1. Introduction

Aerosol Jet micro-additive manufacturing has emerged as an environmentally friendly method of fabricating 3D electronic structures at length scales down to 10 m [1]. The additive fabrication has inherent advantages since no material is wasted and the method does not require the use of harmful chemicals as in the case for lithography based techniques. The Aerosol Jet method also allows a standoff height of up to 5 mm allowing printing on complex 3D surfaces. Electronic structures at sub-mm length scale are of great interest to be used as passives as well as antennas for wireless high-speed.
data transfer for emerging applications such as wearable devices, biometric devices, on-chip electronics for chip-to-chip, and intra-chip communication. Conventional antennas and passives are typically limited to 2D surfaces due to the planar photolithography used in the conventional fabrication processes. Note that the current 2D planar technologies force designers to use differential antennas to achieve desired directivity [2] that increases power consumption and reduces system efficiency either due to extra circuitry used to generate the differential output signal, or the use of lossy baluns to convert single-ended amplifier outputs to differential feeds. In addition, the existing 2D electronic elements are implemented in the top metal layers of an integrated circuit chip, while the physical space that the radio waves propagate in is the top-metal-layer-region as well. Fabrication of 3D metal-dielectric structures away from the top metal layer in IC chips are thus necessary for efficient low-power signal transmission in antenna applications and low energy loss in the case of passives.

To date, researchers have attempted to achieve sub-mm length scale 3D metal-dielectric structures by: (a) manufacturing metal lines in 2D over a dielectric substrate and folding them into 3D shapes similar to an origami [3–6], or (b) printing metal lines on a pre-manufactured 3D surface [7]. The Origami folding of the substrate can result in 3D shapes only if the metal traces at the origami folds are compliant enough to accommodate the extreme strain at or near the Origami folds. In addition, the number of 3D shapes are rather limited. Finally, the degree of folding of Origami is difficult to control due to the inherent structural instabilities and the nonlinear stress–strain response of these structures [8] leading to an unpredictable response over the operating frequencies in the case of its use in antennas [3, 4]. The approach in (b) suffers from the fact that the metal lines need to be stretched well beyond the yield/ultimate tensile strength of metals to reach the final shapes, requiring serpentine structures and thus increasing the device resistance. Direct write processes such as inkjet printing are also available for 2D fabrication of antennas structures [9–11]. Inkjet printing is cheap and allows improved layout flexibility such as post-process deposition of thick dielectric layers and a relatively improved isolation from the substrate. Cook et al [10] demonstrated inkjet fed patch antenna at 24 GHz with a gain of 7 dBi. Adams et al [11] showed electronic traces on a pre-manufactured curved surface at a length scale of up to a centimeter by the inkjet printing technology. Producing complex shapes or geometries along with traces, however, is difficult with inkjet printing at sub-mm length scale mainly because of the passive drop-on-demand nature of the inkjet process.

In this paper, we demonstrate a novel Aerosol Jet micro-additive manufacturing method to fabricate custom-shaped sub-mm length-scale metal-dielectric structures. A UV curable dielectric is dispensed over a substrate (Si or otherwise) [12, 13] where the dispense length scale is 10–100 µm. A simulation study is also carried out to identify the antenna-like structures to be fabricated using the proposed method. The paper demonstrates the feasibility of fabricating complex 3D printed structures at sub-mm length scale using the aerosol jet micro-additive manufacturing method.

2. Simulations

Simulations can be used to establish microstructures that can act as mm wave antennas in 3D with superior directivity and gain. The Aerosol Jet micro-additive manufacturing method will be described later to demonstrate the fabrication of such structures. The electrical simulations were performed using the software, Ansoft HFSS. For the model, micro-strip transmission lines are used to feed two resonant quarter-wave monopole antennas printed onto dielectric support pillars (figure 1). The antennas are designed for input resonance around 60 GHz, and produce a directional gain pattern through the formation of an on-chip antenna array. The relative permittivity of the dielectric was taken as 4.023 (from Loctite 3105 data sheet, Henkel Inc, used in the fabrication section described later), while the loss tangent at 0.031. The resistivity of the metal lines was taken to be $9 \times 10^{-8}$ Ω m. Note that the gain is a key performance figure which describes an antenna’s directivity. The design of such a system, though trivial in apparent complexity, is unavailable to designers with existing fabrication technologies. The example structure proposed for use in the wireless system (figure 1) currently fits within a 4 mm by 2 mm footprint. Figures 2(a) (c) show the gain pattern of the antenna system in various directions. Higher gains indicate directions where the signal is radiated out with higher relative power to a mathematically ideal uniform isotropic radiator. Figure 2(a) shows full radiation pattern assuming far field operation with an antenna placed at the origin. Figure 2(b) shows the gain pattern along the XY-plane corresponding to energy radiated towards other structures placed on the same plane. Figure 2(c) shows gain versus elevation angle, looking in the forward ($\phi = 90\degree$ or $-\phi$) direction. The $0$ and
3. Fabrication process

3.1. Materials

The primary material sets used to create the 3D antenna-like structures include a metallic nanoparticle ink and a UV curable dielectric. Silver nanoparticle ink was used (Advanced Nano Particle Inc., Fremont, CA, AS1:2), while the dielectric material used was a UV curable Acrylic Urethane (Loctite 3105, Henkel Inc.). The size of the metal nanoparticles had about 50 wt % ±5% particle loading with particle size of 50–100 nm with a viscosity of about 160 cP at 0.4 rpm. The dielectric material has a viscosity of 300 cP. A minimum nanoparticle curing regimen was applied at 130 °C/2 h. The resistivity measured in these conditions is about $9 \times 10^{-8} \, \Omega \, \text{m}$ or about 20% of the bulk silver (Optomec data sheet). Glass and a functional Si chip were used as the substrate. The substrates were cleaned with DI water followed by isopropyl alcohol. An atmospheric plasma at 100 W for 1 min was then applied to the substrate to improve the uniformity of the printed patterns.
A programmable oven. The UV was to instantaneously cure a micro-jet \cite{14, 15}. The printed material can be sintered in a programmable oven. The UV was to instantaneously cure a UV curable polymer dielectric and create 3D shapes (similar to that shown in figure 1) directly over the substrate. Note that the stand-off distance between the substrate and the nozzle tip along with the jetting from a tilted nozzle allows the printing over a curved surface—a unique capability for the Aerosol Jet direct write processes. The Aerosol Jet micro-additive printing method has been used in the manufacturing process for solar cells \cite{16, 17}, microelectronics \cite{18, 19}, and sensors \cite{20, 22}. The nozzle exit diameter for the polymer posts was 200 m and for the printed silver lines it was 150 m (the minimum line width is about 10 times smaller than the nozzle diameter based upon the sheath gas pressure). The nozzle was tilted approximately 45° from vertical for the sidewall printing. The dielectric printing used a pneumatic atomizer with an air pressure of 3 psi and a sheath gas pressure of 0.13 psi. We also used a virtual impactor that serves to concentrate the aerosol in between the atomizer and print head. The silver nanoparticle ink used ultrasonic atomizer with a gas pressure of 0.25 psi, and a sheath gas pressure of 0.25 psi. The sheath air pressure for the silver printing is higher than that for the polymer printing because of the smaller nozzle diameter (150 m versus 200 m). The standoff distance between the chip and the tip was about 5 mm. Note that the overspray and hence the printing quality can depend upon (a) the standoff distance (lower overspray for lower standoff distance), (b) ratio of sheath gas pressure to the atomizing pressure for the ultrasonic atomizer, and (c) the combination of sheath gas pressure, atomizing pressure and exhaust pressure for the pneumatic atomizer. The optimized parameters such as sheath gas pressure, atomizing pressure and exhaust pressure may vary for different inks based upon their viscosity, particle size and the solvent used. The process parameters used in the current study were optimized for the nanoparticle ink and the 3D structures to be manufactured. Note that the major advantage of the micro-additive manufacturing methods is that it does not require the use of environmentally harmful chemicals used in subtractive (e.g. lithographic or MEMS) techniques. In addition, the proposed method does not create any material waste.

3.2. Manufacturing process

The manufacturing process to fabricate the antenna-like structures shown in figure 1 involved the in situ curing of a dispensed dielectric material at the micro-scale followed by direct write of metal nanoparticle inks on vertical as well as horizontal walls of the dielectric using a tilted nozzle head. Such a direct write process requires that the dielectric (at 300 °C) as well as the metal nanoparticle ink be jetted at a length scale of tens of micrometer. We used the Aerosol Jet micro-additive manufacturing machine to print materials directly onto a base substrate. The main components of an Aerosol Jet system are shown in figure 4 and includes atomizers (ultrasonic and pneumatic), a programmable XY motion stage with an accuracy of ±6 µm, two deposition heads, a laser (700 mW, 830 nm IR laser) and a UV light attachment (Panasonic Spot Curing System, Aicure UJ35). The nanoparticle ink is placed in the ultrasonic/ pneumatic atomizer, which creates a dense vapor of the ink with droplet sizes of about 1 5 µm that is transferred to the deposition head with the help of a gas ow running through the atomizer towards the deposition head. The mist stream is then focused by a secondary gas ow to form the micro-jet \cite{14, 15}. The printed material can be sintered in a programmable oven. The UV was to instantaneously cure a UV curable polymer dielectric and create 3D shapes (similar to that shown in figure 1) directly over the substrate. Note that the stand-off distance between the substrate and the nozzle tip along with the jetting from a tilted nozzle allows the printing over a curved surface—a unique capability for the Aerosol Jet direct write processes. The Aerosol Jet micro-additive printing method has been used in the manufacturing process for solar cells \cite{16, 17}, microelectronics \cite{18, 19}, and sensors \cite{20, 22}. The nozzle exit diameter for the polymer posts was 200 m and for the printed silver lines it was 150 m (the minimum line width is about 10 times smaller than the nozzle diameter based upon the sheath gas pressure). The nozzle was tilted approximately 45° from vertical for the sidewall printing. The dielectric printing used a pneumatic atomizer with an air pressure of 3 psi and a sheath gas pressure of 0.13 psi. We also used a virtual impactor that serves to concentrate the aerosol in between the atomizer and print head. The silver nanoparticle ink used ultrasonic atomizer with a gas pressure of 0.25 psi, and a sheath gas pressure of 0.25 psi. The sheath air pressure for the silver printing is higher than that for the polymer printing because of the smaller nozzle diameter (150 m versus 200 m). The standoff distance between the chip and the tip was about 5 mm. Note that the overspray and hence the printing quality can depend upon (a) the standoff distance (lower overspray for lower standoff distance), (b) ratio of sheath gas pressure to the atomizing pressure for the ultrasonic atomizer, and (c) the combination of sheath gas pressure, atomizing pressure and exhaust pressure for the pneumatic atomizer. The optimized parameters such as sheath gas pressure, atomizing pressure and exhaust pressure may vary for different inks based upon their viscosity, particle size and the solvent used. The process parameters used in the current study were optimized for the nanoparticle ink and the 3D structures to be manufactured. Note that the major advantage of the micro-additive manufacturing methods is that it does not require the use of environmentally harmful chemicals used in subtractive (e.g. lithographic or MEMS) techniques. In addition, the proposed method does not create any material waste.

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4. Discussion

Figures 5 and 6 show the fabricated antenna-like structures directly over a substrate using the proposed method. A dielectric cylinder is created by dispensing the UV curable Acrylic Urthane from the deposition head followed by its instantaneous curing using the UV light. This arrangement allowed the fabrication of dielectric substrates with extremely high aspect ratio (up to 1 : 20). A schematic is shown in figure 5(a), while a fabricated hollow dielectric cylinder structure is shown in figure 5(b). The average pillar height is about 1.2 mm, the pillar diameter is about 1 mm, while the wall thickness is about 58.5 ± 2.5 µm. The tilted head of the Aerosol Jet AJ300 system used to deposit the metal lines is shown in figures 5(c) (schematic), and figure 5(d) (structure). The metallic interconnects are approximately 22 µm in width. After printing the structure, the nanoparticle traces were thermally sintered. Note that the dielectric permittivity can be easily modulated by...
mixing it with high permittivity particles prior to deposition. Functionally graded dielectric materials can help control the electrical characteristics of antennas, interconnects, and other RF structures and opens up an additional dimension of control to the electrical designers. Additional antenna elements were also fabricated using the same micro-additive fabrication method. An antenna-like monopole structure with high aspect ratio over a glass substrate (similar to that shown in figure 1) is shown in figure 6. The figure 6(a) shows a schematic of the Aerosol Jet micro-additive manufacturing process to create the monopole structure, while figures 6(b) and (c) show the structures fabricated with 75 m dielectric pillar and a 25 m metal trace (the pad dimension in these perspective images is 400 m). Figure 6(d) shows periodic dielectric pillars directly fabricated over a Si chip. Clearly, the novel manufacturing method can fabricate the 3D antenna-like structures at sub-mm length scale.

The metal nanoparticles printed and sintered on the dielectric were characterized for roughness using atomic force microscopy. The surface roughness is highly important at
high frequencies to determine the losses due to skin effect observed in microelectronics. At high frequency, the current may concentrate along the skin of the conductor leading to resistive losses [23]. The skin depth has to be much greater than the surface undulations for this effect to be negligible. The skin depth, δ, in meters, is given by,

\[ \delta \approx \frac{503}{\sqrt{\rho f \mu_r}} \]

where, \( \mu_r \) is the relative permeability of the medium, \( \rho \) is the resistivity in SI units, and \( f \) is the frequency. The skin depth at 60 GHz is about 1.2 mm for sintered silver nanoparticles. The observed roughness of four traces shown in figure 6(b) are shown in figure 7. Figure 7(a) shows the actual metallic trace surface profile, while figure 7(b) shows the same profiles as in figure 7(a) after the moving average has been subtracted from the profile to get a roughness estimate. Clearly, the roughness range is of the order of \(<300\) nm (i.e., less than \(\pm150\) nm). The skin effect is thus not expected to affect the antenna performance at frequencies of interest in the present study. Note that the trace width was within about 10% of the mean for 5 printed traces, a variation comparable to the traces obtained using lithography. The variability in trace width, height and roughness can potentially affect the device performance and will be investigated as part of a future study.

The sintering bonds the nanoink particles in a coherent or organized way by the mechanism of mass transport in atomic scale [24]. The driving force for sintering of micro/nanoparticles of a system is the chemical potential gradient due to surface curvature. Different mass transport phenomena are active in the material movement in the sintering particles.

Figure 6. (a) Schematic of the Aerosol Jet micro-additive manufacturing process to create the monopole structure, (b), (c) fabricated antenna micro-structures, (d) periodic dielectric pillars directly fabricated over a Si chip.

Figure 7. (a) Surface profile of the metallic trace shown in figure 6(b). (b) The same profiles as in figure 7(a) after the moving average is subtracted from the profile to get the roughness estimate.
Generally, the six dominant mass transport mechanisms involved in sintering process are: (i) evaporation and condensation (EC), (ii) surface diffusion (SD), (iii) grain boundary diffusion (GDB), (iv) volume diffusion from the surface of the particle (VDS), (v) volume diffusion from the interior of the particle (VDV) and (vi) viscous ow (VF). In SD, EC and VDS fills the area between the particles. As a result of sintering, the mass center of the particles approach towards each other creating a continuous film. A schematic of the mechanism and an example of the sintered Ag nanopowders are shown in figure 8 along with sintered nanoparticles obtained by the PIs using an Ag ink used to create the structures in figures 5 and 6.

5. Conclusion

We have successfully demonstrated a novel additive manufacturing method to fabricate 3D metal-dielectric structures at a sub-mm length scale. A UV curable dielectric is instantaneously cured upon dispense from an aerosol jet system to form the required 3D shapes at length scale down to 10 - 100 μm. A metal nanoparticle ink is then dispersed over the complex dielectric shapes, also at a length scale down to 10 μm by an Aerosol Jet followed by thermal sintering techniques. The proposed method, being additive, avoids the use of harmful chemicals in the fabrication process and reduces material wastage. The microstructures demonstrated in the paper have potential applications in 3D passives and mm-wave antennas. Antenna simulations are carried out on some of the fabricated geometries and the results indicate superior gain and directivity for the antenna with the proposed fabrication approach. The fabrication method described in this letter opens up the possibility of environmentally conscious manufacturing of an entirely new class of custom-shaped 3D metal dielectric structures at a length scales down to 10 μm.

Acknowledgment

The work was supported by the WSU startup funds for RP. We thank Mr Urs Burger and Dr Kurt Christenson of Optomec Inc for their help during the experiments.

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