Printing Conformal Electronics on 3D Structures with Aerosol Jet Technology

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***Abstract* - Fabrication of 3D mechanical structures is sometimes achieved by layer-wise printing of inks and resins in conjunction with treatments such as photonic curing and laser sintering. The non-treated material is typically dissolved leaving the final 3D part. Such techniques are generally limited to a single material which makes it difficult to integrate high resolution, conformal electronics over part surfaces. In this paper, we demonstrate a novel, non-contact technique for printing conformal circuits called Aerosol Jet printing. This technique creates a collimated jet of aerosol droplets that extend 2-5 mm from the nozzle to the target. The deposited features can be as small as 10 microns or as large as a centimeter wide. A variety of materials can be printed such as metal nanoparticle inks, polymers, adhesives, ceramics, and bio-active matter. The print head direction and XYZ positioning is controlled by CAD/CAM software which allows conformal printing onto 3D substrates having a high level of surface topography. For example, metallic traces can be printed into 3D shapes such as trenches and via holes, as well as onto sidewalls and convex and concave surfaces. We discuss the fabrication of a conformal phase array antenna, embedded circuitry and sensors, and electronic packaging.**

***Index Terms* - Aerosol Jet, print, 2D, 2.5D, 3D, nanoparticle.**

I. INTRODUCTION

Interest in using additive manufacturing methods to produce functional components is growing in a variety of industries. For example, the aerospace industry is interested in integrated electromechanical systems to improve performance and reduce weight [1]. The electronics industry is interested in new processes to deliver next-generation mobile devices with increased functionality in smaller or thinner packaging. To fully realize these goals, a manufacturing method is needed that integrates electronics onto or into 3D structures to reduce footprint, improve performance and simplify electromechanical assembly.

One approach to achieve closer integration of electronics with mechanical structures is to use 2D manufacturing techniques. For example, electronic circuits can be produced on a flexible film and then molded around a 3D surface [2, 3]. There are, however, limitations with this technique, such as registering flexible electronics to the 3D substrate, especially for complex surfaces. For certain surface geometries such as cylinders, where a planer surface can be projected without stretching, the technique can work well, however for geometries such as hemispheres, this approach is difficult to implement.

Another approach is to adapt current injection molding processes to enable the addition of electronic circuitry into thermoplastic devices, also known as Molded Interconnect Devices (MIDs). One production method for MIDs is two-shot injection molding, where two different polymers are bonded to produce the final plastic part, one of which uses a special material that can be plated. Challenges with the two-shot method are polymer to polymer bond strength and interface quality [4]. Another production method for MIDs is Laser Direct Structuring (LDS) where a thermoplastic material, doped with a metal-plastic additive, is selectively patterned with a laser. After laser patterning, a plating process is used to build-up circuit thickness. The limited variety of substrate materials, multi-step processing, and requirement for plating are challenges for both the two-shot and LDS processes [5].

The Aerosol Jet direct write solution addresses these challenges by enabling development of mechanical parts with truly integrated 3D electronics on virtually any substrate material or geometry. For example, Aerosol Jet printing can print on orthogonal surfaces with sharp angles between planes; generate multi-layered circuitry without utilizing common 2D approaches, such as multilayer substrates with plate-mask-etch methods; attach discrete components, such as microprocessors and LEDs on 3D structures; and directly print conformal sensors and antenna on 3D surfaces, such as aircraft wings or fuselages. This paper presents work performed by Optomec and our customers using Aerosol Jet technology to print functional electronics on 3D plastic structures.

II. AEROSOL JET PROCESS

The Aerosol Jet process is a direct-write method that uses aerodynamic focusing of aerosolized droplets to precisely deposit functional materials onto a substrate. This approach begins with aerosolizing a functional liquid into small droplets with diameters between two and five microns. These droplets are then passed through a deposition head where they are focused into a collimated beam as small as 10 microns in diameter or a wide ribbon as large as a centimeter. The aerosol beam is emitted from the deposition head with a velocity of approximately 80 m/s and travels ballistically to where the droplets impinge on the substrate (Fig. 1).

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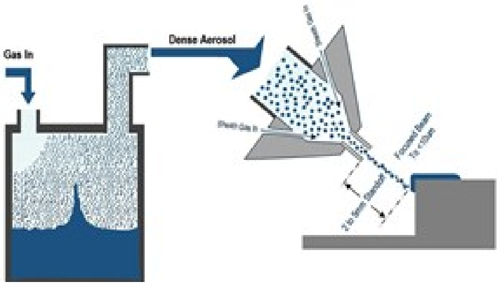

Fig.1. Schematic diagram of Aerosol Jet based printing system. Liquid inks are first atomized to create a dense, aerosol cloud of 2-5 micron diameter droplets. A carrier gas transfers the aerosol to a printing head, where a co-flowing sheath gas focuses the droplets to a 10-100 micron diameter jet. The droplets impinge on substrate that is controlled by a tool path file to form printed features.

Printed features are created by translating the deposition head with respect to the substrate in XYZ and theta directions using a tool path generated from a CAD design file. A distinct difference between the Aerosol Jet printing approach and other direct-write printing processes is that the Aerosol Jet process is a non-contact process that relies on aerodynamic jetting to propel droplets to the substrate. This enables a relatively large standoff distance of approximately 2-5 mm between the deposition head and the substrate and allows the deposition head to print in any orientation including upwards. This eliminates the requirement for a smooth, flat substrate and enables printing on most 3D surfaces. The Aerosol Jet process prints inks with viscosities up to 1000 cP that may include entrained solid particles up to 500 nm in diameter. Typical formulations include nano-particle metal inks, functional organic materials, dielectrics, polymers, adhesives, carbon nanotubes and biological materials.

III. Multi-Layer and Multi-Material Printing

While some electronic devices can be produced by printing a single layer of a single material, many applications require printing multiple layers of different materials to generate a functional device [6]. It has been reported that the Aerosol Jet process is capable of generating multi-layered circuits [7]. Figure 2 shows a circuit consisting of conductive lines crossing over each other while still electrically isolated by an intermediate layer of a dielectric material. The first printed layer consists of conductors produced using a silver nanoparticle ink. Five parallel lines were printed with a center-to-center pitch of 100 um. The silver ink was thermally processed at 180 °C for 30 minutes. The second printed layer consists of a 1mm x 1mm square pad of a PVDF dielectric material that was dried at 100 °C for 10 minutes. The final conductive layer is produced using a PEDOT: PSS conductive polymer which was printed over the PVDF. Electrical measurements were taken after the sample was generated and the resistivity of both conductive materials matched vendor specifications. The electrical resistance between the two conductive layers exceeded 10 GΩ indicating good isolation. All of the above post processing steps were achieved without removing the substrate from the printing system. For this application the possible post processing steps include laser sintering or hot air sintering of the nanoparticle metal ink and hot air or UV curing of the dielectric materials. Cross-over conductive lines, that are smaller than 15 microns wide, have been printed using this process. Interestingly, the conductor-dielectric-conductor stack also forms the basis of printed parallel plate capacitors.

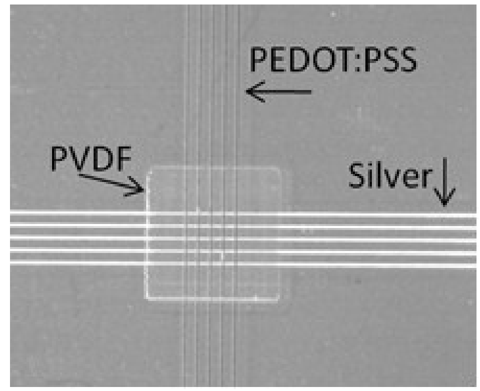

Fig. 2. Crossover circuits formed from 20 micron silver and PEDOT: PSS lines separated by a PVDFdielectric

IV. Conformal Printing

Many advanced 3D applications used in the aerospace and mobile electronics industry require components such as sensors, antennae, or interconnects to be printed onto or embedded into non-planer surfaces or on three orthogonal planer surfaces. Fine line interconnects (at the micron scale) on 3D surfaces may also be required for certain applications.

A. Printing on Non-Planer Surfaces

Like full 3D printing, the requirement to print on non-planer or 2.5D surfaces (substantially planar, but with a gentle slope, curvature or topography) is of general interest. Large scale applications with dimensions of millimeters to centimeters include embedding sensors or antenna onto substrates such as aircraft fuselages or body armor for military personal. Small (sub-millimeter) scale applications can include applications such as IC chip packaging or high density interconnects onto the large scale substrates described above.

An example of a large scale 2.5D application is the phased array antenna shown in Fig. 3. In this instance, a silver nano-particle ink was printed onto a rigid curved substrate. After processing the conductive ink, additional structural material is laminated on the printed surface creating a fully functional, phase-array antenna embedded in the structural component. This solution is both low weight and mechanically robust. The process of generating this component involved translating the deposition head in the XYZ directions with the orientation of the deposition head held normal to the platen of the printing system. No head rotation was required as the Aerosol Jet process is capable of printing on surfaces tilted by as much as 45° from the axis of the deposition head.

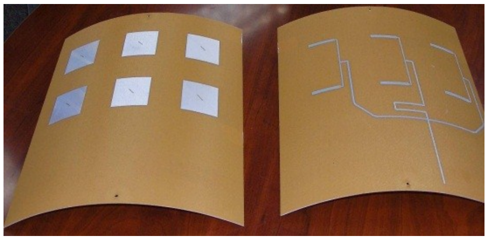

Fig. 3.Phased array antenna printed on a rigid, cylindrical surface.

In another example, the Aerosol Jet process is used to print a conformal sensor, antenna, and power distribution circuit on an Unmanned Air Vehicle (UAV) wing structure that itself is 3D printed using a Stratasys Fused Deposition Modeling (FDM®) process. An aerospace grade thermoplastic material is used to print the wing structure. Prior to printing the electronics, the wing surface is grit blasted to improve ink wetting characteristics and a dielectric undercoat is applied to smooth the surface and fill fissures. Circuits are then printed on the wing structure to power LEDs and propellers. A silver ink is used to print circuits to deliver power (10 Watts) to the propeller and LED. A 5.8 GHz T-Slot antenna and strain gauge sensor are also printed directly on the wing (see Fig. 4).

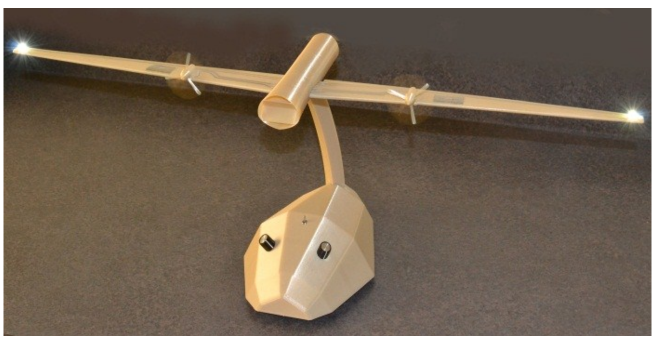

Fig. 4. Circuits, sensor, and antenna printed with Aerosol Jet on UAV structure which was printed with Stratasys FDM.

B. Printing on 3D Surfaces at Micron Scale

It is sometimes necessary to print features at the micron scale on 3D surfaces. Figure 5 is a cross-section micrograph showing silver nanoparticle ink connections on staggered, multi-chip die stacks. High aspect ratio interconnects with 30 micron line width and greater than 10 micron line heights are printed at sub-60 micron pitch. Advanced electronic systems will require the printing of micron-scale features over millimeter or centimeter scale 3D topography.

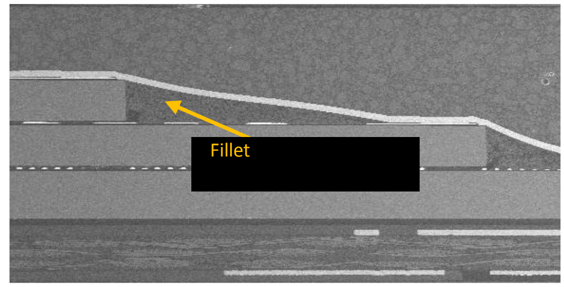

Fig. 5. 30 micron wide interconnects printed on die stack.

C. Printing on Orthogonal Plane Surfaces

As electronic systems such as UAV's become more autonomous, they will become more aware of their surroundings. In order to enable autonomous behavior, sensors and communications devices must be positioned in three orthogonal dimensions. For some applications sensors such as accelerometers can be created to operate in 3D at the IC level. For other applications such as light sensors, strain gauges, or directional antenna, this is not possible. To meet these requirements, devices such as strain gauges are often produced in two dimensions using established technologies and then independently mounted onto a 3D structural component. The resulting system can be larger than desired and can introduce challenges, such as connection of the devices between planes. As size and weight factors become more demanding, there is a growing desire to print these devices directly onto the 3D structure.

Figure 6 illustrates the creation of a 3D sensor structure by printing conductive wires on five sides of a 19 millimeter ceramic cube down to a base substrate. Conductive lines 20 microns wide were printed using a silver nano-particle ink. The Aerosol Jet print head is oriented at a 45° angle with respect to the base during the printing operation. The print head was translated in the X-direction to print along the top surface then lowered in the Z-direction to print down the side wall followed by a small translation in the X-direction to print on the base. Aerosol Jet print heads mounted on full 6-axis motion systems are used for this type of 3D work.

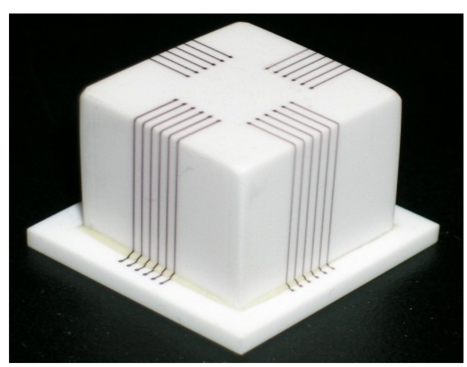

Fig. 6. Ceramic cube with conductive lines printed on five orthogonal surfaces as well as the base.

In another example MID application developed in the FKIA project ("Functionalisation of Plastics with Ink Jet and Aerosol Jet," funded by the Bavarian Research Foundation), Neotech Services MTP printed a functional fluid level sensing circuit on a plastic tank with Aerosol Jet technology as shown in Fig. 7. In this example, two capacitive sensor structures are printed on the ends of a moulded tank. The sensors are connected by printed circuits and surface mounted components to complete the sensor device. When water is pumped into the tank, the sensors register the water level as it rises, lighting the LEDs to indicate the fill level. When the tank compartment is full, the circuit senses the water fill level and reverses the pump direction.

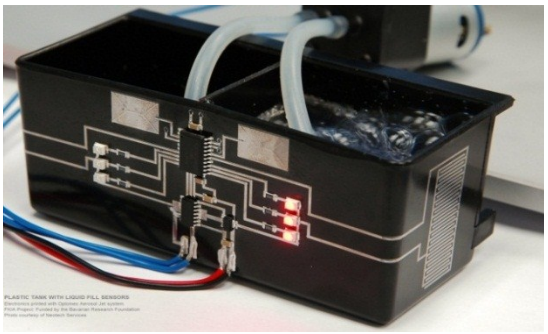

Fig. 7.Two chamber tank with printed fluid level sensors, control and display circuits.

V. ELECTRICALLY CONNECTING DISCRETE COMPONENTS

Advanced 3D electrical systems typically require a variety of discrete components including microprocessors, sensors, and passive electrical components. These components are traditionally connected to a circuit using processes such as reflow soldering. However, challenges can arise when using this technique in 3D structures since reflowing solder on vertical surfaces does not work well. Figure 8 shows an example of mounting discrete components to a vertical substrate and electrically connecting them to the rest of the circuit. In this example, a surface mount device is first attached using a high viscosity, UV/thermal cure epoxy between the two contact pads on the substrate. The chip is then placed between the contact pads using a pick and place process, where the surface tension of the epoxy holds the chip in place for curing with a UV light source. A subsequent thermal cure is performed on the epoxy to enhance adhesion.

Electrical connection to the chip is performed by printing a silver nano-particle ink over the edge of the chip, down the sidewall, and onto the contact pad on the substrate. The deposition head is orientated at a 45° angle with respect to the substrate to ensure good coverage of the side wall. However, the standoff distance of the deposition head from the substrate is not changed. That is, the dispense tip was significantly closer to the top of the package than to the substrate. This is possible due to the large working distance of the collimated Aerosol Jet beam. To reduce the contact resistance between the chip and the underling contact pad, a 200 micron wide contact was printed. The average contact resistance between the chip and the pad was 100 mΩ. The ability to mount and electrically connect discrete components, while also printing interconnects and other multi-layered features, is required to produce fully functional electronic systems.

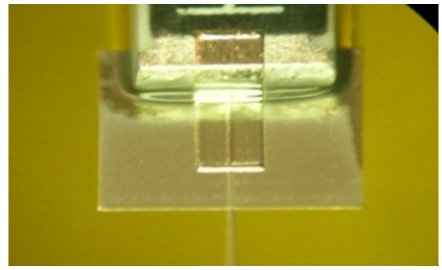

Fig. 8. Surface mount device attached with epoxy and silver ink.

VI. CONCLUSIONS

This work demonstrates some of the capabilities of the Aerosol Jet printing process to produce multi-layer, 3D electronic circuits. It is shown that the process is capable of printing both large scale features, such as phase-array antenna, as well as small scale features, such as 30 micron wide interconnects used for connecting stacked die. In addition to 2.5D surfaces, patterning electronic features onto orthogonal surfaces is also demonstrated.

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