



# Development of a full roll-to-roll manufacturing process of through-substrate vias with stretchable substrates enabling double-sided wearable electronics

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Received: 20 May 2020 / Accepted: 28 October 2020 / Published online: 6 November 2020  
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## Abstract

In the recent years, there has been a growing interest towards printed stretchable electronics used in diagnostics, health-monitoring, and wearable applications. Double-sided electronic circuits with through-substrate vias offer a solution where the amount of printed circuitry and assembled SMDs (surface-mount devices) in direct contact with the human skin can be minimized. This improves not only the wearability and cost-effectiveness of the printed electronic devices but also the product safety and comfort to wear. Another factor decreasing the unit costs in printed electronics is the use of high volume, high speed, and continuous roll-to-roll (R2R) manufacturing processes. In this current paper, a full R2R process for the manufacturing of through-substrate vias on stretchable thermoplastic polyurethane (TPU) substrate was developed and verified. The through-substrate via-holes were manufactured in R2R using either laser-cutting or die-cutting. Rotary screen printing was used to print conductive tracks onto both sides of the stretchable substrate and to fill the via-holes. Eventually, conductive and stretchable through-substrate vias with low sheet resistance and low resistance deviation were reliably achieved with the developed process.

**Keywords** Through-substrate via · Roll-to-roll · Stretchable electronics · Rotary screen printing

## 1 Introduction

Stretchable printed electronic devices have lately been utilized in diagnostics, health-monitoring, and wearable applications. The basic requirement for these devices is that they need to be in direct contact with the human skin. Therefore, they need to be comfortable-to-wear, adaptive to curved and dynamic surfaces, and withstand tensile strain and stretching without losing their electrical functionality. [1–4] For such devices, it is desired to minimize the amount of printed layers in direct contact with the skin for the increased product safety, circuit density, and wearability. Thus, most of the printed layers and assembled surface-mount-devices (SMDs) should be placed onto the opposite sides of the substrate. The realization of such double-sided electronic structures requires the manufacturing of reliable interconnections through the substrate by means of via-holes. [5–11]

Reliable via-hole fabrication and via-filling methods exist in conventional electronics but for the flexible and stretchable printed electronics, the availability of such methodologies is limited. In the printed electronics field, the manufacturing of the through-substrate vias has been so far concentrated on the sheet-based processes where multi-step, complex, high temperature, long-term, and even vacuum processes are combined with the printing technologies. [1, 2, 9–14]. Roll-to-roll (R2R) compatible manufacturing of the through-substrate interconnections has also been studied in sheet-to-sheet (S2S) environment using flexible substrates. [6, 15–19] However, in order to increase the throughput and lower the manufacturing costs significantly, the development of the full R2R processes of the through-substrate interconnects with stretchable substrates is of great importance.

The through-substrate interconnections have been previously manufactured onto flexible substrates, such as polyethylene naphthalene (PEN) [6, 9, 14, 19], polyethylene terephthalate (PET) [3, 8, 15, 16, 19], polyimide (PI) [10, 17–19], and paper [5, 7, 8, 11, 20], but not extensively onto stretchable substrates, such as poly(dimethylsiloxane) (PDMS) and thermoplastic polyurethane (TPU). So far, complex multi-step sheet-based processes with rigid carrier

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substrates and special release layers have been used to manufacture the double-sided circuits onto stretchable elastomer substrates. [1, 2, 8, 12, 13] In order to enable mass-manufacturing of, for example, wearable electronics or diagnostics devices, a more simplified and higher volume fabrication method for the through-substrate vias on stretchable substrate needs to be developed.

In printed electronics, the filling of the through-substrate via-holes is of great importance for the formation of reliable interconnections with low resistance. Typically, this has been achieved by printing multiple layers of conductive ink or adhesive directly into the via-holes either in a separate process or simultaneously with the printing of the electronic circuitry. [6, 7, 15, 16, 19] The separate filling step improves the interconnection quality and reliability but, unfortunately, at the same time the manufacturing costs and throughput time increase because of the need for the extra processing steps. [16, 18] The via-holes are either completely filled with ink or their sidewalls are uniformly covered with ink so that proper electrical contact can be formed between the electric circuitry located on the opposite sides of the substrate. [18, 21] Furthermore, it has been found that the printing of the conductive ink layer before the via-hole cutting might improve the interconnection quality by transferring some ink onto the sidewalls of the via-holes during the cutting. [7]

It is highly important in the case of stretchable electronics that the through-substrate vias withstand bending or stretching without losing their conductivity. Typically, the resistance of the printed vias increases during bending due to the formation of micro-cracks into the conductive layers on the substrate surface or inside the via-holes, or the increased disintegration of the conductive layers around the via-holes [6, 16]. In some cases, the printed layers can even delaminate from the surface of the substrate, thus losing their conductivity completely. Nevertheless, previous studies have shown that printed through-substrate vias manufactured onto flexible substrates can withstand thousands of bending cycles without a significant loss in conductivity [6, 10, 14, 16]. Instead, in the case of stretchable substrates, only the maximum elongation of the conductive vias has been investigated without considering the variable strain levels encountered in wearable applications. [2]

The via-hole size and shape play a major role in the performance and the reliability of the through-substrate interconnects. Via-holes with diameters less than 100  $\mu\text{m}$  are typically more difficult to cut and to fill because of the limitations in the resolution of the cutting process and in the ink flow into the via-hole. Larger via-holes, for their part, suffer easily from the insufficient filling. [6, 16–18] Conical via-holes, reproduced using laser-cutting, can keep the filling layer more reliably inside the via-holes rather than letting it flow through the hole as compared to the punched or drilled cylindrical via-holes. [6,

9, 16] Naturally, the viscosity of the ink has also a great influence on the ink flow and filling degree of the vias. Low viscous inks can easily flow through the hole completely, thus increasing the resistance value. [16]

In this study, a full R2R manufacturing process of the through-substrate vias on a stretchable TPU substrate is developed and verified. The R2R process consists of up to three different steps: (1) cutting of the via-holes using a  $\text{CO}_2$  laser or a rotary die-cutter, (2) rotary screen printing of via-hole fillings, and (3) rotary screen printing of required electrodes, wirings, and electronic circuits onto both sides of the stretchable substrate.

## 2 Experimental

### 2.1 R2R substrate pre-treatment and cutting of the via-holes

Via-holes were cut directly into a 100- $\mu\text{m}$ -thick stretchable TPU substrate, Platilon U073 from Covestro. The TPU substrate was acquired in rolls with a width of 300 mm. Prior to the R2R cutting and printing processes, a 75- $\mu\text{m}$ -thick PET carrier foil was laminated onto the backside of the substrate using a R2R converting line (Delta ModTech) and the substrate stack was thermally pre-treated in the hot air ovens of a R2R printing line. The carrier foil enabled the stabilized R2R processing of the stretchable substrate under web tension, whereas the thermal pre-treatment improved the alignment accuracy between the printed layers and cut via-holes. The carrier foil was semi-adhesive that ensured that the carrier foil could be easily peeled off from the TPU substrate after all the R2R process steps. During the thermal pre-treatment, the temperature of the hot air ovens was set to 140  $^\circ\text{C}$ , the process speed was 5 m/min, and the dwell time in the ovens was 45 s.

The R2R cutting of the via-holes through the TPU substrate was done with either a  $\text{CO}_2$  laser or a rotary die-cutter. Both of the cutting devices were installed into the R2R converting line. The wavelength of the laser was 10.6  $\mu\text{m}$ , the focus point was 400  $\mu\text{m}$ , and the beam diameter was 500  $\mu\text{m}$  at the focus point. In addition, the laser was equipped with a beam attenuator to enable cutting of thin plastic films without damage. Initially, the process parameters of the R2R laser-cutting needed to be carefully optimized to avoid burning and melting of the substrate, minimize the amount of cutting residues around the via-holes, and reproduce via-holes accurately. The cutting speed was set to 1 m/min. In the first two laser-cutting experiments, the energy density of the laser was 0.09  $\text{kJ}/\text{cm}^2$ , the frequency 10 kHz, and pulsed power density from 0.9  $\text{kW}/\text{cm}^2$ . After the optimization of the laser-cutting system, the energy density could be decreased to 0.01  $\text{kJ}/\text{cm}^2$ , the frequency to 5 kHz, and pulsed power density to 0.1  $\text{kW}/\text{cm}^2$ . This also improved the process stability.

In the case of the R2R die-cutting, the geometry of the cutting tool had a larger effect on the quality of the via-holes than the process parameters. The suitable tool geometry depends mostly on the substrate properties, such as thickness and softness. The optimum thickness of the die-cutting plate was found to be 154  $\mu\text{m}$  with a blade height of 450  $\mu\text{m}$ . The process speed of the die-cutting was 2 m/min. For the rotary die-cutting, two laminated PET carrier foils had to be used to enable the reliable separation of the cutting debris from the TPU substrate, as shown in Fig. 1.

The manufactured through-substrate via-holes were circular and their designed diameters ranged between 1 and 10 mm for both via-cutting methods. Additionally, smaller via-holes having a diameter of 100  $\mu\text{m}$  and 300  $\mu\text{m}$  were fabricated onto the un-printed TPU substrate with the  $\text{CO}_2$  laser-cutting to study the resolution limits of the utilized R2R laser process. The minimum diameter of 1 mm was selected because of the limited resolution of the die-cutting tool as well as the trouble-free separation of the die-cutting debris from the TPU substrate. In this study, a single large via-hole per a single interconnection was cut rather than several smaller via-holes in close proximity to each other.

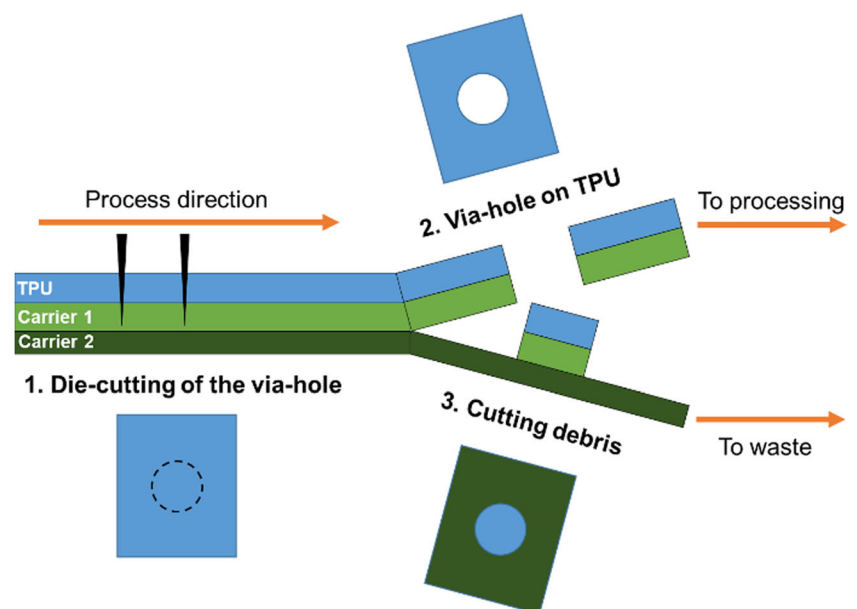
## 2.2 R2R printing of through-substrate vias

In order to manufacture conductive interconnections through the substrate, the via-holes were filled and the electrodes and other conductive tracks and circuitry were printed onto both sides of the stretchable TPU substrate using the rotary screen printing. The via-holes were filled either simultaneously with the printing of the other layers or in a separate via-filling process. The electrodes facing the skin were printed with the

CI-4040 silver/silver chloride (Ag/AgCl) ink from Engineered Conductive Materials. Other conductive tracks and circuitry as well as the separate via-fillings were printed with the CI-1036 silver (Ag) paste from Engineered Conductive Materials. The conductive tracks and circuitry were printed on the opposite side of the substrate than the Ag/AgCl electrodes. The filling layer, for its part, was printed on the top or bottom side of the substrate depending on the process configuration. All the layers were printed at the speed of 2 m/min and dried at 140  $^{\circ}\text{C}$ . The dwell time in the ovens of the R2R printing line was 3 min. Different screen types (Table 1), i.e., ink transfer volumes, were used to analyze the effect of the amount of ink inside the via-holes on the quality of the through-substrate vias.

Totally, four different R2R process configurations were tested to manufacture the through-substrate vias onto the stretchable TPU substrate. Figure 2 clarifies these different configurations and pattern layouts. The purpose was to determine the effects of the process order as well as the more complex layout on the successful manufacturing of the R2R through-substrate interconnections. The via-holes were cut either before or after the printing of the first layer. However, the cutting was always done from the side that was printed first. The order of printing was varied between the filling, electrode, and circuitry layers. In process 1 and process 2 configurations, simple via layouts were used to study mainly the effects of the cutting method, via-hole diameter, separate filling step, and ink layer thickness on the performance of the through-substrate interconnections. Process 3 and process 4 configurations, for their part, were used to manufacture electrodes and lead wires for electrocardiogram (ECG) devices. Hence, these configurations used longer run lengths and more complex

**Fig. 1** Schematics of the rotary die-cutting process using two PET carrier foils



**Table 1** Properties of the used screen types during the R2R printing of the vias. x states the screens used during process 1 and process 2 configurations and o states the screens used during process 3 and process 4 configurations

Screen	Mesh count (meshes/in.)	Open area (%)	Wet ink layer thickness (μm)	Electrode	Filling	Wiring
1	75	53	190		o	
2	215	29	18	xo		xo
3	64	56	120		xo	x
4	100	36	90		x	x
5	88	39	40			x

layout designs, thus giving also some information about the process stability and reliability.

### 2.3 Performance of the through-substrate vias

The performance of the R2R manufactured through-substrate interconnections was analyzed by measuring the resistance between the Ag/AgCl electrode and the Ag electronic circuitry located on the opposite side of the substrate. A common digital multimeter (FLUKE 289) was used for the measurement. At each test point, several dozen interconnections were measured to determine the amount of working, i.e., conductive (resistance less than 50 Ω), interconnections, and calculate their resistance deviations. In addition, the sheet resistance and its deviation values were calculated both within and between test points to evaluate the process stability and to compare the performance of the different process configurations.

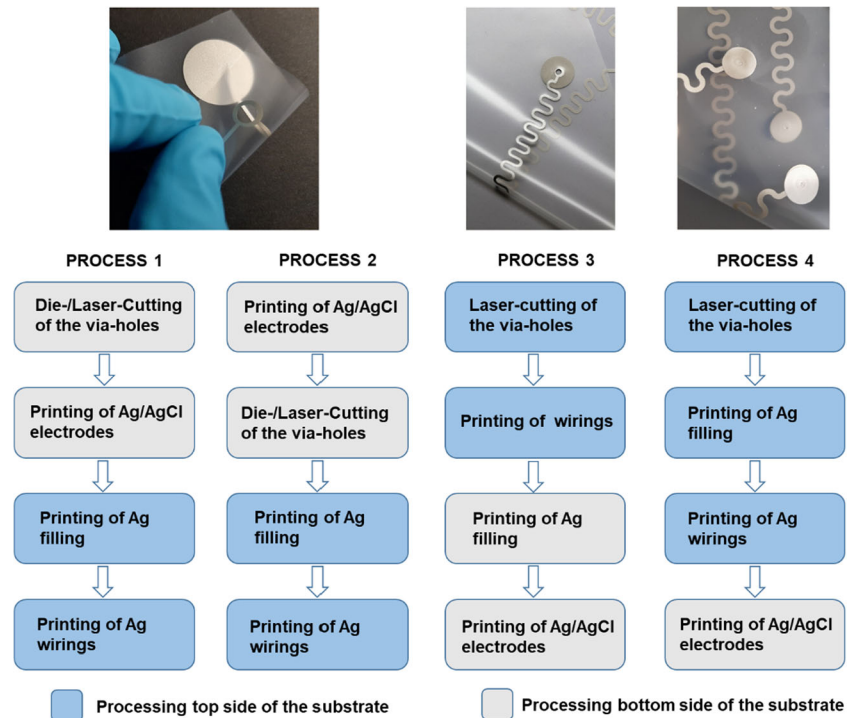
The stretchability of the through-substrate vias was measured using a test setup, shown in Fig. 3. The setup measured constantly the resistance between the Ag/AgCl electrode and the Ag circuitry located on the opposite side of the substrate. The measurement was performed in a cyclic manner: the printed samples were stretched 20% after which the stretch was released and an average resistance of the cycle was recorded. The amount of stretching cycles was 100.

## 3 Results

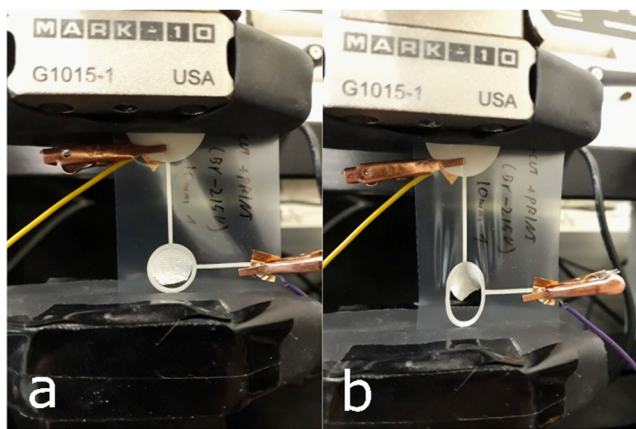
### 3.1 Cutting quality of the via-holes

Through-substrate via-holes can be produced in R2R cutting processes using both the rotary die-cutting and the CO<sub>2</sub> laser-cutting. It can be observed from Table 2 that all the investigated via-hole diameters from 1 to 10 mm can be produced

**Fig. 2** R2R process configurations for the manufacture of the through-substrate interconnections







**Fig. 3** Test setup for the measurement of the stretchability of the through-substrate interconnections. The substrate is initially in a relaxed state (a) after which the sample is stretched (b) before returning to the relaxed state

using both of the cutting methods either before the printing of the Ag/AgCl electrodes or after it. Die-cutting reproduces accurately the nominal diameters of the via-holes whereas laser-cutting increases the nominal diameters by approximately 0.5 mm in process configurations 1 and 2. In addition, the standard deviation of the diameter of the die-cut via-holes is smaller than in the case of the laser-cutting, thus being able to reproduce different via-hole sizes more evenly. After the optimization of the laser-cutting system, the diameters of the laser-cut via-holes obtained in process configurations 3 and 4 are close to their designed nominal values and the standard deviation of the via-hole diameter decreases closer to the deviations achieved in the die-cutting process.

The die-cutting (Fig. 4a, b) has no visual effect on the quality of the printed layer or the via-holes, thus allowing the cutting to be performed either before or after any printing. Figure 4c shows that the laser beam can burn the printed layer near the edge of the via-hole when the cutting is done after the printing of conductive patterns. This may easily prevent the formation of the electrical contact between the electrode and the ink layer located inside the via-hole either completely or partially. Therefore, laser-cutting needs to be done prior to the printing steps, as illustrated in Fig. 4d. The observed

misalignments between the via-holes and printed patterns result from process fluctuations encountered typically in R2R processes when automatic registration systems are not in use. This should not have any effect on the performance of the through-substrate interconnections since misalignments as large as 1 mm in every direction were taken into account already in the layout design. Therefore, ink will cover the via-holes completely in both sides of the substrate although the via-holes are not perfectly located in the middle of the printed pad.

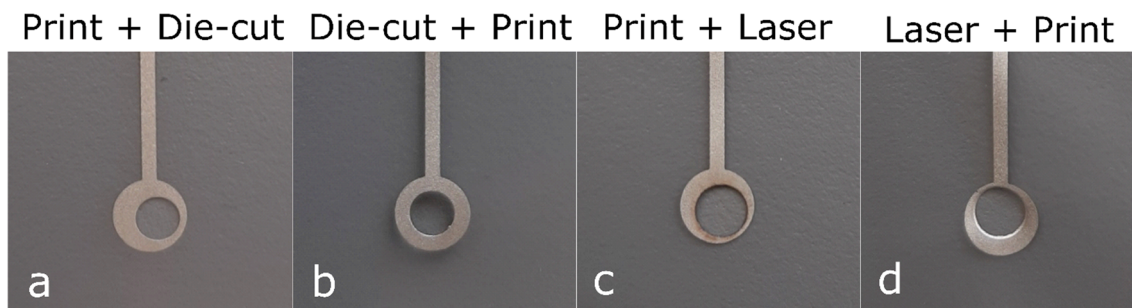
Table 3 presents the diameter of the die-cut and laser-cut through-substrate via-holes measured from both the front side and backside of the cutting, thus giving information about the shape of the via-hole. Die-cutting reproduces cylindrical via-holes with only slightly different diameters. Laser-cut via-holes, for their part, are conical due to which the diameter of the 1.5 mm via-hole is 0.14 mm larger on the cutting side of the substrate than on the backside of the substrate. Therefore, it is beneficial to fill the laser-cut via-holes from the cutting side of the substrate, as in process configuration 4, in order to keep the ink more easily inside the via-hole and to prevent excessive ink flow through the substrate.

In rotary die-cutting, the minimum via-hole diameter is near 1 mm. The limiting level arises from the resolution of the cutting tool and the removal of the cutting debris in the R2R process. However, with the R2R CO<sub>2</sub> laser-cutting, it is also possible to manufacture via-holes having the diameter less than 1 mm, as shown in Table 4. The minimum reliable diameter of the via-hole of the utilized R2R laser-cutting setup is 300 μm. With smaller diameters, only 65% of the via-holes span completely through the substrate and the deviation of the via-hole diameter increases from 3.5 to 16.9%.

From their applicability point of view, both of the cutting methods have their own advantages and challenges and the method should be selected according to the application. R2R laser-cutting is often preferred over R2R die-cutting because of its simpler and faster changes in the cutting layout and its potential to use smaller via-hole sizes. However, the laser beam can easily burn the plastic substrate and printed layers near the via-hole edges. Therefore, a lot of effort for the

**Table 2** Effect of the cutting method on the measured diameter of the via-holes in process 1 and process 2 configurations. The effect of the optimization of the laser-cutting process in process 3 and process 4 configurations on the via-hole diameters is marked as italic

Nominal diameter	Measured diameter (mm)		Difference to nominal (mm)		Standard deviation (μm)	
	Die-cut	Laser	Die-cut	Laser	Die-cut	Laser
1 mm	0.98	1.50/0.98	0.02	0.50/0.02	9	55/14
1.5 mm	1.48	2.03	0.02	0.53	10	67
2 mm	1.97	2.52/2.00	0.03	0.52/0.00	14	31/27
3 mm	2.95	3.52	0.05	0.52	19	53
5 mm	4.95	5.53	0.05	0.53	15	40
10 mm	9.91	10.51	0.09	0.51	28	63



**Fig. 4** Effect of the R2R cutting method on the quality of the via-holes. The cutting was done either after (a, c) or before (b, d) the printing of the first layer. The nominal diameter of the via-hole is 3 mm

optimization of the cutting parameters is required, in particular, if several different via-hole diameters are produced at the same time. In the case of rotary die-cutting, all the via-holes diameters are easily and reliably reproduced and it is well-suited for long production runs. However, the process resolution is limited and a new tool needs to be manufactured and optimized for every layout and substrate. This increases easily the process costs and lead times.

### 3.2 Performance of the printed interconnections

The printing of the separate filling layer in process configurations 1 and 2 improves the filling degree of the via-holes by introducing more ink into the via-holes, as can be seen from Fig. 5. In addition, by increasing the ink transfer volume during the printing of the electronic circuitry, the via-filling degree increases even without the separate filling step. However, this higher ink transfer volume limits the achievable print quality and resolution.

However, as discussed in the introduction chapter, only the sidewalls of the via-holes have to be evenly covered with the ink for the formation of a proper interconnection through the substrate. Figure 6 shows that uniformly covered sidewalls, thus, a proper electrical contact through the substrate, can be achieved by using the separate filling step without needing to increase the ink transfer volume during the printing of the other layers. Without the separate filling step, the sidewalls are only partially covered with the ink and no proper physical contact is formed between the sides of the substrate. As a

result, the electrical contact through the substrate is either completely broken or highly uneven.

As expected, the separate filling layer decreases also the resistance (Fig. 7a) and resistance deviation (Fig. 7b) of the interconnection by introducing more ink into the via-hole and ensuring a more even coverage of the sidewalls of the via-holes. Thus, all the filled through-substrate interconnections are working (Fig. 7c) and have low sheet resistance values of less than 100 m $\Omega$ /square. The amount of working interconnections decreases expectedly when the via-holes are left unfilled and the ink transfer volume of the electronic circuitry layer gets smaller.

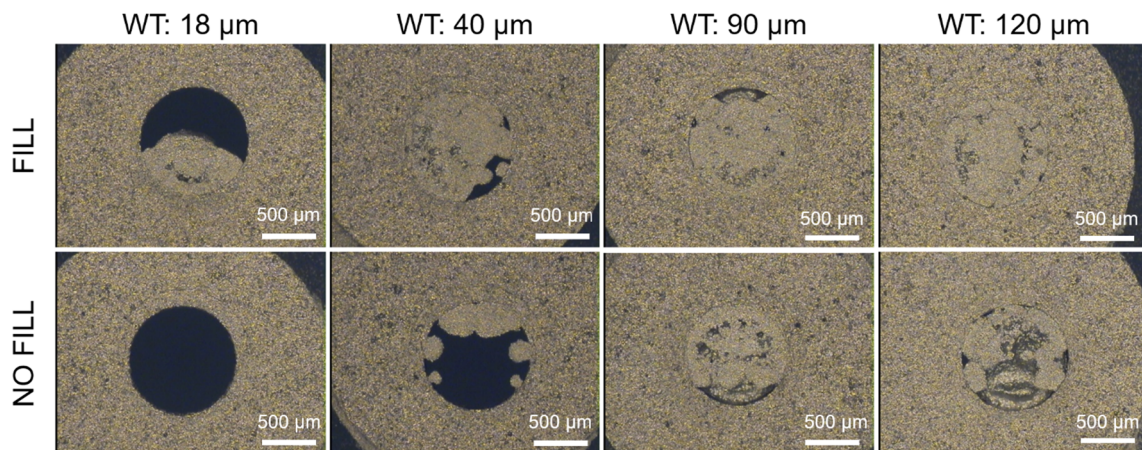
Figure 8 shows the effect of the R2R cutting method as well as the process configuration on the interconnection quality of the separately filled via-holes. According to the results, when the R2R cutting is done as the first process step (Laser + Print or Die-cut + Print), through-substrate interconnections have low sheet resistance and sheet resistance deviation values and all the interconnections are working despite the cutting method. The laser-cutting done after the printing of the electrodes (Print + Laser) decreases the performance of the through-substrate interconnection. As shown earlier, this results from the fact that the laser beam partially burns the printed layer around the via-holes, thus preventing the formation of the electrical contact. For the die-cut samples, on the other hand, smaller sheet resistance values of the interconnections are achieved when the via-holes are cut only after the printing of the electrodes (Print + Die-cut). As discussed earlier, this comes from the partial ink layer penetration into the via-holes caused by the cutting tool [7].

**Table 3** Diameter of the laser-cut and die-cut through-substrate via-holes (nominal diameter 1 mm) measured both from the front side and backside of the cutting

Cutting method	Via-hole diameter (mm)		
	Front	Back	Difference
Die-cut	0.97	0.98	-0.01
Laser	1.50	1.36	0.14

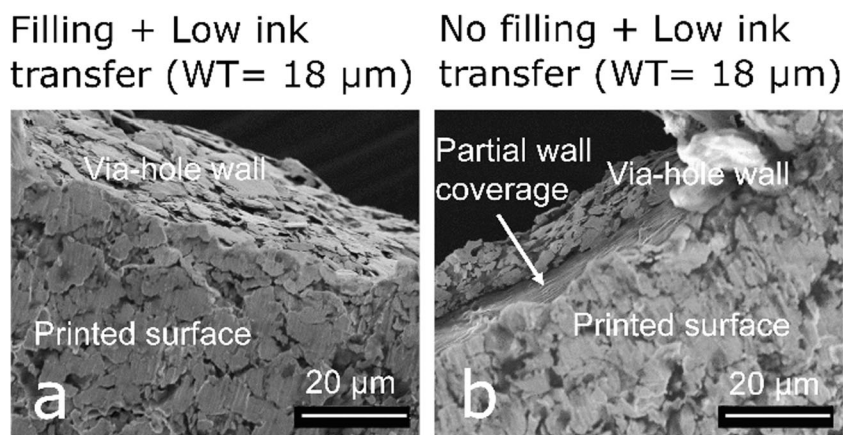
**Table 4** Dimensions and cutting yield of the smaller (100 and 300  $\mu$ m) via-holes cut with the CO<sub>2</sub> laser

Nominal diameter	Measured via-hole diameter		Amount of open via-holes (%)
	Average ( $\mu$ m)	Std. (%)	
100 $\mu$ m	122	16.9	65
300 $\mu$ m	308	3.5	100



**Fig. 5** Effect of the separate filling layer and the ink transfer volume (WT = theoretical wet ink layer thickness of the screen) of the wiring layer on the visual quality of the interconnections. The via-holes are die-cut and the via-hole diameter is 1 mm

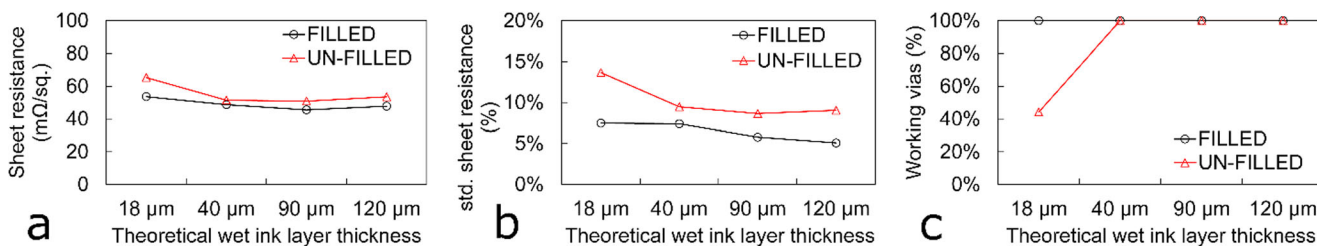
**Fig. 6** Completely covered (a) and partially covered (b) sidewall surfaces of the via-holes



The size of the via-holes has minor effect on the interconnection quality. As shown in Fig. 9, the sheet resistance of the through-substrate interconnection decreases slightly from 58 to 48 mΩ/square as the via-hole diameter increases from 1 to 10 mm. This results from the larger area of the sidewalls of the via-holes that in turn increases the contact area between the two sides of the substrate as well as the amount of ink inside the via-hole. However, the removal of the carrier foil after the R2R process steps causes cracking or partial detachment of the via-hole

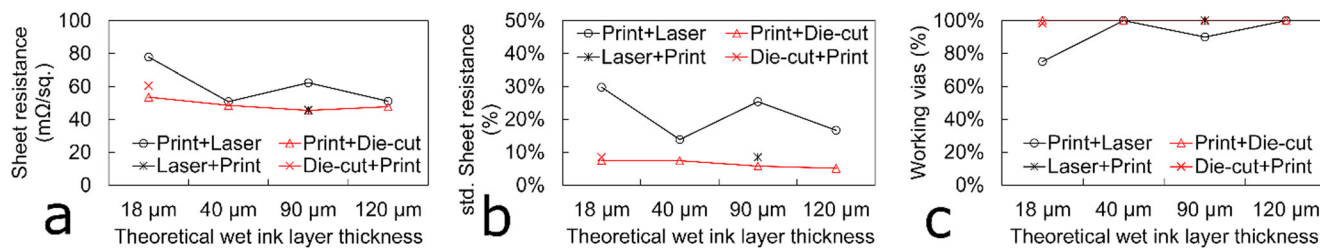
fillings (Fig. 10). This phenomenon is more visible as the via-hole diameter increases, thus impairing the visual appearance of the interconnection but fortunately without disrupting the performance of the interconnections. Consequently, smaller via-hole diameters are preferred in the developed R2R process to achieve not only functional but also visually appealing interconnections.

In Table 5, the performance of the through-substrate interconnections using different process configurations in the case of the conical-shaped CO<sub>2</sub> laser-cut via-holes is

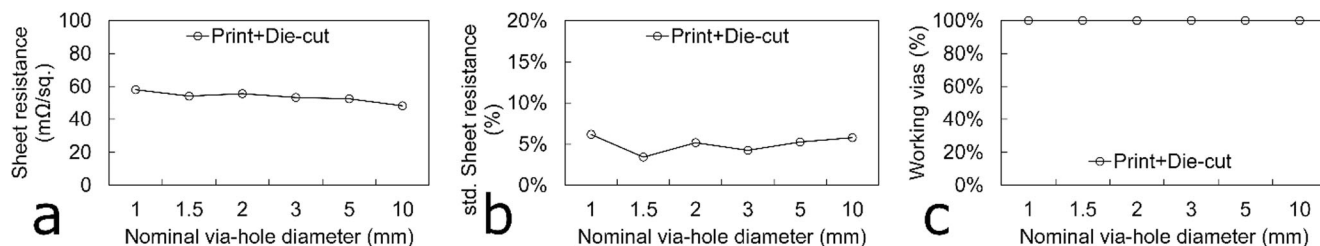


**Fig. 7** Effects of the separate filling layer and the ink transfer volume of the circuitry layer on the sheet resistance (a), sheet resistance deviation (b), and amount of working vias (c) in the case of die-cut via-holes (1 mm diameter)

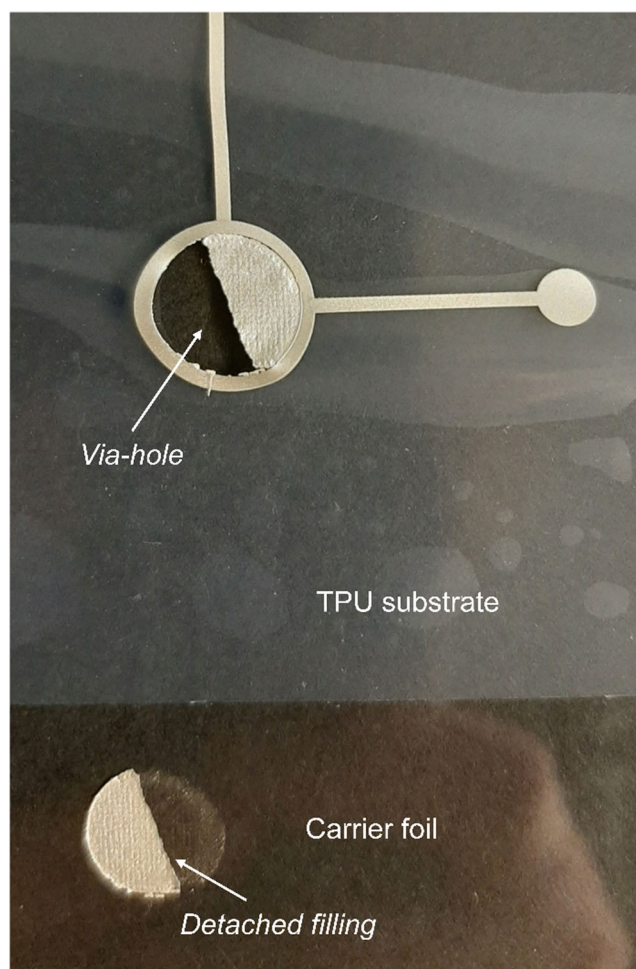




**Fig. 8** Sheet resistance (a) and sheet resistance deviation (b) of the through-substrate interconnections, and amount of working interconnections (c) using different cutting methods and process configurations. The via-hole diameter is 1 mm



**Fig. 9** Effect of the diameter of the via-hole on the sheet resistance (a) and sheet resistance deviation (b) of the through-substrate interconnections as well as the amount of working interconnections (c). The via-holes were separately filled and the theoretical wet layer thickness of the wiring layer was 18  $\mu\text{m}$



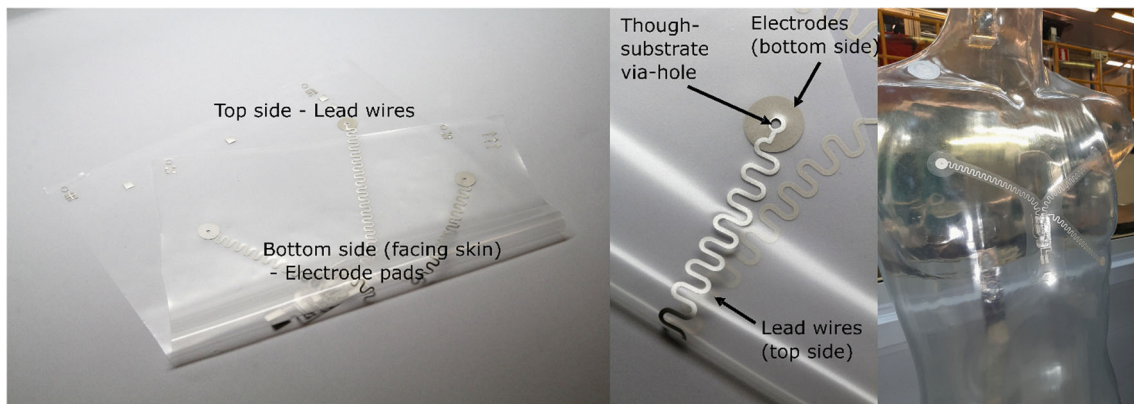
**Fig. 10** Effect of the carrier foil removal on the via-hole filling

shown. When the filling is done from the same side as the cutting (process 4), the sheet resistance deviation is smaller in comparison to those fabricated using the other process configurations. The diameter of the conical via-hole decreases towards the other side of the substrate, thus allowing the filling layer to attach better and more evenly onto the sidewalls of the via-holes and preventing, to some extent, the ink flow through the via-holes [6, 9, 16]. Nevertheless, all the investigated process configurations give low sheet resistance values of less than 50  $\text{m}\Omega/\text{square}$  and a high amount of working through-substrate interconnections on the stretchable TPU substrate. Therefore, the developed R2R process enables the reliable realization of the double-sided electronics in wearable applications and simultaneously increases the product safety by minimizing the amount of printed and assembled layers in direct contact with the skin, as shown in Fig. 11.

**Table 5** Performance of the laser-cut and filled through-substrate vias using different process configurations. In each process configuration, 30–240 individual vias were tested

Process	Filling	Sheet resistance ( $\text{m}\Omega/\square$ )	Sheet resistance deviation	Amount of working vias
Process 1	Backside, 90 $\mu\text{m}$	46.7	7.5%	100%
Process 3	Backside, 190 $\mu\text{m}$	46.2	9.3%	100%
Process 4A	Front side, 120 $\mu\text{m}$	48.7	4.1%	100%
Process 4B	Front side, 90 $\mu\text{m}$	44.3	5.6%	100%





**Fig. 11** R2R-printed ECG electrodes (facing the skin) and lead wires with through-substrate vias on the stretchable TPU substrate. The diameter of the via-hole is 2 mm

### 3.3 Stretchability of the through-substrate vias

The through-substrate interconnections should withstand variable stretching to allow their usage in wearable applications. As expected, the average resistance of the interconnections increases as the number of stretching cycles increases (see Fig. 12). This results from the increased amount of micro-cracks and dissociations of the conductive particles within the printed layers. [6, 16]

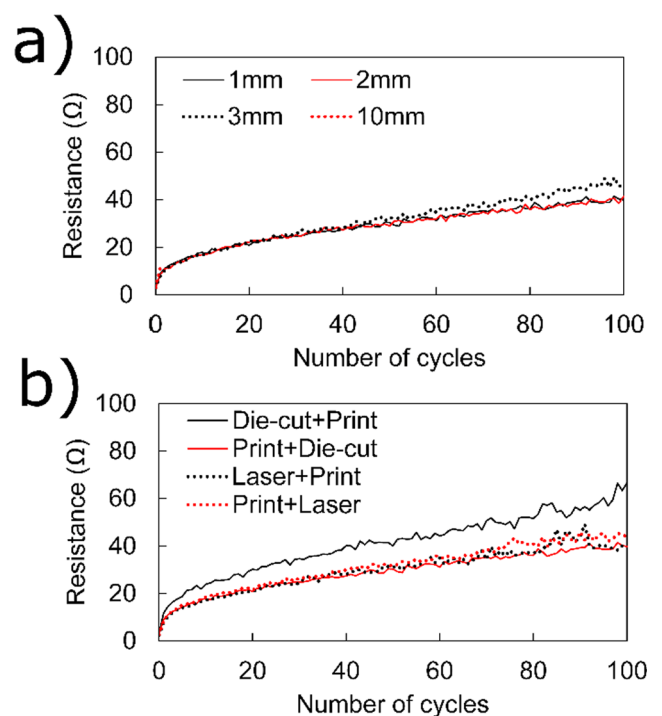
Interconnections, of which the diameter of the via-hole is smaller than 3 mm, withstand easily the tested 100 stretching cycles. As the via-hole diameter increases further, the area being stretched increases and the support from the substrate to the filling layer decreases, thus breaking the electrical connection through the substrate already after just a few stretching cycles (Fig. 12a). The process configuration or the cutting method of the via-hole has no effect on the stretchability but on the resistance increase levels during the stretching cycles to some extent, as shown in Fig. 12b. For example, when the die-cutting is done before the printing (Die-cut + Print), the resistance increase is the highest resulting probably from the fact that the ink cannot fill the cylindrical via-holes as evenly as with the conical laser-cut via-holes. The via-hole cutting after the printing of the first layer (Print + Die-cut) decreases the level of the resistance increase because of the fact that some ink is pushed onto the sidewalls of the via-holes during the cutting [7].

According to results given in Fig. 13, the separate filling of the via-holes improves the stretchability. Filled via-holes withstand a higher number of stretching cycles and have slower resistance increases during the stretching cycles. This comes from both the more uniform sidewall coverage of the via-holes as well as the better bonding of the conductive ink particles to the sidewalls of the via-holes, as shown previously in Fig. 6. Although the higher ink transfer of the circuitry layer increases the amount of ink inside the via-holes, the stretchability of the interconnection decreases resulting probably from the weaker bonding of the ink particles onto the sidewalls. At the same time, it is assumed that the brittleness of this thicker layer

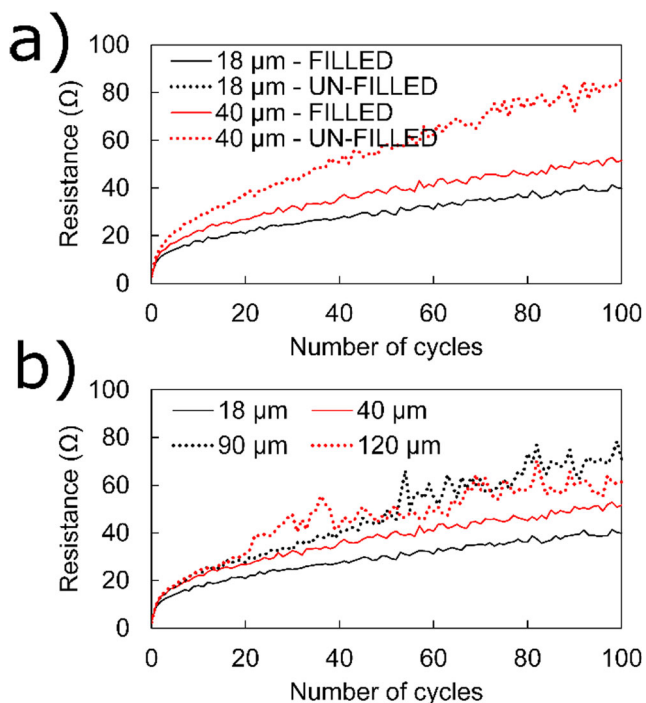
increases and more micro-cracks that increase the resistance are formed into the printed layer. This was also seen from Fig. 10, where the via-hole filling cracked more easily with larger via-holes when removing the carrier foil.

## 4 Conclusions

This paper shows that through-substrate electrical interconnections could be reliably manufactured onto stretchable TPU substrates using the developed R2R process. This process was divided into three parts: the cutting of the via-holes (1), the filling of the via-holes by rotary screen printing (2),



**Fig. 12** Stretchability of the R2R manufactured vias as a function of the via-hole diameter (a) and the process configuration (b) using a via diameter of 1 mm



**Fig. 13** Effect of the separate filling process of the via-holes (a) and the ink transfer volume of the circuitry layer (b) on the stretchability of the through-substrate vias. The via diameter is 1 mm

and the printing of the electronic circuits onto both sides of the substrate (3). The developed process offered:

- Fast, simple, and cost-effective manufacturing of double-sided electronic circuits
- Improved product safety and wearability by decreasing the amount of materials and SMDs in direct contact with the human skin
- Simplified circuit design as compared to the single-sided electronics

R2R cutting of the via-holes was performed either with CO<sub>2</sub> laser or with rotary die-cutter. The cutting method and process configuration should be selected according to the final application and device targets.

- Both of the cutting methods could reproduce reliably via-holes having the width between 1 and 10 mm. Even smaller via-holes (300 μm) were achieved with the CO<sub>2</sub> laser.
- Laser-cutting produced conical via-holes whereas cylindrical via-holes were achieved with rotary die-cutting. However, no difference in the filling or via-performance was seen between these two shapes.
- Die-cutting reproduced via-holes at high and even quality. In particular, this method was found to be suitable for long process runs because of the lead times with the cutting tool. The resistance of the through-substrate interconnection decreased when the cutting was done after the printing of the

first conductive layer since some conductive material was introduced into the via-holes during the cutting.

- Laser-cutting offered fast process and layout changes but the cutting should always be done as the first process step and the process parameters required heavy optimization to avoid any burning of the printed layer or the substrate near the edges of the via-holes. The filling of these via-holes improved slightly when the filling was done from the same side as the cutting because of the conical shape of the via-hole.

The filling and printing onto both sides of the substrate using rotary screen printing enabled the fabrication of the through-substrate interconnections and double-sided electronic circuits with good performance, i.e., high yield, low, and even resistance, as well as high stretchability. The main conclusions of the R2R printing of the double-sided circuits were the following:

- Separate printing of the filling layer improved the performance, evenness, and stretchability of the vias by increasing the amount of ink inside the via-holes, making the sidewall coverage more even and complete, and improving the ink bonding onto the sidewalls of the via-holes.
- Stretchability of the vias got better with smaller via-holes by decreasing the area under stretching and increasing the support to the printed layers from the substrate.

The technology readiness level (TRL) of the developed R2R manufacturing process of the through-substrate interconnections is currently at the level of 6–7 (validation phase). The process has been validated, tested, and operated in the developed high-volume R2R fabrication process. However, some more detailed and more profound analysis of the process stability and repeatability is still needed before entering the commercial phase.

**Acknowledgments** Part of the facilities used were provided by the Academy of Finland Research Infrastructure “Printed Intelligence Infrastructure (PII-FIRI, grant no. 32020). The writers would thank Hannu Sääskilähti, Teemu Jurvanen, Anne Peltoniemi, Markus Tuomikoski, Jari Rekilä, and Pentti Korhonen for their contribution to the R2R manufacturing process, measurement assistance, and layout design. A special thanks goes to Thomas Kraft for his views of the structure of this paper.

**Authors’ contributions** The corresponding author E. Jansson has been responsible for writing this paper, planning, and developing the R2R manufacturing runs, layout designs, and measurements, determining the most suitable materials for the via manufacturing, and analyzing all the obtained raw data. A. Korhonen was responsible for the measurement of the stretchability of the vias. He also developed the stretching test setup and optimized the test conditions for the stretchable through-substrate vias. M. Hietala was responsible for the development of the R2R cutting processes and taking part in the layout design. T. Kololuoma was responsible for determining the suitable structure and contents of this paper. His expertise was also needed in the planning of the R2R print runs.

**Funding** Open access funding provided by Technical Research Centre of Finland (VTT). Research work was completely funded by VTT Technical

Research Centre of Finland. Part of the facilities used were provided by the Academy of Finland Research Infrastructure “Printed Intelligence Infrastructure (PII-FIRI, grant no. 32020).

**Data availability** The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials. The raw data that support the findings of this study are available from the corresponding author, [E. Jansson], upon a reasonable request.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Code availability** Not applicable.

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