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VIEW & PERSPECTIVE

Shooting flexible electronics

Carbon-rich materials are the key.

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The trends of the future electronic devices should be miniaturized, flexible, stable, portable, light, and highly integrated. Although flexible electronic products (i.e., flexible display products [1–3], batteries [4, 5], cell phones [6]) have been commercially available recently, which represents the starting of a new era in electronics, these progresses are still in their infancy and more efforts are required to boom their multifunction and speed up their marketization from lab. Considering their low-cost and mass-productive synthesis technologies, rich species, high performances, and especially, the excellent flexibility and stability, organic materials (insulating, conductive and semiconducting) have triggered the tide of the development of "plastic electronics", especially in transistors, an indispensable logic device in these logic-control based devices (i.e., intelligent electronics).

The applications of organic materials in flexible electronics have been widely witnessed. For example, in organic liquid crystal display (OLCD) devices, flexible transistors can be integrated on a flexible substrate to control the color distribution in every pixel via regulating the crystal liquid layer. Comparing with the traditional silicon-based LCD devices, the OLCD devices exhibit much lighter weight, thinner thickness and smaller bend radius. Another example is the flexible display device based on organic light-emitting diode (OLED), where flexible organic transistors directly control the light-emitting of diodes array with RGB colors. More recently, a two-inch wearable full-color active-matrix OLED display based on MoS_2 backplane TFTs was reported to display high mobility ($>18\ cm^2\cdot V^{-1}\cdot s^{-1}$) and on/off ratio ($> 10^7$) [7]. Although the device can display both tension and compression status of the human skin, the efficiency decreasing at high current densities is a long-standing issue in OLED devices. To address this issue, organic light-emitting transistors (OLETs) might be solution. OLET is a novel organic device with an ambipolar regime, which can transport both holes and electrons and offer a recombination zone [8]. Recently, a flexible OLET with a record external quantum efficiency (EQE) of about 9.0% has been demonstrated in inert atmosphere, paving the way to the application of OLET in flexible display devices [9].

The challenging research in flexible electronics is the circuit integration to perform multiple functions, especially the integration between bionic and intelligent electronics. E-skin is such a typical flexible device, which has great potential applications in future medical devices, intelligent robot, and virtual reality fields [10]. In e-skin, there are two critical functions: tactile and temperature sensing, which now can be realized through organic transistors [11, 12]. Generally, there are three typical types of organic transistor-based tactile sensors (capacitive type, piezoelectric type, and resistive type) and two classes of organic transistor-based temperature sensors (integrated and intrinsic temperature sensor) [13, 14]. Recently, Borchert *et al*. reported a flexible high-frequency (21 MHz) organic transistor that can operate at battery voltage (~3 V), ensuring the portability of the organic transistor-based devices [15]. These advances in sensing and transistor characteristics have speeded up their further industrialization and commercialization.

Besides the tactile and temperature sensors, chemical sensors and photodetectors can also be realized through flexible organic transistors. The interaction between the carriers in the channel and the analytes can affect the transistor characteristics to reach the chemical sensing. According to the recently-reported researches [14, 16], organic transistor-based chemical sensors can sensitively response to a wide range of species, including organic vapor, inorganic gases, organic solvent, inorganic salt solutions, biomolecules, and so on. An important advantage of using organic transistors as chemical sensors is that the active organics can be easily functionalized to sense special analytes. For example, Lee *et al*. found that the introduction of a thin layer of calix[n]arene on the top of the P3HT-azide copolymer semiconductor-based flexible organic transistor can enhance the selectivity to analytes [17]. These transistor-type

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photodetectors are usually called as phototransistors. Comparing with photodiodes, phototransistors possess series of advantages including higher efficiency (benefit from the higher current gain), faster response, low noise and so on. Organic phototransistor has been developed as an important part of phototransistors, particularly in flexible phototransistors. According to the published literatures [18, 19], a lot of organic semiconductors can be used as the active layers of organic phototransistors. Among these materials, except for the commonly used small molecule organic semiconductors (such as pentacene and copper phthalocyanine), polymers are also excellent materials for the fabrication of flexible organic phototransistors due to their good compatibility to polymer flexible substrates. Wang *et al*. showed that the flexible organic phototransistor based on an active layer prepared by a copolymer (PBTIDBIBDFs) blended with poly(1,4-butylene adipate) (PBA) exhibited high on/off ratio (3.45×10^4) and responsivity ($128\ \mathrm{A\cdot W^{-1}}$) [20]. Polymers can work as both the active layer and other parts of phototransistor to realize the photosensitivity of the transistors. Han *et al*. reported a flexible near-infrared (NIR) photo-transistor, in which a conjugated polymer, poly[{2,5-bis-(2-ethylhexyl)-3,6-bis-(thien-2-yl)-pyrrolo[3,4-c]pyrrole-1,4-diyl}-co-{2,2′-(2,1,3-benzothiadiazole)-5,5′-diyl}] (PEHTPPD-BT), worked as a gate-sensing layer [21]. The device can response to the NIR light up to 1000 nm with the responsivity of $0.25\ \mathrm{A\cdot W^{-1}}$ (with shadow mask) at the best PEHTPPD-BT thickness of 80 nm. Moreover, scientists found that the usage of single crystal semiconductors or light-trapping effects can further improve the performance of organic phototransistors [14].

In addition to the display devices and sensors illustrated above, more and more new types of organic transistor-based flexible devices have been developed in recent years, making organic transistor permeate to more and more parts of flexible electronics. The Sekitani group reported a flexible magnetic sensor matrix system based on the integrated organic transistor switches, bootstrap shift registers and other functional modules [22]. The system was fabricated on a super thin polymer substrate to prove its high flexibility and wearability. Such sensors greatly enriched the interaction media between the machine and environment or human. Pak and co-workers proposed a low-power flexible organic transistor-based memory composed of an ultrathin polymer electret layer and blocking dielectric layer [23]. The programming voltage of the as-fabricated device was below 15 V and the retention time was extrapolated up to 10^8 s. Furthermore, the device can maintain its memory performance under a tensile strain of 1.6%. Kim *et al*. developed a flexible organic artificial afferent nerve biomimetic touch sensing system which can collect pressure information so as to realize the detection of object movement and distinguish braille characters [24]. The synaptic transistors in this system were all realized by flexible organic transistors. The success in the artificial afferent nerve marks a big step toward the neurorobotics.

Nowadays, organic transistors have demonstrated to play a critical role in a variety of flexible electronic products. By constantly developing new active semiconductors, designing new device structures, optimizing the surface and interface between different parts of transistors, and integrating the multifunctional devices together, the performance of organic transistor-based flexible electronic devices will be much close to the requirement of the industrialization and the commercialization. On the other hand, organic transistor is competitive in low-cost, massive and large area production. Large-area inkjet printing [25] and three-dimensional monolithic integration technologies [26] for organic transistor fabrication have been demonstrated to further show their significant potential in flexible electronic devices. Although there still exist many challenging issues in flexible electronics, as indicated in Meng's recent review [13], the persistent efforts in development of organic materials-based devices would lead to their wide applications in near future.

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