Direct Digital Additive Manufacturing Technologies:

Path Towards Hybrid Integration

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***Abstract*—In the past decade, additive manufacturing and printed electronics technologies have expanded rapidly on a global scale. As the additive manufacturing techniques have become more capable and affordable, and able to work with a broader range of materials, the machines are increasingly being used to make advanced products at significantly lower costs and risks. The additive manufacturing industry is populated by a broad family of technologies, and the present paper provides an overview of key additive manufacturing technologies and their impact on materials processing, device applications, and future markets. Our R&D efforts on the development of core technologies for the realization of flexible electronics, and 3D microscale structures are also highlighted.**

Keywords—additive manufacturing; inkjet printing; flexible devices; 3D printing

I. Introduction

Additive manufacturing technologies employing, metal, dielectric, polymer, and semiconducting materials are creating a world of possibilities decoupling product development time and complexity of design [1-3]. Besides the ability to manufacture highly complex parts at high resolution, the high recycling rate of additive manufacturing leads to a reduction of material waste compared to conventional subtractive manufacturing processes. Inkjet based contact-free printing technologies are gaining interest in low-cost, large area production of high performance electronic devices and systems meeting the cost, functionality, and environmental demands. The possibility of manufacturing semiconductor devices on flexible substrates opens up a wide expanse of new applications that were not practical with traditional electronics. Current state of the art inkjet printers are capable of printing functional electronic circuits with line-widths as small as 10µm. The inkjet printing technology will play an increasingly dominant role in shaping the printed electronics which is emerging as an estimated $300 billion market [4]. The additive printed electronics technology in combination with additive manufacturing technologies is opening up new possibilities for conformal electronic circuits and systems embedded in advanced 3D structures [5-7]. The 3D additive manufacturing (AM) technologies are advancing at a rapid pace since their introduction more than 20 years ago. AM systems have been used in a variety of applications ranging from conventional prototyping and rapid tooling to more advanced applications such as medical implants, aerospace and automotive manufacturing, 3D electronic devices, and micro-systems [8-12]. Not only does additive manufacturing remove the traditional limits on part geometry, but highly complex components can also be fabricated faster while consuming less material and using less energy. From an engineering and design standpoint, AM technologies are becoming more accurate with features ranging from micron-sized to building sized. The combination of 3D microscale structures and additive printed electronics is going to have a significant impact on the functionality and component design, manufacturing processes, and business model.

Oak Ridge National Laboratory is working with additive manufacturing equipment manufacturers and end users to revolutionize the way products are designed and built. Through collaboration with every aspect of the manufacturing supply chain, ORNL is identifying the critical equipment and materials advancements required to establish additive manufacturing as a mainstream manufacturing process and help realize the vast potential of this technology. R&D projects currently underway will ensure additive manufacturing center-stage status in the next generation manufacturing process. The aim of this paper is to highlight core AM technologies, and R&D efforts at ORNL focused on advanced additive manufacturing technologies.

II. Direct Write Manufacturing

A. Inkjet Printing Technology

In the last few years, there has been growing interest in the development of additive manufacturing and all printed electronics to meet the manufacturing technology demands of higher functionality, reduced material usages and device dimensions, and lower energy consumption of products. The range of materials being processed by additive manufacturing techniques is growing rapidly, and the material list includes organic/inorganic semiconductors, biomaterials, conductive nanoparticles and polymers, dielectrics, ferromagnetic materials, and superconductors. Printed electronics by direct writing techniques show promise for use in a wide range of active and passive device applications, such as thin film transistors, OLED lighting, solar cells, RFIDs, antennas, inductors, capacitors, interconnects, sensors, and displays [13-15]. The increasing demand in flexibility in electronics production has become the driving force for the development of current manufacturing methods and encourages seeking of new manufacturing processes. Additive digital printing offers new possibilities to electronics integration by enabling direct

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writing on even nonplanar surfaces and interconnects without specific substrates for integration. Digital production technologies, such as inkjet printing, have the potential to produce a variety of products on the same manufacturing line. The inkjet technology offers significant advantages with respect to simplicity, resolution, flexibility, and costs over existing technologies. All kinds of hybrid applications can also be envisioned as a result of co-integration with the conventional technology. As an example, as shown in Fig. 1, it is foreseeable that a smart sensor system integrated on flexible substrates will evolve towards all printed technological solution taking us towards "peel-and-stick" wireless sensors. Various R&D efforts at ORNL are focused on the co-integration of existing in-house materials and device technologies to realize such a multifunctional sensor platform.

The inkjet printing technology offers significantly higher print resolution as compared to conventional screen printing technology. In inkjet printing technique, the material loss is minimal, as shown in Fig. 2, due to additive approach; no functional materials are removed as in masking process. The elimination of masking and etching steps alone results in reduced material waste, energy consumption, and processing time and steps. In the all-additive approach, the materials are deposited with controlled location and geometries. Multiple materials (metal, dielectric, and semiconductor) can be deposited in the same process phase employing several printheads, thus eliminating several process steps. Furthermore, inkjet is a non-contact deposition method, which makes it applicable to a broad range of substrates (e.g. metals, ceramics, polymers, and silicon) with characteristic porosity and surface energy. The attainable line widths with a commercial drop-on-demand inkjet are approaching 20µm while reports of finer line widths (~1µm) are already emerging.

Recently, there has been significant development in the use of inkjet technology for printing diverse functional materials, and currently conductive, dielectric, and semiconductive inks are available for the development of a complete electronic system with a single inkjet printer [16-18]. The inkjet printing of the conductive metal inks is probably the most mature and extensively researched topic. A variety of nanoparticle based colloids are used as ink, such as silver, copper, gold, nickel, etc., due to their good electrical properties. As listed in Table I, the metal ink performance has improved significantly over the years, and the conductivity values are fast approaching the bulk values with improvements in the ink quality and advances in

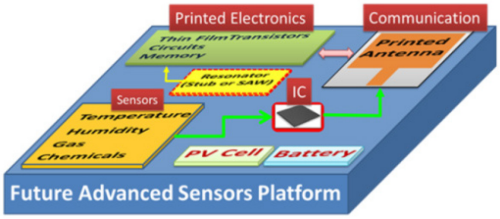

Figure 1. A multifunctional sensor platform for smart buildings.

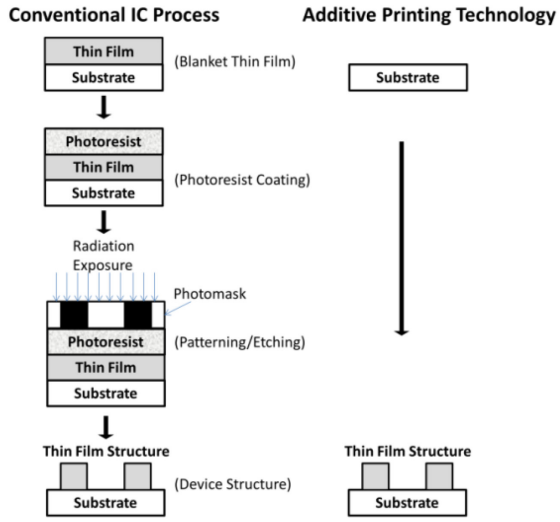

Figure 2. A comparison of substractive IC processing and additive priniting approch for thin film device development.

TABLE I. THE NANOPARTICLE METAL INK PERFORMANCE IN COMPAISON TO BULK MATERIAL.

Metal	Bulk Conductivity (µΩ-cm)	Nanoparticle Ink Conductivity (µΩ-cm)
Ag	1.6	2
Cu	1.7	5
Al	2.8	5
Ni	7.0	20

thermal annealing techniques and systems. The current metal ink conductivities are acceptable for a wide range of PCB and interconnect applications. The electrical performance of applications created using printed electronics is not at the same level as that of Si-based electronics. However, the advances in the materials and processing technology are continuously pushing the performance limits.

B. Pulse Thermal Processing Technology

Novel low temperature, low thermal budget annealing techniques are required to realize highly functional materials and devices on flexible substrates. Fig. 3 shows the key enabling components for the realization of low cost, low temperature flexible electronics. The pulse thermal processing (PTP) technique is being explored at ORNL for the development of cost-effective, high yield, and high quality integrated thin films and devices on low temperature substrates. This technology offers the ability to expose large areas of material to an extremely high energy flux during a very short period of time meeting the demands of roll-to-roll manufacturing technology. The PTP technique has the ability to thermally process thin layers of material at several hundred degrees Celsius while restricting the thermal exposure of underlying materials to a small percentage of that temperature [19]. Thus, this technology has the potential to dramatically

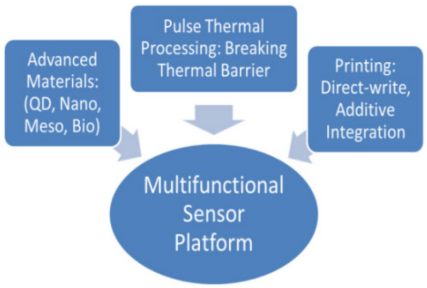

Figure 3. Realizing multifunctional materials and devices: Key enabling components.

impact the manufacturing and thermal processing of a wide range of thin film products. The general benefits of Pulsed Thermal Processing with the plasma arc lamp are low thermal budget, increased throughput, higher heating rates, the ability to process on lower temperature substrates, and being able to control diffusion on the nanometer scale.

Novacentrix and ORNL have been developing the technology for pulsed thermal annealing over the past several years. The high-density plasma arc lamp facility at ORNL is capable of producing extremely high power densities of up to 20 kW/cm^2. In September of 2008, Novacentrix purchased the license to commercially develop ORNL's Pulsed Thermal Processing technology. The PulseForge 3300 is the latest system in NovaCentrix' series of advanced photonic processing tools. PulseForge 3300 tool is designed to process materials demanding higher energy levels, such as silicon, zinc oxide and ceramics, used for printed logic, display, battery, and photovoltaic applications. The system is designed for roll-to-roll and conveyor-based material processing with peak production rate approaching 300 meter/minute. The PulseForge 3300 tool incorporates advanced engineering and it is capable of delivering extremely high power in very short pulses (as low as 30 microseconds). The broadband lamp spectrum is suitable for processing both the thermal and UV-processed material sets. The temperature sensitive substrate supporting the sample can be a biomaterial, polymer, resin, metal, ceramic, or semiconductor. The pulse thermal processing setup at ORNL is suitable for small scale and pilot production, as well as full-speed production when needed. The same PulseForge tool and process conditions can be used for development as well as full-scale commercial production.

Extensive R&D work is being carried out at ORNL on low temperature material and device development. The PTP technique has been explored for the development of diverse functional materials ranging from quantum dots to bulk ceramics. Fig. 4 shows some of the device applications enabled by low temperature, low thermal budget pulse thermal processing technique. The PTP fluence and thermal budget have been successfully exploited for diverse applications: ultra-shallow junctions in CMOS, sintering of quantum dots to improve quantum efficiency for solid state lighting, crystallization of cathode materials for batteries, glass strengthening by photonic curing, metal sheets from nanoparticles, flexible solar cells, structured materials for automobiles, etc [20-23].

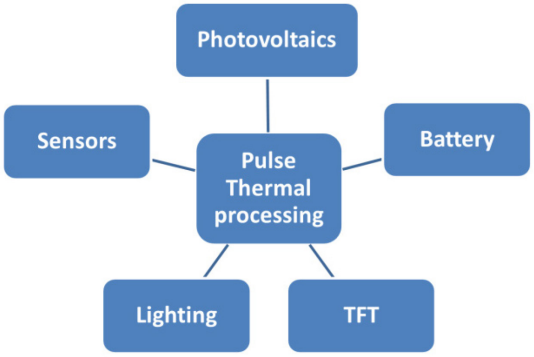

Figure 4. Low temperature electronics enabled by pulse thermal processing technology.

III. Hybrid Additive Manufacturing

The versatility, flexibility, and simplicity of additive manufacturing processes and great potential for time and cost savings in comparison to conventional manufacturing technologies have resulted in a rapid rise in worldwide R&D efforts focused on diverse materials and systems. Since their introduction more than 20 years ago, AM has become an integral part of modern product development and the AM systems have been used in a variety of applications ranging from conventional prototyping and rapid tooling to more advanced applications such as aircraft and automotive parts, medical devices, buildings technology, medical implants, 3D electronic devices, and space technology. From a business-strategic standpoint, AM technologies are becoming faster, cheaper, safer, more reliable, and environmentally friendly. The technology manufactures parts for every phase of the product life cycle - from predevelopment and prototyping up to rapid manufacturing or the supply of spare parts; essentially, moving design rules from a "manufacturing-driven design" to a "design driven manufacturing approach".

Various AM techniques offer the capability to process mechanically capable and geometrically accurate components with unique internal geometrical complexity. The representative AM processes include stereolithography (SL) using a laser and liquid photocurable resin, beam sintering using a laser or an electron beam and powder material, fused deposition modeling (FDM) using heated extrusion nozzles and solid thermoplastic filament, ultrasonic additive manufacturing (UAM) for low temperature rapid prototyping, and 3D printing (3DP) using inkjet printer heads and liquid jettable photocurable resin. The layer thickness and vertical dimensional accuracy of these AM techniques are now well below the level of 100µm.

The advances in the AM techniques have only recently been explored in the context of electronics integration. The hybrid additive manufacturing enabled by the design freedom of AM techniques and additive printed electronics technology is changing not only how things are made, but what is made. The combination of additive manufacturing approaches to form hybrid 3D structures of arbitrary and complex form with directly integrated printed electronics offers unique functionality and market opportunities while addressing the cost/performance demands of the manufacturing technology.

The hybrid AM merges the boundary line between component development and system integration. The co-integration of roll-to-roll manufacturing technology with AM techniques will lead to entirely new products and markets. Embedding of electronics components in 3D structures will allow a high degree of miniaturization, and eliminate the need for discrete electronic components and wiring network to realize a highly functional system at reduced cost and weight. The 3D integration of metal, dielectric, and semiconducting materials and interconnects can realize a complete microelectronic system co-integrated with 3D structure. Diverse active and passive components such as resistors, capacitors, inductors, rf, TFTs, batteries, and solar cells can be integrated on 3D structures to form novel devices and structures. The concept of hybrid additive manufacturing has been well demonstrated with the printing of a conformal sensor, antenna, and power and signal circuitry directly onto the FDM printed wing of a UAV model. The Optomec's 6-axis 3D printing utilizing Aerosol Jet technology shows promise for true 3D printed electronics with current line widths approaching 10µm which is sufficient for diverse electronic components and circuits [24]. In another hybrid AM approach, curved-layer fused deposition modeling (CLFDM) has been exploited to print curved plastic parts that have conductive electronic tracks and components printed as an integral part of the plastic component [6]. Many aspects of technology development such as high resolution additive processes, flexible substrates, and low thermal budget processing are coming together to realize low cost, multi-functional printed electronics. Extensive R&D efforts are underway at ORNL's Manufacturing Demonstration Facility with focus on technologies impacting numerous application areas, from aeronautic to robotic and automotive to biomedical.

IV. Conclusions

The increasing competition and shortage of resources raise a challenge for future manufacturing technologies. Additive manufacturing has become an integral part of modern product development and the industrial applications are apparent in diverse technology areas. Our efforts on inkjet printing and low thermal budget pulse thermal processing techniques are critical to realize the hybrid additive manufacturing technology based on the co-integration of 3D structures with printed electronics. Through collaboration with every aspect of the manufacturing supply chain, ORNL is identifying the critical equipment and materials advancements required to establish additive manufacturing as a mainstream manufacturing process and help realize the vast potential of this technology.

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