Newly developed soft blanket reverse-offset (SBR) printing technology for forming widely patterned layers on curved surfaces

Konami Izumi1, Hikari Saito2, Yasunori Yoshida1, Shizuo Tokito2, and Hirobumi Ushijima1

1Human Augmentation Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Kashiwanoha, Kashiwa, Chiba 277-0882, Japan
2Research Center for Organic Electronics (ROEL), Yamagata University, Yonezawa, Yamagata 992-8510, Japan

Received September 2, 2019; revised January 27, 2020; accepted February 4, 2020; published online February 21, 2020

We have been employing novel printing technologies in three-dimensional printed electronics applications, to form electronic devices on curved or three-dimensional object surfaces. In this paper, we report on a newly developed printing technology named “soft blanket reverse-offset” (SBR) printing, which was developed to create wide and flat patterned layers with uniform thicknesses on curved surfaces. SBR printing is an extension of conventional reverse-offset printing and uses an extremely thick and soft blanket (referred to as a “soft blanket”) as an offset roller. We also created a new thick stencil printing plate and a two-layered soft blanket construction that avoids the formation of contact-defects. In addition, we have also succeeded in printing wide and flat patterned layers onto curved surfaces using commercially available silver nanoparticle inks. The printed layers are also characterized by uniform thicknesses and low resistivities, equivalent to those of layers printed on planar substrates.

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1. Introduction

Printed electronics (PE) or electronic devices that are fabricated using printing methods have attracted considerable attention in recent years. Many studies have been dedicated to fabricating electronic devices or components, such as antennas for RFID technologies,1–3) metal mesh,4) or silver nanowire5) as a transparent conductive material to replace indium-tin-oxide,25) or circuit systems for wearable sensors.6) Various printing technologies have also been developed for PE technology namely screen printing,7,8) inkjet printing,9,10) and gravure offset printing.11) However, similar to photolithography, which is the conventional electronic patterning technology, these printing technologies can only be used to print on planar surfaces even in the case of paper or flexible plastic substrates. Thus, the performance of PE devices has been compared with that of devices fabricated by using photolithography. These shortcomings prompted us to develop the concept of “three-dimensional printed electronics” (3D-PE), which consists of an electronic device fabrication technology for printing layers on the surfaces of curved or three-dimensional objects. We have researched various printing technologies for 3D-PE because we expect 3D-PE to become a new manufacturing technology to create future electronics devices, such as smart mobile devices12) or floating transparent displays,13) which could only be fabricated by using printing technologies.

Several printing technologies capable of printing patterns onto curved surfaces already exist, for example pad printing,14,15) screen pad printing,16) which is the combination of pad printing with screen printing, screen offset printing,17) which combines offset printing with screen printing, and gravure offset printing.18) However, considering the process of conventional or PE components or devices, we believe that at least two types of printing techniques are needed, the first type to form the fine patterns for fabricating interconnects, and the second type to form the wide patterns with uniform thicknesses for fabricating dielectric layers or interlayers. Both of these types of patterns should also preferably have flat surfaces, because they are stacked to fabricate electronic circuits. Specifically, 3D-PE manufacturing technology can be used to produce electronic circuits on any existing object surface. These directions motivated us to propose and develop new printing technologies for 3D-PE applications with the aim of realizing new fabrication technologies. One of these printing technologies is named “Omnidirectional Inkjet” printing, in which the inkjet printing system is attached at the tip of a robotic arm,19) and another is named “soft blanket gravure-offset” (SBG) printing, which is based on conventional gravure offset printing and combined with a very soft and thick blanket (known as a “soft blanket”) instead of the conventional offset roller.20–22) These printing technologies can form finely patterned lines such as conductive wiring or interconnects in electronic applications.

We also require new printing technology that can be used to create wide and flat patterns with uniform thicknesses for use as dielectric layers or interlayers to manufacture electronic components such as thin film transistors or capacitors. Previous studies in PE often employed chemical vapor deposition to form Parylene layers,23,24) oxygen plasma for growing aluminum oxide layers,25) or coating methods such as spin coating,26) blade coating, or slit coating to fabricate dielectric layers with smooth surfaces and uniform thicknesses. This is because a suitable printing technology did not yet exist, despite the existence of various established printing technologies that were able to form finely patterned lines such as inkjet printing,27) gravure offset printing,28) and reverse offset printing.29) Inkjet printing was also used to form dielectric layers, but the layer uniformity proved to be problematic30) because the coffee-ring phenomenon occurs easily with low viscosity inks. Moreover, the conventional coating method or inkjet printing cannot be used to form wide patterns of uniform thickness on the surfaces of curved or three-dimensional objects.
Therefore, we focused on conventional reverse-offset printing. The advantage of this technique is that, even though it has been used to form fine patterns, it is capable of printing flat layers of uniform thickness such as overlays because low viscosity inks are coated directly to the blanket surface. This research led to us to develop a new technology, “soft blanket reverse-offset” (SBR) printing, to form wide patterns consisting of uniformly thin, flat, and smooth layers on curved surfaces. This technology is based on conventional reverse-offset printing with a soft blanket which is used in SBR printing technology as an offset roller.

In this research work, we evaluated the SBR printing technology by forming wide silver patterns using commercially available silver nanoparticle ink. We used a two-layered structure soft blanket and thick stencil printing plate. The two-layered structure of soft blanket was used to form printed layers with flat surface, and the stencil plate was used to avoid the contact-defects. As a result, we successfully printed patterns on both planar and non-planar surfaces. These experiments enabled us to confirm that SBR printing is suitable for fabricating wide and flat patterned layers of uniform thickness. In addition, we clarified that these patterned layers formed on curved surfaces by using SBR printing have almost the same characteristics as those obtained on flat surfaces. In this research work in which we used ink consisting of silver nanoparticles, the patterned layers on curved surfaces have almost the same uniform thickness and low resistivity as those on planar surfaces.

2. Experimental methods

2.1. SBR printer configuration and printing conditions

The SBR printing process [shown in Figs. 1(a)–1(c)] resembles conventional reverse offset printing whereby the following three-step process is involved: (a) the coating process: a coating of ink is applied to the surface of the soft blanket via the slit coater [Fig. 1(a)], (b) the removal (patterning) process: unnecessary sections of the ink coating are transferred from the soft blanket to the surface of the stencil printing plate [Fig. 1(b)], and (c) the transfer (printing) process: the remaining ink pattern is transferred from the soft blanket onto the target substrate [Fig. 1(c)]. During the transfer process, the shape of the soft blanket changes with the surface of the target substrate, thereby allowing SBR printing to form patterns on curved surfaces.

The SBR printer [shown in Fig. 1(e)], which was designed and constructed for our previous SBR printing studies as a prototype system with a plate-to-plate configuration, was remodeled to add a coating base to which the slit coater could be fixed. The printer consists of a soft blanket roller that moves back and forth while rotating on two stages with fixed position and adjustable height.

Printing parameters that affect the printability are the speed, pressure, and waiting time. The printing parameters (listed in Table I) include the coating speed \(v_0\), removal speed \(v_1\), transfer speed \(v_2\), removal compression depth \(h_1\), transfer compression depth \(h_2\), waiting time before removal process \(w_1\), and waiting time before transfer process \(w_2\). The coating speed \(v_0\) refers to the blanket rotation speed, and the removal and transfer speeds \((v_1, v_2)\) indicate the relative speed of the soft blanket core against the printing plate (or target substrate). In the SBR printing process, the printing pressure is determined by the compression depth, as shown in Fig. 1(d). Therefore, we indicated the compression depth in millimeters as a printing pressure. In addition, to avoid the distortion of printed patterns resulting from the deformation differences of the soft blanket during the removal and transfer process, the transfer compression depth \(h_2\) and the transfer speed \(v_2\) were adjusted to have the same values as the removal compression depth \(h_1\) and the removal speed \(v_1\), respectively.

2.2. Characteristics of the soft blanket and other components of the SBR printer

Table II provides the properties of the conventional and soft blankets we created and used in this study as a comparison. The conventional blanket consists of a poly(dimethylsiloxane) (PDMS) sheet wrapped around a metal cylinder. In contrast, in our work, the soft blanket was fabricated from soft PDMS, which was molded into a cylindrical shape. These two blankets differ in terms of their hardness and thickness. The conventional blanket has a hardness of 45 degrees (shore A) and a thickness of approximately 0.5 mm, whereas the soft blanket has a hardness of less than 1 degree (shore A) and a thickness of 20 mm. The soft blanket roller attached to the SBR printer has a diameter of 100 mm and is 150 mm long.

In SBR printing, the flatness of the blanket surface is essential because the flatness of the printed patterns reflect the flatness of the blanket surface. Further, conventional sheet blankets have a flatter surface than soft blankets. In addition, our previous research showed that the conventional blanket was unable to change its surface into the grooves of a gravure printing plate under printing pressure. This indicated that the conventional blanket could be applied to avoid contact-defects. Therefore, the soft blanket for SBR printing comprised a two-layered structure consisting of a thick and soft layer underneath a thin and hard layer (shown in Tables II). In particular, a conventional commercially available blanket (STD#700, Fujikura Composites Inc.) was used as the outer layer (i.e. on top), and a commercially available soft blanket (SBG-CB, Katsura Roller Mfg. Co., Ltd.) was used underneath the outer layer as the soft inner layer. The outer layer is easily removable, because they can be pasted together without adhesive. Moreover, the outer layer does not peel from the underlying soft layer during the printing process because the surface of the soft blanket is tacky. The use of the two-layered structure enables the flatness of the soft blanket surface to be improved, the formation of contact-defects to be avoided during the removal process, and various patterns to be printed on curved surfaces.

The stencil plate [shown in Fig. 1(f)], which we used in this study, contains oriﬁces with a depth of 1 mm (=plate thickness) and maximum width of 30 mm. More specifically, the stencil plate contains rectangular, circular, and diamond-shaped oriﬁces which have widths of 3.0, 2.5, 2.0, 1.5, and 1.0 mm. We specially fabricated the stencil plate with a thickness of 1.0 mm, which is larger than the removal compression depth, to prevent contact-defects. This adjustment was necessary because the use of the conventional printing plate with such large patterns in SBR printing would result in the occurrence of contact-defects.
In this study, we used commercially available silver nanoparticle ink (RAGT, DIC Corporation). Although, SBR printing technology is designed to form dielectric layers or interlayers, we used silver nanoparticle ink to clarify the printability of this printing technology, because dielectric inks for reverse-offset printing were not commercially available at this time.

![Diagram of SBR printing process and printer configurations](image)

**Fig. 1.** (Color online) Schematic diagram of the process flow of SBR printing and images of SBR printer configurations. The process steps are: (a) the coating process, whereby ink is coated on the soft blanket surface by using the slit coater; (b) the removal (patternning) process, whereby redundant sections of the ink layer are removed from the soft blanket and transferred to the stencil plate, and (c) the transfer (printing) process, whereby the ink layers are transferred from the soft blanket to the target substrate. Shown in (d) are details of the printing pressure (removal and transfer pressure), which relates to the soft blanket position, lowering it to the compression depth against the printing plate (or target substrate) from the contact position. Shown in (e) is the SBR printer we designed and constructed and (f) is the stencil plate developed for this study.
2.3. Measurement of compressive stress of soft blankets
Before printing examinations, uniaxial compression tests were performed to clarify that SBR printing can be conducted on curved surfaces even with the two-layered soft blanket. The samples were single-layered and two-layered soft blankets that were the same as those used for the printing examinations. The compressive stress of the soft blankets was measured using a digital force gauge (ZAT-20N, Imada Co., Ltd.) by applying pressure. The measurements were conducted with a compressive deformation rate of 10 mm min\(^{-1}\) and a deformation range of 0–2.5 mm, which is the same as the compression depth at the transferring process on curved surfaces.

2.4. Coating conditions and SBR printing
In conventional reverse offset printing, the dependence of the printed layer thickness on the coating speed is well known. First, we confirmed that this would similarly occur when using SBR printing with its soft blanket and then decided the coating conditions we would be using in this research. We printed silver layers using coating speeds of 18.0, 36.0, and 54.0 mm s\(^{-1}\) on flat glass substrates and measured their thickness by using a laser microscope (LEXT OLS 4100, Olympus Corporation) without sintering.

### Table I. Parameters for the SBR printing experiments.

| Parameter              | Step       | Symbol | Value          | Remarks                      |
|------------------------|------------|--------|----------------|------------------------------|
| Printing speed         | Coating   | \(v_0\) | 18, 36, 54 mm s\(^{-1}\) |                               |
|                        | Removing   | \(v_1\) | 30 mm s\(^{-1}\)    |                              |
|                        | Transferring | \(v_2\) | 30 mm s\(^{-1}\)    |                              |
| Printing pressure      | Removing   | \(h_1\) | 0.7 mm           | On flat surfaces             |
|                        | Transferring | \(h_2\) | 0.7 mm           | On curved surfaces           |
| Waiting time           | Before removing | \(w_{r1}\) | 60–80 s        | Depends on humidity         |
|                        | Before transferring | \(w_{r2}\) | 0 s            |                              |

### Table II. Comparison of conventional and soft blanket properties.

| Structure (Cross-sectional views) | Conventional blanket | Soft blanket |
|----------------------------------|----------------------|--------------|
| Metal cylinder                   | PDMS/PET/under blanket | PDMS/PDMS |
| Metal core                       | PDMS (hard, thin)    | PDMS         |
| Under blanket                    | PDMS (soft, thick)   | Outer layer: Sheet soft layer: Cylinder |
| Stacking structure               | PDMS/PET/under blanket | PDMS/PDMS |
| Material                         | PDMS                 | Outer layer: Sheet soft layer: Cylinder |
| Shape                            | Sheet                | 20.5 mm (20.0 mm + 0.5 mm) |
| Thickness                        | 0.5 mm               | Outer layer: 45 Soft layer: less than 1 |
| Hardness (degree)\(^a\)          | 45                   | 45           |

\(^a\) ISO7619 (Shore A).
Next, we printed silver layers on a flat glass substrate by using SBR printing to investigate the roughness and uniformity of each printed silver layer and also measured their respective resistivities. The printing parameters are listed in Table I, and in the following experiments, a coating speed \( \nu_0 \) of 36.0 mm s\(^{-1}\) was adopted. We used laser microscopy, scanning electron microscopy (SEM) (SU8000, Hitachi High-Technologies Corporation), a resistivity processor (MODEL Sigma-5+, NPS Inc.), and a digital force gauge (ZAT-20N, Imada Co., Ltd) to measure the thicknesses, microstructures, resistivities and adhesion force, respectively, after sintering the silver layers at 180 °C for 30 min.

Finally, we formed wide patterns of silver layers on curved substrates to demonstrate that SBR printing can be used to fabricate wide patterns with uniform thickness on curved surfaces. Furthermore, we printed fine patterns on curved substrate using conventional reverse offset printing plate to confirm the resolution of SBR printing. This printing experiment was conducted using the same soft blanket and printing parameters as the above wide patterning. The thickness and resistivity of each of the layers was measured to clarify that these properties of the layers are the same on the curved surfaces as those on flat surfaces.

3. Results and discussion

3.1. Measurement of compressive stress of soft blankets

Figure 2 shows the stress–deformation curves measured for single-layered (SBG-CB) and two-layered soft blankets (STD#700/SBG-CB). The stress tendencies of both blankets are almost the same and increase slightly with increasing deformation. These stress–deformation curves show an almost linear relationship, indicating that Young’s modulus is almost constant. The deformation of 2.5 mm includes the compression depth during the SBR printing process. This result indicates that SBR printing on curved surfaces can be performed effectively by using the two-layered soft blanket consisting of a hard and thin blanket sheet laminated onto the surface of a soft and thick blanket.

3.2. Coating conditions and SBR printing

The dependence of the thickness of the patterned layer on the coating speed is plotted in Fig. 3. An increase in the printing speed causes the thicknesses of the patterned layers to increase linearly, which is also observed in conventional reverse-offset printing. However, we found that SBR printing formed thicker layers than those obtained with conventional reverse-offset printing.29,31

Figures 4(a)–4(d) show the results of SBR printing on a planar glass substrate. An image of the glass substrate is shown in Fig. 4(a), which shows that none of the printed patterns have contact-defects. The cross-sectional profiles shown in Fig. 4(b) were measured at the points of 1–4 in Fig. 4(a). These profiles indicate that the printed wide patterns have uniform thicknesses. The SEM images of a printed layer, shown in Figs. 4(c) and 4(d), reveal the absence of pinholes or micro-cracks and show that the printed layer has superior flatness and uniform thickness.

Figures 5(a)–5(d) show the SBR printing results on three kinds of curved surfaces. Figure 5(a) shows the rectangles with widths of 5, 10, 20, and 30 mm and circles with diameters of 5, 10, 20, and 30 mm on glass screw bottles with diameters of 5, 10, 20, and 30 mm on glass screw bottles with widths of 5, 10, 20, and 30 mm and circles with diameters of 5, 10, 20, and 30 mm on glass screw bottles with diameters of 5, 10, 20, and 30 mm. The SBR printing can form fine patterns as well as wide patterns on curved surfaces because

![Fig. 2. (Color online) Dependence of the stress–compression curves of soft blankets on their structure. The dashed and dotted lines are the results of soft blankets with a multilayered and two-layered structure.](image-url)

![Fig. 3. (Color online) Dependence of the thickness of the printed silver layer on the coating speed (before sintering).](image-url)

with a radius of 20.0 mm. Figures 5(b) and 5(c) show the rectangle with a width of 30 mm and the circle with a diameter of 30 mm on a curved surface with a radius of 220 mm and a nonuniformly curved surfaces, respectively. Figure 5(d) shows the cross-sectional profiles which were measured at the points of 1–4 on the glass screw bottle shown in Fig. 5(a). The printed pattern is assumed to have flat and uniform thickness. The apparent increase in the thicknesses as the position increases was attributed to the fact that the measurement was conducted on curved surfaces. These results confirm that SBR printing can form wide and flat patterned layers of uniform thickness on non-planar surfaces with various curvatures as well as on flat surfaces.

Figures 6(a)–6(c) show the result of the printed fine pattern on a glass screw bottle with a radius of 20 mm. This result indicated that the SBR printing can print fine patterns with a width of at least 30 μm. The SBR printing can form fine patterns as well as wide patterns on curved surfaces because
Semi-dried ink on a blanket is removed by a printing plate with fine patterns, like reverse offset printing.

Table III lists the average thickness, resistivity and adhesion force value for silver layers by SBR printing. The thickness and the resistivity were measured on both flat and curved surfaces but the adhesion force was measured on flat glass substrates. The silver layers by SBR printing had thicknesses of 0.82 μm on flat substrate and 0.80 μm on curved substrate, and resistivities of 21.5 μΩ cm on flat substrate and 23.8–26.0 μΩ cm on curved substrate. The thickness and resistivity value for silver layers on flat and curved substrates were almost the same. The silver layers on flat substrates had an adhesion force of 3.90 N. It is considered that printed layers on both flat and curved substrates have the same characteristics, because semi-dried ink on a soft blanket is transferred to a substrate, and then the transferred ink is baked to exhibit function, in SBR printing.

3.3. Discussion
In this study, a two-layered soft blanket was adopted to improve the flatness of printed patterns. Consequently, it was possible to suppress the surface deformation of the soft blanket during the removal process and to prevent contact-defects. Moreover, because the outer layer of the soft blanket did not inhibit deformation of the soft blanket during the transfer process, it was possible to print on curved surfaces.

SBR printing was performed on the external (convex) surfaces of cylindrical shape, in this study. Whether SBR printing is possible on a curved surface depends on various printing condition, such as the shape of the object, the size of the soft blanket, the printing direction, etc. For example, SBR

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| Table III. Properties of SBR-printed layers. |
|---------------------------------------------|
| Thickness (μm) | Resistivity (μΩ cm) | Adhesion force (N) |
|----------------|---------------------|-------------------|
| On a flat surface | 0.82 | 21.5 | 3.90 |
| On a curved surface [wide pattern, Fig. 5(a)] | 0.80 | 23.8 | — |
| On a curved surface [fine pattern, Fig. 6(b)] | 0.80 | 26.0 | — |

a) The force was measured on a square sheet with an area of 1 cm².
printing excels at printing on a convex surface, and can be printed with a curvature of at least 2 (mm$^{-1}$) regardless of the soft blanket size. On the other hand, in printing on a concave surface, it is preferable that the curvature is smaller than that of the soft blanket.

In addition, it is important to note that the layers that were printed on non-planar surfaces maintained their functionality, i.e. their resistivity values. This means that the patterns printed on non-planar surfaces have the same functionalities as those printed on planar surfaces, indicating that SBR printing can form wide layers with good flatness and uniformity, and are characterized by the inks that are used.

4. Conclusions

We have developed “SBR” printing technology in order to fabricate wide patterned layers with uniform thicknesses as applicable to the dielectric layers or the interlayers in PE devices. In this study, we demonstrated that wide and flat patterned layers of uniform thickness could be formed without contact-defects by using a two-layered soft blanket, a thick stencil printing plate, and commercially available silver nanoparticle ink. The silver layers that were printed using SBR technology have uniform thicknesses and low resistivities. Moreover, the printed layers retained their low
resistivities on curved surfaces. These results demonstrate the ability of SBR printing technology to form flat layers with uniform thicknesses for wide patterns applicable to dielectric layers or interlayers. SBR printing technology is foreseen to become one of the most useful methods to fabricate uniform patterns for PE technology.

In future, we aim to develop dielectric ink suitable for SBR printing, considering that we used commercially available silver nanoparticle ink for reverse-offset printing because dielectric ink is commercially unavailable. We also plan to fabricate multilayer elements such as capacitors or transistors with the aim of fabricating high-quality dielectric layers for PE devices.

Acknowledgments
This research is partially supported by the Matching Planner Program from Japan Science and Technology Agency, JST (Grant No.: VP29117940259) and by the Fujikura Foundation.

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