MEMS Program at DARPA

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ABSTRACT

Microelectromechanical Systems (MEMS) is one of the three core enabling technologies within the Microsystems Technology Office (MTO) of the Defense Advanced Research Projects Agency (DARPA). Together with Photonics and Electronics, MEMS forms the foundation for a broad variety of advanced research projects sponsored by MTO as well as other offices within DARPA. MEMS technology merges the functions of compute, communicate and power together with sense, actuate and control to change completely the way people and machines interact with the physical world. Using an ever-expanding set of fabrication processes and materials, MEMS will provide the advantages of small size, low-power, low-mass, low-cost and high-functionality to integrated electromechanical systems both on the micro as well as on the macro scales. Further, demands for increased performance; reliability, robustness, lifetime, maintainability and capability of military equipment of all kinds can be met by the integration of MEMS into macro devices and systems. In the post-cold-war era, U.S. forces must be able to conduct prompt, sustained, and synchronized operations with our allies in specific situations and with the freedom to operate in all four domains of military engagement—sea, land, air, and space. MEMS technology has now been demonstrated in all four domains. The long-term goal of the DARPA MEMS program is to merge information processing with sensing and actuation to realize new systems and strategies to bring co-located perception and control to systems, processes and the environment.

Keywords: MEMS, DARPA

1. INTRODUCTION

The central mission of DARPA is to pursue radical innovation in support of national security. Its charter is to be at the leading edge of critical new technologies that will revolutionize military platforms. The infusion of advanced technologies into military systems is accelerating because of the vital necessity to the Armed Forces to keep pace with the exponential growth in information collection and accessibility. In the post-cold-war era, U.S. forces must be able to conduct prompt, sustained, and synchronized operations with our allies in specific situations and with the freedom to operate in all domains—sea, land, air, and space.

In 1992, DARPA identified MEMS as an emerging technology critical to the nation's security needs, and formally established the MEMS program. Numerous projects were launched for a broad range of feasibility studies on fabrication, designs, and performance limits for various applications. Since MEMS has its roots in the planar integrated circuit (IC) technology, several key advantages are inherent in MEMS-fabricated devices that are similar to IC chips. These include batch fabrication that enables mass production to lower per-unit cost, photolithographic techniques that miniaturize the resulting devices with high degree of feature definition, and integration capability to collocate various functions on the same substrate. At the same time, MEMS devices perform functions that are beyond what electronics can offer. The most frequent uses of MEMS are in the creation of microsensors and microactuators, which serve as the interfaces between the physical, chemical, and biological worlds and the world of electronics to enable a highly automated and intelligent machines with superior perception, computation, and execution capabilities. These unique advantages offered by MEMS are highly attractive for modernizing military platforms because at the core of every military operation is the ability to collect, process, verify, communicate, and act on vast amount of information in a timely manner[1].

2. CURRENT PROGRAM ACTIVITIES

Since the beginning of the DARPA MEMS program, numerous feasibility studies in applying MEMS to military platforms have been demonstrated. These platforms span the four domains of military operations: sea, land, air, and space. Currently, the program is categorized into seven major thrust areas to address this broad range of platform applications: process/materials, sensors, space, signal processing, flux control, IMU, and micro power generation (Fig. 1). The process/materials thrust area aims at exploring and innovating in the enabling fabrication foundation to support new MEMS devices. The Inertial Measurement Unit (IMU) thrust continues to explore MEMS alternatives in acceleration and rotation

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sensing. Early successful demonstration in this area has contributed to establishing a DARPA program within the Special Projects Office (SPO), the Inertial Navigation Systems (INS) program, which leverages on MEMS-fabricated, ultra-miniaturized IMU. One of the projects within the Flux Control area is the development of miniature safe/arm-and-fuze devices for 6.25-inch-diameter anti-torpedo torpedoes. Two successful sea run demonstrations have led to the decision by the Navy to invest in follow-on development and eventual fleet deployment. A pair of "pico-satellites," each measuring only 2.5 cm by 7.5 cm by 10 cm and weighing 0.3 kg, was launched and operated in low-earth orbit in early 2000, demonstrating the ability of the on-board MEMS devices to survive the launch and to function in the hostile space environment. It points to the potential of a new paradigm of space-based defense augmentation. This first pair of pico-satellites demonstrated the first-phase feasibility of low-cost, launch-on-demand, space-qualified, cooperative constellations for space-based military operations. New types of microsensors are developed to perform sensing functions that have never been realized. An example is the "Polychromator" project, which uses micro mirror strips to differentiate and analyze photon emission signatures and identify chemical species remotely. Successful demonstrations within the Micro Power Generation and Signal Processing thrusts have led to two new programs: the Micro Power Generation (MPG) and the Nano Mechanical Array Signal Processors (NMASP) programs. These two programs are described in the following section.

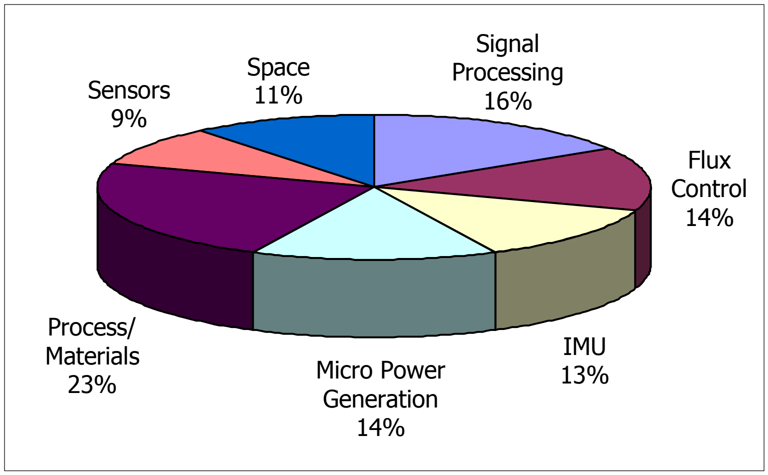

Fig. 1: The seven thrust areas within the DARPA MEMS program.

3. NEW FOCUS AREAS

There are two recently established programs that are enabled by MEMS: Micro Power Generation (MPG) and Nano Mechanical Array Signal Processors (NMASP), which are examples of the future MEMS activities in DARPA.

3.1 Micro Power Generation (MPG)

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 systems and strategies for weapons systems, processes and battlefield environments[2]. The advantages of these micro sensors and actuators systems are severely limited by the associated bulky batteries. 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. 2). 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.

The development of micro power sources will enable ultra miniaturization and functionality of standalone new systems. The use of MEMS technology has already demonstrated size reduction, mass reduction, power reduction, performance enhancements, new sensing concepts and new functionality in weapon systems and platforms. Micro power sources 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 in clusters to drastically enhance superiority of weapon systems and field awareness.

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 thermo-electric 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.

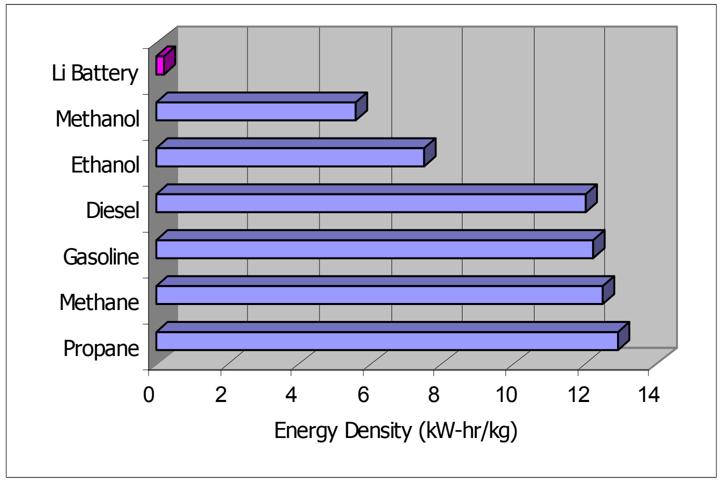

Fig. 2: Energy density comparison.

3.2 Nano Mechanical Array Signal Processors (NMASP)

The NMASP program[3] aims at creating arrays of precision, nano mechanical structures (Fig. 3) for RF-signal processing that will achieve:

- >100X reduction in size (from 80 cm^2 to 0.8 cm^2 or smaller),
- >100X reduction in power consumption (from 300 mW to <3 mW during receive, and from 30 mW to <0.3 mW during standby, compared to current cell phones), and
- >10X improvement in RF performance (spectral efficiency and bandwidth).

The development of nano mechanical array signal processors will enable ultra miniaturized (wristwatch or hearing aid in size) and ultra low power UHF communicators/GPS receivers. The use of these ultra miniature communicators/GPS receivers can greatly improve the mobility and location identification of individual war fighters. They can also be used for miniaturization and integration of stand-alone, self-contained, wireless micro sensors and micro actuators that can be deployed remotely in clusters to drastically enhance superiority of weapon systems and field awareness. Other potential uses for military applications include ultra portable spectrum analyzer, Fourier signal-transformer, programmable equalizer, frequency converter, parametric amplifier, and other UHF signal processing. Core NMASP technologies can also be used for mass spectrometer, calorimeter, bolometer, and high-resolution IR imager applications. All of these NMASP applications will be characterized by significant power reduction and/or ultra miniaturization while meeting or exceeding the performance levels of the state-of-practice approaches.

The program includes three technical tasks:

- Exploit and adapt emerging technology in nanofabrication to create nano resonators by chemical and physical transfer of materials on nano-scale patterns.
- Use parallel processing of nano patterning to create uniform arrays of nano resonators.
- Integrate nano patterning with CMOS circuits to create chip-level integration.

The key technical focus of the NMASP program is on optimized combinations of innovative solutions in micro or nano fabrication, materials processing, device design, transduction mechanism, interconnects, and other relevant engineering approaches that directly address the performance issues in high-Q UHF mechanical resonator arrays for RF transceiver and signal processor applications. These issues include: (1) temperature stability, tunability, signal-to-noise (S/N) ratio, and environmental sensitivity of individual resonators; (2) uniformity, repeatability, and variability within the arrays; (3) cross-talk, coupling, and isolation among the resonators; (4) clear potentials for chip-level integration with Si, Si-Ge, SiC, III-V, or other appropriate circuit technologies; and (5) compatibility with on-die or second-level hermetic packaging. Fabrication, materials choices, device design, and other engineering approaches are tightly coupled in influencing the performance of the mechanical resonator arrays. For example, by using a structural material with very high stiffness, one can design a resonator with dimensions that are not necessarily all in the sub-micron regime to achieve resonance in the UHF range. Another coupling and engineering tradeoff may be manifested in the balance of employing precision machining to create the resonators and the use of innovative electronic interface and compensation techniques to achieve controls in the desired frequencies within the array. Also, in the dimensions of interest, surface-to-volume ratios of the UHF mechanical resonators are likely to be very high compared to lower-frequency resonant structures, and thus surface effects and sensitivity to mass loading, among others, may need to be considered. These considerations are expected to bear important implications in the requirements for some form of isolation, surface treatment, on-die and/or second-level packaging, or possibly other innovative approaches in order to achieve stability, useful S/N ratio, Q, and other performance parameters of interest that are relevant to RF transceiver and UHF signal processing applications.

When successful, the NMASP program is expected to drastically impact frequency-domain analog signal processing in general, and particularly in wireless UHF communication.

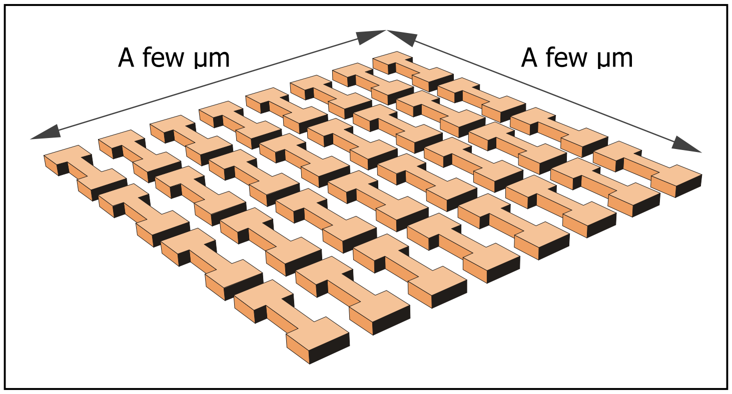

Fig 3. Conceptual drawing of a array of nano mechanical resonators.

4. CONCLUSIONS

DARPA will continue to establish MEMS-enabled programs with focused objectives. MEMS will be successful in all applications where size, weight and power and cost must decrease concurrently with increases in functionality. MEMS devices will be widely used in both the military and commercial arenas. Applications will range from fighter aircraft to automobiles and from munitions to printers. While MEMS devices per se will account for only a relatively small fraction of the cost, size and weight of these systems, they will be critical to system operation, reliability and affordability. MEMS devices, and the products they enable, increasingly will be the performance-defining factor for both defense and commercial systems.

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