Silver Tape: Inkjet-Printed Circuits Peeled-and-Transferred on Versatile Substrates

TINGYU CHENG*, Georgia Institute of Technology, USA
KOYA NARUMI*, The University of Tokyo, Japan
YOUNGWOOK DO, Georgia Institute of Technology, USA
YANG ZHANG, Carnegie Mellon University, USA
TUNG D. TA, The University of Tokyo, Japan
TAKUYA SASATANI, The University of Tokyo, Japan
ERIC MARKVICKA, University of Nebraska-Lincoln, USA
YOSHIHIRO KAWAHARA, The University of Tokyo, Japan
LINING YAO, Carnegie Mellon University, USA
GREGORY D. ABOWD, Georgia Institute of Technology, USA
HYUNJOO OH, Georgia Institute of Technology, USA

We propose Silver Tape, a simple yet novel fabrication technique to transfer inkjet-printed silver traces from paper onto versatile substrates, without time-/space- consuming processes such as screen printing or heat sintering. This allows users to quickly implement silver traces with a variety of properties by exploiting a wide range of substrates. For instance, high flexibility can be achieved with Scotch tape, high transparency with polydimethylsiloxane (PDMS), heat durability with Kapton polyimide tape, water solubility with 3M water-soluble tape, and beyond. Many of these properties are not achievable with conventional substrates that are used for inkjet-printing conductive traces. Specifically, our technique leverages the commonly undesired low adhesion property of the inkjet printing films and repurposes these films as temporary transfer media. We describe our fabrication methods with a library of materials we can utilize, evaluate the mechanical and electrical properties of the transferred traces, and conclude with several demonstrative applications. We believe Silver Tape enriches novel interactions for the ubiquitous computing domain, by enabling digital fabrication of electronics on versatile materials, surfaces, and shapes.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing systems and tools**; • **Hardware** → *Sensors and actuators.*

6

*Both authors contributed equally to this research.

Authors' addresses: Tingyu Cheng, tcheng32@gatech.edu, Georgia Institute of Technology, USA; Koya Narumi, narumi@akg.t.u-tokyo.ac.jp, The University of Tokyo, Japan; Youngwook Do, Georgia Institute of Technology, USA, youngwookdo@gatech.edu; Yang Zhang, Carnegie Mellon University, USA, yangz3@andrew.cmu.edu; Tung D. Ta, The University of Tokyo, Japan, tung@akg.t.u-tokyo.ac.jp; Takuya Sasatani, The University of Tokyo, Japan, sasatani@akg.t.u-tokyo.ac.jp; Eric Markvicka, University of Nebraska-Lincoln, USA, eric.markvicka@unl.edu; Yoshihiro Kawahara, The University of Tokyo, Japan, kawahara@akg.t.u-tokyo.ac.jp; Lining Yao, Carnegie Mellon University, USA, liningy@andrew.cmu.edu; Gregory D. Abowd, Georgia Institute of Technology, USA, abowd@gatech.edu; HyunJoo Oh, Georgia Institute of Technology, USA, hyunjoo.oh@gatech.edu.

2474-9567/2020/3-ART6 $15.00
https://doi.org/10.1145/3381013

Additional Key Words and Phrases: inkjet-printed circuit, sticker circuit, personal fabrication, rapid prototyping, flexible electronics

ACM Reference Format:
Tingyu Cheng, Koya Narumi, Youngwook Do, Yang Zhang, Tung D. Ta, Takuya Sasatani, Eric Markvicka, Yoshihiro Kawahara, Lining Yao, Gregory D. Abowd, and HyunJoo Oh. 2020. Silver Tape: Inkjet-Printed Circuits Peeled-and-Transferred on Versatile Substrates. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 1, Article 6 (March 2020), 17 pages. https://doi.org/10.1145/3381013

Table 1. Summary of different printing techniques for rapid fabrication of conductive patterns.

		Fabrication Methods	
		Transfer	Non-transfer
Sintering Type	Sintering free	Our methods	Instant Inkjet Circuit [13, 14]
	Heat sintering	ObjectSkin [1, 3, 5, 7, 16, 29]	Others [15, 30]

1 INTRODUCTION

In the past decade, digital fabrication tools such as laser cutters and 3D printers have benefited not only manufacturers and suppliers but also researchers, makers, artists, and even children to fabricate their own designs. Such tools allow users to play with a wide range of materials (*i.e.*, paper, metal, plastic, rubber-like material, etc.) in easy, fast, low-cost, and compact processes. Our motivation is to further extend the benefits of easy fabrication and design freedom that digital fabrication allows for, and achieve a novel digital fabrication method of electric circuits with both accessible processes and diverse material selection at the same time. For this purpose, the inkjet-printed circuit [13] shows a promising potential due to its "sintering-free" printing process.

Typically, conductive inks for inkjet-printing require either a heat sintering or chemical sintering (known as sintering-free) process in order to dry out or dissolve the polymer shell outside the conductive particles, which prohibits the agglomeration of the ink. The heat sintering process requires additional equipments such as heat guns or ovens to heat up the printed traces, which is relatively costly and time-consuming. Moreover, if not handled professionally, such procedures can damage the printing substrates [13]. In this regard, the chemical sintering process shows brighter advantage, since it offers relatively precise and highly conductive traces without the need of expensive machines or non-reusable stencil sheets that are typically required by other methods such as 3D printing or screen printing. However, conventional inkjet printing of silver traces with a sintering-free process has been limited to the specially-coated paper that ensures the formation of bulk silver and good adhesion of the traces to the substrate. This limitation has heavily restricted people's design choices with this fabrication technique, which prevents such techniques from being adopted in a broader spectrum of applications.

In this paper, we propose Silver Tape, an extension of sintering-free inkjet printed circuitry process, which allows us to explore many types of materials as substrates for printing conductive traces, without losing the benefits of its easy, rapid, low-cost, and compact nature. With our technique, users simply inkjet print the target pattern onto Kodak photo paper (Kodak AZERTY5149), Fujifilm Paper Kassai Pro, or Epson premium photo paper GLOSSY which are commercially available; customized Mitsubishi PET film, which is not yet commercially available, apply substrates (*i.e.*, Scotch tape, PDMS elastomer, 3D printed soft structure, etc.) on top of the printed traces, and peel the pattern off for practical use. The applied substrates enable printed traces with corresponding properties, many of which could not be previously achieved by conventional paper substrates.

The most significant yet simplest finding in this project was that we can transfer inkjet-printed silver traces only when we use less sticky paper substrates as printing media whose property has been regarded bad for substrates of inkjet-printed circuits – because less adhesive surfaces cannot maintain the silver traces against mechanical scratches. However, we turned this undesired disadvantage of low adhesiveness of a substrate into advantages by using less-adhesive surfaces as temporary transfer media. Table 1 shows a comparison that highlights the novelty of our technique compared among other fabrication methods. We summarize the contributions of this work as follows:

(1) We describe our method to transfer silver traces from paper to diverse sticky materials, along with a wide range of transfer paper, sticky materials, and assembling techniques.
(2) We investigate the electrical property of multiple sticky materials, after they were transferred and applied onto different materials and geometries.
(3) We demonstrate several applications of Silver Tape exploiting the versatile functionalities of different substrates.
(4) We report a workshop which we ran to validate the accessibility of the technique and its potential design space. Our key findings are summarized and discussed later in the paper.

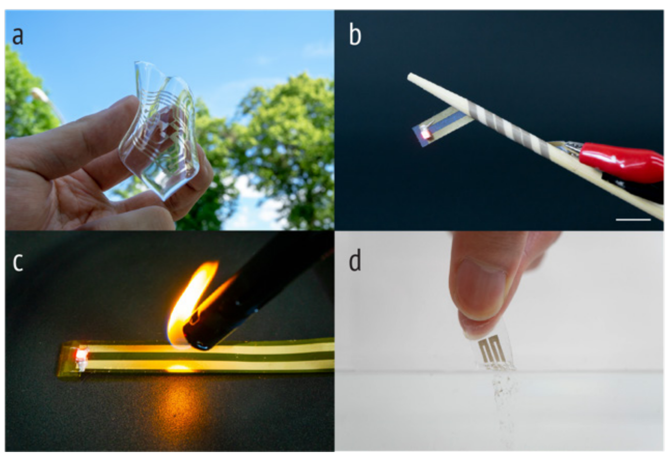

Fig. 1. Different functions enabled by different substrates with unique properties, including (a) transparency, (b) conformability, (c) fire tolerance, and (d) water solubility.

2 RELATED WORK

Silver Tape intersects with several related research fields, which we summarize in this section. We start by introducing conventional inkjet printing methods on paper substrates with a sintering-free process. We then discuss conventional circuit fabrication techniques that achieve multiple properties by using different types of substrates. Our proposing method aims to hold to a "middle way" of these two conflicting topics: rapid fabrication with paper substrates versus functional fabrication with multiple substrates, combining the advantages of both methods.

2.1 Inkjet Printed Circuits on Paper Substrates

Instant Inkjet Circuits [13, 14] can print highly conductive silver ink traces (approx. 0.2Ω /sq.) using an off-the-shelf desktop inkjet printer for rapid prototyping. This method uses a specific type of silver ink and coated paper from Mitsubishi Paper Mills [17] and realized sintering-free process and the strong adhesion of silver traces on paper which users do not need any post-processing like heat sintering in the oven. However, only three substrates are compatible with this technique: resin-coated white paper, translucent PET film, and white PET film, all of which are limited in color, thickness (> 130 um), heat durability (they can endure only up to 120 °C), and water insolubility – properties that are important in many application scenarios.

There are also some other ink materials which users can print with a desktop inkjet printer (*i.e.*, PEDOT:PSS [5, 30]). However, they require heat sintering post-processing and the resistance of the end results is too high (*i.e.*, around 900 kΩ/sq. [5]) to make general circuitry. As a result, sintering-free silver circuitry is considered to be a more preferable approach for rapid prototyping. Previous work has demonstrated customizable touch [4, 22], pressure [6], flex [32], and soil moisture sensors [14], antennas [28], extension of a touch screen for mobile devices [12], interactive energy harvesting books [10], haptics [11], actuators [18, 23], and even 3D construction of functional objects [21]. Recently, inkjet printed conductive materials have also been used as a low-cost fabrication method for large-scale sensing interactions [33].

2.2 Fabricated Circuits on Multiple Substrates

There is a significant body of research in the HCI community which has explored methods of implementing functional flexible circuitry on several different substrates (*i.e.*, transparent, stretchable PDMS elastomer for on-skin touch sensors [34] and electroluminescent displays [35]; conformable tattoo paper for multi touch sensors [9, 20]). Others adopted methods which are not restricted to the specific substrates: screen printed electroluminescent displays on leather, ceramics, and even stone [24]. People have also demonstrated copper tapes/sheet circuits for extension of touch screens [27], for low-tech fabrication [25, 26] and conductive sprays/paints for large-scale touch/hover sensors [36, 37]. Recently, [15] introduces printed circuits with versatile functionalities by printing with different inks including conductive, highly stretchable, isolation or even cleaning inks directly on temporary tattoo paper, textiles, and thermoplastics, though it surely broadens the ink and printing material selections, However, the selections are still limited to five different kinds of substrates, and all the printed traces need to undergo a heat sintering post-treatment, which does not leverage the benefit of rapid prototyping with a sintering-free inkjet process in [13]. Instead, our motivation is to keep a sintering-free process while allowing multiple substrates.

Our approach is similar to those of sticker circuits which install circuit components on the sticker in advance as an extension module [2, 8]. Here, our approach presents three core novelties: (1) we allow rapid prototyping of fully customizable conductive traces with near-to-zero cost and an extremely easy fabrication process, as we demonstrated with a toolkit study, (2) our method can support a wide range of substrate materials with unique properties, and (3) our method transfers circuits not only to substrate films but also these films can be directly applied onto a variety of everyday surfaces, which unlocks applications beyond previous possibilities.

Similar ideas of transferring printed circuitry from paper to other objects have also been demonstrated in ObjectSkin [5]. This method achieved the circuit on non-developable surfaces by water-transferring unsintered conductive ink to the surface of the object and heating it up for sintering after the transfer step. The most significant benefits of our approach are that (1) we do not need any pre- or post- processes to transfer circuitry, and (2) we do not need any additional equipment like a water tank. At the same time, our approach has drawbacks that the precise transfer of the circuits is only limited to developable surfaces.

Finally, even though, in prior work, researchers have explored transfer printing techniques in the material science community, special facilities such as CVD machine, annealing oven, cleanroom-/lab grade environments, and pre-/post-processes are required [1, 3, 7, 16, 29]. Our approach provides comparable outcomes without special equipment or complex procedures, which can be easily integrated into rapid fabrication routines.

3 FABRICATION PROCESS

The fabrication process of Silver Tape consists of three simple steps: **printing** (Figure 2a), **transferring** (Figure 2b) and **assembling**. Instead of relying on additional heat sintering, our Inkjet-printed pattern becomes conductive due to the chemical sintering reaction on the surface of the chosen temporary transfer paper. Additionally, our method can be achieved with a standard desktop inkjet printer loaded with silver ink, and a wide selection of sticky tapes, which is easy, fast, compact, and low-cost as we will describe in greater details later.

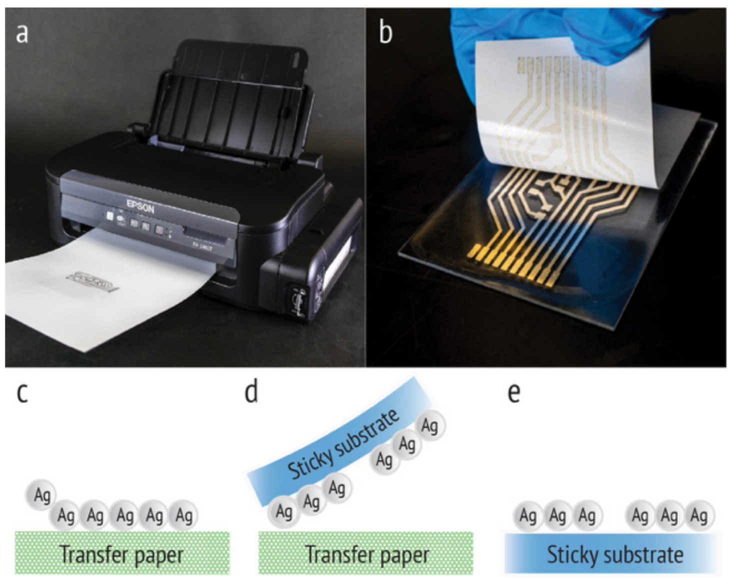

Fig. 2. Overview of Silver Tape. Conductive patterns are (a) printed on transfer paper, (b) peeled off and transferred by hand. (c-e) Schematics of the transfer process of silver nanoparticles from transfer paper to a sticky substrate.

3.1 Printing

For printing silver ink, we used a desktop inkjet printer (Epson PX-S160T) and silver nanoparticle ink (Mitsubishi Paper Mills NBSIJ-MU01) in order to carry out all the testings and applications. We adopted the printing method based on the literature [13, 14].

For the printing paper selection, we investigated four different papers: commercialized glossy photo paper (Kodak AZERTY5149), Fujifilm Paper Kassai Pro, Epson premium photo paper GLOSSY, and customized Mitsubishi PET film, all of which are commercially available except the PET film. All four papers can cause a chemical sintering process on the surface [13], and support the transfer process.

3.2 Transferring

We first apply the adhesive side of a sticky substrate such as a piece of tape onto a piece of transfer paper. To facilitate a successful peeling/transferring process, we rub the tape gently to ensure a seamless contact between the adhesive and the printed pattern, and then slowly peel off the adhesive.

Our method is compatible with a wide range of tapes, several of which we selected as examples for demonstration and evaluation next, including Scotch tape (3M Scotch 810), polyimide electrical tape (3M 1205), vinyl insulation tape (3M Super 33+), Scotch transparent tape, water soluble tape (3M 5414), Scotch removable tape (3M Scotch 811), and masking tape (3M Scotch 234) (Figure 3b) . We evaluated the above example substrates and proved their compatibility with our method. We also observed that the low adhesion and rough surface of Scotch removable tape and masking tape caused the silver nanoparticle residuals left on the printing paper after transfer. We report the procedure and several key results of a comprehensive performance evaluation in the electrical and mechanical analyses section.

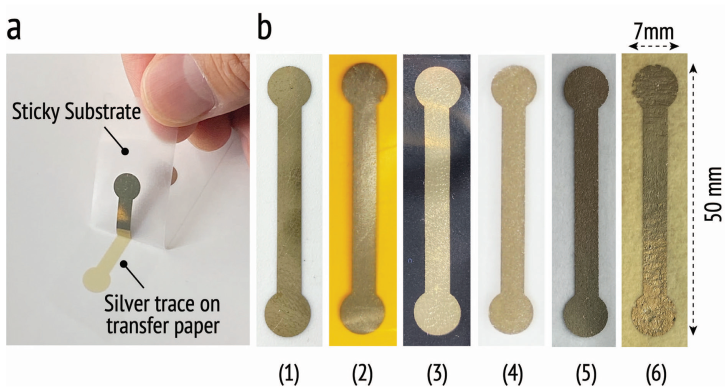

Fig. 3. Silver traces transferred to different substrates. (a) Transfer process. (b) Successfully transferred conductive patterns on various substrates: (1) Scotch tape (3M Scotch 810), (2) polyimide electrical tape (3M 1205), (3) vinyl insulation tape (3M Super 33+), (4) water soluble wave soldering tape (3M 5414), (5) Scotch removable tape (3M Scotch 811), (6) masking tape (3M Scotch 234).

3.3 Assembling

After we transfer the patterns onto target substrates, we connect the conductive traces with other electronic components. Figure 4 shows four common connection methods allowed by Silver Tape: (a) sticky tapes pasted together with two conductive patterns in contact, (b) conductive paste (Bare Paint) /epoxy (CW2400) for permanent connections, (c) fixing a stable, solderable connection with metal pierce punch (SK11 pierce punch), and (d) liquid metal eutectic gallium indium (EGaIn) for temporary connection to connect with, for example, the probes to measure electric properties of the testing circuit.

3.4 Re-transferability

On top of printing, transferring, and assembling. Sometimes the transferred pattern might get damaged, for example when overly bent or accidentally scratched which are likely to happen in reality but rarely considered in previous literatures. Our technique allows users to quickly fix the damaged portion by re-transferring a new trace onto the damaged part to recover the conductivity of the trace, or even using commercially-available circuit erasers [19] to erase the unwanted part of the silver traces and retransfer with a desired one. In Figure 5, we show that we partially remove the transferred pattern and replace with a new one. Figure 5e also shows a

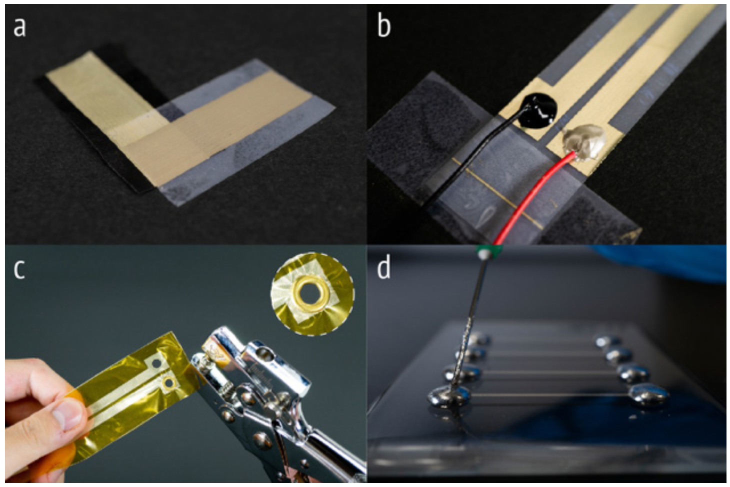

Fig. 4. Connection methods. (a) Pasting two sticky substrates using their own adhesive force. (b) Conductive paste/epoxy. (c) Pierce punch to make a stable, solderable connection. (d) Temporary liquid metal connection mainly for measurement.

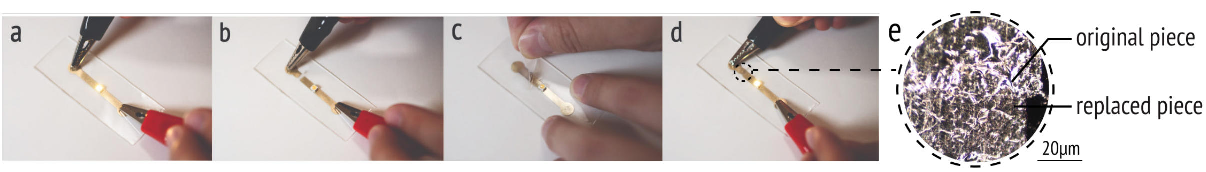

Fig. 5. (a) Silver trace is transferred onto PDMS and connected with LED. (b) Part of the trace is removed. (c) Recovering the damaged portion with a new silver trace. (d) The silver trace is recovered. (e) Microscopic image of the edge between the original and the replaced silver trace.

microscopic image of the edge between the original and the replaced patterns, where the new replaced silver trace is recovering the conductivity of the whole pattern by filling the removed portion and gets well integrated into the original pattern.

4 ELECTRICAL & MECHANICAL ANALYSES

To better understand the transferring process and evaluate the electrical and mechanical performance of our technique, we carried out several tests. We also summarized our key findings in this section to help predict and guide the design procedures for researchers, makers, and hobbyists to adopt our method in their applications.

4.1 Transfer Resolution

We first tested the transfer resolution, which decides the widths of printed traces. An ideal circuit fabrication approach should be high-resolution, able to provide thin traces to support fine-grained circuitry patterns. Figure 7a shows the transferred silver patterns with seven different widths we tested. In this test, we printed the pattern in different widths on Mitsubishi PET film and transferred onto PDMS sheet. We took multiple trials and measurements and found the thinnest pattern we could achieve was 0.1 mm. Traces less than 0.1 mm caused breakage. Note that the 0.1 mm resolution achieved by Silver Tape compares more favourably than the prior work [13]. We speculated this difference mainly came from the high resolution of the printer we used.

Table 2. Resistance variance before and after transfer for different printing substrates.

Substrates	Printing Patterns		Resistance (ohm/sq)	
	On Tapes	On Sustrates	Before	After
Kodak Premium Photo Paper			0.53±0.02	1.44±0.61
Epson Premium Photo Paper			0.16±0.03	0.27±0.04
Fujifilm Paper Kassai Pro			0.14±0.01	0.30±0.06
Mitubishi PET Film			0.15±0.01	0.28±0.05

Table 3. Resistance variance before and after transfer for different transfer materials.

Peeling F.	Substrate	Printing Patterns		Resistance (ohm/sq)		Peeling F.	Substrate	Printing Patterns		Resistance (ohm/sq)	
		On Tapes	On Sustrates	Before	After			On Tapes	On Sustrates	Before	After
Unclear	Scotch Double Sided			0.14±0.01	0.27±0.05	2.5N/cm	Scotch Magic Tape			0.14±0.01	0.20±0.03
Unclear	PDMS			0.14±0.01	0.20±0.02	Unclear	Tango Black +			0.15±0.01	0.31±0.08
6N/cm	Scotch Heavy Duty			0.14±0.01	0.21±0.03	Unclear	Scotch 2080			0.14±0.01	0.32±0.11
0.4N/cm	3M Water Soluble Tape			0.15±0.01	0.21±0.05	1.5N/cm	Scotch 2093			0.15±0.01	0.40±0.13
2.4N/cm	Polymide Tape			0.14±0.01	0.23±0.05	3.5N/cm	Scotch 234			0.14±0.01	0.30±0.09
1.55N/cm	Scotch Transparent			0.15±0.01	0.28±0.05	3.5N/cm	Scotch General Purpose			0.14±0.01	0.36±0.09
2.8N/cm	Scotch Super 33+			0.14±0.01	0.24±0.05	0.3N/cm	Scotch Removable			0.14±0.01	0.32±0.09

4.2 Resistance Change Using Different Substrates

We investigated the resistance variance before and after transfer, where we used the same tape (Scotch transparent tape) to transfer 7 mm wide traces (with a 50 mm length) from different printing substrates, including Kodak photo paper, Fujifilm Paper Kassai Pro, Epson premium photo paper GLOSSY and customized Mitsubishi PET film (Table 2). For each substrate, the pattern was printed and transferred 20 times, where we measured the resistance of the traces before and after the transfer. Table 2 summarizes our results. We found that all the printing substrates showed promising conductivity after transfer, while Fujifilm Paper Kassai Pro, Epson premium photo paper GLOSSY and customized Mitsubishi PET film showed much smaller resistance variance before and after transfer than the Kodak photo paper. We used the customized Mitsubishi PET film for the rest of the testings and most of the applications. Comparing with the Fujifilm and Epson photo paper, the customized Mitsubishi PET film, made by Mitsubishi Paper Mills, is providing a surficial "releasing layer" composed of non-sticky particles. This releasing layer helps us peel the sticky substrate off the transfer paper surface more easily than from the commercial photo paper, even they all provide the similar final electrical performances. The sample of customized Mitsubishi PET film is also available as "Transfersheet" at E-mail: agnano@mpm.co.jp.

4.3 Resistance Change Using Different Adhesives

We also investigated the electrical performance with different adhesive materials when we used customized Mitsubishi PET film as the printing substrate for all these tests. To facilitate others' access to our technique, we only used off-the-shelf tapes. We did an extensive search and purchased 14 different tapes we found on the market. We used these tapes together with PDMS sheets, soft 3D printing material Tango Black plus to transfer the designed pattern printed on the customized Mitsubishi PET film (Table 3). Following the same procedure as the test before, we measured the variance of the resistance before and after the transfer. The pattern was printed 20 times and transferred 20 times. Table 3 summarizes our results. As we can see, all transfer materials consistently show successful transfer, whereas the highlighted transfer materials on the right side of the table are showing relatively higher resistance variances mainly due to the stickiness difference or the surface roughness level of the transfer materials. Additionally, we looked into the datasheet of these tapes and found that in order to achieve a relatively smaller resistance variance, adhesion between 0.4N/cm to 6N/cm would be a good selection range. Adhesion lower than 0.4N/cm could also show successful transfer but might result in bigger resistance variance, while adhesion that is too strong might make the transfer material harder to be peeled off and result in damaged traces.

4.4 Transfer to Everyday Surfaces

With the adhesive nature of the tapes, we can transfer and directly paste the conductive pattern onto different everyday surfaces for real-world uses. In Figure 6, we show conductive patterns (*i.e.*, 7 mm width, 50 mm length) are transferred and pasted onto a wide array of materials including aluminum, glass, granite, wood, foam, fabrics, and acrylic. From the microscopic images, we also visualized the connection of the silver nanoparticle when they were on the tapes, and perceived some minor cracks which may have caused the increase of the resistance.

Fig. 6. Silver traces transferred onto different materials and geometries.

4.5 Transfer to Different Geometries

Besides different materials, we also tested how the resistance varies when we transfer the conductive patterns onto different geometries. We drew three basic geometries – flex, corner, and twist, which exemplify most of the everyday objects. We measured the resistance before and after the substrate is coated onto the geometry. In general, we found the resistance increases after transfer, due to the local stretching of the substrates. The flex geometry caused the resistance to increase from 0.37 to 1.22 Ω/sq, corner from 0.37 to 4.04 Ω/sq, and twist from 0.37 to 6.54 Ω/sq. As we can see, the twisty shape shows a much larger resistance change than the other two. We speculate when under twisting, the transferred silver traces were subjected to multiple local stretches along with the twist, which could reduce the density of silver nanoparticles, and increased the resistance.

4.6 Bending Tests

From the geometry test, we found mechanical status especially bending is a strong factor on the resistance variance of the transferred traces by using our method. Here we investigated bending – both inward and outward bending. We measured resistance at different bending angles and Figure 7 (b,c) summarize our results. In the case of outward bending, the sheet resistance decreases as the bending radius is increased, since along with the increase of the bending radius, the less propagation of cracks will happen with silver traces. For the inward bending tests, the sheet resistance gets higher as we increase the bending radius. This is because the density of silver decreases at the bent region. Based on this result, we recommend inward bending for more consistent and reliable electrical connections.

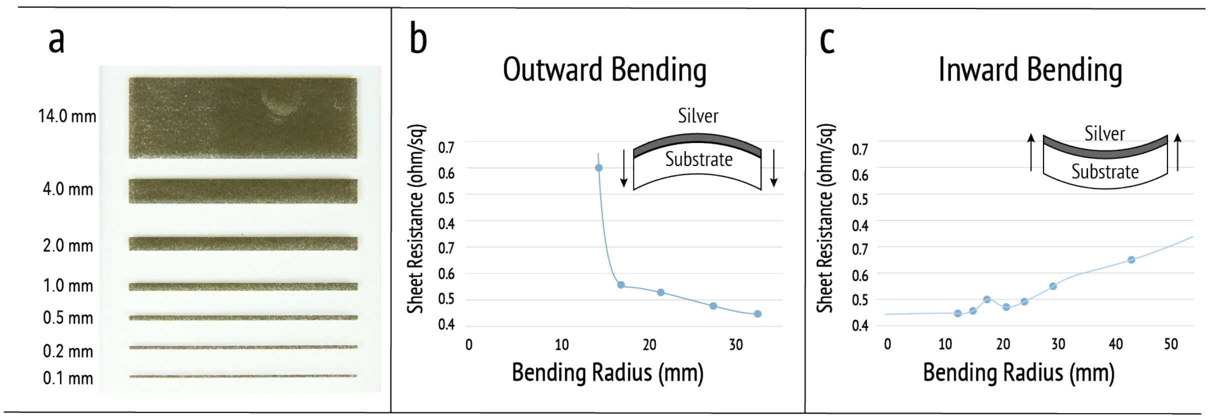

Fig. 7. (a) Transfer resolution. (b) Resistance under outward bending. (c) Resistance under inward bending.

5 APPLICATIONS

Based on the results from previous evaluations, we developed six application examples applying our technique. These applications present different key features of prototyping processes, including sensing and actuating, single- and multi-layer circuitry, domain-specific usage and daily usage in varied scales.

5.1 LED Decorations

We built a large LED display (100 cm by 30 cm) to demonstrate how Silver Tape can provide a fast and easy routine for fabricating a large conductive pattern (Figure 9a). We inkjet-printed seven Christmas tree patterns on different A4-sized Mitsubishi PET films and transferred them onto one big PDMS sheet, where the PDMS sheet is cured on top of an acrylic board backing in a ratio of base to cure 20:1 (Dow Coring Sylgard 184) under room temperature. Note that the size of this demo is beyond what a standard desktop printer can print. However, the modular nature of this technique allows us to print and transfer part by part, eliminating the need for large

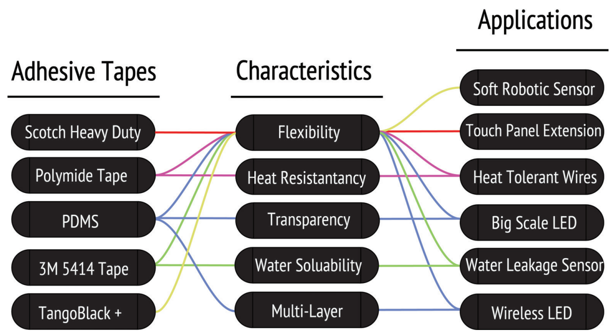

Fig. 8. Application Overview

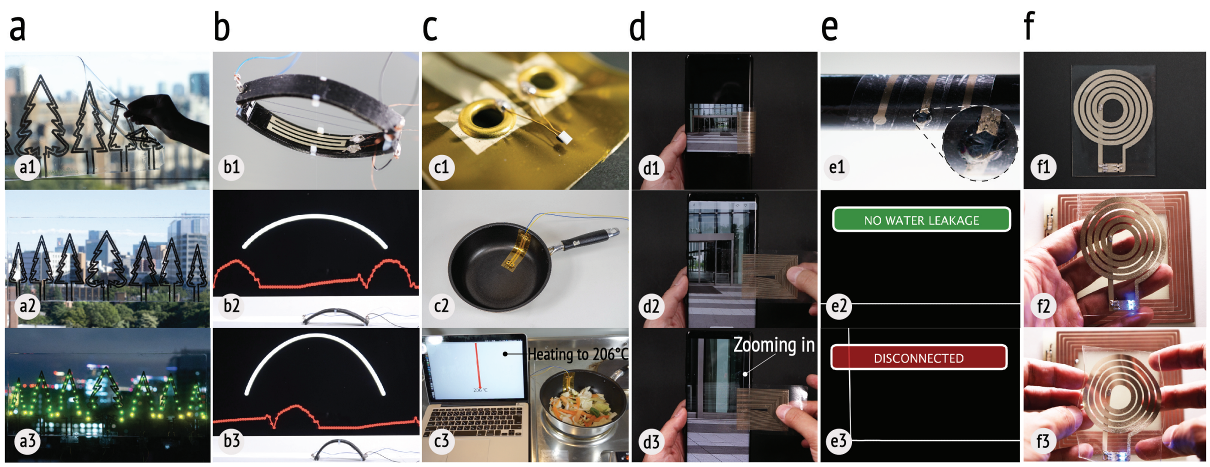

Fig. 9. Applications: (a1) Pasting the patterns sequentially onto the window. (a2, a3) In the daytime, it does not interfere with the field of vision, while at night works as a decoration. (b1) The resistance sensor pattern is transferred onto the soft robot. (b2, b3) The resistance reading changes accordingly when the robot is resting and moving accordingly. (c1) Closeup of the connection between the transferred silver traces and temperature sensor. (c2) Add-on temperature sensor on a frying pan. (c3) Reading of the temperature sensor (can tolerate up to 250°C). (d1) The touch panel is folded to the back of the mobile device when not in use. (d2, d3) Flip the touch panel back to its working mode and perform the zoom-in function. (e1) Water leakage occurs and dissolves the Spiral pattern which is wrapped outside the black pipe. (e2, e3) Our sensor detects when there is no water leakage and when water leakage occurs. (f1) LED circuit fabricated by two layers of transferred silver nanoparticle traces. (f2, f3) LED device is powered up wirelessly.

printers. Specifically, seven Christmas tree patterns are printed and transferred separately. LEDs are mounted later on with Cemedine SXECA48 conductive paste. Daytime and nighttime views of the LED circuit are shown in Figure 9 a2 and 9 a3.

5.2 Bending Sensors for Soft-bodied Robots

Attaching sensors to close the loop in controlling soft-bodied robots is challenging due to the non-compatibility of traditional sensors with soft-bodied materials. This application shows that Silver Tape can be a promising method as it easily enables loading soft-bodied robots with sensors without any additional layers. Our soft robot has been 3D printed by Objet260 Connex3 with soft 3D printing material TangoBlack +, which is quite sticky and made it a good substrate for Silver Tape (Figure 9b). We transferred a resistance-based bending sensor to a 3D printed inching worm robot and actuated the robot with a shape memory alloy (SMA). The bending motion of the robot changes the resistance of the bending sensor. We used an Arduino board with a voltage divider to read the resistance change which was calibrated using the Kinovea motion analyzer to map the corresponding bending angle. Similarly, this bending sensor can also be applied to on-body locations for posture sensing.

5.3 Circuitry for High-Temperature Applications

Conventional inkjet-printed paper circuits could not endure heat over 120°C, which limits prior work from applications on hot surfaces. This example application shows an attachable temperature sensor to a frying pan (Figure 9c). We printed the conductive pattern on Mitsubishi PET film and transferred to Kapton tape (Lifework Concierge LCA110, heat tolerant up to 250°C) to wire up a tiny platinum resistance thermometer (RS Pro PT100) on both ends of the two silver traces. The resistance change of the sensor, caused by temperature changes, was measured by an Arduino.

5.4 Touch Panel Extensions for Mobile Devices

We made a striped pattern based touch panel extension, which was printed on Mitsubishi PET film and transferred to Scotch heavy-duty tape. The touch input is generated when fingers are in contact with the printed conductive lines. The whole panel extension patch can be fully folded and attached to the back of the phone when not in use. A user can perform quick commands on the extended touch panel without blocking the phone screen. For example, Figure 9 d2 and d3 demonstrate a zoom-in gesture.

5.5 Water Leakage Sensor

Figure 9e shows a water leakage sensor, which we made by printing and transferring a spiral pattern onto the 3M 5414 water soluble tape. Leaked water dissolves the substrate and the conductive patterns, which can be detected by measuring the resistance change with an Arduino. We threshold the resistance measurement for detection. Figure 9 e1 shows the moment when water leaks from the pipe and dissolves the spiral pattern which was detected and shown on the computer screen in Figure 9 e3.

5.6 Wirelessly Powered Resonator by Multi-layer Circuit

We demonstrate a design of multi-layer circuit by transferring a silver coil pattern on the top/bottom side of the PDMS substrates and connecting them with silver conductive epoxy via holes. Figure 9f demonstrates wireless power transfers to the fabricated coil. AC power (*i.e.*, 6.78 MHz) was emitted from an external power source via a transmitter coil. The emitted energy was then inductively coupled to the fabricated coil and transferred to an LED via this inductive link.

6 WORKSHOP AND FINDINGS

In order to investigate the ease of using our technique, we conducted a workshop with seven students (4 females and 3 males). Among our participants, 3 were from engineering background, and the other 4 participants were from design background. They all had experience with prototyping interactive systems except one participant.

None of our participants had printed silver ink with inkjet printers before. Our hypothesis is that participants could replicate our transfer technique with minimum effort.

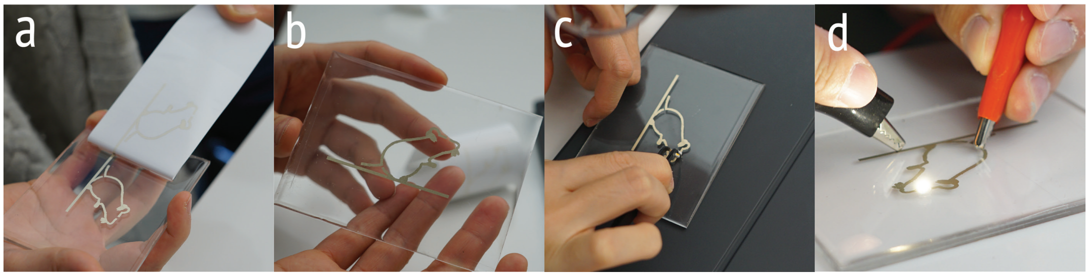

Fig. 10. Workshop Results: Participants completing fabrication steps from transferring the mouse pattern to PDMS sheet, mounting the LED with conductive Epoxy, and lighting it up with DC power supply.

6.1 Procedure

We conducted a workshop in a studio-like lab space and followed a 3-hour timeline with three sessions: (1) a 15 minute introduction session, (2) a design and prototyping session for 2.5 hours, and (3) a discussion and survey session for 15 minutes. The workshop started with the introduction of Silver Tape, our study scope, related works and application examples described in the previous section and we demonstrated the fabrication process of Silver Tape. Then we provided a variety of materials including adhesives (*i.e.*, Scotch double-sided tape, Scotch transparent tape, Scotch heavy duty tape, Capton tape, water soluble tape, PDMS sheets and etc), connection materials (*i.e.*, silver conductive epoxy, Bare paint, copper wire), and tools (*i.e.*, DC power supply, multi-meter, scissors etc) and proposed a task for the design session. Participants were asked to complete a simple LED circuit (Figure. 10 a) within 20 minutes. The pattern was designed by us before the workshop, and participants were asked to complete the fabrication steps: (1) print the mouse pattern on paper (Fujifilm Paper Kassai Pro was used), (2) transfer the mouse pattern onto tape (PDMS sheets were used), (3) mount the LED with silver epoxy glue, and by the end, power the circuitry with DC power supply. This task was designed to validate the ease of use of our technique. Participants were given a 2-hour design session to complete the tasks and create more complex designs with any time spared. At the end of the workshop, participants had a group discussion and finished a questionnaire to summarize their experience of using Silver Tape.

6.2 Results

All participants completed the replication task within 20 minutes. We observed that everyone had no trouble throughout the printing and transferring processes, while two of them encountered minor technical issues during the mounting step: one participant (P2) first mounted a LED to the wrong part of the transferred traces, and another participant (P4) applied too much silver epoxy and caused short circuits. These two participants took a second trail to finish the circuit. The other five participants successfully completed building the circuit with their first trials using Silver Tape.

6.3 Evaluation and Reflection

Based on our observations, results from the questionnaires, and the discussion with participants during the workshop, we derived several design implications in terms of the ease of use and accessibility of our fabrication technique along with the transfer quality of the printed patterns.

6.3.1 Ease of Use. The participants responded positively to this transferal-based inkjet printing technique. We verified that all participants learned Silver Tape techniques and completed the tasks of the simple circuitry within one hour. Participants could easily follow the printing and transferal procedures without any difficulties. Additionally, in a rating scale of "absolutely easy; easy; neutral; hard; absolutely hard", 3 participants rated our technique as absolutely easy, 3 other participants as easy, and one participant as neutral. This result confirmed our hypothesis that Silver Tape is easy to replicate, which means users can adopt our technique without any special training.

6.3.2 Transfer Quality. In this project, transfer quality plays an essential role in fabricating electronics. Based on the deliverables of the task ($7(participants) \times 1(PDMS\ adhesive) + 1(participant) \times (PDMS\ adhesive) + 1(participant) \times (Scotch\ doublesided\ tape) \times 2(printing\ paper) = 10\ datapoints.$), we found the transfer quality remained sound and stable across all deliverables. We consider this result to be compelling, especially given that participants rubbed the printed traces onto the adhesives in various ways, with different peeling speeds, directions, and forces.

7 DISCUSSION AND LIMITATIONS

7.1 Stretchabilities

As mentioned previously in this paper, due to the limitation from the material itself, silver nanoparticle traces are barely stretchable. However, stretchability plays an irreplaceable role in many applications such as wearable devices. We expect that prestretching the PDMS substrate before transfer can be a method to increase the stretchability of Silver Tape, without losing the benefits (*i.e.*, simplicity) of our method.

7.2 On Skin Transfer

As for the silver transfer on skin, only a short length (1 cm) of the conductive trace was successfully transferred so far in our pilot test, mainly due to the wrinkles on the skin surface, which might cause the cracks on the transferred traces. However, we regard directly transferring silver onto our skin as a possible future research direction, like tattoo paper-based methods described in [9, 20].

7.3 Robustness

There are two aspects to consider: the robustness of the transfer step and the longevity of the transferred traces. For the first one, similar to what have been discussed in the transfer quality section, the transferred pattern quality has been barely affected when different participants were conducting the transfer step with different peeling direction, force, speed, or even geometries. However, the transferred pattern could be fragile. Two participants also raised a concern about the fragility in the questionnaire. This is mainly due to the brittle nature of the silver nanoparticles. Any accidental scratches or over bending would cause the permanent breakage of the transferred pattern. Laminating a cover layer like [13] or simply applying another tape layer on top of the transferred circuitry could potentially prevent the circuit breakage.

7.4 Hysteresis of Silver Nanoparticles

We observed the hysteresis of the transferred silver nanoparticle traces when conducting experiments, where the resistance will take sometime to recover or settle to a stable value. Inspired by the work [31] of rubbing liquid metal particles (EGaIn) into the printed silver nanoparticles, we might be able to minimize the hysteresis effect of the silver nanoparticles.

For the future research directions, fabricating large scale electronics with multi-functionalities is in high priority. This work provided a solution for large scale electronic fabrication, but still many manual steps are involved. We would like to explore more automated systems which could provide an end-to-end solution for users by not only designing and printing the conductive traces, but also auto-mounting the electronics. For example, robotic arms or remote-controlled robots equipped with a conductive dipping machine might be worth investigating. Another research direction would be how to apply the conductive patterns and electronics onto conformal surfaces robustly without losing the rapid and easy nature. We believe the transfer technique has a promising potential to solve this. Instead of transferring non-stretchable silver nanoparticles, one could transfer stretchable conductive material such as carbon grease, PEDOT:PSS, with the help of a deformable transfer media like foam. We believe both directions are worth exploring for further investigation in order to reach the goal of rapid digital fabrication of electronics.

8 CONCLUSION

In this paper, we presented Silver Tape, a simple yet novel fabrication technique to achieve both rapid prototyping capability derived from inkjet-printed paper circuits and multi-functional property derived from different substrates at the same time. By utilizing a less sticky paper substrate as a temporary transfer film, we can peel off and transfer inkjet-printed, sintering-free silver traces to multiple sticky substrates without pre- or post-processes. We also demonstrated the ease of use nature of our approach with a workshop study. We hope our technique can support and inspire various types of makers from children to professional researchers to enlarge the design space of digital circuit fabrication.

ACKNOWLEDGMENTS

This work was partially supported by JST ERATO Grant Number JPM-JER1501 and JSPS KAKENHI Grant Number JP17J09630. The authors would also like to thank Shigeki Shino, Mitsubishi Paper Mills for supplying a special PET film for silver ink transfer.

REFERENCES

[1] Brian Corbett, Ruggero Loi, Weidong Zhou, Dong Liu, and Zhenqiang Ma. 2017. Transfer print techniques for heterogeneous integration of photonic components. *Progress in Quantum Electronics* 52 (2017), 1–17.

[2] Artem Dementyev, Hsin-Liu Cindy Kao, and Joseph A Paradiso. 2015. Sensortape: Modular and programmable 3d-aware dense sensor network on a tape. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 649–658.

[3] Liangjin Ge, L Jay Guo, Xudi Wang, and Shaojun Fu. 2012. Silver lines electrode patterned by transfer printing. *Microelectronic Engineering* 97 (2012), 289–293.

[4] Nan-Wei Gong, Jürgen Steimle, Simon Olberding, Steve Hodges, Nicholas Edward Gillian, Yoshihiro Kawahara, and Joseph A Paradiso. 2014. PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 1407–1410.

[5] Daniel Groeger and Jürgen Steimle. 2018. ObjectSkin: augmenting everyday objects with hydroprinted touch sensors and displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 4 (2018), 134.

[6] Takahiro Hashizume, Takuya Sasatani, Koya Narumi, Yoshiaki Narusue, Yoshihiro Kawahara, and Tohru Asami. 2016. Passive and contactless epidermal pressure sensor printed with silver nano-particle ink. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 190–195.

[7] DR Hines, VW Ballarotto, ED Williams, Y Shao, and SA Solin. 2007. Transfer printing methods for the fabrication of flexible organic electronics. *Journal of applied physics* 101, 2 (2007), 024503.

[8] Steve Hodges, Nicolas Villar, Nicholas Chen, Tushar Chugh, Jie Qi, Diana Nowacka, and Yoshihiro Kawahara. 2014. Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1743–1746.

[9] Hsin-Liu Cindy Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: rapidly prototyping on-skin user interfaces using skin-friendly materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers*. ACM, 16–23.

[10] Mustafa Emre Karagozler, Ivan Poupyrev, Gary K Fedder, and Yuri Suzuki. 2013. Paper generators: harvesting energy from touching, rubbing and sliding. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 23–30.

[11] Kunihiro Kato, Hiroki Ishizuka, Hiroyuki Kajimoto, and Homei Miyashita. 2018. Double-sided printed tactile display with electro stimuli and electrostatic forces and its assessment. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 450.

[12] Kunihiro Kato and Homei Miyashita. 2014. Extension sticker: a method for transferring external touch input using a striped pattern sticker. In *Proceedings of the adjunct publication of the 27th annual ACM symposium on User interface software and technology*. ACM, 59–60.

[13] Yoshihiro Kawahara, Steve Hodges, Benjamin S Cook, Cheng Zhang, and Gregory D Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*. ACM, 363–372.

[14] Yoshihiro Kawahara, Hoseon Lee, and Manos M Tentzeris. 2012. Sensprout: Inkjet-printed soil moisture and leaf wetness sensor. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*. ACM, 545–545.

[15] Arshad Khan, Joan Sol Roo, Tobias Kraus, and Jürgen Steimle. 2019. Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits Using a Commodity Inkjet Printer. In *Proceedings of the 32Nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. ACM, New York, NY, USA, 341–354. https://doi.org/10.1145/3332165.3347892

[16] Changhong Linghu, Shun Zhang, Chengjun Wang, and Jizhou Song. 2018. Transfer printing techniques for flexible and stretchable inorganic electronics. *npj Flexible Electronics* 2, 1 (2018), 1–14.

[17] Mitsubishi Paper Mills Limited. 2019. Silver Nano-particle Ink. http://www.k-mpm.com/agnanoen/agnano_ink.html

[18] Kenichi Nakahara, Koya Narumi, Ryuma Niiyama, and Yoshihiro Kawahara. 2017. Electric phase-change actuator with inkjet printed flexible circuit for printable and integrated robot prototyping. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 1856–1863.

[19] Koya Narumi, Xinyang Shi, Steve Hodges, Yoshihiro Kawahara, Shinya Shimizu, and Tohru Asami. 2015. Circuit Eraser: A Tool for Iterative Design with Conductive Ink. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 2307–2312. https://doi.org/10.1145/2702613.2732876

[20] Aditya Shekhar Nittala, Anusha Withana, Narjes Pourjafarian, and Jürgen Steimle. 2018. Multi-touch skin: A thin and flexible multi-touch sensor for on-skin input. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 33.

[21] Hyunjoo Oh, Tung D Ta, Ryo Suzuki, Mark D Gross, Yoshihiro Kawahara, and Lining Yao. 2018. PEP (3D Printed Electronic Papercrafts): An Integrated Approach for 3D Sculpting Paper-Based Electronic Devices.. In *CHI*. 441.

[22] Simon Olberding, Nan-Wei Gong, John Tiab, Joseph A Paradiso, and Jürgen Steimle. 2013. A cuttable multi-touch sensor. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 245–254.

[23] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 223–232.

[24] Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: fabricating highly customizable thin-film touch-displays. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. ACM, 281–290.

[25] Jie Qi and Leah Buechley. 2014. Sketching in circuits: designing and building electronics on paper. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1713–1722.

[26] Jie Qi, Leah Buechley, Patricia Ng, Sean Cross, Joseph A Paradiso, et al. 2018. Chibitronics in the Wild: Engaging New Communities in Creating Technology with Paper Electronics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 252.

[27] Valkyrie Savage, Xiaohan Zhang, and Björn Hartmann. 2012. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 579–588.

[28] Xinyang Shi, Yoshiaki Narusue, Yoshihiro Kawahara, and Tohru Asami. 2015. Rapid antenna prototyping method by evolutionary computation and inkjet printing. In *2015 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*. IEEE, 1–3.

[29] Donghoon Song, Ankit Mahajan, Ethan B Secor, Mark C Hersam, Lorraine F Francis, and C Daniel Frisbie. 2017. High-resolution transfer printing of graphene lines for fully printed, flexible electronics. *ACS nano* 11, 7 (2017), 7431–7439.

[30] Chavis Srichan, Thitirat Saikrajang, Tanom Lomas, Apichai Jomphoak, Thitima Maturos, Disayut Phokaratkul, Teerakiat Kerdcharoen, and Adisorn Tuantranont. 2009. Inkjet printing PEDOT: PSS using desktop inkjet printer. In *2009 6th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, Vol. 1. IEEE, 465–468.

[31] Mahmoud Tavakoli, Mohammad H Malakooti, Hugo Paisana, Yunsik Ohm, Daniel Green Marques, Pedro Alhais Lopes, Ana P Piedade, Anibal T de Almeida, and Carmel Majidi. 2018. EGaIn-Assisted Room-Temperature Sintering of Silver Nanoparticles for Stretchable, Inkjet-Printed, Thin-Film Electronics. *Advanced Materials* 30, 29 (2018), 1801852.

[32] Nirzaree Vadgama and Jürgen Steimle. 2017. Flexy: Shape-customizable, single-layer, inkjet printable patterns for 1d and 2d flex sensing. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 153–162.

[33] Yuntao Wang, Jianyu Zhou, Hanchuan Li, Tengxiang Zhang, Minxuan Gao, Zhuolin Cheng, Chun Yu, Shwetak Patel, and Yuanchun Shi. 2019. FlexTouch: Enabling Large-Scale Interaction Sensing Beyond Touchscreens Using Flexible and Conductive Materials. *Proceedings*

of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 3, 3 (2019), 1–20.
[34] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2991–3000.
[35] Michael Wessely, Theophanis Tsandilas, and Wendy E Mackay. 2016. Stretchis: Fabricating highly stretchable user interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 697–704.
[36] Yang Zhang, Gierad Laput, and Chris Harrison. 2017. Electrick: Low-cost touch sensing using electric field tomography. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1–14.
[37] Yang Zhang, Chouchang Jack Yang, Scott E Hudson, Chris Harrison, and Alanson Sample. 2018. Wall++: Room-scale interactive and context-aware sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 273.