Highly conductive metal interconnects on three-dimensional objects fabricated with omnidirectional ink jet printing technology

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In this work, we demonstrate that highly conductive metal interconnects can be fabricated on the surface of three-dimensional objects using “omnidirectional ink jet” (OIJ) printing technology. OIJ printing technology makes it possible to perform ink jet printing in all directions by combining the motion of a 6-axis vertically articulated robot with precise positioning and a thermal drying process, which allows for the printing of stacked layers. By using OIJ technology, we were the first to successfully fabricate printed interconnect layers having a very low electrical resistance of 12 mΩ over a 10 mm length. Moreover, the results of the high-current test demonstrated that the printed interconnects can withstand high-current-flow of 5 A for 30 min or more.

1. Introduction

Printed electronics has potential for fabricating electronic circuits with low processing costs and minimal burden on the environment, and is expected to be a next-generation electronic device production technology. Most patterning processes are performed on flat surfaces, but are rarely applied to curved surfaces, except with the use of a soft pad.1–4) Because the soft pad process enables patterning on curved surfaces owing to the deformation of the pad, it has been used in attempts to fabricate printed electronic circuits on curved surfaces.2–4) However, it was found that such pad printing possessed some manufacturability issues, such as considerable pattern distortion, poor scalability, and unstable printing conditions.

An alternative solution for fabricating electronic circuits on curved surfaces is to use three-dimensional molded interconnect devices (3D-MID), which is based on plating technology.5–15) 3D-MID makes it possible to add electronic functionality on three-dimensional objects without the use of conventional cable wiring, which effectively contributes to producing more attractive products, especially for automotive electronics applications. 3D-MID may lead to reduced total weight compared with conventional wire harnesses and to minimizing the costs of manually assembling the interconnect wiring.

On the other hand, 3D-MID has a high production cost because an additional mold is required to form the metal wiring. Moreover, the negative impact on the environment made by the waste liquid used in the plating processes is a concern.

Given these limitations, various methods for forming electronic wiring on the surface of three-dimensional objects without the use of plating have been studied, and the use of an aerosol is considered the most promising alternative.16–20) Aerosol jet printing can directly form metal interconnects on three-dimensional objects by jetting atomized metal ink with an airflow. However, it is rather difficult to control the formation of a printed dot because of the airflow, and it is a challenge to expand to multiple nozzles. Moreover, aerosol jet printing cannot yield thick metal interconnects,21) suggesting that aerosol jet printing is not a fully effective or productive patterning solution.

Ink jet printing has advantages over aerosol jet printing in terms of productivity because it can easily be expanded to multiple nozzles because of its simple printing mechanism. For this reason, aerosol jet printing and ink jet printing are often compared, but aerosol jet printing has remained superior for patterning three-dimensional objects.21–25) Here, we introduce “omnidirectional ink jet” (OIJ) printing technology, newly developed by the authors, which makes it possible to print patterns on three-dimensional objects.26–28)

In this work, we have demonstrated that printed interconnects can be fabricated on both sides and across the edge of a three-dimensional object using OIJ printing technology. In addition, we will review the electrical characteristics and high-current stability of printed interconnects for practical use.

2. Experimental methods

2.1 OIJ printing system

The OIJ printing system (Fig. 1) consists of a vertical 6-axis articulated robot DAIHEN FD-H5, and the ink jet print head unit, which uses a single-nozzle piezo ink jet head and the omnidirectional ink supply mechanism.26,27) Multiple teaching points were set by the 6-axis vertical articulated robot in advance, and the printing processes were performed by linear or circular interpolation between teaching points.

2.2 Conductive ink and target surfaces

The conductive ink used in the patterning processes was...
silver nanoparticle paste, NPS-J, provided by Harima Chemicals Group. The target surface was a glass slide, Matsunami Glass S1112 which was configured vertically during the printing process. The dimensions of the glass slide were 76 mm long, 26 mm wide, and 1.0–1.2 mm thick.

2.3 Fabrication process

The fabrication process included both printing and thermal drying processes. The printing process was carried out by combining the motion of the robot arm with the emission of the ink, whereby the ink jet print head was moved along the surfaces of the glass slide by the robot motion, and the ink was emitted during the motion. Figure 2(a) shows the details of this operation. The print head was set at the initial position (i) and then moved upwards with linear interpolation to position (ii) at a constant speed of 100 mm/min (segment S-1). In segment S-2, the print head was rotated by 90° with circular interpolation at a constant speed of 800 mm/min. In segment S-3, the print head was rotated continuously by 90° at the same speed as in segment S-2 to position (iv). By combining segments S-2 and S-3, the print head was rotated around the edge of the glass slide. Finally, the print head moved downwards with linear interpolation to position (v) at a constant speed of 100 mm/min. The lengths of segments S-1 and S-4 were about 20 mm, and the emission frequency was 60 Hz during the patterning of each segment.

A thermal drying process was performed after each printing step, at 300 °C for 3 min on a hot plate. The printed interconnects were made up of stacked layers by repeating the printing and drying processes to form $N$ stacked layers, where $N = 10, 30, \text{ and } 50$. Three samples were generated for each number of layers, $N$, and all measurement values were calculated using the sample averages.

2.4 Electrical measurements

Electrical measurements were carried out by a four-terminal method with a precision multimeter, Tektronix DMM4050 [Fig. 2(b)]. The distance between voltmeter probes was 10 mm. High-current testing was also performed by the same four-terminal method, except that the current source was replaced with a regulated DC power supply, Kenwood PW18-1T. In the high-current tests, the current level was set to a high value of 5 A to simulate practical usage, which meant that only interconnects with $N = 50$ stacked layers and low electrical resistance could be used.

3. Results and discussion

3.1 Morphological observations

Figure 3 shows the results of the morphological observation using a scanning electron microscope (SEM; Hitachi High-Technologies SU8000). Figures 3(a)–3(c) show images taken over a wide area at the edge of the printed interconnects with $N = 10, 30, 50$, respectively. Figures 3(d)–3(f) show enlarged images of the area surrounded by the rectangles in Figs. 3(a)–3(c), respectively. In the case of $N = 10$, the printed interconnect was not thick, and edge coverage was
As $N$ increased, both the thickness and the coverage increased. Note that these printed interconnects are wider at the edge of the glass slide (the upper portion in the SEM image) than on the surface of the glass slide (the side portion in the SEM image) owing to a difference in surface wettability. This phenomenon should be minimized by applying a surface treatment to the edge of the glass slide.

### 3.2 Interconnect profiles

The cross-sectional profiles for printed interconnects were measured with a laser microscope (Olympus OLS4000). The widths of the printed interconnects were about 1.3 mm at $N = 10$, about 1.1 mm at $N = 30$, and about 1.4 mm at $N = 50$. The thicknesses of the printed interconnects were about 10 µm at $N = 10$, about 32 µm at $N = 30$, about 68 µm at $N = 50$ [Fig. 4(a)]. The cross-sectional areas were about 6600 µm$^2$ at $N = 10$, about 13000 µm$^2$ at $N = 30$, and about 38000 µm$^2$ at $N = 50$ [Fig. 4(b)].

The cross-sectional area is proportional to the ratio of the solids contained in the ink and the total number of ink droplets that reached the sample surface. Since the ratio of solids contained in the ink is constant and the total number of ink droplets is proportional to $N$, and the cross-sectional area is ideally proportional. However, as in the case of $N = 30$ in Fig. 4(b), $N$ and the cross-sectional area are not always proportional. This is due to the anisotropic wetting of the ink on the sample surface. Additionally, the misalignment of the printing position also promotes deviation from the proportional relationship. The wetting anisotropy of the sample surface may be reduced by surface treatment, and the misalignment of the printing position should be solved by improving the positional accuracy of the experimental apparatus.

### 3.3 Electrical characteristics

Figure 5(a) shows the results of electrical resistance measurements. The horizontal axis is the number of stacked printed layers ($N$), and the vertical axis is the electrical resistance. The electrical resistances were $45 \pm 7$ mΩ at $N = 10$, $20 \pm 2$ mΩ at $N = 30$, and $12 \pm 2$ mΩ at $N = 50$, with volume resistivities of 3.0, 2.5, and 4.4 µΩ cm, respectively [Fig. 5(b)]. Despite the fact that the printed interconnects were on both sides across the edge of a glass object, they had an extremely low electrical resistance, which indicates that there is a good possibility that OIJ printing technology can be employed in fabricating high-current interconnects.

Figure 6 shows the results of the high-current test. The horizontal axis is the duration for which the high-current-flow was applied to the printed interconnect, and the vertical axis is the electrical resistance. The current was set at 5 A in this test. Upon first applying current flow, the resistance increased immediately for 2 to 3 min, implying that heat was generated by the electrical current. After another 2 to 3 min, a stable resistance was reached and maintained for more than 30 min, demonstrating that the printed interconnect reached thermal equilibrium, and heat generation and dissipation were in balance. In this test, no deterioration of or disconnections in the printed interconnects were observed. Therefore, it was demonstrated that the printed interconnects can withstand high-current-flow of 5 A for 30 min or more.
Note that we were successful in fabricating metallic interconnects with low electrical resistance as a result of a thermal drying process that was applied after each printing step; this may have helped to sinter the silver metal. However, if the printing is to be performed on a material having a low thermostability, such as resin, it could be more difficult to sinter the silver metal because the thermal drying temperature may be limited by the lower glass-transition temperature of the material. If the target object consists of a material with low thermostability, an innovative sintering technique would likely be required. Accordingly, it is necessary for us to further assess these fabrication results for three-dimensional objects of various materials.

4. Conclusions
We have demonstrated that printed interconnects can be fabricated on both sides and across the steep edge of a three-dimensional object such as a glass plate, by a newly developed patterning technology called, “omnidirectional ink jet” (OIJ) printing. The printed interconnects fabricated in this study exhibited an extremely low electrical resistance and a high durability against high-current-flow. These results represent an important milestone towards the practical realization of printed electronics for 3D objects by ink jet printing.

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