Aerosol-Based Direct Writing of Interconnects

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Abstract
Optomec is developing an aerosol-based technology for high-precision, maskless deposition of a wide variety of materials. The system functions by atomizing commercial inks and pastes, and then depositing the droplets under CAD/CAM control. Feature sizes of 25 microns and smaller are achieved and millimeter-scale tool standoff allows non-contact deposition into vias, trenches, and three-dimensional geometries. The compatible materials include a variety of commercial metals, resistors, dielectrics, and polymers as well as custom specialty materials. The materials can be laser sintered or thermally cured and are compatible with ceramic and glass substrate as well as various low-temperature substrates such as epoxy circuit board and flexible polymer film. This technology is called Maskless Mesoscale Materials Deposition (M^3D).

Introduction
As electronic circuit packages continue to shrink and take on three-dimensional aspects, the need arises for tooling that will deposit electrical interconnects to high density and into conformal geometries. Conventional solutions such as screen printing, syringe dispense, and photolithography have well known geometrical limitations. These limitation make it difficult to form interconnects with sub-50 micron resolution[1] on non-planar surfaces.

To address this need,[2] we have made tremendous progress on a new direct write deposition tool. This tool uses aerosol-droplet dispensing to deposit micron-scale features on both planar and non-planar substrate.[3] The tool is compatible with a wide variety of commercial inks and pastes. Additionally, a class of low-fire inks[4,5] has been developed for deposition of conductive features onto low-temperature plastics and epoxy boards. Typically the start materials are deposited into specified geometries, and then fired according to a supplier's specified protocol. The deposited materials can also be scanned with a focused laser to locally fire the material without damaging the underlying substrate.

Aerosol Deposition Technology
The Optomec M3D process deposits liquid droplets of inks and pastes by aerodynamic focusing. Shown in Figure 1, the process starts by atomizing liquid inks. The ink may consist of various precursor molecules in solution or suspensions of micron- and nanometer-sized particles. Either ultrasonic or pneumatic methods are typically used and the droplet size is in the 1-5 micron size range. The atomized mist is entrained in a carrier gas, typically nitrogen, and directed to a deposition head. Depending on details of the atomization method and start materials, the droplet stream may be modified in-flight to the deposition head. In particular, it can be advantageous to strip carrier gas or to dry the droplets before deposition.

As shown in Figure. 2, two apertures in the deposition head collimate the particle stream. Between the first and second aperture the particle stream is combined with an annular gas stream, called the sheath air. Both the sheath- and particle-streams are forced through a final small aperture. The sheath air is in contact the aperture walls but the particle-laden stream is focused through the center. In this configuration the particles ideally never contact the wall and therefore clogging is minimized. The particle stream is focused to diameter typically 5 times smaller than the aperture diameter. The aperture diameter is in the 100-500 micron range and the corresponding particle steam diameter is 20-100 microns. The 100micron diameter is a practical a lower limit, since smaller dimensions lead to low deposition rates. Diameters larger than 500 microns are possible, but they usually fall outside the scope of typical application. The particle stream diameter also has strong dependence on the flow rates of the individual gas streams.

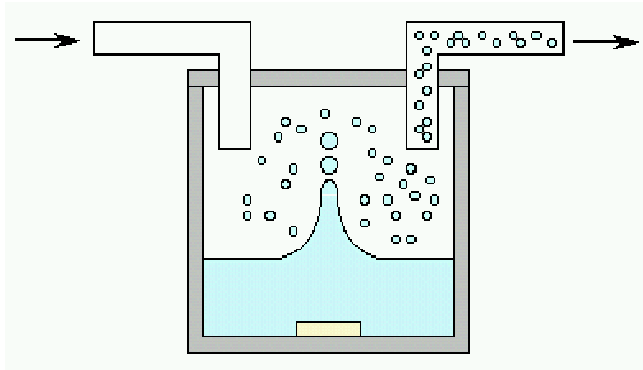

Figure 1 - Schematic Diagram of the M3D Deposition Process. Liquid Inks and Pastes are First Atomized to Form 1-5 µm-Sized Droplets. The Droplets are Entrained in an Air Stream and Directed Toward a Deposition Head

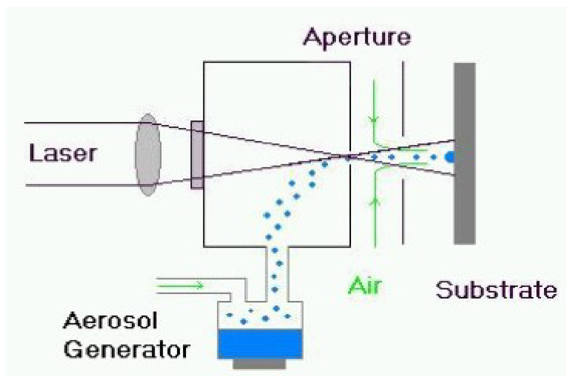

Figure 2 – Schematic Diagram of the M3D Deposition Head

Within the deposition head the droplet stream is collimated by passing through successively smaller apertures. Immediately before reaching the final orifice the droplet stream combines with an annular air-stream. This air stream serves as a sheath to focus the droplets to small diameter and prevent particles from striking the aperture walls. The final aperture diameter is 100-500 microns, but the emerging droplet stream diameter is approximately 5x smaller than the aperture. As discussed below, a laser can be included in the process for sintering the deposited material.

The emergent particles are accelerated to more than 100 m/s and maintain good collimation over a distance of several mm. Figure 3 shows a CCD image of a particle stream emerging from a 500-micron diameter aperture. The long-distance collimation is visually evident. Figure 4 shows broadening of ink deposits as a function of tool height above a substrate. In this case the conditions were optimized to isolate the broadening mechanism caused by the stream divergence. All other line-broadening mechanisms were negligible. As can be seen the line width reduces slightly when the tool is raised above contacting the substrate and then is roughly constant for a few mm. Above a few mm the deposits broaden roughly in proportion to the standoff height.

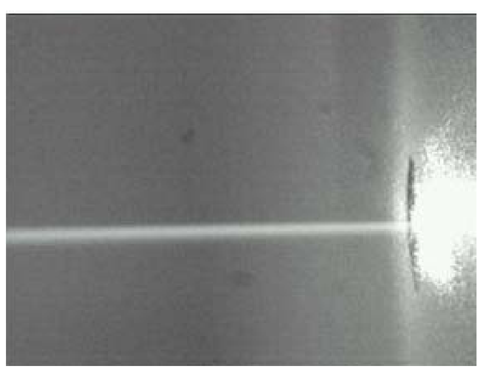

Figure 3 - Droplet Stream seen Emerging from a 500-micron Diameter Aperture

The stream diameter is approximately 100 microns. The focusing of the stream to small diameter is caused by an annular sheath air stream, which surrounds the particle-laden stream. Both the sheath air and the particle-laden air stream pass through the same final orifice.

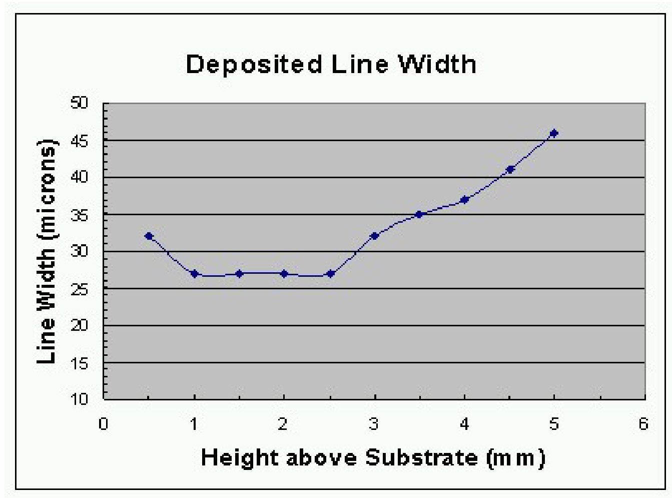

Figure 4 - Width of Deposited Lines as a Function of Height of the Nozzle above a Substrate

In this case the nozzle diameter is 150 microns and the minimum particle stream diameter is 27 microns at a height of 2 mm above the substrate. The data show the particle stream is well collimated over a distance of a few mm. This feature is useful for the conformal deposition of materials without the need for height control.

The nearly constant line width with standoff height is important for application to depositing materials onto non-planar surfaces. As an example Figure 5 shows silver interconnects deposited into a 500 micron deep by 500-micron wide trench. The sidewalls are tilted 20 degrees relative to vertical. During deposition the deposition tool was held stationary and the substrate was translated underneath the tool. The 65 microns line width on the surface above the trench is approximately equal to that at the bottom of the trench. The line width on the sidewall is 50% wider than the top and bottom surfaces. Electrical continuity is maintained across the trench.

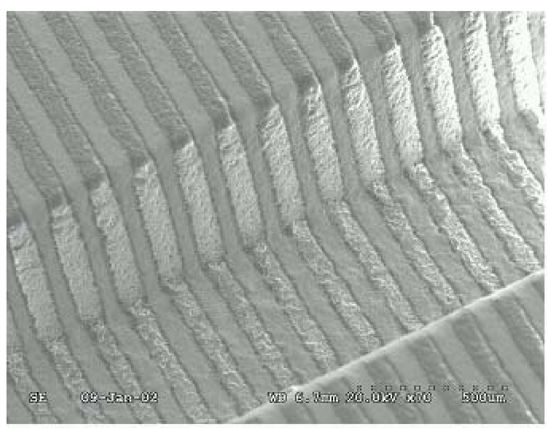

Figure 5 - Micrograph Showing the Deposition of Silver Ink over a Step Edge and into a Trench

The depth and width of the trench is 500 microns and the walls are tilted at approximately 20 degrees relative to vertical. As can be seen the line width is approximately the same at the top of the step compared to the bottom of the trench. The line width on the walls is broadened by 50%. This micrograph illustrates the long working distance capability of the aerosol deposition head.

Materials Compatibility

The M3D deposition process is compatible with a wide range of commercial inks and pastes as well as research grade materials. In order to atomize the liquid start materials the viscosity should be in the range of 1-1000 cP. The start material can consist of dissolved precursor materials as well as particle suspensions. The size of particles in suspension are optimally 0.5 microns or smaller. Larger particles do not atomize efficiently and these suspensions typically are not stable. High-fire and polymer thick film pastes can be used in the M3D process when the pastes are diluted to <1000cP. The preferred solvents have low vapor pressure, to minimize droplet drying, and are miscible with the pastes. Examples include Alpha Terpineol and Ethylene Glycol. Table 1 below lists a variety of commercial pastes that have been shown to be compatible with the M3D process.

Along with the development of the M3D deposition tool, various low temperature ink systems have been developed.[4,5] These inks are typically either precursor-based, nanoparticle-based, or are they can be combinations of the two. Metal-organic precursor chemistries have a specific advantage in that the precursors can decompose to pure metal at very low temperatures, 150-250C range. Because of this the inks can be deposited on many plastics and then heated to decompose to metal. The drawback is that the metal yield of precursor inks is typically low and is in the 1-10% range. The low yield reduces the overall deposition rates.

Metal nanoparticles also have drastically reduced treatment temperatures. Because of the high surface energy, nanoparticles will melt at temperatures hundreds of degrees lower than micron-sized particles. Nanoparticle inks in particular have been shown to sinter in the 150-250C range.[5] Such ink systems are ideal for M3D. It is possible to deposit the inks on a heated substrate, and the ink will sinter to dense metal within minutes. The metal yield of nanoparticle inks can be in the 10-50% range, which leads to highly efficient deposition.

While considerable progress has been made in low-temperature ink development, the sintering temperatures are still significantly higher than the softening temperature of many common plastics. For example PMMA softens at around 100C and most nanoparticle and precursor inks will not become conductive or ductile at this temperature. In order to be able to densify inks on these plastics, Optomec has developed a laser treatment process. The essential mechanism uses a laser beam like a localized source of heat to fire the ink at a focal spot. It is well know that Gaussian laser beams can be focused to micron-scale spot size and can produce heat affected zones of comparable dimensions. Figure 6 shows a simulated temperature rise on a PMMA surface that has been illuminated by a focused 100 mW CW laser. A 5-micron thick film of nanoparticle silver ink has been deposited on the substrate. As can be seen, the heat spreading is well localized along the substrate surface and only penetrates a few microns into the interior. The peak temperature of 500K is sufficient to sinter many of the low temperature inks. The sintered inks show low resistivity (less than 10X of bulk metal) and good adhesion to plastics such as PMMA.

Table 1- Material Systems Compatible with M3D

	Vendors	Sintering Method
Conductor Pastes(Ag, Au, Cu, Pt, Pd)	DuPont, SMP, Paralek	Oven- and laser-fire
Resistor Pastes (thick film and PTF)	DuPont, Asahi	Oven- and Laser-fire
Dielectric Pastes (thick film and PTF)	SMP, Dupont, Asahi	Oven-fire
Polymers and Epoxy	various	Oven-cure

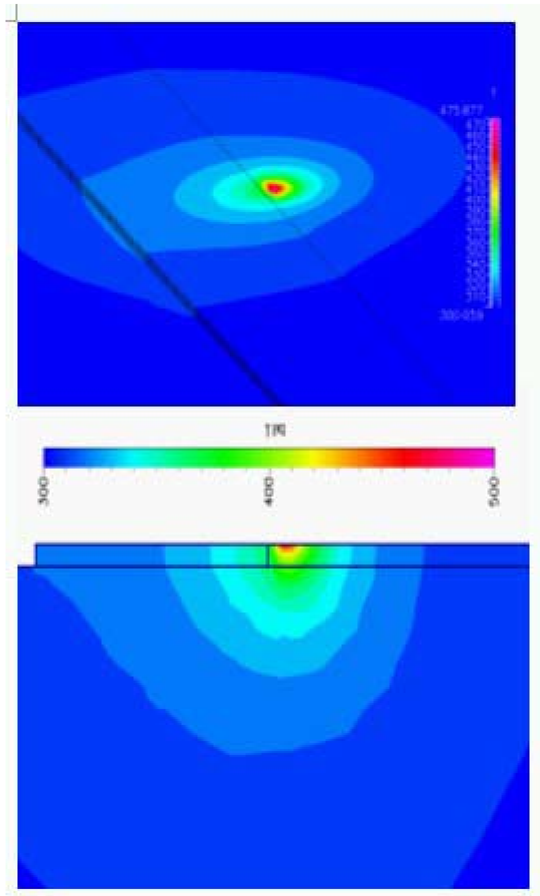

Figure 6 - Simulation Showing the Localized Heating of a Nanoparticle Ink Film Deposited on PMMA Substrate

The film is 5 microns thick and is illuminated by a 100mW, 532nm CW laser. The laser is focused to approximately a 5-micron spot size. The heat-affected zone extends several microns lateral to the surface and a few microns into the surface. The peak temperature of 500K is sufficient to sinter various nanoparticle inks and produce well adhered, conductive deposits.

Application Examples

The combination of large standoff height, fine feature definition, and low-temperature inks make possible some unique interconnecting applications. Three such applications are illustrated in Figures 7-9. Figure 7 shows silver interconnects deposited on PMMA for a polymer display application. It illustrates the capability of M3D to deposit and laser-fire conductive inks on low temperature polymer. The silver nanoparticle ink was deposited into 35 micron wide lines on the PMMA. The ink was then allowed to dry for 5 minutes at 80C. After drying, a 50 mW, 532nm CW laser was focused onto the deposits and scanned at 20 mm/s. The measured resistance of 6 cm-long interconnects was 100 Ohms. This corresponds to a resistivity of 16 μOhm-cm or approximately 10x larger than bulk silver. The lines were well adhered and passed an adhesive tape test.

Figure 8 shows the deposition of silver traces connecting an IC chip to a substrate. The IC chip is epoxy bonded to a copper/polyimide laminate substrate. The application calls for the silver interconnects to be deposited conformally from the chip I/O pads, across the epoxy and polyimide layers, and down to the copper connection pad. To accomplish this, the M3D tool was set to deposit a low-temperature silver ink into discrete traces 35-microns wide. The traces extended from the I/O pads to the Copper pad and several traces were overlapped to form a 150-micron wide ribbon. After deposition the part was heated on a hot plate at 180C to sinter the ink. The resulting interconnects have measured resistance below one-ohm.

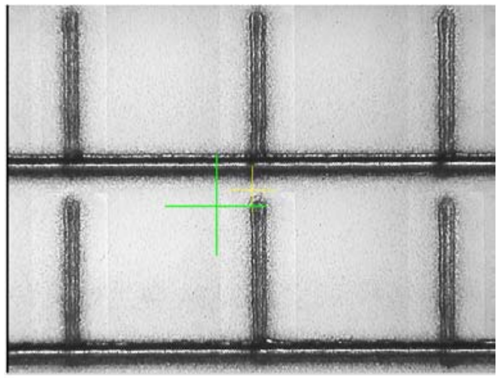

Figure 7 – Micrograph of Laser Treated Silver Interconnects on PMMA Substrate

Silver nanoparticle ink is deposited with the M3D process and allowed to dry at 80C. The deposits are then sintered by scanning a focused laser over the ink. The laser is 532 nm, CW and the power is approximately 50 mW. The scan speed is 20 mm/s. The resistivity of the horizontal interconnects is approximate 16 μOhm-cm or 10x greater than bulk silver.

The example in Figure 9 illustrates the capability to deposit metal traces into non-conventional geometries. In this case helical silver wires have been deposited on 1mm OD Kapton tubing. Similar to a conventional lathe, the tubing is turned by a rotational stage while the deposition head is translated along the length to deposit material. Both the pitch and line width of the helical winding can be controlled through the tool path. After deposition the part was fired on a hot plate at 250C to convert the ink to conductive traces.

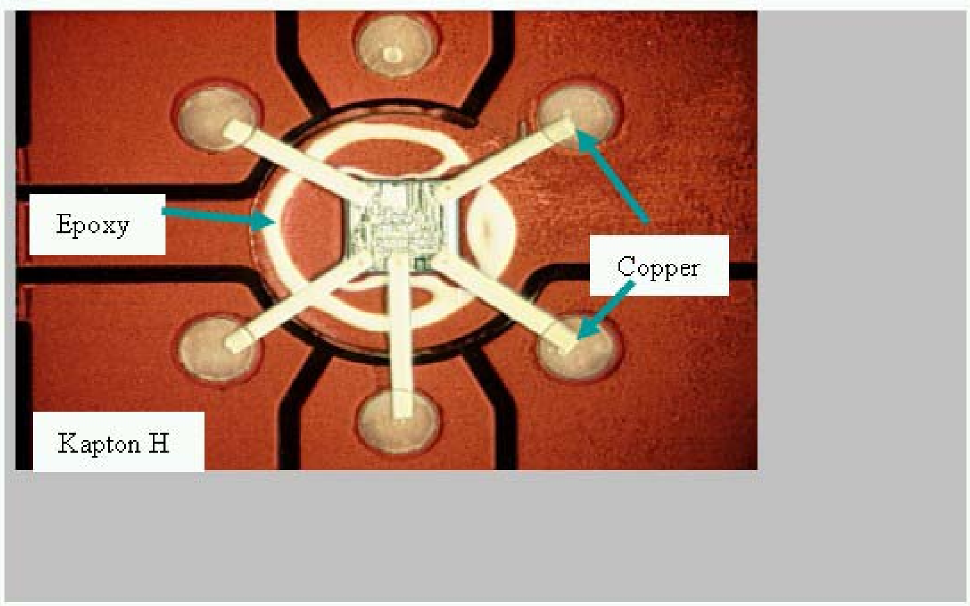

Figure 8 - Micrograph of Direct Write Silver Interconnects Deposited for Electrically Connecting an IC to a Substrate

The IC has been attached to the substrate with a dot of epoxy. The interconnect ribbons are each 150 microns wide and are formed by depositing 35 micron wide traces of silver ink in a raster format. Conformal interconnects such as these have the advantage of producing flatter and more robust packages than traditional wire bonding.

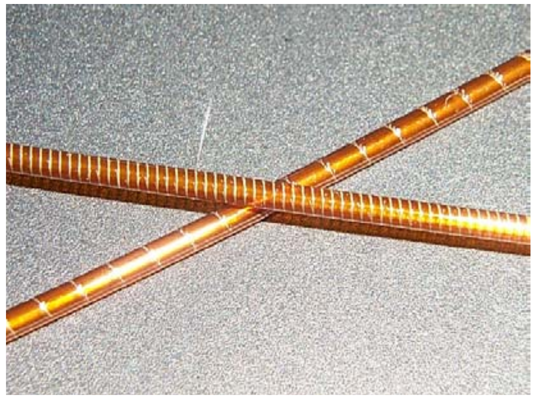

Figure 9 - Micrograph of Helical Silver Wires Deposited on the Exterior Surface of Polyimide Tubing

The tube OD is 1mm and trace width is approximately 35 microns. This deposit is made by rotating the tube and synchronously translating the deposition head along the length.

Conclusion

Optomec has developed an innovative deposition process capable of depositing inks and pastes down to 25-micron feature size. The process does not require masking and it is performed under ambient conditions. The large standoff height makes it possible to deposit ink into conformal geometries such as curved surfaces, sidewalls, trenches, and via. Conventional materials are compatible with the process, and various low-temperature inks have been developed for metallization of plastic substrates. A laser treatment process makes it possible to sinter the inks on low-melting-temperature plastics. These features add up to a tremendous new capability and resource for creating novel interconnects.

References

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