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Printing practice for the fabrication of flexible and stretchable electronics

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Recently, flexible and stretchable electronics have experienced tremendous surge due to their promised applications in fields such as wearable electronics, portable energy devices, flexible display, and human-skin sensors. In order to fabricate flexible and stretchable electronics, a high-throughput, cost-saving, and eco-friendly manufacturing technology is required. Printing, which is an additive patterning process, can meet those requirements. In this article, printing fabrication is compared with conventional lithography process. Practices at the author's group utilizing printing for the fabrication of flexible thin-film transistors, flexible hybrid circuits and stretchable systems are presented, which has proven that printing can indeed be a viable method to fabricate flexible and stretchable electronics.

printed electronics, flexible electronics, stretchable electronics, electronic inks

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1 Introduction

After more than 50 years of development and advances, silicon integrated circuit (IC) based microelectronics has come to the stage that it has penetrated into almost every aspect of electronic applications. However, recent development in wearable electronics and conformable electronics renders silicon based electronics powerless because of its rigidness. The new class of flexible electronics are inherently bendable, rollable or even foldable. Some applications also demand the electronic system working under strained condition, which requires the system to be stretchable as well, enabling it to be attached to non-planar surfaces. The flexibility and stretchability have opened a wide spectrum of applications which are not possible by conventional silicon based or PCB (Printed Circuit Boards) based rigid electronics [1].

Although silicon ICs and PCBs are rigid by nature, they can be adapted into a flexible system. There have been attempts to make the silicon ICs extremely thin, only a few micrometers thickness, so that it can be bent a few percent [2]. Another rather traditional approach is to make individual IC chip extremely small, less than a millimeter square, so that the overall system becomes flexible. A typical example is the radio frequency identification (RFID) tags which can be flexible because the attached IC chip is small enough not enduring a damage when the tag is bent in fairly large radius. There are also approaches to stretchable electronics using conventional silicon chips. By constructing meandered metallic interconnects on a pre-stretched elastic substrate, small and thin silicon ICs can be connected into an electronic system which becomes stretchable [3].

Regarding flexible electronics or stretchable electronics, one should distinguish whether it is at system level or component level. The component level flexibility or stretchability is rather difficult to realize. There have been many years of research activities to make transistors, which are the core components of electronics, to be flexible or stretchable. Reasonable success has been achieved in making

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flexible transistors based on organic semiconductors, metal oxide semiconductors or semiconducting carbon nanotubes. Making transistors stretchable, however, is a quite different matter and only a limited success was reported very recently [4]. On the other hand, the system level flexibility or stretchability is much easier to realize. Conventional rigid components can be utilized and only the substrate material and electric interconnect need to be flexible or stretchable. While the flexible components such as transistors still need to improve their performance, the conventional rigid components such as the IC chips are mature and ready to perform complex functions, therefore, much closer to real applications. This is the so-called flexible hybrid electronics (FHE). Recent trends showed that FHE is the quick route to lead flexible and stretchable electronic systems into practical applications and real products.

The author's group has engaged in the development of flexible and stretchable electronics technologies since setting up the Printable Electronics Research Center (PERC) in 2010 at the Suzhou Institute of Nanotech and Nanobionics. Different from the conventional lithography based approach for the fabrication, PERC has been developing printing approach to making the flexible and stretchable electronics. In this article, printing is first compared with conventional lithography. Electronic inks developed at PERC, which enable printed electronics, are described, together with matched printing processes. Various examples of flexible and stretchable electronics which were made by printing are presented. Among them, a hybrid printing technique has been implemented at industrial scale to manufacture flexible transparent conductive films, which have been used in commercial touch panel products. The article is not attempting to review the worldwide work on printing fabrication of electronics, but only the practice at PERC, which is reasonably comprehensive and covers both flexible and stretchable electronics made by printing methods.

2 Printing vs lithography

Fabrication of electronic circuits, either as complicated as ICs or as simple as PCBs, is basically a patterning process, i.e. turning a thin film into a pattern as illustrated in Figure 1. The processes involve deposition of a functional material (conductor, semiconductor or insulator) into a thin-film on a carrier substrate (normally flat), coating a layer of photoresist, exposure of photoresist using a mask which contains the circuit design pattern, developing the exposed photoresist, using the patterned photoresist as mask to etch into the thin film, stripping off the photoresist so that the photoresist pattern is transferred into the thin film. The functional material is then patterned to become a part of electronic circuit structures [5].

Printing is also a patterning process, as illustrated in Figure 2. Instead of patterning a thin film by photolithography and etching, printing can directly deposit an ink form of functional material into a pattern. The only additional step is annealing or sintering to convert the ink into solid material. Compared to the lithography process, printing is much simple and is an additive process. Lithography process as shown in Figure 1 is not easy to perform on a flexible substrate. A rigid substrate is often required to carry the flexible film substrate. After all the fabrication processes, the film is detached from the carrier. For printing fabrication, electronic inks can be directly printed onto a flexible film. In addition, printing can be performed on large size flexible substrate, can be done in roll to roll manner which facilitate high throughput manufacturing and is of much lower cost than lithography fabrication. The additive nature of printing is also a green process, meaning no or much less discharge of pollutants and much less energy consumption, whereas lithography process involves acidic etching and produces pollution due to the etchant wastes [6].

According to whether a template is employed, printing can be divided into two categories. The printing without using a template is jet printing, which includes ink-jet printing, aerosol-jet printing, dispensing printing, and electrohydrodynamic (EHD)-jet printing. For printing that relies on a template is replicate printing, including screen printing, gravure printing, flexographic printing and gravure offset printing.

Jet printing, also called non-contact printing or digital printing, is popular in research laboratories, because it deposits inks directly on substrate without the need for a prefabricated template or a mask, and without any direct contact between equipment and substrate. The patterned deposition of electronic ink material is digitally controlled, making it much easier to change designs. Inkjet printer is the most commonly used jet printing tool. Much similar to the desktop printer used in office, inkjet printers push out inks by either thermal bubble expansion force or piezoelectric force. The resolution of an inkjet printer depends on the nozzle diameter, which is normally in the range of 20–50 μm. That is not to say that the smaller the nozzle the higher the printing resolution. When the nozzle becomes too small the jetting becomes much difficult. So the aerosol jet and EHD jet printers have been developed. The aerosol jet printer relies on air pressure to push out the ink which is in the form of aerosol droplets. Assisted by aerodynamic focusing, an aerosol jet printing can achieve resolution around 5 μm. Further enhancement of resolution is achieved by EHD jet, which relies on electrostatic force to pull out the ink. An EHD jet printer can have sub micrometer resolution, which is the highest among all printing processes. Generally, jet printing is only suitable for sampling and prototyping because of its low throughput nature.

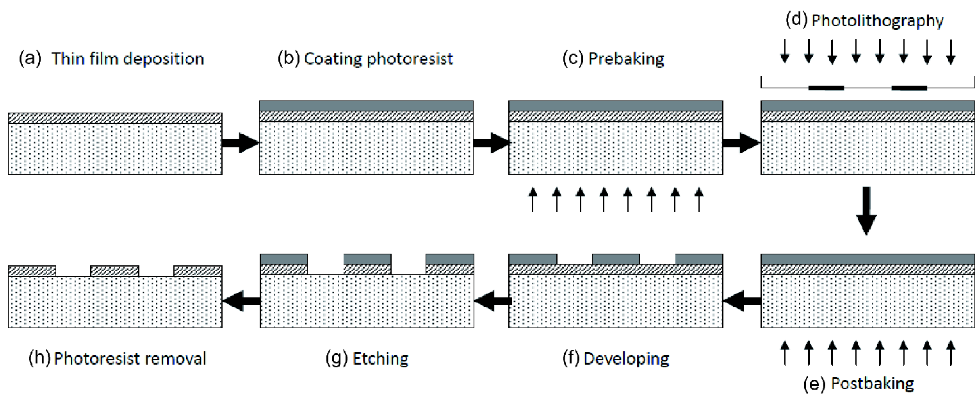

Figure 1 Conventional lithography patterning process.

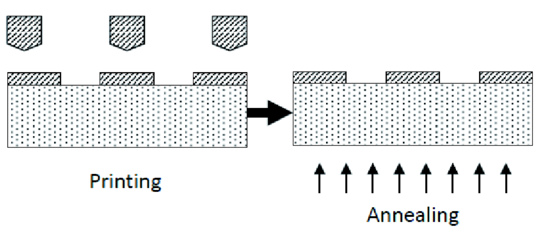

Figure 2 Printing process.

The replicate printing on the other hand is a high throughput process. It is basically replicating the images or patterns from a master template. Different replicating processes have different ways to transfer ink from template to substrate. The screen printing uses a stencil mask which is patterned into transparent and nontransparent regions. Ink material is squeezed through the transparent regions of stencil to become printed ink pattern. Gravure printing carries inks on the template which is made of a web of dents. These dents carry the ink and work as pixels. A pattern on the gravure template consists of the pixels which transfer the ink onto a substrate. For a gravure offset printer, the ink in the dents is first transferred onto a soft surface such a rubber roller and then the ink pattern on the rubber roller is transferred onto the substrate, instead of directly transferring ink from a gravure template onto a substrate. While the template of a gravure printer is normally made of steel, the flexographic printer uses a rubber template which has surface relief patterns. These protruded surface relief structures carry the ink and transfer the ink onto a substrate by direct contact between protruded reliefs and substrate surface. In term of printing resolution, a gravure printer has better resolution capability than flexographic printing and screen printing. Around 10 μm printed features have been reported with gravure printing. In term of process complexity, screen printing is of the lowest, though the printing resolution is also the lowest. As aforementioned, replicate printing processes are of much higher throughput than jet printing processes, because the pattern is formed not point by point but by a single replication. The replication can be sheet to sheet or roll to roll. The roll to roll process can have the printing speed from a few meters to a few hundred meters per minute. Printing is a very traditional technology and there are plenty of literatures giving detailed descriptions of different printing equipments and processes.

It has been shown that the patterning processes between conventional lithography and ink printing are distinctively different. Printing inks is simple but difficult to achieve high resolution. Conventional lithography can achieve high resolution but making a functional structure is complicated. In recent year, PERC's team developed a novel hybrid printing process which combines a part of conventional lithography and a part of ink printing. It employs the conventional imprinting technique to create narrow trenches and fills trenches with electronic ink [7]. As illustrated in Figure 3(a), conventional printing has less control on the size of ink pattern because of its rheological nature. By filling the ink into a trench, the size of ink feature is no longer defined by the ink rheology but by the trench boundary. Figure 3(b) shows the nanosilver ink embedded in a trench after sintering. To create the trenches, an imprinting template is needed which is done by conventional lithography. Once the template is made, high throughput imprinting process can be performed, so can the high throughput ink filling process.

3 Electronic inks

Printing fabrication is only possible provided there are printable inks available. The booming of printed electronics is all because of the advances in electronic inks development. Going back to the history, the early electronic inks were mostly organic electronic materials. Organic materials, in particular polymeric materials, are naturally dissolvable in aqueous or solvent solutions. Making organic electronic inks have no major obstacles. However, the electronic properties

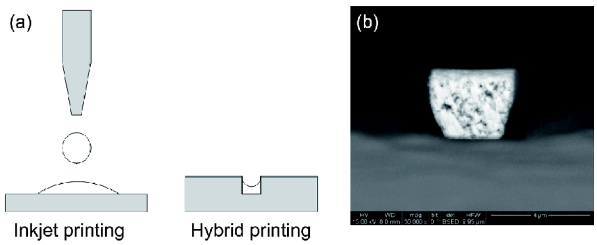

Figure 3 (a) Schematic comparison of conventional inkjet printing and hybrid printing; (b) embedded nanosiliver in a trench after sintering.

of organic polymeric materials, typically the conductivity or charge mobility, are always poorer than organic small molecular materials. In addition, the printed organic small molecular devices are always poorer than the devices made by vacuum evaporated organic small molecular materials [8]. So the choice is obvious: vacuum evaporation is preferred to fabricate organic electronic devices. This has been the reason that printed electronics did not take off along the path of organic electronics. Printed electronics only attracted wide attention in 2008 onwards, long after the development of organic electronics. The technology got noticed because inorganic nanomaterials started being employed as electronic inks. The marked event was the announcement of Kovio's printed silicon transistors and RFID tags in 2008.

Compared to organic materials, inorganic materials have inherently better electronic properties. In the example of printed silicon transistors, they demonstrated charge mobility over 100 cm^2/vs whereas the printed organic transistors had mobility two orders of magnitude lower. Another vital property is the environmental stability. Organic electronic materials are generally prone to degrade when exposed to oxygen and humidity whereas inorganic materials are more environmentally stable. The way to print inorganic materials is to use their powder form and fully dispersed in solvents or aqueous solutions. Some surfactants may have to be employed to avoid aggregation of particles in the ink. Once printed, a subsequent sintering or annealing step converts the ink into its original solid inorganic material and restores most of its properties. The advantage of using nanoscale inorganic material is that the sintering temperature is much lower than sintering micrometer size materials, which can be lower than 150^{o}C allowing printed functional materials on ordinary plastic thin-films or even on papers. The electronic inks made of inorganic nanomaterials truly brought printed electronics to a wide community and realistic applications became possible. There was an article published in 2011, with the title as "Nanomaterials are becoming synonymous with printed electronics" [9]. Since then, printing process is widely accepted as a viable technology to make electronics.

When PERC was established in 2010, it put great emphasis on developing inorganic nanomaterial inks and using them for printed electronics. In the last 8 years, a wide range of inorganic electronic inks have been developed at PERC. For conductors, nanosilver, nanocopper and indium tin oxide (ITO) inks have been developed. For semiconductors, semiconducting single-walled carbon nanotube (sc-SWCNT) inks and metal oxide inks have been developed. In the example of carbon nanotube ink, special techniques have been developed to separate semiconducting nanotubes from the mixture of metallic nanotubes [10,11]. As the result, printable ink with the purity of 99.9% semiconducting nanotubes can be obtained. The purification process has been optimized so that batch to batch stable production of semiconducting carbon nanotube inks becomes possible. Table 1 gives the relevant information about the ink which has been supplied to other research groups for printing transistors.

4 Printing flexible electronics

4.1 Printing flexible electronics at component level

As mentioned in the introduction section, flexible electronics can be categorized as component level flexible and system level flexible. Component level flexible would be truly flexible as nothing in the system is rigid, including transistors, resistors and capacitors, and interconnects. For component level flexible, the crucial part is the transistors. Silicon based transistors (ICs) are rigid. Thin-film transistors (TFTs) can be made on flexible substrates. There are amorphous silicon TFTs, poly silicon TFTs, metal oxide TFTs and organic TFTs. All these TFTs except organic TFTs have to be

Table 1 Properties of semiconducting single-walled carbon nanotube ink

Property (1)	Parameters (1)	Property (2)	Parameters (2)
Purity of sc-SWCNTs	99.9%	Relative density	<1 g/cm^3
Sc-SWCNT content	1 wt%	Viscosity	<100 cps
Polymer content	1 wt%	Shelf life	> 3 months
Sc-SWCNT diameter	Approx. 1.5 nm	Solvent type	Toluene or xylene
Sc-SWCNT length	Approx. 1–2 μm	Clean up	Toluene, xylene
Applicable substrates	Glass, PET, Pl, PEN, SiO_2, HfO_2, Al_2O_3	Post-treatment	Annealing at 120°C for 30 min (in air)
Deposition method	Inkjet printing, spin-coating drop casting, spraying, slot die or doctor blade coating	Storage condition	Keep container tightly closed in a dry and well-ventilated place

made by conventional lithography and require high temperature annealing. Once lithography is used it can only be done on a flat rigid substrate. Once high temperature annealing is needed, only a limited type of substrate materials can be used. The way these TFTs can be made flexible is to attach a polyimide (PI) film to a flat rigid carrier substrate. After all the conventional lithography processes are done, the film is detached from the carrier substrate so that the TFTs sheet becomes flexible. Only the PI film can be used because this is the only polymeric material which can withstand annealing temperature up to 350°C. So far these TFTs are mainly for driving color pixels in display panels, the so-called backplane, including flexible display panels. Although organic TFTs do not need high temperature annealing and can be printed, the charge mobility is the lowest compared to other type of TFTs and therefore not as widely used as the others in display panels. They found some applications as a part of flexible sensor unit. If a sensor is flexible, organic TFTs can be made with the flexible sensor together as a pre-amplifier, or the organic TFT itself performs as a flexible sensor [12].

The other option to print flexible TFTs is to use semiconducting single-walled carbon nanotube (sc-SWCNT) inks. The previous section has introduced the sc-SWCNT ink developed at PERC. It is known that single-walled carbon nanotubes (SWCNTs) can be either semiconductive or metallic. The as-produced SWCNTs are always the mixture of both, with one third of metallic tubes and two third of semiconducting tubes. The sc-SWCNT has much higher charge mobility compared to organic semiconductors (three orders of magnitude higher). Once high purity sc-SWCNTs are obtained, they can be dispersed in various solvents to become printable inks. The sc-SWCNT ink can be printed directly into the channel of a TFT. The process is low temperature and the TFTs can be made on flexible plastic substrates. PERC's team has been working on printed carbon nanotube TFTs for a number of years. Figure 4(a) shows an example of printed TFT array on a polyethylene (PET) substrate. Charge mobility more than 100 cm^2/v.s has been achieved. The TFTs can be very flexible, as shown in Figure 4(b) . The TFT characteristics changed a little after bending 15000 times at bending radius of 5 mm [13]. Unlike the organic TFTs, these TFTs are also environmentally very stable. After stored in ambient condition for 12 weeks the TFTs remained the same as shown in Figure 4(c) .

The advantage of printing fabrication is the potential of roll-to-roll (R2R) process, which is of high throughput and low cost. R2R manufacturing practice at component level of flexible electronics was also carried out at PERC. In this case, it was the printing of conductive tracks. One of the successful examples is the mass manufacturing of metal mesh transparent conductive films. The hybrid printing technique shown in Figure 3 was applied by PERC's team to make fine silver metal mesh on transparent PET film, as shown in Figure 5(a) . The metal mesh line was made less than 3 μm in width, which is invisible to naked eyes. The silver mesh lines make the surface conductive while the mesh holes are optically transparent; so that the PET film with the hybrid printed metal mesh is both conductive and transparent. Most transparent conductive films (TCF) are made of indium tin oxide (ITO) coated films. ITO is not a good conducting material and is brittle. Hybrid printed metal mesh TCF is highly conductive and much flexible. Figure 5 (b) compares the sheet resistance and bending characteristics between an ITO and the silver metal mesh TCFs. Since ITO TCFs have been widely used as touch sensors for displays, the metal mesh TCF is well positioned to replace ITO in those applications. In fact, the hybrid printed metal mesh developed by PERC's team has successfully replaced ITO for touch panels, as seen in Figure 5(c). By collaborating with O-film Corp., the leading manufacturer of touch panels in China, this technology has been implemented in large scale R2R manufacturing as shown in Figure 5(d) [7], and touch panels integrating the metal mesh TCFs for notebook computers have been commercialized. With nanosilver inks or pastes, R2R manufacturing of conductive tracks is possible on other materials as well, as the examples shown in Figure 6 where RFID antennas were R2R printed on ordinary paper material and electrodes were R2R printed on textile material.

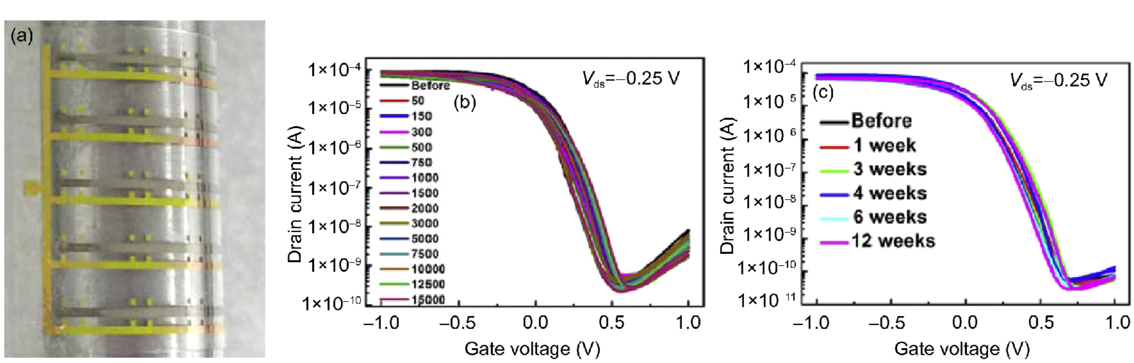

Figure 4 (a) Printed flexible carbon nanotube TFTs; (b) bending experiment at radius of 5 mm; (c) environmental stability.

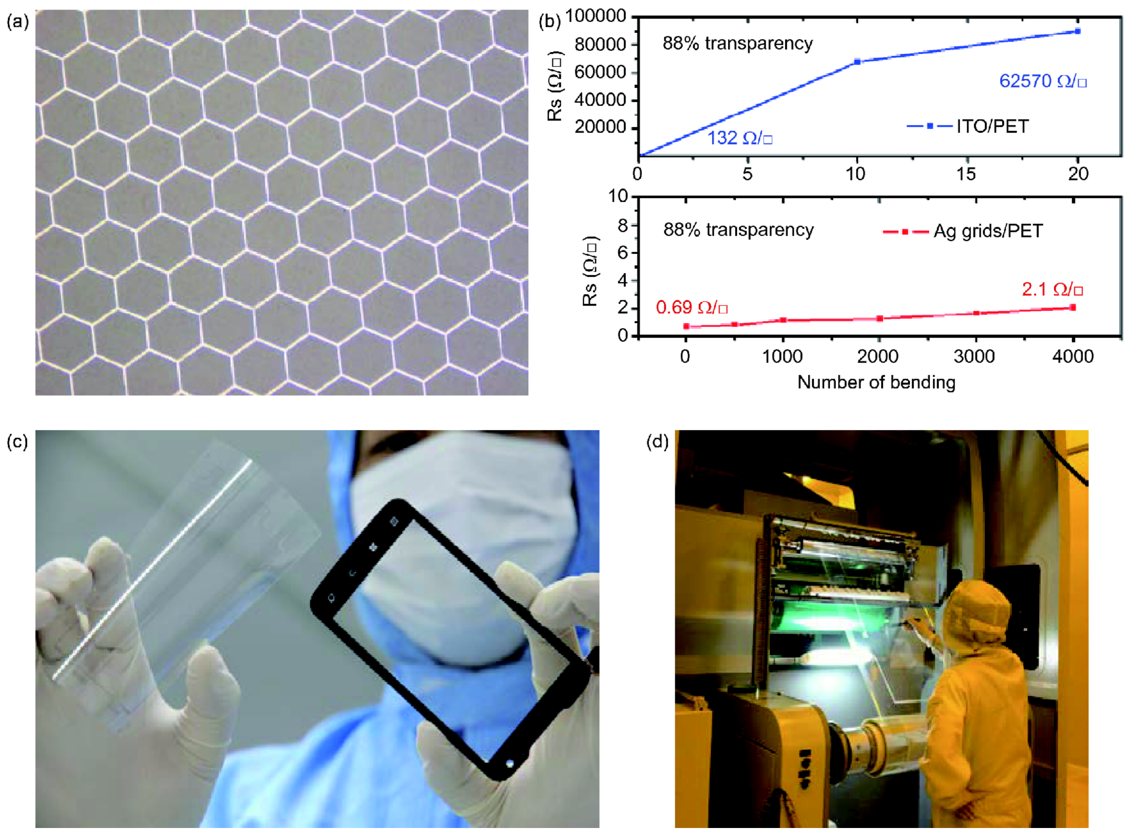

Figure 5 (a) Metal mesh made hybrid printing silver ink; (b) comparison between ITO and metal mesh; (c) metal mesh transparent conductive film to replace ITO for touch sensor; (d) high throughput R2R printing metal mesh transparent conductive films.

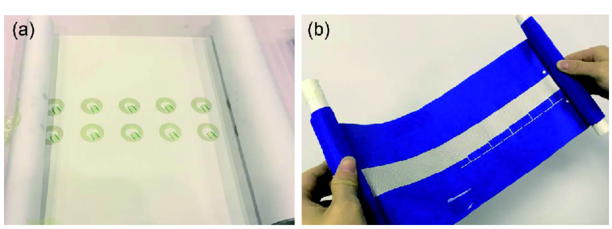

Figure 6 (a) R2R printed RFID antennas on paper; (b) R2R printed silver conductive wires on textile.

4.2 Printing flexible electronics at system level

Once the TFTs are made by printing as described in previous section, an electronic circuit can be constructed by printing as well. Figure 7(a) shows such a printed circuit array on a flexible PET substrate. One of the logic circuit is shown in Figure 7(b), which is a NOR gate circuit consisting of two TFTs in parallel and two TFTs in serials, as shown in the circuit diagram (T1, T2, T3, T4) [14]. The operation voltage is V_{DD} = 2 V, and two input voltages (V_A and V_B) are 0 and 2 V, regarded as logic "0" and "1". Researchers at PERC also developed methods to convert p-type TFT into n-type, so that CMOS circuits can also be made by printing carbon nanotube inks [15].

Despite many years of efforts, large scale application of TFTs only succeeded as display backplane and those TFTs are not printed. The work on printed TFTs at PERC is so far confined to simple circuits only. In all other application areas, silicon ICs are still dominant, because these TFTs cannot match the performance of silicon ICs. On the other hand, most flexible electronics applications do not require all the components to be flexible. Unless bending at extremely small radius, conventional rigid components can be integrated to a flexible substrate if they are sufficiently small in size. For example, RFID tags have long been flexible because the core IC chips are too small to influence the flexibility of whole tag. The advantages of using commercial-off-the-shelf (COTS) components are their proven functionality, availability and low cost.

To achieve system level flexibility, despite the COTS components are rigid, the interconnecting electrodes which connect the rigid components together to form a functional system have to be flexible. Flexible printed circuit board (FPCB) technology already exists. However, the making of conductive tracks on the FPCB still relies on conventional lithography, as shown in Figure 1, which can be replaced by printing processes. In fact, a new trend has emerged in the last few years that combine printed interconnecting electrodes with rigid COTS components to create the so-called flexible hybrid electronics (FHE). FHE utilizes the best of

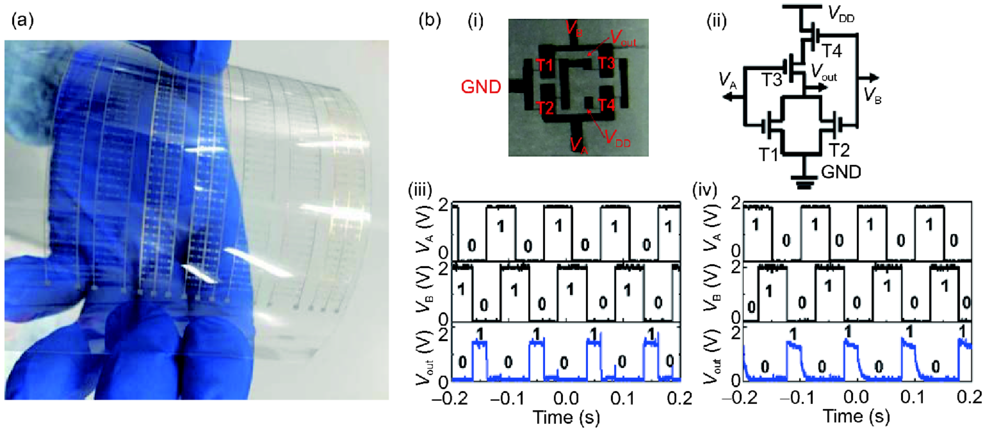

Figure 7 (a) Flexible CMOS circuits made by printed carbon nanotube TFTs; (b) a NOR gate logic circuit showing (i) optical image of printed citcuit, (ii) the circuit diagram, the output characteristics at (iii) 0 kHz and (iv)1 kHz.

both worlds: the simplicity of printed electronics and complexity of silicon electronics.

PERC's team has been exploring the FHE approach for a number of years. Using nanosilver ink to print conductive tracks, various flexible electronic circuits have been created. Figure 8 shows a collection of such circuits. All the components including IC chips, resistors and capacitors are COTS components. All the conductive lines are printed silver lines. The components are attached to the flexible substrate and electrically connected each other with anisotropic conductive film (ACF) technique. Because of the use of nanosilver ink, the sintering temperature is low, which allows the use of PET film instead of PI film as the substrate. Because there is no acidic etching to remove metals, paper substrate can be used as well.

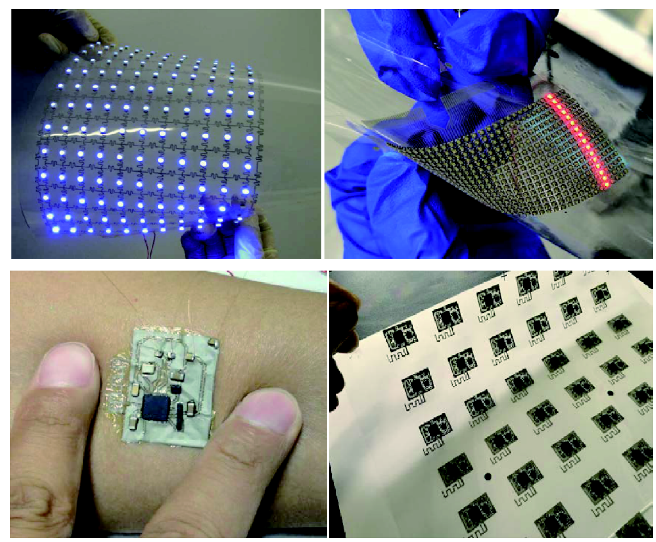

Figure 8 Flexible hybrid electronic systems using printed interconnect wiring.

5 Printing stretchable electronics

Although flexible electronics opens up many new application possibilities, for some applications flexible along is not enough. For example, a flexible circuit sheet such as those made on a PET film may perfectly attach onto a cylindrical surface but not onto a spherical surface. For wearable electronics such as a sensor patch, the system should be not only flexible but also stretchable in order to conformably stick to human skin. The essence of stretchable electronics is to make the electronic system on a stretchable substrate and its electronic performance has no change or minimum change when stretched. Researchers have noticed such demands and developed a range of new materials and fabrication techniques to enable an electronic system to be stretchable. On the materials side, some polymeric electronic materials have been synthesized which demonstrated some stretchability while maintaining their electronic properties. Though quite revolutionary, much of the electronic properties have been sacrificed for its stretchability. On the fabrication side, meandering thin film electrodes were made on a pre-stretched elastic substrate so that subsequent stretching would not break its electric connections. Designing such meandering electrode system would be a daunting task, not to mention the difficulty of lithography patterning on a stretched substrate. Among the many approaches, printing would be the simplest to design and the easiest to implement.

Research work on stretchable electronics at PERC first focused on inks. Conventional silver ink is made of silver nanoparticles. Once is sintered, the printed conductive lines cannot withstand stretching. Instead, silver nanowires (Ag NWs) replaced the nanoparticles as the main ingredient. Ag NWs with diameter of 90 nm and length of 30–40 μm were mixed with high boiling point solvent at the mass ratio of 7:1:2 for Ag NWs:ethanol:terpineol. Then a transfer printing process was developed as illustrated in Figure 9. The conductive lines are first printed on a rigid glass substrate. Then elastic material, usually PDMS, is poured over the glass.

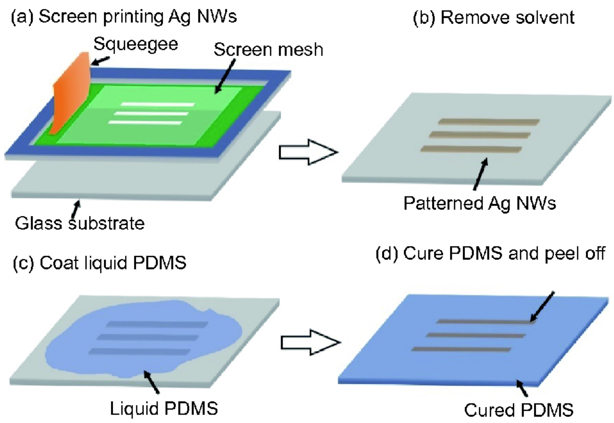

Figure 9 Printing of stretchable conductive patterns.

Once the PDMS is cured and peeled off, the printed conductive lines are transferred to the PDMS surface, resulting in the stretchable electronic circuit pattern [16]. The Ag NWs ink or rather a paste does not need sintering. It becomes conductive once dried in ambient condition. An interesting phenomenon was found that the initial resistance at stretching linearly increases, as shown in Figure 10(a). Once released, the resistance becomes stabilized at a constant in any subsequent stretching, as shown in Figure 10(b). Microscopic examination of the Ag NWs lines revealed that winkles were formed after the very first stretch and release (Figure 10(c)). For following stretching, the surface state of Ag NWs lines simply goes back to its first stretched state, without incurring resistance changes.

Having stretchable conductive connections is not enough. Other components, such as resistors, capacitors and integrated circuit (IC) chips, are needed to form a complete circuit. Then there is the issue how to attach a rigid component to a soft stretchable substrate and to ensure reliable electric connection with the printed stretchable conductive lines. The solution developed at PERC is to use PDMS of different modulus to encapsulate rigid electronic components and stretchable wiring, as illustrated in Figure 11(a). The stiff PDMS covers the area of rigid components and the soft PDMS covers the stretchable interconnect wiring. Figure 11 (b) shows a LED connected by printed stretchable wire. With this approach, the LED circuit worked perfectly under tensile strain of 50% to 100%, as shown in Figure 11(c). The technique has been extended to construct fairly complicated circuits such as stretchable lighting chain wrapping around fingers (Figure 11(d)); washable lighting fabric with high mechanical strength (Figure 11(e)), and a simple functional circuit with a MCU chip, capacitors, resistors and a LED, which can control the LED to flash at a programmed frequency [17].

6 Summary

Electronics has come to the era that conventional rigid systems are not enough. Many new application scenarios demand an electronic system to be flexible and/or stretchable. There are two ways to approach the flexibility and stretchability: at component level and at system level. While at component level there are already successes such as making flexible transistors for applications in flexible displays, the fabrication still relies on complicated and expensive lithography processes. Printing method offers a simple solution. There are many advantages by using printing for the fabrication of flexible and/or electronics as previously mentioned. There are also challenges in the printing approach, which limit the scope of applications. For example, printing is of low patterning resolution, less ideal in surface morphology, prone to creating defects at interface for multilayer printing, limited range of materials which can be printed, less optimum in property for ink materials compared to their solid counterparts, etc. These challenges have been the subjects of research and many progresses have been made. The system level flexibility is rather simple to realize, as only the interconnect wiring need to be flexible or stretchable and all the components such as resistors, capacitors and IC chips can still be rigid and they are readily available commercially. Printing offers a simple route to make the interconnects. The author's group (PERC) has been working on both component level, printing transistors with purified semiconducting carbon nanotube inks, and on system level, printing conductive

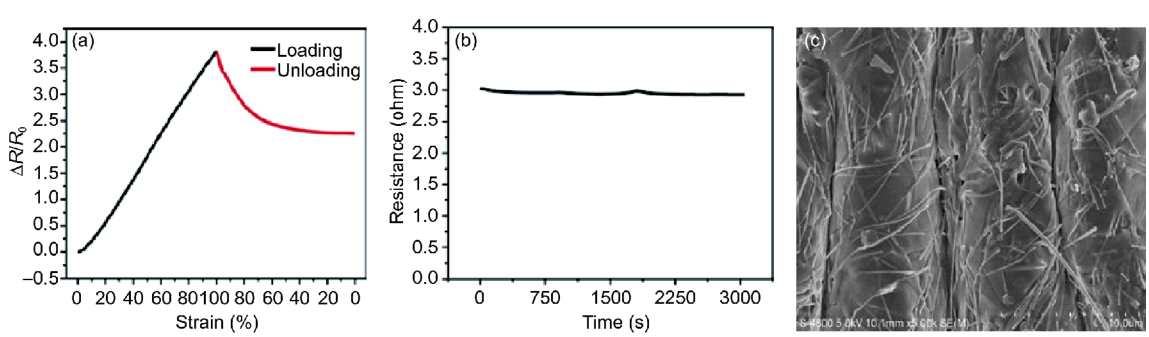

Figure 10 Behavior of printed Ag NWs stretchable conductors (a) initial stretching, (b) repeated stretching, (c) microscopic surface of Ag NWs conductor.

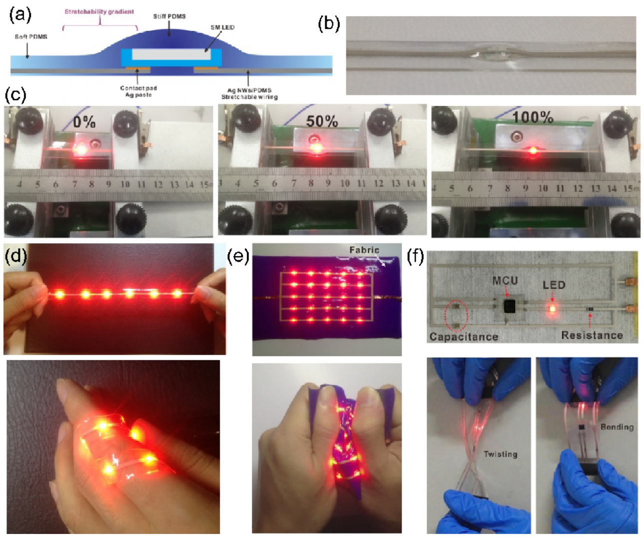

Figure 11 Encapsulation of rigid components and examples of stretchable circuits.

wires on flexible or stretchable substrates. The results presented in this article have proved that the printing approach is simple, low cost and can be implemented in R2R high throughput manner. The process is also green, meaning no acidic etchant discharge to pollute the environment. Utilizing COTS components in the flexible hybrid electronic systems means no compromise in performance because of the flexibility and stretchability, which is good for real applications and expected to prevail in the near future.

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1 Liu Y, Pharr M, Salvatore G A. Lab-on-skin: A review of flexible and stretchable electronics for wearable health monitoring. ACS Nano, 2017, 11: 9614–9635
2 Sevilla G A T, Rojas J P, Fahad H M, et al. Flexible and transparent silicon-on-polymer based sub-20 nm non-planar 3D FinFET for brain-architecture inspired computation. Adv Mater, 2014, 26: 2794–2799
3 Rogers J A, Someya T, Huang Y. Materials and mechanics for stretchable electronics. Science, 2010, 327: 1603–1607
4 Xu J, Wang S, Wang G J N, et al. Highly stretchable polymer semiconductor films through the nanoconfinement effect. Science, 2017, 355: 59–64
5 Cui Z. Nanofabrication: Principles, Technologies and Limits. New York: Springer, 2008
6 Cui Z, Su W M, Zhao J W, et al. Printed Electronics: Materials, Technologies and Applications. Singapore: Wiley, 2016
7 Cui Z, Gao Y. Hybrid printing of high resolution metal mesh as a transparent conductor for touch panels and OLED displays. SID Symposium Digest Technical Papers, 2015, 46: 398–400
8 Kelley T. Organic Electronics: Materials, Manufacturing and Applications. Klauk H, ed. Berlin: Wiley, 2006
9 Rogers D. Nanomaterials are becoming synonymous with printed electronics. Printed Electronics Now, 2011, 3: 35
10 Wang C, Xu W, Zhao J, et al. Selective silencing of the electrical properties of metallic single-walled carbon nanotubes by 4-nitrobenzenediazonium tetrafluoroborate. J Mater Sci, 2014, 49: 2054–2062
11 Zhang X, Zhao J, Tange M, et al. Sorting semiconducting single walled carbon nanotubes by poly(9,9-dioctylfluorene) derivatives and application for ammonia gas sensing. Carbon, 2015, 94: 903–910
12 Sekitani T, Zschieschang U, Klauk H, et al. Flexible organic transistors and circuits with extreme bending stability. Nat Mater, 2010, 9: 1015–1022
13 Xing Z, Zhao J, Shao L, et al. Highly flexible printed carbon nanotube thin film transistors using cross-linked poly(4-vinylphenol) as the gate dielectric and application for photosenstive light-emitting diode circuit. Carbon, 2018, 133: 390–397
14 Xu W, Liu Z, Zhao J, et al. Flexible logic circuits based on top-gate thin film transistors with printed semiconductor carbon nanotubes and top electrodes. Nanoscale, 2014, 6: 14891–14897
15 Zhang X, Zhao J, Dou J, et al. Flexible CMOS-like circuits based on printed p-type and n-type carbon nanotube thin-film transistors. Small, 2016, 12: 5066–5073
16 Yuan W, Gu W, Lin J, et al. Flexible and stretchable hybrid electronics systems for wearable applications. SID Symp Digest Tech Papers, 2016, 47: 668–671
17 Yuan W, Wu X, Gu W, et al. Printed stretchable circuit on soft elastic substrate for wearable application. J Semicond, 2018, 39: 015002