Novel Concepts in Direct Writing of Electronics and Sensors

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Abstract

This paper outlines new capabilities in the arena of maskless direct writing of advanced materials for applications in thick film electronic circuits and sensors. The genesis of this capability lies in advanced concepts based on a thermal spray particle-based deposition technology which allows for printing of 3D conformal mesoscale components of metals, ceramics, composites and polymers onto a range of substrates at low substrate temperatures. The capabilities derived offer new approaches towards integrating structures with electronics and sensors.

Introduction and Background

Additive manufacturing especially as a means for rapid prototyping and small volume manufacturing has received considerable attention in recent years, especially as it relates to thick film electronics and sensors. Such approaches provide alternatives to screen printing and lithography-based methods which dominate the electronic manufacturing enterprise, but are inefficient when it comes to lean manufacturing or prototyping concepts especially in application specific areas such as thick film sensors and large area microwave components. Among the additive manufacturing technologies, dispensing and ink-jet technologies using electronic materials in paste or aerosol form the basis of modern day "maskless direct writing" concepts. This CAD-driven technology combined with precision 2D and 2 1/2D motion capability offers the ability to precisely deposit materials of different character and functionality in a given location. In principle this enables the fabrication of multilayer electronic circuitry and interconnection devices in the form of through-hole vias.

Electronic pastes can be readily dispensed onto prepared substrates and patterned. However, just as in the case of screen printing these pastes have to be cured at high temperatures in order to sinter and impart full functionality. The temperatures can range from a minimum of 400^{o}C for low melting point metals to upwards of 1400^{o}C for high performance capacitor materials. There is considerable interest in developing direct writing technologies that will not only allow maskless fabrication but also allow low temperature integration of multiple materials (e.g., ceramics and metals onto plastic substrates). Furthermore true 3D capability will enable integration of electronics with engineering components and structures.

An innovative *Maskless Direct Writing* technology has recently come of age based on the concept of thermal spray particle deposition. *Direct Write Thermal Spray* (DWTS) is a new and exciting manufacturing technology capable of depositing a large number of electronic materials on a wide range of substrates, enabling direct write fabrication of multilayer thick-film electronic devices. Examples include sensors, passive electronic components (capacitors and inductors), connectors, antennas, etc. Of particular importance is the ability to directly fabricate sensors and electronics on truly three-dimensional objects, which would enable a radical new capability for integrating sensors and electronics on engineering systems and components hitherto not envisioned.

DWTS was conceived and developed under DARPA's Mesoscale Integrated Conformal Electronics (MICE) program by Stony Brook University and program partners. DWTS has the ability to deposit a number of high quality electronic and sensor materials onto a variety of substrates and conformal geometries. Because the temperature of the substrate is kept low (<200^{o}C) and no post treatment (such as annealing or firing at high temperature) is required the DWTS process naturally lends itself to fabrication of multilayer devices using disparate materials, which is particularly useful for sensor and electronics applications. This is a *unique differentiating* attribute of DWTS even when compared with other direct writing technologies such as ink-jet printing, aerosol guided deposition, laser forward transfer etc. The ability to produce functional electronics and sensors without the need for post processing allows whole new concepts for sensor and electronics integration into engineering systems. Research to date has demonstrated considerable capability of these concepts leading to a potential "disruptive" transformation to both design and additive integration of novel sensor concepts and technologies.

Technology Description & Capabilities

Thermal spray is a directed spray process in which material, generally in molten form, is accelerated to high velocities and impinged upon a substrate, where a dense and strongly adhered deposit is formed by rapid solidification. Material is injected in the form of a powder, wire or rod into a high velocity combustion or thermal plasma flame, which imparts thermal and kinetic energy to the particles. By controlling the plume characteristics and material state (e.g., molten, softened), it is possible to deposit a wide range of materials (metals, ceramics, polymers, semiconductors and combinations thereof) onto virtually any substrate in various conformal shapes. The ability to melt, rapidly solidify and consolidate introduces the possibility of the synthesizing useful deposits at or near ambient temperature. For metals the particles can be deposited in a solid or semi-solid state. For ceramic deposits the particle temperature is generally well above the melting point, which is achieved by either a combustion flame or a thermal plasma arc.

The deposit is built-up by successive impingement of droplets, which yield flattened, solidified platelets, referred to as *splats*. The deposit microstructure and, thus its properties, depends strongly on the processing parameters, which are numerous and complex. In recent years, through concerted, integrated efforts of the *Center for Thermal Spray Research* at Stony Brook and other organizations, significant fundamental understanding of the spray process has been achieved, allowing for an enhanced control of the process.

The *virtues and unique advantages* of thermal spray with respect to direct write electronics fabrication and related processes are numerous:

- High throughput manufacturing based on high speed direct writing capability
- *In-situ* application of metals, ceramics, polymers or combinations of thereof;
- - without thermal treatment or curing
- - incorporation of mixed or graded layers
- Useful properties in the as-deposited state
- Cost effective, efficient processing at ambient conditions in virtually any environment
- Limited thermal input during processing, allowing for deposition onto low temp substrates
- Robotics-capability for difficult-to-access/severe environments (for example on-site-applicability using portable systems.)
- Ready availability for customizing special sensor systems (i.e., prototyping)
- Green technology *vis-à-vis* plating, lithography.
- Applicability on a wide range of substrates and conformal shapes

DWTS can produce blanket deposits of films and coatings as well as *patches, lines* and *vias*. Multilayers can be produced on plastic, metals and ceramics substrate, both planar and conformal. Embedded functional electronics or sensors can be over-coated with a protective coating, allowing for applications in harsh environments. Such embedded harsh environment sensors are useful for condition-based maintenance of engineering systems.

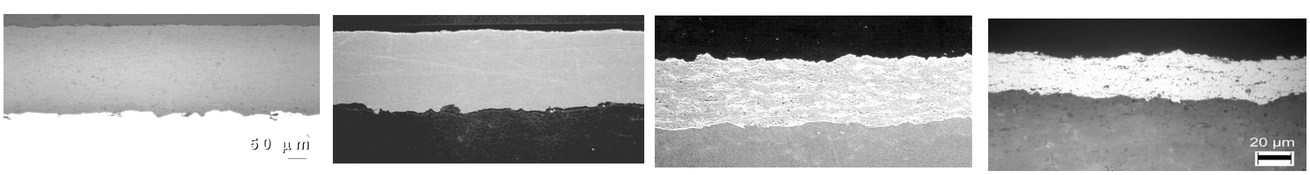
Materials Versatility and Materials Capability

The spray deposition process starting from powder feedstock allows the ability to deposit a wide range of metal, ceramic and polymeric materials. The materials capabilities developed to date include both low K (dielectric constant), mid K and high K inorganic dielectrics based on alumina and spinels in the K range of 7-10, yttrias, zirconia and composites in the K 10-30 range and $BaTiO_3$ and $Ba(Sr)TiO_3$ in the high K regime. Low losses have been achieved (<0.007) for the low K system up to a 5 GHz operation frequency. In addition, polymer based dielectrics have been examined with dielectric constants of 2-3 with less than 1% losses. Conductor line patterns have been produced using both silver and copper materials and in principle any metallic material can be deposited. The resistivities of Ag lines are ~ 3-4 µΩ-cm and represents approximately 2X bulk value. The typical deposition temperature for metals is < 50C, while for ceramics is <150°C. In addition, composites and graded mixtures can be easily produced with no post processing. Microstructure and properties of various materials is shown in Figure 1.

Through the DARPA MICE program the Stony Brook University-led team has demonstrated a variety of direct write based functional electronics and sensor systems fabricated onto virtually any substrates. In the following discussion several functioning electronic devices are presented.

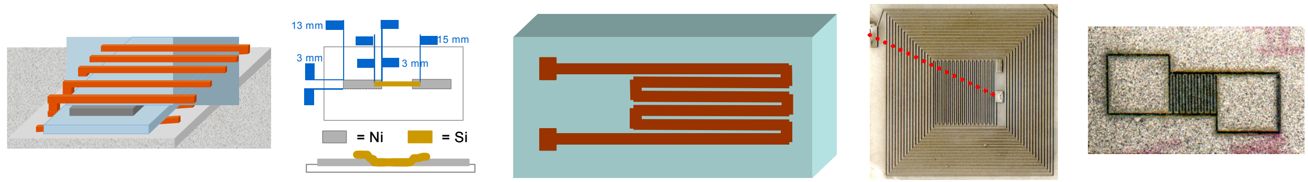
Direct-Write Sensors

A wide range of sensors have been demonstrated as part of the DARPA MICE program. They include: magneto-resistive sensors for position, displacement and rotation; multilayer inductors and transformers based on direct deposited ferrites; capacitors; L-C resonant circuits for passive wireless sensors; harsh environment sensors such as thermocouples (that have survived over 1200°C) and thermistors, strain gauges, and heaters; and power harvesting concepts based on thermopiles. Several such samples are shown in Figure 2. Figure 3 shows an example of conformal direct write sensor on a mock turbine blade. The DARPA MICE program was a technology and tool development program and has laid the foundation for this process technology.



Alumina	Silver	$BaTiO_3$	Silicon
Dielectric Constant 9	Resistivity 3.2 Ω -cm	Dielectric constant 225	Resisitivity 24 Ω·cm
Dielectric loss 0.007 at 5 GHz	Sheet Resistance 1 ohm/sq	Dielectric loss 0.01 at 5 GHz	Hall mobility 14 $cm^2/V \cdot s$
Surface roughness 1 µm	Surface Roughness 1 µm	Surface roughness 3 µm	Surface roughness 2 µm
	Deposit thickness ~ 50 µm		

Figure 1. Microstructure and properties of DWTS electronic materials



Inductors/ Transformers **Thermistors** **Magnetic Sensors** **RF Elements** **Microheaters**

Figure 2. Sample of sensors and electronic components fabricated to date using DWTS

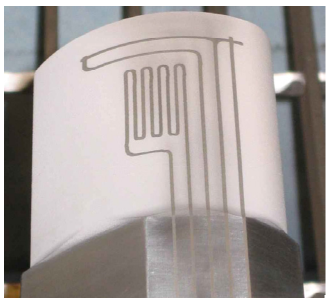


Figure 3. Example of a conformal DWTS sensor on a mock turbine blade.

Direct Fabrication of Antennas & RF Systems

As discussed earlier an important attribute of this capability is that the device is fully functional and ready for operation *without any further processing*. No curing or post-firing at high temperatures is generally required. This allows the fabrication of electronics and sensors on large pre-existing structures such as buildings, ships, aircraft, etc. Writing onto conformal (non-flat) geometries opens up numerous additional possibilities. Figure 4 shows the direct write capability of conductive lines onto concrete, composites, and textiles. Furthermore DWTS circuits can be overcoated with a protective coating (polymer overcoat, paint or other thermal spray coating) to enhance survivability in extremely harsh environments (e.g., high-temperature, high abrasion, marine, and space). Examples of such systems might include antennas on the nose cone or tail section of aircraft, sensor systems on ship surfaces, buildings and towers, etc. This ability both enhances current technology and also offers a new means to provide sensor arrays for remote, untethered sensing and detection.

DWTS Conductors & Semi-conductors on Flexible Materials and Textiles

Feasibility studies have shown that deposition can be achieved onto woven fibers, including flexible textiles, polyethylene, and rigid carbon fiber composites. Figure 4 provides an example of the types of components that can be fabricated on textiles at low temperatures. These deposits in general can perform a function in the as-fabricated state and has been shown to have considerable promise for flexibility. This will enable new concepts in direct write applications.

Technology and Systems

The basis of the DWTS capability lies in the ability to control the foot print of the spray stream along with ability to achieve requisite material characteristics. The core technology is described in a recently awarded US patent 6,576,861. It has been shown that a feature size of 300 microns is routinely possible and demonstrations have been done to dimension smaller that that.

The first-generation integrated fabrication tool based on a high-precision robot for conformal sensors and electronics fabrication has been setup at Stony Brook University and is shown in Figure 6. This tool provides the ability to direct write highly conformal surfaces. Finally, an important attribute of this technology is *portability*. A portable mobile direct write tool will allow translation of the laboratory technology into large area conformal applications. An alpha version of the tool was developed and demonstrated as part of a student senior design exercise at Stony Brook University.

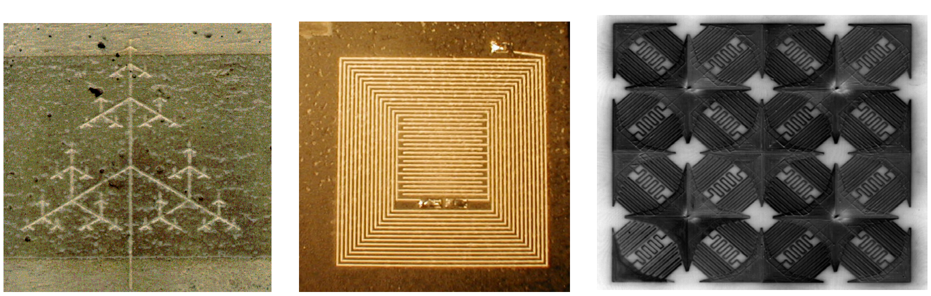


Figure 4. (a) Fractal antenna by DWTS on concrete (with polymer overcoat) (~ 2 x 2 inches) (b) L-C resonance tag on carbon-epoxy structural composite (~ 2 x 2 inches) (c) Frequency selective surface example (~2 x 2 inches)

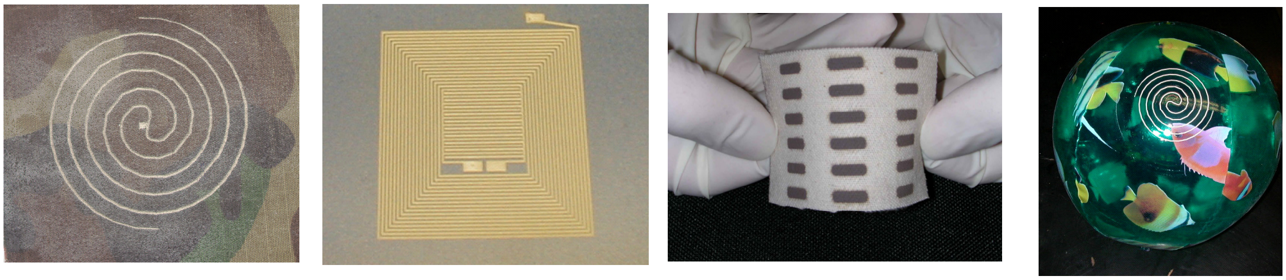


Figure 5. Separate examples of electronics applied to the surface of flexible cloth and plastic materials. Left to right: spiral antenna on cloth, RF tag on polyethylene (ink jet transparency), silicon deposited onto cloth (canvas) and inflatable concepts: antenna on plastic beach ball (written and then inflated)

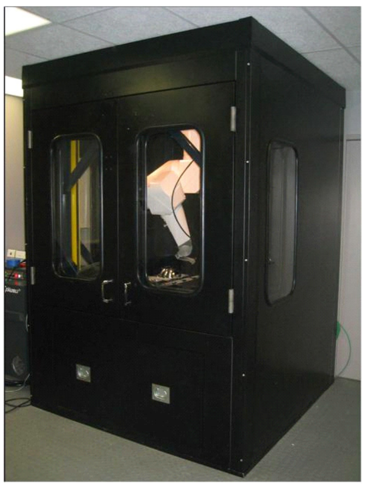


Figure 6. Photograph of a 3D conformal direct write fabrication cell.

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Author Biography

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