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Review

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Progress in flexible organic thin-film transistors and integrated circuits

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Abstract Organic thin-film transistor constructs the headstone of flexible electronic world such as conformable sensor arrays and flexible active-matrix displays. With solution-processed methods, it forges ahead toward large-area, low-cost manufacturing goals. As an indispensable complement to traditional silicon-based transistors, organic thin-film field-effect transistors have made great progress in materials, performance, bending capacity, and integrated circuits in recent few years. Flexible transistors and circuitry have extremely promising application prospects and possess irreplaceable status in foldable displays, artificial skins and bendable smart cards. In this review, we will discuss the evolution of flexible organic transistors and integrated circuits in terms of material, fabrication as well as application.

Keywords OTFT · Flexibility · Integrated circuits

1 Introduction

As conducting polymers came to our sights in the 1970s [1], organic electronics has obtained rapid development in the past two decades. Compared with inorganic materials, organic electronics have many advantages such as low cost, low temperature, light weight, flexibility, and large-area fabrication. The first organic thin-film field-effect transistor (OTFT) was reported using polythiophene as semiconductor in 1986 [2], and subsequently, great progress has been achieved over the last two decades. p-Type OTFTs have already caught up with amorphous silicon in mobility and is replacing the position of amorphous silicon in display. More and more new n-channel materials with better air stability and high mobility have emerged. As a result, organic complementary circuits operated under low voltages came into our vision although further improvements are still needed for large-scale, practically applicable circuitry. Fabrication technology based on solution-processed method, such as spin-coating, dipping, inkjet printing, has overcome the shortcomings for OTFTs brought by traditional photolithography process, such as high-temperature, expensive, toxic, time-consuming procedure. Compared with traditional vacuum evaporation craft, these fabrication methods provide an effective approach to inexpensive organic electronics. What's more, they are compatible with flexible devices and roll-to-roll processing [3]. In the meantime, flexible devices have made great progress, stepping toward bending scales of submillimeter [4]. In this review, we review the development in flexible organic transistors and talk about prerequisites for a good rollable and foldable device. Then, flexible organic circuitry and application are discussed briefly. In the end, challenges that researchers face in this field are presented.

2 Outline for OTFT

Organic thin-film transistors are mainly consisted of four parts: gate electrode, gate dielectric, semiconductor layer,

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and source/drain electrode. Surely, they should be supported by a substrate. According to gate electrode and the relative position of semiconductor and S/D electrode, OTFTs are usually divided into four types (illustrated in Fig. 1): top-gate bottom-contact (TC-BG) geometry, top-gate top-contact (TG-TC) geometry, bottom-gate bottom-contact (BG-BC) geometry, and bottom-gate top-contact (BG-TC) geometry. There are also dual-gate and side-gate geometry in some special cases. In bottom-gate structure, semiconductor layer is exposed to ambient air, inducing performance degradation of devices for a period of time. This can be avoided using top-gate configuration. Unfortunately, there are difficulties in fabrication procedures in this geometry. Dielectrics prepared by traditional methods such as sputtering, e-beam evaporation may lead to doping of previous deposited semiconductor layers. Other methods such as printing should be employed to realize this structure. Bottom-contact is mostly utilized in early time for it is compatible with traditional photolithography way. However, in BG-BC geometry, it universally involves inferior performance as a fact that morphology of semiconductor shows a distinct difference at the surface of electrodes and dielectrics due to their remarkably dissimilar surface energies. Although TC-BG OTFTs exhibit better properties, it is difficult to obtain fine channel lengths because electrodes are usually patterned by shadow masks or printing techniques. OTFTs with bottom-contact have been preferred rather than TC geometry, especially for large-area integration taking into consideration that semiconductors will be damaged when making vias in organic circuit.

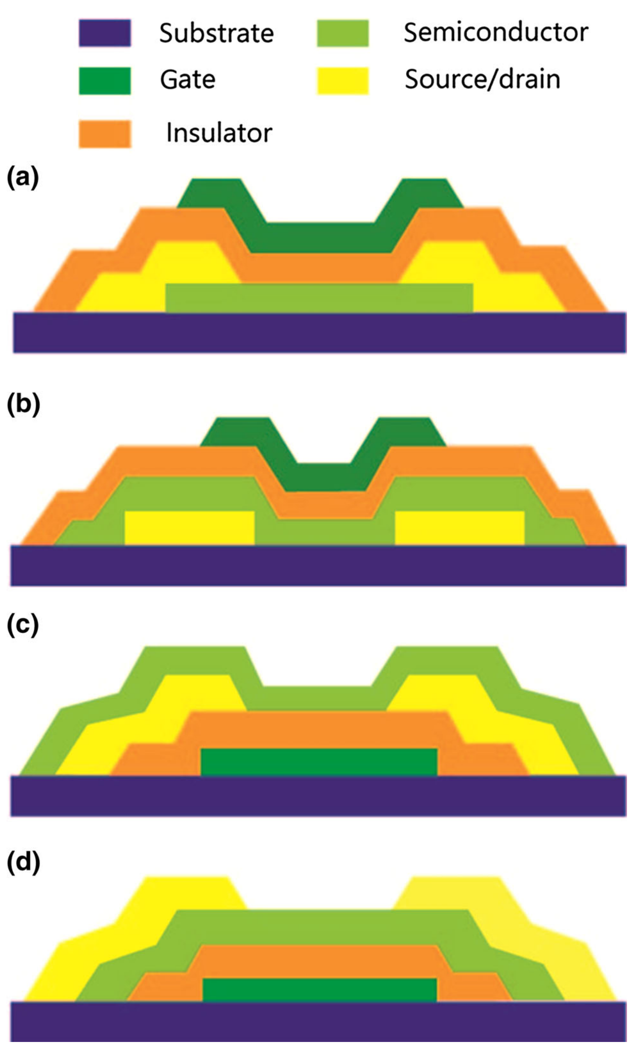

Fig. 1 Schematic structure of OTFT. **a** TG-TC; **b** TG-BC; **c** BG-BC; **d** BG-TC geometry

Commonly used parameters to characterize OTFT are carrier mobility (μ), threshold voltage (V_T), ratio of on/off current (I_{on}/I_{off}), and subthreshold slope (SS), which can be concluded from transfer characteristic curve I_{DS}–V_{GS} and output characteristic curve I_{DS}–V_{DS}. Switching speed of transistor depends on carrier mobility, which is usually much lower than its intrinsic nature as a reason of defects existed in thin films. V_T lies on charge trap density at the dielectric interface, contact quality of electrodes, and built-in conducting channel. On/off ratio is restricted to off-state current, namely leakage current, which is determined by device itself. Different from Si-based metal-oxide-semiconductor field-effect transistor (MOSFET), SS is not only affected by the quality of channel interface, but also influenced by the quality of electrode interface. It is advised that an applicable organic transistor device should exhibit a mobility up to 1 $cm^2/(V\ s)$, I_{on}/I_{off} close to 10^6, low operating voltages <10 V, and SS as low as possible. It also requires air stability and longtime operating in practical application.

In rollable OTFTs, it is crucial to use flexible materials for all parts. Although ultrathin silicon has flexibility to a certain extent, it is not as good as organic materials with the same thickness. Polymer plays a nonsubstitutable role in fabricating flexional transistors, which is usually employed to replace rigid materials, such as inorganic dielectrics and glass substrates. There are reports on all-polymer transistors with high mechanically flexibility as well [5]. Thin oxides and metals also can be used to construct bendable transistors. The flexibility may be restrained by the critical strain of metal electrodes [6], while this situation can upturn for the better with extra improvements. Thickness is especially sensitive in making flexible devices. With thinner thickness of each layer, the whole device goes further on suppleness.

3 Flexible substrate

In flexible OTFTs, flexibility depends on the thickness of substrate to a great extent. There are mainly three kinds of