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# Newly Developed Patterning Technologies for Three-Dimensional (3D) Printed Electronics

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## Abstract

*We report on two newly developed patterning methods for three-dimensional (3D) printed electronics applications, which are known as soft blanket gravure (SBG) and omnidirectional inkjet (OIJ) printing technologies. These technologies make it possible to print various inks directly onto non-flat or 3D object surfaces, and have a capability that could enable new electronic applications and markets.*

## 1. Introduction

Electronic device manufacturing using printing methods has been attracting significant attention in research and development due to several advantages, including as low cost, environmentally friendliness, and the potential for flexibility and scalability to large areas. Unlike conventional thin film electronic device production that relies on the ability of photolithography to produce ultra-fine patterns, printed electronics promises to complement or replace this approach due to lower capital investment in printing equipment, lower running costs and higher throughput. Printing methods are generally low-temperature processes that allow for electronic devices to be fabricated on a thin plastic film substrates, which enables low cost flexible electronics. The resulting electronic device applications are expected to create next-generation business opportunities and markets. However, the advantage of printed electronics should be its potential to produce devices that could not have been produced with the photolithography [1-3].

We recently succeeded in patterning silver nanoparticle inks onto curved or three-dimensional (3D) objects and surfaces by using two newly developed printing technologies, which we call soft blanket gravure (SBG) printing and omnidirectional inkjet (OIJ) printing technologies [4,5]. We believe that these new technologies can used in a wide range of industries, not only for thin film electronics manufacturing, but also in conventional printing applications. These new technologies make it possible to fabricate antennas, sensors and circuits on 3D objects or surfaces, towards creating a new field called 3D-printed electronics (3D-PE). For use in 3D-PE applications, we have also developed a silver (Ag) nanoparticle ink that was carefully optimised for these printing technologies.

In this paper, we report on both of these unique printing technologies for potential use in 3D printed electronic applications, and demonstrate patterned silver (Ag) layers that are fabricated on curved or 3D surfaces.

## 2. Soft Blanket Gravure Printing

### 2.1. Fundamentals of Soft Blanket Printing

Soft-Blanket Gravure (SBG) printing was developed for patterning on curved surfaces by employing conventional gravure offset printing. The blanket is extremely soft and thick, which allows it to deform and fit the curvature of the target surface. Figure 1 shows an illustration of the SBG printing processes. The grooves of a printing plate or "cliché" are first filled with ink then the soft blanket is rolled over the plate to transfer the ink in the grooves to the surface of the soft blanket (receiving process). The soft blanket is then pressed onto the substrate and rotated to transfer the ink to its curved surface (transfer process). In order to allow the blanket to deform into a curved surface the blanket was made of very soft, thick materials, which is primarily polydimethylsiloxane (PDMS) with a thickness of more than 10 mm thickness with a rubber hardness of less than 5 (JIS A). Figure 2 shows a cylindrically-shaped soft blanket (W:1000mm, D:510mm). The maximum printing area as defined by the printer stage was 120 x 150 mm.

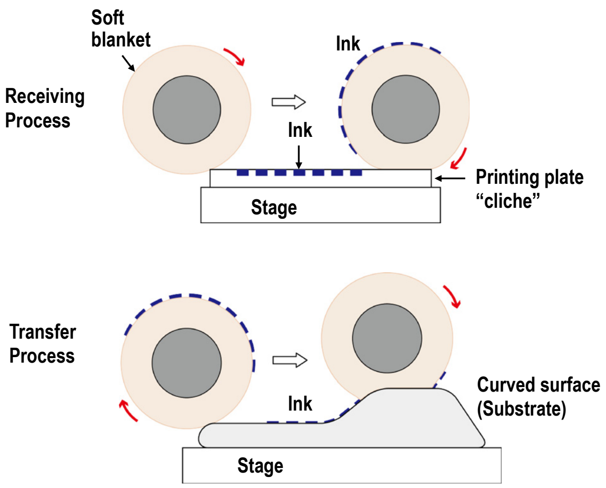



***Figure 1**. Illustration of the SBG printing processes*

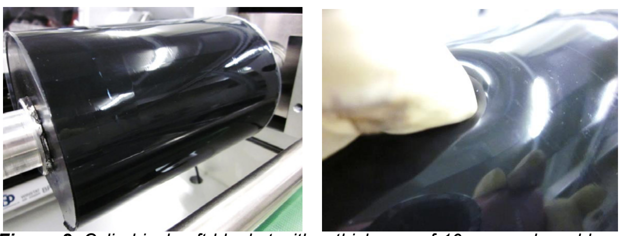


***Figure 2.** Cylindrical soft blanket with a thickness of 10 mm and a rubber hardness of 1 (JIS A).*

During the printing operation, the process of receiving the ink and transferring it to the surface of the target substrate or object surface is extremely important. Therefore, we varied the receiving process (ink to printing plate) pressure and the receiving speed to optimize the printing conditions. Because this system could not be controlled by pressure itself, the receiving pressure was controlled by the depth (pitch of 0.01mm) at which the blanket is pressed against the printing plate (Figure 3). Before the receiving operation, the surface of the blanket is positioned with the surface of the printing plate and the substrate surface is brought into contact, which called the "kiss-touch" position. The receiving speed was adjusted to between 0.01 and 100 mm/sec. The printing pressure in the transfer process was also dictated by the blanket position against the substrate from the kiss-touch position.

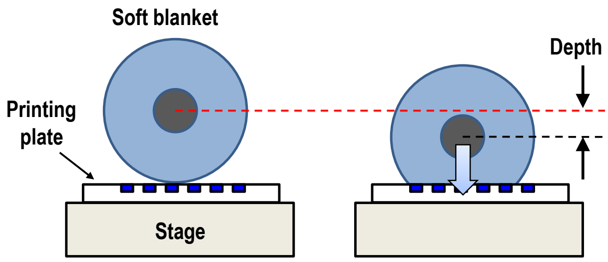



*Figure 3. Control of receiving pressure against the printing plate by varying the depth from an initial position of soft blanket.*

## 2.2. High Viscosity Silver Nanoparticle Ink

We recently developed inks with low viscosities of about 10 mPa·s for inkjet printing using nanometer-sized silver particles (silver nanoparticles), which were synthesized through a silver complex. Unlike ink jet printing, gravure offset printing uses high-viscosity inks. Ink viscosity can generally be increased by blending a resin material additive into lower viscosity inks. However, we observed aggregation of the silver nanoparticles during the blending process. In order to solve this problem, we added the resin material at the beginning of the synthesis process, allowing to formulate high viscosity nanoparticle inks. Figure 4 shows the a typical high-viscosity silver nanoparticle ink, which contains silver particles with diameters of about 15 nm and has a concentration of approximately 80% by weight, and a viscosity of 1 Pa·s. We found that the viscosity is maintained over a broad shear speed region of 50–1000/sec, which is suitable for the gravure offset printing process.

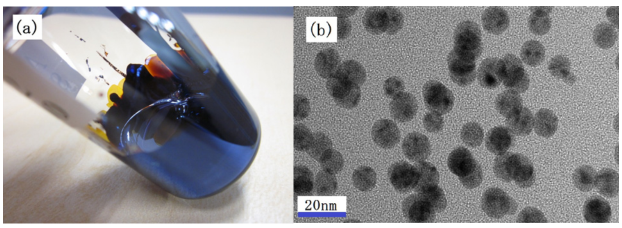



*Figure 4. High viscosity silver nanoparticle ink for gravure offset printing.*

Initially, we patterned the newly formulated silver nanoparticle ink onto a flat glass substrate using the SBG printing method, and obtained the silver lines ranging in width from 10 to 100 µm under same printing conditions, which is quite useful for printing complex patterns. The printed silver lines after thermal sintering at 200 °C exhibited a smooth cross-section with a thickness of 2 µm.

## 2.3. Printing Fine Silver Interconnect Layers on Curved Surfaces

We attempted to print the silver nanoparticle ink onto various curved surfaces by using the SBG printing method. Figure 5 shows the printed silver interconnects and pads. The finest line width was about 20 µm as shown in the figure. These results confirm that the newly developed SGB printing technology makes it possible to pattern inks regardless of changes in substrate curvature. We succeeded in printing the silver ink on these curved surfaces as if they were planar or flat surfaces.

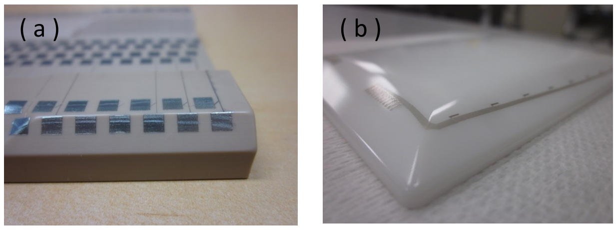
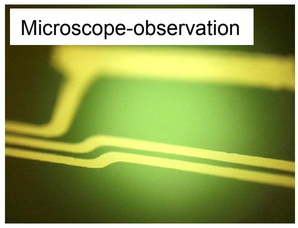



*Figure 5. (a) (b): Printed silver patterns on curve surfaces, and a microscopic view of the patterns (b).*




## 3. Omnidirectional Inkjet Printing

### 3.1. Multifunctional Inkjet Unit

Among the available printing methods, inkjet printing is the considered ideal because it is a digital on-demand process with and almost 100 % material utilization and no need for a printing plate. However, conventional inkjet printers can only jet inks in a downward direction, and not in lateral or upward directions. The omnidirectional inkjet (OIJ) printing technology is able to jet inks in multiple directions. By combining OIJ technology with a vertically articulated robot, inks could be printed on 3D object surfaces. Figure 6 shows the OIJ printer configuration, consisting of an inkjet nozzle, ink supply unit, and camera. The position of the inkjet nozzle unit can be adjusted by a precision XYZ stage.

Because the inkjet head can move in all directions, it is important to continuously supply the ink in a stable manner regardless of the direction or height of the nozzle. We developed a new ink supply mechanism that uses a sealed ink tank filled with ink and an applied external pressure appropriate for ejecting the ink. The ink droplet jetting speed was increased to maintain the printing precision by employing an industrial inkjet head. An observation system for ink droplets was also mounted to the inkjet unit by employing a camera and strobe LED. The ejected ink droplets are shown in the same figure.

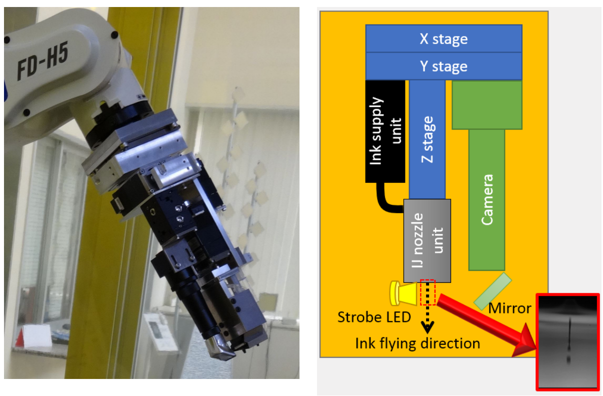



*Figure 6. OIJ printer and inkjet printing head showing the nozzle unit, supply unit and camera on XYZ stages.*

### 3.2. Interactive Control System

The OIJ printing machine consists of a six-axes robot, precision linear motion XYZ stages, the inkjet printer head with the ink supply unit and a camera system. Each of the units coordinate with each other to print ink at precisely the right positions on the substrate. We developed an interactive control system to operate these with a personal computer equipped with various I/O boards as shown in Figure 7. By associating the precision linear stage motion with the inkjet head motion, ink could be printed on the substrate at specific coordinates at a programmed movement speed and drop pitch. The inkjet printer and ink supply system were associated by counting the number of droplets ejected from the inkjet head and operating the ink supply actuator in response to this value. Moreover, the motion of the robot arm and precision linear motion stages (XYZ) were controlled so that once the printing action was completed, the robot automatically moved to the next programmed point. In this way, we developed an interactive control system for accurately printing inks over the entire area of 3D object or surface.

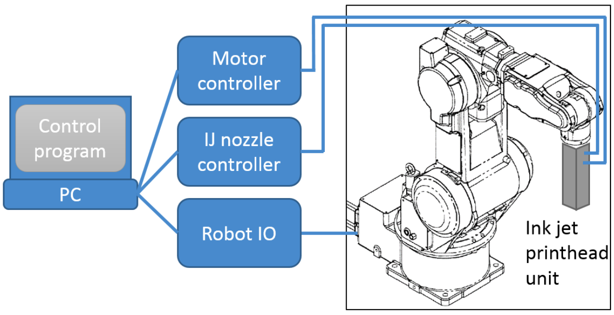



***Figure 7**. Interactive control system consisting of a motor controller, IJ nozzle controller and robot I/O boards.*

## 3.3. Printing Silver Inks onto 3D Surfaces

For this experiment, we diluted the silver nanoparticle ink formulated for SBG printing to match the viscosity required for inkjet printing, such that the optimized viscosity was about 10 mPa·s. Using this new technology, we attempted to print the low-viscosity silver nanoparticle ink onto the curved surface of a wine glass. Figure 8 shows a printed silver antenna and a printed conductive metal line. The finest line that we could pattern was about 100 µm in width and about 100 nm in thickness. The silver ink could be also printed over high steps in the target surface. As a result, we succeeded in the printing the silver nanoparticle inks on 3D objects with curved surfaces.

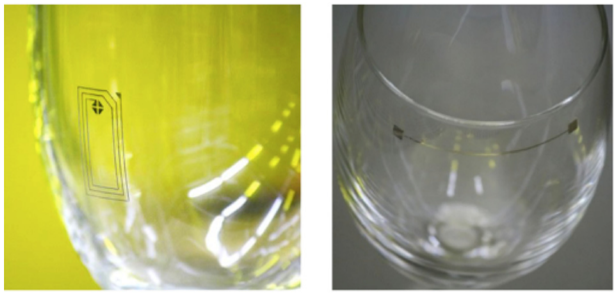


***Figure 8.** A printed silver antenna and conductive metal line patterned on wine glasses.*

## Summary


To expand printing technology to a wider variety of applications, we developed two new patterning methods based on gravure offset printing and inkjet printing, and successfully demonstrated the direct patterning of silver nanoparticle inks onto the surface of curved or three-dimensional (3D) objects. These newly developed technologies can potentially be used to manufacture various thin film devices, such as sensors, integrated circuits and displays in 3D printed electronics applications, potentially creating new markets and business opportunities.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