Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits Using a Commodity Inkjet Printer

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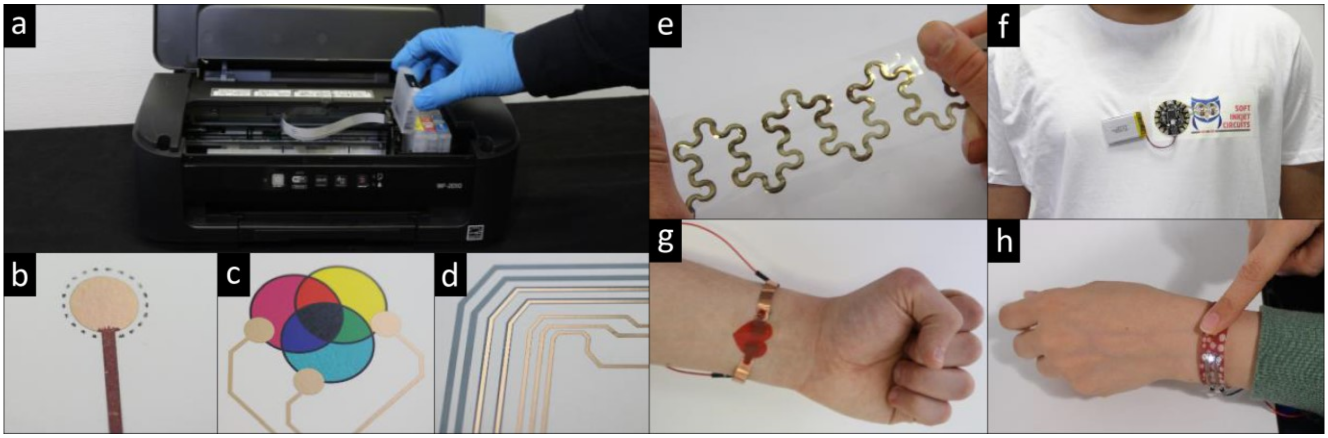

Figure 1: An inexpensive desktop printer (a) can be used to print functional multi-material and multi-layer designs (b-d). The technique enables fabricating stretchable circuits (e), e-textiles (f), on-body interfaces (g), and re-shapeable interfaces (h).

ABSTRACT

Despite the increasing popularity of soft interactive devices, their fabrication remains complex and time consuming. We contribute a process for rapid do-it-yourself fabrication of soft circuits using a conventional desktop inkjet printer. It supports inkjet printing of circuits that are stretchable, ultrathin, high resolution, and integrated with a wide variety of materials used for prototyping. We introduce multi-ink functional printing on a desktop printer for realizing multi-material devices, including conductive and isolating inks. We further present DIY techniques to enhance compatibility between inks and substrates and the circuits' elasticity. This enables circuits on a wide set of materials including temporary tattoo paper, textiles, and thermoplastic. Four application cases demonstrate versatile uses for realizing stretchable devices, e-textiles, body-based and re-shapeable interfaces.

Author Keywords

Fabrication; printed electronics; conductive inkjet printing; circuits; new materials; ubiquitous and wearable computing.

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CCS Concepts

Human-centered computing → Human computer interaction (HCI); Ubiquitous computing, Interface design prototyping

INTRODUCTION

Soft interactive devices are becoming increasingly popular, as they offer unique features and can be seamlessly embedded in demanding physical contexts. Moving beyond flexible-only devices, a wide array of soft interfaces have been explored, including stretchable objects [61], conformal skin-worn interfaces [59], e-textiles [3,21] and shape-changing devices [8,37,42,66]. These devices are commonly created using techniques such as screen printing [38,62], sewing [13], or silicone casting [8,34,59,67]. While versatile, these techniques are complex and time consuming, as they commonly require extensive manual steps, expert knowledge and advanced equipment. For instance, creating a screen-printed or silicone-cast circuit typically takes multiple hours. This significantly limited the research and maker communities in exploring new soft devices and interactions.

Our goal is to significantly reduce the time and complexity required for fabricating soft and stretchable circuits, down to minutes and to the ease of using a desktop inkjet printer. We were inspired by the pioneering work on instant inkjet printing by Kawahara et al. [19,20]. It empowered the HCI community to print custom flexible circuits within less than a minute on an inexpensive desktop inkjet printer, in turn enabling a considerable amount of research that uses flexible circuits [10,11,35,36,44,55]. However, the approach was limited to a single ink and few substrate materials, not compatible with stretchable, textile, or micron-thin devices.

In this paper, we present *Soft Inkjet Circuits*, the first systematic approach for rapid fabrication of soft circuits on a commodity inkjet printer, demonstrating multiple functional inks compatible with multiple substrates. Using an inexpensive desktop printer (<$50) and commercially available materials, our approach supports inkjet printing of circuits that are stretchable (up to 50%), ultrathin (down to 1 µm), high resolution (down to 100 µm), and integrating a variety of materials used for prototyping.

We achieve this by introducing *multi-ink functional printing* on a desktop inkjet printer. Our technique supports multilayer printing of a variety of inks with diverse functions: highly conductive silver nanoparticle ink, intrinsically stretchable conductive polymer ink, and an electrically isolating ink alongside graphical inks. Those inks can be combined in a single printer, enabling various functionalities. By printing an isolating top layer, circuits can be selectively isolated, while leaving desired elements exposed. This offers a rapid method for creating exposed electrodes, connection pins or VIAs that connect the circuit with a second layer. By printing conductive alongside graphical inks, full-color designs can be printed with the circuit in a single pass.

For advanced mechanical properties of circuits, we match these functional inks with a *varied set of soft substrate materials*. Those include highly stretchable Thermoplastic Urethane (TPU) foil, 1-micron thin rub-on tattoo film, textile transfer film, and re-shapeable thermoplastic materials that can transition between a soft and a rigid state. We characterize their behavior and report on designs and print parameters that work with commodity inkjet printers. We significantly expand the set of materials that can be printed by presenting do-it-yourself methods for activation of low-energy substrates and for integrating printed circuits on textiles. Next, we investigate strategies to considerably *improve the stretchability* of designs printed on a commodity inkjet printer. These include leveraging pre-stretched substrates and improved print designs, along with their empirical evaluation.

Finally, we demonstrate the practical benefits for interface prototyping with a set of technical demonstrations fabricated with our approach. These show that it can significantly speed up the fabrication of applications in many important areas of soft circuits, such as e-textiles, e-tattoos, stretchable circuits and re-shapeable interfaces.

Collectively, we call our process, materials, inks and patterns *Soft Inkjet Circuits*. As is detailed in this article, optimizing for functionality, a wide array of mechanical properties and ease-of-fabrication required extensive iterative experimentation, process contributions and technical studies. We believe these benefits make Soft Inkjet Circuits an important enabling technique, allowing for a more widespread investigation of soft electronic devices.

RELATED WORK

Many alternatives for fabricating custom-designed circuits have been explored in related work, with different degrees of versatility and ease of production:

Do-it-yourself fabrication of soft circuits

One of the most popular alternatives used to print on various substrates is screen printing [38]. By taking advantage of the wide range of thermally cured inks and compatibility with viscous pastes, a wide range of devices can be printed. Applications include printed displays [26,38,61], interactive paper [25,37], actuation [37], and electronic tattoos [30,35,60]. Another very versatile alternative is silicone casting, which allows for creating transparent, highly stretchable [34,61] devices, while being thin and conformal [59] and optionally containing internal channels for conductive liquids [34] or pressurized fluids [8,65]. The main limitation of these approaches is that they are mostly manual and require extensive time and specialized equipment, as dedicated screen-printing frames or casting molds have to be prepared.

An alternative for soft interfaces is e-textile [39,41]. Ideal for wearable applications, e-textile fabrication requires either trained skills or dedicated hardware. Prototyping techniques involve additive methods such as sewing and stitching using conductive yarn, either manually [56] or digitally assisted [13,15], while subtractive methods cut conductive fabric [2], and hybrid methods combine both [40]. Screen printing has also been used to create e-textiles [21].

It is possible to hand-fabricate circuits using conductive ink [33,43,46], enabling a hands-on, artistic approach with virtually no tools required. Limitations include lower resolution and repeatability of design, with high manual effort. To speed up fabrication, follow-up work proposed digitally assisted subtractive methods, such as a computer-controlled vinyl cutter to cut copper tape for rigid or flexible circuits [47], or a laser cutter to cut conductive materials for fabrication of circuits with custom stretchability [6].

Inkjet-printed circuits

We can learn about the potential of inkjet printing for fabricating circuits by looking at research in material science and the science of printing [1]. These research areas explored inkjet-printed electronics early on [24,48,53], printing a variety of materials, such as carbon nanotubes [58], metallic nanoparticles [5,22,23,51], graphene [54] and titanium oxide [28], among many others. As a result, it has been possible to print foldable and soft circuits [48,51], circuits on fabrics using custom inks [18], transistors [49] and super transistors [5,51,58], and memories [28]. However, these are commonly printed on expensive research-grade printers that typically cost >$10,000, are complex to operate and slow to print.

In contrast, Instant Inkjet Circuits [19,20] pioneered a method for printing custom circuits on a commodity inkjet printer in less than one minute and in high-resolution on a flexible substrate. This enabled considerable research on flexible circuits in the HCI community. However, the approach is subject to important limitations, as it supports only a single type of silver ink and few substrate materials (PET foil, photo paper); thus it cannot be used to fabricate stretchable, textile, or micron-thin devices. Preliminary explorations have been performed on printing polymer conductors on non-stretchable substrates [12,45,50]. Other work has combined commodity conductive inkjet printing with liquid metal to realize e-tattoo devices, by printing with silver ink first and then applying subsequent manual steps of coating with liquid metal and acid treatment [52]. In addition to the high manual effort, the approach requires materials that are problematic for use on skin (EGaIn) and result in comparably low adhesion on the substrate. We extend over prior work by contributing an approach for direct printing of multiple functional materials (including isolators) on a single commodity printer and various stretchable substrate materials, showing that commodity inkjet printers have a larger application area for rapid fabrication than previously assumed.

FABRICATION OVERVIEW

The workflow process for fabricating soft circuits using a commodity inkjet printer consists of the following five steps:

1. Creating the digital design

The designer starts by creating a digital design of the circuit to be printed. Any 2D-vector graphic tool can be used. We use Adobe Illustrator or InkScape. The design is a black-and-white graphic if only one ink is printed. If the design contains multiple inks, the color of a vector element defines what cartridge it is printed with: if the element is to be printed with ink from the K (black) cartridge of the printer, the element's color is black. For ink from the C (cyan) cartridge, the element is cyan, etc. The design is sent to the printer using the print dialog.

2. Ink selection

Next, the designer selects one or multiple inks available off-the-shelf or that can be easily formulated from commercially available materials. The ink is loaded into an empty ink cartridge. A major contribution of this work is to move beyond silver ink and enable printing of multiple functional inks with commodity printers. Several inks can be loaded on the same printer and combined in one design.

3. Substrate material selection

The substrate material that the circuit is printed on defines its physical properties. Our process enables direct commodity inkjet printing of soft circuits that have a variety of desirable mechanical properties. The designer can choose from a variety of substrates (Figure 4) offering stretchability (up to 600 % stretch), ultra-slim form factor (<1µm thick), compatibility with textiles (using iron-on transfer), and transition between soft and rigid states for re-shapeable curved designs (leveraging thermoplastics).

4. Printer selection

Selecting an appropriate inkjet printer is a critical step toward supporting more inks and substrates. To help readers make an informed choice, we tested a variety of printers and identified the following requirements for best performance:

Piezoelectric technology: Piezoelectric heads use vibration to jet the ink, in contrast to thermal printing heads, which use heat; heating and boiling the printed fluid has potentially undesirable effects. In addition, ink cartridges for thermal printers typically include the printing head. This makes cartridges more expensive and complicates buying empty ones. We therefore recommend choosing a piezoelectric printer.

Standard heads: To keep our results as generally applicable as possible, we focused on printers with standard printing heads shared among several models. This ensures that printers can be easily replaced in a working setup, even in case a specific printer model is discontinued.

Small cartridges: To avoid wasting ink during testing, cartridges should only require a small volume of ink and ideally work even when the cartridge is almost empty.

Short tubing: In some inkjet printers, the cartridges are near the printing nozzle, typically right on top. This setup is strongly preferable, as it reduces the risk of clogging and the amount of ink wasted when performing cleanings.

Availability of empty cartridges: It is essential that empty cartridges with auto reset chips be available on the market and compatible without complications.

Based on these criteria and extensive experimentation with various inks and substrates, detailed below, we recommend printers from the Epson Stylus series (USA) and Epson WorkForce series (Europe). Both series use piezoelectric technology, have small cartridges (capacity: 10 ml, 4 ml minimum) located right above the printing head and can be shared with a large family of printers. For this paper, we focused on the Epson WorkForce WF-2010W, given its local availability, low price (~50€) and availability of empty cartridges (~20€), but the findings extend to similar printers.

5. Post-treatment

After printing, the circuit undergoes a post-treatment step. Curing ensures that the printed traces will be functional. All our functional inks are thermally curable: the printed sample is cured with a heat gun, put into an oven, or ironed. Then electronic components and connections can be added using copper tape, vertically conductive z-tape, sewing or soldering.

MULTI-INK FUNCTIONAL PRINTING

Many prototypes require multiple functional materials in one circuit. In this section, we contribute an approach to inkjet print functional inks with various properties (conductive, isolating, color) using a single commodity printer. For instance, this technique can realize circuits with isolating elements, circuits with full-color artwork, and circuits that combine the benefits of metallic and polymeric conductors (Figure 3).

Criteria for ink selection

To avoid a trial-and-error–based selection of inks, we recommend a more principled approach. It is possible to predict the printability of a given ink by evaluating its fluid dynamics in relationship to the printing nozzle. This is reflected in the Fromm number (Z) [1,16], which relates the inertia to viscous forces (Reynolds number, Re) and inertia to surface forces (Weber number, We):

$$Z = \frac{\mathrm{Re}}{\sqrt{\mathrm{We}}} = \frac{\frac{\nu a \rho}{\eta}}{\sqrt{\frac{\nu^2 a \rho}{\gamma}}} = \frac{\sqrt{a\rho\gamma}}{\eta} \quad \begin{cases} a = & \textit{nozzle diameter} \\ \rho = & \textit{ink density} \\ \gamma = & \textit{ink surface tension} \\ \eta = & \textit{ink dynamic viscosity} \\ \nu = & \textit{ink velocity} \end{cases}$$

The recommended value of Z for inkjet printability is within $1 < Z < 10$ [1]. Figure 2 highlights this area in green and situates the inks we use in this paper. If the Z value is outside this range, it would be too viscous to print, have insufficient energy to create a drop, or contrarily create satellite drops or splashing. An additional parameter to take into account when printing nanoparticle inks is the particle size. To prevent clogging, the particle should be around 50 times smaller than the nozzle diameter (typical nozzle diameter in commodity inkjet printers: 20 µm) [1]. An ink's Z value and particle size can be found in its datasheet.

Functional inks

Based on those principles, we selected and formulated inks to obtain a base of highly conductive, highly stretchable, and isolating inks among metallic and polymeric inks that can be printed on a variety of substrates. All inks require thermal sintering at temperatures reached by a simple electric oven (Sage, BOV820 BSS) and that do not damage the substrates. Our findings show that users do not have to be very careful with the heating profiles they apply. Provided the profile is within a wide range of temperature and duration, the inks will be cured to achieve consistently good results.

Silver ink for high conductivity

Silver nanoparticle ink is the most frequently used type of ink for printing conductors in do-it-yourself settings. It offers high conductivity and is easy to print. Prior work has demonstrated that this type of ink can be inkjet-printed on commodity printers [19], however, it was restricted to a small set of specifically coated substrate materials for chemical curing. To enable printing on a considerably wider set of uncoated substrate materials, we investigated inks that can be thermally cured, which is the most common curing technique.

We tested two varieties of commercial inks: DGME-AgNP (Sicrys™ I40DM-106) and TPM-AgNP (Sicrys™ I50T-13), purchased from Pvnanocell. After testing, we selected the first ink (Fromm value of Z=3, curing temperature of 120°C for 5 min). The second ink requires a comparatively high curing temperature (180°C). Although printable (Z=1.2 is borderline), its high viscosity resulted in clogging of the printing head if stored in the cartridge for a longer period of time.

Polymeric conductive ink for high stretchability

Due to the brittleness of metallic particles, traces of nanoparticle ink possess low stretchability. Polymeric conductors address this problem by offering intrinsic stretchability and superior robustness to mechanical strain. *Poly(3,4-ethylenedioxythiophene) - poly(styrenesulfonate)* (PEDOT:PSS) is a well-known conductive polymer characterized by its transparency (~90%), high stretchability and ease of printing. We selected off-the-shelf available PEDOT:PSS inkjet ink (0.8% in H_2O) from Sigma Aldrich (Orgacon™ IJ-1005, 739316), one of the largest suppliers providing this material in small quantities. This ink is specifically formulated for inkjet printing (Z=2.1) and can be cured at 80°C in 3 mins using a simple electric oven. We recommend printing 3 layers of PEDOT:PSS to enhance its conductivity.

Isolating ink

To print isolating layers or to selectively isolate elements of a circuit, we investigated inkjettable materials that are non-conductive. We experimented with PolyVinylPyrrolidone (PVP), a non-conductive polymer. An inkjettable ink can be easily prepared from commercially available materials: by mixing PVP polymer powder (Sigma Aldrich 418560, 5% by weight) and the crosslinking agent poly(melamineco-formaldehyde) (Sigma Aldrich 418560, 1% by weight) with the solvent 1-hexanol (Sigma Aldrich 471402), through mechanical stirring at room temperature for 10 mins. This ink formulation has a Fromm value of Z=1.9 and can be heat cured at 120°C in 10 mins. The ink remains stable for several months in the cartridge.

Cleaning ink

To ease the practical handling of inks, we propose a new approach for automatic cleaning. We therefore prepared a printable cleaning ink. This ink cleans the nozzles of the printing head and the internal tubing. Such cleaning is required when changing the type of ink on a given color channel. It also helps clean any quick drying ink at the end of the day to prevent clogging (e.g., PEDOT:PSS). The cleaning ink can be easily formulated by mixing glycerin with ethylglycol (water based, by weight: 1% glycerin, 10% ethylglycol; Z=3.1). Printing 1-3 pages with about 90% page coverage of this formulation removes any remaining ink from that particular printing head.

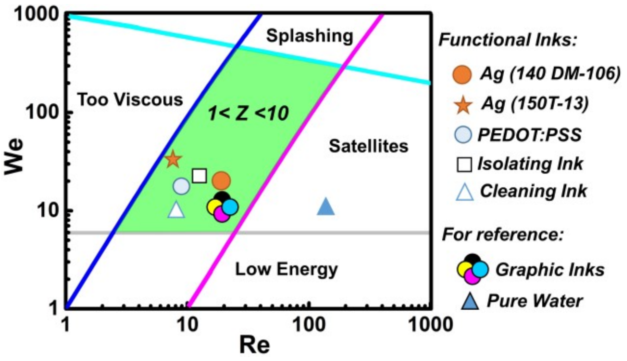

Figure 2: Properties of inks required for inkjet printing.

Combining multiple inks on the same printer

Commercial inkjet printers print full color graphics based on half-toning. The primary inks (typically cyan C, magenta M, yellow Y and black K) are printed in dotted matrices of different densities. Their combination creates the perceived color. Of note, the inks are not mixed in the printing head. They are also printed in a defined order, in three passes: K and C first, then M, and finally Y. Last, commodity inkjet printers combine inks differently depending on the desired finishing; this is particularly important for black: Matte presets use the K channel for black, while Glossy presets create black by combining CMY. This knowledge allows us to use the same printer to combine multiple functional inks directly on the substrate. This can be done either during a single printing pass (thanks to half-toning) or multiple passes (thanks to the page feeding's low registration error). We successfully realized the ink setups shown in Table 3.

Circuit with isolating layer: It is possible to selectively add a continuous or patterned top layer to the circuit using PVP. This acts as an isolating and protective layer, allowing for selective exposure of circuit elements, e.g., for creating exposed electrodes or pins for connection as presented in Figure 3a (6 layers of PVP). This setup is realized by filling conductive silver ink (Ag) into the K cartridge and filling PVP into the C, M and Y cartridges. Conductive traces are printed in a first pass, followed by the isolating layer. Using three cartridges for PVP adds extra thickness to the top layer.

Circuit with VIAs: Combining conductive and isolating inks with folding allows for realizing dual-layer circuits with VIAs (vertical interconnect access). First, both layers of the circuit are printed side-by-side on one sheet. The design of one layer is horizontally mirrored. A top isolating layer is printed on the circuits, leaving all areas uncovered that later will be VIAs. After printing, the sheet is folded once, such that both designs face each other, with the respective exposed VIA areas placed directly on top of each other. The layers are sandwiched using 3M vertically conductive tape ("z-tape"). An example is shown in Figure 3b (6 layers of PVP).

Circuits with full-color art layer: Aesthetic art layers have been reported as a desired feature for paper-based, wearable and on-body electronics [17,30]. Circuits that include full-color graphical elements can be printed in a single pass. An example is shown in Figure 3c. For this setup (2nd in Table 3), the conventional graphical C, M and Y inks are used, while silver ink (Ag) is filled into the K cartridge.

Multi-Ink Setup	*Cartridge*			
	C	**M**	**Y**	**K**
Silver & Isolator	PVP	PVP	PVP	Ag
Silver & Full color	C	M	Y	Ag
All functional inks	PEDOT:PSS	Ag	PVP	K

Table 3: Tested combination of inks for a single printer.

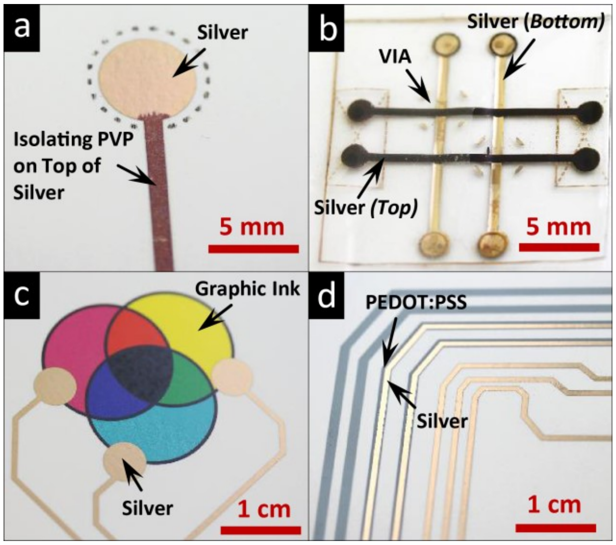

Figure 3: Multiple inks using a single printer: (a) Circuit with exposed electrode and patterned top isolating layer (darker), which enables (b) the creation of folded devices with VIAs. (c) Combining silver and graphic inks. (d) Traces printed with silver, PEDOT:PSS and the combination of both.

All functional inks: Finally, it is possible to combine all functional inks in a single setup, with black ink added for printing labels or artwork. This gives the user the largest flexibility for combining functional inks. In addition to printing isolating elements on top of traces of conductive silver or conductive polymer, the designer can print circuits that combine the complementary benefits of silver-based and polymeric conductors as shown in Figure 3d.

SOFT AND STRETCHABLE SUBSTRATE MATERIALS

A crucial aspect for high-quality printing results is the interaction between ink and substrate material. The substrate materials that have been predominantly used with commodity conductive inkjet printing thus far are comparably easy to print on. In contrast, substrate materials with advanced mechanical properties, such as stretchability or conformality, tend to be considerably more demanding to print on, as they are optimized for their physical properties rather than for printability.

With the goal of extending the set of substrate materials from deformable-only PET films and photo paper to stretchable materials, we have explored a broad set of materials that exhibit the mechanical properties we seek and did extensive experimentation with the inks presented above. This allowed us to identify a set of candidate substrate materials. While some combinations of inks and substrates directly resulted in high-quality prints, it became evident that many ink-substrate combinations suffer from principled printability issues. We will present easily implementable strategies to overcome these issues. Ultimately, this allows us to present a set of inkjettable substrates with varied properties. All inks presented above can be printed on each substrate.

Highly stretchable substrate

Thermoplastic PolyUrethane (TPU) is an attractive substrate material for stretchable electronics (Figure 4a). The versatile chemistry enables TPU to have high tensile strength and abrasion resistance in addition to high elasticity (600% at break), making TPU a better candidate than silicones such as PDMS. In addition, because of thermoformability, TPU can be laminated on various surfaces, including itself. For our experiments, we used TPU films with thicknesses of 50µm and 100µm (Platilon® U073, Covestro). For our selected printer, the feed accepts sheets with a thickness of up to 300 µm. We use this to our advantage to print on TPU, which requires an additional backing layer, as these films are too thin and soft to be fed directly into the printer. We use photo paper as a backing layer (HP Glossy, 160 µm thick) and attach the TPU film using non-permanent glue (Tesa, 565259) so that it can be easily detached after printing.

The silver nanoparticle ink can be directly printed on TPU. However, traces printed with PEDOT:PSS suffer from de-wetting. De-wetting occurs when the surface tension of the ink is higher than the substrate's interfacial energy, and results in disconnected drops of ink. Conventional countermeasures include chemical modification of the material, activation in a plasma chamber, and surface etching. This requires specialized equipment [63] unavailable in a do-it-yourself setting. To find a simple and inexpensive alternative, we tested commercially available sprays for their capability to reduce a substrate's interfacial energy. We found that inexpensive anti-fog spray (B077HVXKMZ, Battic technologies) deposits a particle film with low interfacial energy that makes the substrate more wettable and compatible with all inks in our setup. The solution is sprayed onto the substrate directly before printing. This step requires a few seconds and is easy and versatile.

Ultrathin substrate

Recently, tattoo decal paper emerged as a class of promising substrate candidates for wearable ultra-soft electronics, whose stiffness and mass density match well with those of human epidermis. Applied onto skin, it can achieve ultimate conformability to various skin textures, forming noninvasive but most intimate coupling with skin (Figure 4b). Of note, the substrate is not restricted to use on skin; it can be applied onto other materials and objects, for applications that require a very thin and soft electronic layer. The substrate is made of a very thin (< 1 µm) film of polymeric materials such as polyvinyl alcohol (PVA) or polyvinyl pyrollidone (PVP). The film is bonded to a temporary backing layer that allows it to be fed through a printer. The ultrathin film can be transferred to the desired location using an adhesive. The film is stretchable (around 10%) and can withstand temperatures up to 120°C without changing its physical properties.

Tattoo decal paper has been used in prior work on body electronics [17,30]; however it required time-consuming screen printing. We demonstrate how to realize circuits using inkjet printing. We found that the diethylene glycol monoethyl ether (DGME) solvent contained in the silver nanoparticle ink dissolved the PVA layer of the tattoo paper, leading to non-functional printed designs. We succeeded in solving this issue while retaining a thin overall thickness and very good electrical conductivity using the following scheme: at any position later covered by silver ink, we first inkjet a layer of PEDOT:PSS or color ink. This layer protects the tattoo paper and prevents the silver ink's solvent from attacking it.

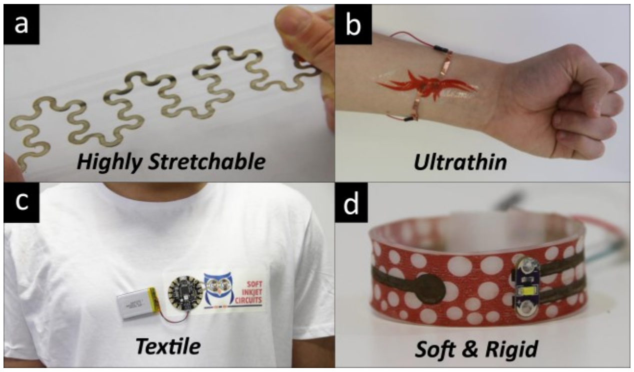

Figure 4. Supported substrate materials: (a) highly stretchable TPU, (b) sub-micron thin tattoo paper; (c) transfer polymer film for e-textiles, (d) re-shapeable shrink film.

Substrate for e-textiles

Textiles are a very demanding substrate material for printing, as the woven structure is highly uneven and porous. These structures may lead to excessive absorption of the ink droplets, thus generating isolated circles rather than the desired connected traces. This is particularly problematic for the low viscosity inks used for inkjet printing.

To add textiles to the realm of commodity inkjet-printed circuits, we propose a rapid transfer approach. The circuit is first inkjet-printed on a thin polymer film and then transferred onto the textile (Figure 4c). We use a commercially available textile transfer film from *SKULLPAPER* as a substrate. This is comprised of a thin polymer film (10 µm) of polyurethane binder and inorganic white pigment, protected by a layer of carrier paper that is removed after printing.

The transfer film is compatible with all the conductive inks presented above; thus, the desired design can be directly printed on the sheet. Designed for washability, this substrate partially absorbs the ink. To increase conductivity, we recommend printing two layers of silver ink or three layers of PEDOT:PSS. After printing, the polymer film including the printed circuit is adhered to fabric by ironing it for 3 min with a conventional electric iron. A further benefit of the iron-on transfer is that an additional curing step is not required, as the heat from the iron cures the ink during the transfer step. Given the transfer film is very thin and further adheres with the textile when heated, the haptic feel and deformability of the textile material is largely preserved.

Thermoplastic substrate for re-shapeable 2.5D designs

Shrink film is another soft substrate material with desirable properties that have been explored in prior work [31]. As it presents thermoplastic properties, shrink film can be used to create circuits that transition between a rigid and a deformable state when heat is applied. This enables heat-forming the material to a desired shape. For instance, this material can be used to create 2.5D designs for electronics that include curved geometries (Figure 4d). Prior work required manual ink deposition [31]. We demonstrate how to realize circuits on shrink film with commodity inkjet printers.

We recommend using shrink film from *SKULLPAPER*. This material is composed of a polymer (Polyolefin) that reduces its area when activated with heat, down to 50% of its original size. While in transition and if heated afterward, the material presents thermoplastic properties. As a result, it can be deformed to create non-planar designs for electronics. The challenge of this substrate material is that it presents non-wetting results and, a priori, cannot be printed on with functional inks. It can be made compatible with our inks using the spray-on technique introduced above (anti-fog spray).

EVALUATION OF PRINTING RESULTS

Figure 5 displays the visual results of printing conductive silver nanoparticle and PEDOT:PSS ink on each substrate, along with conductivity values. Photo paper is included as a baseline reference. TPU film shows very good conductivity, even better than photo paper, as the ink adheres to the surface. In comparison, the conductivity of absorbent substrates is reduced, primarily for textile transfer and to a lesser extent for tattoo and photo paper. Depending on the degree of absorption, the circuit can reach acceptable conductivity by simply printing a second or third pass, as for PEDOT:PSS on all substrates. The shrink film has the opposite effect, where the conductivity is increased as the ink particles are packed together by the shrinking process. To our knowledge, it presents the best conductivity results (0.06 Ω/□) for silver ink reported for commodity inkjet printers thus far.

The visual results show that the inks can be printed in high quality on all substrates. TPU, textile transfer paper, and shrink film present a print with fine and continuous traces that is on-par with photo paper. On tattoo paper, the blueish base layer of PEDOT:PSS makes thin silver lines less visible.

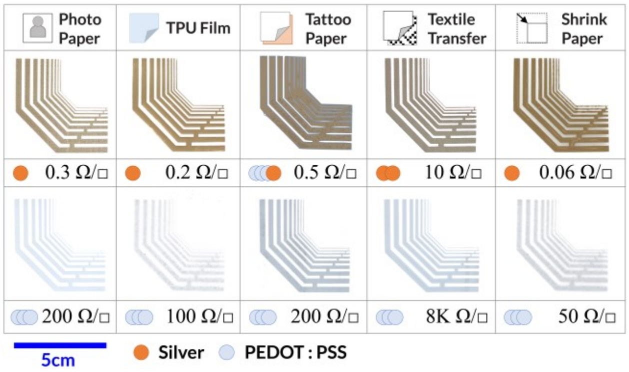

Figure 5. Visual printing results and sheet resistance (in Ω/□) of silver and PEDOT:PSS printed on the selected substrates.

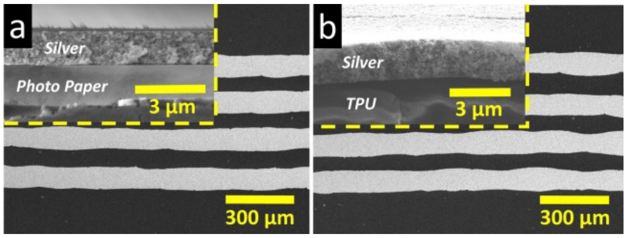

Figure 6: Top and cross-section SEM images for silver nanoparticle ink (traces: 100 µm width, 100 µm separation) on photo paper (left) and TPU film (right).

Figure 6 shows Scanning Electron Microscope (SEM) images of printed silver traces on two representative substrates: photo paper (ideal printing quality) and TPU (highly stretchable non-absorbent substrate). The insets display the cross-section. It is evident from the images that the printed traces have a thickness of approximately 2 µm, which is one order of magnitude thinner than screen-printed silver traces. This is important for the conformality of printed devices onto non-planar surfaces as highlighted in prior work.

Our selected printer can reliably print horizontal conductive lines down to 75µm line width; vertical lines down to 100 µm width show consistent conductivity. For reference, research grade printers report resolutions down to 30 µm [9]. Also, the registration error for successive prints on the same printer (<100 µm) and across printers (<200 µm) is remarkably low. Feeding the substrate does not require extra care to get this accuracy. We achieved this resolution just by casual alignment of the substrate to one side of the feeding rack of the printer. This enables using multiple printers for the same design when the number of inks exceeds the number of available cartridges (four with our printer).

Table 4 characterizes the dielectric behavior of our PVP ink. For this experiment, we printed three samples. Each sample contained a silver-printed electrode of 6 mm2 that was covered with 6, 9 or 12 inkjet-printed layers of PVP using a single cartridge, respectively. (By using 3 cartridges for PVP, the number of passes can be considerably reduced.) We covered the topmost PVP layer with copper tape to realize a parallel plate capacitor for measuring the capacitance, using a precision LCR meter (Agilent, 4284A).

PVP layers	*Thickness*	*Area*	*Capacitance*	*Dielectric constant (ε)*	*Resistance through*
6	2.1 µm	6 mm^2	73 pF	2.88	5.1 MΩ
9	3.2 µm	6 mm^2	48 pF	2.89	9.5 MΩ
12	4.2 µm	6 mm^2	37 pF	2.91	>10 MΩ

Table 4: Characterization of the PVP dielectric behavior. (The thickness of each PVP layer ≈350 nm is estimated based on literature using same formulation [32].)

A dielectric constant of ε ≈ 2.9 at 1 MHz was calculated based on these measured capacitor dimensions using the parallel plate method. For reference, this value is similar to other standard dielectric materials used for electrical insulation such as PET (ε = 3 at 1MHz), and Teflon (ε = 2.4-2.9 at 1MHz) [64].

ENHANCING THE STRETCHABILITY OF CIRCUITS

The most straightforward approach for realizing conductors that are very stretchable is to print a polymeric conductor, such as our PEDOT:PSS ink, as this ink is intrinsically stretchable. This is the preferred choice in applications where the trace resistance is not critical. However, its conductivity is 2-3 orders lower than that of silver nanoparticle ink, which prohibits its use for some applications, e.g. with high-frequency signals. In contrast, the maximum tolerance of metallic nanoparticles to strain is around 4%, as it creates micro-cracks in-between the solid particles [66]. We present do-it-yourself techniques to overcome this limitation and considerably improve the stretchability of silver conductors by pre-stretching the sample and using improved print designs.

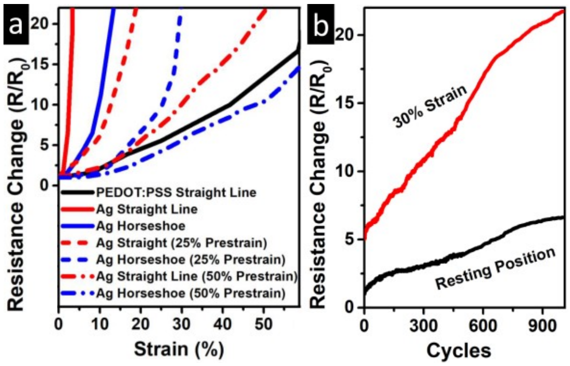

Figure 7. Stretchability tests: (a) Resistance change upon strain for different techniques. (b) Strain behavior for 1000 cycles for a silver-printed sample.

Pre-stretching the substrate before printing is a common technique in material science to increase the stretchability of inkjet-printed traces [27]. We make this technique compatible with commodity printers by using an A4-sized sheet of photo paper as a flexible carrier layer that can be fed through the printer. First, we adhere a patch of cardboard (170 gr/m²) to the photo paper. We chose cardboard as it is stiff enough to remain flat despite the strain added by the sample. We then stretch the sample of TPU to the desired length and firmly adhere it to the cardboard using masking tape. Once printed, the sample is sintered in an electric oven for 10 min at 125°C before it is released. This method mechanically supports pre-stretch up to 50% for 100 μm thick TPU substrates. To speed up the process, several samples can be simultaneously affixed and printed on the same A4 sheet.

To further increase the stretchability of conductive traces, we recommend designing serpentine patterns to spread the stretch over a longer distance and incur it as a bending force rather than straight tension. Among the many existing patterns, the horseshoe is recognized as one of the best. It offers elastic, low-modulus responses to large strain deformations [7]. We successfully printed horseshoe patterns with our technique. Given the high-resolution features required, we recommend a trace width and curvature radius of no less than 200 μm and 2 mm respectively.

Evaluation of stretch behavior

We empirically evaluated the effect of different levels of pre-stretching (0%, 25% and 50%) and conductor designs (straight or horseshoe 45°; 1mm trace width) with silver ink for 0–50% strain. These experiments were performed using TPU, our most stretchable substrate material.

The results are plotted in Figure 7a. For reference, results for a straight line of PEDOT:PSS are also presented, showing a fairly linear increase in resistance upon strain, increasing up to 13-fold at 50% strain. In contrast, a straight line of silver sustains only up to 4% strain. However, if printed on a pre-stretched sample, a silver conductor is considerably more stretchable. More pre-stretch results in a considerably lower increase of resistance upon strain. Our results further show that horseshoe designs clearly outperform straight lines. The effects of pre-stretch and improved print designs add up. Combining 50% pre-stretch with a horseshoe design yields the best results. This strategy allows for printing highly conductive silver conductors on a desktop inkjet printer that are stretchable by 50% and show a resistance increase of 10-fold at 50% strain. Note that this outperforms a straight PEDOT:PSS line, while the base resistance of silver is two orders of magnitude lower.

To investigate durability, we subjected a 50% pre-stretched TPU sample (with a silver conductor in horseshoe design) to 1,000 stretching-and-releasing cycles of 30% strain. The variation in resistance is plotted in Figure 7b. The results show the good mechanical and electrical endurance of the sample, which remained functional after 1,000 iterations. The baseline resistance increased fairly linearly up to 6-fold after 1000 cycles. The resistance change ratio within each stayed fairly constant, from initially 4.2-fold to 3.8-fold after 1000 cycles. According to these results, the stretchability of the traces is considerably better than reported in prior work on inkjet printed circuits [29].

APPLICATION EXAMPLES

To demonstrate the versatility and ease of use of the fabrication technique for rapid prototyping, we present a set of technical demonstrations. Table 5 summarizes the time required for the physical fabrication of the circuits.

Device	**Printing**	**Curing**	**Assembly**
Stretchable input device	30 sec	8 min	5 min (adhering)
E-textile circuit	1 min	3 min	5 min (sewing)
Electronic skin tattoo	5 min	18 min	3 min (application)
E-bracelet	5 min	3 min	2 min (components)

Table 5: Time required for fabricating the applications.

Stretchable input device

We leverage the stretchability of TPU and our techniques for stretchable silver traces to realize an inkjet-printed prototype of a stretchable input device (Figure 8).

A stretchable membrane made of TPU, placed over an origami paper box, detects deformation input. It contains four resistive strain sensors printed in a matrix layout. Each sensor is made of a spiral trace of 1mm width. The sensor was printed in a single pass. To accelerate the fabrication process, the print was dried with a heat gun first; then, the traces were sintered in an electric oven for 5 minutes to guarantee homogeneous heat. The origami box was folded from an A4 photo paper during the sintering time. The total fabrication process required less than 10 minutes.

Resistance readings are collected and processed using an Arduino Nano. By interpolating individual sensor readings, 2D deformation is captured on a 3x3 grid. First, each sensor is calibrated by computing its minimum and maximum resistance, which allows computing a normalized stretch value. At each frame, the microcontroller computes the gradients between normalized resistances, and then streams data to a processing application for live visualization. Here we aimed for a simple solution for a low-fidelity prototype. It can be noted, however, that the empirical findings reported in the previous section suggest that our technique supports printing of resistive strain gauges of high dynamic range.

E-textile circuit with full-color art layer

We inkjet-printed a circuit with a full-color art layer for an interactive e-textile. It features two LEDs that illuminate a full-color logo as shown in Figure 9. It is controlled using an Arduino Lilypad and powered by a LiPo battery. The circuit was printed in two passes (around one minute) using silver and color (see Table 3): a first pass printed both color and conductive traces. An additional pass reinforced the conductive traces. Then, the print was integrated with a conventional textile using ironing, which also acts as curing step. Finally, the Lilypad microcontroller [3,4] and LEDs were directly sewn on the patch using conductive yarn, connecting them with the circuit and affixing them on the textile. Preliminary tests suggest that the circuits can be washed, as the transfer polymer is designed to partially absorb the ink, which after sintering with iron forms a conformal contact preventing the traces from washing away. Our test with 10 manual washing cycles confirmed less than 1% resistance increase per cycle for silver traces.

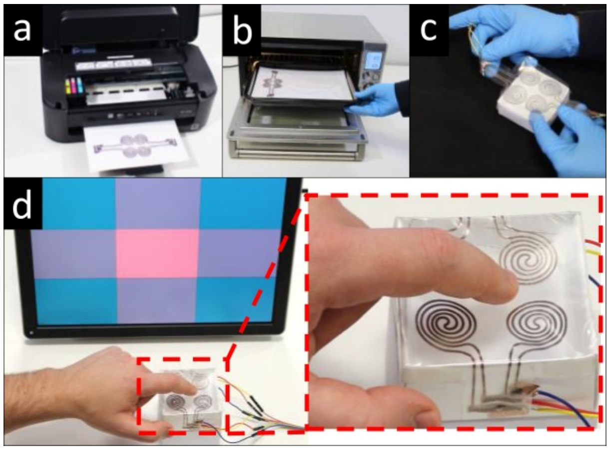

Figure 8. Stretchable input device: (a) Printing on TPU substrate, (b) heat sintering, (c) connecting, (d) stretch input.

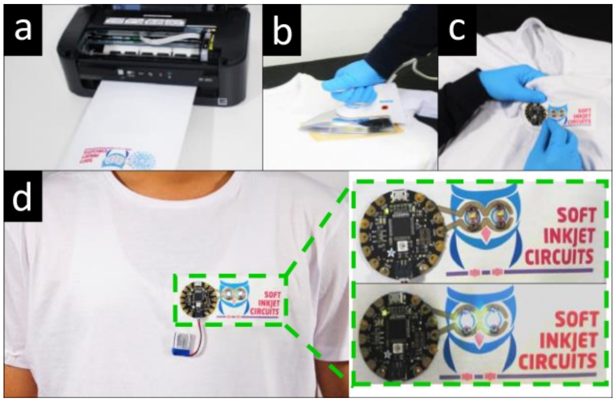

Figure 9. Printed e-textile circuit with full-color art layer: (a) Printing on textile transfer polymer, (b) iron-transfer to textile, (c) connecting electronic components using conductive yarn, (d) illumination of two LEDs.

Inkjet-printed, ultra-thin electronic skin tattoo

Our approach allows us to present the first electronic skin tattoo directly fabricated using a simple desktop inkjet printer and commercial temporary tattoo decal paper. The tattoo contains skin-mounted printed electrodes for continuous measurement of electrodermal activity (EDA, the level of skin conductance and among others is linked to emotional arousal), integrated in an aesthetic artwork (Figure 10). First, a heart-shaped symbol was printed on the decal transfer paper with color ink (Figure 10). A design of circular electrodes (10 mm diameter, 15mm center-to-center distance) was printed on top of the color layer, protecting the tattoo substrate from being attacked from solvent in the silver ink. For electrical isolation, a layer of PVP was printed over the conductive traces, while leaving the electrodes exposed. Finally, the device was transferred to skin using the standard transfer procedure reported in the literature [17,30]. The change in skin resistance is monitored with an Arduino Nano and visualized in real-time with a processing application. We successfully deployed the tattoo on a user's forearm for an eight hour-long period of capturing the EDA signal.

While previously such a device had to be realized using time-consuming screen printing, our device was printed in less than 5 minutes. Moreover, inkjet-printed silver traces are one order of magnitude thinner than screen-printed ones (reported 20 µm thick [62]). This further enhances the conformality of e-tattoos on human skin.

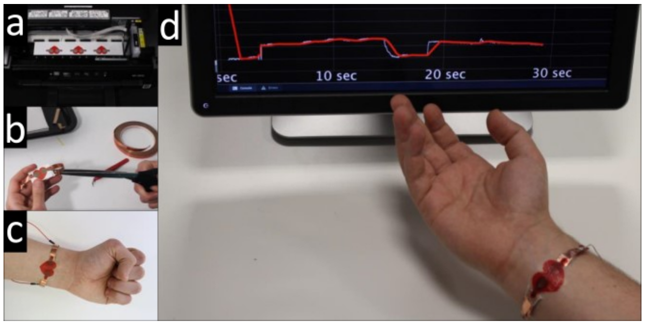

Figure 10. Ultrathin electronic skin tattoo for monitoring electro-dermal activity: (a) Printing on temporary tattoo paper, (b-c) transfer to skin, (d) body-worn monitoring tattoo.

Thermoplastic inkjet-printed e-bracelet

To demonstrate the potential of inkjet printing on thermoplastic, we designed an interactive body accessory using shrink film. The interactive bracelet features a custom curved shape and full color artwork, while containing a printed capacitive touch sensor, a printed circuit and surface-mount electronic components (Figure 11). Capacitive touch information is read by an Arduino Pro Mini, which controls LEDs mounted on the wristband. The result is an interactive wearable device, customizable in both shape and appearance. Additional sensors and output components could be included, e.g., for self-monitoring and self-expression.

First, the color design was printed on shrink film. A second pass added the conductive traces with silver ink. Once dry, a third pass was performed to add a PVP layer for electrical isolation of the traces, while keeping pads exposed for connecting components. Then, the material is placed in an electric oven at 110°C for 3 minutes to activate the shrink film and simultaneously cure the conductive traces. The resulting piece can then be reheated to 100°C to reshape it to the desired curved shape. Electronic components can then be directly soldered onto the final piece.

DISCUSSION AND LIMITATIONS

Prior approaches for fabricating flexible circuits can be broadly classified into one of the following: (a) fast computer-controlled fabrication, yet low versatility by imposing strong restrictions on supported materials and stretchability (instant inkjet printing [19]); or (b) supporting diverse materials and high stretchability, at the cost of time and dedicated equipment: screen printing [30,59], sewing [13], or silicone casting [34,61]. Our approach combines key benefits of both categories, providing stretchability and versatile materials, while benefiting from the high speed and ease of use of digital fabrication using a desktop inkjet printer. Table 5 gives the time that was required for fabricating our examples.

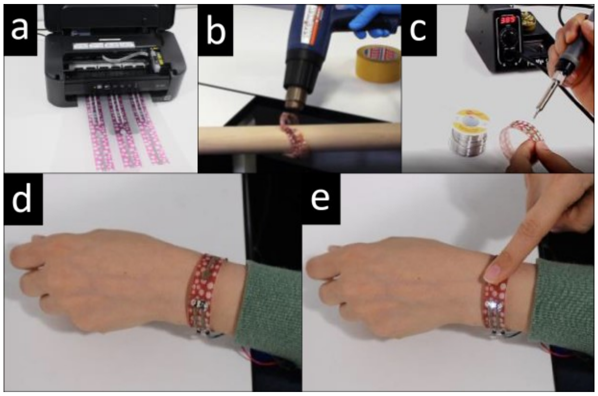

Figure 11. Thermoplastic inkjet-printed e-bracelet: (a) Printing on shrink film, (b) re-shaping with heat gun, (c) soldering of the LED, (d-e) final prototype.

It is important to note that our technique is not exclusive but can be combined with existing ones. For instance, inkjet printing can be used to speed up the printing and iteration process, while screen printing can address problematic inks (such as phosphor [38] or binders). Our approach can also be combined with subtractive alternatives such as laser cutting to create full multilayer devices [14] or variable stretchability [6]. At the moment, our process still requires manual heat curing, and re-feeding the substrate when more than one pass is needed. These issues can be addressed by modifying the printer: adding a heating plate and considering the usage of duplex units. Furthermore, pre-stretching would greatly benefit from a flatbed printer. Research has also shown that using software it is possible to control each nozzle independently [57], which adds versatility to the quantity and order of inks. The main limitation of the current work is the inability to print on top of PVP: the solvent of the silver ink (DGME) attacks PVP, while PEDOT:PSS presents wettability issues. Once this challenge is addressed, it would be possible to directly print multi-layer circuits. Adding semiconductors would enable the creation of transistors and move further toward the creation of full-stack inkjet electronics.

CONCLUSION

In this paper, we presented *Soft Inkjet Circuits*, demonstrating the potential of inkjet printing for the creation of soft and stretchable devices. This is achieved by considerably expanding the set of functional inks and substrates that can be used with commodity inkjet printers. We introduced the simultaneous usage of multiple inks on one printer, combining metallic and polymeric conductors with isolating and graphical inks. All inks can be printed on the full set of substrates that offer diverse mechanical properties. We further demonstrated that it is possible to achieve dual-layer devices and enhance stretchability by combining pre-stretch substrates and improved designs. Finally, a set of technical demonstrations shows that our technique allows for realizing e-textiles, e-tattoos, stretchable input devices and re-shapeable devices. We consider that this approach has great potential for researchers, makers, and the do-it-yourself community alike. It also presents a viable path toward the vision of ultimately providing a desktop printer for everyone at home to print personalized interfaces, wearables and interactive tattoos.

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