

# ROLL-TO-ROLL-COMPATIBLE UV IMPRINTING AND IPL SINTERING PROCESS FOR FLEXIBLE TRANSPARENT CONDUCTIVE ELECTRODES

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**Abstract:** Flexible transparent conductive electrodes are key components in next-generation optoelectronic devices, such as touch panels, displays, solar cells, transparent heaters, and wearable electronics. However, conventional indium tin oxide electrodes are limited by brittleness, high cost, and poor compatibility with flexible substrates. In this study, a roll-to-roll-compatible fabrication method for flexible transparent conductive electrodes is proposed using UV imprint lithography, silver nanoparticle paste filling, hot-plate heating, and intense pulsed light (IPL) sintering. A silicon wafer with microchannel patterns was used as the master mold to fabricate a pillar-patterned PET soft mold, which was subsequently used to replicate microchannels on another PET film. Silver nanoparticle paste was filled into the imprinted microchannels by blade coating, followed by hot-plate heating and IPL sintering to form conductive silver microstructures. The fabricated microchannels were approximately 6–7  $\mu\text{m}$  wide and 10  $\mu\text{m}$  deep. Increasing the number of filling cycles from one to three increased the silver thickness from 4.70 to 6.75  $\mu\text{m}$  and reduced the sheet resistance from 7.0 to 3.5  $\Omega/\text{sq}$ . The electrodes maintained an optical transmittance of approximately 94%, with haze values ranging from 4.0% to 4.3%. SEM observations confirmed the formation of continuous conductive silver pathways, although some shrinkage gaps were observed near the channel walls. These results demonstrate the potential of PET-based soft molds, repeated silver-paste filling, and rapid IPL sintering for the low-cost and scalable fabrication of flexible metal-mesh transparent conductive electrodes.

**Keywords:** flexible electrode, IPL sintering, metal mesh, silver nanoparticle, UV imprint lithography

## 1. INTRODUCTION

Flexible transparent conductive electrodes (FTCEs) are essential components in next-generation optoelectronic devices, including flexible displays, touch panels, solar cells, transparent heaters, photodetectors, and wearable electronics (Chang, Chen, Chen, Zhu, & Guo, 2021; Wang et al., 2021). These electrodes must simultaneously provide high optical transmittance, low sheet resistance, and good mechanical flexibility. The rapid

development of flexible and wearable electronic systems has therefore increased the demand for transparent electrodes that can maintain stable electrical and optical performance under bending, deformation, and large-area manufacturing conditions (Chang et al., 2021; Langley et al., 2013). Previous studies have emphasized that desirable flexible transparent electrodes should combine high transparency, low electrical resistance, and good flexibility (Khan et al., 2016; Yang et al., 2025; Zhang et al., 2023).

Indium tin oxide (ITO) has long been the most widely used transparent conductive material because of its high optical transparency and good electrical conductivity (Cao, Li, Chen, & Xue, 2014; Ma, Li, Liu, Ye, & Sorger, 2014; Minami, 2008). However, ITO has several limitations for flexible applications. Its brittleness can cause cracking and performance degradation during bending, while its fabrication often requires high-temperature or vacuum-based processes that are not fully compatible with low-cost polymer substrates. In addition, the limited supply of indium and high processing cost restrict its use in large-area flexible electronics. Consequently, alternative transparent conductive materials have been widely investigated, including carbon-based materials, conductive polymers, metal nanowires, ultrathin metal films, and metal mesh electrodes (Cheng, Zhang, Lai, & Huang, 2015; Dai et al., 2020; Park, Vosguerichian, & Bao, 2013; Zhu et al., 2019).

Among these alternatives, metal-based transparent electrodes are particularly promising because metals possess intrinsically high electrical conductivity. By forming metals into thin films, nanowire networks, or mesh/grid structures, both optical transparency and electrical conduction can be achieved. Compared with conducting polymers and carbon-based materials, metal-based electrodes generally provide lower sheet resistance and are more suitable for high-performance optoelectronic devices (Gaynor, Burkhard, McGehee, & Peumans, 2011; Hofmann, Cloutet, & Hadziioannou, 2018; Wu et al., 2013). Metal mesh electrodes are especially attractive because their electrical and optical properties can be controlled through the metal line width, spacing, thickness, and pattern geometry. Light passes through the open areas of the

mesh, while current is transported through the continuous metallic lines (Nguyen et al., 2022). Therefore, metal mesh electrodes can provide a favorable balance between high transparency and low sheet resistance (Lu, Zhang, & Zheng, 2021).

Nanoimprint lithography (NIL) is a promising method for fabricating micro- and nanoscale structures because it replicates a patterned mold through mechanical contact rather than diffraction-limited optical exposure (Ok, Shin, Park, & Guo, 2015). NIL can produce high-resolution patterns through relatively simple processing steps and is suitable for large-area and high-throughput nanopatterning (Peng et al., 2023). In particular, UV nanoimprint lithography is appropriate for polymer substrates because the patterned resin can be rapidly cured by ultraviolet light (Yi, Wu, Zhang, Peng, & Lai, 2015). Roll-to-roll nanoimprint lithography further enables continuous patterning on flexible substrates. In this process, a flexible mold is wrapped around a roller, the substrate passes through the contact zone, and UV exposure completes the pattern transfer (Ahn & Guo, 2008). Therefore, the development of a flexible soft mold is an important step toward adapting laboratory-scale imprinting to continuous roll-to-roll manufacturing.

For transparent electrode fabrication, the combination of imprint lithography and metal filling provides an effective route for producing conductive metal mesh structures. Microchannels are first replicated on a flexible polymer substrate, after which conductive paste or ink is filled into the channels. The patterned channels confine the conductive material and define continuous electrical pathways. Silver nanoparticle paste is particularly suitable because of its high electrical conductivity and good processability, and it can be

deposited by blade coating and converted into conductive metal lines through thermal or photonic sintering (Fernandes et al., 2020; Kim, Jung, Oh, & Kim, 2017; Vida et al., 2025). Intense pulsed light (IPL) sintering can rapidly convert metallic nanoparticles into conductive structures within a very short processing time (Jang et al., 2021). Compared with conventional furnace heating, IPL can selectively heat the metallic material while limiting thermal damage to heat-sensitive polymer substrates such as PET. It is also compatible with large-area and continuous processing, supporting its potential integration into roll-to-roll production lines (Han et al., 2025).

Based on these considerations, this study proposes a roll-to-roll-compatible process for fabricating flexible transparent conductive electrodes using UV imprint lithography, silver nanoparticle paste filling, hot-plate heating, and IPL sintering. The main novelty of the proposed process is the use of a PET-based soft mold replicated from a silicon master. Unlike direct imprinting from a rigid silicon wafer, the flexible soft mold can potentially be wrapped around a roller and used for continuous pattern replication. The soft mold was used to form microchannels on another PET film, followed by silver paste filling, wiping, heating, and IPL sintering. The objective of this study is to evaluate

the fabrication of silver micro-mesh electrodes through this soft-mold-based process and to investigate the influence of the filling process under selected heating and IPL conditions on sheet resistance, optical transmittance, haze, and silver microstructure. This process provides a practical basis for future integration of imprinting, silver filling, and sintering into a continuous roll-to-roll fabrication system.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The materials and equipment for the fabrication and characterization of flexible transparent conductive electrodes are shown in Table 1. A silicon wafer with a microchannel pattern was used as the master mold for the initial imprinting process. A negative UV-curable photoresist, 311RM resin, was used to replicate the microstructures. PET film was used as the flexible and transparent substrate due to its optical transparency, mechanical flexibility, and potential compatibility with roll-to-roll processing. Silver nanoparticle paste was used as the conductive material and was filled into the imprinted microchannels to form metallic conductive lines. After filling, excess paste was removed by wiping, followed by hot-plate heating and intense pulsed light sintering to obtain conductive silver microstructures.

**Table 1. Materials and equipment**

| <b>Material / Equipment</b>      | <b>Manufacturer/ Provider</b>      | <b>Type / Description</b>                                 |
|----------------------------------|------------------------------------|-----------------------------------------------------------|
| Silicon wafer                    | NTTU                               | Rigid patterned master mold                               |
| 311-RM UV-curable resin          | Minuta Technology Co., Ltd.        | Negative UV-curable photoresist                           |
| PET film                         | I-OneFilm Co., Ltd.                | Flexible transparent polymer substrate thickness 0.1 mm   |
| Silver paste FTL-99M             | FPCo., Ltd.                        | Conductive silver paste (particles diameter about 100 nm) |
| Trichloro(octadecyl) silane, 90% | Sigma-Aldrich                      | Anti-adhesion agent                                       |
| PulseForge 1300                  | Novacentrix                        | Intense pulsed light machine                              |
| Napson EC-80P                    | Napson Corporation                 | Eddy-current sheet resistance measurement                 |
| Haze Meter HM-150L2N             | Murakami color research laboratory | Optical measurement system                                |

## 2.2 Fabrication of Microchannel-Patterned PET Substrate

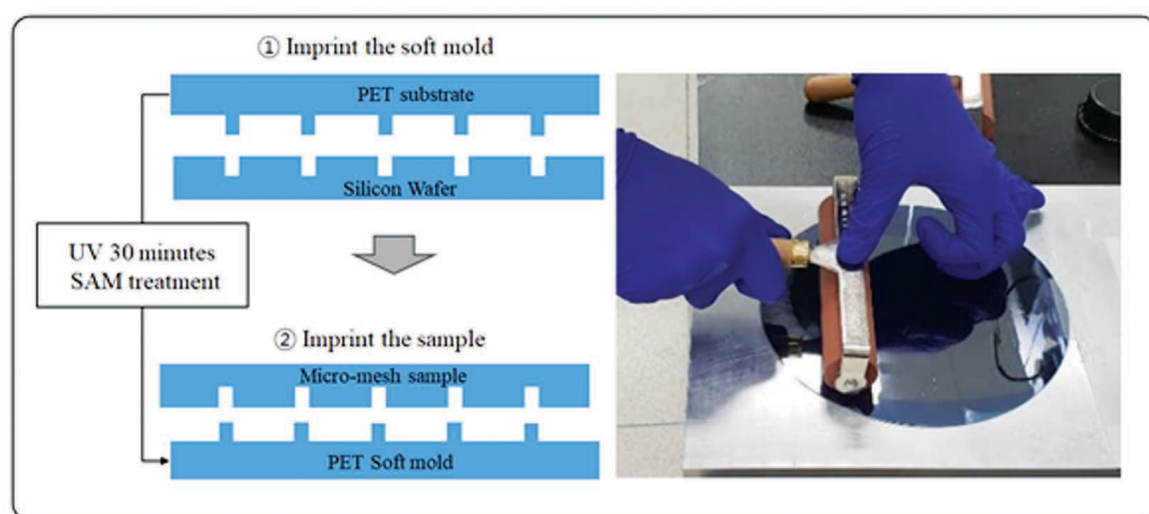
The microchannel-patterned PET substrate was fabricated through a two-step UV imprint lithography process (Figure 1). In the first step, a PET soft mold was replicated from a silicon wafer containing the original microchannel pattern. Before imprinting, the silicon wafer was treated with a self-assembled monolayer (SAM) using trichloro(octadecyl)silane (90%) to increase the surface hydrophobicity and improve the release property during demolding. After SAM treatment, a sufficient amount of 311RM negative UV-curable resin was spread onto the patterned surface of the silicon wafer. A PET film was then placed on top of the resin-coated wafer. The imprinting process was carried out manually by using a rubber roller to press and drag

from top to bottom, allowing the resin to fill the microchannel pattern uniformly and ensuring intimate contact between the PET film and the silicon wafer. The sample was then exposed to UV light for 10 s to partially cure the resin. After UV exposure, the PET film was carefully peeled from the silicon wafer. As a result, the pattern was transferred from the silicon wafer to the PET film, forming a pillar-patterned PET soft mold. The obtained PET soft mold was further exposed to UV light for 30 min to enhance the curing degree and improve the mechanical stability of the replicated pattern.

In the second step, the fabricated PET soft mold was used to prepare the microchannel-patterned PET substrate. Similar to the first imprinting step, the PET soft mold was first treated with SAM using

trichloro(octadecyl) silane (90%) to reduce adhesion between the soft mold and the resin. A sufficient amount of 311RM resin was then spread onto the patterned surface of the PET soft mold, followed by placing a new PET film on top of the resin layer. A rubber roller was used to manually press and drag from top to bottom to ensure complete filling of the resin into the mold pattern and uniform contact between the layers. The sample was exposed to UV light for 10 s, and the new PET film was then carefully peeled from the PET soft mold. Through this

replication process, microchannel structures were formed on the PET substrate. Finally, the microchannel-patterned PET substrate was further exposed to UV light for 30 min to fully cure the resin and strengthen the patterned structure. This two-step UV imprinting approach enables the fabrication of flexible microchannel-patterned PET substrates while avoiding repeated direct use of the silicon wafer. In addition, the use of a PET-based soft mold provides potential compatibility with future roll-to-roll imprinting processes.



**Figure 1. The imprinting process of soft mold and micro-channel samples**

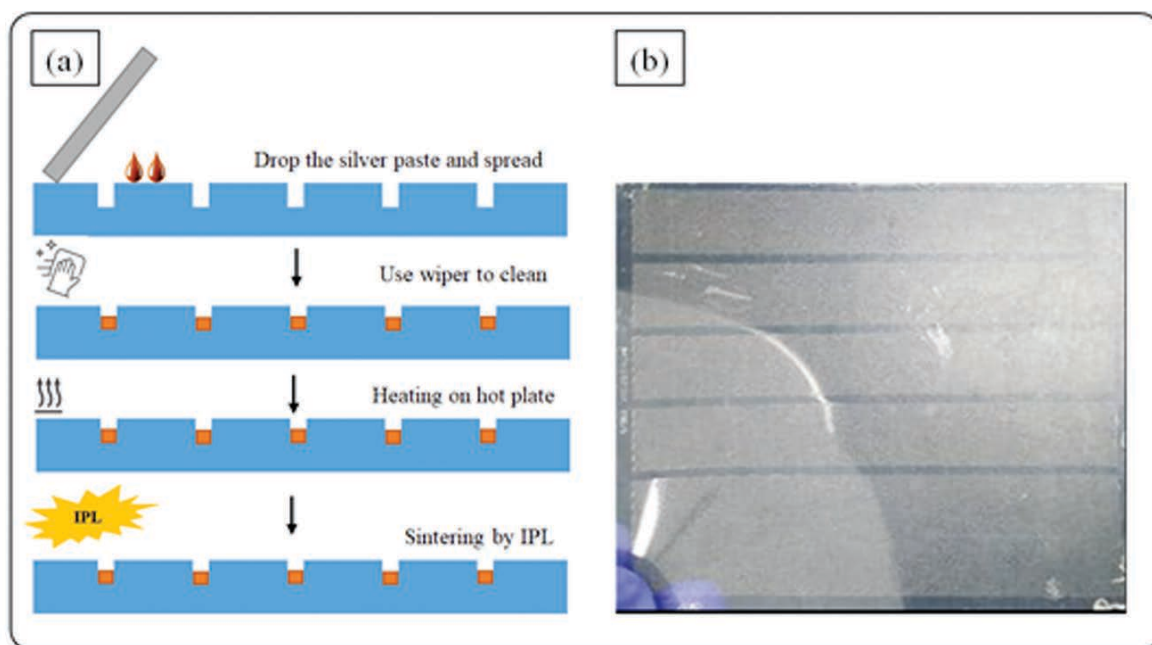
### 2.3 Silver Paste Filling, Sintering, and Characterization

After fabrication of the microchannel-patterned PET substrate, silver nanoparticle paste was applied to the microchannel-patterned PET substrate by blade coating. Excess paste remaining on the surface was removed by wiping, while the paste retained inside the microchannels formed the conductive pattern. The hot-plate heating and IPL sintering conditions used in this study were

selected after several preliminary trials to determine suitable operating parameters for drying and sintering the silver nanoparticle paste without damaging the PET substrate or the imprinted microchannel structure. Based on these trials, the samples were heated on a hot plate at 130 °C for 3 min, followed by IPL sintering at 400 V with an exposure time of 1000  $\mu$ s. The process is illustrated in Figure 2a, while the final sample after filling and sintering is shown in Figure 2b. The fabricated samples were characterized in terms of electrical, optical,

and morphological properties. Sheet resistance was measured using a Napson EC-80P system based on the eddy current method. Optical properties, including total light transmittance, diffuse transmittance, and haze, were measured using a Haze Meter HM-150L2N. This instrument is

suitable for evaluating transparent materials such as plastics, glass, and liquid samples. The microstructure of the silver-filled channels was observed by scanning electron microscopy (SEM) to examine the filling quality, continuity of the silver structures, and possible defects after sintering.

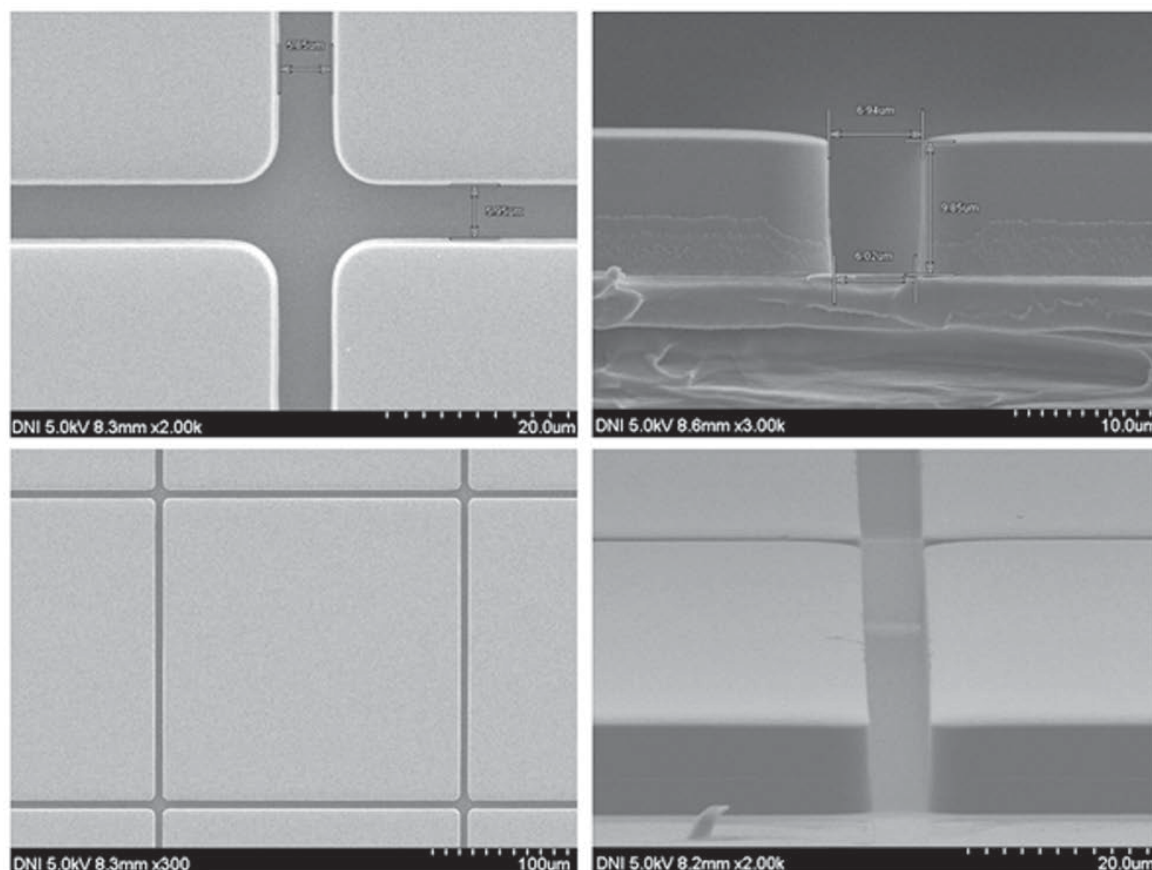


**Figure 2. (a) Filling and sintering process (b) sample after processing**

### 3. RESULTS AND DISCUSSION

The morphology and dimensional accuracy of the imprinted micro-mesh structure were first examined to evaluate the quality of pattern replication and its suitability for subsequent silver paste filling. Figure 3 shows the SEM image of the micro-mesh sample after UV imprinting. The patterned resin was successfully detached from the PET soft mold,

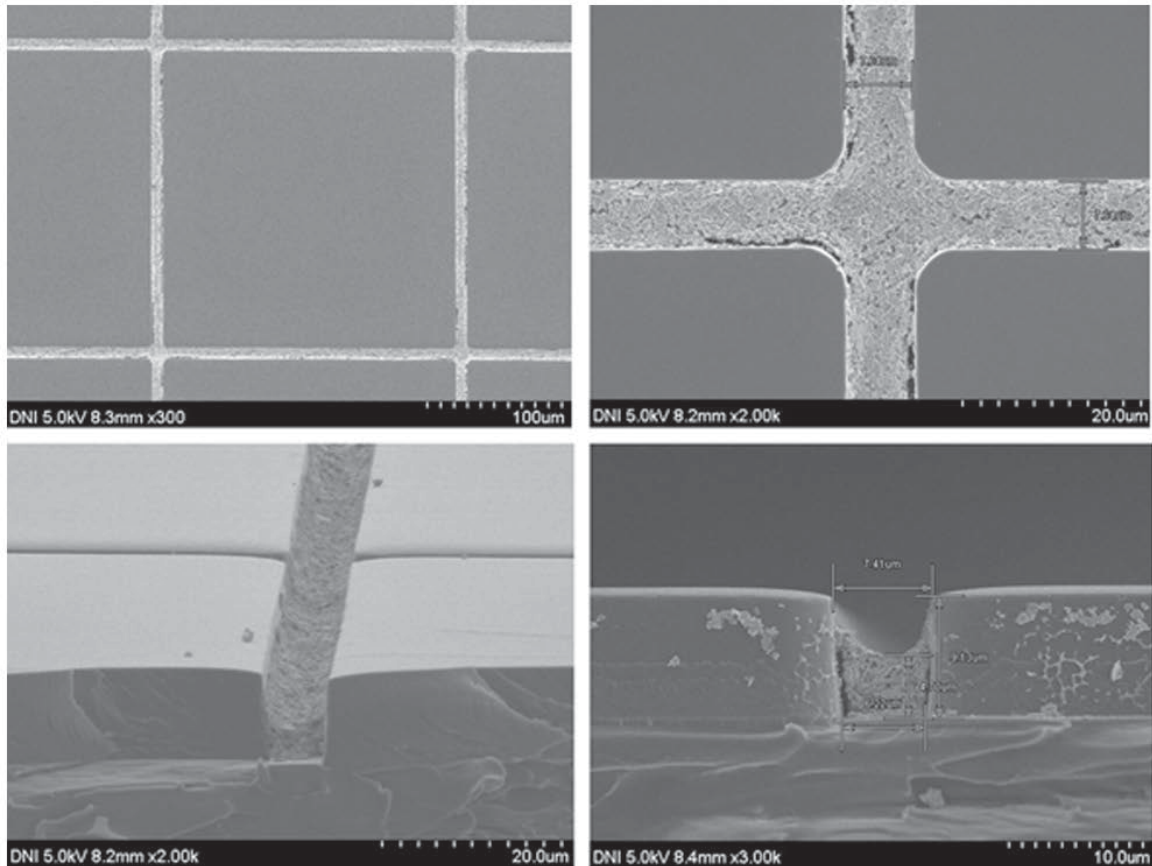
indicating good release performance during the imprinting process. A well-defined microchannel structure was obtained, with a channel width of approximately 6–7  $\mu\text{m}$  and a depth of about 10  $\mu\text{m}$ . The clear and uniform channel geometry is beneficial for the subsequent silver paste filling process because it provides sufficient space for paste confinement and helps form continuous conductive paths.



*Figure 3. Micro-mesh sample after UV imprinting*

Figure 4 presents the sample prepared with one silver paste filling cycle, followed by hot-plate heating at 130 °C for 3 min and IPL sintering at 400 V for 1000  $\mu$ s. The SEM image shows that the silver filling thickness was approximately 4.7  $\mu$ m, which occupied only about half of the channel

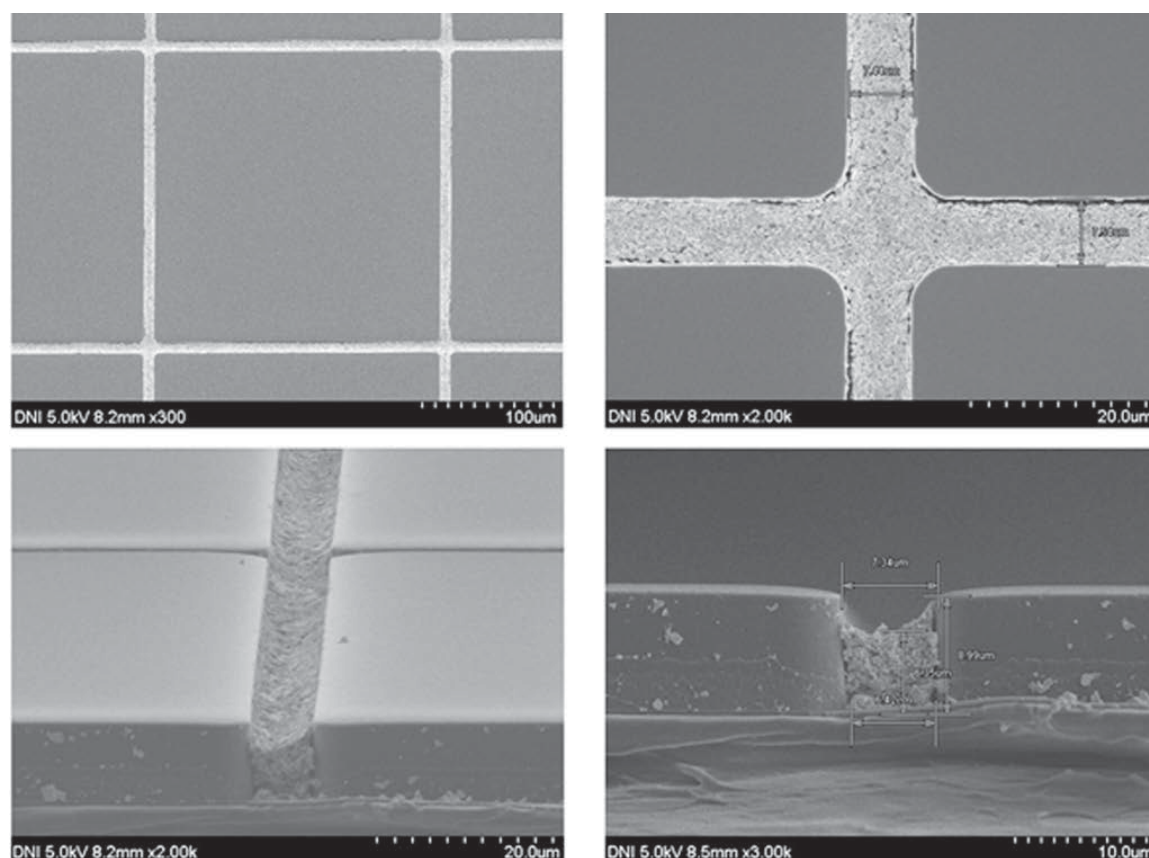
depth. The measured sheet resistance was 7  $\Omega$ /sq. Although the silver particles were successfully filled and sintered inside the microchannels, the filling amount was not sufficient to fully utilize the channel volume. Therefore, a second filling condition was investigated.



**Figure 4. Micro-mesh sample after 1 filling time(s)**

Figure 5 shows the sample prepared with two silver paste filling cycles under the same heating and IPL sintering conditions. The silver filling thickness increased to approximately  $6.35\ \mu\text{m}$ , and the sheet resistance decreased to  $4\ \Omega/\text{sq}$ . This result indicates that increasing

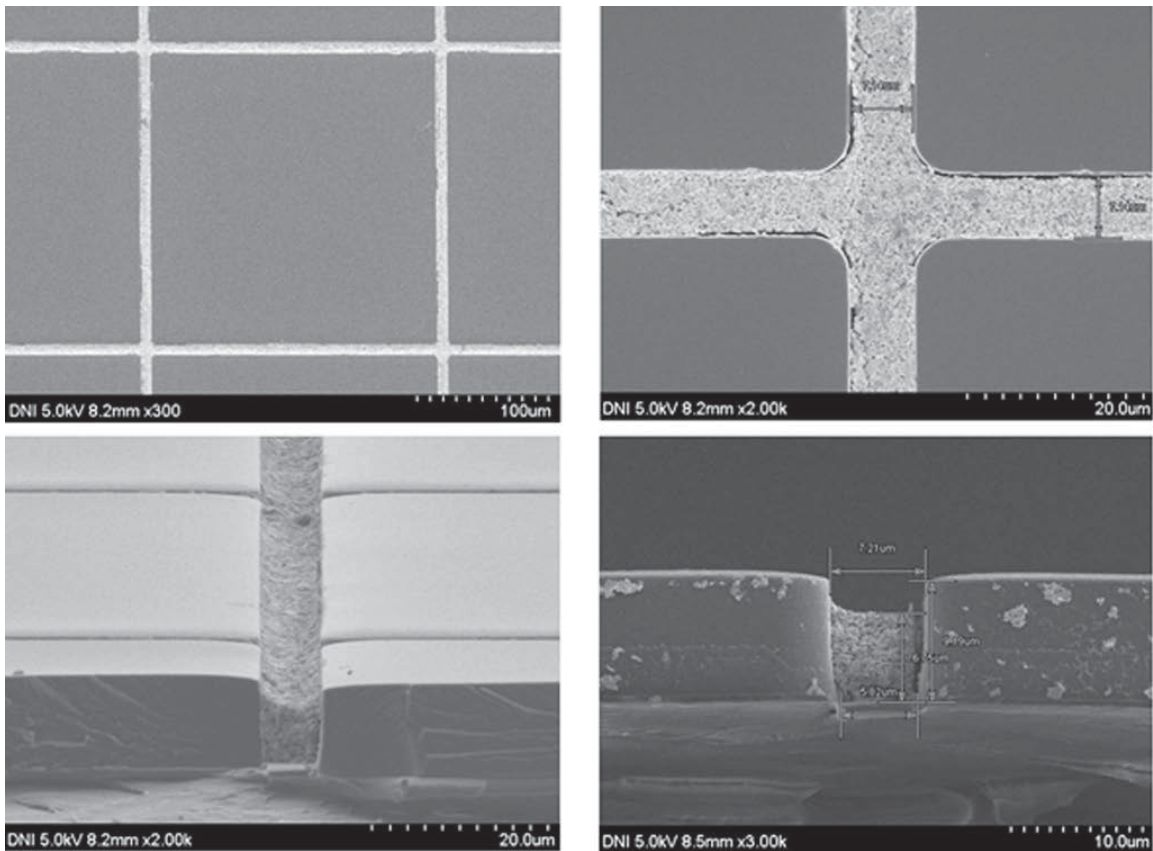
the number of filling cycles improved the amount of silver paste inside the microchannels and enhanced the electrical conductivity of the electrode. However, the microchannels were still not completely filled, so a third filling condition was further examined.



**Figure 5. Micro-mesh sample after 2 filling time(s)**

Figure 6 shows the sample prepared with three silver paste filling cycles, followed by the same heating and IPL sintering process. The SEM image shows that the silver filling thickness slightly increased to approximately  $6.75\text{ }\mu\text{m}$ , while the sheet resistance further decreased to  $3.5\text{ }\Omega/\text{sq}$ . Compared with the two-filling case, the improvement was relatively small: the filling thickness

increased only from  $6.35\text{ }\mu\text{m}$  to  $6.75\text{ }\mu\text{m}$ , and the sheet resistance decreased from  $4\text{ }\Omega/\text{sq}$  to  $3.5\text{ }\Omega/\text{sq}$ . This suggests that the filling process approached a saturation condition after two cycles. Nevertheless, both the two- and three-filling samples exhibited very low sheet resistance, which can be considered highly suitable for transparent conductive electrode applications.



**Figure 6. Micro-mesh sample after 3 filling time(s)**

Overall, all fabricated samples showed good silver particle distribution inside the microchannels after heating and IPL sintering. The SEM images indicate that the silver particles were well connected, confirming the effectiveness of the selected sintering condition. Small gaps were observed between the microchannel walls and the silver paste after drying and IPL sintering. These gaps may be attributed to the evaporation of solvent and organic

supporting components in the silver paste during thermal drying and photonic sintering. Despite this shrinkage effect, the silver structures remained continuous within the channels, and the resulting electrodes showed good electrical performance. Therefore, the fabricated microchannel-based silver electrodes demonstrate strong potential for flexible transparent conductive electrode applications. The summary results are shown in Table 2.

**Table 2. Silver filling thickness and sheet resistance**

| Number of filling cycles | Heating condition | IPL sintering condition   | Ag filling thickness ( $\mu\text{m}$ ) | Sheet resistance ( $\Omega/\text{sq}$ ) |
|--------------------------|-------------------|---------------------------|----------------------------------------|-----------------------------------------|
| 1                        | 130 °C, 3 min     | 400 V, 1000 $\mu\text{s}$ | 4.70                                   | 7.0                                     |
| 2                        | 130 °C, 3 min     | 400 V, 1000 $\mu\text{s}$ | 6.35                                   | 4.0                                     |
| 3                        | 130 °C, 3 min     | 400 V, 1000 $\mu\text{s}$ | 6.75                                   | 3.5                                     |

The optical properties of the samples remained almost unchanged with increasing number of silver paste filling cycles. As shown in Table 3, all samples exhibited a high transmittance of 94%, indicating that the silver-filled microchannel structure maintained excellent optical transparency even after repeated filling. The haze values were also low and relatively stable, ranging from 4.0% to 4.3%. The sample with two filling cycles showed the lowest haze value

of 4.0%, while the one- and three-filling samples showed the same haze value of 4.3%. These results indicate that increasing the filling number from one to three did not significantly reduce transparency or increase light scattering. Therefore, the proposed silver-filled microchannel electrode can achieve low sheet resistance while maintaining high optical transparency and acceptable haze. The optical properties are shown in Table 3.

**Table 3. Optical properties of samples with different filling cycles**

| Optical property  | 1 filling cycle | 2 filling cycles | 3 filling cycles |
|-------------------|-----------------|------------------|------------------|
| Transmittance (%) | 94              | 94               | 94               |
| Haze (%)          | 4.3             | 4.0              | 4.3              |

#### 4. CONCLUSION

In this study, a roll-to-roll-compatible process for fabricating flexible transparent conductive electrodes was developed using UV imprint lithography via a PET soft mold, silver nanoparticle paste filling, hot-plate heating, and IPL sintering. The two-step soft-mold imprinting process produced well-defined microchannels with a width of approximately 6–7  $\mu\text{m}$  and a depth of about 10  $\mu\text{m}$ , while the selected treatment conditions of 130 °C for 3 min followed by IPL sintering at 400 V for 1000  $\mu\text{s}$  formed continuous conductive

silver pathways. Increasing the filling cycles from one to three increased the silver thickness from 4.70 to 6.75  $\mu\text{m}$  and reduced the sheet resistance from 7.0 to 3.5  $\Omega/\text{sq}$ , although the improvement became smaller after two cycles. The electrodes maintained a high transmittance of 94% and low haze values of 4.0–4.3%. These optoelectrical properties are favorable compared with recently reported AgNWs–PEDOT:PSS electrodes with 27  $\Omega/\text{sq}$  and 90% transmittance (Dcosta, Ochoa, & Sanaur, 2024), Ti3C2Tx MXene films with 77  $\Omega/\text{sq}$  and 83.4% transmittance (Guo

et al., 2023), and Ag nanowire/dielectric multilayer electrodes with 19.8  $\Omega/\text{sq}$  and 83.4% transmittance (Yu, An, & Dong, 2026). Overall, the use of a flexible PET soft mold, rather than direct imprinting from a rigid silicon master, provides a practical basis for future integration of imprinting, silver filling, and IPL sintering into a continuous roll-to-roll manufacturing process.

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**Dr. Phan The Nhan:** Visualization, manuscript revision, figure editing, and manuscript editing.

**Artificial Intelligence (AI) Transparency Statement:**

☒ The author(s) declare transparency in the use of artificial intelligence (AI) tools. AI was not used to generate scientific content, develop research ideas, design methodologies, analyze data, or draw scientific conclusions in this study. If any AI-based tools were used, they were limited to technical assistance such as language editing or formatting. The authors take full responsibility for the content of this manuscript.

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# QUY TRÌNH UV IMPRINTING VÀ THIÊU KẾT BẰNG IPL TƯƠNG THÍCH VỚI ROLL-TO-ROLL ĐỂ CHẾ TẠO ĐIỆN CỰC TRONG SUỐT LINH HOẠT

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**Tóm tắt:** Điện cực dẫn điện trong suốt linh hoạt là thành phần quan trọng trong các thiết bị quang điện tử thế hệ mới, chẳng hạn như bảng cảm ứng, màn hình, pin mặt trời, bộ gia nhiệt trong suốt và thiết bị điện tử đeo được. Tuy nhiên, các điện cực indium tin oxide truyền thống bị hạn chế bởi tính giòn, chi phí cao và khả năng tương thích kém với các đế linh hoạt. Trong nghiên cứu này, một phương pháp chế tạo điện cực dẫn điện trong suốt linh hoạt tương thích với quy trình roll-to-roll được đề xuất bằng cách sử dụng UV imprint lithography, điền đầy hạt nano bạc, gia nhiệt trên bàn gia nhiệt và thiêu kết bằng ánh sáng xung cường độ cao (intense pulsed light, IPL). Một tấm silicon wafer có cấu trúc kênh dẫn micro được sử dụng làm khuôn chính để chế tạo khuôn mềm trên tấm nền PET. Khuôn mềm này sau đó được sử dụng để sao chép các kênh dẫn micro lên một tấm PET khác. Hạt nano bạc được điền vào các kênh dẫn micro bằng phương pháp phủ bang dao gạt, sau đó mẫu được gia nhiệt trên bàn gia nhiệt và thiêu kết bằng IPL để hình thành các vi cấu trúc bạc dẫn điện. Các kênh dẫn micro chế tạo được có chiều rộng khoảng 6–7  $\mu\text{m}$  và chiều sâu khoảng 10  $\mu\text{m}$ . Khi số chu kỳ điền đầy tăng từ một lên ba, chiều dày lớp bạc được điền đầy tăng từ 4,70 lên 6,75  $\mu\text{m}$ , trong khi điện trở tấm giảm từ 7,0 xuống 3,5  $\Omega/\text{sq}$ . Các điện cực duy trì độ truyền qua quang học khoảng 94%, với độ mờ dao động từ 4,0% đến 4,3%. Kết quả quan sát SEM xác nhận sự hình thành của các đường dẫn bạc liên tục, mặc dù xuất hiện một số khe do co ngót nhỏ gần thành kênh. Những kết quả này cho thấy tiềm năng của khuôn mềm trên tấm nền PET, quá trình điền đầy paste bạc nhiều lần và thiêu kết IPL nhanh trong việc chế tạo điện cực dẫn điện trong suốt dạng lưới kim loại linh hoạt với chi phí thấp và khả năng mở rộng quy mô trên hệ thống Roll-to-Roll.

**Từ khóa:** điện cực linh hoạt, hạt nano bạc, lưới kim loại, thiêu kết IPL, UV imprint lithography

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## Ghi chú

Các tác giả xác nhận không có tranh chấp về lợi ích đối với bài báo này.