Chapter-1. Introduction

1.1 ORGANIC ELECTRONICS: HISTORY AND MARKET AVENUES

A transistor is an active element used for building several electronic circuits used in radios, mobile phones, laptops, personal computers, tablets, smart watches, TVs etc. Due to their small size and embedded (buried inside the die) nature many times they go unnoticed by the consumer. As per the report published online in *IEEE Spectrum* [1], the volume of transistors produced in the year 2014 is approximately 250 billion billion (250×10^{18}). An increase in the volume of production combined with the fact that the price per transistor has declined over the years has made transistor technology and hence electronics more affordable to common people. The tremendous growth in the production and sales of transistor is possible due to technological advancements in the Complementary Metal Oxide Semiconductor (CMOS) technology. This technology, offers several advantages which include: low power consumption, less area per circuit: which helps in packing more functionality in a given area and above all economical. The success of CMOS technology is so profound that, even today a majority of ICs produced and consumed globally are silicon based and employ CMOS technology or a variant of it. The success in silicon VLSI technology has solved several problems of the world especially the ones involving computation.

The ever growing consumer electronics market has come up with new demands. Especially, rapid growth in the consumption of personal digital assistant (PDA) products; which include mobiles, tablets and smart wearable devices has created a need to focus on the display technology. Therefore, the consumer electronic industry has shifted its focus from computation to display. The existing technology, which is predominantly silicon based is not suitable to cater the needs of display devices due to its indirect bandgap nature. Hence, the search for alternative technology which can address the issues related to display devices has gained prominence over the years. It is to be noted that silicon ICs are indeed the best for computing applications and shall continue to remain as the leading technology for design of processors. However, for display applications which mostly comprise: Light Emitting Diodes(LEDs) and Liquid Crystal Displays (LCDs) silicon is not a good choice. Other than the indirect band gap nature of silicon,s the need for high temperature processing makes it a poor choice for optical applications. In addition to this, the need for transparent, flexible and low cost display devices has opened up a new avenue of electronics.

In 1970's, a new class of transistors: Thin Film Transistors (TFTs) emerged due to the improvement in the processing technology. These transistors used a semiconducting active layer which is thin (few tens of nanometer). They have readily found application in diverse fields like: pixel driver circuitry for flat panel displays, biological and chemical sensors. In the year 1979, Spear and Le Comber at the University of Dundee in Scotland has demonstrated the first ever hydrogenated amorphous silicon (a-Si:H) TFT and its application in driving active matrix (AM) displays [2], [3]. This invention has given an impetus to the concept of large area display technology. Furthermore, the shorter production cycle has ensured that the revenues are good, which motivated several consumer electronics manufacturers to start production immediately. However, a-Si:H is a photo-conductor and needs an additional opaque layer between the LCD and the driver plane to limit the leakage current. This drawback, has lead up to the discovery of new technology: oxide-TFTs; especially ZnO TFTs have emerged as a potential alternative for a-Si:H TFTs. The transparent nature of ZnO and its high mobility when compared to a-Si:H has made it a strong contender for display devices.

Among all the materials discussed above, a common aspect is that; they are all inorganic materials, need sophisticated and expensive equipment (to create and sustain vacuum) for fabrication, limited choice while choosing material and they are brittle. These issues can be addressed by choosing 'organic' materials (polymers) for display technology. Polymers, are not new materials to electronics industry. They have been put to use for various applications like: electronic packaging, photoresist material in photolithography process and insulators for capacitors and electrical isolation.

However, the discovery of organic semiconductors (OSCs) has drawn attention from both the industry and academia, which lead to the development of a new area *organic electronics*. A breakthrough invention of developing conduction polymers 1977 by H. Shirkawa, A.G. MacDiarmid and A.J. Heeger has accelerated the development in the field of organic electronics [4]. This invention had a profound impact on the human life. Which was later recognized with a Noble Prize in the field of chemistry in the year 2000. The demonstration of conducting polymers has subsequently paved path for the development of organic solar cells, organic LEDs and Organic Field Effect Transistors (OFETs). Organic electronics, offers advantages like mechanical flexibility, a variety of materials to choose from, ease of fabrication and low cost. These features, make this technology attractive. Persistent efforts from the industry and academia has helped organic electronics to evolve into a promising technology, which can compete with the existing technologies. Organic electronics, due to its immense potential and unique features has added a new dimension in the field of electronics. As per a market survey report published by *verifiedmarketresearch.com* "*Organic Electronics Market was valued at USD 56.2 Billion in 2019 and is projected to reach USD 408.3 Billion by 2027, growing at a CAGR of 28.1% from 2020 to 2027.*"[5]

This indicates that, organic electronics is a promising technology which has several attractive features in comparison to the existing technologies. A few notable points about organic electronics are:

1. Organic electronics is one such technology which is not an alternative for silicon based electronics but a new technology with potential to do things which are otherwise not possible using silicon based devices.
2. Organic electronics could be made more energy efficient and eco-friendly thereby, leading to sustainability. It could be a reality where bio-degradable, recyclable and devices with longer life cycles are possible using an appropriate choice of materials.
3. Organic electronics, can be manufactured using low cost, room temperature processing steps. This eliminates the need for high temperature, high vacuum steps which necessitate sophisticated equipment. Quite possibly, printable electronics which could lead to fabless processes and resource friendly.

A few applications of the organic electronics are shown in Fig. 1-1. Organic electronics covers a broad spectrum of areas which include: energy storage elements like flexible batteries, wearable sensors for health monitoring, display devices and solar cells.

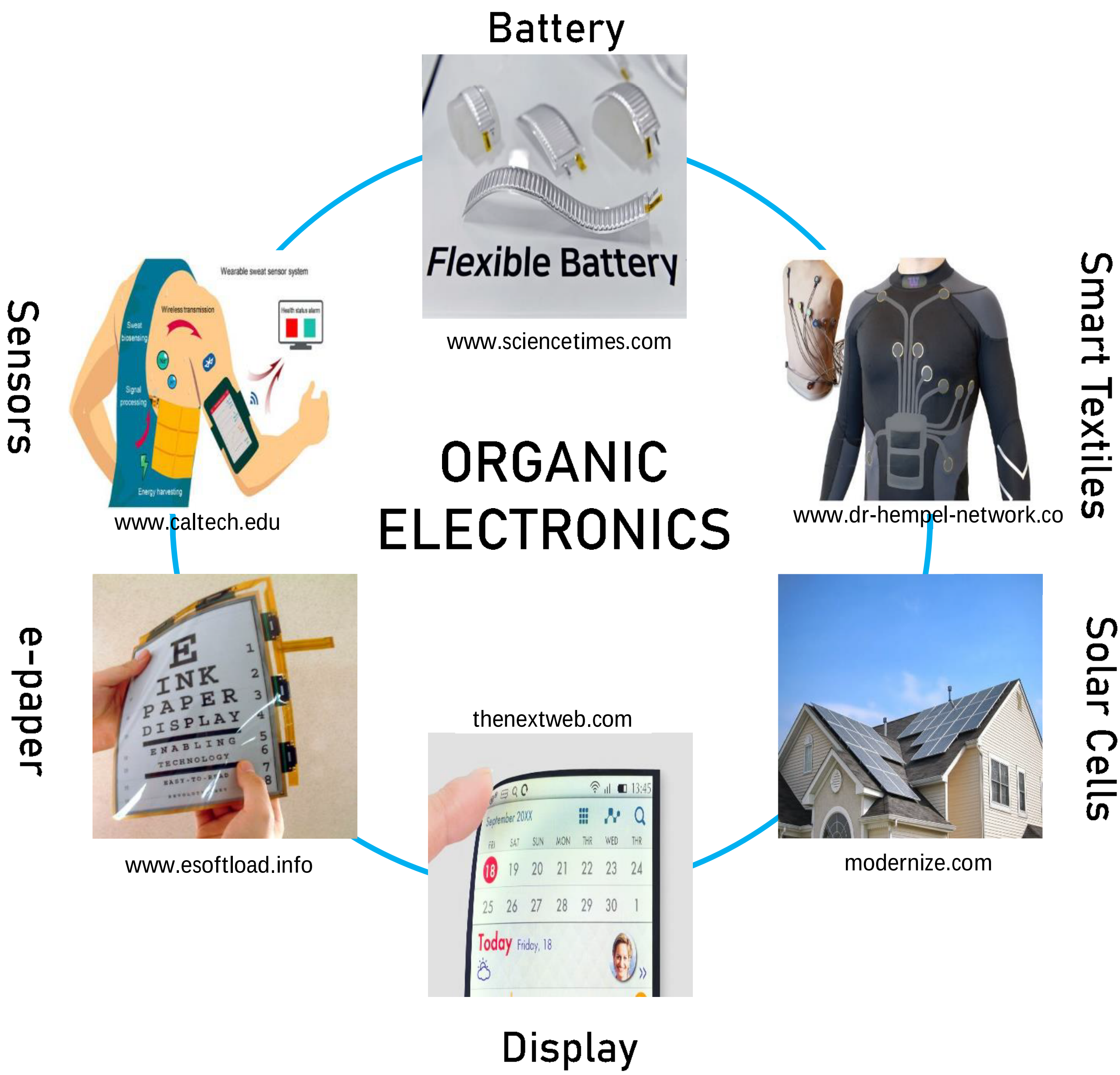

Figure 1-1 Major Industry Sectors which are target applications of Organic Electronics

1.2 ORGANIC THIN FILM TRANSISTOR (OTFT) : STRUCTURE AND APPLICATIONS

In 1987, Koezuka and co-workers have successfully fabricated and characterized a Field Effect Transistor (FET) using polythiophene as active semi-conducting layer. This was the first ever reported Organic TFT (OTFT). OTFT is a special class of TFT which uses a thin film of organic semi-conducting material as the channel layer (also referred as active layer). The word organic in OTFT should not be taken in strict sense since, state of the art OTFTs continue to use inorganic materials; especially for gate insulator and electrodes. OTFTs are extensively used in the back plane of Active Matrix Liquid Crystal Displays (AMLCD), low cost Radio Frequency ID (RFID) tags, e-ink, electronic newspapers, smart textiles, artificial skin [6]–[8] etc.

Fig.1-2 shows the schematic view of a typical OTFT. OTFT is a three terminal device similar to that of a MOSFET. OTFT can be visualized as a multilayer structure with each layer having a specific purpose. A mechanically flexible, thermally stable substrate layer provides the necessary mechanical support for the device. A conductive layer which acts as the gate electrode is on the top of substrate. A dielectric layer separates the *gate* (G) from the active layer (channel layer), making the device an insulated gate FET (IGFET). The active layer has contacts, one at each end, which acts as the *source* (S) and *drain* (D). The *source* and *drain* terminals are interchangeable, making the device symmetric. This structure is referred as the Bottom Gate Top Contact (BGTC) structure based on the location of the electrodes with respect to the active layer. This is one of the four possible structures of an OTFT; other variations too exist in the literature [9]–[12].

An OTFT is a normally OFF device, with little or no current flowing when no bias applied (V_{GS}=0). However, when the bias increases ($V_{SG} > 0$, for p-channel device) the channel conductivity enhances, as a result the current starts flowing. Hence an OTFT operates in accumulation mode, unlike a MOSFET which operates in an inversion mode.

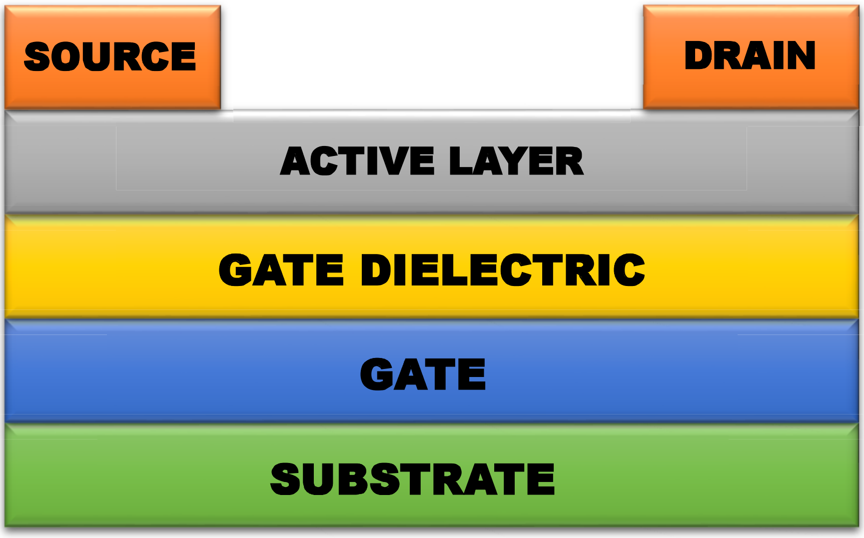

Figure 1-2 A Schematic view of the Bottom Gate Top Contact (BGTC) Organic Thin Film Transistor (OTFT)

Based on the type of mechanism involved in attaining the current modulation in the channel region, OTFTs can be classified in various ways. One such classification is presented in Fig.1-3. The list is not exclusive and a few more variants could exist in the literature. Following are the types classified on the basis of mechanism involved in charge carrier modulation in the channel region.

- *Organic electrochemical transistors (OECTs)*: These transistors are those in which the current modulation in the channel layer is a result of the reduction or oxidation reaction, that influences the drain current I_D.
- *Electrolyte-gated organic field effect transistors (EGOFETs)*: An electrode layer which could be either a liquid or a solid is introduced between the gate and the semiconductor layer (there is no dielectric layer between the gate and the semiconductor in this case). This electrolyte layer is one such medium where the ions can freely move, there by an interface charge is created and hence alter the drain current.
- *Ion-sensitive OFETs (ISOFETs)*: This is a counter part of the silicon based ion-sensitive FET (ISFET). ISOFETs closely resemble EGOFETs as these devices, have an electrolyte layer at the gate electrode. But, ISOFETs additionally have a dielectric layer, which isolates the electrolyte from the semiconductor.

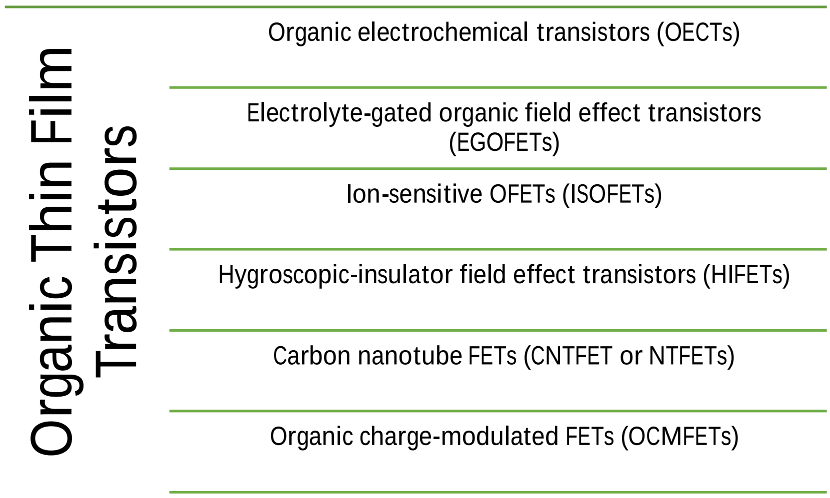

Figure 1-3 A classification of Organic Thin Film Transistors based on the mechanism involved in charge carrier modulation in the channel

- *Hygroscopic-insulator field effect transistors (HIFETs)*: In these transistors, the dielectric layer is made of hygroscopic material. This creates a moist environment where the ions can move freely, which in turn interacts with the semiconductor layer and hence modulates the drain current.
- *Carbon nanotube FETs (CNTFET or NTFETs)*: a channel layer is created either by using a single or a bundle of carbon nanotubes between the source and drain electrodes. These devices exhibit excellent electrical properties and find applications frequently in sensing.
- *Organic charge-modulated FETs (OCMFETs):* Developed as a specialized structure for sensing, OCMFETs resemble ISOFETs in structure. They have two gate electrodes: one, which is fixed at a potential termed as "reference gate", the other one which is exposed to an analyte and hence a "floating gate". A dielectric layer connects the floating gate to the rest of the device. This structure has an advantage that the transistor itself could be made small and isolated from the sensing environment.

Having studied the structure and operation of an OTFT it is time to focus on the applications of an OTFT. OTFT are never a replacement for the conventional silicon based transistors. Silicon based IC technology shall continue to dominate the world of computing. OTFTs are a potential competitor to the oxide TFTs. They are attractive for display applications especially with its low cost and mechanical flexibility they have immense potential to replace the oxide TFTs. Alongside display, they also find application in the field of sensors. The subsequent section shall present a few applications of OTFT technology. A comparison of a:Si-H TFT and OTFT are shown in Table 1-1.

1.3 APPLICATIONS OF OTFT

- *Display Devices:* Modern day display in laptops, computers, smartphones and tablets are using active matrix display technology. In an active matrix display technology, it is possible to control each pixel on the screen individually through a dedicated TFT per pixel. Therefore, it is possible to have clear, brighter and high quality fast displays. When the pixels are realized using a OLED, it is referred as AMOLED. In such AMOLED displays, OTFTs are employed as the pixel drivers in the back plane. Use of AMOLED with OTFT backplane enables displays to be flexible, which can be rolled, bended or folded.

Table 1-1 Comparison of a:Si-H TFT with an OTFT [13]–[15]

S.No.	Property	a:Si-H TFT	OTFT
1.	Temperature	300^{o}C	~100^{o}C
2.	Mobility	< 1cm^2/Vs	0.1 – 5 cm^2/Vs
3.	Substrate	Glass	Plastic
4.	Processing Technology	Vacuum	Solution processing
5.	Cost/Area	Medium	Low
6.	Device Type	n-type	n-type, p-type
7.	Dark Current	Poor	Excellent
8.	Current driving Stability	Poor	Excellent
9.	Impact Resistance	Poor	Excellent

- *Smart Healthcare:* Smart healthcare is an amalgamation of technologies. It involves communication, computation and monitoring of a person's health in real time. In typical scenario, a subject is equipped with sensors, which are capable of sensing essential signals like pulse, heart rate and sweat analysis. These signals are then pre-processed and transmitted to a remote sever where the data is analyzed and reported to a health care provider. The health care provider shall initiate necessary action to ensure that the subject's health is maintained. In this system, OTFTs play a significant role in the development of wearable sensors.
- *Bio-sensing*: OTFT based biological sensors are known for their low cost, flexibility, high-sensitivity and bio-compatible nature. The use of OTFTs for detection of glucose, pH, ion, DNA and enzyme has been successfully demonstrated. The operation principle is based on the modulation of the channel conductivity when the analyte interacts with the organic semiconductor.
- *Pressure and Chemical Sensors:* OTFTs can also be used in pressure sensors and chemical sensors (e-nose). Volatile organic compound sensing and chemical explosive sensing are an interesting area of application. Light weight, flexible pressure sensors could be developed using an OTFT. In these pressure sensors, OTFTs not only act as the transduction devices but also amplify the signals. Such devices when used in the form of an array could be used for tactile sensing,
- *E-ink:* Although it's a special case of display applications, it has a significance. Electronic ink is a form of electronic paper. This could be used in a variety of applications which includes: packaging, e-newspapers, counterfeit bank notes, interactive labels and indoor large area signage.

1.4 RESEARCH MOTIVATION AND OBJECTIVES

With a tremendous possibility to revolutionize the world, organic electronics as a whole and organic thin film transistor in particular provides ample opportunities both for academia and industry to pursue research. Thrust areas in OTFTs which needs rigorous, systematic investigations can be classified as shown in Fig. 1-4

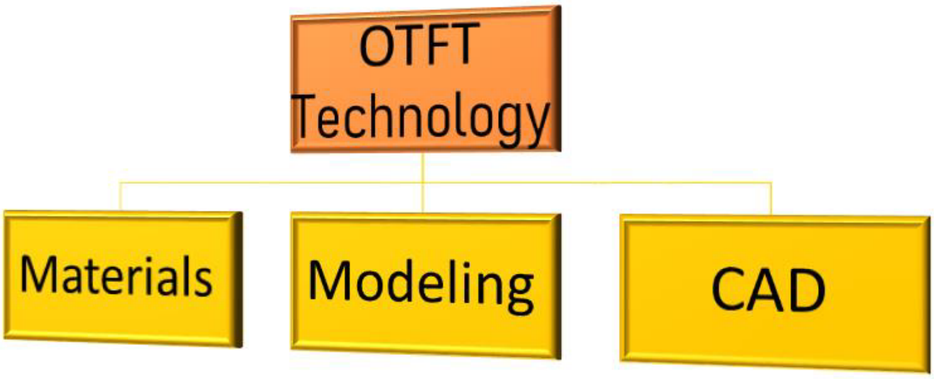

Figure 1-4 List of possible thrust areas in the field of OTFT technology

1.4.1 Materials

One advantage which organic electronics possess over the existing technologies is existence of wide variety in the material database. This provides the design engineer an opportunity to choose the materials. An added advantage with organic materials is that: the field of polymers is well studied and significant work already exists in the area of physical & chemical properties and synthesis processes. The structure of an OTFT as shown in Fig.1-1 has four different layers: *substrate*, *gate dielectric*, *active-layer* and the *source/drain electrodes*. Each of these layers has a specific purpose and hence needs a different material for their fabrication.

Substrate: This is an important layer. It forms the base for the whole device. It offers mechanical stability to the system. Preparing a low cost, smooth and compatible substrate material is a challenging task.

Gate dielectric**:** The overall performance of an OTFT largely depends on this layer. A proper choice is necessary to ensure that the threshold voltage of the device is reduced and thereby the operating voltage. It not only helps in reducing the operating voltage but also plays a significant role in improving the mobility, stability and reducing the off state current.

Active layer**:** This is the channel layer designed using an organic semiconductor (OSC). Choosing a suitable OSC is one of the most extensively pursued area in this field. It should also be noted that in addition to the purpose of channel creating between the source-drain electrodes, a functionalized active layer could help building various sensors.

Gate, Source-drain (electrodes): To make a flexible OTFT it is very essential to use non-metal electrodes. Combined with the additional requirement of transparency it becomes a challenge to find a suitable material for the electrodes.

When we discuss the materials aspect of OTFTs, it is imperative to discuss the challenges and opportunities in processing these devices. As stated earlier, a prime advantage with OTFTs is their low cost. Low cost is a consequence of the relatively less complex processing steps adapted in fabricating an OTFT. Since, most of these steps can be performed at room temperature and ambient conditions, the need for high temperature and high vacuum is eliminated. This greatly reduces the fixed cost involved in procuring and maintenance of these high end equipment. Several processing techniques which includes: spin coating, printing, casting and dip coating are employed to fabricate state of the art OTFTs. It is to be noted that: although, a few steps like thermal evaporation and sputtering are occasionally used for the deposition of electrodes and active layer, the ultimate goal of organic electronics and hence OTFTs is to standardize an end-to-end solution processable fabrication flow.

1.4.2 Modeling: charge carriers and transport

Semi-conductivity when discovered in materials was an interesting topic in the field of solid state physics. This is due to the significant difference in the charge carrier mechanism in these new class of materials when compared to the metals which were extensively studied by then. Similarly, OSCs are a new class of materials with distinguished physical and chemical properties from that of inorganic materials. It is gross generalized to say that the transport mechanism in the inorganic and organic semiconductors is similar. The fundamental physics remains the same for most of the case and deviations if any, can be modeled with slight modifications to the existing theories. However, OSCs warrant a specialized study regarding their charge carrier statistics and transport.

OSCs are a class of materials which could be either Π-conjugated oligomers or polymers. They offer properties similar to that of semiconductors alongside offering the flexibility of plastic materials. In OTFTs, the charge conduction mechanism in the channel region is a two-step process: (1) charge injection and extraction near the *source* and *drain* regions (2) charge transport along the channel near the gate dielectric-semiconductor interface. The charge-transport in conjugated materials depends on several factors like: packing of the molecules, degree of disorder in the material and the functional groups in the backbone network. Along with these, microscopic features like structural defects, impurities can also significantly impact the mobility of the charge carriers. Hence sample quality can greatly influence the performance of an OTFT.

Band like transport is missing in OSCs. This can be seen only in highly pure molecular crystals in confined environment that too at very low temperatures. Hence the use of constant mobility model (commonly used in inorganic materials) is not suitable in OSCs. At elevated temperatures, and in poly-crystalline OSC materials, defect states dominate the transport. These defects are not to be mistaken for the structural defects. These defect states are a result of the localization of charge carriers due to the weak van- der Waals forces between the molecules. In such materials, a new transport theory which could explain the carrier transport via these defects has to be explored.

1.4.3 Computer Aided Design (CAD)

The role of CAD tools in the progress of silicon VLSI is remarkable. CAD tools are an essential feature which any technology should possess for quick and faster design cycles. Availability of CAD tools greatly cuts the design time, saves resources and offers flexibility to optimize the designs without actually fabricating the device. Therefore, it is ostensibly required to develop a CAD tool for OTFTs. To be precise, CAD tool is not just a single tool, rather a set of tools which come with various capabilities like: process simulation, circuit simulation, parasitic extraction and design validation. Among these, circuit simulation stands at the top priority. Circuit design engineers are inclined to use simulators for rapid design and optimization of multi transistor circuits. Simulation Program for Integrated Circuit Environment (SPICE) tools are one such standard tools employed by circuit designers.

Developing SPICE model for OTFTs is a problem tightly coupled to the modeling of charge carrier transport in OTFTs. Several existing models although are successful in replicating the behavior of an OTFT through mathematically fitting functions it is not a true solution to the problem. Although empirical models can serve the starting point but, ultimate goal would be to develop models which reflect upon the physical phenomena involved in a real time device.

We have broadly classified the various thrust areas in the field of OTFTs. These areas can further be classified based on the intensity and scope of the research in a certain aspect. However, to the best of our knowledge, several research articles which are published in the area of OTFTs could be classified in one of these areas.

Based on the challenges presented above, we formulate the following objectives for the thesis.

1. To investigate the role of dielectric material in the performance of an OTFT and to select an appropriate dielectric material for the OTFTs.
2. To investigate the role of substrate material in the reliability of an OTFT and to choose a suitable material which can improve the reliability of OTFT.
3. To study the transport phenomena in OSCs with energetic disorder and develop a physics based analytical model for OTFTs to explain the I-V characteristics.
4. To develop a physics based SPICE model for OTFT which could be readily incorporated into existing SPICE tools.
5. To demonstrate the use of SPICE models in design and optimization of a few frequently used circuits.

1.5 ORGANIZATION OF THE THESIS

Chapter-1: is an introduction to the area of organic electronics in general and OTFTs in particular. Organic electronics, and how it differs from conventional electronics, capabilities and applications are presented. Along with this, a summary on what is OTFT? Its similarities and deviations from existing TFTs is outlined. Several commercial applications of OTFTs has been presented. A brief discussion on the challenges posed, opportunities existing in the research domain are listed and the objectives of the thesis are stated.

Chapter-2: A detailed description on the operation, performance and modeling issues of an OTFT is presented. The performance metrics of a device, their relevance to the circuits are discussed. Then a relation between the performance metrics and device structure and materials is discussed. In addition to these, the concept of charge carrier transport mechanism and its implications to the device models is presented. A brief discussion on the SPICE models is also presented.

Chapter-3: The role of gate dielectric in determining the overall performance of an OTFT is outlined. Also the various choices available for gate dielectric material, their limitations and capabilities are discussed. Then the problem of gate dielectric material selection is formulated as a Multi-Criteria Decision Making (MCDM) approach. Scientific methods to solve MCDM problems which include *Technique for Order Preference by Similarity to Ideal Solution* (TOPSIS) *VlseKriterijumska Optimizacija I Kompromisno Resenjein* in Serbian (VIKOR) and multi-objective optimization on the basis of simple ratio analysis (MOOSRA) has been proposed. A conclusion is drawn on the basis of the outcome from these techniques.

Chapter-4: Flexibility, a feature which makes OTFT an exciting choice among the existing TFT technologies, warrants the need for reliability investigation under mechanical stress due to bending. Along with mechanical stress other possible non-electrical failures due to the thermal stress are discussed and the role of substrate in mitigating or delaying these failures is presented. Subsequently, various possible substrate materials which can be solution processed are discussed and then using the interval TOPSIS technique, conclusions are drawn regarding the best fit choice for substrate material in flexible OTFTs.

Chapter-5: The focus in this chapter is to develop a surface potential based current model for an OTFT. Since, OTFTs are accumulation mode devices, I-V models based on threshold voltage are not a good fit. Since the definition of threshold voltage, which was originally defined for inversion mode devices can't be implied for accumulation mode devices. The trap states in the OSC layer are modeled using a double exponential density of states function and subsequently an all-region I-V expression is derived by calculating the surface potential near the semiconductor-dielectric interface.

Chapter-6: A SPICE model has been developed for OTFTs. A semi-empirical SPICE Level-3 model is adapted for the case of OTFTs. Furthermore, the use case of these models is presented in terms of their applicability in circuit design both in analog and digital circuits is presented.

Chapter-7: A summary of the work is presented along with the significant research outcomes and their implications for the real world problem is elucidated. Along with these, a set of problems are presented as a future scope along with the need and a suggestive solutions based on our understanding of the field.