Electric characterisation of fine wires formed with capillary-effect-based screen-printing

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To improve the productivity of electronic devices, it is imperative to develop screen-printing techniques that can form finer wires with a higher-aspect ratio. The electric characteristics of conductive wires formed by the proposed screen-printing process combined with an imprinting technique were evaluated. Fine wires with a high-aspect ratio can be realised, owing to the capillary force of parallel-walled structures (PWSs) on polymer films. With the proposed process, printed wires with a line width of only 7.0 μm and an aspect ratio of up to 8.6 were obtained. To optimise the shape of the PWS, the dependence of the shape of PWSs was evaluated electrically. They compared the electric resistance of wires with a width of 10 μm formed using the proposed process to that of 81 μm wires formed using a conventional process. The measured resistance was almost the same, at around 54 kΩ/mm, despite the fact that the proposed process realised wires that were an eighth of the width. By controlling the printing conditions, they confirmed that capillary-effect-based screen-printing is also feasible using highly conductive ink. The resistance of a 13 μm wide printed wire achieved 3.0 Ω/mm.

1. Introduction: The screen-printing process offers many advantages such as excellent productivity and large-area patterning, because it is a simple process that involves a screen mask used to selectively apply ink to a substrate [1]. In recent years, the reliability of screen-printing has improved, as the manufacturing process has progressed with component technologies for fabricating screen plates. Since organic transistors have been realised through printing processes [2, 3], screen-printing is attracting attention as a key technology for printed electronics [4]. Screen-printing is anticipated to serve as a technology that can be applied widely, with applications such as transparent touch panels [5, 6], sensors [7], organic solar cells [8], and wearable devices [9]. Indeed, transparent touch panels require transparent electrodes such as indium tin oxide (ITO). Since ultrafine wires show optical transparency, metal nanowires [10–13], which meet the requirements of transparency and conductivity, have attracted considerable attention as an alternative to ITO films. However, some of these devices have been manufactured using conventional lithographic processes, because current screen-printing methods have limited resolution. Using printing processes, the production cost can be reduced significantly. Hence, resolution-enhancement techniques for screen-printing are highly desirable, insofar as the minimum resolution of conventional screen-printing in mass-production lines is more than 50 μm. The limited resolution is mainly caused by ink spreading on a substrate and ink clogging in a screen mesh. To overcome this limitation, several printing methods have been reported [14, 15]. Nomura *et al.* [14] developed screen-offset printing that yielded sharply printed patterns with a minimum resolution of 30 μm.

On the other hand, the electric resistance of a printed wire increases as the pattern width becomes thinner, because the height of the printed wire is reduced. To obtain low resistance in fine printed wires, high-aspect-ratio wires are needed. However, it is difficult to realise high-aspect-ratio wires due to ink spreading. Recently, Hokari *et al.* [15] combined a screen-printing process with an imprinting technique, which obtained fine and high-aspect-ratio patterns. Though this process requires the rough alignment of the positions of an opening in a screen mask and an imprinted microstructure, fine patterns can nevertheless be formed with a high-aspect ratio that is unobtainable with conventional screen-printing. In addition, since printed products have textured patterns (e.g. with automobile instrument panels or home appliances) that are mainly formed with imprinting methods, the combination of an imprinting process with a printing process has been established as a continuous production line for these products. Therefore, the screen-printing process can be applied to production lines, without the need for considerable capital investment. Therefore, the total cost of the process is low compared with the cost of the photolithography process. Though fine and high-aspect-ratio patterns formed by the process can be used as electric wires, their electrical characteristics have not been fully investigated.

In this Letter, we evaluate the electrical characteristics of printed wires formed by the screen-printing process combined with an imprinting method. The electric resistance of printed wires formed by the proposed process was compared with that of a conventional process. To clarify the relationship between the printed wire and the shape of the imprinted structure – that is, the parallel-walled structure (PWS) – the height dependence and the pitch dependence of the PWSs were investigated. In addition, we demonstrated that a highly conductive wire can be realised with capillary-effect-based screen-printing.

2. Principle: Fig. 1 shows a schematic representation of the concept for the proposed screen-printing process. In the conventional process, it is difficult to obtain fine patterns with a high-aspect ratio, because ink bleeding and spreading occur on the substrate. With the proposed process, on the other hand, fine patterns with a high-aspect ratio can be obtained according to a shape of PWSs, because ink spreading is suppressed by the PWS. Fig. 2 shows a schematic for the proposed screen-printing process. The process consists of two steps: the imprinting process that forms the PWSs, followed by the screen-printing process. A special imprint apparatus and a special screen printer are not required. The height and gap distance of the PWS are represented by h and w, respectively. The clearance refers to the distance between the screen and the substrate. The proposed technique

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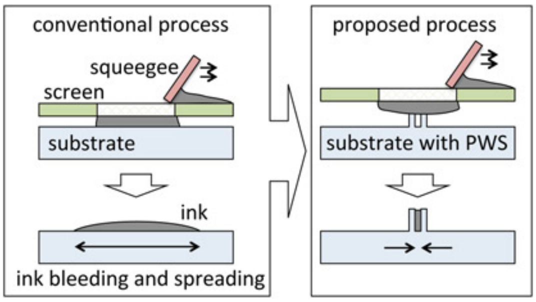

Fig. 1 *Concept for the proposed screen-printing process*

utilises the capillary effect of imprinted PWSs. The capillary-force effect increases as the gap distance w decreases. During the printing process, ink ejected from an opening in the screen mask is absorbed and kept inside the PWS, when that w is narrow. When the contact angle of the ink-drop with respect to the surface of the PWS is <90°, the ink inside the PWS enters the bottom. Though the ink is pulled from the screen mask when the screen mask is moved away from the PWS, the ink is retained inside the PWS, owing to a strong capillary-force effect. When w is wide, on the other hand, the ink inside the PWS is pulled from the screen mask, because the capillary-force effect is consequently weak. The salient feature of the proposed process is that the line width of the printed patterns is dramatically smaller than the opening width of the screen mask. This feature contributes significantly to the prevention of ink clogging in screen masks because the screen mask with a larger opening and a lower mesh count can be used. In addition, ink patterns inside the PWSs become high-aspect-ratio wires. The volume of the ejected ink depends on the printing conditions: namely, the squeegee's speed, pressure, and angle. Consequently, the volume of the ink that remains inside the PWS can be controlled according to the printing conditions.

The electrical characteristics are evaluated with the electric resistance per unit length r, which is expressed as follows

$$r = \frac{R}{L} = \frac{\rho}{A}, \tag{1}$$

where R, L, ρ, and A denote the electric resistance, the length of a printed wire, the resistivity of the ink, and a cross-sectional area, respectively. By considering the printed wire as a cuboid, A is expressed as a product of the width and the height of the wire. Therefore, r decreases with an increase to the aspect ratio of the printed wires when the width is constant.

3. Experiments: Fig. 3 shows the fabrication process of the PWSs. PWSs were formed with an imprinting technique, utilising an ultra-violet (UV) curable resin (PAK-02, Toyo Gosei Co., Ltd.) and a silicon (Si) mould. First, pairs of groove patterns were formed with a dicing process, as shown in Fig. 3*a*. The pitch and depth of the groove patterns were regulated with micron accuracy. The width of the groove patterns was ~12 µm, which is the approximate width of the dicing blade. The pitch p and height h of the PWSs was directly correlated with the pitch and depth of the groove patterns. Next, a release agent was coated on the Si wafer, in order to release the UV-curable resin from the Si wafer easily. A polyethylene terephthalate (PET) film was employed as the substrate for the UV-curable resin layer. Then, the resin was compressed between the PET film and the Si mould and exposed to UV light, as shown in Fig. 3*b*. Finally, the resin was completely cured and released from the mould to create the PWSs, as shown in Fig. 3*c*. PWSs with an h of up to 120 µm were fabricated successfully.

The standard printing conditions for the screen-printing process are listed in Table 1. We used a stainless screen mask (Mitani Micronics Co., Ltd.) with a mesh count of 500/inch, a wire diameter of 18 µm, a mesh thickness of 29 µm, and a mesh opening of 33 µm. The screen mask contained patterns of 100 µm lines and spaces (200 µm period). Carbon-rich ink composed of carbon ink (FC-415, Fujikura Kasei Co., Ltd.) and silver ink (FA-353N, Fujikura Kasei Co., Ltd.) was employed. The direction of the walls of the PWSs with respect to the squeegee's travel direction was arranged such that it was perpendicular or parallel. Fig. 4 shows optical micrographs of the printed results. The contact angle of an ink-drop on the surface of the UV-curable resin was measured at about 65°. Figs. 4*a* and *b* show the results when the squeegee's travel direction was perpendicular to the walls of the PWSs. In Fig. 4*a*, a wire ~130 µm wide was obtained using the conventional screen-printing process on a flat surface. By contrast, Fig. 4*b* shows the results of the proposed process, revealing that the

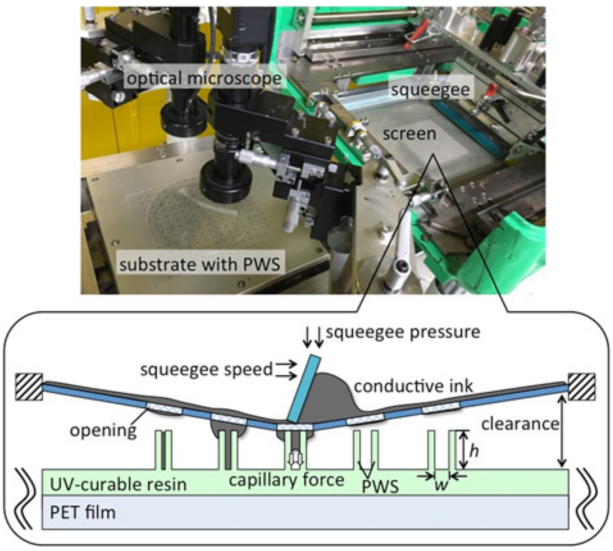

Fig. 2 *Picture of the screen printer and a schematic of the proposed screen-printing process*

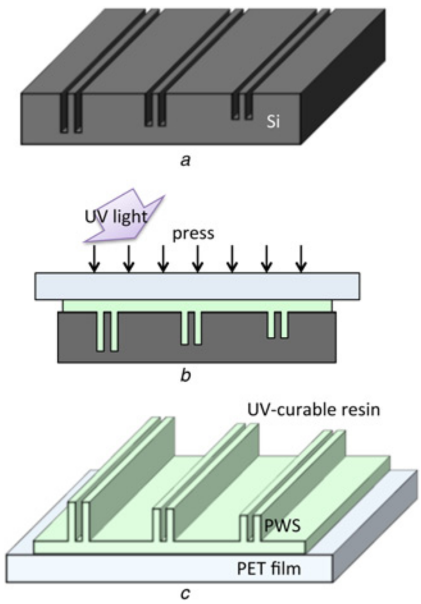

Fig. 3 *PWS fabrication process*
a Dicing
b UV-imprinting
c Release

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Table 1 Standard screen-printing conditions

Squeegee pressure	0.18 MPa
Squeegee speed	28 mm/s
Clearance	1.0 mm
Squeegee angle	70°

ink remained inside the PWSs, with a wire width of 16.4 µm regulated by *w*, despite using a 100 µm wide opening in the screen mask. Figs. 4*c* and *d* show the results when the squeegee travelled parallel to the walls of the PWSs. Figs. 4*e* and *f* show cross-sectional views of Figs. 4*c* and *d*, respectively. The height of the PWS was 103 µm, measured from the cross-sectional image. In Figs. 4*c* and *e*, a wire ~126 µm wide was obtained with the conventional screen-printing process. The height of the ink pattern was 9.0 µm, with an aspect ratio of 0.07. In Figs. 4*d* and *f*, on the other hand, a 7.0 µm wire was obtained using the proposed process. The height of the ink pattern inside the PWS was measured at 60.1 µm, with a high-aspect ratio of 8.6.

To characterise the conductive wires formed by the proposed process, the electric resistance was measured and compared with that of wires formed with the conventional process. Since carbon-rich ink has relatively low conductivity, the two-terminal method was used for the electrical evaluation. First, the relationship between the electrical resistance of the printed wire and the shape of the PWS was evaluated. The resistance from varying *w* and *h* was measured. In the evaluation of the wire-width dependence, *w* was set between 10 and 40 µm, with *h* set at 100 µm. Standard screen-printing conditions were used. Fig. 5 shows the measured electric resistance per unit length of the printed wires. Each point represents the average of ten experiments. The measured values

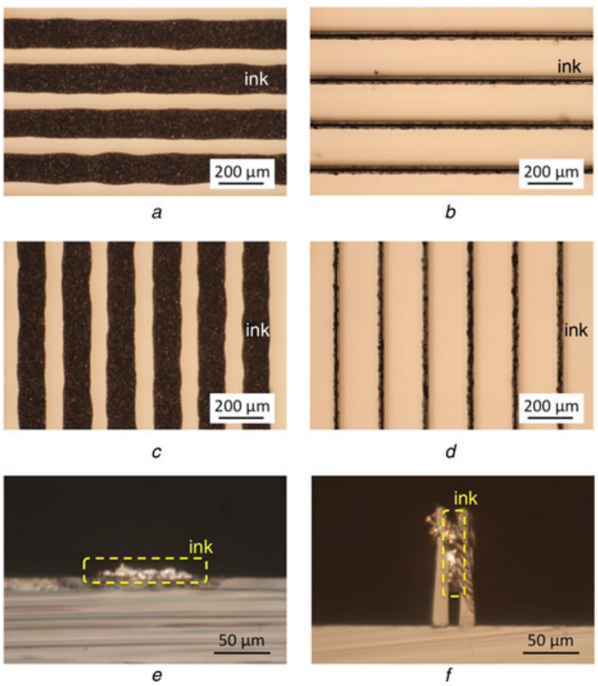

Fig. 4 *Optical micrographs of the printed wires formed by (a), (c), and (e) the conventional screen-printing process on a flat surface, and (b), (d), and (f) the proposed process: (a)–(d) top view and (e), (f) cross-sectional view*
a Without PWS
b With PWS
c Without PWS
d With PWS
e Without PWS
f With PWS

of the resistances were comparatively high, owing to the use of carbon-rich ink. However, this relative evaluation of the resistance suffices for comparing the printed patterns formed by the proposed process to those of the conventional process. In the case of the conventional process, the average resistance gradually increased from 6.9 to 133 kΩ/mm, as the wire decreased in width from 220 to 52 µm, according to (1). With the proposed process, on the other hand, the resistance remained relatively low compared with the results from using the convention process, despite a gradual increase to the resistivity from 17 to 54 kΩ/mm as the width of the wire decreased from 40 to 10 µm. We compared the resistance of a 10 µm wire formed with the proposed process to that of an 81 µm wire formed with the conventional process. Indeed, the measured resistance was almost same, in spite of the difference in wire width. Therefore, the proposed process is effective at decreasing the electric resistance in fine wires.

Next, we evaluated the height dependence of PWSs. To do so, *h* was varied from 50 to 120 µm, with *w* set at 10 µm. Again, standard screen-printing conditions were used. Fig. 6 shows the measured electric resistance per unit length as a function of *h*. Each point represents the average of ten experiments. In this experiment, the resistance was directly correlated with the real height of the printed wire inside the PWSs, because the wire width was almost the same. The diamond-shaped dots show the results when the squeegee travelled perpendicular to the walls of the PWSs. The circular dots show the results when the squeegee travelled parallel to the walls of the PWSs. When the squeegee was perpendicular, as *h* increased from 50 to 120 µm, the average resistance decreased from 158 to 54 kΩ/mm in inverse proportion to *h*. The dashed curve, which is inversely proportional to *h*, represents the fitted curve calculated based on the measured cross-sectional areas of the printed wires. When the squeegee was parallel to the walls of PWSs, as *h* increased from 50 to 120 µm, the average resistance decreased from 152 to 44 kΩ/mm in inverse proportion to *h*. According to these results, the resistance is unaffected by the squeegee's travel direction using this process. In addition, we confirmed that the real height of the ink inside the PWSs increased with an increase to *h*. As shown in Fig. 4*f*, however, because the ink did not reach the bottom, each real wire height was smaller than each *h*. This might be caused by the high viscosity of the ink or by air inside the PWSs. We believe that the filling property of the ink can be controlled by the screen-printing conditions – i.e. by adjusting the squeegee pressure and speed.

For electronic applications, it is important to demonstrate capillary-effect-based screen-printing using a highly conductive ink. Thus, we experimented with highly conductive ink (silver ink: RA FS 074, Toyo Chem Co., Ltd.), by measuring its electric resistance and comparing it with that of the conventional process. The ink was dried at 110°C for 90 min. The four-terminal method was used for the electrical evaluation. To evaluate wire-width dependence, we set *w* to 13 µm and *h* to 100 µm. Since the printability depends on the ink formulation, the screen-printing

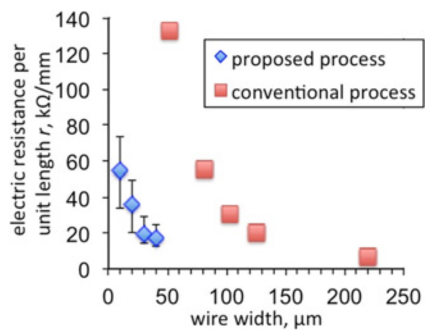

Fig. 5 *Measured electric resistance per unit length of the printed wires as a function of the wire width*

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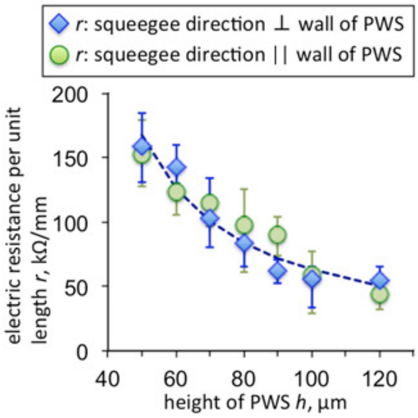

Fig. 6 *Measured electric resistance per unit length r of the printed wires as a function of h*

conditions were slightly changed for this experiment in order to form clear patterns: the squeegee pressure and speed were set to 0.15 MPa and 40 mm/s, respectively. The clearance and squeegee angle were again set to the standard screen-printing conditions. Fig. 7 shows the measured electric resistance per unit length of the printed wires as a function of the wire width. Each point represents the average of seven experiments. The dashed line represents the following equation

$$r_1 = \frac{\rho_1}{w_r h_0}, \tag{2}$$

where ρ_1, w_r, and h_0 denote the resistivity of the ink, the wire width, and the wire height at a width of 407 µm, respectively. Thus, r is inversely proportional to w_r. The dotted line represents the following equation

$$r_2 = \frac{\rho_1}{w_r\left(h_0(w_r/w_0)\right)}, \tag{3}$$

where w_0 denotes a wire width of 407 µm. This equation corresponds to changes in the wire height at the same rate the wire width changes. In the case of the conventional process, the average resistance gradually increased from 0.2 to 4.8 Ω/mm, with a decrease to the wire width from 407 to 74 µm. Since the results agree well with (3), the wire height decreased with a decrease to the wire width. In the case of the proposed process, on the other hand, an average resistance of 3.0 Ω/mm was obtained

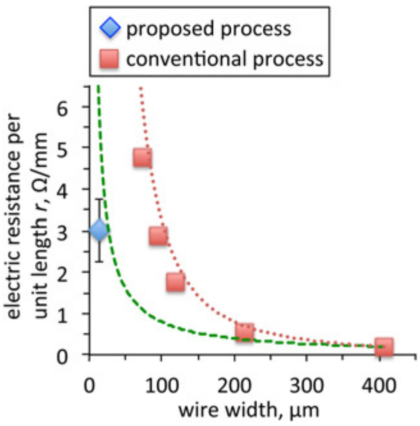

Fig. 7 *Measured electric resistance per unit length of the printed wires made of a highly conductive ink as a function of the wire width*

with a 13 µm wire. In comparing the resistance of a 13 µm wire formed with the proposed process to that of a 95 µm wire formed with the conventional process, the measured resistance was found to be almost the same. Therefore, the proposed process is also effective at decreasing electric resistance in fine wires when using highly conductive ink.

4. Conclusions: In this Letter, we analysed the characteristics of printed wires formed with the proposed screen-printing process. A 7 µm wide wire with a high-aspect ratio of up to 8.6 was formed with the screen-printing process, using the capillary effect of the PWS, which was formed through a UV-imprinting method. An aspect ratio of 8.6 is difficult to realise with conventional screen-printing techniques. In the electrical evaluation of wire-width dependence, the average resistance of the printed wire formed with the conventional process gradually increased from 6.9 to 133 kΩ/mm with a wire decreasing in width from 220 to 52 µm. In the case of the proposed process, on the other hand, even though the average resistance also increased gradually, from 17 to 54 kΩ/mm with a wire decreasing in width from 40 to 10 µm, low resistance was nevertheless retained relative to the increase in resistance with the conventional process. Therefore, the proposed process was effective at decreasing the electric resistance of fine wires. When the squeegee travelled perpendicular to the walls of the PWSs, as h increased from 50 to 120 µm, the average resistance decreased from 158 to 54 kΩ/mm in inverse proportion to h. When the squeegee travelled parallel to the walls of the PWSs, as h increased from 50 to 120 µm, the average resistance decreased from 152 to 44 kΩ/mm in inverse proportion to h. According to these results, the resistance is unaffected by the squeegee's travel direction when using the proposed process. By controlling the printing conditions, we also confirmed that capillary-effect-based screen-printing is feasible using highly conductive ink. The resistance of a 13 µm wide printed wire achieved 3.0 Ω/mm resistance.

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