AEROSOL JET® DIRECT WRITE PRINTING FOR MIL-AERO ELECTRONIC APPLICATIONS

Bruce King and Mike Renn
Optomec, Inc., 3911 Singer, NE, Albuquerque, NM 87109, USA. info@optomec.com

ABSTRACT

A new Direct Write technology, Aerosol Jet® printing, is finding wide use in a number of electronic manufacturing applications. The Aerosol Jet technology, originally developed under a DARPA contract, has been commercialized by Optomec. This paper will discuss how the Aerosol Jet process is being used to deposit a wide variety of materials onto a wide variety of substrates without conventional masks or thin-film equipment. The process is non-contact, enabling traces to be printed over steps or curved surfaces. Printed features can be less than 10 microns.

The Aerosol Jet process utilizes low viscosity inks in the range of 1-2500 cP. Typical materials that can be printed include nanoparticle metal suspensions, polymers and adhesives. Conductor traces can be printed using gold, silver or other nanoparticle inks. Conductors can also be formed by printing a seed layer, followed by electroless plating. Polymer thick film pastes can be printed to form embedded resistors. Polyimide and various epoxies can be printed for adhesives, overcoat dielectrics, etc.

The Aerosol Jet process is compatible with a variety of substrates, including silicon, polyimide, glass, FR-4 and aluminum oxide. In principle, virtually any substrate can be used provided that the ink is compatible with the substrate.

Mil-Aero applications for the Aerosol Jet technology include flexible displays, EMI shielding, solder-free electronics, high efficiency solar cells, and embedded components including sensors, resistors, and antennae.

INTRODUCTION

In recent years, a new class of manufacturing techniques has become available, which offer significant cost, time and quality benefits across a broad spectrum of industries. These new techniques are collectively known as additive manufacturing. During additive manufacturing, material is deposited layer by layer to build up structures or features. This is in contrast to traditional subtractive manufacturing methods where masking and etching processes are used to remove material to get to the final form. Advantages of additive manufacturing processes include direct CAD-driven, “Art-to-Part” processing, which eliminates expensive hard-tooling, masks, and vertical/horizontal integration, which lead to fewer overall manufacturing steps. These features combine to offer diverse benefits:

- Greater Product Design and Manufacturing Flexibility – This benefit offers the potential for revolutionary new end-products with improved performance based on novel size, geometries (including 3D Interconnects), materials and material combinations.
- *Time Compression and Increased Manufacturing Agility* – CAD driven, tool-less processes speed up product development and manufacturing, while allowing greater flexibility in mass customization. Active and passive components as well as interconnects can be printed with the Aerosol Jet tool thereby enabling Trusted Manufacturing for military electronic systems.
- *Lower Costs* – This benefit arises because hard-tooling and mask costs are eliminated thereby enabling cost effective manufacturing even in low volume production runs. Process costs in terms of operator input, supplier chain complexity and work flows are reduced.
- Green Technology – The Aerosol Jet process utilizes raw material more efficiently than traditional methods, thus reducing waste levels. Caustic chemicals typically required in subtractive manufacturing processes are not required with the Aerosol Jet process.

This paper will introduce an additive manufacturing, direct write technology that offers significant potential in the manufacturing of Mil-Aero printed electronics: Aerosol Jet printing. (See Figure 1.)

Figure 1. Photo of the Aerosol Jet System

AEROSOL JET DEPOSITION SYSTEMS

The Aerosol Jet process was originally developed to fill a neglected middle ground in microelectronic fabrication. Current manufacturing techniques create very small electronic features, for example by vapor deposition, and relatively large ones, for example by screen-printing. No technology was capable of satisfactorily creating crucial micron-sized (10-100μm) production of interconnects, components, and devices. As electronic devices continue to shrink, thick-film fabricators are approaching the physical limits of stencil printing. Thin-film technology can deposit micron scale features but requires a highly skilled workforce and a major capital investment in new manufacturing capability for each new application. Thick- and thin film techniques are 2D processes and are not ideal for manufacturing 3D conformal electronics

HOW THE AEROSOL JET PROCESS WORKS

The Aerosol Jet process uses aerodynamic focusing for the high-resolution deposition of colloidal suspensions and/or chemical precursor solutions. An aerosol stream of the deposition material is focused, deposited, and patterned onto a planar or 3D substrate. The basic system consists of two key components, as shown in Figure 2:

- a module for atomizing liquid raw materials (Mist Generation), and
- a second module for focusing the aerosol and depositing the droplets (In-Flight Processing).

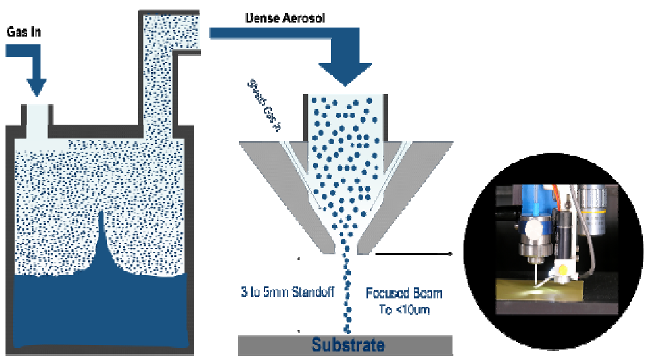

Figure 2. Schematic of the Aerosol Jet process and photo of the deposition head.

Mist Generation is accomplished using an ultrasonic or pneumatic atomizer. The aerosol stream is then focused using a flow deposition head, which forms an annular, co-axial flow between the aerosol stream and a sheath gas stream (Figure 2). The co-axial flow exits the print head through a nozzle directed at the substrate. The Aerosol Jet print head is capable of focusing an aerosol stream to as small as a tenth of the size of the nozzle orifice. The deposition process is CAD driven; the process directly writes the required pattern from a standard .dxf file. Patterning is accomplished by attaching the substrate to a computer-controlled platen, or by translating the flow guidance head while the substrate position remains fixed.

Thermal post processing of the deposited material is often needed to cure the material or increase properties such as electrical conductivity. Depending on the application, either conventional sintering or curing is used for low temperature substrate materials.

AEROSOL JET CAPABILITIES AND MIL AERO APPLICATIONS

Aerosol Jet printing is already being applied to a range of conformal and non-conformal printed electronics applications (see Figure 3).

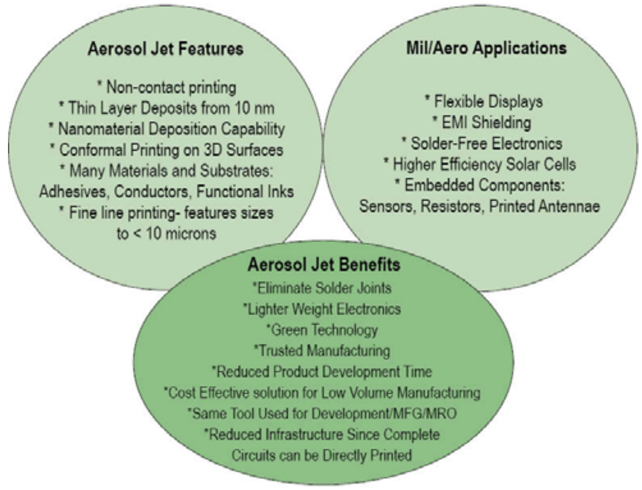

Figure 3. Aerosol Jet Features, Mil Aero Applications and Benefits

This section of the paper will investigate the capabilities of Aerosol Jet systems and provide some general application examples.

Printing Sensors on Non-planar surfaces

Aerosol Jet systems can precisely deposit materials on both planar and non-planar substrates. The unique ability of the Aerosol Jet system to print on non-planar surfaces makes it an ideal solution for printing sensors that can be integrated into military-specific applications. This is made possible by the relatively high (1 to 5mm) stand-off point of the deposition head above the substrate and long focal length of the material beam exiting the nozzle. There is no physical contact with the substrate by any portion of the tool (other than the deposition stream), and therefore conformal writing is easily achieved. This allows the process to build 3D conformal features onto shaped components, write into trenches (see Figure 4), or over steps and contours (see Figure 5, next page).

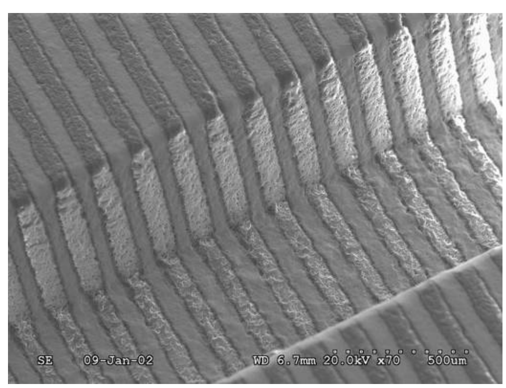

Figure 4. 60µm Ag lines written over a 500µm trench.

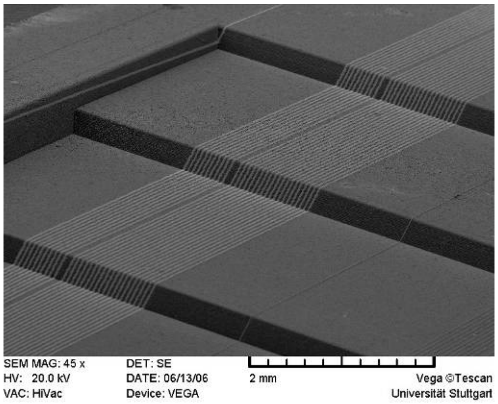

Figure 5. 20 μm Ag lines written over stepped injection molded LCP (Courtesy HSG-IMAT).

Figure 6 shows an example of conformal packaging in a Smart Card application. This involves 3D direct writing of several different kinds of materials; the interconnect is made from the Cu pad, over the Kapton layer and epoxy adhesive and onto the control IC. In this case the height difference is approximately 150μm between the Cu pad and the IC. This allows the replacement of the traditional wire bond and reduction of overall part thickness. An additional benefit is improved mechanical reliability as the relatively delicate wire bonds are eliminated. After the Ag interconnects were written the device is processed in an oven at 200°C to sinter the interconnects.

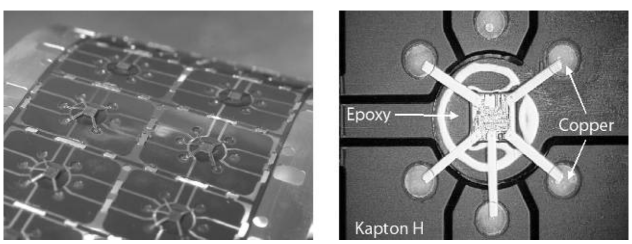

Figure 6. 150μm wide silver interconnect over an epoxy bump and Kapton.

For 3D surfaces with larger surface profiles the Aerosol Jet system makes use of 3 Axis printing. This allows writing over steps of up to 50mm in the current Aerosol Jet 300 system. Figure 7 shows an example of where this capability has been applied.

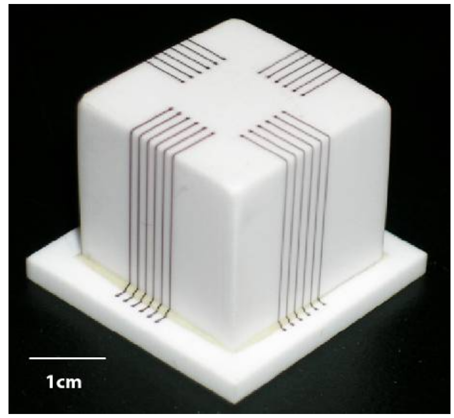

Figure 7. 3D Silver Interconnects (150μm line width) written over an alumina cube.

This low volume application requires conformal direct writing Ag interconnects on an alumina substrate over a 25mm height range. In this case the deposition head is first tilted at a 45° angle and is then moved in the Z-direction to be able to write on the vertical walls and accommodate the required height change. Conventional oven sintering is applied and the IC package is then flip-chip mounted onto the cube shaped alumina substrate.

Printed Antennae

A traditional approach to make conformal antenna is to first print the antenna elements on a Kapton sheet and then glue the Kapton sheet on a composite layer. This approach is not suitable for producing an antenna, since metallic printing is possible only on a planner surface when using traditional technologies (such as chemical etching). Additionally, it results in a weak structure and complicated assembly process due to multiple bonding. The Aerosol Jet process provides a solution to the above-mentioned problems. With Aerosol Jet technology, the metallic patches can be printed directly on a curved surface. This streamlines the assembly process by eliminating the extra bonding steps and alignment problems.

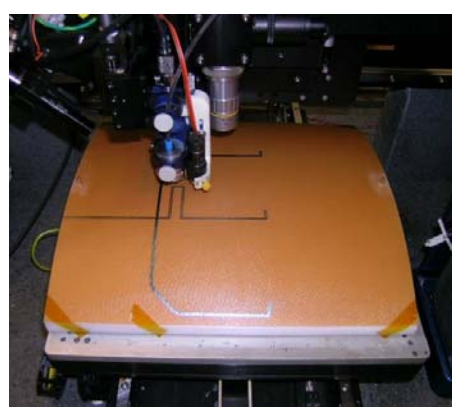

Figure 8. Photo of the Aerosol Jet system printing antennae directly on a curved surface. Photo courtesy of NexGen.

Low Temperature Processing

Once the material has been deposited, conventional approaches for many commercial metal inks require high-temperature treatment often up to 250°C or higher. For non-sensitive polymer substrate materials such as LCP, PA6/6T, re-flow or cure ovens can be used to sinter the deposited material. However, certain substrates tend to have limited temperature capability, for example polycarbonate and polyester, have a temperature limitation of around 100°C. This sensitivity requires a manufacturing process that can deposit and process the material at low temperatures. Aerosol Jet systems can locally process the deposition on substrates, using an integrated laser module that sinters the deposit while leaving the substrate unharmed. The end result is a high-quality thin film with excellent edge definition and near-bulk resistivity, typically 2-3x bulk but dependent on ink type. An example of low temperature processing is shown in Figure 9. This is a low cost polymer display application where temperature sensitive PMMA is used as the substrate to reduce costs. The Aerosol Jet process was used to write the Ag gates and interconnects, which were then laser sintered without damaging the PMMA.

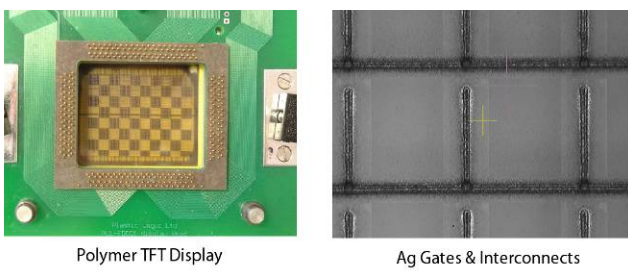

Figure 9. Low Cost Polymer Display. Laser processed Ag gates and interconnects on PMMA, (Resistivity ~8 μOhm-cm).

High Quality Deposits

Deposit quality is dependent on the ink type used, the ink-substrate combination and other factors such as substrate roughness. The Aerosol Jet process does not change the chemical or physical properties of the materials deposited or the substrates. In general terms, the Aerosol Jet process can deposit with:

- feature sizes down to 10 microns with +/- 10% edge roughness and pitch down to 20 microns,
- good conductivities,
- thickness as low as 100nm or as high as 5 microns (single layer deposit),
- low surface roughness, and
- good adhesion.

Aerosol Jet systems reliably produce ultra fine feature circuitry well beyond the capabilities of thick-film and ink-jet processes. Most materials can be written with a resolution of down to 20μm. For Ag, electronic features as small as 10μm with a 20μm pitch can be written.

This capability offers a solution for the production of smaller, high performance components critical to size-sensitive applications like those in the wireless and hand-held device markets where component density is increasing dramatically. The ability of the Aerosol Jet technology to create fine features with complex geometries in 3D from a wide range of materials makes it suitable for the production of both passive and active components, including resistors, inductors, capacitors, filters, micro-antennae, micro-batteries, and sensors. The precise edge definition and repeatability of the process are particularly relevant to high frequency requirements. In comparison to screen-printing, embedded resistors can be made smaller and more accurately with the Aerosol Jet process, such that no laser-trimming is needed to tune the resistor to the right value.

Gold and Silver inks generally display conductivities approaching bulk properties with conventional sintering and 2-3x bulk with laser sintering. Low viscosity inks can produce mirror-like surfaces while thick film inks have micron scale roughness. Deposit adhesion is highly dependent on ink-substrate combinations. For example, gold inks adhere to a wide range of substrates, including glass, ceramics, and various polymers. Silver is more sensitive, but also has good adhesion to a wide range of substrates. Typically, Aerosol Jet deposits satisfy the standard tape test.

Higher Efficiency Solar Cells

Used in conjunction with Light Induced Plating, the Aerosol Jet process is enabling the industry's first, non-contact fine line printing solution for higher efficiency Crystalline solar cells. Fine feature collector lines with widths between 18 um and 60 um have been produced with the Aerosol Jet process by using new and modified versions of existing screen-printing materials. The narrower, high integrity collector lines reduce shadowing effects thereby increasing photovoltaic cell efficiency. The Fraunhofer Institute for Solar Energy has independently confirmed absolute efficiency gains of 1% using Aerosol Jet in conjunction with a Light Induced Plating process. Because the process is non-contact, Aerosol Jet systems can print on thinner wafers and with less breakage than traditional screen-printing techniques.

All Aerosol Jet Printed Carbon Nanotube Thin Film Transistors

Printing thin-film transistors (TFTs) on flexible substrates at room temperature offers a cost-effective way to achieve mass production of large-area electronic circuits without using special lithography equipment. Recently, the University of Massachusetts and Brewer Science, Inc. demonstrated that a CNT (Carbon Nanotube) TFT on a DuPont® Kapton® FPC polyimide film was produced by using the Aerosol Jet printing system. A high-speed (5 GHz) TFT with a large high on-off ratio of over 100 was obtained. Aerosol Jet printing of flexible TFTs at room temperature allows for the mass fabrication of large-area electronic circuits on virtually any flexible substrate at low cost and high throughput for many emerging applications, such as flexible displays, RFID tags, electronic papers, and smart skins. (See figure 10).

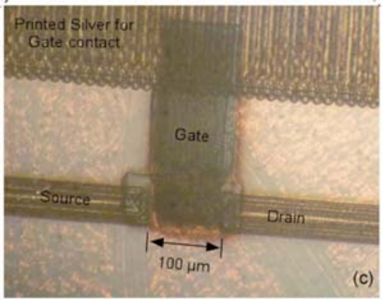

Figure 10: Top view of the CNT-TFT printed by Aerosol Jet

Solder-free Electronics

Since Aerosol Jet can print active and passive components as well as interconnects, the need for soldering may be eliminated. Proof of concept work, in conjunction with Boeing, and Wright Patterson Air Force Base is currently underway.

Wide Range of Materials & Substrate Combinations

Aerosol Jet systems can deposit a wide variety of materials, including metals, conductors, insulators, ferrites, polymers, adhesives, and biological materials. Deposits can be made on virtually any surface material – polymers, silicon, glass, metals, and ceramics. This flexibility opens the way for many different applications using a single process. The Aerosol Jet process uses a wide range of commercially available inks from many different sources.

Many devices that are manufactured for electronics products require multi-layer manufacturing techniques. The ability of the Aerosol Jet system to deposit conductive, insulating, and adhesive materials layer-by-layer within a single system makes it an attractive solution for the production of embedded passives. A simple 2D example of this multi-layer capability is the deposition of a dielectric and then an Ag layer onto a Cu circuit board pad to create a basic capacitor, as shown in Figure. 11. Other examples of multi-layer applications include sub-micron layers for fuel cell applications, high-density interconnect backplanes (organic and metal) for flat panel displays, and micro-sensors for avionics. Other successes with multi-layer deposits have been in the life sciences area, such as the generation of bio-sensor structures.

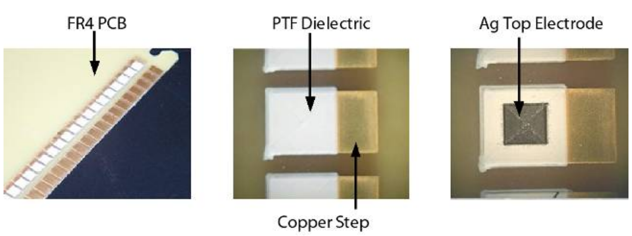

Figure 11. Multi-layer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor. Capacitance: 19 pF/mm2 @ 15mm Dielectric thickness.

Environmental Aspects

The Aerosol Jet process works without the need for masks or resists, which results in minimal waste and less environmental impact. As the process writes very finely and precisely, this reduces the amount of material required and waste generated for a given application.

Competitive Cost Basis

One of the main drivers for cost reduction using the Aerosol Jet process is the elimination of physical tooling. Aerosol Jet software creates the deposition tool paths direct from standard .DXF CAD data. This digital tooling approach also offers manufacturing agility by allowing designers to quickly and cost effectively test new design alternatives and prototypes. This also offers manufacturing agility which allows designers to quickly and cost-effectively test new prototypes and products. It eliminates the delays and costs associated with tooling sets and other upfront capital required by conventional electronics manufacturing techniques. This direct write feature also makes it much easier to carry out cost effective Rapid Product Development and to validate design changes without the need for "re-tooling." The result is reduced cost and faster time-to-market for new products.

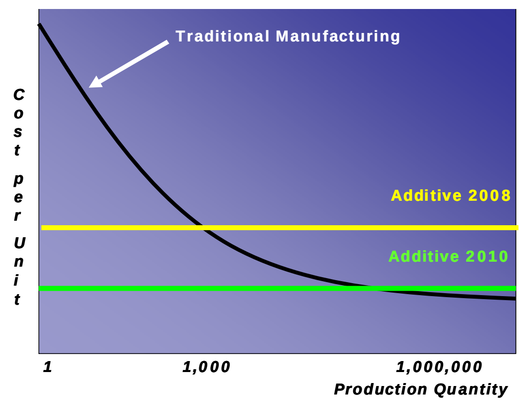

Figure 12. The Aerosol Jet process provides a cost effective solution for low to moderate volume production runs or where mass customization is required. The cost per unit for Direct Write technology is flat regardless of volume.

The Aerosol Jet process can reduce the overall number of processing steps, which in turn can help to reduce both capital and operating costs. Since the system can process a wide range of materials and substrates, greater utilization of the capital equipment can be obtained. Process costs in terms of operator input, supplier chain complexity and work flows are reduced.

Material efficiency can often play a key role in reducing the cost of manufacturing operations. The tiny droplets dispensed by the Aerosol Jet process allow for very thin coatings, which also allow for good interaction between differently applied layers. These same femto-liter sized droplets allow for very careful control of dosages dispensed. Since many electronics materials are expensive, the Aerosol Jet technology is a key enabler for reducing the cost of each device by reducing material use and waste

Figure 13. Demonstrator test pattern (Cu plated on PI) created by the catalyst-layer approach.

Another alternative for reducing processing steps and cost, compared to traditional mask-etch techniques, is the catalyst-layer approach for producing interconnects or other features. Aerosol Jet systems can directly deposit an activator/catalyst solution in the exact pattern required. The process is then completed by curing at 80^{o}C, and then followed by a standard electroless Cu plating step (see Figure 13).

In this sample, the catalyst test pattern has been printed onto a polyimide film and conventional electroless plating for two hours has been used to plate approximately10mm thick Cu onto the pattern. The traces in Figure 10 are 50 mm long and range in width from 10mm down to 500mm. Gap spacing ranges from 1.8 mm down to 300mm. All traces are highly adherent to the substrate and pass the standard tape test. Deposit conductivity is near bulk and similar to standard electroless Cu deposits. The process has also been demonstrated on polymer matrix composites and PET. This technique can be used to reduce cost, especially in patterns requiring combined fine and large area deposits.

PROCESS SCALABILITY

The current Aerosol Jet 300 system is aimed at low volume manufacturing and rapid prototype product development. The system is equipped with a single nozzle deposition head. It can write at speeds up to 200m/s with a high level (±6µm) of dynamic accuracy. As higher volume applications are developed, there is a need to scale up the speed of the Aerosol Jet manufacturing. For these higher volume applications, the Aerosol Jet system can be equipped with multi-nozzle deposition heads and high performance atomizers to meet production requirements. Aerosol Jet systems are involved with ongoing projects in scaling atomizer throughput, development of multiple nozzle deposition heads, and closed loop control of the deposition process. These developments are being driven by high volume (millions of parts p.a.) production applications.One high volume production example is the front side metallization of Crystalline solar cells. The Aerosol Jet technology is currently in pre-production trials for printing collector lines and bus bars on PV cells. Equipped with an integrated 40 nozzle material deposition head, the Aerosol Jet PV printing system is printing the front side metallization pattern at the rate of one 156mm PV wafer every ~ 3 seconds. The modular design enables the addition of parallel print stations for higher throughput. A tandem Aerosol Jet print station for bus bars can also be added.

CONCLUSIONS

This paper has introduced the novel Aerosol Jet deposition process and outlined its features, benefits, and some select application areas. This CAD driven, direct write process is currently being used in a wide range of Mil Aero electronics applications. Designers of a wide range of Mil Aero printed electronics applications can now harness the unique features of Aerosol Jet systems to create designs which offer a wide range of time, cost and quality benefits.

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