High Resolution Conformal Printing with Aerosol Jet®

Jason A. Paulsen, Michael J. Renn, Kurt Christenson; Optomec Inc; Saint Paul, MN

Abstract

Fabrication of 3D devices is often done by layer-wise printing of inks and resins in conjunction with treatments such as photonic curing and laser sintering. The nontreated material is typically dissolved leaving the final 3D part. Such techniques are generally limited to single materials and it can be difficult to build high resolution, 3D structures over existing 3D surfaces. In this paper, we demonstrate a novel, non-contact technique called Aerosol Jet® printing. This technique creates a collimated jet of aerosol droplets that extend 3-5 mm from the nozzle to the target. The deposited features can be as small as 10 um and a wide assortment of materials can be printed such as metal nano-particles, polymers, adhesives, ceramics, and bio-active materials. The nozzle direction and XYZ positioning is controlled by CAD/CAM software which allows conformal printing onto 2.5D substrates which have a high level of surface topography as well as fully 3D surfaces. For example, metallic traces can be printed onto 3D shapes such as trenches and vias, 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.

Introduction

The desire to use additive manufacturing methods to produce functional components is quickly growing in a variety of industries. This is especially true in the electronics industry where the demands of cost, size, and performance of electronic devices are driving a need for more integrated electronic systems. Particularly, interest in directly printing electronic components is rapidly growing in the aerospace industry where the need to embed sensors and communication devices within structural components is becoming more important due to the improved performance and weight of such systems [1]. Additionally, the mobile electronics industry needs new processes to develop the next generation of devices that provide a higher level of performance in a smaller package. To fully realize these goals, a method to create fully functional devices on non-conformal 3D structures is needed to reduce the footprint, improve performance, as well as place the electronic systems closer to where they are needed.

Many groups are trying to use 2D manufacturing techniques to realize these goals. One example is printing on flexible substrates and molding the substrates around a 3D surface [2,3]. There are, however, many limitations to these approaches such as registration issues and limitations of the shape of the device. Although these approaches may work on geometries such as cylinders onto which a planer surface can be projected without stretching, geometries such as hemispheres are difficult to accommodate.

The Aerosol Jet® solution addresses the set of challenges that hinder the innovation and development of truly 3D electrical systems. Some of the challenges involved with this are printing on conformal and orthogonal surfaces with sharp angles between planes, generating multi-layered circuitry without utilizing common 2D approaches such as plating-masking-etching methods, attaching discrete components such as microprocessors and sensors on 3D structures and working with conformal surfaces such as aircraft fuselages. This paper presents work that was performed to address some of these industry challenges using Aerosol Jet® printing technology.

Aerosol Jet Process

The Aerosol Jet® process is a direct-write method that uses the 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 um in diameter or as large as 3 mm. The aerosol beam is emitted from the deposition head with a velocity of approximately 80 m/s and travels ballistically to where the droplets impact the substrate.

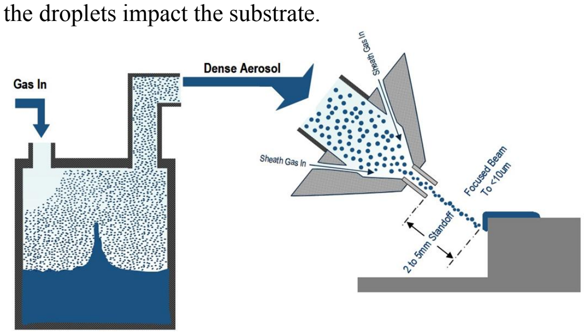

Figure 1: *Schematic diagram of Optomec's aerosol-jet based printing system. Liquid inks are first atomized to create a dense, aerosol cloud of 2-5 um sized droplets. A carrier gas transfers the aerosol to a printing head, where a co-flowing sheath gas focuses the droplets to a 10-100 um diameter jet. The droplets impact on a computer controlled substrate 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 CAD/CAM system. A distinct difference between the Aerosol Jet® printing approach and other direct-write printing processes is that it is a non-contact process that relies on aerodynamic jetting to propel the droplets to the substrate. This enables a relatively large standoff distant 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 of a smooth, flat substrate and enables printing on most 3D substrates. The Aerosol Jet® process is able to print inks with viscosities up to 1000 cP and 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.

Multi-Layer and Multi-Material Printing

While some functional devices can be produced by printing a single layer of a single material, many applications require the printing multiple layers of different materials to generate a functional device or circuitry features [4]. It has been previously reported that the Aerosol Jet® process is capable of generating multilayered circuits [5]. Figure 2 shows a crossover 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 a silver nano-particle material produced by Cabot Inc. (CSD-66). 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 consisted 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 was 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 of the conductive materials matched the vendors' specifications. The electrical isolation between the two conductive layers exceeded 10 GΩ indicating good isolation. Although it is not shown in this example, printed features such as this have been printed with smaller feature sizes (<15 um wide) and processing conditions that do not require the substrate to be removed from the printing system. These conditions include laser sintering or hot air sintering for the nano-particle metal ink and UV curing of the dielectric materials. Interestingly, the conductor-dielectric-conductor stack also forms the basis of printed parallel plate capacitors.

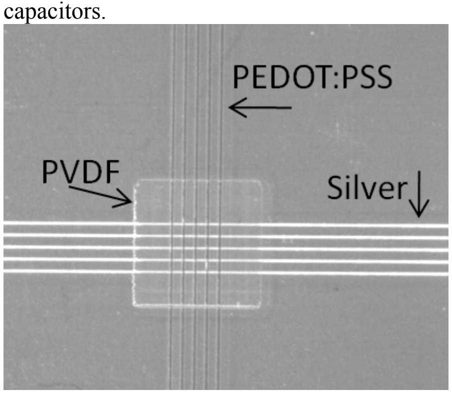

Figure 2: *Crossovers formed from 20 um silver and PEDOT:PSS lines separated by a PVDF dielectric.*

Conformal Printing

Many advanced 3D applications such as those used in the aerospace and mobile electronics industry require components such as sensors, antennae, or interconnects to be printed onto or embedded into conformal, non-planer surfaces or on three orthogonal planer surfaces.

Non-Planer Surfaces

The importance of printing on non-planer or 2.5D surfaces (surfaces which are substantially planar but have some curvature or topography) is quickly growing both on a large scale as well as a micro scale. Large scale applications with dimensions of millimeters to centimeters include embedding sensors or antennae 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 Figure 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 orientations of the deposition head held normal to the platen of the printing system. No head rotation was needed as the Aerosol Jet® process is capable of printing on surfaces tilted by as much as 45° from the axis of the deposition head.

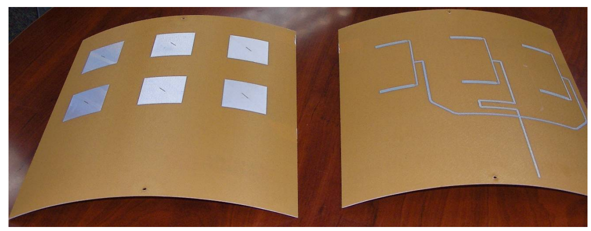

Figure 3: *Phased array antenna printed on a rigid, cylindrical surface.*

Figure 4 shows a fully printed strain gauge on a curved substrate produced with a FDM process. This part was generated with a similar process to the antenna shown in Figure 3, but with the width of the printed line maintained below 50um for improved strain gauge performance.

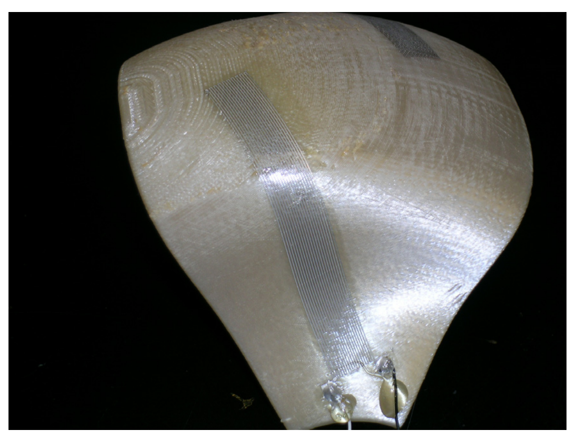

Figure 4: *Strain gauge printed on an elbow shield.*

It is sometimes necessary to print on conformal surfaces on the micron scale. Figure 5 is a cross-section micrograph showing silver nanoparticle ink connections on staggered, multi-chip die stacks. High aspect ratio interconnects with 30 um line width and greater than 10um line height have been demonstrated at sub-75 um pitches. Advanced electronic systems will require the printing of micron-scale features over millimeter or centimeter scale 3D topography.

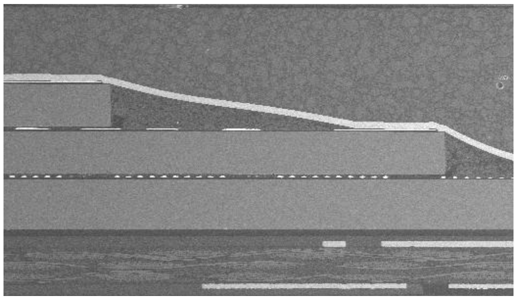

Figure 5: *Silver interconnects between staggered multichip stack.*

Orthogonal Plane Printing

As electronic systems such as UAV's become more autonomous, they need to be more aware of their surroundings. This has led to a need for sensors and communications devices to be placed in three orthogonal dimensions to allow UAV's to more accurately sense their surroundings. In some cases such as accelerometers, these types of devices can be created to operate in 3D at the IC level. In other situations such as light sensors, strain gages, or directional antennae this is not possible. When a need for 3D functionality is restrained to 2D devices, they have traditionally been produced in two dimensions using established technologies and independently mounted onto a three dimensional 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 be able to create these devices directly onto a three dimensional component.

Figure 6 illustrates the creation of a 3D sensor structure by printing conductive wires from five sides of a 0.75" ceramic cube down to a base substrate. 20 μm lines of a silver nano-particle ink were dispensed from a deposition head oriented at a 45° angle with respect to the base. 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. In this example, the substrate was rotated to allow the print head to print on all four sides of the cube. Full 6-axis motion systems are used for this type of 3D work.

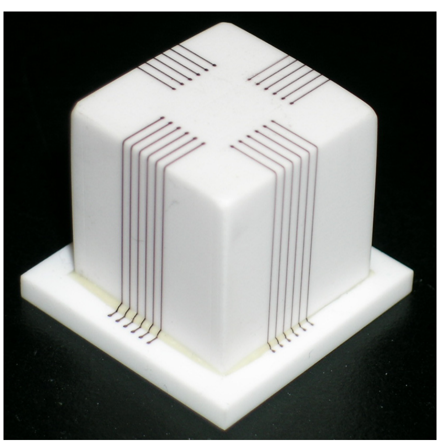

Figure 6: *Ceramic cube with conductive lines printed an five orthogonal surfaces as well as the base.*

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, which are well established for 2D applications. However, challenges can arise when used in 3D applications since reflow techniques on vertical surfaces do not work well. Figure 7 shows an example of mounting discrete components to a vertical substrate and electrically connect them to the rest of the circuit. In this example, an 0804 SMD device was first adhered to a substrate by a high viscosity, UV/thermal cure epoxy between the two contact pads on the substrate. The chip was placed between the contact pads using a pick and place process where the surface tension of the epoxy held the chip in place until it could be cured using a UV light source. A subsequent thermal cure was performed on the epoxy to enhance adhesion.

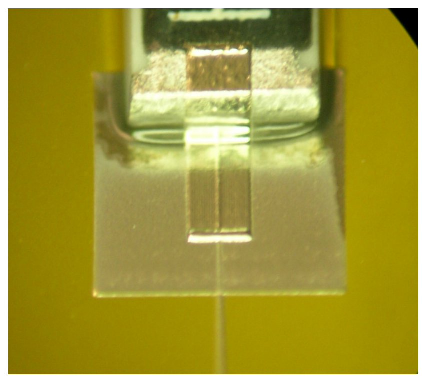

Figure 7: *An 0603 device attached with epoxy and silver ink.*

Electrical connection to the chip was 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 was 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 was not changed. That is, the dispense tip was significantly closer to the top of the 0603 package than to the substrate. This is possible due to the large focal length of the collimated aerosol beam. To reduce the contact resistance between the chip and the underling contact pad, the print head was rastered back-and-forth over the chip ten times to generate a 200 micron wide contact. The average contact resistance between the chip and the pad was 100 mΩ. The capability to mount and electrically connect discrete components in conjunction with printing interconnects and multi-layered features are required to produce fully functional electronic systems.

Conclusion

This work demonstrates some of the capabilities of the Aerosol Jet® printing process to produce multi-layer, 3D electronic circuits. It has been shown that the process is capable of printing both large scale features such as phase-array antenna as well as 30 µm- scale features as shown in 3D IC packaging onto 2.5D conformal surfaces. In addition to conformal surfaces, patterning electronic features onto orthogonal surfaces has also demonstrated.

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Author Biography

The authors work at Optomec's Applications Development Laboratory in St. Paul, Minnesota where they perform customer demonstrations of the current capabilities of the Aerosol Jet process. They also participate in advanced R&D developing all aspects of Aerosol Jet printing including processes, mechanical and electrical hardware along with the required software.