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Organic Thin-Film Transistor: A Review of the Transport Model, Operating Principle, and Different Structures

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Abstract: ***Organic Thin-Film Transistors (OTFTs) offer significant potential for further developing flexible electronics owing to their unique features and numerous benefits. These benefits include low-cost manufacturing, mechanical flexibility, and integration with various substrates such as plastic or paper. OTFTs' characteristics make them ideal for the evolution of flexible displays, wearable electronics, and electronic textiles. The paper presents a comprehensive overview of OTFT technology, focusing on its fundamental properties of organic materials. Furthermore, this article discusses the various charge transfer models such as the Polaron model, Multiple traps and release model (MTR), and Variable range hopping (VRH).Also highlights the operating principle along with the different structures of OTFT.***

Keywords: Organic Thin-Film Transistors, Variable range hopping, Organic semiconductor, Dual gate, low-cost manufacturing, flexible displays

1. Introduction

Silicon has been the prevalent material in electronics for a long time due to its semiconducting properties and low cost. However, a lot of research has been done on alternative materials in recent years. Heeger*et.al* found a novel carbon-based highly conductive polymer in 1977, making a key breakthrough in the area of organic electronics. Carbon-based semiconductors generated from organic materials have unique characteristics and low costs, making them possible to use in various electronic applications. OTFTs have been identified as a promising technique for the development of flexible electronics and displays. In contrast to typical transistors, which are constructed of inorganic materials such as silicon, OTFTs are built of organic materials, which have various benefits. One of the primary benefits of OTFTs is their flexibility. Organic materials enable the manufacturing of transistors on flexible substrates such as plastic or paper, allowing for the creation of bendable and rollable electrical devices. This adaptability offers a world of possibilities for wearable devices, flexible displays, and even smart packaging. Another benefit of OTFTs is their cost-effective fabrication process. Organic compounds may be solution-processed, which means they can be deposited onto surfaces using methods like inkjet printing or spin coating. Because costly and sophisticated manufacturing methods are no longer required, OTFTs are a more cost-effective alternative to conventional transistors.

The remainder of the article is arranged as follows: Organic semiconductors (OSC)are explained in Section 2. Section 3 describes Different charge transport models. Furthermore, the Operating principle of OTFT are presented in Section 4. After that different structures are summarized in section 5. Finally, the conclusion is highlighted.

1.1 Organic semiconductors (OSC)

Organic materials consist of carbon-based small molecules or polymers. Due to their characteristic energy gap being within the range of 1.5 to 3.5 eV, these materials exhibit a limited number of charge carriers at standard room temperature. As a result, these material at room temperature behave as insulators. The sp^2-hybridized orbitals form strong planer σ-bonds with large binding energy. The unhybridized p-orbitals are for π-bonds with inferior binding energy as shown in fig. 1. In the present scenario, the phenomenon of conduction is attributed to electrons that are characterized by weak binding forces.

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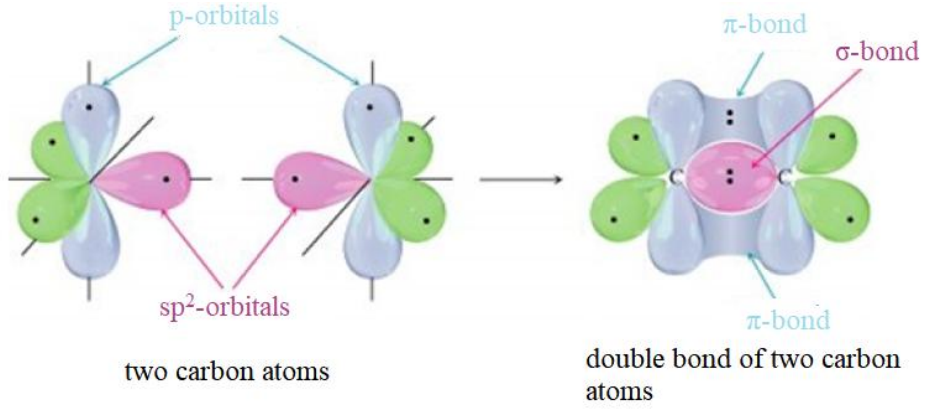

Figure 1: sp^2-hybridization and double bond formation of carbon atoms

The л-orbitals can be considered similar to the valence band and conduction band in inorganic semiconductors. The highest occupied molecular orbital (HOMO) refers to the highest bonding orbital occupied by electrons, while the lowest unoccupied molecular orbital (LUMO) refers to the lowest antibonding orbital that remains unoccupied.

The σ-bonds and л-bonds are intramolecular bonds that connect atoms to create a single organic molecule. In contrast, intermolecular interactions, such as van der Waals forces, are characterized by their weak nature and the limited overlap of wave functions between adjacent molecules [1]. Consequently, the solid exhibits a disordered structure.

As a result, the transport of electrons and holes in disordered solids is not fully understood. Some models are discussed in the next section to understand the conduction of carriers.

1.2 Different charge transport models

The charge transport phenomena in organic materials are often described using three models: VRH, MTR, and polaron models. These models will be further examined in the subsequent sections.

A. Variable range hopping (VRH)

Localized states in organic polymers arise from defects and the non-crystalline nature of their structure. Charge carriers in these materials undergo hopping between localized states, requiring them to overcome the energy difference between these states. This process involves the emission or absorption of phonons during the transitions. Motte and Conwell were among the first to propose models for hopping in inorganic semiconductors. They were then succeeded by Miller and Abrahams, who defined the rate at which single phonon jumps occur [2].

A theory proposed by Vissenberg and Matters (1998) to calculate carrier mobility in transistors utilizing amorphous organic semiconductors [3]. The researchers noted that the transportation of carriers is influenced by the inter-hop distances and the energy distribution of the states. Under conditions of low bias, there is a limited number of charge carriers that transition to a free state, while the majority of carriers stay confined within localized states.

As a result, the system may be represented mathematically as a configuration of resistors and a conductance (G_{ij}) between hopping site i and site j is given by equation1,

$$G_{ij} = G_0 exp(-P_{ij}) \quad (1)$$

Where G_0 represents the prefactor for conductivity.

$$P_{ij} = 2\alpha D_{ij} + \frac{|E_i - E_F| + |E_j - E_F| + |E_i - E_j|}{2kT} \quad (2)$$

The first term of the equation represents the phenomenon of tunneling, which relies on the extent of overlap between the electronic wave functions of sites i and j. The symbol E_F denotes the Fermi energy, whereas E_i and E_j represent the energies associated with sites i and j, respectively. In the context of the simplest approximation, the tunnelling process can be distinguished by the distance Dij separating the sites and an effective overlap parameter α.

B. Multiple traps and release model(MTR)

The MTR model, initially suggests by Shur and Hack in 1984, is used to describe the mobility of the a-Si:H semiconductor [4]. Horowitz developed this idea to gain a deeper understanding of the mechanisms involved in the trapping and releasing of charge carriers in organic semiconductors [5]. The primary factor influencing charge transport in OSCs is the presence of numerous structural and chemical defects. Traps can be classified as deep or shallow depending on their alignment with the energy levels near the center of Eg. If the traps are located near to the HOMO or LUMO levels, they are considered shallow. This is illustrated in Figure 2 [4].

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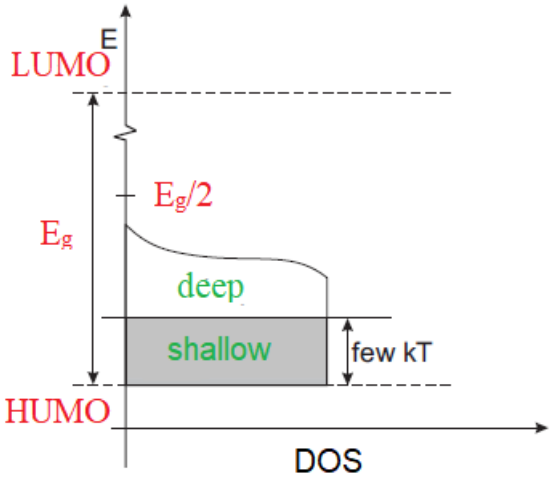

Figure 2: Distribution of trap states

The underlying assumption of the model is that the transportation of charge is mostly facilitated by extended states. Nevertheless, a significant proportion of injected carriers become confined to localized states situated within the forbidden energy range. Moreover, the thermal release of carriers through these states results in drift mobility, denoted as μ_D [5],

$$\mu_D = \mu_0 a exp\left(-\frac{E_{tr}}{k_B T}\right) \quad (3)$$

The energy level of a single trap is denoted as Etr. The parameter 'a' represents the relation of the effective density of states (DOS) to the trap concentration. The Fermi function is affected by temperature, leading to variations in the quantity of charge carriers. As a result, reducing the temperature diminishes drift mobility while increasing intrinsic mobility.

C. The Polaron model

Yamashita et al. (1958) initially proposed the idea of polarons in the context of inorganic semiconductors [6]. The model proposed by Holstein and Fesser et al. was expanded upon to provide a more comprehensive understanding of charge transport in molecular crystals and conjugated polymers [7]. Polarons are used within the domain of organic semiconductors to clarify the underlying process of charge transfer. A polaron is a composite entity consisting of an electron and the associated polarization field that it generates. Within organic polymers, an electric charge prompts a distortion in the conjugated chain, creating polarons.

During the process of condensation, organic molecules engage in interactions with neighboring polarizing molecules, resulting in a decrease in their energy levels. Furthermore, the process of phonon absorption by an organic molecule may lead to the production of an excitation that has the capacity to separate into charge carriers. As a consequence of an attractive force, the electron in an excited state and the hole amalgamate, forming an electron-hole pair instead of their individual existence as charge carriers. The theoretical binding energy of this pair has the capability to surpass the energy found under typical room temperature conditions, perhaps by a magnitude of 10. The binding energy is described by Holstein's model [7] in equation 4.

$$E_b = \frac{A^2}{2Mw_0^2} \quad (4)$$

In this context, ω0 denotes frequency, A represents constant, and M indicates decreased mass of molecular sites. Horowitz found localized states in the energy gap between polythiophene's highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels [5]. Defects and chain deformation generated charge self-trapping and trap states.

1.3 Operating principle of OTFT

Organic transistors (OTFTs) have a similar operating concept to MOSFETs but differ in the method of channel creation. In OTFT, a channel is created through charge accumulation, similar to that in bulk semiconductors, but in MOSFETs, an inversion process occurs to create a layer of charge carriers. OTFTs, similar to MOSFETs, operate as voltage-controlled current sources. The introduction of a gate voltage between the gate and source terminals (Vgs) leads to the formation of a layer of charge carriers in close proximity to the interface of the semiconductor and dielectric materials. This accumulation of charge carriers facilitates the passage of electric current through the channel when a suitable drain-to-source voltage (Vds) is imposed.

Although organic transistors exhibit distinct charge transport mechanics, the current-voltage relationship may be similar to MOSFETs. The current grows linearly when the V_{ds} stays lower than the overdrive voltage ($|V_{ds}| < |V_{gs} - V_t|$) and reaches saturation, when the channel undergoes pinch-off, at $V_{ds} = V_{gs} - V_t$. Further increases in V_{ds} have no effect on the drain current. When a positive or negative gate-source voltage (Vgs) is applied to a p-type or n-type organic semiconductor respectively, an OTFT exhibits capacitive behavior by generating an electric field inside the dielectric material. This field causes holes or electrons to accumulate by aligning the metal's Fermi level (EF) with the HOMO or LUMO levels of p-type or n-type semiconductors, respectively.An energy map depicting the interaction between a source/drain contact composed of gold (Au) and a pentacene semiconductor is shown in Figure 3.

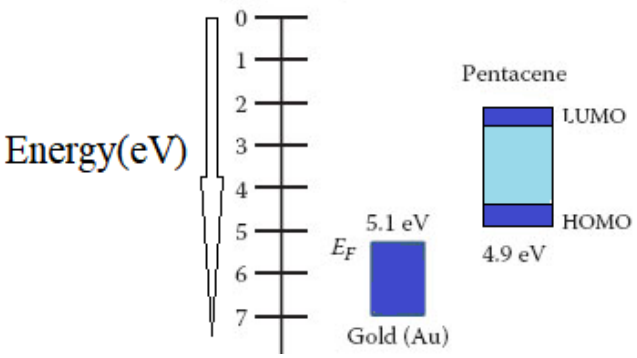

Figure 3: Energy band diagram

In the present arrangement, the Fermi level is considerably far from the edge of the lowest unoccupied molecular orbital (LUMO). Therefore, using a positive gate bias leads to insufficient electron injection. Reversing the gate voltage, however, allows for injecting holes via the source because the highest occupied molecular orbital (HOMO) level is near

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the Fermi level. As a result, a positively charged channel is formed. Pentacene is classified as an organic material with p-type conductivity and exhibits the highest level of charge carrier mobility compared to other small molecules of p-type.

2. Different structures of OTFT

The alignment of the source (S), drain (D), gate (G), and the organic semiconductor layer is the main factor used to categorize OTFT structures. The different structures are presented in sub-sections.

2.1 Top gate structures

As the name suggests the gate is located on top of the structure. This structure is further classified based on the position of the electrode with respect to the OSC layer. The contacts may be placed on top of the OSC layer (through shadow masking)

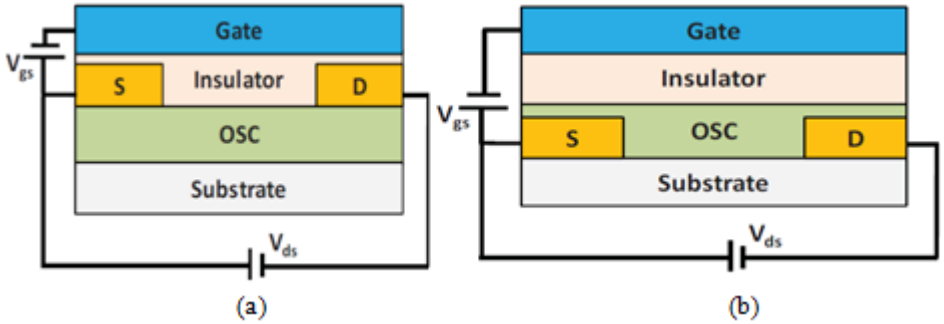

Figure 4: Top gate structures (a) top gate top contact (TGTC) and (b)top gate bottom contact (TGBC) [8]

or at the bottom (by Microlithography), resulting in TGTC and TGBC structures, as illustrated in Figure 4a and b, respectively [9].

2.2 Bottom gate structures

In TG structures the gate is formed with high-temperature process after the OSC layer deposition. Due to this OSC layer gets contaminated and defective in this structure. As a result, BG structure is preferred over TG. Bottom gate (BG) architectures, as seen in Figures5a and b, are therefore favoured over TG structures.

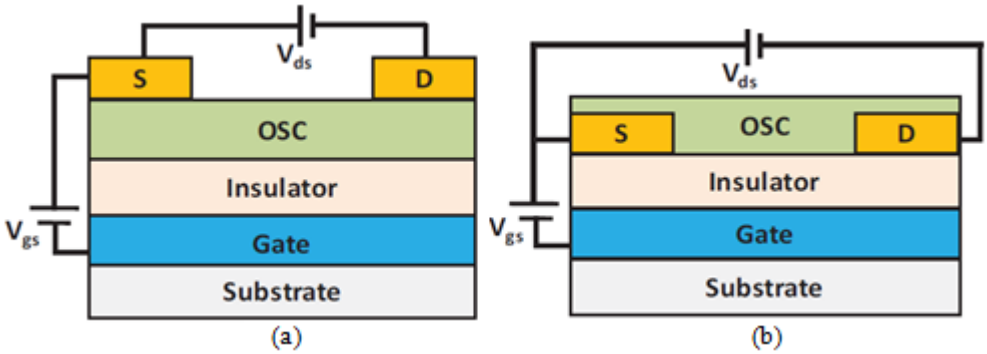

Figure 5: Bottom gatestructures (a) BGTC and (b) BGBC [8]

However, when the injection area is expanded, the resistance of BGTC structures diminishes considerably [10].

2.3 Dual gate structure

Compared to single gate transistors (SG), dual gate (DG)-OTFTs are built of additional dielectric material and gate positioned above, resulting in increased on-current and enhanced threshold voltage control.Figure 6 illustrate the dual gate (DG) transistors, respectively [11].

Table 1: Performance comparison of different OTFT structures

Ref.	Structure	material	Mobility μ (cm^2/Vs)	Threshold voltage (V)	ION/IOFF	Subthreshold slope (mV/dec)
[12]	BGBC	P3HT	0.11	-	1.9×10^6	-
[13]	BGBC TGBC DG	P3HT	0.001 0.00003 0.0041	6.6 8.5 -9.3	1.0×10^5 $5.6x10^4$ $6.0x10^6$	1130 4540 830
[14]	TC	pentacene	0.1	-32	10^5	-

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	BC		0.04	-30	10^5	-
[15]	-	C60	1	1.13	10^5	252
[16]	-	ZnO	10.03	0.6	$2.1x10^4$	170
	-	Pentacene	1.12	-1.05	$1.2x10^4$	110
[17]	BGTC	Pentacene	0.16	-1.4	$3x10^4$	250
	TGTC		0.15	-1.2	$4x10^3$	280
	BGBC		0.11	-1.1	$3x10^3$	300
	TGBC		0.12	-1.0	$2x10^3$	360

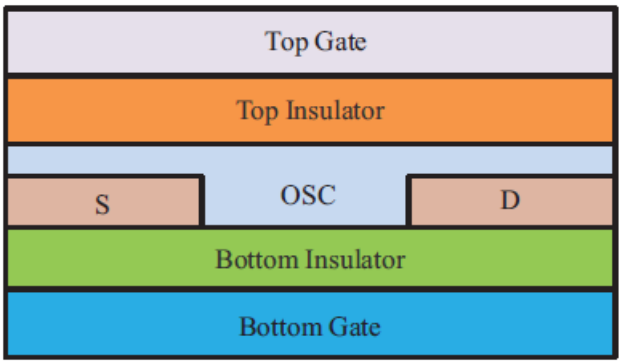

Figure 6: Schematics of dual-gate structures [8]

3 Conclusion

This paper highlighted the basic physics of organic semiconductors and the intermolecular bonds such as σ-bonds and л-bonds that make a single organic molecule. Thereafter, various charge transport models including Variable range hopping (VRH), Multiple traps and release model (MTR), and the Polaron model are presented. Furthermore, the working principle of OTFTs is presented with their energy band diagram. Lastly, Different OTFT structures including TG, BG, and DG are discussed. Some of them are compared based on performance parameters including mobility, current on/off ratio, threshold voltage, and sub-threshold slope.

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Data Availability: The data used and analyzed during the current research are not widely available but it may be accessible from the consistent author at reasonable request.

Ethics Approval: Not applicable

Consent to Participate: All authors are agreed.

Conflict of Interest: The authors declare no conflict of interest concerning the content of this research article.

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