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Materials capability and device performance in flexible electronics for the Internet of Things

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The Internet of Things (IoT) has a broad vision of connecting every single object in the world to form one network. Flexible electronic devices, including RFIDs, sensors, memory devices, displays and power sources, are considered to be the technological basis of the IoT. The development of flexible electronic devices has been extremely rapid in the last decade. Many novel applications have been demonstrated, showing a strong potential impact on human life. In this review, we will summarize the recent progress in the research of flexible electronic devices and related flexible material within the framework of the IoT.

1 Background

The phrase "Internet of Things" (IoT) was first used by Kevin Ashton, director of the Auto-ID Center, as the title of his presentation at Procter and Gamble (P&G) in 1999. Ten years later, he clarified his meaning in an article in the RFID Journal. He pointed out that data on the internet now almost all originate from people. However, people's limits with regards to time, attention and accuracy result in imperfect or incomplete input. This can lead to imperfect data about real world objects.[1] The IoT should take the burden of inputting data off the shoulders of people.

As described in *ITU Internet Reports*: *The Internet of Things*,[2] the IoT builds upon the revolutionary success of mobile and internet networks by expanding the world's network of networks even further. Instead of only connecting people, like the conventional internet, the IoT includes everything in the network. Thus, a new dimension will be added to the world of information and communication technologies. From anytime, anyplace connectivity to anyone, we will now have connectivity to anything. This became the core idea of the original concept of the IoT. Connectivity to anything requires the unique addressability of things. The RFID tag is considered the key technology for addressing physical objects. Ambient intelligence and autonomous control have been integrated into the concept of the IoT as it has developed. The core idea behind the resulting IoT has now become to seamlessly gather and use

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information about the physical environment and about, potentially, any kind of object in the real world during its entire lifecycle.[3] In the extended concept of IoT, additional technologies become indispensable, including sensors for gathering information, memory for information storage, displays for information exhibition, and so on.

The IoT has now a very broad vision. As shown in Fig. 1, many smart environments can be involved in the infrastructure of IoT, such as smart health, smart home, smart cities, and so on. There are varies applications which can be used in these smart environments. For example, the smart home is composed of applications such as smart home security, smart goods preservation and remote control. All the applications are based on one or several key technologies, including RFID, sensor, memory, display, power solution, and so on.

How many things are going to be connected in IoT? The answer must be a huge number. Assuming 1000 things per person, the total number of things in the IoT will be several trillion. With such a huge number, the corresponding electronic devices have to be low cost. In addition, these things are different in size, shape, rigidity, and so on. Obviously, conventional electronics technologies are facing a lot of difficulties because of the extremely broad scope of the IoT.

Flexible electronics based on organic and inorganic nanostructured materials have the exact features that are required for the IoT: (1) the devices are highly mechanically flexible, because the devices are made of flexible organic and inorganic nanostructured materials and fabricated on paper, plastic, silk and other textile substrates; (2) the materials in flexible electronics are generally inexpensive, especially for organic materials; (3) the fabrication methods for flexible electronics are also low cost, such as solution processing, inkjet printing and even roll-to-roll; (4) the devices have low environmental impact, and are sometimes disposable.

In this review we describe the recent progress in research and the future prospects of flexible electronics, focusing on their possible application to the IoT. First, the key technologies, including flexible RFID, sensor, memory and display technologies are described in detail. Then, a flexible solution for power supply is also introduced. As the mechanisms of flexible electronics have been insightfully reviewed elsewhere, we will focus on their character and potential usage in the IoT. Considering the trends in these fields, we summarize current tasks that are considered to be bottlenecks delaying future advances, and finally describe the future prospects of these electronics.

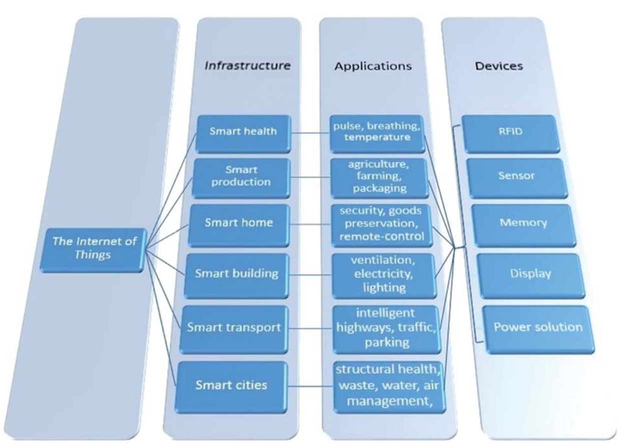

Fig. 1 A schematic illustration of the infrastructure of IoT, the related practical applications and the key electronic devices.

2 Flexible RFID

The history of RFID could be said to have started in the 1940s, when it was used for military purposes. It took almost half a century before its first true consumer application. In the early 1990s, due to a collaboration between IBM and Walmart, massive goods monitoring systems based on passive, very low-cost tags were implemented.[4] The success of this collaboration greatly advanced the technology. However, the widespread use of RFID tags is still hindered because of price, flexibility and environmental impact.

Based on the method of supplying power, RFID systems are generally classified as passive, active and semi-active. Both active and semi-active RFID systems have an on-board power source, while the passive system uses an antenna to accept power emitted from the reader. Compared to active and semi-active systems, the passive RFID systems have a simpler structure and therefore are more commonly used. Most flexible RFID tags are also passive systems. The standard passive RFID system includes an antenna and an integrated circuit (including rectifier and transponder).

2.1 Flexible passive organic RFID tags

In 2003, the first organic thin-film integrated RFID circuits with no rectifier were formed on 2 in $\times$ 2 in glass plates, shown to operate at 125 kHz, 6.5 MHz, and were powered directly with radiofrequency.[5] Although the organic thin-film transistor (OTFT) itself is flexible, it still took three years to realize flexible organic RFID tags. At ISSCC 2006, two pioneering research works about flexible organic RFIDs were presented. One was from PolyIC, which presented a proof-of-concept organic RFID transponder on flexible polyester film, operating at a carrier frequency of 13.56 MHz, but with no ID.[6] The other, from Philips Research, reported that a capacitively coupled flexible 64b RFID tag, the most complex organic transponder at that time, operated at 125 kHz and employed 1938 transistors.[7]

Their following paper provided more details and more advanced results.[8] The p-type OTFTs based on pentacene have been fabricated on a 25 μm-thick polyimide foil. The manufactured circuit contained 1938 pentacenes. In this work, code generators with a limited number of bits (up to 6 b) could be read out using a base carrier frequency of 13.56 MHz by a capacitive antenna. One year later, an inductively-coupled 64 b organic RFID tag operating at 13.56 MHz with a data rate of 787 b s^{-1} was reported by the Holst Centre.[9]

Although these pioneering works have demonstrated the basic functions of organic RFID tags, the performances (such as code size, bit rate and reading distance at reasonable and allowed field strength) are still fairly poor. To match the data rate requirement of electronic product coding, the same research group succeeded in demonstrating an 8 bit RFID transponder chip with critical dimension of 2 μm having a data rate of 50 kb s^{-1} at $V_{DD} = 18$ V, using a self-assembled monolayer of trichloro(phenethyl)silane treated Al_2O_3 as high-*k* gate dielectric,[10] shown in Fig. 2.

Their other attempt at lowering the supply voltage was published in 2011.[11] A dual-gate technology was adopted for organic transistor circuits, which not only increased the robustness, but also allowed for lowering the supply voltage to as low as 10 V.

Another important trend in flexible organic RFIDs is to make the devices using a more cost-effective method, namely printing technology. To be able to compete with conventional RFID systems, the product price is one of the crucial factors. Recently, a research group from CEA-Grenoble first tested the possibility of printing organic complementary circuits on plastic substrates with a first generation of p- and n-type semiconductors and lower mobility ($\mu_N < 0.06/\mu_P < 0.04$ cm^2 V^{-1} s^{-1}),[12] and then fabricated fully printed flexible organic digital and analog complementary circuits based on n and p-type OTFTs with high mobility n-type and p-type small-molecule semiconductors (0.55 and 1.5 cm^2 V^{-1} s^{-1} respectively),[13,14] and demonstrated the capability of this technology to enable organic RF applications. Finally, Kjellander *et al.* from the Holst Centre have ink-jet printed a blend of 6,13-bis-(triisopropylsilylethynyl)pentacene (TIPS-PEN) and polystyrene as the active layer for flexible TFTs. They succeeded in integrating almost 300 such TFTs on a surface area of 34 mm^2 of plastic foil for 8 bit RFID transponder circuits,[15] see Fig. 3b and c. The output oscillation character of the RFID transponder is shown in Fig. 3a.

2.2 Flexible passive RFID tags based on other materials

Besides organic semiconductors, there are other materials that have shown potential in the making of flexible RFID tags, such as metal oxides, carbon nanotubes, and emerging 2D materials. Compared to organic semiconductors, these materials usually have better mobility but are more difficult to handle in the fabrication process.

One of the main problems in forming a good metal oxide semiconductor thin film with a mobility of over 1 cm^2 V^{-1} s^{-1} on flexible substrates is that the most common flexible substrates (plastic, paper and textile) cannot withstand the high temperature involved in the process. Fabricating high-performance, flexible RFIDs is challenging, owing to a trade-off between processing temperature and device performance. In 2004, Nomura *et al.* reported a novel semiconducting amorphous metal oxide semiconductor from the In–Ga–Zn–O system (a-IGZO).[16] Using a-IGZO as the active layer, the authors manage to fabricate TFTs on flexible polyethylene terephthalate sheets, exhibiting saturation mobilities of 6–9 cm^2 V^{-1} s^{-1}. This research achievement became a stepping stone for the development of flexible oxide RFID tags. After conquering the problem of operational stability, in 2010 the researchers finally presented the first flexible a-IGZO 8 bit RFID transponder circuit with high field-effect mobility (around 17 cm^2 V^{-1} s^{-1}) TFTs,[17] as shown in Fig. 4.

A thin film of carbon nanotube networks has proved to be a good candidate for the active semiconducting channel in

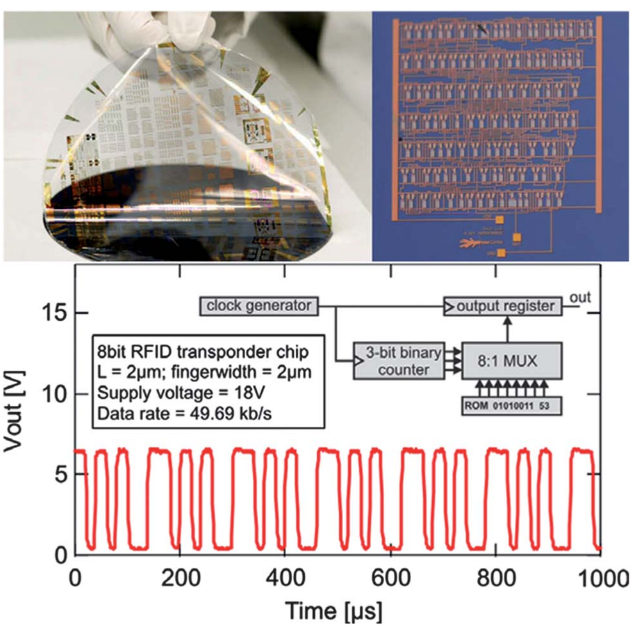

Fig. 2 Photograph of the 150 mm foil being delaminated from the carrier wafer (top left) and a detailed die picture of the 8 bit RFID transponder chip on foil (top right). The die size is 24.73 mm^2. The design is comprised of 294 transistors. Measured signal of the 8 bit RFID transponder chip with schematic overview of its digital logic portion. Reprinted, with permission, from ref. 10.

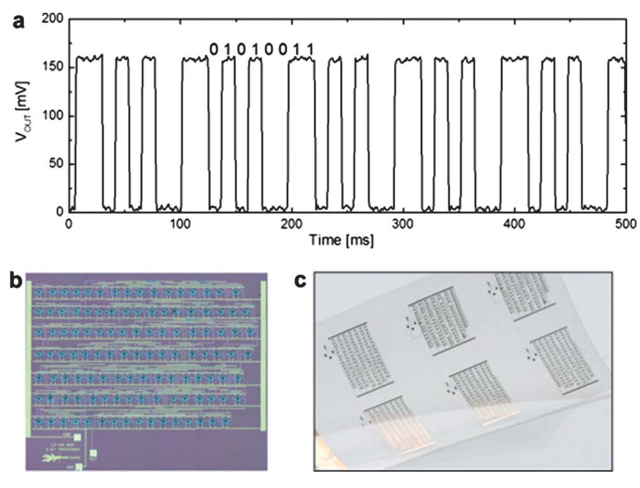

Fig. 3 Output oscillations for an 8 bit RFID transponder, using the 'single-droplet' design, the active layer was ink-jet printed TIPS-PEN:PS blend. (b) Crossed polarized micrograph of an 8 bit RFID transponder, 'single-droplet' design. The blue colored circles are the ink-jet printed TIPS-PEN:PS blend. Each droplet covers one logic gate consisting of 2–4 transistors. (c) Photograph of four 8-bit RFID transponder chips, with 'single-droplet' design, on plastic foil. One transponder has a footprint of 34 mm^2. Reprinted, with permission, from ref. 15.

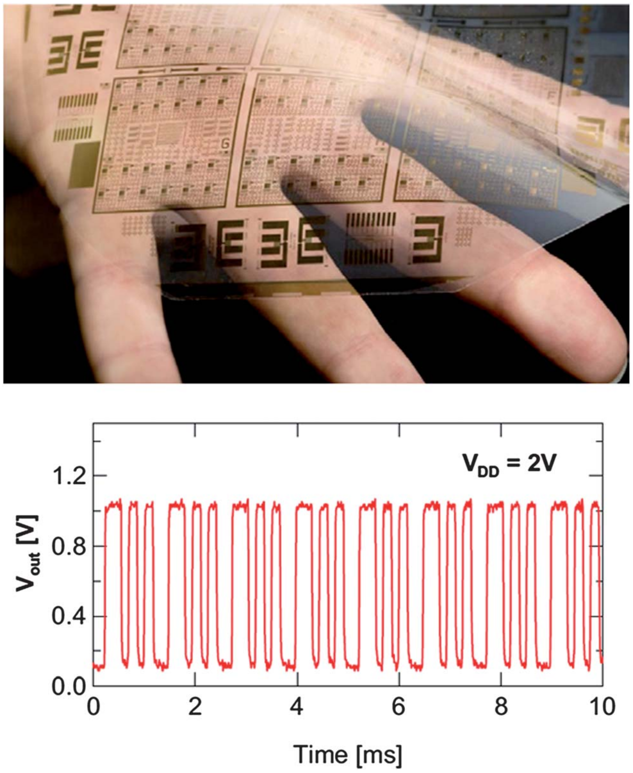

Fig. 4 Top: Photograph of IGZO TFTs and circuits on 25 μm PEN foil delaminated from the Si wafer after complete processing; bottom: output pattern of an 8 bit RFID transponder circuit yielding data rates of 6.4 kb s^{-1} at 2 V supply voltage. Reprinted, with permission, from ref. 17.

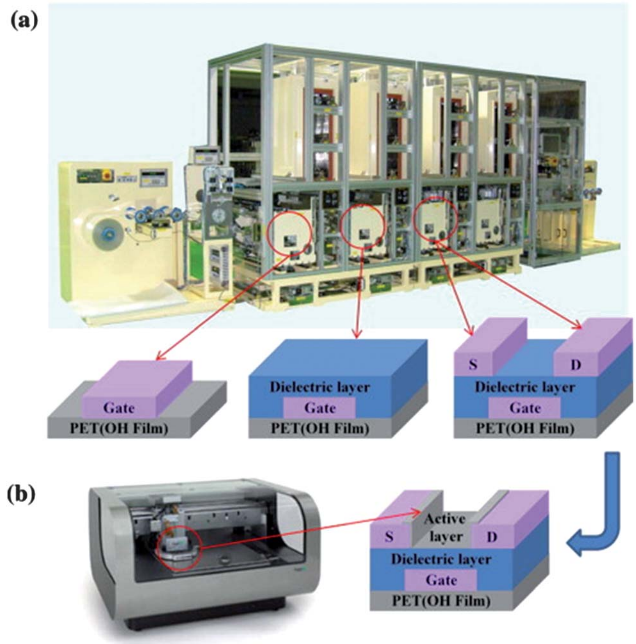

Fig. 5 Actual image of R2R gravure with four color units (a) and inkjet printer (b). Reprinted, with permission, from ref. 21.

flexible TFTs.[18,19] However, the on–off ratios of the printed TFTs made from active-layered Single Wall Carbon Nanotubes (SWCNTs) still need to be improved, before they can be integrated into RFID circuits. Recently, Prof. Cho's group has succeeded in making all-printed and roll-to-roll printable 13.65 MHz 1 bit tags.[20] Antennas, electrodes, gate electrodes, wires, and dielectric layers are printed by a gravure printer at a web speed of 5 m min^{-1}, where the active layer and the source and drain electrodes were composed of ink-jet printed SWCNTs.[21] The architecture of the SWCNT-TFTs is illustrated in Fig. 5, with the gravure and inkjet printers. The SWCNT-TFTs show a mobility of 5.24 cm^2 V^{-1} s^{-1} at an on–off ratio of 100, which is good enough to operate 1 bit RF tags at a switching speed of 100 Hz. The 1 bit RF tag in this work has an estimated cost of $0.03 per unit. After this achievement, the group has continuously improved their technologies, and successfully demonstrated all gravure printed 13.56 MHz operated 16 bit RFID tags and 32 bit RFID tags, at Printed Electronics & Photovoltaics Europe 2010 and 2011 respectively.

2D materials, such as graphene and MoS_2, are ideal materials for flexible electronics, due to its high carrier mobility, optical transparency, and mechanical flexibility. Although, there are still no reported flexible RFID tags based on 2D materials. They have shown strong potential in the RF applications. Recently, IBM has demonstrated graphene RF devices have been successfully fabricated on flexible polyimide substrates, and a cutoff frequency as high as 10 GHz has been attained.[22] An MIT group succeeded in fabricating a MoS_2 based five-stage ring oscillator with oscillation frequency from 0.52 to 1.6 MHz.[23]

To make the comparison easier for readers, the performances of the flexible RFID tags according to the materials are listed in Table 1.

2.3 Chipless RFID, an emerging technology

The earliest concept of chipless technology was in the electromagnetic and radar community in the 1940s. In fact, the well-known device that is considered a predecessor of current RFID technology is more like the concept of chipless RFID. The simplicity of the chipless RFID structure has many advantages, such as that it is wireless, powerless, there is almost no degradation and most importantly, it is cheap. Another remarkable property of chipless technology is its compatibility with flexible electronics. Since no integrated circuit is involved, chipless RFID tags can be fabricated with various flexible conductive materials, such as metal film, carbon nanotube networks and graphene, and can be fabricated using different methods, including spin coating, inkjet printing and even roll-to-roll printing. However, chipless technology is still in its infancy. More functions are required to be explored and many scientific challenges face its development. According to the adopted encoding principles, these chipless tags can be basically classified into two categories: time domain signature based RFID tags[24–26] and frequency domain footprint based RFID tags.[27,28]

Table 1 Comparison of the performance of three types of RFIDs

	Field-effect transistors		RFID		
	Mobility ($cm^2 V^{-1} s^{-1}$)	ON/OFF	Band	Operating voltage	Code generator
Organic from ref. 15	0.55 (n) and 1.5 (p)	10^8	HF	10 V	8 bit
IGZO from ref. 17	17 (n)	10^8	HF	2 V	8 bit
SWCNT from ref. 20	5.24 (p)	100	HF	10 V	1 bit (32 bit presented later at conference)

The first time domain chipless RFID tag based on electromagnetic reflectors was proposed in 2006 by Zhang *et al.* from the KTH Royal Institute of Technology (KTH) in Sweden.[24] However, the device was on rigid PCB board. Later in the same year, another type of time domain chipless RFID tag based on microwave circulators was reported by Chamarti *et al.* from Louisiana Tech University.[25] Each type of RFID tag has its own advantages. The former solution is believed to possess advantages in printability and coding capacity over the latter. Although Linlin *et al.* have theoretically proved that RFID tags are fully printable on flexible substrates,[29] the mission of making a flexible RFID tag was accomplished by Botao *et al.* from KTH.[30] They managed to fabricate an ultra-low-cost RFID tag with 1.67 Gbps data rate by inkjet printing on a paper substrate. Tapered microstrip lines were employed to overcome the limitations of low conductivity and the thin film thickness of ink-jet printed metal tracks.

Compared to time domain RFID, frequency domain chipless RFID has a better potential for coding capacity and therefore has drawn much attention. An early example was the chipless RFID tag developed by using arrays of identical microstrip dipoles capacitively tuned to be resonant at different frequencies.[31] After Preradovic *et al.* succeeded in printing a novel chipless RFID tag on PCB board with the remarkable coding capability of up to 35 bits,[32] an LC resonator-based chipless RFID tag printed on packaging paper was demonstrated[33] (shown in Fig. 6).

2.4 Summary

Nowadays, the price of a conventional silicon-based passive tag is approaching five cents.[34] However, considering the number of RFIDs required in the IoT, item-level tags are expected to be less than 2 cents or even less than a cent. Given such a requirement, RFIDs based on cheap flexible substrates and fabricated using low-cost printing technologies have drawn more and more interest. Although some aspects of the performance of flexible RFID tags need to be improved, such as tag-read rates and reading distance, we might dream of a world where people can have the current and historical information of any uniquely identifiable objects.

Fig. 6 (left) Inkjet printing process of the proposed RFID tag; (right) RFID tag directly printed on packaging paper.

At the University of Washington, a microcosm of the IoT has been built using RFID. Sixty-seven users were invited to join a four-week user study, which measures trends in adoption and utilization of the premature tools and applications. Forty-one of them expressed an interest in using personal trending applications such as the Digital Diary.[34] This simple microcosm study has shown us how the incredible amount of information captured by a trillion RFID tags will have a tremendous impact on our lives in the future.

3 Flexible sensors, memory and display

Simple passive RFID tags only provide basic identification of objects, but in the context of the IoT, item-level real-time tracking and in-depth sensory monitoring of real world objects are required. Therefore, more flexible electronic devices are needed for the collection, storage and exhibition of rich sensory information. In this chapter, flexible sensors, memory devices and displays will be described separately, showing how powerful the system can be if these electronic devices are embedded in RFID.

3.1 Flexible sensors

How smart the smart application can be is determined by the richness of the obtained sensory information. Therefore, key sensory information including temperature, pressure and chemical information, is requisite for the smart application. A temperature sensor for the smart packaging of a milk carton is a good example of showing the importance of sensory information.

Temperature sensors are usually made of materials with a temperature-dependent resistance, called a thermistor. For example, a conventional platinum resistance temperature sensor has been fabricated on a flexible polyimide substrate with a detecting temperature range up to 400 °C.[35] Although it has shown very good performance, the low price requirement of the IoT has driven researchers to look for other solutions. Thermo-sensitive polymers are very good candidates and they have been studied recently.[36] An organic diode with a simple sandwich structure has also proved to be thermo-sensible.[37,38] Another approach that has been reported is the screen printing of a polymeric thermo-sensitive material on Kapton as a prototype textile sensor dedicated to human body temperature measurements.[39] A good temperature sensitivity of metal nanoparticle/organic blend thermistors has also been discovered. In 2013, Jin *et al.* reported a flexible temperature sensor based on a Ni particle filled binary-polymer composite, which demonstrate desirable properties such as tunable temperature ranges, large resistance modulation by temperature and improved thermal cycling stability.[40] By integrating the silver nanoparticle/pentacene thermistor to the gate electrode of a pentacene OTFT, Ren *et al.* demonstrated a 10 bit dynamic range temperature sensor with an operating range from 20 to 70 °C[41] (see Fig. 7).

Besides organic temperature sensors, in 2012, De *et al.* discovered that an inkjet-printed graphene electrode had a temperature sensitivity similar to that of conventional negative temperature coefficient materials, but with a faster response time by an order of magnitude.[42] They believe that their finding suggests the potential use of the inkjet-printed graphene electrode as a writable, very thin, mechanically flexible, transparent temperature sensor.

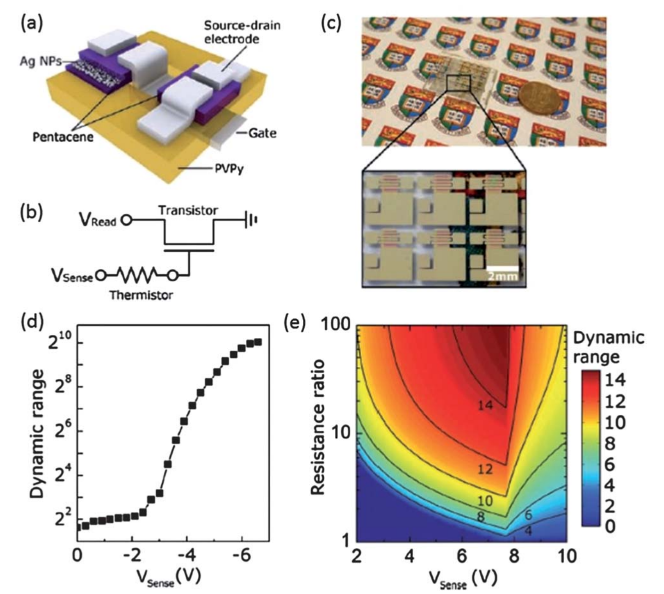

Fig. 7 (a) The schematic diagram of the (one transistor)–(one thermistor) temperature sensor; (b) the circuit diagram of the temperature sensor, V_{Sense} is the voltage bias applied on the thermistor and gate of the transistor, and V_{Read} is applied on the drain–source of the transistor; (c) the optical image of the device and the zoom-in image of the thermistor–transistor temperature sensor; (d) the measured dynamic range as a function of V_{Sense}, (e) the simulation dynamic range of the current temperature sensor at different resistance ratio and V_{Sense}. Optimum V_{Sense} can be observed for a given resistance ratio, and if V_{Sense} is larger than the optimum value, the value of DR will start to roll over. Reprinted, with permission, from ref. 41.

Pressure sensors are some other very important sensory devices and are already being used in touch screens, artificial skin and scales. Recently, organic TFTs have shown a promising function for pressure sensing. In 2010, the Bao Research Group of Stanford University developed highly sensitive flexible pressure sensors with microstructured rubber dielectric layers, which can sense weight as light as that of a fly.[43] After decreasing the thickness of the polymer substrate to 1 μm, the electronic circuits are light (3 g m^{-2}) and ultra-flexible and conform to their ambient, dynamic environment,[44] as shown in Fig. 8.

Although the pressure sensors based on organic TFTs have shown impressive performance, some researchers believe that other materials might still have a chance to compete with organic semiconductors. Inorganic nanowire is one option. The single-crystalline nature of the inorganic nanowires enables low-voltage operation with high device stability, which presents an important advantage in their use for electronic and sensory applications over organic TFT technologies. Kuniharu *et al.* succeeded in fabricating a 7 × 7 cm^2 flexible pressure sensor with Ge/Si core/shell NW parallel arrays by a contact-printing method.[45]

Flexible gas sensors have also drawn a lot of attention due to their potential application in environmental monitoring and chemical and biological sensing. Again organic TFTs have proved to be excellent gas sensors. The gas sensing ability of organic TFTs is mainly generated by the chemically sensitive active layer. Research groups from the Institute of Chemistry at the Chinese Academy of Sciences have made a remarkable contribution in this field. Recently, they have synthesized a new tetrathiafulvalene derivative and fabricated organic TFTs with a high hole mobility of up to 0.73 $cm^2 V^{-1} s^{-1}$, showing fast responsiveness toward chemical vapors of diethyl chlorophosphate, $POCl_3$ and TNT.[46] They have also reported pentacene analogue-based organic field-effect transistors (OFETs) exhibiting a mobility of 0.8 $cm^2 V^{-1} s^{-1}$that have displayed high sensitivity, selectivity, and reproducibility in the detection of ethanol gas.[47] Other gases, including NH_3,[48] SO_2,[49] and moisture,[50] can be sensed by various organic TFTs as well. Flexible gas sensors based on carbon nanotubes for the detection of organic agents,[51] such as NH_3,[52] NO_2 [53] and H_2,[54] have also been reported.

3.2 Flexible memory

With all the sensors in the ideal IoT, there will be a lot of real time sensory information from the objects. We now need to find a place to store it. There are two different ways of keeping it. One is sending the information in real time by wireless communication by assembling the sensor on a wireless platform. The other is keeping it locally, which requires data storage media and flexible memory.

Organic nonvolatile memory can be based on a configuration of either memristors or TFTs. They can be further categorized by different structures and mechanisms. Floating gate,[55] polymer

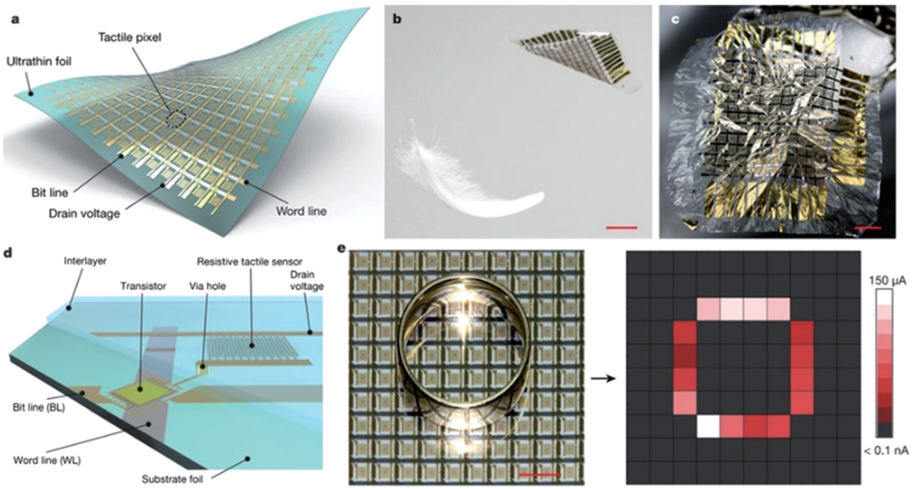

Fig. 8 (a) Illustration of a thin large-area active-matrix sensor with 12 × 12 tactile pixels. (b) Ultrathin plastic electronic foils are extremely lightweight (3 g m^{-2}); they float to the ground more slowly than a feather and are therefore virtually unbreakable. Scale bar, 2 cm. (c) At only 2 μm thickness, the devices are ultra-flexible and can be crumpled like a sheet of paper. Scale bar, 1 cm. (d) Design of a tactile pixel comprising a switching transistor and a resistive touch sensor. The control transistor is fabricated directly on the 1.2 μm substrate. An interlayer of 800 nm parylene insulates the switching matrix backplane from the sensing layer. (e) Top-view photograph (left) and corresponding drain current of a metallic ring placed on the sensing sheet (right). A difference of more than six orders of magnitude is observed in drain current between contacted and non-contacted pixels. Scale bar, 1 cm. Reprinted, with permission, from ref. 44.

electret[56] and ferroelectric[57] are the three main types of TFTs. For memristors, the mechanisms can include changing molecular structures,[58] field-induced charge transfer,[59] resonant tunneling and charge storage,[60] the Simmons–Verderber model,[61] and electron donor–acceptor polymers,[62] formation and annihilation of filament,[58] electrode-induced two-dimensional single-electron tunneling,[63] redox switch at an organic/electrode interface,[64] ferroelectric phase-separated blends,[65] *etc.*

Despite continuing debate about the mechanism, flexible memory device performance is improving and approaching the requirements of practical application. In 2012, a printed flexible NAND flash memory device based on a polymer electret was fabricated, showing excellent non-volatile memory characteristics: an opened memory window of more than 90 V, a high on/off-current ratio of $\sim 10^5$, a relatively low operation voltage of less than 20 V, and a long retention time of $\sim 10^7$ s, as well as a stable writing/reading/erasing cycling endurance and multi-level memory capability.[66]

Although memristors are included here as organic devices, memristors were in fact first experimentally identified in 2008 based on the electrical switching observed from an inflexible, TiO_2-based, two-terminal device. It took only one year before its flexible brother was born. By spinning a TiO_2 sol–gel on a commercially available polymer sheet, the flexible TiO_2 memristor can be inexpensively fabricated.[67] In the following year, ZnO,[68] ZrO_2 [69] and CuO[70] were included in this metal oxide memristor family.

3.3 Flexible display

Now with flexible sensors and memory, people can collect and store an object's information. But sometimes you may want to show it. That is why flexible displaysare needed in IoT. Nowadays, we use organic light-emitting diode (OLED) displays in everyday life in mobile devices. The potential of these devices is that they can be put on flexible materials (like plastic or metal foil), so it is possible to make bendable, flexible displays. In fact, the first flexible OLED was reported more than 20 years ago by Professor Alan Heeger's group.[71] However, it took a long time to realize the first practical flexible OLED display, due to the obstacle of flexible TFT technology. But now flexible OLEDs are commercially available, such as Samsung's YOUM.

However, flexible OLED technology is still not mature. The cost has to be further reduced and more applications need to be explored. One of the main costs for flexible OLEDs comes from the anode material, ITO. To place ITO, semitransparent metal,[72] graphene[73] and carbon nanotubes[74] have been tried by various research groups, with impressive results. Flexible OLEDs have also been put on biodegradable flexible substrates for biomedical purposes[75] and ultrathin substrates for flexible, stretchable and surface-conforming electronics;[76] integrated into textiles[77] for the potential usage of wearable electronics; embedded with pressure sensors to enable an instantaneous pressure visualization function,[78] which will make the sensor user interactive (shown in Fig. 9); and so on.

3.4 Summary

In this chapter, we have introduced flexible sensors, memory devices and displays, which will be used for information collection, storage and exhibition, respectively. The recent research progress in device function and performance has been briefly reviewed. Although the development of these flexible electronic devices is remarkable, their feasibility has been restricted to functional demonstration of unit components. The realization of a flexible electronics system for practical

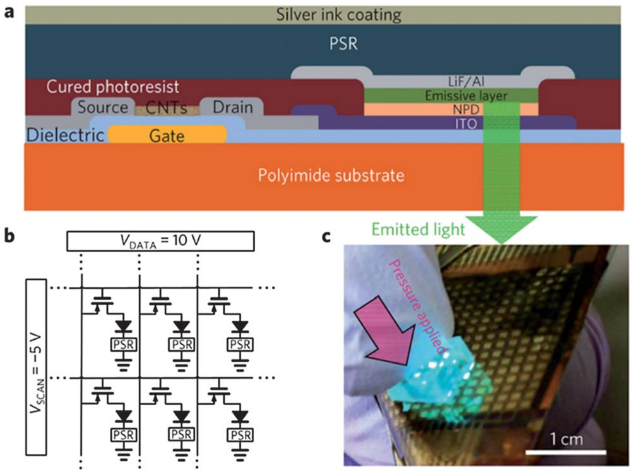

Fig. 9 (a) Cross-sectional schematic showing one pixel of the interactive e-skin device, consisting of a nanotube TFT, an OLED and a pressure sensor. Light from the OLED is emitted through the substrate and the brightness of the OLED is determined by the magnitude of the applied pressure. (b) Circuit schematic of the e-skin matrix. (c) Photograph of a fabricated device (16 × 16 pixels), showing that light is locally emitted where the surface is touched. Only the pixels being pressed are turned on. Reprinted, with permission, from ref. 78.

application is facing an obstacle: the development of a flexible high-power source. Compared to flexible passive RFID tags, all the flexible sensors, memory devices and displays require a power supply. A power solution for flexible electronics is becoming an important issue that cannot be bypassed.

4 Power solution for flexible electronics

The design of flexible electronic equipment requires the development of power solutions that are flexible. Obviously, conventional power solutions cannot fulfill the requirements of flexible electronics. Recently, several routes toward the development of flexible power solution have been explored, including flexible batteries, flexible solar cells, flexible supercapacitors and piezoelectric and thermoelectric energy harvesters, all of which demonstrate a good ability to power up flexible electronics.

4.1 Flexible battery

Rechargeable lithium ion batteries are considered one of the likeliest candidates for a flexible power source because of their high operating voltage, high energy capacity, and long-term cyclability. However, making a flexible lithium-ion battery requires flexible electrode active materials. Two recent Proceedings of the National Academy of Sciences (PNAS) papers have reported the development of flexible electrodes in lithium ion batteries. Na *et al.* have presented flexible graphene-based lithium ion batteries showing fast charge and discharge rates.[79] A unique 3D graphene macroscopic structure, graphene foam (GF), has been used as a frame to form flexible $LiFePO_4$/GF and $Li_4Ti_5O_{12}$/GF electrodes. Yuan *et al.* have proposed and realized an approach that involves patterning battery flexible electrodes at the micron scale to fabricate transparent flexible batteries, which can function as the power supply in transparent flexible electronics. With the increase in performance of lithium ion batteries, researchers have started to integrate them into flexible electronics systems. For example, Min *et al.* have succeeded in integrating flexible thin-film lithium ion batteries into a flexible light-emitting diode, which makes an all-in-one flexible electronic system,[80] as shown in Fig. 10.

4.2 Flexible solar cell

The history of flexible solar cell research extends back into the 1990s. Ultralight flexible amorphous silicon solar cells were reported, but did not draw enough attention.[81] It is only in the last few years that flexible solar cells have attracted a lot of interest because of the development of the organic solar cell and CuInGaSe2 (CIGS) thin film solar cells. According to research from the National Renewable Energy Laboratory (NREL), the best CIGS solar cell efficiency is now 20.4%, for a solar cell developed by the Swiss Empa lab (which is actually on flexible polyimide film). The best organic solar cell efficiency is 11.1%, for a solar cell developed by Mitsubishi Chemical Co.

Recently Martin *et al.* have reported ultrathin and lightweight organic solar cells with extremely high flexibility,[82] as

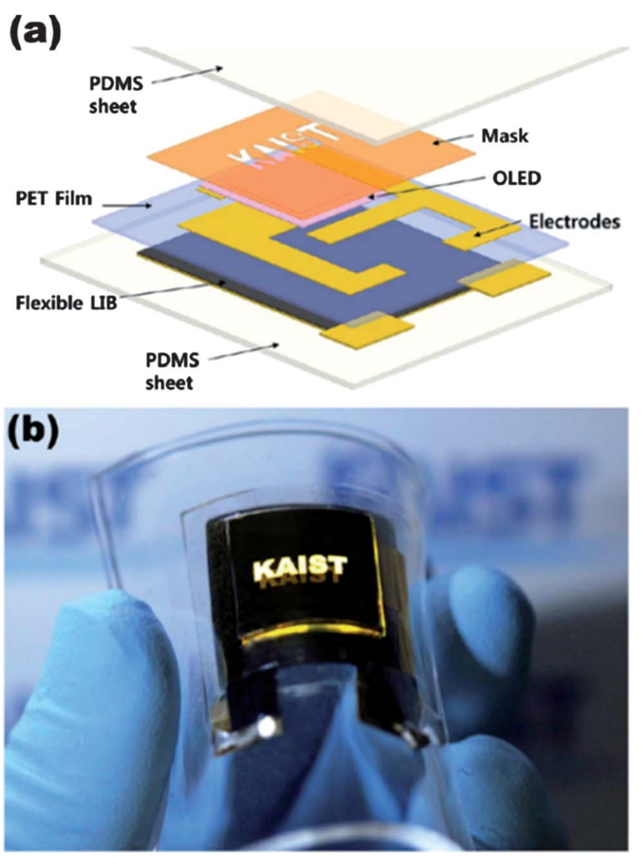

Fig. 10 (a) Schematic diagram of an all-flexible LED system. (b) Picture of an all-in-one flexible LED system integrated with a flexible LIB. Reprinted with permission from ref. 80.

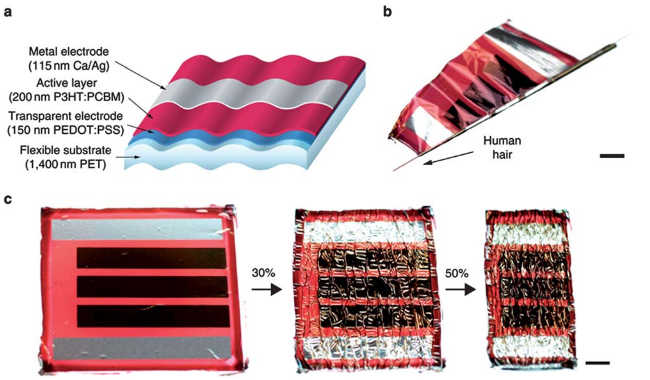

Fig. 11 (a) Scheme of the ultra-light and flexible organic solar cell. The layer thicknesses are drawn to scale. (b) Extreme bending flexibility demonstrated by wrapping a solar cell around a 35 μm-radius human hair. Scale bar (also in c) 2 mm. (c) Stretchable solar cells made by attaching the ultrathin solar cell to a pre-stretched elastomer. They are shown flat (left) and at 30% (middle) and 50% (right) quasi-linear compression. Reprinted with permission from ref. 82.

shown in Fig. 11. They fabricated the polymer solar cell on plastic foil substrates less than 2 μm thick with an efficiency of 4.2%. Moreover, when people consider the solar cell for flexible applications, the value of power output per weight becomes more important. Using this metric, this ultrathin solar cell so far has the best record in the world: 10 W g^{-1}.

Using flexible solar cells as a power source, many novel applications have been invented. For example, flexible solar cells can be embedded in cloth to provide power for portable electronic devices,[83] fabricated as core–shell nanofibers and woven into solar cloth,[84] and used as power supplies for future smart textiles applications.

4.3 Other flexible power supplies

Besides flexible batteries and solar cells, there are other devices that can be used as flexible power supplies. Flexible supercapacitors have been progressing rapidly in recent years because they have a particularly high power density, long life cycle, rapid charge/discharge rate, a wide operating temperature range, and are environmentally safe.[85] Recently, researchers from UCLA have reported a scalable fabrication of high-power graphene flexible micro-supercapacitors with a world record power density of ~200 W cm^{-3}, which are capable of on-chip energy storage. With the rapid development of flexible supercapacitors, researchers are now able to integrate them into textiles to produce an "energy textile" as part of a smart garment.[86]

Piezoelectric energy harvesting is one of the promising ways to harvest the energy (even if it is tiny) from ambient environments, including from ultrasonic waves,[87] sounds,[88] wind,[89] air/liquid pressures,[90] body movements[91] and heartbeats.[90] In order to fabricate in a cost effective way, solution-processable flexible piezoelectric thin film materials are the key component for piezoelectric energy harvesters. Most conventional inorganic piezoelectric thin film materials require an annealing process at a high temperature, which the flexible substrate cannot handle. Therefore, conventional piezoelectric energy harvesters are fabricated using the film transfer method. But recently, a low-temperature process was adopted to deposit piezoelectric ZnO thin films directly onto the plastic substrates without any thermal damage. In addition, a screen-printing of silver was applied to form a contact on the top of the all-solution-processed flexible thin film piezoelectric nanogenerator.[92] Compared to inorganic materials, piezoelectric copolymer poly(vinylidenefluoride-co-trifluoroethylene) thin films are naturally compatible with the low temperature solution process. The Rogers Research Group at the University of Illinois at Urbana-Champaign has reported high-performance piezoelectric devices based on aligned arrays of nanofibers of this copolymer.[93]

Thermoelectric devices are based on the Seebeck effect that utilizes a temperature difference across the device to drive the diffusion of charge carriers. In the ambient environment, there are many places with a temperature difference sufficient for collection by thermoelectric devices. The efficient thermoelectric harvest of polymer–nanomaterial composites has been recently discovered. Professor Zhong Lin Wang from Georgia Tech has demonstrated a flexible thermoelectric nanogenerator based on a Te nanowire/P3HT polymer composite, which has a positive Seebeck coefficient of about 285 μV K^{-1}.[94]

4.4 Summary

Energy harvesting from ambient environments is an attractive process in scientific and industrial fields for the purpose of building self-powered wireless systems. It is even more important for the flexible electronics in applications for the IoT. The rapid development of flexible power supplies enables various flexible electronic devices to be integrated into novel flexible electronics applications that can be attached to any object in the world.

5 System integration and future outlook of flexible electronics for IoT application

5.1 Integration of flexible electronics systems

So far we have reviewed a wide range of technologies, such as RFID, sensor, memory, display and power source technology that will be involved in building the IoT. In this chapter, we will show some examples of how these building blocks can be assembled to be able to connect with the IoT.

In general, every flexible device has to integrate with a wireless communication component, so that it is physically possible to be directly or indirectly connected to the communication networks infrastructure (*e.g.*, through ultra-wideband networks or 3G and 4G networks) of the IoT. For example, sensors can be directly connected to the networks of the IoT through a wireless connection. Or each sensor can act as a wireless sensor node, and the nodes can self-organize to form a wireless sensor network (please refer to *Fundamentals of wireless sensor networks: theory and practice*[95] for more details), and connect to the networks of the IoT through a gateway sensor node.

In 2006, Antonio *et al.* reported their first attempt at integrating sensors, batteries and RFID tags on ultra-low-cost paper-based substrates as wireless sensor nodes, which was done by inkjet printing technology.[96] They demonstrated a prototype sensor node, which could eventually facilitate low-cost autonomous data acquisition.

Battery-driven systems have an obvious disadvantage: the life time of a sensor node is limited by the battery's charge. A more sustainable strategy is to harvest energy from the ambient environment. One of the most widely used sustainable power solutions is the use of piezoelectric energy scavengers. Orecchini *et al.* have proposed an RFID-embedded shoe powered by piezoelectric generators, which harvest mechanical energy from human beings.[97] The tag antenna has been designed in the shape of the shoe's brand logo and can actually be used as the logo, which meets the requirements of being conformal, unobtrusive, low-profile and comfortable to wear.

Another self-powered system that works wirelessly and independently for long-distance data transmission was reported by Professor Wang's group from Georgia Tech.[98] In this system, the nanogenerator using the piezoelectric effect of ZnO nanowires is used as the power source, integrating with a rectification circuit, a capacitor for energy storage, a sensor, and an RF data transmitter. Wireless signals sent out by the system were detected by a commercial radio at a distance of 5–10 m, showing the capability of the self-powered system for wireless sensing applications.

Solar cells are another widely used power solution for wireless sensor systems, especially for outdoor applications. Win *et al.* have proposed solar energy harvesting circuits for wireless sensor nodes. The solar energy harvester was also tested with a crossbow wireless sensor node to monitor temperature in the actual outdoor field environment, extending the lifetime of the wireless sensor node to almost indefinite.[99]

Self-powered wireless sensor nodes are able to operate all the time, generating enormous amounts of data. The in-network data processing activities will increase the communication costs or even cause delays in network response. More local data processing (compression and aggregation) helps to reduce this problem, as suggested by Mathur *et al.*[100] Therefore the integration of memory into wireless sensor nodes becomes very important. Ping *et al.* have proposed a sustainable wireless sensor node design using solar energy and phase change memory, which solves flash memory's endurance issue.[101]

In summary, some recent studies of the integration of flexible electronic systems for IoT application have been briefly reviewed. Although they have all demonstrated promising functions and ambient compatibility, there is still an obvious distance between prototype systems and practical applications.

5.2 Future outlook

The development of flexible electronics in the last decade has been rapid. Some developments have already been commercialized, such as flexible OLEDs, flexible TFTs, and so on. Others are catching up, like flexible solar cells. But to serve as the technology basis for the IoT, more advances still need to take place.

1) So far, flexible power supplies can only drive electronic systems with low power consumption, which, of course, limits system functions. Increasing the power capacity will allow more electronic components to be integrated, such as actuators and microprocessors.

2) Integration of flexible electronics is still a big challenge. Conventional technologies for integration are not available anymore. For example, soldering for chip bonding is now becoming extremely difficult because of the inability of flexible materials to withstand high temperatures. Inkjet printing seems like a good solution for integration, but its performance still needs to be improved.

Moreover, an issue of greater concern is that, compared to the advanced status of technological development, the utilization of these novel technologies is lagging far behind. As Kevin Ashton said, “We've made a lot of progress, but we in the RFID community need to understand what's so important about what our technology does, and keep advocating for it”.[1]

As illustrated in Fig. 1, between IoT infrastructure and devices, there is an important bridge, applications. Under the IoT vision, we will all wear smart clothes that monitor our health, live in smart homes that are decorated according to our emotion, drive smart cars with more safety protection and so on. There will be no gap between us and information about any object, or even between any two objects. Obviously, to realize this vision, a lot of novel applications, using the above reviewed flexible devices, need to be invented.

Nevertheless, we still strongly believe that in the end, “The Internet of Things has the potential to change the world, just as the Internet did. Maybe even more so”.[1]

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