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Aerosol-jet printing and flash sintering of conformal conductors on non-planar surfaces

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AEROSOL-JET PRINTING AND FLASH SINTERING OF CONFORMAL CONDUCTORS ON NON-PLANAR SURFACES

by

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ABSTRACT

The printed electronics have been broadly applied in our daily lives, many new manufacturing methodologies are studied and investigated. The research here presented the full manufacturing process of printed conductors of aerosol printing and flash sintering techniques on substrates such as planar and non-planar surfaces.

The aerosol printing (AJP) was introduced because of its simplicity in experimental setup and flexibility of printing. It produces less ink waste and consumes less manufacturing cost. Furthermore, it has the direct-write ability to print in any customized patterns or shapes on non-planar surfaces. In this study, the Cu NPs was selected as the functioning material ink because of its low cost and great cost performance. Additionally, the flash sintering was performed on non-planar surfaces while the AJP method was applied in printing on non-planar surfaces.

Conductivity ratio (the conductivity measured that is compared to the bulk copper) was calculated and plotted for characterizing the flash sintering applications on non-planar surfaces. Analysis indicated that a back reflector was needed for a uniform conductivity ratio on the surface. Simulations have been also demonstrated with experimental results in the study of applying back reflector. Results showed averaging 13% of conductivity ratio on planar surfaces and the performance on non-planar surface was 12% of that of bulk copper.

The close conductivity performance can sum up this manufacturing technique in printing conformal conductors on either surface is very alike and may potentially be used in many fields and customized manufacturing in the future.

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1. INTRODUCTION

1.1 AEROSOL PRINTING

Many conventional masked-based printing processes are widely used for printed electronics[1-3], such as the screen printing[4-6], flexography[7-9] and gravure printing[10]. However, they are subtractive manufacturing methods which have considerable material waste and high manufacturing cost. On the contrary, mask-less printing or direct-writing techniques, are widely used in the additive manufacturing of printed electronics[11-13]. They offer more flexibility, scalability, rapid and relatively cheaper than the mask-based techniques. In the literatures, AJP techniques can provide precise and non-contact deposition of printing materials by using programmable and motorized positioning stages. Moreover, AJP has the advantages that it can be applied to three-dimensional (3-D) non-planar objects substrates such as spheres, trenches and turning angles.

The AJP process is based on the nebulization of the to-be deposited ink into droplets ranged in 1-5 μm with either pneumatic or ultrasonic nebulizer. The nebulized droplets are formed into a mist and pushed out by the carrier gas. The carrier gas can transport the nebulized ink to the deposition nozzle head. A pneumatic controller is needed in the process because a large amount of gas is needed during nebulization. The nozzle head is dependent to the diameter of the initial splats and the resolution in the printing process. The AJP setup is allowed for continuously depositing and works well with a large variety of viscosities of functional inks (0.5 to 2500cP). The AJP is also considered as the non-contact manufacturing that the distance from the nozzle to the deposition surface can range up to 15mm because the stream of mist is being well focused on the nozzle head.

Combined with the aerosol printer, a motorized stage can be applied into the system for mounting and moving the to-be-deposited object steadily. AJP is a flexible manufacturing method that allows customizing patterns and able to print on non-planar substrates.

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1.2 COPPER NANOPARTICLES

Generally, the metallic inks made with nanoparticles are widely used for highly electrically conductive interconnects[14-16]. Various metallic inks have been developed and documented for their conductive characteristics. Noble metals that have been noticed as good ink-material options because of their high conductivity, facile sintering ability and stability under ambient environment[17]. Kim et al.[18] developed the Ag NP ink for printing that can be sintered at temperature around 200°C under the ambient condition. Ko et al.[19] investigated in the Au nano-ink production and sintering. Although the silver (Ag) and gold (Au) are reported to have high conductivity ratios, these noble metallic inks are considered to be relatively expensive. Alternatively, the copper (Cu) material has attracted attentions in this field recently due to its low cost and electrical conductivity. Unfortunately, Cu is very easily oxidized in the air which would form a stable oxide shell surrounding itself, which leads to the limitation of formation of the electron paths and prevents from fabricating highly conductive Cu films. Nevertheless, Park et al.[20] have developed a low-viscosity conductive ink with dispersed Cu NPs through a polyol process that allows Cu materials to be printed in electronics.

Due to the oxide shell that Cu NPs can not be sintered under the ambient conditions. To solve the Cu sintering issues, various approaches such as laser sintering and plasma treatment have been developed to sinter the Cu directly without the oxide shells. These approaches are highly complicated, only required in small irradiation areas and they are relatively expensive treatments. In the search of various sintering methods, flash sintering is found to be meeting all these requirements. It is found to be reducing the copper oxide (CuO) shell and able to sinter the Cu particles combined with polyvinylpyrrolidone (PVP) in only a few seconds. Therefore, Cu NPs flash sintering is widely studied and compared to other Cu sintering methods in many literatures.

1.3 FLASH SINTERING

According to many literatures, Cu flash sintering is considered as a rapid, simple and relatively large-area sintering process. It is an appropriate solution for mass production of low-cost electronics. Additionally, it is a developed sintering method that does not damage the substrates such as polyimide films. Flash sintering relies on the irradiation of impulse flash light source and release high thermal energy in a very short time. Mostly the bandwidth of the flash lamp is very broad, starting from 240 to 1000 nm. Generally, Cu patterns are printed and placed planarly can be sintered in the exposure during flash sintering. With the strategically placed back reflector, Cu patterns on non-planar surface may also be sintered by this approach. Although no literatures have found on Cu flash sintering on planar surfaces, optimizing the reflectors to redirect the light to the non-planar patterns for uniform light distribution suggests that non-planar flash sintering can be achieved, and it is a potential non-planar sintering process for the printed electronics.

2. SCOPE AND OBJECTIVE

In the study, a new facile manufacturing process of additive manufacturing on non-planar surfaces is reported. An aerosol printer has been used in the non-planar printing using copper (Cu) nano-inks. Cu patterns are printed on both planar and non-planar surfaces. Cu flash sintering processes have been demonstrated and the conductivity ratio on planar was (defined as the ratio of conductivity of the printed conductors to that of bulk copper) reported to be around 13% and 12% on non-planar surfaces. Characterization of flash sintering on non-planar objects is investigated. By optimizing sintering voltages, mounting heights and the angle of the back reflectors, the localized conductivity ratio can be studied. The success of this manufacturing process can eventually be demonstrated the conformal printed conductors on the non-planar surface as its electrical conductivity and the robustness are tested when connected to a power source.

PAPER

I. AEROSOL-JET PRINTING AND FLASH SINTERING OF CONFORMAL CONDUCTORS ON NON-PLANAR SURFACES

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ABSTRACT

In this work, the flash sintering of aerosol-printed copper nanoparticles was performed for additive manufacturing of conformal conductors on non-planar objects. Various patterns on both planar and non-planar surfaces were prepared by aerosol jet printing (AJP) using the copper nanoparticles (Cu NPs) based ink. Pulsed flash light introduced a fast, steady and uniform Cu sintering in the ambient condition which resulted in highly conductive Cu patterns with conductivity averaging ~12% of that of bulk Cu. Effects of different sintering conditions, including flashing voltages, mounting distances and reflector angles on the conductivity of sintered patterns were studied for

optimization. For the non-planar patterns, a back reflector was introduced for the uniformity of flash sintering. The light propagation modeling with back reflector on non-planar surfaces was also performed, which showed consistent results with the experimental section. By accounting these modeling results, the aerosol-printed patterns on non-planar surfaces are demonstrated, and the conductivity results are compared to the light propagation models. At last, some simple demonstrations of conductive Cu patterns on different non-planar objects showed that the method combining AJP and flash sintering could be considered as a facile manufacturing process of conductors on non-planar surfaces.

1. INTRODUCTION

The printed electronics today have received a great amount of attention for its diverse applicable fields, such as the radio frequency identification (RFID) tags, capacitors, thin-film displays, sensors and memory devices.[1-5] Many conventional masked-based printing processes are widely used for printed electronics, such as the screen printing, [6] flexography[7] and gravure printing[8]. However, they are subtractive manufacturing methods which have considerable material waste and high manufacturing cost. On the contrary, mask-less printing techniques, for instance, aerosol-jet printing (AJP) is applicable for the additive manufacturing of printed electronics. [9-11] The AJP techniques can provide precise and non-contact deposition of printing materials by using programmable and motorized positioning stages. Moreover, AJP has the advantages that it can be applied to three-dimensional (3-D) non-planar objects substrates such as spheres, trenches and turning angles.

Generally, the metallic inks made with nanoparticles are widely used for highly electrically conductive interconnects.[12-16] Generally, noble metals that have been good ink-material options because of their high conductivity, facile sintering ability and stability under ambient environment.[17] Kim et al.[18] developed the Ag NP ink for printing that can be sintered at temperature around 200°C under the ambient condition. Ko et al.[19] investigated in the Au nano-ink production and sintering. Although the silver and gold are reported to have high conductivity ratios, these noble metallic inks are costly. Alternatively, the copper material has attracted attentions in this field recently due to its low cost and electrical conductivity. More, Park et al.[20] developed a low-viscosity conductive ink with dispersed Cu NPs through a polyol process.

However, the Cu NPs can not be thermal sintered under the ambient conditions because of the nanoparticles are covered with oxide shell. There are various sintering methods can be applied to Cu, such as reduction of aqueous Cu precursor,[21] polyol processes,[22] metallic nanoparticles suspensions[23] and laser irradiation.[24] These approaches have limitations and it is not ideal for mass production. Nevertheless, flash sintering is a relatively simple sintering process for copper. It has no complex procedures, rapid and it is able to operate under ambient environment. Flash sintering is found on the emission of the intense light from the high voltage lamp to superheat the particles in projected area (mostly in cm^2 scale) and it is a rapid process that can provide high energy density in a very short time.[25-27] Most important of all, non-planar sintering can be easily done with flash sintering by absorbing irradiated light.

In the Cu sintering process, the Cu patterns are generally sintered on a planar surface and there are no literatures in Cu non-planar sintering. It is therefore necessary to develop this non-planar sintering methods because printed patterns can happen to appear on any complex geometries. Moreover, once the printed Cu patterns are transformed into conductors, it can reduce a lot of material waste and it can create more space for utility. To satisfy these issues, we combine the AJP technique and flash sintering to develop a facile manufacturing process on non-planar surfaces.

In this study, the non-planar sintering process is discussed. The setup of the non-planar sintering and the conductivity results of flash sintering are demonstrated. Then, the characterization of the parameters on localized conductivity is investigated. Finally, the tests on more complex structures are done and suggest the insights of the applications on non-planar surfaces.

2. EXPERIMENTAL SECTION

In Figure 2(a), the self-synthesized Cu NPs were applied (average diameter of 70-100 nm) for the preparation of the copper nanoinks. Copper nanoparticles were synthesized by mixing polyvinylpyrrolidone ($\mathrm{PVP}, 55.5$ g) and sodium hypophosphite ($\mathrm{NaH_2PO_2}, 20$ g) into ethylene glycol ($(\mathrm{CH_2OH})_2, 200$ ml) inside a flask, stirring at room temperature under ambient atmosphere. The mixture was heated to 90℃. Then, solution of copper sulfate $\mathrm{CuSO_4}$, 50 ml of 1M) in $(\mathrm{CH_2OH})_2$ at 90 ℃ was rapidly added into the PVP/ $\mathrm{NaH_2PO_2}$ solution stirring vigorously. As reduction occurred, the color of the suspension turned from green to black within 2 minutes, indicating the formation of copper nanoparticles.

The reaction was quenched, and the suspension was rapidly cooled by adding chilled deionized (DI) water. The copper nanoparticles were separated and washed with DI water by centrifugation for 4 times, while using acetone as a non-solvent, to remove excess PVP and side products. The resulting precipitates were dried under vacuum at 50℃ for 6 hours.

Copper nanoparticles (3.375 g) were dispersed in a mixed solvent of N-Methyl-2-pyrrolidone (NMP, 99%; Sigma-Aldrich) (11.25 g) and PVP (MW 40,000; Chemcenter) (0.375 g). To mix the copper nanoinks, the homogenizer (Bio-Gen PRO200) was applied at 10,000 rpm for 40 minutes. Before printing, the ink was sonicated for 15 minutes.

The fabricated copper nano-inks were aerosol printed on Kapton tape (Kapton ® Polyimide Tape, Thickness: 10 μm), employing both pneumatic nebulizer (Collison Nebulizer) and a motorized 5-axis stage (Standa) printing the patterns at average stage speed of 1 mm/s. Aerosol printing was achieved by using pneumatic nebulizer as schematics shown in Figure 1(a1) with carrier gas applied to nebulize the ink and to carry the aerosol mist to the deposition nozzle head in Figure 1(a2). Mass flow controllers were used to set the nebulizer flow rate (0.4 LPM) to obtain stable nebulization.

Regarding using the Kapton tapes, they were made from polyimide (PI) film with silicone adhesive. Kapton tapes were compatible to a wide range of temperature, from -269 to 400 ℃. Kapton tapes were mostly known for its low thermal conductivity. Moreover, with the excellent flexibility and good scalability, Kapton tapes can be easily attached on objects in all geometries and sizes. In our setup, the patterns were printed on the Kapton-taped glass slides and cylindrical rods for printing demonstrations of planar and non-planar surfaces respectively.

After the printed Cu pattern was dried, the full pattern was sintered by Flash Light irradiation in air from 2.1 kV to 3.1 kV. To sinter the printed Cu films, flash white light from xenon lamp (Sinteron 2000-L; Xenon Corp.) was used, as shown in Figure 1(b). The flash white light emitted from the xenon lamp has a wide broadband spectrum of 200-1000 nanometers, providing the output energy of 16.56 $\mathrm{J/cm^2}$ to 34.1 $\mathrm{J/cm^2}$ with voltages varying from 2.1 kV to 3.1 kV and a pulse duration of 2 milliseconds, was used to sinter the copper printed patterns.

In the planar sintering, the printed patterns on glass slides were planarly placed under the xenon lamp. On the other hand, printed patterns on the cylindrical rods were mounted off the ground. Additionally, the back reflector was later introduced in the experiment for the non-planar sintering, as shown in Figure 1(b), used for redirecting the emitted light from the Xenon lamp back to the non-planar rod.

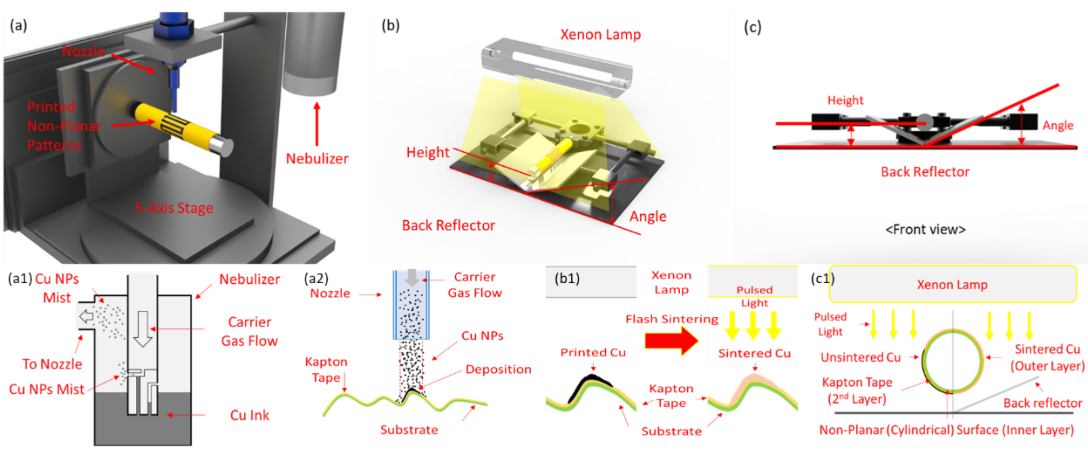

Figure 1. Schematics of non-planar printing and sintering setup with back reflector mirrors: (a) Printed patterns on non-planar surface with aerosol jet printing method. (b) Printed patterns got 3-D sintered under the lamp. (c) The back reflector. (a1) The Cu NPs were nebulized from Cu ink. (a2) The Cu NPs were sprayed from the nozzle. (b1) Sintered Cu after flash sintering. (c1) The application of the back reflector.

To study the light distributions on the rod and the effects of optimizing the reflective angles and mounting heights of the additional back reflector, models of the light propagation and beam density calculations were performed on the COMSOL software.

The electrical resistances of the sintered Cu films were measured by using a digital multimeter (Tektronix DMM4050). The linewidth of the bulk pattern was measured using optical microscope (Hirox KH-8700). The thickness and the microstructure of the copper nanoink film were characterized using a scanning electron microscope (SEM, Hitachi S-4700).

3. RESULTS AND DISCUSSIONS

In Figure 2(a) and Figure 2(c), both planar and non-planar aerosol-jet printed lines were demonstrated. Customizable patterns such as zigzags and spirals can be printed on either surface. The lines were continuous and smooth with only minor splats at the starting point. The linewidth of the printed patterns was ranged from 200 to 300 µm.

After flash sintering, both sintered lines on planar and non-planar surfaces were observed to be continuous and smooth. As shown in Figure 2(b), the planar patterns were successfully sintered as the color turned from black into metallic light pink/orange. The conductivity ratio was (defined as the ratio of conductivity of the printed conductors to that of bulk copper) reported to be around 13%. In Figure 2(d), the printed Cu patterns on the cylindrical rod were also sintered, reaching the conductivity ratio of around 12%.

To understand the transformation of microstructures of the printed Cu patterns, both before- and after-sintered patterns were examined under SEM. Figure 3(a) showed the SEM images of the 70-100 nm sized unsintered nanoparticles indicating the Cu NPs were mostly individually separated. As shown in Figure 3(b), the particle coalescence could be observed, and the grain growth was significant compared to unsintered Cu NPs. The Cu NPs have been necked to each other into conductive paths and eventually made the whole sintered Cu patterns conductive.

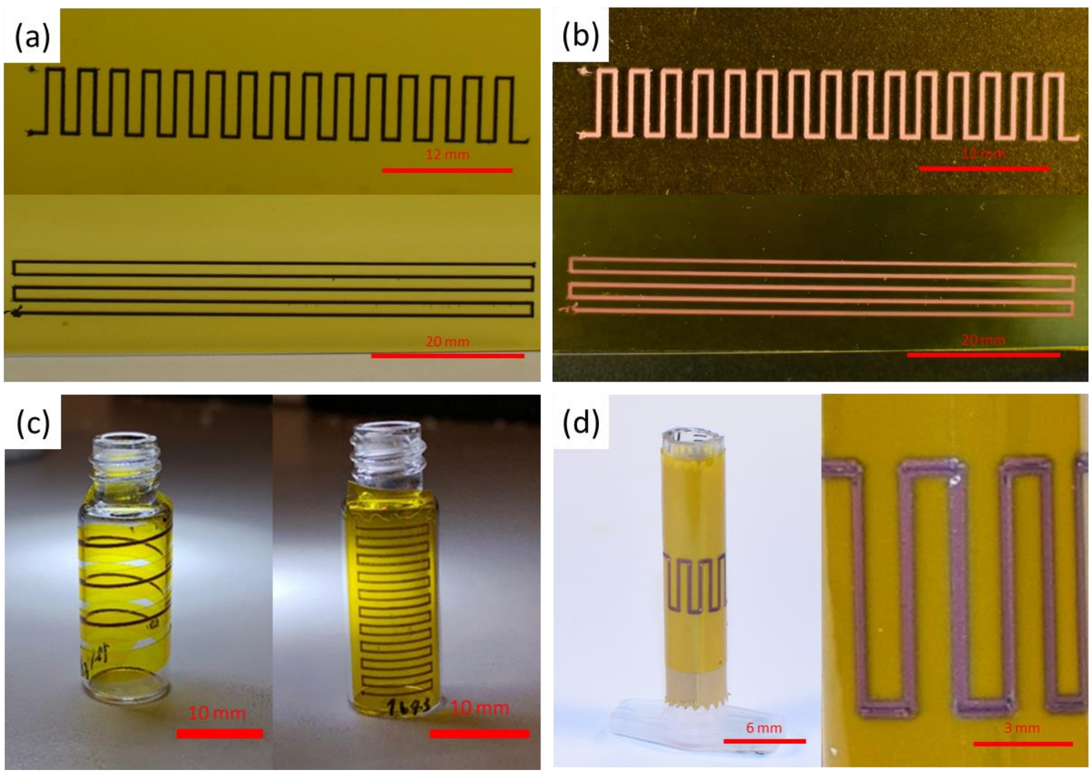

Figure 2. Sintered and unsintered printed patterns: (a) Unsintered planar patterns. (b) Sintered planar patterns. (c) Unsintered non-planar patterns. (d) Sintered non-planar patterns.

In Figure 4(a), the microscopic image showed the top view of the printed line on the non-planar which was found to be continuous and smooth. The SEM image in Figure 4(b) indicated the Cu NPs were sintered well referring to the SEM image in Figure 3(b).

Figure 4(c) showed the interface between the substrate and the printed copper structure were fused together. It could be that the Cu NPs were sintered at a very high temperature during flash sintering and after evaporating the PVP from the Cu ink, the excessive heat from the process slightly fused part of Cu into the Kapton tape.

The best conductivity ratio results we collected from planar and non-planar sintering was averaging 13% and 12% respectively. According to other literatures,[28-30] there are reportedly high conductivity ratio around 10~20% on planar flash sintering.[31-34] Although our results on planar surfaces are slightly lower than the reported references, the results on non-planar were still very compatible to that on planar surfaces, which indicates that the conductivity ratios compared have no big differences in printing and sintering on either surfaces and the results of conductivity can be improved by more elaborative experiments afterwards.

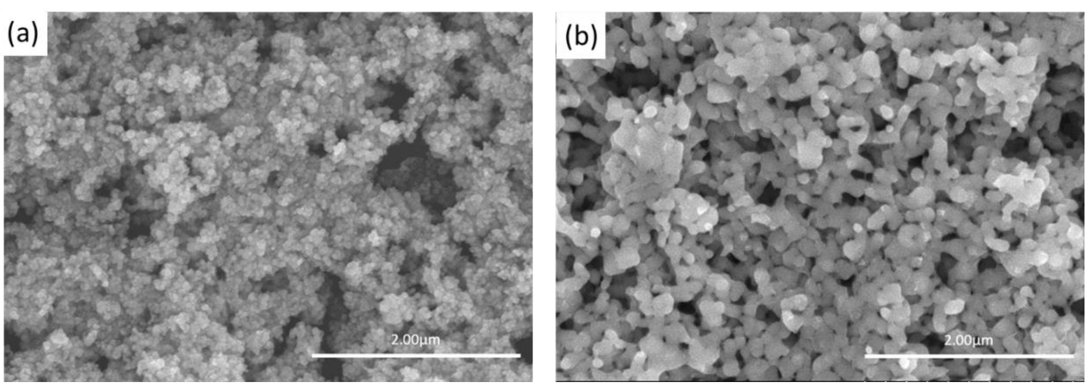

Figure 3. The SEM images of Copper Nanoparticles in different conditions: (a) Before sintering. (b) After sintering.

In the parameter study of sintering conditions, it was found that the non-planar surface sintering was performed differently from the general planar sintering. Figure 5 showed that the sintering voltage, mounting height and the use of back reflector affected the conductivity results. As seen in Figure 5(a) and (b), the optimized conductivity on planar surfaces (with conductivity ratio of ~13%) were found at sintering voltage of 2.1-2.3 kV and mounting at 4.5-mm high. However, the best results out of non-planar surfaces (with conductivity ratio of ~12%) were found at voltage of 2.7-2.9 kV, and height at 10.8-mm. With the back reflector applied, the conductivity of the patterns on non-planar surfaces were significantly enhanced. Figure 5(c) showed that with the angle of the back reflector increased to 25 degree, the conductivity ratio was gradually increased.

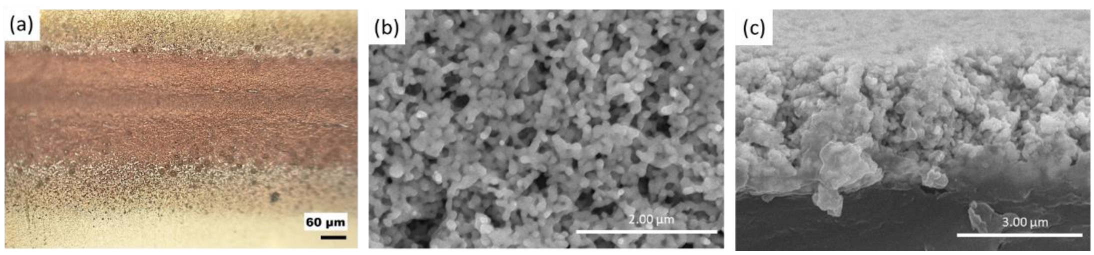

Figure 4. The Microscopic images of non-planar copper layers. (a) Top-view microscopic image. (b) Top-view SEM image. (c) Cross-section SEM images.

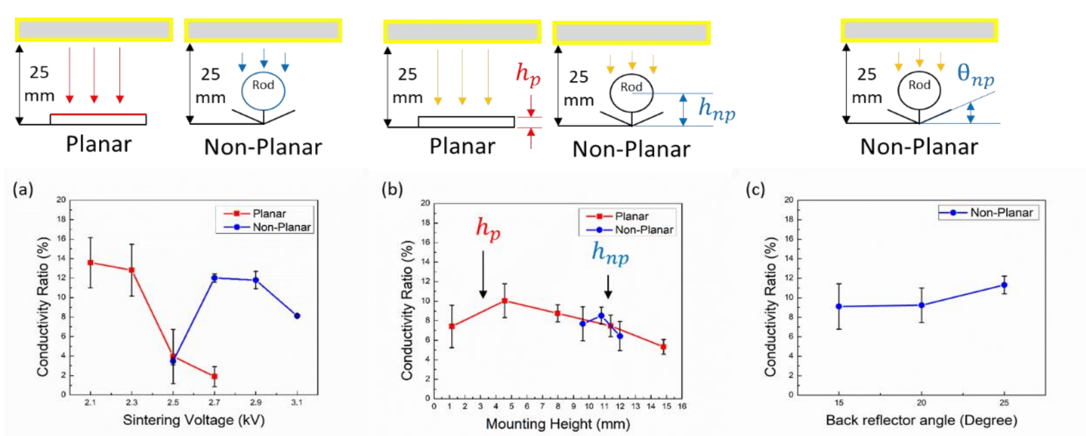

Figure 5. Conductivity results based on: (a) Voltages (V). (b) Heights (h). (c) Back reflector angles (θ).

Further, the sintering effect at different locations on the non-planar rod was studied. Generally, locations on planar patterns absorbed the light at a equal distance and there were no angle difference between the direction of the emitted light and the normal vector of the surface. This resulted in a uniform light distribution on planar sintering. However, in the non-planar sintering, the same sintering condition (mounting a cylindrical rod at 10.8 mm height, leaving around 15 mm away from the lamp without placing any back reflector at the bottom for one single flash) did not give satisfactory results. Figure 6(a) showed that only less than half of the rod was sintered, and the conductivity started to degrade from 0 to ±90 degrees, eventually leaving the backside mostly unsintered. In order to fix the back-sintering problem, double flash sintering was introduced and done by flipping the rod over 180 degrees after one side was sintered. It was assumed to have uniform conductivity ratios. However, after the double flash sintering, only the locations at 0 and 180 degree were able to reach the best results as plotted in the same figure. Clearly, locations on the side parts of the rod (±90 degrees), were not well sintered. It seemed that these locations had troubles absorbing the emitted light because of the direction of the light was not in parallel with the surface normal vector. This induced the problem of the light distribution over the rod surface during the process. To solve this problem, the back reflector was introduced to uniformly sinter the rod.

Initially, a horizontal back reflector was used. However, as shown in Figure 6(b), it did not help enhance the conductivity at any locations because the light was not effectively reflected onto the surface. The tilted angle of the back reflector changed the direction of the reflected light, thus the weak parts such as the sides could absorb more energy in order to be sintered more uniformly. As shown in Figure 6(c), it indicated that the conductivity was increased significantly at ±90-degree position with the additional angled back reflector applied. The conductivity ratio was measured to be averaging 10% on the cylindrical rod, with slight drop of conductivity on the side parts.

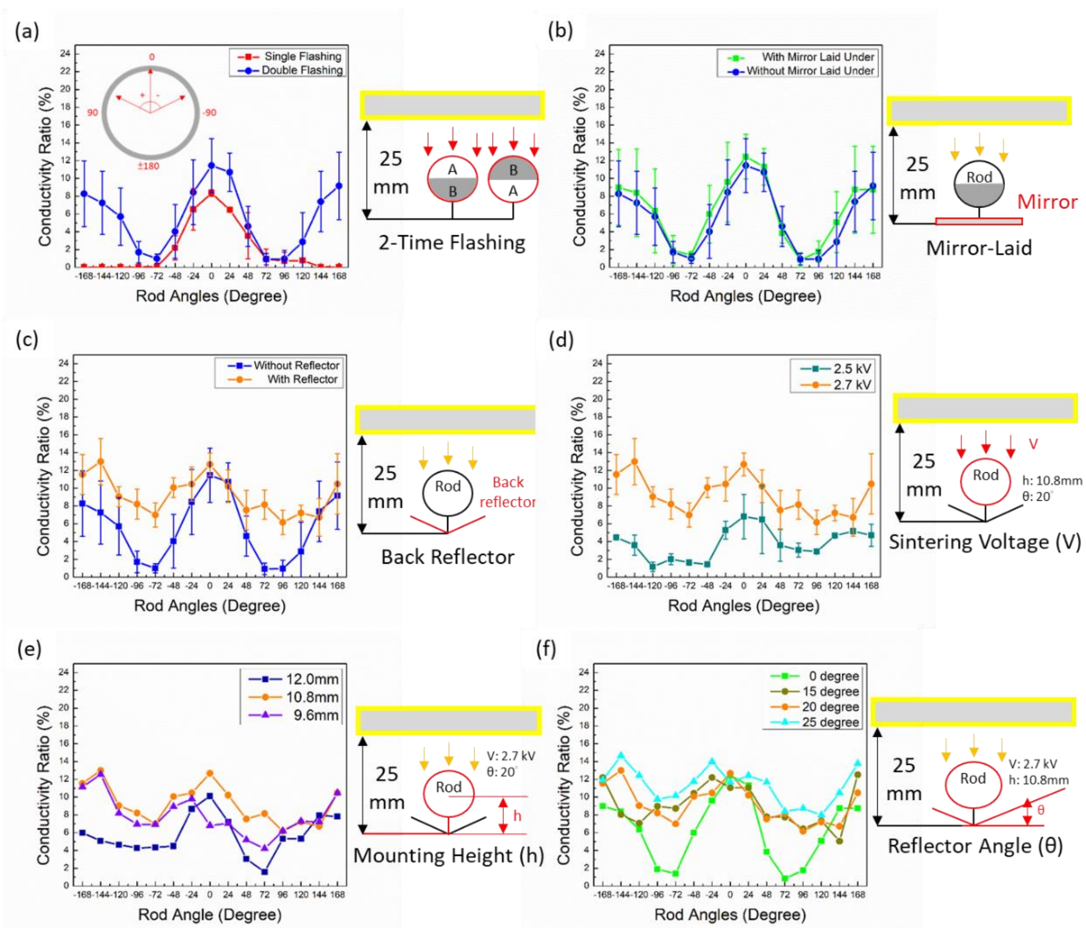

Figure 6. Conductivity results at rod angles based on: (a) Flashing times at 2.7kV. (Second-time is flashing after flipping the rod 180°.) (b) Comparison in horizontal back reflector laid during 2-time sintering. (c) Comparison of the tilted back reflector. (d) Local differences in sintering voltages. (e) Mounting heights. (f) Back reflector angles comparison on non-planar surfaces.

Further, the localized conductivity was also studied. Parameters such as sintering voltages, mounting heights and angles of the back reflector could impact local conductivities. It was found that the conductivity ratio was significantly escalated with sintering voltage increased from 2.5 kV to 2.7 kV at all the locations of the rod. Figure 6(d) showed at 2.5 kV the copper lines were not sintered well enough with the conductivity ratio only reached to around 4%. On the contrary, at 2.7 kV the copper lines were mostly sintered and able to reach the conductivity ratio of 10%. It was considered to be well sintered in contrast to the results of sintered planar results. In Figure 6(e), it showed the results of mounting heights were averaged at around 10% with voltage at 2.7kV and with the back reflector at 20 degrees. Mounting height of 10.8 mm was found to provide better results compared to the greater (12.0 mm) or smaller (9.6 mm) heights. The conductivity of the higher mounting was dropped because the zenith lines on the rod were too close to the lamp which led to partial sintering failure. Also, when distance between the object and the back reflector was too far, the sintering energy might be slightly reduced as the light travelled due to the absorption of energy by the ambient air. In Figure 6(f), various angles applied in the back reflector were compared. It was found that by redirecting the sintering light with the back reflector (angles increasing from 0- to 25-degree), the conductivity was gradually increasing and inclined to be uniform.

In order to find out the light distribution locally on the non-planar surfaces, the light propagation model, as shown in Figure 7, was studied with the experiments. By calculating the light beam density, the results of conductivity ratio were plotted based on the distribution of light. The distribution clearly pointed out the lines around ±90-degree on the rod, the beam density gradually escalated as the angle was adjusted. In the modelling, the density distribution with back reflector at 25 degree appeared to be very uniform and it highly matched with the experiment results.

Finally, the AJP tests were demonstrated on complex structures as shown in Figure 8. We have initially printed Cu patterns on the rod and flash sintered them by non-planar sintering. The performance of the printed patterns was only shown by the measured conductivity ratios. To further test the robustness of this process, we applied a micro LED and attached to the aerosol-printed Cu patterns on the non-planar cylindrical rod. Then we connect the patterns with to wires in order to apply with the power source. Eventually, the LED was lit up and has proven the high conductivity, robustness of the device and the simplicity of this manufacturing process in conformal printed conductors on non-planar surfaces.

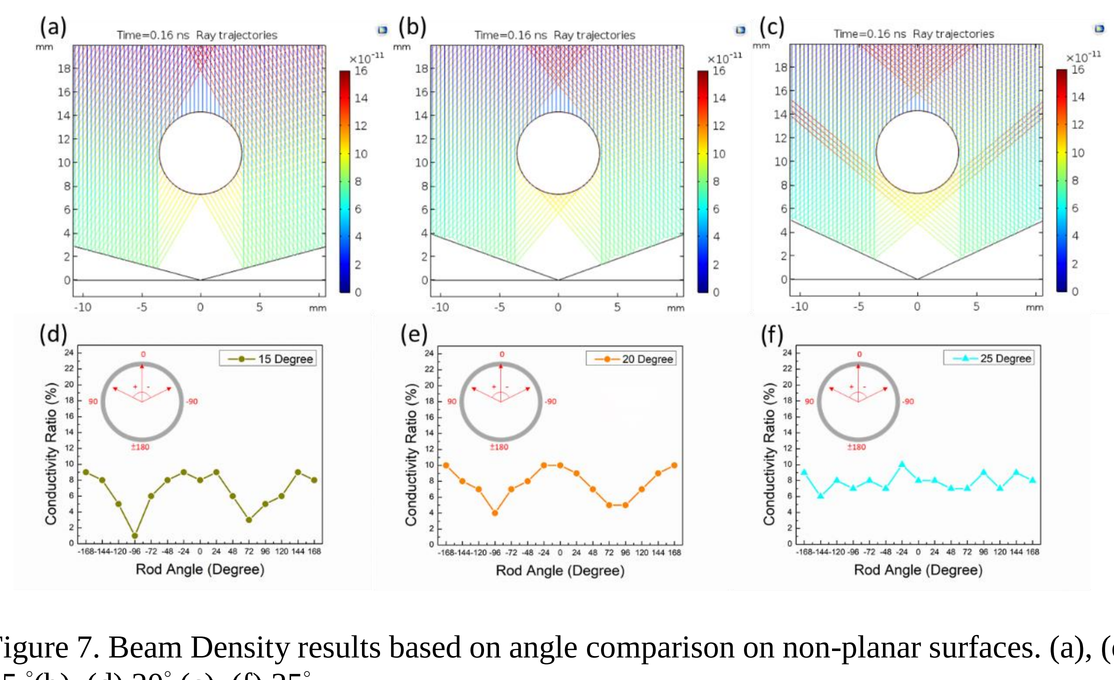

Figure 7. Beam Density results based on angle comparison on non-planar surfaces. (a), (d) 15 $^{\circ}$(b), (d) 20° (c), (f) 25°

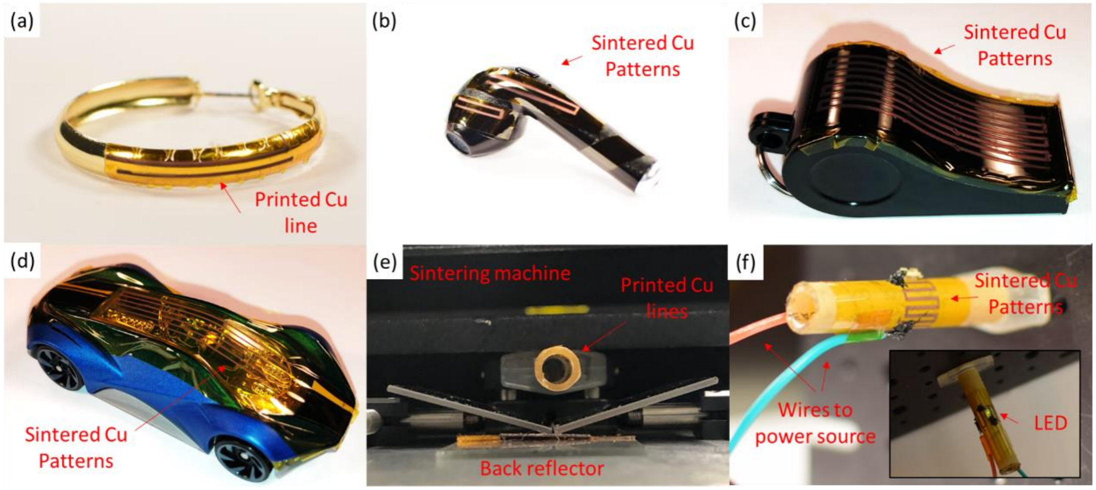

Figure 8. Applications of conductor are demonstrated on non-planar surfaces: (a) Printed lines on a earring. (b) Sintered patterns on a wireless earphone. (c) Sintered patterns on a whistle. (d) Sintered patterns on a toy car. (e) Printed lines on cylindrical rod with back reflector before flash sintering. (f) Cylindrical rod conductors after sintering.

4. CONCLUSION

A customizable, low-cost, facile manufacturing method of printed conductors on non-planar surfaces was developed. The aerosol printer was applicable to both planar and non-planar geometries and the pulsed flash light was able to flash-sinter the printed copper layers into highly conductive patterns on both planar and non-planar surfaces. The characterization of flash sintering of the Cu NPs on non-planar surfaces was investigated and the light propagation models were studied. By optimizing the back-reflector angle to achieve the uniform light distribution, the conductivity ratio of the printed Cu patterns on the curved surface have effectively increased. The average conductivity ratio of non-planar patterns was reported to reach 12% on PI substrate tape which is similar to that of planar patterns (~13%). Conformal printed patterns and conductors were also demonstrated on various non-planar surfaces in this work.

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SECTION

3. CONCLUSION

In conclusion, a new methodology of manufacturing printed conductors on non-planar surfaces is developed. It is a low-cost process, an alternative option for printing electronics in industry. Instead of using the traditional techniques, the aerosol-jet printing (AJP) is an excellent methodology for fabricating the patterns on the complex geometries. The flash sintering is also proven in the experiment that it can operate on non-planar surfaces with the assistance of back reflector, which was used to manipulate the beam density for a more uniform exposure on the surface.

The average electrical conductivity of the copper nanoparticles (Cu NPs) is reported to reach 12% of that of bulk Cu on non-planar surfaces, which showed a similar conductivity ratio compared with that on planar (~13%).

Still, there are many challenges in this manufacturing process. The patterns in the experiment that was printed by AJP can be improved in a better resolution, printed with more creative lines and presented in more sophisticated patterns. More, the flash sintering can be developed into global sintering method fitting any shapes, surfaces and sizes. There are still much to do, and it is only the breakthrough. It is still believed that AJP and flash sintering on non-planar surfaces is a very promising manufacturing technique for future electronics fabrications and sure can open the gate for the research in 3D sintering and in printed electronics.

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