Inkjet Printed Devices for Armament Applications

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ABSTRACT

U.S. Army Armaments Research Development and Engineering Center (ARDEC) is developing the capability to custom design, manufacture and integrate novel technologies into functional devices for the creation and advancement of active systems, including printed electronics, sensors, and detonation systems. Significant advancements in material deposition technology provide tangible opportunities to print function-specific devices using nano-inks and novel materials on a variety of flexible substrates via drop on demand and direct write systems. Material printing processes greatly reduce the time, environmental impact, and costs associated with device prototyping and fabrication. Military devices are often expected to endure extended storage, which may be greater than 20 years, in extreme environments. The impacts of packaging, storage, transportation, and operating environments on the long-term performance of flexible electronics and printed devices in DOD systems are not well understood at this time. This study characterized the effects of substrate preparation, ink type, annealing steps and encapsulation techniques to determine optimal printing processes.

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

1 INTRODCUTION

Recent conflicts demonstrate that the Army must transform and, "lighten up the heavy forces and heavy up the capabilities of the light forces," requiring systems to be deployable, be 70% lighter, and 50% smaller than current systems, while maintaining equivalent lethality and survivability [1]. To that end, U.S. Army scientists and engineers are capitalizing on new technological breakthroughs in materials printing, direct write technologies, nanotechnology, microelectronics, etc., to develop materials and devices 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 and materials printing capabilities for prototyping, sensing, electronics, data collection/storage, and power alternatives.

Members of the ARDEC's Materials, Manufacturing & Prototype Technology 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 nano-materials to determine the best combinations to create specific formulations and recipes [2].

To meet the ARDEC vision of innovative armament solutions, the team is developing the capability to custom design, manufacture, and integrate novel technologies into functional devices for the creation and advancement of armaments and weapon systems. Research is being performed to develop flexible detonators, sensor systems, flexible devices, power solutions, and other components for military applications.

Military systems that employ printed electronics and components must function and survive after extended periods of inactivity and extreme transportation profiles. It is not uncommon for military systems to be expected to endure extend storage, which may be greater than 20 years, in extreme environments. Any materials and devices developed for material printing processes must be able to survive in such harsh conditions.

2 BACKGROUND

Research is underway to employ material printing techniques to develop and manufacture micro-electromechanical systems (MEMS), microelectronics, sensors, flexible electronics, and device components. The U.S. Army is capitalizing on this enabling technology to add capabilities to current and future Army assets. Printed electronics provide opportunities to print function-specific devices while expanding on its nanomaterial development and utilization. Rapid parts prototyping, parts replacement and in-field manufacturing capabilities and technology gaps are being addressed.

The utility of printed electronics lays in reduced cost, faster prototyping, conformal designs and more efficient manufacturing [3]. Much work must still be done to bring printed electronics to the functional capacity currently provided by silicon based devices.

There is an increasing need for reliable, multi-function materials, sensors, devices, etc. that will increase functionality without increasing weight, power, or budget constraints. The Army is exploring materials printing, direct write, flexible devices and their related technological advances for use in unmanned systems, soldier technologies, armaments, vehicles, etc.

Significant advancements in printed electronics provide tangible opportunities to print function-specific 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 [4].

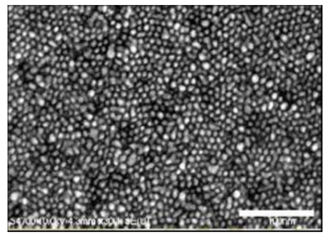
Direct write energetics is a fairly new specialty within material printing and direct write applications. Developed within the last few years to meet rapidly growing Department of Defense (DoD) microdevice demands this field continues to evolve, yielding new deposition techniques and energetic formulations [5].

3 MATERIALS & PROCESSES

A balance between the proper materials, processing, and fabrication techniques is key to the advancement of material printing and direct write technologies. Furthermore the materials and processes selected must meet or exceed current and future military tests and standards. The research team has characterized the effects of substrate preparation, ink type, and annealing techniques to determine optimal printing processes for several prototype and test devices. In addition, the effects of design, feature dimension and shape on device properties such as adhesion and resistivity are also incorporated.

For deposition of inks via material printing, the particles within the inks should be less than one tenth of the nozzle diameter in size. Various printers and nozzles have been researched and continue to be developed. No one solution set exists since the process is dependent upon the inks to be utilized, as the ink formulations are related to the device type and function. For flexible detonator applications, and several sensor systems developed by ARDEC [6], piezo based ink-jetting of the ink-materials has provided the best results to date. There are several factors that impact the distribution of nano-ink droplets from printer to surface. The characteristics investigated include surface tension, viscosity of the ink, jetting speed, particle size, surface conditions, temperature, humidity, as well as other physical conditions.

Nano-silver, with its high conductivity per volume and low curing temperature, is currently the most widely used nano-ink in materials printing. However, other materials, both organic and inorganic, are also being researched within the industry. Figures 1, 2, and 3 show micrograph images of nano-inks used by ARDEC. 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 from where the base materials originate.



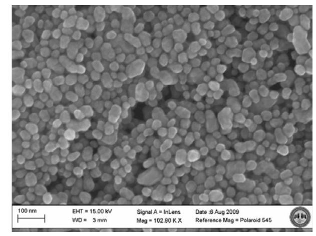


Figure 1. SEM of base nano-material before dispersion.
Figure 2. Micrograph of Ag nano-ink particles

Previous work by Lim and Zunino [7] investigated the development and modification of ink recipes for active sensor systems. 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 as well as additives.

There have been numerous inks and bases researched to date, but their full potential, either alone or combined, has not yet been realized. By using different base materials and polymers, active/reactive materials can be developed and these materials can then be chemically or mechanically modified to formulate inks for various deposition processes**.** These material combinations will allow for numerous inks types to be created, in-turn expand the number of devices and type of devices possible.

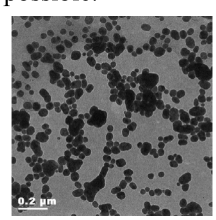


Figure 3. TEM micrograph of nano-silver inks showing agglomeration of the particles.

Another class of materials is jettable/direct write compatible energetic inks. Research described by Stephanov et al. as well as Wilson et al. describe components developed by ARDEC specifically for use in military applications [8,9]. This work has demonstrated detonation and patterning behaviors of nano-scale energetics and has lead to current efforts to investigate and understand micro/nanodetonation and deposition techniques.

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. The success of nano-ink recipes are reliant upon the substrate to which they are printed. If the substrate is changed then the ink formulation may also need to be changed. Research is required to match the recipe formulation to the specific substrate to enable the desired function, always keeping in mind the Army's goal of lighter and cheaper.

Consistency, repeatability, and reliability are keys to the adoption of these new material printing and similar fabrication techniques by the Army and Department of Defense. All aspects must be considered and meet military standards, protocols, tests, and policies. Substrate preparation, ink analysis, device design, fabrication, annealing, characterization, and testing processes must be optimized, tested and validated.

A study was performed and results documented to determine the optimal process for cleaning 50 µm thick polymide substrates often used in flexible electronics [10]. Droplets formed on a clean surface will behave differently than an uncleaned surface and can lead to unwanted electrical shorts and functional degradation.

Consistent and repeatable ink processing must be maintained. Device design and substrate selection are directly related to the in formulations developed. Wrist Action Shakers, ultrasonic baths, and mixers are often used to ensure uniform dispersion of the particles in the inks. Inks are then filtered to avoid clogging, undesirable particle sizes, conglomerations, re-crystallization, and other undesirable affects.

Once a device is designed, substrate selected, inks chosen, and the material is deposited; the next step is the annealing process. The melting temperature of a material on the nanoscale is significantly reduced. Therefore, the nanoparticles can be deposited while suspended in a solvent solution and then annealed to evaporate the solvent and sinter the nanoparticles together. Care must be taken not to contaminate the printed pattern with dust particles or accidental contact prior to annealing. Several techniques are used including oven heating, low temperature soaking, hotplate, pulse forging, as well as other processes. Just as there are an almost endless array of ink types and formulations, there is a vast array of annealing processes and techniques. Further studies are underway to optimize the time and methods of annealing for desired device properties.

4. ARMAMENT APPLICATIONS

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. These advancements will add capabilities to current and future Army assets. Rapid parts prototyping, parts replacement and in-field manufacturing capabilities and technology gaps are being addressed.

Prototype sensor modules have been fabricated with an aqueous dispersion of the intrinsically conductive piezo-electric polymers containing organic solvents, polymeric binders, and sintered nano-particles. Some of the sensing capabilities include temperature, damage, scratch, flow, pressure, strain, impact, shock, pH, humidity, chemical and biological agent detection and acoustics. Other sensor capabilities are under development.

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.

Combinations of individual sensors, allows the team to create custom sensor suites with desired capabilities. Other variations of the sensors are being transitioned for ammunition surveillance projects, unmanned ground / aerial systems, and other DoD projects. These sensor systems will also allow the monitoring and tracking of logistic profiles during storage, transportation, and mission/operational environments.

Besides sensor system applications, material printing and flexible electronic techniques are being utilized for other applications as well. Prototyping and manufacturing cost effective conformable microelectronics are another key research objective of interest to ARDEC. Material Printing techniques are under investigation to miniaturize controllers, circuits, and components in ammunition items to free up volume. Resistors, capacitors, and transistors have been designed. Figure 4 shows prototype capacitors fabricated at ARDEC.

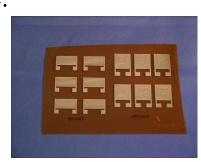


Figure 4. ARDEC printed capacitor design.

Demands for future force munitions include reduced size and weight with enhanced scalability and selectability. These requirements are in direct opposition with each other and will not be realized with the use of traditional design and manufacturing techniques. Fuzing, the fire control of munitions, has begun a transition to the MEMS scale, and as a result energetics needed to exhibit smaller critical diameters and easier means of application and integration into devices. Energetic direct write enables the loading of explosive materials into micro structures while alleviating the need for the pressing or casting of micron-scale pellets while reducing the subsequent safety and logistical challenges of loading traditional energetic at that scale.

A major breakthrough is the ability to integrate energetic and flexible electronics to yield fully written, conformal detonation systems with plans to then incorporate active sensors, and power solutions to develop new classes of weapon systems and devices. Integrating Energetics with printed electronics will provide more capabilities to be added to current and future armaments and free up volume for added lethality. Conformal electronics will facilitate better utilization of available space within ammunition. The reduced mass will enhance survivability during high G gun launch. This also reduces the amount of energetic quantities and handling while increasing manufacturability, repeatability and safety.

Figure 5. Energetically loaded flexible detonator.

ARDEC researchers recently developed and demonstrated the first directly written flexible detonator (Figure 5). The flexible detonator design was created using design software to match the performance requirements. A specific resistance was needed across the narrow bridge-wire (Figure 6) and the ratio of that resistance to the leads had to be controlled. The heat from the high resistance after a voltage is applied initiates the device.

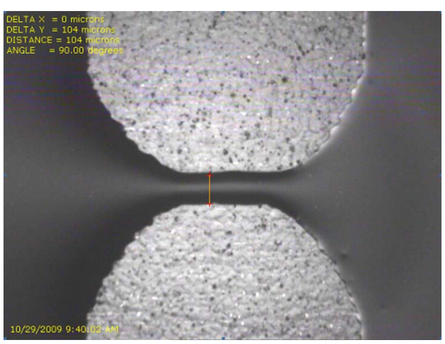


Figure 6. Optical microscope image of bridge-wire.

A high speed digital camera with a telescoping lens was used to first characterize the reaction of the printed initiators when a voltage was applied across the leads. This test was successful and showed that the small bridge-wire functions properly with energetics loaded onto it. Next, actual energetic was loaded onto the initiators and the devices were successfully tested in a blast chamber [10, 11]. The prototype flexible initiators worked and set off the primary explosives which in turn set-off the secondary explosives.

5. CONCLUSIONS

The cost effectiveness of device prototyping and fabrication via materials printing facilitates its utilization by the U.S Army. By providing capabilities that were once considered impractical, these enabling technologies will ease the U.S. Army's transition to the Future Force. ARDEC is enhancing Army capabilities by integrating state–of-the-art technology into and on military systems. These technologies will result in new and modernized weapons systems fielded globally that are capable of meeting current and potential challenges. This will assist the U.S. Army in protecting both national and international interests while it advances into the twenty-first century and beyond.

The research being performed will directly and indirectly support the warfighter and allow the U.S. Army to remain in the forefront of flexible electronics and conformal systems technologies. Materials printing is a viable option for prototyping sensors and other devices for Army applications.

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