Advancement of Prototyping and Fabrication Techniques for Active Sensors and Microelectronics

J. L. Zunino III* and D.R.Skelton*
*U.S. Army RDE Command, AMSRD-AAR-MEE-M
Bldg 60 Picatinny Arsenal, NJ, james.zunino@us.army.mil; donald.skelton@us.army.mil

ABSTRACT

U.S. Army ARDEC is developing the ability to custom design and integrate novel technologies into functional systems for the creation and advancement of active systems. This research being performed will directly and indirectly support the warfighter and allow the DOD to remain in the forefront of active systems technologies. Several military programs are developing flexible electronic capabilities for sensing, communication, data collection/storage, and power. Several different fabrication and manufacturing techniques are used to develop such systems. Besides techniques common to the development of microelectronics, MEMS, and the like, the development of nano-inks and related materials printing techniques will revolutionize the development of active systems, electronics, and other custom devices.

Keywords: Army, military, sensors, material printing, nano-inks

1. INTRODUCTION

In the ever-changing world in which the U.S. Army must operate, there is a need for advanced materials and systems that can operate and survive in a variety of environments. Recent conflicts require the Army to transform into a lighter more lethal force. To accomplish this transition, weapon systems to be rapidly deployable, 70% lighter, and 50% smaller than current armored combat systems while maintaining equivalent lethality and survivability [1]. To that end, U.S. Army scientists and engineers are capitalizing on new technological breakthroughs in nanotechnology, MEMS, microelectronics, etc., to develop materials and active systems that meet the Army's objectives for "smarter," more rapidly deployable, lighter and smaller weapons systems.

Several military programs are investigating the use of flexible electronic capabilities for sensing, communications, data collection/storage, and power alternatives.

2 ACTIVE SENSOR SYSTEMS & MICROELECTRONICS

Active sensor systems enable the U.S. Army to add advanced capabilities while maintaining weight and lethality requirements, though they require the development of advanced technologies across various energy domains (e.g., electrical, mechanical, chemical, optical, biological, etc.). Active systems are utilized to perform condition-based maintenance, battlefield damage assessment, ammunition assurance and safety, and other military applications. Transitioning from scheduled maintenance to condition-based maintenance is one plausible method to save resources and increase operational readiness.

Active sensor systems with the ability to perform condition-based maintenance, rather than scheduled maintenance, can help preserve resources and provide improved operational readiness.

Significant advancements in printed electronics provide tangible opportunities to print function-specific active sensor systems using nano-inks and novel materials on a variety of flexible substrates via ink-jet printers and direct write systems. These capabilities allow the further design and development of various active sensors systems that meet the Army's needs for decreased size and weight, lower power requirements, and greater range, sensitivity and resistivity.

Some of the sensing capabilities include temperature, damage, scratch, flow, pressure, strain, impact, shock, pH, humidity, chem/bio and acoustics [2]. Other sensors' capabilities are under development.

2.1 Nano-Inks & Materials

Nano-silver, with its high conductivity per volume and lower curing temperatures, is currently the most popular nano-ink utilized in materials printing. However, other materials, both organic and inorganic, are also being researched within the industry. Previous research at universities and governmental labs has shown that small molecules can be chemically modified to make them soluble, and recent patent filings suggest that commercialization of small-molecule inks is considerably advanced. Unfortunately, there is little information available regarding what "recipes" are used, the properties of the different inks, and where the base materials originate from.

Members of ARDECs Materials, Manufacturing & Prototype Division are leading several research programs for utilizing advanced materials and material printing techniques for device prototyping and manufacturing. Research is being performed to understand the properties of individual nano-materials to determine the best combinations to create specific formulations and recipes.

Although nano-silver is the one of the most popular nano-inks being used, there are often issues with shelf-life, long-term durability, and material compatibility. For certain applications and fabrication techniques, nano-silver and the common solvents in which it is dispersed cause device and material compatibility issues. Other materials such as nickel, gold, and copper have been used as alternative ink bases. These materials have various conductive properties, thermal expansion, surface tension, cure rates, and particle sizes; all of which affect the ink properties. Single and Multi-walled nanotubes (SWNT & MWNT) have also been used for ink bases. There are numerous inks and bases researched to date, but their full potential, either alone or combined, has not been realized. Different materials and combinations of base nano-materials will allow for numerous inks types to be created, in-turn expand the number of and type of devices possible.

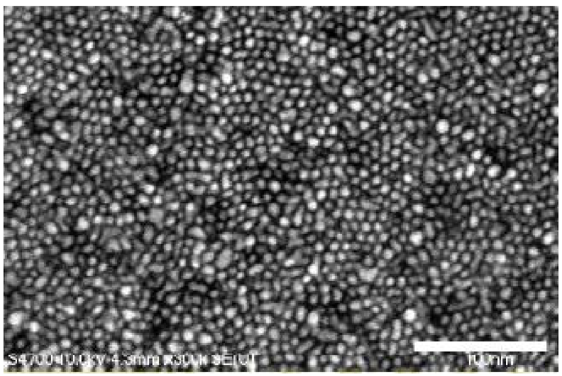

Figure 1: Base nano-material for ink dispersion

Using nano-inks for material printing and direct write applications is more environmentally friendly, uses less material, enables higher productivity and simpler design customization / modification than conventional photolithography methods. The increasing interest and use of ink-jet printing for printed electronics, sensors, energetic, and other applications is spurring the market growth for nano-inks.

Similar efforts are required to identify the substrates and polyimide films upon which the inks will be printed and which can be used in the ink-jet printing process. The success of nano-ink recipes are reliant upon the substrate to which they are printed; therefore if the substrate is changed, then the ink formulation must also be changed. Research is required to match the recipe formulation to the specific substrate to enable the desired function, always keeping in mind the U.S. Army's goal of lighter and cheaper.

Software modeling programs can assist in this research, allowing researchers to enter in the different properties of metals and materials and determine the viability of a given combination. The value of such programs is that they typically aide a researcher in determining which combinations are *not* feasible, saving valuable research time and related costs.

2.2 Materials Printing

The numerous innovations in materials printing technologies are enabling the U.S. Army to shift from typical MEMS micro-fabrication processes, often requiring cleanrooms or similar environments, to a material printing process that greatly reduces the time and cost associated with active sensor development.

There are several factors that impact the distribution of nano-ink droplets from printer to surface. These include surface tension, viscosity of the ink, jetting speed, particle size, surface conditions, temperature, humidity, as well as other physical conditions.

For deposition of inks via material printing, the particles with in the inks should be less than a tenth of the nozzle diameter in size. Various printers and nozzles have been researched, but no one solution set exists since the process is dependant on the inks to be utilized, as the ink formulations are related to the device type and function.

Since the operational and storage requirements for the Army are often unique and require specialized and custom materials. The particles, polymers, solvents, binders, etc., needed to develop nano-inks and printable materials for desired applications need to be further researched and developed.

Prototype sensor modules have been fabricated via materials deposition printer as part of the Active Coatings Technologies Program. These sensors are fabricated with an aqueous dispersion of the intrinsically conductive piezo-resistive or piezo-electric polymers containing organic solvents, polymeric binders, and sintered nano-particles of gold, silver or carbon. The conductive polymer ink is a hole-injection material (HIM) with a conductivity or a minimum surface resistivity depending on formulation recipe. The sensors have good photonic stability and good thermal stability of up to ~210°C.

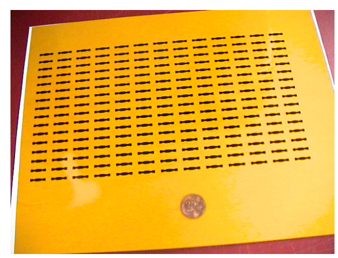

Figure 2: Fabricated sensor array.

In order to ensure better film to substrate adhesion condition the flexible substrates used have been thoroughly pre-cleaned with the 3-cycle standard pre-clean procedure with Plasma Enhanced Chemical Vapor Deposition (PECVD) surface roughness modification.

These sensor modules are constructed on flexible polyimide substrate membranes and encapsulated with layers of dielectric and SiNx. The dielectric layers used are flexible polyimide resist inks that are inert to the ambient environment. The sensors with the final dielectric encapsulation layers are annealed at an elevated temperature of 300º C. Customizable devices with various sensing range and sensitivity can be modified by varying the sensing element's polymer thickness. Due the nature of the inks, these sensors can be used in harsh environments such as marine (salt water), outdoor (acid rain), rapidly fluctuating relative humidity, and thermal shock conditions often required for Army operational missions.

NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1782-7 Vol. 1, 2009

The combination of the individual modules allows one to create custom sensor suites with desired capabilities. Currently, a suite of active sensors are planned for integration into the AH-64 Apache Helicopter, and planned transition to unmanned aerial systems as part of RDECOM's ATO-M, "Embedded Sensor Processes for Aviation Composite Structures.[3]"

Other variations of the sensors are being transitioned for ammunition surveillance projects, unmanned ground / aerial systems, and other Army and Department of Defense projects. These sensor systems will also allow the monitoring and tracking of logistic profiles during storage, transportation, and mission/operational environments.

Figure 3: Prototype active sensor for ammunition surveillance.

Beyond active sensor system applications, material printing and flexible electronic techniques are being utilized for other applications as well. Prototyping and manufacturing cost effective microelectronics are another key research objects of interest to ARDEC.

Material Printing techniques are under investigation to miniaturize and shrink controllers, circuits, and components in ammunition items to free up volume. This will allows more capabilities to be added to current and future armaments and free up volume for added lethality.

Using flexible substrates and nano-inks also allows for conformal microelectronics and gun hardened devices.

The potential payoff for armaments include better interior volume utilization, mission tailored devices, versatility, faster transition from prototype to manufacturing, immunity to obsolescence, reduced reliance on non US manufacturers.

The ability to apply electronics to interior surfaces of rounds will allow for more room for energetic components. This will result in higher sensitivity, lower power consumption, lower production costs, and added payload volume.

Besides the ability to create devices tailored to specific missions or applications, material printing technologies can facilitate rapid parts replacement and "in-field" manufacturing.

Work is also being performed to integrate Energetics with flexible electronics by material printing and direct write fabrication processes.

Specialized inks containing energetic and explosives are under development by the Army for numerous applications.

CONCLUSIONS

Through the advancement of active systems and microelectronics, capabilities can be added to current and future military assets. This will assist the U.S. Army to protect both national and international interests. It is in the Army's best interest to use the latest technologies to protect these assets. The current and future technological advances made are leading to the development of novel materials and systems that ultimately will allow the Army to advance into the twenty-first century and beyond. Through its R&D efforts, ARDEC is helping advance Army capabilities by integrating state–of-the-art technology into and on military system, easing its transition to the Future Force. These technologies will result in new and modernized weapons systems fielded globally that are capable of meeting current and potential challenges.

The research being performed will directly and indirectly support the warfighter and allow the U.S. Army to remain in the forefront of active systems technologies.

REFERENCES

[1] *Future Combat System (FCS)*: Article. www.globalsecurity.org.

[2] Research performed on the *Active Coatings Technology Program,* U.S. Army ARDEC-RDECOM, Picatinny, NJ.

[3] Army ManTech Highlights, "ATO-M: Embedded Sensor Processes for Aviation Composite Structures," RDECOM Army ManTech / 2008 Brochure, U.S Army RDECOM, ATTN: AMSRD-SS-T, Pg. 12, 2008.

[4] J. L. Zunino III, L. Ayers, D. Skelton, "Advancement of Prototyping and Manufacturing Techniques for Active Sensor Systems," Defense Manufacturers Conference, DMC 2008, Dec 2008 [3581].

[5] H.C. Lim, M. Pulickal, S. Liu, G. A. Thomas, J. Zunino, and J. F. Federici, Sensors and Actuators A. "Material corrosion determination via Young's modulus measurement using flexible membrane force sensor," *Sensors and Actuators A.*