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A Review on Organic Field-Effect Transistors

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***Abstract*—In recent decades, electronic waste has been increasing drastically. In the process of reducing the impact of electronic waste on the environment, several flexible electronic devices on biodegradable substrates have been studied. Because of its innate abilities, organic electronics have drawn its attention. One among them in organic electronics is the OFET (organic field-effect transistor). This review outlines the short overview of various types of OFETs and the development of OFETs on novel substrates, various materials used, several deposition techniques, and some high-performance devices.**

***Index Terms*— Organic semiconductors, flexible electronics, organic field-effect transistors.**

I. INTRODUCTION

Organic electronics became popular and gained a lot of attention in the field of electronics, since the discovery of the first organic semiconductor polyacetylene in 1977 [22]. Electronics, it started with the invention of the diode and later on, the miniaturization started. Initially, the inorganic semiconductors like Silicon or Germanium were used to model these devices. Later on, these devices are modeled using organic semiconductors to overcome the limitations of the inorganic semiconductors. Limitations like integrated circuits can only be made on a single crystal of semiconductor by using relatively high-temperature processing steps. Integration of components on other substrates such as glass, plastic is not possible.

The properties of organic semiconductors can easily be altered by doing a little modification in molecular structure. The organic semiconductors are molecular in nature and can be vaporized very easily at very low temperatures [20] to form thin films because the molecules in these semiconductors are held by weak van der Waal forces [15]. Because of these innate abilities, organic FETs are employed in various applications like ring oscillators, shift registers, and flexible displays, smart cards, low-cost RFID tags [14].

II. TYPES OF OFET'S

An OFET is of three-terminal device. Those are Gate, Drain, and Source [17]. In OFET the organic semiconductor is separated by a gate electrode and dielectric layer. This dielectric layer is made up of inorganic materials or organic material or the combination of both organic and inorganic material depending upon the need of the device. Depending upon the position of the source, drain, and gate terminals this OFET'S can be configured in four different ways.Fig.1(a) shows top-contact, bottom-gate configuration (TCBG), Fig.1(b) [top contact, top-gate (TCTG)], Fig.1(c) [bottom-contact, bottom-gate (BCBG)] and Fig.1(d) [bottom-contact, top contact (BCTC)] respectively. BCBG, BCTG configurations have the coplanar structure which means that the conducting channel, drain, and source are in the same plane. TCBG, TCTG configurations both have a staggered structure. In these structures, the source and the drain plane are offset

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with the conducting channel [9,16].

Depending upon the need of the device and the ease of fabrication, one can adopt any one of the four structures, because each structure has its pros and cons. Example: In BCBG structure all three terminals were fabricated initially and the layer of organic semiconductor is deposited in the final step. This provides the ease of examining the new semiconductor compounds. However, it has the drawback that, when the semiconductor is exposed to the external environment, it results in the deterioration of the device due to humidity, temperature, and oxygen in the atmosphere [9]. The drawback of bottom-gate configuration can be overcome by top gate electrode configuration which reduces the degradation of an organic semiconductor due to ambient conditions, as in this configuration the O. S. C is encapsulated with the gate dielectric.

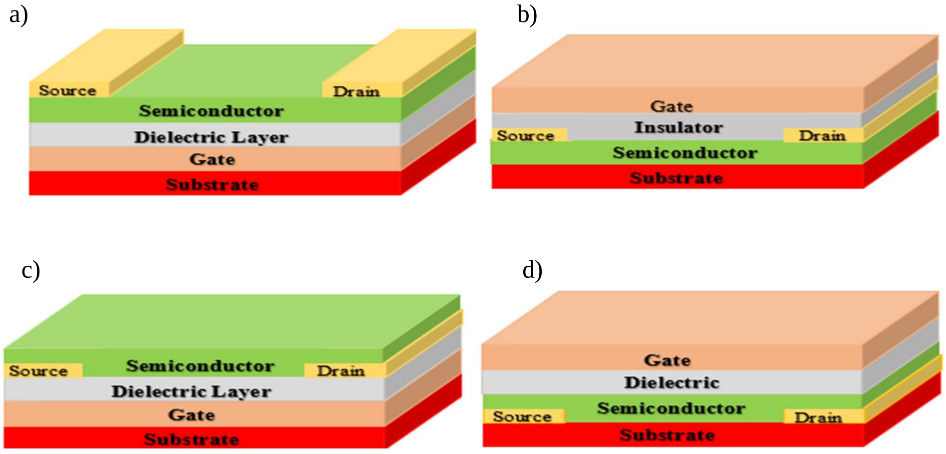


Fig.1."Basic OFET structures: (a) top contact, bottom gate, (b) top contact, top gate, (c) bottom contact, bottom gate, (d) bottom contact, top gate." Source: Adapted from [21]

III. OPERATION

"When a voltage (V_{GS}) is applied to the gate terminal, charges of the opposite polarities are accumulated at the semiconductor and dielectric interface, and the channel is formed between source and drain terminals" [21]. When V_{GS} is not applied, there won't be any accumulation of charge at dielectric and at the interface of the semiconductor and the device is in OFF state.

After applying a voltage at drain terminal (V_{DS}) along with V_{GS}, the charge carriers which are accumulated starts moving from source to drain end and this is how the drain current (I_D) is measured [16].

IV. MATERIALS REQUIRED

Different layers of the device (OFET) sample requires different materials for fabrication.

A. Substrate

OFETs can be fabricated on a rigid substrate as well as on a flexible substrate. Silicon which is oxidized thermally is the most familiar and traditional substrate used for OFETs, where the substrate itself acts as the gate insulator. But it becomes rigid and cannot be used for foldable applications.

Organic FETs can be even fabricated on the glass. Fluorine doped Tin Oxide (FTO) [27] glass is a promising material for substrate because it is relatively stable under external environment conditions, chemically inert, and resistant to high temperatures. "It is electrically conductive and can be easily fabricated. Indium Tin Oxide (ITO)" [27][6] coated glass can also be used as a substrate which has good electrical properties. OFET'S can also be fabricated on paper, silk fiber, and also on a plastic.

B. Dielectric

The most familiar and the oldest dielectric that is being used is Silicon dioxide (SiO_2). Depending upon the type of application that the device is used for, the dielectric material is decided. If flexibility is not the criteria, SiO_2 is the best choice. Due to its ease of processing, it has been used for decades in MOSFETs and has been used in organic electronics as well. The drawback of using SiO_2 as a dielectric is that it has more

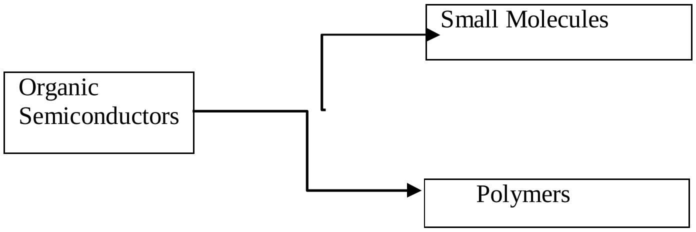
number of surface states and these states result in the formation of charge traps. “Charge traps can be overcome if passivation is done to SiO_2 surface” [9].
The flexible substrate requires a flexible dielectric as well. Flexible dielectrics like polymethyl methacrylate (PMMA), cytop [13]. Polyimide is the first dielectric that was used in organic transistors [23]. After polyimide, many dielectrics like PVP (poly (vinyl pyrrolidine)), PVA (poly (vinyl acetate)) showed good dielectric properties and the mobility of the device has been increased when used these materials as dielectrics. As it is clear that the capacitance (C) of the device is governed by the dielectric constant (k), and thickness (d) of the material which is given by the equation-1 [7].

$$C = (\varepsilon * k) / d. \qquad (1)$$

So, selecting a material with proper ‘k’ value matters. “A high k-material is a good choice for dielectrics because of its insulating properties, but high k-materials have surface polarization higher than that of low k-materials which hinders the performance of the device” [7]. Hence the usage of multilayer or bi-dielectric layer (a high k-material placed upon a low k-material) materials came into existence. Ex: PMMA, a high k-dielectric along with PVA [2], a low k-dielectric started showing good mobilities with good operating voltages. PVA which induces good carrier transport along with PVA as double dielectric showed a significant increase in mobility of the device. In recent decades the dielectrics like Gelatin [8], Silk Fibroin [3], Al_2O_3-Nylon11 [5], which significantly increased the device performance.

C. Semiconductor Materials

Nature is well supplied with π-conjugated molecules that can be used as semiconductors. Based on the number of monomer units, organic semiconductors are broadly categorized into two types [20].



In small molecules, they contain a limited number of conjugated monomers. As the name polymer says that it contains several numbers of conjugated monomers sometimes forming complicated structures. In general, organic semiconductors are pure semiconductors (intrinsic).

Small molecules
Mostly small molecules organic semiconductors which were based on polyacenes and heteroacenes will act as p-type channels in OFET’S. In recent times Rubrene and Pentacene [26][21] have gained a lot of attention due to their simple structure which consists of only carbon (C) and hydrogen (H) groups. TIPS-Pentacene, one of the derivatives of the Pentacene [11][12] group is a widely used small molecule in OFET application for high performance. Besides Pentacene, Rubrene [21] is also widely used small molecule with the highest carrier mobility and high photoconductivity, but Rubrene cannot form thin films, despite it can form small crystals and it can easily oxidize under light, which is the major drawback.
Heteroacene derivatives like di-fluorinated triethyl- silylethynyl anthradithiophene (diF-TES ADT) and triethyl- silylethynyl anthradithiophene (TES ADT) [10] are several other small molecule organic semiconductors. C8-BTBT (2,7 dioctyl(1) benzothieno[3,2b](1) benzothiophene) [4] which is a small molecule, along with polystyrene blend reported highest mobility of 43 cm^2/Vs .

Polymers
Compared to small molecules, polymers show inferior performance and low crystallinity because of their long repeated conjugated monomer units. Several polymers that are incorporated as channels (n-type & p-type) in OFET's are P_3HT (poly (3-hexyl thiophene)), a p-type polymer organic semiconductor which exhibited hole mobilities higher than $0.1 cm^2/Vs$. N-type polymers are very few in number, that showed good mobilities. Polymers like poly (benzimidazo benzophenanthroline) (BBL) which is of n-type O.S.C, reported mobility of $0.1 cm^2/Vs$ initially [24]. Later on, polymers like C_{60} [2] and halogenated Tetraazapentacene (TIPS-TAP) reported mobility greater than 13 cm^2/Vs [1].

V. DEPOSITION METHODS

The deposition of organic semiconductors (O.S.C) can be done in two ways either from the solution phase or vapor phase. Various methods of deposition lead to different crystal formation and molecular structure by the device performance is governed.

A. Solution Deposition

It can be done in many ways. Spin coating, drop-casting, spray coating, and inkjet printing are the various methods available.

Drop casting: In this solution-based deposition technique, the semiconductor solution is placed onto the whole substrate drop by drop, which eventually after some time the solvent on the substrate gets evaporated on its own leaving thin film or individual crystal. This method is the simplest technique but, in this technique, the film thickness is hard to control and sometimes the non-uniform films are formed. To overcome this, several modified methods like Vibration assisted crystallization (VAC) [25], in which the substrate is vibrated at a certain frequency during drop-casting.

Spin coating: This method is the most commonly used technique in recent times. In this technique, onto the center of the substrate, some small amount of semiconductor solution is placed and allows the substrate to run at very high speed (~1000-1500 rpm). The solution on the substrate spreads all over the substrate due to centripetal acceleration and a thin film is formed after solvent evaporation. Various factors like the type of solvent, viscosity, and spin speed, decide the quality and thickness of the film [8].

Spray coating: Spray coating technique is an industrially employed technique where large-sized substrates are used. In this method, an inert gas is used to convert the small liquid droplets to aerosols (suspension of liquid or solid particles in the air) which is sprayed onto the substrate. This technique provides high throughput and helps to obtain good quality films [19].

TABLE I. VARIOUS OFETS AND THEIR RECORDED ELECTRICAL PARAMETERS

S.NO	Organic semiconductor	Type	Dielectric material	Mobility of the device (μ)	Threshold voltage (V_{TH})	Reference
1.	C8-BTBT and polystyrene blend	p-type	PVP	43 cm^2/Vs	~10V	[4]
2.	Pentacene	p-type	Gelatin	~16 cm^2/Vs	-1V	[8]
3.	Halogenated TIPS-TAP	n-type	CDPA-AlO_x / SiO_2	27.8 cm^2/Vs	~14-15 V	[1]
4.	C_{60}	n-type	PMMA/PVA	13.6 cm^2/Vs	7.9V	[2]
5.	Pentacene	p-type	Silk Fibroin	23.2 cm^2/Vs	-3V	[3]
6.	Indium(III) phthalocyanine chloride (InClPc)	p-type	Al_2O_3- Nylon 11	36.2 cm^2/Vs	-0.59 V	[5]

B. Vapour Deposition

Vapor deposition methods provide high purity and quality films because there is no interaction of solvent in the crystal growth process. Vapor deposition methods like physical vapor deposition (PVD) [17] and vacuum sublimation are employed. In vacuum sublimation, the semiconductor is sublimed in a clean quartz tube. To one side of the quartz tube, a vacuum pump is connected in the presence of a temperature gradient [9], and the other end is sealed. In the cooler region, the semiconductor which is sublimed will be recrystallized due to convection current. In PVD, at ambient pressure, the sublimed semiconductor is carried to a cooler region by an inert gas. The temperature gradient and the tube shape decide the crystal morphology.

Various OFETs that recorded the highest mobility and their threshold voltages in recent decades have been mentioned in Table-I.

VI. CONCLUSION

The organic semiconductor driven field-effect transistors are the basic blocks in many applications and it became a good platform for explicating the fundamental properties of various O.S.C. In recent decades, new semiconductor materials were developed and magnificent progress has been seen in the synthesis, processing, and design of OFETs, thereby the performance of OFETs has increased steadily. To accomplish high charge carrier mobility and low operating voltage, good air stability especially in n-channel type OFETs, several efforts have been taken. However, it is inconceivable to replace organic transistors with silicon-based transistors in applications like high-frequency operation, large integration density, and small chip size, as in these types of applications the use of silicon-based transistors are more economical.

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