or mechanical outputs are parts of the design; and (5) energy storage and power distribution methodologies if there is a mismatch between the rates of energy conversion and energy consumption. Success of the MPG program will revolutionize energy storage and generation for micro and hand-held devices.

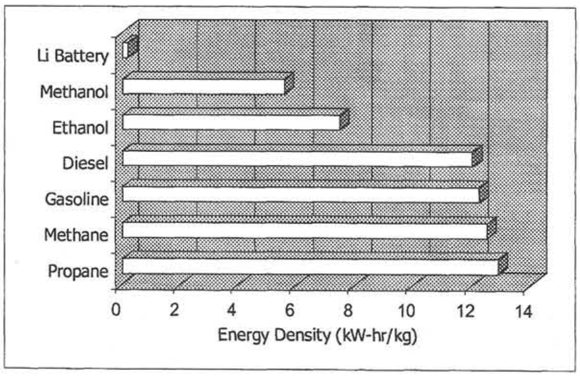

Fig.1. Energy density comparison

3. Recent Accomplishments [2]

Micro Combustion Reactors

Scaling down combustion chambers results in higher surface-to-volume ratios. As a result, thermal and radical losses to the chamber walls and quenching become dominant factors in energy conversion efficiency. Both theoretical and experimental studies indicate that the practical minimum dimension can be as small as 1 mm^3. An experimental combustion reactor has been demonstrated at Battelle, with an active reactor volume of less than 0.4 mm^3. With this reactor, catalytic combustion of hydrogen/air and n-butane/air was found to be self-sustaining without the need for air preheats. A catalytic fuel reformer measuring 1 mm^3 has also been demonstrated, which yields 10.5 moles of hydrogen per mole of butane. A 3-D microfabrication technique is used to create a swissroll thermoelectric generator without moving components (USC). Counter-flow channels in this device are designed to maximize heat exchange between the incoming reactants and the outgoing combustion products, while minimizing thermal energy loss to the ambient. The challenges of incorporating thermoelectric elements at the 3-D heat exchange interfaces are being addressed with innovative fabrication processes. Multiple-cycle auto-ignition operations of a free-piston engine with a few cubic-mm-internal volume was demonstrated at the Honeywell Laboratories (Fig. 2). The goal is to pneumatically couple mechanical energy output. Combustion of hydrocarbon fuels as well as sealing leak tests of a mini rotary engine have been completed with encouraging results (UC Berkeley). The design and fabrication of an improved micro rotary engine based on silicon and silicon carbide are underway.

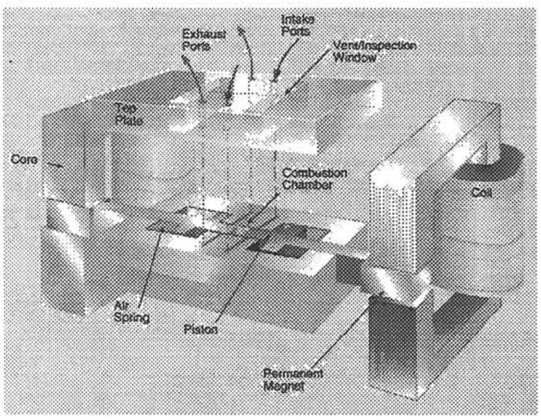

Fig. 2. Conceptual drawing of free piston micro-engine.

Micro Hydrogen Fuel Cells

At Case Western Research University, microfabricated fuel cells have been integrated and tested with a self-contained hydrogen source (Fig. 3). The source is based on aqueous solutions of sodium borohydride. Over 67% hydrogen utilization has been demonstrated with this design. A reproducible steady-state power output of 2 mW/cm^2 has been demonstrated with hydrogen and air at 50% RH. The micro fuel cells are also capable of producing 10-ms-pulse power levels of over 50 mW/cm^2. A noteworthy design innovation is that the proton exchange membrane (PEM) is based on phosphoric-acid-doped polybenzimidazole (PBI), which enables fuel cell operation at over 150°C and very low relative humidity. In contrast, traditional Nafion PEM fails at these operating conditions. This micro fuel cell will be integrated with the hydrocarbon fuel reformer developed at Battelle, which generates a trace amount of CO as a by-product. Operating the fuel cell at elevated temperature avoids CO poisoning. It has been demonstrated that the fuel cell continues to operate at current densities up to 200 mA/cm^2 with fuel streams containing 5% CO.

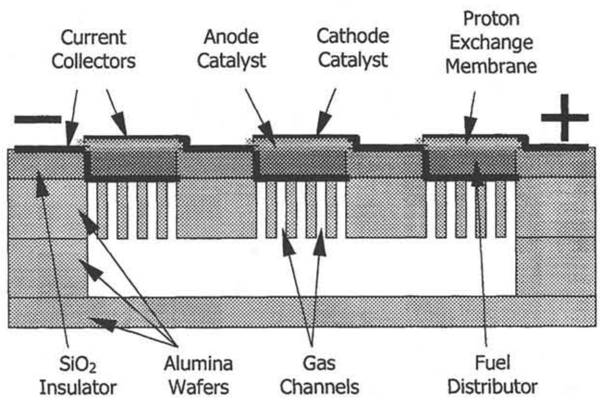

Fig. 3. Conceptual drawing of micro hydrogen fuel cell.

4. Future Work

The DARPA MPG program will continue the work in micro combustion engines, thermoelectric generators, micro hydrogen fuel cells and hydrocarbon fuel reformers. It will also explore direct-methanol micro fuel cells, solid-oxide fuel cells, innovative thermal engines, and radioisotope-based electric generators. The final goal is to demonstrate a standalone self-sustained micro power generation unit that can be integrated with micro sensors and actuators with wireless communication capabilities.

Acknowledgments

The author would like to express sincere thanks to all the principal investigators of the DARPA MEMS and MPG programs. Their contributions and impacts reach far beyond DARPA.

References

[1] Broad Agency Announcement 01-09 "Micro Power Generation," *Commerce Business Daily*, October 3, 2000, Issue No. PSA-2698.

[2] URL: http://www.darpa.mil/MTO/MEMS/Summaries