Chapter-2. Organic Thin Film Transistors – an Overview

In the previous chapter, we presented the possibilities of OTFT as an alternative for the existing TFT technologies because of its distinguished features like: low cost and flexibility. With this premise, in this chapter, we present an overview of the OTFT device, which include: operation, device architectures, materials used, carrier transport mechanism and modeling. In each section, we present a brief note on the existing literature, its significance and shortcomings. Thereby, identifying the possible gaps in existing research and scope for improvement.

2.1 OPERATION AND DEVICE ARCHITECTURE

OTFTs are multilayered structures. The flow of charge carriers in the channel layer can be controlled by the external potential applied through its three terminals: *source (S), gate (G)* and *drain (D).* The three terminals are functionally similar to their inorganic counterparts. The major difference between an inorganic TFT and OTFT is the material used for *active layer:* where the channel region is created and conduction of charge carriers occur between the *source* and *drain* electrodes. In an OTFT, the *active layer* is formed using an organic semiconductor (OSC). Whereas, in the inorganic TFTs the semiconductor could be: doped silicon or III-V compound semiconductor. OTFTs are normally OFF devices. Channel region is not present at time of fabrication. When a suitable bias voltage is applied between the *gate* and *source* terminals (V_{GS}), a very thin channel layer is created near the dielectric-semiconductor interface due to charge carrier accumulation. The channel region is a very thin layer, usually not exceeding the thickness of a few monolayers. Therefore, quality of the interface is extremely important for proper operation of the device. OTFTs are essentially unipolar devices. It is possible to realize both n-type as well as p-type OTFTs by properly choosing an OSC material. However, the distinction between an n-type and p-type OTFT is not analogues to the inorganic case where, n/p-type is determined by the nature of the dopants donors/acceptors. Essentially, n/p-type in an organic electronics indicates the intrinsic ability of an OSC to transport electrons/holes. A OTFT is classified as n-type OTFT if it starts conducting when V_{GS} is made positive (V_{GS}>0) and p-type OTFT, if it starts conducting when V_{GS} is made negative (V_{SG}>0).

In chapter-1, we presented one of the most commonly used device architecture of an OTFT: a bottom gate top contact (BGTC). Other possible variations of the OTFT are shown in Fig.2-1. The top-contact(TC) structures are also referred as staggered architectures while the bottom-contact (BC) ones are referred as the co-planar. Each of these structures have their own advantages over the other. These devices are referred as lateral devices. Lateral devices employ either a photolithography or a metal shadow mask step to create the *source/drain* regions in case of TC structures and to create an active layer in case of BC structures. Since photolithography is a costly process (needs sophisticated equipment) it is avoided to retain the low cost advantage. Therefore, a metal shadow mask is routinely used for patterning. This could lead to contamination if proper precautions are not exercised. Moreover, it becomes a challenge to realize OTFTs with short channel lengths. Architecture and process innovations are needed to address this challenge.

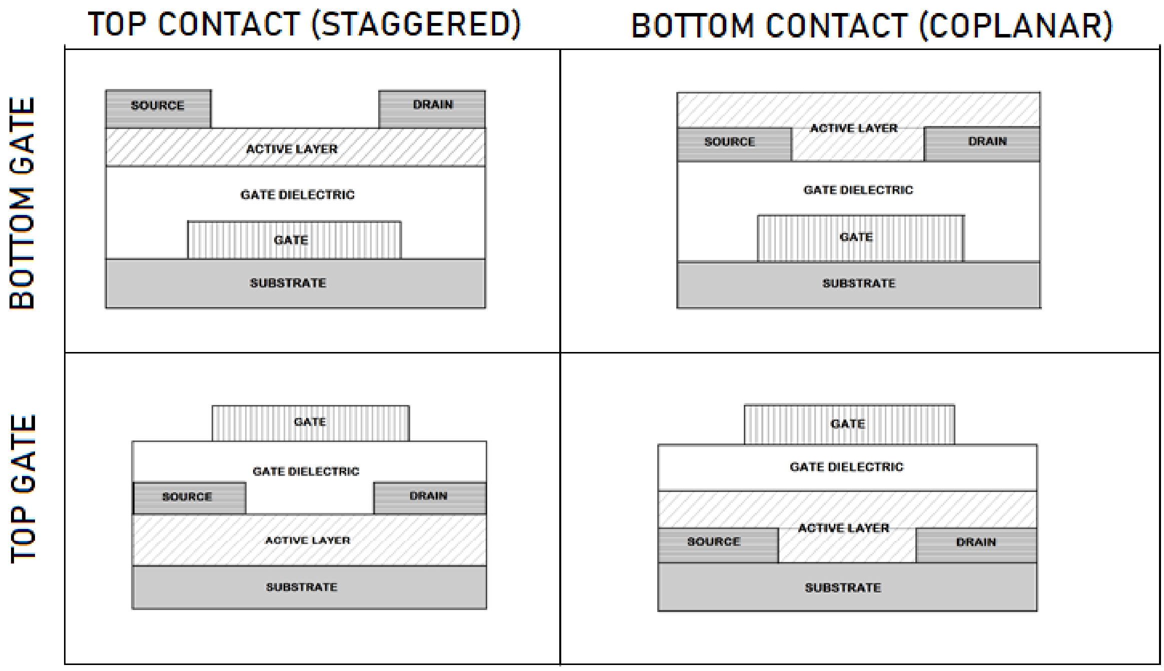

Figure 2-1 Four different reported OTFT structures which vary by the placement of the contacts (source/drain) and gate terminal

The behavioral characteristics of an OTFT depends on the critical geometrical parameters of the device indicated in Fig.2-2 which include: length (*L*) and width (*W*) of the channel, length ($L_{S/D}$) and thickness ($t_{S/D}$) of the source drain electrodes, overlap of the source/drain electrodes with the gate electrode ($L_{S/Dov}$), thickness of the active layer (t_{OSC}) and the thickness of the gate dielectric layer (t_{ins}). These dimensions have a significant impact on the I-V characteristics of the OTFT [16] [19].

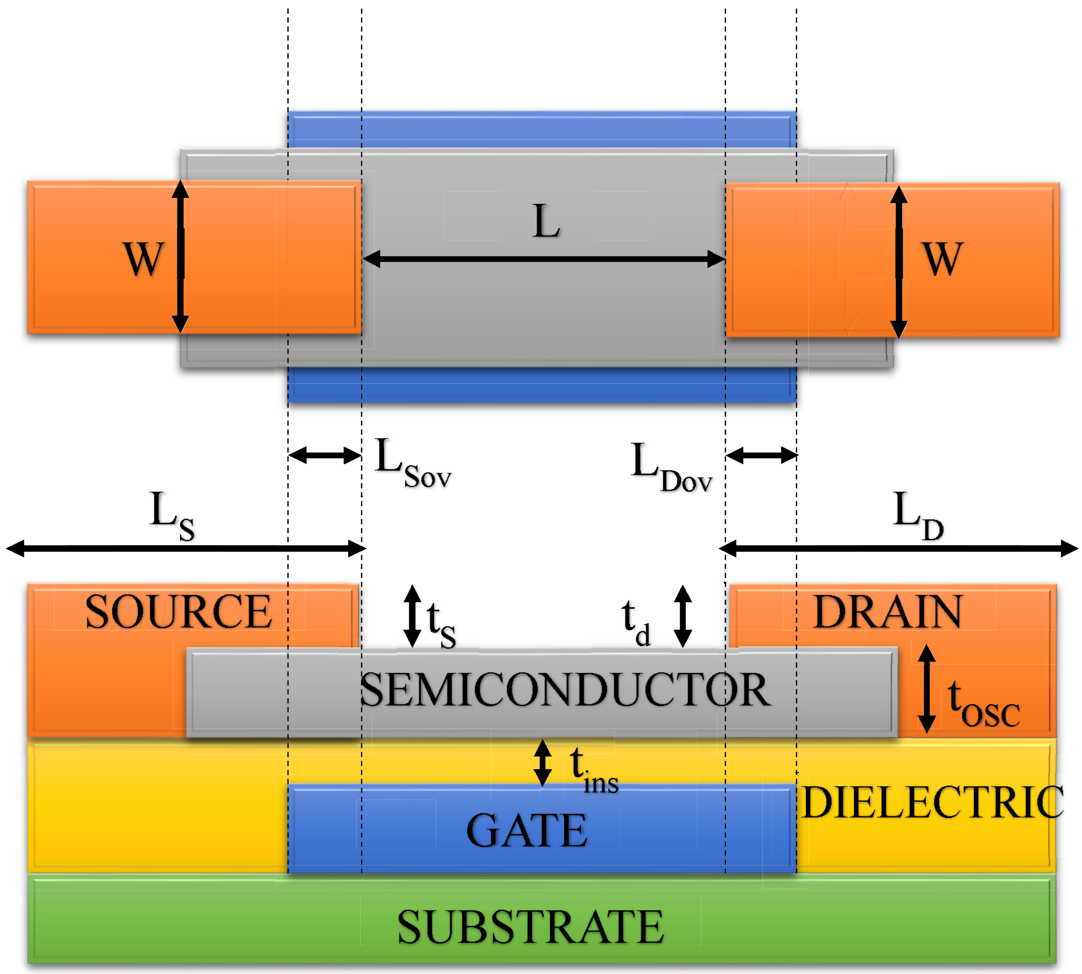

Figure 2-2 Geometrical dimensions of an OTFT which can influence its characteristics

Gundlach D.J. et al. [20] has presented a detailed investigation on the impact of device architecture on an OTFT's performance. It was observed that, the TC structures offer superior performance to the BC structures. The superior performance of the TC structures over the BC structures could be due to the better charge carrier injection in TC structure. In addition to charge injection, another important reason could be the morphology of the OSC film. In TC structures, the active layer is deposited first followed by the contacts. Hence the portion of an active layer where the channel will be created is not affected by the contact deposition process. Whereas, in the BC structure, contacts are deposited first above which the active layer is deposited subsequently. Therefore, near the contact edges, non-homogeneities and structural imperfections can occur, which leads to poor field effect mobility.

In bottom-gate (BG) architectures, the active layer is exposed to the ambient environment which leads to performance degradation. While using top-gate (TG) architecture solve the problem of environmental exposure by covering the active layer from ambience, it is difficult to fabricate such structures given the nature of dielectric deposition processes like: sputtering, thermal evaporation. There is a probability that the pre-deposited OSC gets doped during this process. If a complete solution-processable fabrication flow could be developed for OTFTs, the TG structures might gain prominence. Since, such a process is yet to mature, a majority of the OTFTs reported today are BGTC structures [21].

2.2 CHARGE CARRIER TRANSPORT

Charge transport mechanism in organic materials deviates substantially from the inorganic semiconductors materials. Organic semiconductors are highly disordered (because in most cases amorphous/poly-crystalline organic materials are used), therefore, the conventional band transport doesn't apply to OSC. The molecules in an organic material are held together by weak van der waals forces, consequently the electrons are localized over the molecules and the transport is governed by the individual molecules and not by their interaction with their neighbors. In contrast the electrons in an inorganic material are de-localized and behave as if they are free to move over all through the lattice and do so in the bands. Due to the weak inter-molecular forces and dis-orderedness, the bands formed in OSC are very narrow and are different from the conduction and valence band. The terms **L**owest **U**noccupied **M**olecular **O**rbital (LUMO) and **H**ighest **O**ccupied **M**olecular **O**rbital (HOMO) which are analogous to E_C and E_V are used in the context of organic electronics [22].

Charge transport in disordered systems (polycrystalline and amorphous material) is addressed by several researchers [23]–[25]. The localized electrons in organic materials are referred as sites; each site has energy and position. Electron hops from one such site to another site. This process is thermally activated, hence, the mobility increases with temperature in organic materials [26] unlike inorganic materials. In general, conduction mechanism is modeled as hopping if the room temperature mobility is lower than $1cm^2/Vs$ otherwise band transport model is used.

Various theories were developed to explain the charge transport in organic materials [24], [25], [27]–[30] which include variable range hopping (VRH) theory (often used synonymously with percolation), multiple trapping and release (MTR) model and small polaron model. However, none of them could comprehensively explain the conduction mechanism in OTFT [27]. VRH theory is based on the concept of quantum mechanical tunneling through the energy barriers. The height of the energy barrier is proportional to the distance between the hopping distance and the energy distribution of the localized states [31]. MTR model takes into account the traps that appear in the LUMO-HOMO gap. The charge carriers often get trapped in these energy levels with a probability close to one and are thermally released [32]. The interaction of an electron with lattice vibrations (phonons) is modeled as a quasi-particle called polaron. The polaron based models could successfully explain the large mobility at lower temperatures and also the mobility at room temperatures, hence can model mobility over a wide range of temperatures [33].

2.3 I-V CHARACTERISTICS AND PERFORMANCE PARAMETERS OF AN OTFT

The I-V characteristics of an OTFT are as shown in Fig.2-3. The transfer and output characteristics resemble their inorganic counter parts. However, several non-idealities exist in these curves which we shall present in the subsequent sections. As a first order approximation, the I-V characteristics can still be approximated by the gradual channel approximation (GCA) and the expression for the linear and saturation region are presented in Eq.(2.1) and Eq.(2.2) respectively.

$$I_D = \mu C_i \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} \tag{2.1}$$

$$I_{DSat} = \frac{1}{2}\mu C_i \frac{W}{L}\left(V_{GS} - V_T\right)^2 \tag{2.2}$$

where V_T is the threshold voltage, V_{GS} is the potential difference between the gate and source terminals, V_{DS} is the potential difference between the drain and source terminals, I_D is the drain current, μ is the field effect mobility, C_i is the gate-dielectric capacitance per unit area.

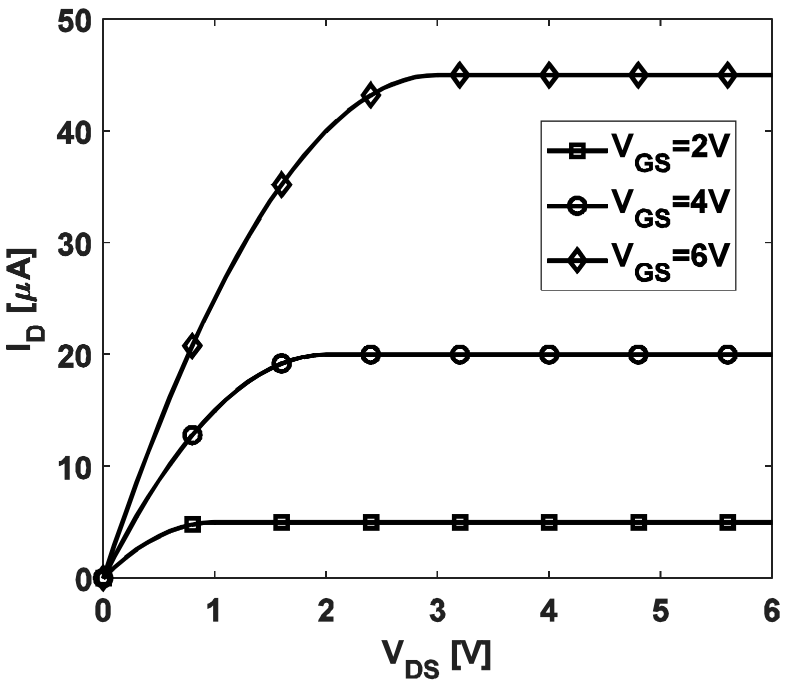

Figure 2-3 I-V characteristics of a n-type OTFT, W/L=10,μC_i=1μA/V^2, V_T=1V

2.3.1 Threshold Voltage (V_T)

Threshold voltage, refers to the minimum potential difference that need to be applied between the *gate* and *source* terminals to turn ON the OTFT. OTFTs are normally-OFF devices (I_D=0 when V_{GS}=0), that conducts only when a suitable potential is applied between the *drain-source* (V_{DS}) and *gate-source* (V_{GS}) terminals. The convention is to express the voltage at a terminal with reference to the *source* terminal (reference terminal). Although, the behavioral meaning of V_T is similar to the one in MOSFET, the physical meaning of V_T is different in both these devices. In MOSFETs, the value of V_{GS} for which an inversion (strong-inversion) occurs near the dielectric-semiconductor interface is referred as threshold voltage. Since, OTFTs are accumulation mode devices, it would be inappropriate to apply the definition of threshold voltage developed for conventional MOSFETs. To eliminate this confusion, few researchers often use the term switch on voltage [34]. However, a majority of the research articles use the term threshold voltage in their report, since, the electronic design engineer community is acquainted with this terminology.

Threshold voltage is a very crucial parameter for an OTFT. It determines the operating voltage of the circuit. A major concern with OTFTs is their extremely high operating voltage (greater than 10V). High operating voltage limits the use of OTFTs in power critical applications especially, battery operated devices. A plausible reason for high operating voltages could be the poor field effect mobility (discussed later), which necessitates higher voltages to draw appreciable current from the device. However, high V_T remains the primary cause behind high operating voltages. Moreover, the performance parameters of an OTFT based circuit (analog as well as digital) depends on the value of V_T. To realize high speed, noise immune digital circuits with low power consumption low-V_T transistors are preferred. Similarly, in analog applications, to derive high gain, large output swing and area optimization low-V_T is preferred.

2.3.2 Mobility

Field effect mobility or simply mobility is a measure of how fast a charge carrier can move (*drift*) in the presence of an electric field. Hence it is an important performance metric of an OTFT. OTFTs in general have lower mobility ($<1cm^2/V$-s) values in comparison to the other TFT technologies. Low field mobility is intrinsic to OSCs. A main reason for poor mobility is the molecular nature of the material. In molecular solids, which result from covalent bonds, have less interaction among the neighbors. Due to the weak van der waals forces that binds the molecules, charge carriers are severely localized. As a result, band like transport is rarely observed. Although in crystalline OSCs and poly-crystalline OSCs, band like transport can be observed by carefully controlling the grain size and orientation.

Charge carrier mobility in disordered semiconductors in general and OSCs in particular has remained an active area of research[35]–[37]. Given the wealth of organic materials and the varied morphologies encountered in OTFTs, this topic still needs to be explored. A few models which are available in the literature include variable range hopping, multiple trapping and release (MTR) model [38], Gaussian Disorder model (GDM)[39] etc. Another important aspect on mobility in OTFTs is the fact that it is dependent on the gate voltage.

2.3.3 Subthreshold Swing (SS)

Subthreshold swing (expressed as mV/decade) is a measure of how fast the transistor can change its state from ON to OFF state and vice-versa. An important performance metric in determining the switching speed of the digital circuits. A smaller value of *SS* is expected for higher speeds of operation. From a device perspective, *SS* is a measure of the quality of dielectric-semiconductor interface. The trap state density at this interface is directly proportional to *SS*. The dependency of *SS* on trap density is shown in Eq.(2.3) Hence the emphasis should be on reducing the interface trap state near the interface. State of the art OTFTs exhibit *SS* in the order of few hundreds of mV/decade while the other TFTs have *SS* in the order of few tens of mV/decade. One possible reason from the perspective of fabrication for large *SS* value could be the relaxation on high vacuum. This could probably lead to some defect creation near the interface. Therefore, conquering *SS* in OTFTs which are fabricated using solution processing techniques is an interesting challenge.

$$SS = \frac{kT \ln 10}{q}\left[1 + \frac{q^2}{C_i} N^*\right] \tag{2.3}$$

where N^* denotes the contribution of both bulk traps and interface traps per unit area and per unit energy, q- charge of an electron, k- Boltzmann constant, C_i is the gate dielectric capacitance per unit area and T- absolute temperature.

2.3.4 Current Modulation Ratio (I_{ON}/I_{OFF})

The maximum current which an OTFT can source in its saturation region. This is normally taken as the I_{ON} while the current that flows through the OTFT in an OFF state is referred as I_{OFF}. Both I_{ON} and I_{OFF} themselves are important performance metrics but their ratio is even more critical for a good OTFT. A high value of current modulation ratio is desired. Therefore, this can be viewed as two-fold problem. Though the idea of increasing I_{ON} seems more relevant, it has a little impact on the ratio. Also, improvement in I_{ON} comes at the cost of area, operating voltage and power consumption. Instead, focus on reducing I_{OFF} could result in the improvement of current modulation ratio in the orders of magnitude. This ratio is a critical parameter in determining how closely an OTFT behaves as an ideal switch. This is very critical in digital circuit applications. Larger I_{OFF} leads to wastage of power even when the OTFT is OFF (stand-by). This is a serious concern especially in battery operated devices. Therefore, necessary care has to be taken to minimize I_{OFF}.

2.3.5 Transition frequency (f_T)

This is an important dynamic characteristic of an OTFT. f_T denotes the upper limit on the utility of an OTFT as an amplifying device. Beyond this frequency, the parasitic capacitances effect becomes significant and the gain rolls-off. Therefore, f_T is an important performance metric of an OTFT. It determines the useful range of frequencies for which the OTFT can operate. It is advisable to have high $f_{T.}$ In the initial phase of research in OTFTs this was not much addressed. Later when the initial barriers for the technology like high operating voltage and low field effect mobility got conquered, the focus has shifted on improving the $f_{T.}$ Improvement in f_T can be attained by an improvement in field effect mobility, reduction in the channel length and most importantly reducing the lateral overlap of the gate region with the *source* and *drain* regions. These techniques are successfully employed to realize OTFTs with operation frequency in the order of MHz. Such operation is very much essential when designing circuits for RFID applications.

2.3.6 Stability and Reliability

Stability and reliability are two essential features of any device. It is observed that these two terms are used interchangeably. However, they represent two different aspects and the techniques to mitigate them also differ greatly. Stability deals with those changes which are reversible in a device. These changes, could be the result of processes like trapping and de-trapping. Hence a shift can be observed in the characteristics. Such a shift could be a result of prolonged stress on the device. Provided with a sufficient recovery time or by applying external stimulus, the original characteristics can be imparted for the device. Whereas, reliability deals with the irreversible changes in the device [40]. This could be due to creation of new traps, deformation or damage to the device. In case of OTFTs, stability can be investigated under various categories: air stability, operation stability, bending stability and thermal stability [41]. Reliability issues are a consequence of failure mechanisms which need to be identified and addressed at the design level. Study of stability, reliability along with efforts to model and mitigate them is essential to make the technology market friendly.

2.3.7 Contact Resistance

Contacts play an important role in OTFTs. Unlike other TFTs technologies, where the contact resistance is either negligible or show ohmic nature, OTFTs often have a non-linear contact behavior. This becomes an important factor especially in the short-channel devices (channel length comparable to the source drain electrode lengths). In OTFTs, the charge flowing in the channel is injected from the source electrode and extracted from the drain electrode. This process of injection and extraction of charge at the metal-semiconductor junction sees a Schottky barrier. Hence a contact resistance can be attributed to the metal-semiconductor junctions. In addition to the barrier, it is also observed that the poor conductivity of the OSC could contribute to the contact resistance. This is because, the injected charge has to travel through the OSC before it enters the channel region. This effect leads to a larger values of contact resistance in top contact devices when compared to bottom contact structures. Since in a bottom contact structure, injection/extraction less area is available for charge injection, they have more contact resistance when compared to top contact structures. Minimizing the contact resistance is an essential task to improve the high frequency limit, reduce the operating voltage, increase the maximum current in the ON state and to eliminate the non-linear effects arising due to the contact resistance in the I-V characteristics.

A summary of the performance parameters of an OTFT are shown in Fig.2-4.

OTFT Performance Parameters		
DC	**AC**	**Reliability**
Threshold Voltage	Transition frequency	Hysteresis
Mobility	Parasitic Capacitances	Air Stability
Current Modulation Ratio		Shelf life
Subthreshold swing		V_T degradation
Contact Resistance		

Figure 2-4 Performance parameters of an OTFT

2.4 MATERIAL ISSUES IN OTFT DESIGN

Organic semiconductors (OSCs) are an important class of materials which form the basis for an OTFT. In addition to OSCs, organic materials which can be used as substrate, electrodes: *gate*, *source* and *drain* are equally important to realize a bendable, flexible OTFT. From the literature it can be observed that in the early phase of OTFTs other than the OSC, other layers of the device were actually inorganic materials[21], [42]–[45]. However, in the subsequent years "fully organic" OTFTs were fabricated [46]–[48]. In the following discussion, the role of the materials and the challenges related to them are presented.

2.4.1 Substrate

Substrate provides support to the entire device hence it has to be stable, flexible, clean, chemically non-invasive on the subsequent layers, free from imperfections and defects. Furthermore, it should have a smooth surface, compatible with all the layers to be deposited over them and above all economical. The role of substrates is critical when it comes to live up to the expectation of "flexible" devices. Other than being a mechanical support it also serves as a "barrier layer", which protects the active layer from ambient moisture and oxygen. In case the substrate is not capable of doing this an additional passivation might be needed. A list of a few commonly used substrates in the OTFT include: silicon, glass, polyethylene terephthalate, poyimide, polyethylene naphthalete, polystyrene, polycarbonate and parylene-N[49]. The most recent trends in substrate materials include paper and other bio-degradable material. Zschieschang U and Klauk H [50] has summarized the use of paper substrates for OTFTs.

2.4.2 Gate Electrode

Gate electrode is an important aspect in OTFT. Conducting material is used to form an electrode. It is observed that thin metal films which are deposited either by thermal evaporation or sputtering are employed in OTFTs. New developments include polymer gate dielectric materials too. Gate electrode plays an important role in determining the electrical characteristics of the OTFT. Threshold voltage is directly dependent on the work function of the gate. Also it can impact the mobility, hysteresis effects in the device. Han C.Y. et al. [51] has studied the impact of gate and substrate material on the performance of OTFT. They presented three possible ways in which a metal gate can help improve mobility: (i) Remote Phonon Scattering, (ii) Remote Coulomb scattering and (iii) Carrier injection at the source. The first two phenomena improve the field effect mobility while the last one helps in reducing the contact resistance.

2.4.3 Source/Drain electrodes

Source and *drain* electrodes are symmetric and made of similar material. The role of the electrodes is dependent on the potential difference applied between them. Contact length, placement and thickness are important physical dimensions. Along with these, the work function of these electrodes is an important parameter.Fig.2-5 shows the energy barriers for the injection of charge carriers near the metal-semiconductor junctions in an OTFT. It can be observed that, the work function of a metal is an important parameter. In general, electrodes with low work function are needed to facilitate injection and extraction of electrons at the metal-semiconductor junctions [52]. Metals like: gold (Au), silver (Ag), copper (Cu), platinum (Pt), aluminum (Al), chromium (Cr), titanium (Ti) and calcium (Ca) are used as electrodes [49]. However, there are also polymer alternatives available. Contact resistance an important performance metric largely depends on the source and drain electrodes. Contact engineering is an interesting area where the focus is on improving the device performance through paying special attention on the contacts. A very good review paper on contact engineering is available from Liu C et al. [53]. The two most important techniques used in contact engineering are (i) self-assembled monolayers (SAM) and (ii) contact doping. SAM when used above the metal surface reduce the work function and thereby improving the injection efficiency. Contact doping is a technique in which the OSC is locally doped near the contact surface using a p-type or n-type metal-oxide. This creates a thin depletion region, which assists in tunneling of charge carriers rather, thermionic emission and hence results in reduced contact resistance.

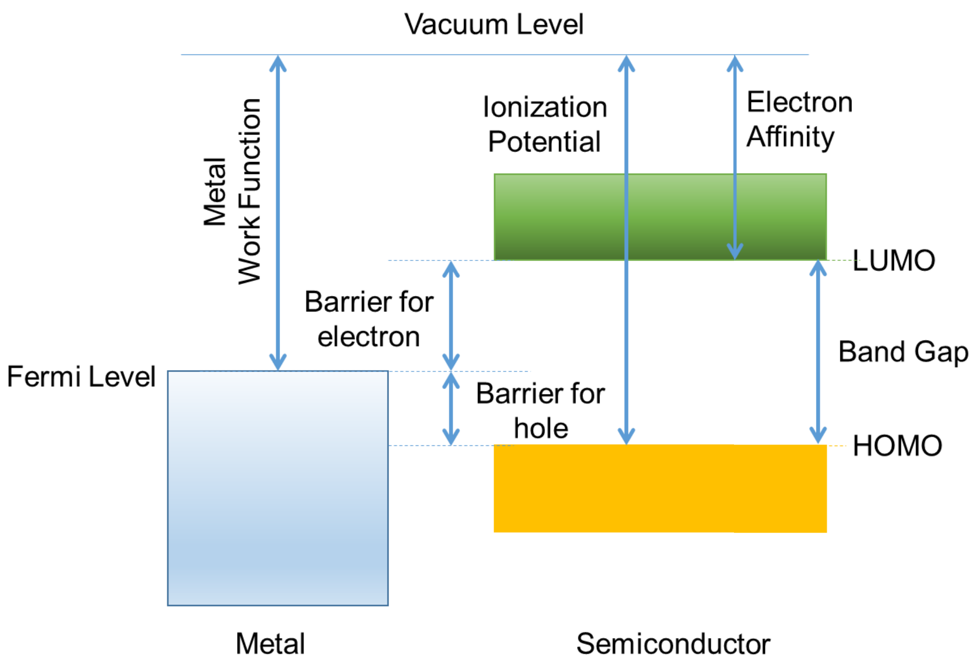

Figure 2-5 Energy level barriers for electron and hole injection near the metal-semiconductor junctions of an OTFT

2.4.4 Active Layer: Organic Semiconductor

This is the layer in which channel region is created due to the process of accumulation. The performance of an OTFT is significantly affected by the choice of material, deposition technique and mainly the morphology and microstructure of this region. OSCs employed in OTFT can be classified either as n-type or p-type based on whether they permit electron or hole transport through them. In OTFTs, p-type OSCs are often used because, when compared to the n-type OSCs, they produce high mobility OTFTs. The lack of n-type OSCs with comparable mobility to p-type OTFTs is a challenge while developing complementary circuits in the OTFT technology. A few commonly used OSCs and their chemical structures are shown in Fig. 2-6. The p-type OSCs includes: pentacene, 6,13-Bis(triisopropylsilylethynyl)pentacene (TIPS-pentacene), regi-regular poly(3-hexylthiophene-2,5-diyl) (P3HT), dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT), Poly(3,3‴-didodecyl[2,2′:5′,2″:5″,2‴-quaterthiophene]-5,5‴-diyl) (PQT-12). The n-type OSCs includes: N,N'-Ditridecyl-3,4,9,10-perylenetetracarboxylic Diimide (PTCDI-C13), N,N'-bis(n-octyl)-(1,7&1,6)-dicyanoperylene-3,4:9,10-bis (dicarboximide) (PDI8-CN2), copper hexadecafluorophthalocyanine ($F_{16}CuPc$).

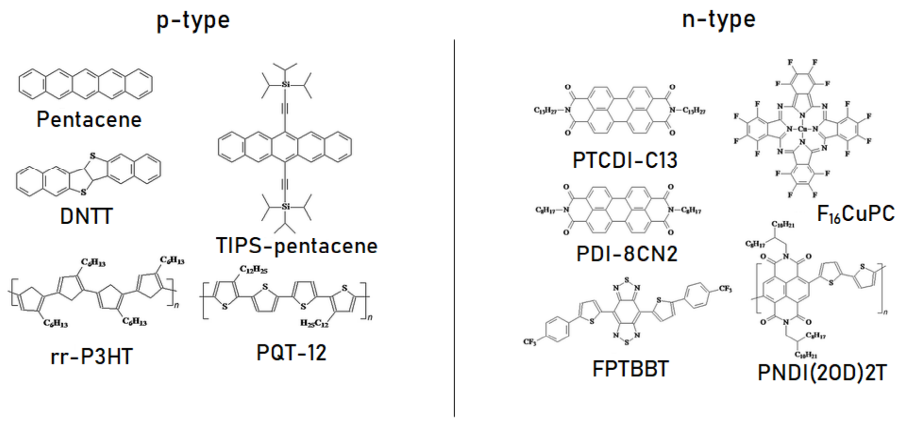

Figure 2-6 A few commonly used organic semiconducting materials

The OSC chosen for active layer can be broadly classified as (i) π-conjugate small molecules and (ii) conjugated polymers. Small molecules are the most studied organic materials. Small molecules outperform polymers in terms of mobility [54], purity, structural homogeneity and run-to-run reproducibility [55]. The major drawback with small molecules is that they are insoluble and can't be solution processed. They are mostly deposited by vapour deposition techniques eliminating the potential advantage of solution processability in OSC.

Polyacenes and thiophenes are among the most studied materials among small molecules [30], [54], [56]–[58]. Among polyacenes, although the initial studies started with anthracene and tetracene, it is pentacene that has dominated the OTFT technology due to its high field effect mobility (>1 cm^2/Vs) and controllable grain size. Choi et al. [59] has demonstrated a precursor based approach for solution processed OTFT. He used a variant of Pentacene 6,13-Bis(triisopropylsilylethynyl)pentacene (TIPS PEN) for fabricating an OTFT on polyimide substrate with a threshold voltage of $|1V|$ and field effect mobility of 0.64 cm^2/Vs. The major drawback of pentacene is that it is moderately stable when exposed to air and light. Therefore, pentacene is mostly preferred in applications like RFID where mobility is more important [60]. It is also used as a benchmark for vapour-deposited OTFT. Other than poly-acenes oligo-thiophenes are another important class of small molecules. Sixithiophene (6T) and the alkyl substituted di-hexyl-sixithiophene (DH6T) are among the most studied. They offer good mobility in poly-crystalline phase too. They pose the problem of easy oxidation due to their large HOMO energies. Several other small molecules like copper phthalocyanine (CuPC), benzodithiophene (BDT), rubrene, etc. are also studied, each have their own advantages and limitations over the other [61].

The second type of organic materials which are used for active layer formation in an OTFT are polymer based OSC. They are highly suitable for solution processed techniques and hence favour large area electronics through processes like spin coating, spray coating, screen printing and dipping. They offer roll-to-roll reproducibility which suits batch fabrication. One great advantage with polymer based active layers is that their performance is independent of the morphology[21] and has good reproducibility[21]. However, due to their large molecular weights and complex chemical structure it is very difficult to obtain an orderly arrangement. As a result, they suffer from poor mobility. Since the purification techniques are not so well developed for polymers in comparison to small molecules, obtaining highly pure polymers is a challenge. Purity of the polymers directly affects the parameters like mobility, threshold voltage and off current (I_{OFF}) in an OTFT. Poly-thiophenes are the most investigated materials among polymers since they exhibit good mobility comparable to that of small molecules (>0.6 cm^2/Vs) [28]. Salleo et al. [28] has fabricated and characterized Poly-(3-hexyl thiophene) (P3HT) based solution processed OTFT. It was observed that P3HT self assembles into crystalline form when deposited and thermally annealed. It is also reported that there is anisotropy (direction dependent properties) in P3HT. In addition to the above in recent studies, some researchers [21], [62], [63] have revealed that DNTT (dinaphtho-[2,3-b:2′,3′-f] thieno[3,2-b] thiophene) and its didecyl- and diphenyl derivatives C_{10} -DNTT and DPh-DNTT exhibits p-type behavior with mobility in the order of 10 cm^2/Vs. [57].

The non-availability of n-type materials has greatly hampered the progress of OTFT beyond display technology. Though a few air stable n-type materials were developed in the past few years [60], their mobility is at-least a few orders lower than the p-type material [64]. Because of this large gap in mobility, low power systems which need complementary devices could not be realized. Fluorinated copper phthalocyanines especially $F_{16}CuPc$ (hexa-deca-copper-phthalocyanine) which has an electron affinity of 4.5 eV is reported to have good air stability and electron mobilities as large as 0.27 cm^2/Vs [65]. Compounds having PTCDI (Perylene tetra carboxylic diimide) as core shows n-type operation and with mobility closer to p-type pentacene [66]. NTCDI (naphthalene-tetracarboxylic-diimide) and its derivatives that can be solution processed and with promising features at ambient temperature are also developed [67]. The fullerene structure C_{60} which exhibits a large electron affinity 3.5eV is also reported to show n-type behavior with a mobility as large as 3.5 cm^2/Vs [68]. With the discovery of such new materials OTFT technology is expected to make strides further in the field of consumer electronics.

Quin T.E.J. et al.[69] has presented the reasons for poor mobility in n-type OTFTs. A key reason identified is the limited options available while choosing building blocks that behave as electron withdrawers. Also, electrons when injected into OSCs with low electron affinity (EA) they react with –OH or O_2 in the environment and gets trapped. In addition to this, lack of stable metals with low work functions is a reason for the poor performance of n-type OTFTs. Since gold (Au) (work function ~5.1 eV) is the most commonly used metal as source/drain it favors the hole injection rather electron due to the large barrier. However, consistent efforts from the research communities have alleviated the problem. Okamoto T et al. has recently reported on the molecular design of robust high performance, environmentally stable n-type semiconductors [70]. A similar kind of report, but in a more generic sense on: developing efficient, high performance electron transport layers for organic electronics is published by Sun H et al [71].

2.4.5 Gate Dielectric

Gate dielectric is perhaps the most important layer which dominates several performance metrics of an OTFT. The role of a dielectric material in TFTs is significant. In the case of OTFTs, which are interface devices, meaning: a device in which the channel layer is confined to a very thin layer close to the dielectric-semiconductor interface its role gets further accentuated. Parameters which are paramount for OTFTs like threshold voltage, mobility, sub-threshold swing and stability are influenced by the choice of dielectric layer. Several research works have investigated this topic and have made a few conclusive evidences. Among these conclusions a key aspect is to choose a high-k dielectric material.

High-k dielectrics to reduce the operating voltages are extensively studied. alumina (Al_2O_3, $\epsilon_r \sim 8$)[72], hafnium oxide (HfO_2, $\epsilon_r \sim 30$) [73], barium strontium titanate (BST,$\epsilon_r \sim 16$), barium zirconate titanate (BZT, $\epsilon_r \sim 17.2$)[74], lanthanum incorporated transition metals [75], hafnium titanium oxide (HfTiO, $\epsilon_r \sim 15$) [73] and several other materials are also studied. In addition to the above materials, a few polymers like PMMA (poly-methyl-methacrylate) [76], Parylene-C [63], commercial photo resists [77], PPVs (poly-phenylene-vinylenes) [78] etc. can be also used as gate dielectric. They provide smooth interface with the active layer, thereby reducing the surface roughness effects and enhancing the mobility [68]. H.Klauk et al. [79] applied the concept of polymer gate on bottom gate pentacene OTFT and observed that the electrical characteristics improved when compared with SiO_2 based OTFT, but the hysteresis in IV characteristics, is large in polymer gate OTFT. Another limitation with polymer gate dielectric is that their dielectric constant is low (typically <10) leading to poor current drive capability. In order to exploit the surface smoothness effect of polymers and high-k of inorganic materials, hybrid bi-layer dielectrics were explored [80]. A.L.Deman et al. employed a PMMA-Ta_2O_5 bi-layer as gate dielectric and observed a reduction in the operating voltage, increase in field effect mobility and reduction in the gate leakage current [81].

The dielectric constant of the gate dielectric is very important, since it determines the charge accumulated in the channel for a given V_{GS}. Hence, dielectric constant has to be sufficiently large. In addition to the above, material chosen should have good insulating properties and high dielectric breakdown voltage so that they can be deposited as thin films with minimum leakage and reliability issues. Moreover, they should be free from traps and defects. Since traps can raise the *SS* of the device and could probably lead to hysteresis and other stability issues, traps should be reduced. Surface energy is another important attribute. Having a smooth surface with low surface energy assists the deposition of active layer with large grains and hence less grain boundaries. Such large grained OSCs are known to have higher mobilities.

2.5 MODELING ISSUES IN OTFT

Modeling is an essential requirement for transistor technology to progress. Modeling essentially tries to capture and explain the electronic behaviour of the device. In general, modeling deals with the estimation and replication of I-V characteristics of the device. However, other aspects, which includes: high-frequency response, noise, bias-stress effects and reliability models too exist. There are two approaches in device modeling: physics based model and behavioral models. Physical models, are based on the device physics, carrier statistics and transport mechanism. The focus is to understand the underlying physical phenomena responsible for the device characteristics. Physics based models involve complex mathematical expressions and are mostly useful for material design and processing. Whereas behavioral models focus on the replication of characteristics in terms of equivalent circuit models, semi-empirical or empirical relations with emphasis on design parameters like threshold voltage, mobility, aspect ratio and external voltages.

OSCs are disordered semiconductors and characterized by traps. The trap-state distribution plays an important role in determining the device characteristics. These trap-states could be created due to chemical impurities, grain boundaries, surface defects and structural disorder [70]. The trap-states are unwanted electronic states in the HOMO-LUMO gap of an OSC. The traps are classified based on their closeness to the intrinsic fermi level (midway between E_{HOMO} and E_{LUMO}). States close to the middle of the bandgap are referred as *deep* states while those away from it and near the band edges are called *tail* states. Several models exist in the literature to model the trap-state density like: Gaussian, double exponential and single exponential[33], [82]–[86]. Using the trap-state density, one can assess the surface potential near the dielectric-semiconductor interface. This surface potential can be subsequently used to obtain the I-V characteristics of the device.

Behavioral models form the core for computer aided design (CAD) tools used in the VLSI industry. Availability of standardized models for OTFT is essential to facilitate design and development of complex ICs. A sector of electronics industry: electronic design automation (EDA) is dedicated for the purpose of CAD development. To make OTFTs, in compliance with EDA it is necessary to have a compact model. The first step for such a model would be to comprehensively model the IV characteristics of OTFT. Since the region of operation in the IV characteristics of an OTFT and MOSFET are similar, one might think to employ MOSFET like approach to model IV characteristics of OTFT. The first challenge in such a model is to define threshold voltage for OTFT. Since an OTFT operates in accumulation mode, one can't apply the definition of V_T as in the case of a MOSFET, which operates in inversion region. A common procedure adapted for extraction of V_T from the I_D-V_{GS} curves is to take the intercept of $\sqrt{I_D}$ Vs V_{GS} plot. But this leads to an erroneous result since the mobility is a strong function of V_{GS}. Ambiguity in the definition of V_T and uncertainty in the extraction procedure limits the use of threshold voltage based I-V models. B.Iniguez et al. [87], implemented a universal compact model for IV characteristics of both short and long channel TFTs. They employed an empirical model based on eight parameters, but such an approach is not reliable since the underlying physics is not considered in the model. F.Torricelli et al. [88] developed a compact DC/dynamic model for OTFT valid for both linear and saturation regions of operation and doesn't need the explicit definition of V_T. But this model is computationally intensive and doesn't fit well into the CAD framework developed for circuit simulation. T.K.Maiti et al. [89] used a surface potential model to capture the IV characteristics of the OTFT. They incorporated pseudo 2D-resistor model to account for the structural aspects of OTFT. However, this model doesn't take the contact resistances into account and may not be so accurate for short channel (L<50µm) OTFT where contact resistance plays a key role. V.Vaidya et al [90] used a model similar to gradual channel approximation (GCA) in FET. This model is optimized for SPICE implementation and doesn't necessitate a closed form equation for drain current. However, this model assumes that the mobility remains constant across the channel which is not the practical case. It also depends on a new term switch-on-voltage (V_{so}, flat band voltage of OTFT). The need for a simple, easy to use and computationally efficient SPICE model is due in the case of OTFTs.

2.6 CONCLUSION

OTFTs has made large strides from their infancy thirty years ago to the present day. It is neither humanly possible nor necessary to discuss each of the reported works. Therefore, a brief yet detailed description, major challenges, methods and techniques used to overcome the issues, their limitation and implications are summarized. In this chapter, we presented an overview of the OTFT devices starting from the device architecture followed by performance metrics, materials and their role in performance improvement, charge carrier transport mechanism and modeling aspects of OTFT. A few notable conclusions from the existing literature has been presented. The relevance and impact of these observations, their limitations, scope and need for improvement is also discussed. In the subsequent chapters, we try to address a few of them which are pre-defined in chapter-1 of the thesis as objectives.