AEROSOL JET® PRINTED ELECTRONICS OVERVIEW

SUMMARY

Optomec's Aerosol Jet® technology is a fine-feature material deposition solution used to directly print functional electronic circuitry and components onto low-temperature, non-planar substrates. The system is quickly gaining traction in Photovoltaics, both as a near-term production solution that can increase Solar Cell efficiencies by >1% absolute (ie: 5-10%), and as an enabler for next-generation ultra-high efficiency cell architectures.

Aerosol Jet printing is a breakthrough manufacturing technology that is an emerging replacement for traditional thick-film processes like screen-print, photolithography and micro-dispensing, as well being far more capable than inkjet. The patented Aerosol Jet process utilizes an innovative aerodynamic focusing technology to produce electronic and physical structures with feature sizes as small as 5 microns, and can also produce wide area conformal coatings. The Aerosol Jet system supports a wide variety of materials, including nanoparticle inks and screen-printing pastes, conductive polymers, insulators, adhesives, and even biological matter. Aerosol Jet has been used to successfully demonstrate many advanced applications, including:

- High-Efficiency Solar Cells
- High-Efficiency Fuel Cells
- EMI shielding
- Fully-Printed Thin-Film Transistors
- Embedded Resistors, Antennae, Sensors, etc.
- Flexible Displays and Flex Circuitry
- High-Density Assays for Drug Discovery

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 directly be printed with the Aerosol Jet tool thereby enabling seamless integrated manufacturing for 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.

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).

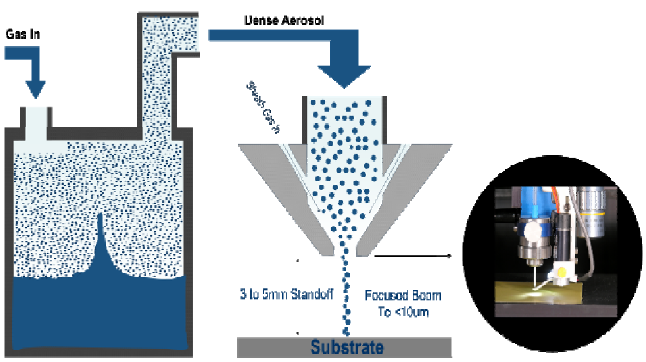

Figure 2. Schematic of the Aerosol Jet process and photo of the deposition head.

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.

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.

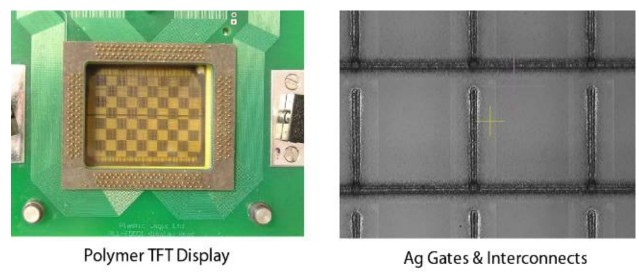

Figure 9. Low Cost Polymer Display. Laser processed Ag gates and interconnects on PMMA, (Resistivity ~8 μOhm-cm).

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%
- high placement accuracy, +/- 1micron repeatability.
- very good edge definition
- very high good conductivity due to high metals loading
- single pass thickness from 10nm to 5+ microns
- 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.

AEROSOL JET CAPABILITIES AND PRINTED ELECTRONICS APPLICATIONS

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

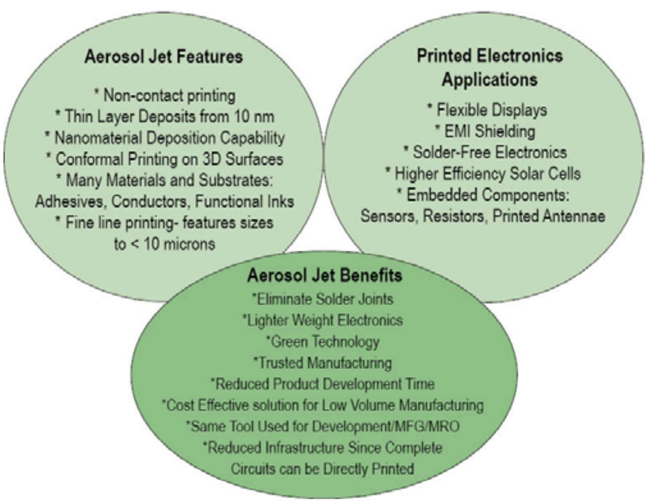

Figure 3. Aerosol Jet Feature/Benefits for Mil-Aero Applications.

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).

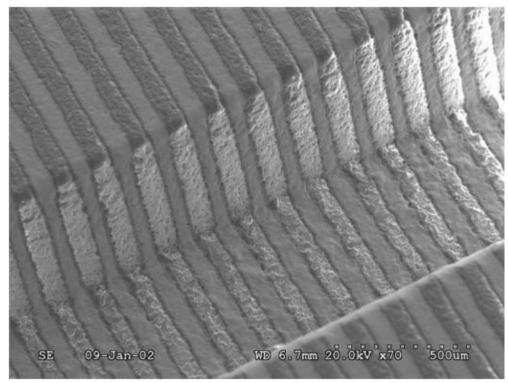

Figure 4. 60μm Ag lines written over a 500μm trench.

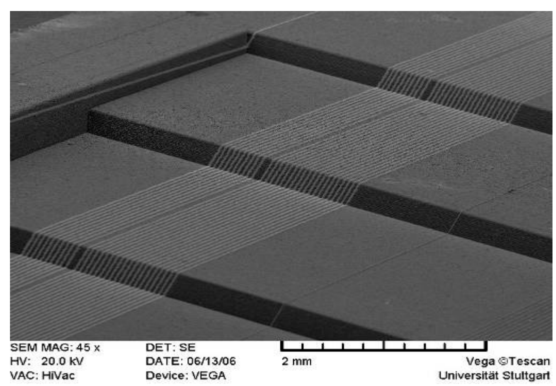

Figure 5. 20 μm Ag lines written over stepped injection molded LCP (Courtesy HSG-IMAT).

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.

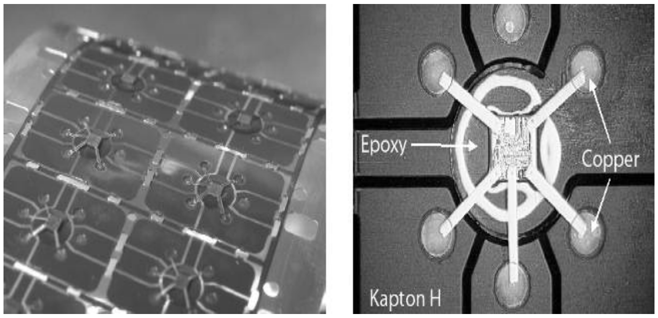

Figure 6. 150µm wide silver interconnect over an epoxy bump and Kapton.

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.

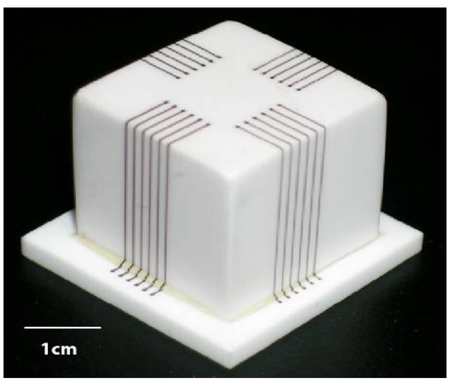

Figure 7. 3D Silver Interconnects (150µm line width) written over an alumina cube.

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.

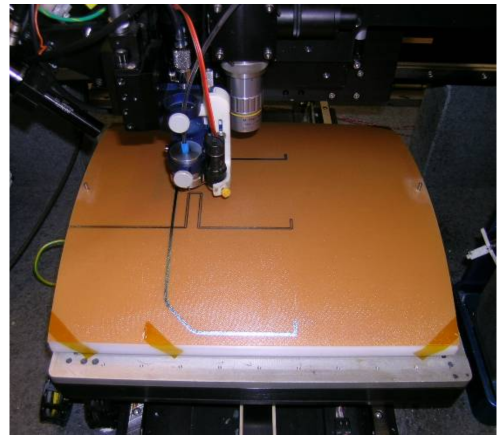

Figure 8. Photo of the Aerosol Jet system printing antennae directly on a curved surface. Photo courtesy of NextGen.

Higher Efficiency Solar Cells

A proven, near-term production application of the Aerosol Jet technology is the high-throughput production of High Efficiency Solar Cells. Working with the world-renowned Fraunhofer Institute of Solar Energy Systems (ISE), Optomec's Aerosol Jet has been used to produce narrow collector lines on Crystalline Silicon Solar Cells, with widths as small as 20um – versus the current state of the art with screen printed lines of ~100um. In addition to reduced shadowing through width reduction, the shape of the Aerosol Jet lines also exhibit high reflectivity that translates to an optical width that is <50% of their geometric width. These reductions in shadow affect coupled with the use of high conductivity materials translates to an increase in Solar Cell efficiencies of more than 1% absolute on average.

More specifically, using Aerosol Jet, ISE has demonstrated cell efficiencies up to 16.7% and fill factors of 79% on 15.6 cm x 15.6 cm multi-crystalline Si solar cells, and efficiencies up to 18.3% and fill factors of 81% on 12.5 cm x 12.5 cm Czochralski (Cz) Si cells with an aluminum back surface field. Best cell performance exceeded 20%.

In addition to the functional gains, Aerosol Jet is projected to dramatically reduce overall Cost of Ownership through the following improvements:

- Reduced Equipment Consumables - ie: Screens
- Reduced Material Consumption - ie: Silver (paste)
- Reduced Silicon Consumption - ie: thinner wafers
- Improved Yield - ie: less breakage and Rejects
- Improved Printer Uptimes

In order to meet the throughput requirements of the solar industry, Optomec has multi-plexed its technology into 40-nozzle configurations that can print collectors at a rate of 3 sec per cell. Also, Optomec has partnered with a leading automation (ie: wafer handling) company to build a system that is capable of processing an industry-leading 2400 cells/hr, which is greater than 50MW annual production.

Optomec is continuing to develop Aerosol Jet printing for other photovoltaic applications, including:

- Multi-Material Collectors
  - *to separately optimize contact and conductivity*
- Local Doping
- Local Etching
- Backside Grids
- Thin-Film PV Metallization
  - *collectors and interconnects*
- Thin-Film PV Coatings

All Aerosol Jet Printed Carbon Nanotube 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).

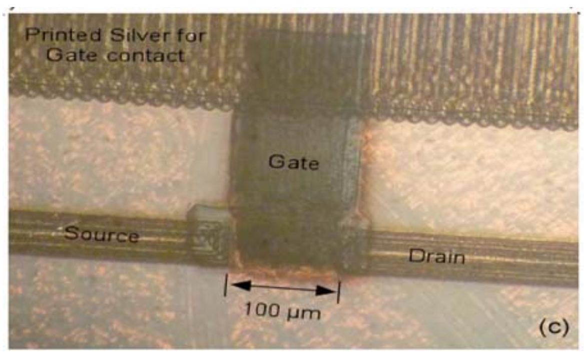

Figure 10: Top view of the CNT-TFT printed by Aerosol Jet

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.

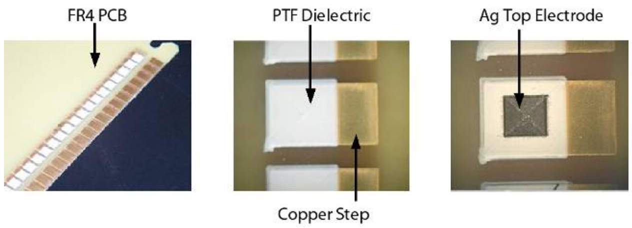

Figure 11. Multi-layer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor.

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. 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.

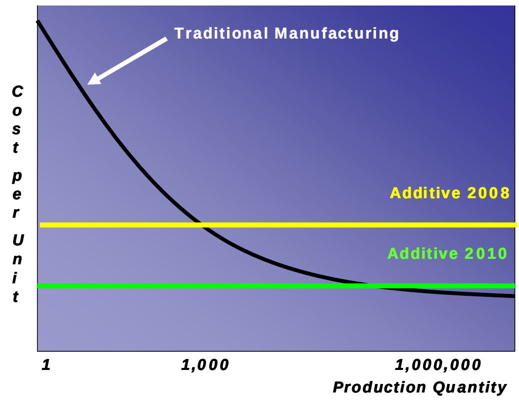

Figure 12. The Aerosol Jet process provides a cost effective solution for low to moderate volume production runs or where mass customization is required. The cost per unit for Direct Write technology is flat regardless of volume.

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 standard electroless Cu plating (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.

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.

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 Printed Electronics applications with proven advantages over legacy technologies like screen-printing, as well as key differentiation with emerging Ink-jet based processing.

Please contact Optomec for more information at:

www.optomec.com

Optomec is the world-leading provider of additive manufacturing systems for high-performance applications in the Electronics, Aerospace & Defense, Solar, and Biomedical markets. These systems utilize Optomec's proprietary Aerosol Jet printed-electronics and LENS powder-metal fabrication technologies. The company has a global customer base of industry-leading manufacturers, including more than 50 users in 10 countries.

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