Ink development and printing of conducting polymers for intrinsically stretchable interconnects and circuits

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Abstract: Printable elastic conductors open up new opportunities in large-area fabrication of wearable electronics and prosthetics. Furthermore, they have the potential to advance health monitoring and continuous diagnostics by implementing sensor arrays in close proximity to the skin. Such devices need to be comfortable to wear and must accommodate strains and deformations such as twisting and stretching. Here, we introduce a conductive polymer ink for elastic interconnects and electrodes. The processability by inkjet printing enables versatile, contactless and maskless large area processing. Our printed PEDOT:PSS-based interconnects have conductivities as high as 700 S/cm, sustain strains above 100% and show good stability in air (less than 5% change in resistance in one month). The conductivity is among the highest reported for inkjet-printed PEDOT:PSS and makes this work interesting not only for stretchable circuits, but also for printed flexible and rigid PEDOT:PSS-based applications such as solar cells, OLEDs or electrochemical sensors.

1. Introduction

Traditional electronics are rigid and stiff and are typically fabricated on silicon wafer or glass substrates. However, research over the past two decades has shown the possibility of realizing flexible electronic circuits on plastic and paper. Given the significant advancements in flexible electronics, there has been a growing interest in realizing wearables on similar substrates. Emerging areas are artificial skin on prosthetics or epidermal, health-monitoring sensors to bring personalized medicine to the next level. These envisioned electronic devices should

ideally be conformable to the skin and/or accommodate for deformations such as twisting and stretching. Therefore, the next frontier is to merge mechanical and electrical requirements and realize not only flexible but also elastic electronics that are compatible with the soft, curvilinear surfaces of biological tissue.^[1–10]

Recent progress in stretchable, conductive polymers has led to a number of intrinsically stretchable devices and sensors including stretchable transistors,^[11–15] logic circuits,^[16,17] light emitting devices,^[18–20] strain,^[20–22] touch^[23] and temperature^[24,25] sensors. Despite these first demonstrations of intrinsically stretchable devices, there are still several challenges on the road toward elastic sensors for health monitoring and conformable integrated circuits. Here, we address one essential, but often underestimated circuit element that is paramount for the realization of all elastic circuits, namely reliable, stretchable interconnects that link the constituent circuit components.

One solution is to render rigid, highly conductive materials stretchable, for example by advanced structural engineering approaches using wavy patterns^[26–29] or 3-dimensional kirigami structures.^[30] These approaches, however, are not readily scalable, since processes such as vacuum evaporation or photolithography are required and the resulting patterns occupy large areas.

An alternate approach toward elastic interconnects, is the development of intrinsically stretchable, electrically conductive materials. Previously investigated thin-films of the conductive polymer mixture PEDOT:PSS, which was doped with various ionic liquids, were found to be promising in terms of their electrical conductivity and stretchability.^[31] To enable patterning of such elastic conductors and therewith their application in stretchable interconnects and to facilitate large-area processing, suitable fabrication steps need to be established.

Here, we report the characterization of inkjet-printed, elastic interconnects based on the conductive polymer mixture PEDOT:PSS and the development and formulation of the respective ink. The inkjet printing process enables the direct patterning of interconnects without the need of masks and lift-off processes and therefore offers versatility, unlike earlier reports on printable elastic conductors that utilized printing methods such as stencil printing and screen printing.^[32,33]

A compilation of reports on inkjet-printed PEDOT:PSS is given in Table 1 and Figure S1. Commercial dispersions of PEDOT:PSS are commonly diluted with water and/or co-solvents such as DMSO, ethylene glycol, glycerol to optimize the viscosity of the ink and influence the microstructure of the printed films. A direct comparison of the electrical performance is difficult, as substrates and dimensions vary and are not always reported.

Table 1: Summary of inkjet-printed PEDOT:PSS

Literature	Printing method	Purpose, application	Conductivity/ Sheet Resist.	PEDOT-ink composition ³⁾	Substrate	Dimensions ⁵⁾	Comments
Bihar 2017 ^[36]	Inkjet	Electrodes, electrocardiography	~240 S/cm 150 Ohm/sq	Clevios PH1000, ethylene glycol (20 wt%), org. solvents (0.8 wt%), GPTMS ⁴⁾ , proprietary surfactants (0.3%)	paper	t: 85-280 nm	bendable, cycling stability
Chen 2003 ^[37]	Inkjet	RC filters	> 10 ⁶ Ohm/sq	Baytron P, diluted	n/a	n/a	
Cho 2011 ^[38]	Gravure	OPVs ¹⁾	280 S/cm ²⁾ 360 Ohm/sq	Clevios PH 510, DMSO (7%)	PET	t: 100 nm	flexible
Eom 2009 ^[39]	Inkjet	OPVs ¹⁾	164 S/cm	Baytron P Al 4083, glycerol (6 wt%), ethylene glycol butyl ether (0.2 wt%)	ITO	n/a	
Ely 2011 ^[40]	Inkjet	OLEDs	n/a	Clevios P VP AL4083	SU8 on ITO/glass	t: 110-300 nm	
Garnett 2005 ^[41]	Inkjet	OLEDs, OPVs ¹⁾	51 S/cm 650 Ω/sq ²⁾	Baytron P HCV2, water, DMSO (5%), Surfynol (1%)	glass	t: 300 nm	tuning of work function
Ha 2017 ^[42]	Inkjet	Electrodes for OFETs ¹⁾	~ 200 S/cm ²⁾ ~90–450 Ω/sq	E-157 (Contech)	Arylite film	t: 105-525 nm	bendable
Hong 2014 ^[43]	Aerosol printing	Electrodes for EGTs ¹⁾	15 S/cm ²⁾ 960 Ω/sq	10 vol% ethylene glycol, 90% PH500	SiO ₂ /Si wafer	t: 750 nm, W: 40 μm	comparison of electrode materials
Jung 2013 ^[44]	Inkjet	Resistors	resistance: 800 Ω -217 MΩ	Clevios PH1000, DMSO (0-5 vol %), Dynol 607 (Air Products), Zonyl FSO-100	PEN	t: 105-525 nm	five orders of magnitude in resistance
Jung 2014 ^[34]	Inkjet	OPVs ¹⁾	~600 S/cm ²⁾ ~ 85 Ω/sq	Clevios PH1000, DMSO (5 wt%), Zonyl FS-300 (0.1 %)	glass	t: 110-200 nm	all-inkjet-printed org. solar cell
Kang 2012 ^[45]	Inkjet	Resistors, capacitors inductors	n/a	Batron P Al 4083, ethylene glycol	polyimide	n/a	RC circuit
Kawase 2003 ^[46]	Inkjet	Electrodes for OFETs ¹⁾	0.1–100 S/cm	Baytron P	plastic	n/a	high resolution, electrophoretic display
Kim ^[47]	Inkjet	Electrodes for sensor arrays	~400 S/cm ²⁾ ~110 Ω/sq	PEDOT:PSS/polyurethane (PU), lower resistance with silver-bilayer	polyimide, PDMS	t: 150-250 nm	5000 bending cycles
Koidis 2011 ^[48]	Gravure (roll-to-roll)	Electrodes	120 S/cm 1388 Ω/sq ²⁾	Clevios™ FET, Heraeus	PET	t: 60 nm W: 10 mm	study on annealing temp.
Kommeren 2018 ^[49]	Inkjet	OPV ¹⁾	n/a	Clevios CH8000 or HILHC5i (AgfaGevaert N.V.), surfactants, alcohols	glass, P3HT/PCBM	t: 300-400 nm	
Lim 2006 ^[50]	Inkjet	Electrodes for OFETs	0.8 S/cm	Baytron P (Bayer AG), dispersion in water; DMSO	Si/SiO ₂ /OTS+ P3HT	n/a	solvent effect of DMSO
Mabrook 2005 ^[51]	Inkjet	Sensors for organic vapors	n/a	PEDOT:PSS dispersion in water/ organic solvents, 50% water, 10% ethylene glycol, 1% dodecyl sulfate sodium salt	polyester film	n/a	posttreatment with alcohol
Mannerbro 2008 ^[52]	Inkjet	OEETs ¹⁾	20 kΩ/sq.	Baytron PH500 (from H.C. Starck); 60 wt.% ethylene glycol	photo paper	n/a	printed ring oscillators
Singh 2015 ^[53]	Inkjet	OPV ¹⁾	0.02 S/cm ~4 GΩ/sq ²⁾	Clevios P CH8000	glass	t: ~ 120 nm, W: 10, 1.5 mm	variation of ink viscosity
Soltman 2008 ^[54]	Inkjet	control of coffee ring effect	n/a	PEDOT/PSS 1.3 wt% in water	coated glass (crosslinked PVP)	n/a	detailed study of printing parameter
Steirer 2009 ^[55]	Inkjet	OPV ¹⁾	<1 S/cm ²⁾ 11 GΩ/sq.	Baytron P VP Al 4083 (from HC Starck), 75% DI water	ITO coated glass	t: 5-27 nm	
Thomas 2007 ^[35]	Inkjet	Electrodes	80 S/cm	EDOT, cyclopentanol, Baytron C, anisole, polyurethane in cyclopentanol,	glass, PET	n/a	stretchable (~100%)
Wilson 2011 ^[56]	Inkjet	study surface microstruct.	1000 Ω/sq.	PEDOT/PSS 1.3 wt% in water; DMSO (0 - 5 wt%), Surfynol 2502 (0 or 1 wt%)	glass	n/a	study of co-solvent DMSO
Xiong 2012 ^[57]	Inkjet	n/a	~82 S/cm ~285 Ω/sq ²⁾	PEDOT:PSS, glycerol (5-35 wt%), water	glass	t: 250-450 nm	solvent post-annealing
Xing 2017 ^[58]	Inkjet	OLEDs ¹⁾	n/a	CLEVIOS™ P VP Al4083, isopropanol	ITO coated glass	t: 10-300 nm	
Yoshioka 2007 ^[59]	Inkjet	OLEDs ¹⁾	~60 S/cm ²⁾ 1850 Ohm/sq	Baytron P (86 vol%), glycerol (4.5 %), triton X-100 (0.045 vol %), H ₂ O (9.5 %)	glass	t: ~100-200 nm	
Our work	Inkjet	Stretchable interconnects	700 S/cm 75 Ohm/sq	Clevios PH 1000, H ₂ O, ionic additive (see exp. details), DBSS surfactant, DMSO	stretchable polymers (SEBS,PU),	t: 100-300 nm W: 100-200 μm	stretchable, cycling tests

¹⁾ OPV: organic photovoltaics, OLED: organic light-emitting diode, OEETs: organic electrochemical transistor, OFET: organic field-effect transistor, EGT: electrolyte-gated transistor; ²⁾ value calculated for this comparison from reported data ($\sigma = 1/(R_{\text{sheet}} \cdot t)$); ³⁾ suppliers of PEDOT:PSS: HC Stark, Sigma Aldrich, Heraeus, Bayer AG, AgfaGevaert, Contech; ⁴⁾ GPTMS: glycidoxypolytrimethoxysilane; ⁵⁾ t: thickness, W: width.

While a sheet resistance (conductivity) as low (as high) as 85 Ω/sq ($\sim 600 \text{ S/cm}$) was achieved by Jung, Sirringhaus et al. on rigid glass substrates,^[34] the performance of printed, stretchable PEDOT:PSS so far was limited to conductivities around 100 S/cm.^[35]

The conductivity of our printed interconnects reaches 700 S/cm, which is among the highest values reported for printed PEDOT:PSS patterns. The reported results will therefore not only be of interest for the advancement of stretchable circuits, but also for flexible electronics and bioelectronics applications. For example, patterned PEDOT:PSS structures are commonly explored for stimulation and recording brain electrodes^[60,61], organic electrochemical transistor sensors^[62] and for flexible solar cells.^[63]

Since the realization of non-trivial circuits will require several layers of (overlying) conductive traces that are isolated from each other, but can be connected at specific locations, we have also developed a compatible printing process to define via-holes (through connections) and thereby connect elastic PEDOT:PSS wires through insulating layers of stretchable polymers.

2. Results and discussion

2.1 Ink development

Commercial PEDOT:PSS is a conductive polymer mixture, for which thin film conductivities up to thousands of S/cm have been reached.^[31,64] Intrinsically, this material is not stretchable, but it can be rendered stretchable with plasticizing additives such as Zonylfluorosurfactants^[65,66] or ionic liquids^[31,67]. In the latter case, the additives also act as dopants and have a charge screening effect that weakens the interactions between PEDOT and PSS. This effect leads to more aggregation of PEDOT-rich domains, which results in efficient charge delocalization and transport and in an increase in local crystallinity/molecular order.^[31,68–72] The conducting thin films are highly stretchable (4100 S/cm under 100% strain; 56 S/cm under 800% strain) and transparent ($>95\%$).^[31]

To formulate an ink for inkjet printing of elastic interconnects, we started from aqueous solutions of PEDOT:PSS and ionic additives, similar to those reported previously^[31] for spin-coated stretchable thin-films. To optimize the viscosity and prevent the nozzles from clogging, the aqueous solutions were diluted with deionized water and PEDOT:PSS patterns were printed on elastomeric substrates (SEBS, styrene ethylene butylene styrene). Several parameters such as the surface tension of the substrate, the substrate temperature, the temperature of the printing

head, the applied voltage to the printer nozzles (waveform) and the drop-to-drop spacing, were investigated and optimized. However, despite promising conductivity values (~ 600 S/cm), all printed features suffered from an uneven morphology and defects in the printed lines (Figure 1, left). These artifacts are unfavorable for their stretchability and indeed, stretching to 40% resulted in crack formation and an increase in resistance by orders of magnitude.

In order to improve the morphology of the printed patterns and the wettability of the ink on the substrate, a surfactant, namely dodecyl benzene sodium sulfonate (DBSS), which also has a beneficial effect on the conductivity of PEDOT:PSS films^[31,73] was added to the ink. The result of adding DBSS to the ink is an improvement in the morphology of the printed conductors and a smaller contact angle of the ink on the substrate, as shown in Figure 1 (middle). However, the printed lines still suffer from a pronounced coffee-stain effect (uneven distribution of the material). To prevent this effect, we took advantage of the Marangoni effect by adding higher boiling solvents with a lower surface tension than the primary solvent (here water) to the ink. [During the drying of the printed droplets, a surface tension gradient occurs when the main solvent (with the lower boiling point) evaporates at the side of the droplet. This surface tension gradient leads to a Marangoni flow^[74–76] from the edge of the droplet to its center, transporting some of the dispersed PEDOT:PSS back to the center and therefore counterbalancing the counter-directional convective flow, which causes the undesired coffee-stain effect.^[74]]

Here, the addition of secondary solvents ethylene glycol (surface tension: 48 mN/m, boiling point: 197°C) and dimethyl sulfoxide, DMSO (surface tension: 44 mN/m, boiling point: 189°C), to the aqueous ink (surface tension of H₂O: 72.8 mN/m, boiling point: 100°C) was investigated, because both solvents have additionally shown a beneficial effect on the conductivity of PEDOT:PSS films.^[31,71,77–79] In our study, the addition of ethylene glycol (various concentrations) lead to bulging of the printed lines and obstructed the printability of the ink. In contrast, smoother patterns were achieved when adding DMSO to the ink formulation (Figure 1, right). To confirm the good printability of the ink, the transient behavior of the drops from the printer nozzles is shown in Figure S2. No spreading of the ink at the nozzle surface is visible and the drops have a spherical shape with no artifacts.

Inkjet-printed patterns using the optimized ink formulation (a detailed description of the ink preparation is given in the experimental section) have a conductivity of 700 S/cm (line width: 150–200 μ m). Height profiles of printed lines using the different ink formulations are shown in the SI (Figure S4). The optimized ink can also be printed on alternate stretchable substrates such as polyurethane (see Figure S5).

Figure 1: Optimization of PEDOT:PSS-based ink for stretchable interconnects: a) Chemical structures of the ionic additive bis(trifluoromethane) sulfonimide lithium salt, the surfactant DBSS and the high-boiling solvent DMSO, which was added to suppress the coffee-stain effect. b) Contact angles of the modified aqueous PEDOT:PSS inks on stretchable SEBS substrates, 30 min after plasma treatment of the substrate. c) Micrographs of inkjet-printed lines using the different ink formulations.

2.2 Characterization of elastic interconnects

To further characterize the inkjet-printed interconnects, we investigated the bias stress stability, the shelf-life stability and the cycling stability under stretching (see Figures 2 and 3). The linear I-V characteristic (Figure 2b) depicts the consistency of the resistance/conductivity over a large voltage range. Figure 2c shows the evolution of the normalized resistance of printed conductors within one month of exposure to ambient air. The resistance increases by less than 20% within one month for pristine PEDOT:PSS patterns. When applying solvent post-treatments (washing with water, DMSO or methanol, followed by a short annealing step; see experimental section), the shelf-life stability can be significantly improved. This observation can be related to the removal of PSS during solvent treatment,^[63,64,77,79,80] because the water uptake of the hygroscopic PSS can lead to an increase in the overall resistance.^[81,82]

Figure 2: Electrical characterization of the inkjet-printed interconnects, stretching and cycling stability: a) Bias stress stability, b) linear current-voltage characteristic and c) shelf-life stability in ambient air. d) Photograph of printed patterns being stretched. e)-g) Cycling stability (applied strains: 0% to 40%). The change in resistance is expressed as a ratio between the instantaneous resistance (R) and the initial resistance (R_0), displayed as a function of e) the applied strain and f),g) of the number of cycles. The oscillation in resistance originates from the dimensional change when strained (increase in line length and decrease in line width).

An important parameter is the cycling stability, as circuits that are attached to the skin, e.g. for health monitoring purposes, will endure many stretching cycles. To test the cycling stability of the printed interconnects, test structures were mounted on automated stretch-equipment and stretched for 1000 cycles while the change in resistance was monitored as a function of the applied strain (0%-40%). The resistance increases during the first cycle and then stabilizes at around 120% of the initial value (Figures 2e-g). After 1000 cycles, the normalized resistance increased by less than a factor of 1.5. (Note that the oscillation of the normalized resistance during cycling originates from a change in dimensions, namely an increase in length and decrease in the cross section, when stretched.)

Figure 3 shows the connection of commercial micro-LEDs with the printed, stretchable interconnects. The LEDs can be operated up to strains of 50% (Figure 3a). By connecting seven

micro-LEDs, a simple seven-segment digit was realized, as shown in Figure 3b. Such a display can be utilized for simple visual output in health monitoring devices.

Figure 3: a) Interconnection of micro-LEDs and b) demonstration of a seven-segment display. Commercial micro-LEDs were contacted by using the customized ink and the developed printing process.

2.3 Process for printing via holes/ through connections

For the realization of more sophisticated circuits, the development of a printing process for via holes (through connections) is important, to enable the interconnection on several layers. In a display, for example, the word-lines and bit-lines that address single pixels may not be in contact and must be isolated. This can be realized by implementing the lines on two different, insulated layers. For the interconnection of both layers, via holes through the insulating layers must be realized.

In our process (see Figure 4), we first print conductive PEDOT:PSS lines on stretchable SEBS substrates. Afterwards, an insulating SEBS layer (a few μm thick) is laminated onto the sample. Then, via holes are realized by printing toluene onto the top SEBS layer. The via holes are generated when the SEBS is dissolved by the printed toluene. (A similar process using flexible materials was reported earlier by Siringhaus and coworkers.^[83,84]) Then, several layers of PEDOT:PSS ink are subsequently printed into the via hole to ensure a good connection of the stacked layers of conductive lines. Afterwards, the sample is exposed to a short oxygen plasma treatment for surface activation of the upper SEBS layer and finally the next layer of

interconnects can be printed. A schematic of the process is shown in Figure 4. No significant increase in resistance was observed at the connections through via holes. To relate the number of printing passes to the depth of the holes that have been printed into SEBS, 10 to 50 consecutive passes of toluene were printed on/into SEBS and the depth of the printed features was determined by using a Dektak profilometer. As depicted in Figure 4a, the depth scales linearly with the amount of the printed solvent. Using this process, PEDOT:PSS interconnects can be printed on several overlying layers and can be connected through via holes at the desired locations (Figure 4b).

Figure 4: Printing of via holes/through connections: a) Dependence of the height/depth of the via hole on the number of printed layers and micrographs of holes fabricated by inkjet printing of toluene into SEBS. b) Schematic of the process flow for inkjet printing via holes and connecting PEDOT:PSS interconnects that are printed on stacked layers c) Micrographs of a via hole filled with PEDOT:PSS to connect the underlying PEDOT:PSS interconnect and open via hole to printed silver electrodes.

3. Conclusions

For the deployment of elastic materials as interconnects and electrodes, patterning is crucial. Therefore, we developed a process for inkjet printing of intrinsically stretchable PEDOT:PSS-based interconnects and conductors and also via holes. The printed interconnects have a conductivity of 700 S/cm (sheet resistance: 75 Ohm/sq), sustain strains above 100% and show good stability in 1000-cycle stretching experiments. The elastic interconnects can be utilized to build stretchable circuits and to interconnect rigid circuit components such as commercial micro LEDs. Furthermore, the measured conductivities are the highest reported to date for inkjet-printed PEDOT:PSS based conductors. PEDOT:PSS is used in a broad range of applications including electrodes for medical sensors, solar cells, OLEDs and electrochemical sensors and

novel drug delivery devices. Hence, the developed ink and procedure are not only of interest for stretchable, but also for a variety of flexible and rigid applications.

4. Experimental Section

Materials: Clevios PH 1000, PEDOT:PSS dispersion [poly(2,3-dihydrothieno-1,4-dioxin)-poly(styrenesulfonate)], purchased from Sigma-Aldrich, ~1.1 wt% solid content; bis(trifluoromethane) sulfonimide lithium (purchased from Alfa Aesar), DBSS (dodecyl benzene sodium sulfonate) from Sigma Aldrich used as surfactant, Styrene Ethylene Butylene Styrene (SEBS) (H1062Z from Kraton™ G Polymers), toluene (Fisher Chemicals).

Substrate preparation: A solution of Styrene Ethylene Butylene Styrene (SEBS) in toluene (180 mg ml⁻¹, stirred over night at room temperature), was drop-casted on glass slides, covered and dried overnight.

Ink preparation: 3 ml of filtered (1.0 µm Nylon filter) PEDOT:PSS dispersion (Clevios PH 1000) was stirred at room temperature while 1 ml (10 mg/ml) of an aqueous solution of the ionic additive bis(trifluoromethane) sulfonimide lithium was added. Afterwards 1.5 ml of the surfactant DBSS (5 mg/ml) and 1.2 ml of DMSO were added to the respective inks while stirring and the inks were diluted by adding deionized water to obtain 12 ml of the final ink. Finally, the inks were stirred overnight.

Inkjet printing: The interconnects were printed using a Dimatix Material Printer DMP-2831 from Fujifilm with 10 pL droplet size cartridges. After stirring of the ink overnight, ~3ml were added to the cartridge through a 0.7 µm Nylon filter to remove any large particles and avoid clogging of the nozzles. Then, the ink was degassed in vacuum for at least 30 min.

Conductive lines with a length of 1-2 cm were printed on oxygen plasma treated (Technics Micro-RIE, 150 W, 20 sec) substrates (see also Figure S3). The printer parameters were optimized to: 35°C substrate temperature, 32°C printing head, 35 µm drop-to-drop spacing, 3 nozzles and ~ 25 V applied voltage to the printer nozzles (the applied waveform is shown in Figure S7). The ink was stable for several hours (> 5h) when rinsing regularly with water.

Via holes were printed into SEBS using toluene and the following printer parameters: 35 °C substrate temperature, 32 °C printing head, 20 µm drop-to-drop spacing, 4-6 nozzles and ~ 25-30 V applied voltage to the printer nozzles (the applied waveform details are shown in Figure

S8.) Please note, that this printing step has to be performed prior to subsequent plasma treatment.

Solvent-treatment: Post-deposition solvent treatment was carried out by dropping the respective solvent on samples with the printed PEDOT:PSS patterns and spinning of the liquid after 1 min of soaking (3000 rpm for 1 min). Afterwards, the samples were annealed at 80°C for 20 min.

Characterization: For the realization of good contacts for the electrical characterization, vertical gold stripes were deposited through shadow masks by thermal evaporation in vacuum on both sides of the printed lines (evaporation rate: 0.2-0.3 Å s⁻¹). Consecutively, the resistance R of the lines was measured by four-probe measurements to exclude the contribution of the contact resistance using a Keithley 2400 Source Meter. The length (L) of the investigated test structures is 1 cm. The line width (W) was determined by optical microscopy and using a Dektak 150 profilometer (Veeco) at various locations of a line. (For the calculation of the conductivity the averaged values were utilized.) The line thickness (t) was determined with the Dektak profilometer (various scans per printed line). The conductivity σ was calculated with $\sigma = L/(R \cdot t \cdot W)$ and the sheet resistance was calculated with: $R_{\text{sheet}} = 1/(\sigma \cdot t)$.

Stretching/Cycling stability

For the investigation of the resistance change during stretching and the cycling stability of the printed conductors, an encapsulation layer of SEBS was laminated on the samples. To continuously measure the resistance while stretching, the printed interconnects were attached to a homemade stretching station and connected to a LCR meter (Agilent E4980A).

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