Characterization and Contact Effects of Organic Thin Film Transistor

A thesis is submitted in partial fulfilment of the requirements for the degree of

B.Sc. in Electrical Electronics and Communication Engineering

Submitted by

Md. Sayem Rahman Bhuiyan	Student ID : 201116045
Hasib Ahmed Mazumder	Student ID: 201116058
Nasim Ben Zafar	Student ID : 201116059

Under the Supervision of

Dr. MD.Kawsar Alam

Assistant Professor, Department of Electrical and Electronics Engineering

Bangladesh University of Engineering and Technology

Department of Electrical Electronics and Communication Engineering

Military Institute of Science and Technology

December, 2014

CERTIFICATION

This thesis paper titled Characterization and Contact Effects of Organic Thin Film Transistor submitted by the group as mentioned below has been accepted as satisfactory in partial fulfillment of the requirements for the degree B.Sc. in Electrical Electronics and Communication Engineering on December 2014.

Group Members:

MD.Sayem Rahman Bhuiyan
Student ID: 201116045
EECE – 09, MIST

Hasib Ahmed Mazumder
Student ID: 201116058
EECE – 09, MIST

Nasim Ben Zafar
Student ID: 201116059
EECE – 09, MIST

Supervisor:

Dr.Md. Kawsar Alam
Assistant Professor
Dept of EEE, BUET

DECLARATION

This is to certify that the work presented in this thesis paper is the yield of study, analysis, simulation and research work carried out by the undersigned group of students of Electrical Electronics and Communication Engineering (EECE-09), Military Institute of Science and Technology (MIST), Mirpur Cantonment, under the supervision of Dr. Md.Kawsar Alam, Assistant Professor, Department of Electrical and Electronics Engineering (EEE), Bangladesh University of Engineering and Technology, Dhaka, Bangladesh**.**

It is also declared that neither of this thesis paper nor any part of this thesis has been submitted anywhere else for the award of any degree, diploma or other qualifications.

Group Members:

MD.Sayem Rahman Bhuiyan
Student Number: 201116045
EECE – 09, MIST

Hasib Ahmed Mazumder
Student ID: 201116058
EECE – 09, MIST

Nasim Ben Zafar
Student ID: 201116059
EECE – 09, MIST

Supervisor:

____

Dr. Md.Kawsar Alam
Assistant Professor
Dept of EEE, BUET

ACKNOWLEDGEMENT

We are thankful to Almighty Allah for his blessings for the successful completion of our thesis. We would like to take the opportunity to express our heartiest gratitude, profound indebtedness and deep respect go to our supervisor Dr. Md.Kawsar Alam, Assistant Professor, Department of Electrical and Electronics Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, for his constant supervision, affectionate guidance and great encouragement and motivation from the very beginning to the final accomplishment of the thesis work. His keen interest on the topic and valuable advices throughout the study was of great help in understanding of the subject, trace out the line of works and make out the final output to complete the thesis.

We are especially grateful to other reputed Professors / Professionals as well as students of both Bangladesh University of Engineering and Technology (BUET) and Department of Electrical Electronics and Communication Engineering (EECE) of Military Institute of Science Technology (MIST) for providing their all out support during the thesis work.

Finally, we would like to thank our families and our course mates for their appreciableassistance, patience and suggestions during the course of our thesis.

ABSTRACT

Contact effects in OTFTs are affected by the materials used for substrates, electrodes, or semiconducting films. Electrical characteristics of organic thin film transistor is frequently affected by contact effects and thus it strongly influence the performance of transistor. The contact effects are stronger when the value of channel length is small where the contact resistance is comparable to or larger than channel resistance. To understand the effects of the contacts in OTFTs, the physical or geometrical origins of these effects are treated organic-thin-film structures. In this paper, we focus on the incorporation of the contact effects in compact models of OTFTs. We used a simple resistance model and a compact model for considering the contact resistance effect and extract the I-V characteristics of organic thin film transistor.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

Chapter 1: Introduction

During the last decades there has been an enormous interest in the development of electronic devices based on polymers and organic films. Since the first fabrication of polymeric and organic materials, characterized by their long and short lengths of their molecules, respectively, many efforts have been devoted to realize inexpensive polymeric and organic thin film transistors [1].

All Organic TFTs became technologically attractive due to the possibility to be realized by low temperature and low cost manufacturing, on large area and flexible substrates [2]. However, there are disadvantages too that must be solved. Many efforts are devoted to improve the performance of organic thin film transistors by increasing the charge carrier mobility. Also efforts are devoted to treat the effects associated to the contacts regions of the transistor. It has been seen that a substantial part of the externally applied drain – source voltage, V_{DS}, drops across the contact between the organic material and the source and drain metal electrodes, mainly between the source and the organic material [3]. Thus, in addition to the limited drift in the organic film, there is one more limit for the charge flow in OTFT owing to contact effects. The contact regions can alter the output characteristics of the transistor making the traditional crystalline MOS model unable to interpret the performance of the transistor.

In that sense, many efforts are also devoted to develop models aiming to reproduce output characteristics in the transistor, and to develop methods of parameter extraction [3] [4] [5] [6]. The objective of this study is to compare the theoretical models of organic thin film transistors considering the contact effects.

1.1 Transistor

The transistor is invented by three scientists at the Bell Laboratories in 1947. It has replaced the vacuum tube as an electronic signal regulator. The main function of a transistor is regulating the current or voltage flow and also it acts as a switch or gate for electronic signals. A transistor consists of three layers of a semiconductor material, each capable of carrying a current. A semiconductor is a material such as germanium and silicon that conducts electricity. It's somewhere between a real conductor such as copper and an insulator.

The semiconductor material is given special properties by a chemical process called *doping*. The doping results in a material that either adds extra electrons to the material (which is then called *N-type* for the extra negative charge carriers) or creates "holes" in the material's crystal structure (which is then called *P-type* because it results in more positive charge carriers). The transistor's three-layer structure contains an N-type semiconductor layer sandwiched between P-type layers (a PNP configuration) or a P-type layer between N-type layers (an NPN configuration) [7].

There are three terminals of a transistor. (1)Emitter; (2) Base; (3) Collector. Emitter is a negative lead whereas collector being a positive led and base the activating lead. Transistors are the fundamental building blocks of modern electronic devices and all existing transistors contain semiconductor junctions. The most common type of junction is the p–n junction, which is formed by the contact between a p-type piece of silicon doped with impurities to create an excess of holes and an n-type piece of silicon, doped to create an excess of electrons.

1.2 History

The transistor was invented by John Bardeen, Walter Brattain and William Shockley at Bell Labs in December, 1947. Announced to the public in June, 1948, this new device had characteristics which could be used to overcome many of the fundamental limitations of vacuum tubes - transistors had very long life, were small, lightweight and mechanically rugged, and required no filament current. The commercial use of transistors increased dramatically in the 1950's, beginning with telephone switching equipment and military computers in 1952, hearing aids in 1953, and portable radios in 1954. In 1953. The rapid rise of transistor technology in the 1950s can be attributed to the contributions of a few major companies, including Bell Labs/Western Electric, Fairchild, General Electric, Motorola, Philco, Raytheon, RCA, Sylvania and Texas Instruments.

The first types of transistors available in the 1950s were made from germanium. This is an element known as a semiconductor, which is a category of material that is neither fully conducting nor fully insulating when an electrical voltage is applied. Semiconductors are ideally suited for the construction of amplifying crystals, as the earliest transistors were sometimes described. Another semiconductor element, silicon, was the basis for extensive research in the early 1950s because it was recognized that transistors fabricated from silicon would have superior performance at higher operating temperatures. By 1954, commercial silicon transistors were available from Texas Instruments and the basic concepts used in the development of these devices have been continuously improved over the decades and have led directly to the development of today's integrated circuit and microprocessor devices.

During these first two decades of transistor history, a variety of different device types were developed and this diversity of technologies has lead to a rich historical backdrop of early transistor shapes, sizes, specifications and circuits. [8]

After the invention of inorganic field-effect transistors (FETs) have been the backbone of the semiconductor industry. However, organic thin- film transistors (OTFTs) have received increasing interest because of their potential applications in chemical vapor sensors due to a strong charge transport dependence on chemical environments. [9] [10] [11] [12] [13] Although the performance, such as carrier mobility, of organic semiconductor devices does not compete with those of single-crystalline inorganic semiconductors, such as Si, Ge, and GaAs, they still have considerable advantages in terms of large-area and low-cost manufacturing of the electronic devices, chemically sensitive field-effect transistors (Chem FETs) and sensors. For example, the unique processing characteristics and demonstrated performance of OTFTs suggest that they can be competitive candidates for existing or novel thin film transistor applications requiring chemical vapor sensing, structural flexibility and low temperature processing. Research efforts on semiconducting conjugated organic thiophene oligomers, thiophene polymers, metal phthalocyanine (MPc) and the small pentacene molecule have led to dramatic improvements in the mobility of these materials by five orders of magnitude due to innovative chemistry and processing, as well as the increasing ability to control the self-assembly and ordering of oligomers, polymers, and Nano crystals over the last few decades.

1.3 Transistor Type

There are a varieties and different types of transistors created in different step of transistor revolution.

1.3.1 BJT (Bipolar Junction Transistor)

The most common type of transistor is called bipolar and these are divided into NPN and PNP types. Their construction-material is most commonly silicon (their marking has the letter B) or germanium (their marking has the letter A). Original transistor were made from germanium, but they were very temperature-sensitive. Silicon transistors are much more temperature tolerant and much cheaper to manufacture.

The BJT can be effectively operated in there different modes according to the external bias voltage applied at each junction. i.e. Transistor in active region, saturation and cutoff.

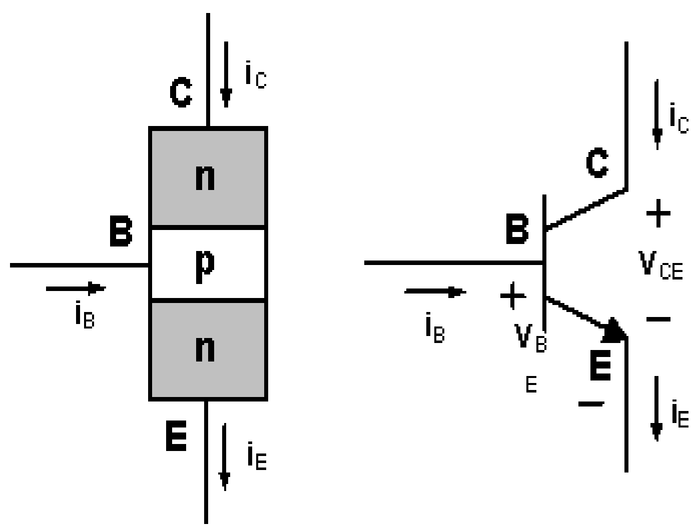

Figure 1-1: Schematic symbol of an npn, BJT [14]

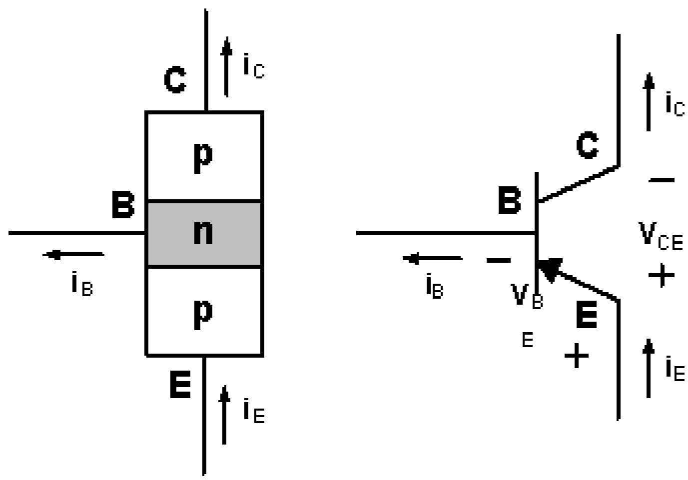

Figure 1-2: Schematic symbol of an npn, BJT [14]

- Active Region – the transistor operates as an amplifier and $I_c = \beta \times I_b$
- Saturation – the transistor is “Fully-ON” operating as a switch and $I_C = I_{sat}$
- Cut-off – the transistor is “Fully-OFF” operating as a switch and $I_C = 0$

1.3.2 FET (Field Effect Transistor)

The **field-effect** transistor (FET) relies on an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material. FETs are sometimes called *unipolar transistors* to contrast their single-carrier-type operation with the dual-carrier-type operation of bipolar (junction) transistors (BJT). The *concept* of the FET predates the BJT, though it was not physically implemented until *after* BJTs due to the limitations of semiconductor materials and the relative ease of manufacturing BJTs compared to FETs at the time.

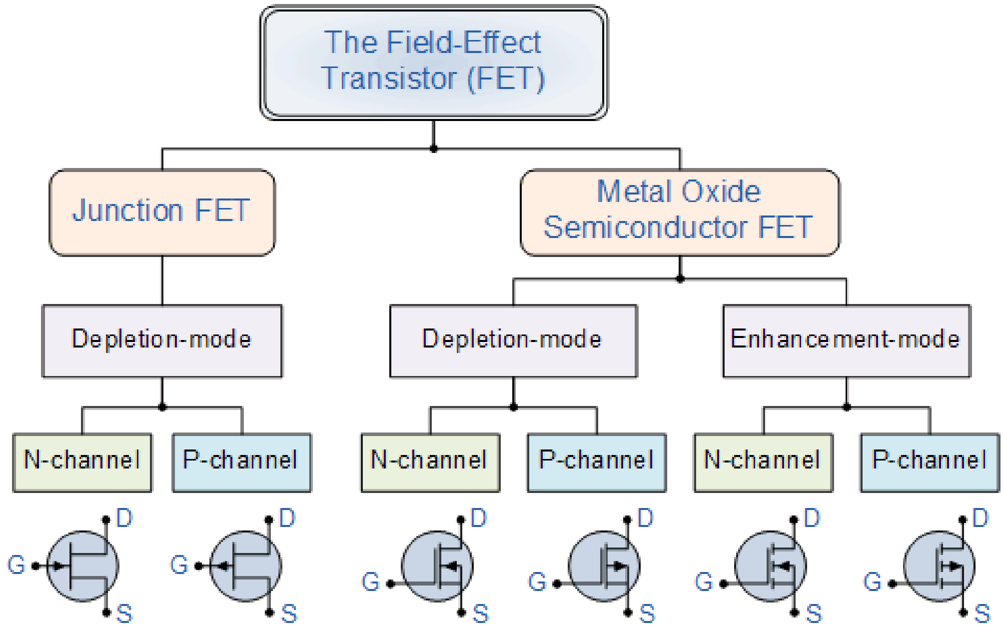

Figure 1-3: Different types of FET [15]

FETs can be majority-charge-carrier devices, in which the current is carried predominantly by majority carriers, or minority-charge-carrier devices, in which the current is mainly due to a flow of minority carriers. The device consists of an active channel through which charge carriers, electrons or holes, flow from the source to the drain. Source and drain terminal conductors are connected to the semiconductor through ohmic contacts. The conductivity of the channel is a function of the potential applied across the gate and source terminals.

The FET's three terminals are:

- Source (S), through which the carriers enter the channel. Conventionally, current entering the channel at S is designated by IS.

- Drain (D), through which the carriers leave the channel. Conventionally, current entering the channel at D is designated by ID. Drain-to-source voltage is VDS.
- Gate (G), the terminal that modulates the channel conductivity. By applying voltage to G, one can control ID.

There are two main types of field effect transistor, the Junction Field Effect Transistor or JFET and the Insulated-gate Field Effect Transistor or IGFET), which is more commonly known as the standard Metal Oxide Semiconductor Field Effect Transistor or MOSFET for short.

1.3.3 JFET

JFET is a unipolar-transistor, which acts as a voltage controlled current device and is a device in which current at two electrodes is controlled by the action of an electric field at a p-n junction. Field effect transistor is a device in which the current is controlled and transported by carriers of one polarity (majority) only and an electric field at the p-n junction region controls the current between other two. There are two basic configurations of junction field effect transistor, the N-channel JFET and the P-channel JFET. The symbols and basic construction for both configurations

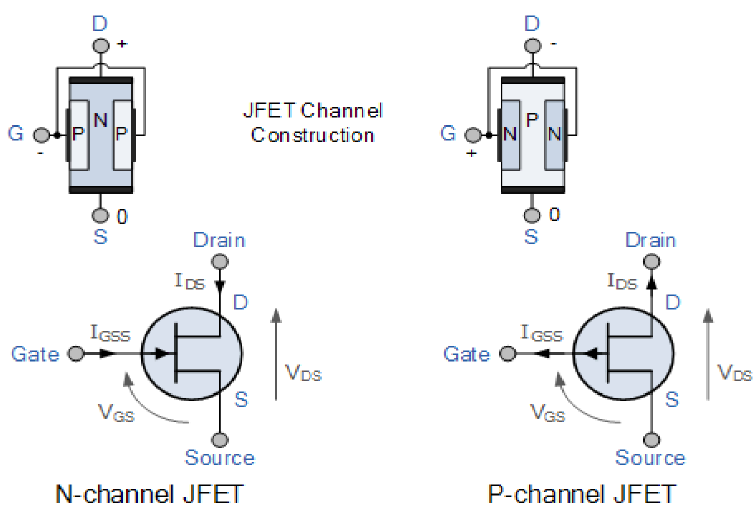

Figure 1-4 : Symbol and basic configuration of two types JFET [16] of JFETs are shown below. A N-Channel JFET is a JFET whose channel is composed of primarily electrons as the charge carrier. This means that when the transistor is turned on, it is primarily the movement of electrons which constitutes the current flow. An N-Channel JFET is composed of a gate, a source and a drain terminal.

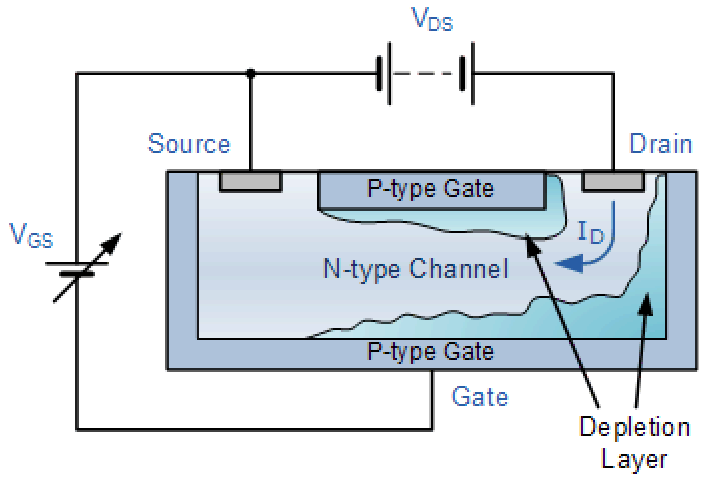

Figure 1-5: Cross Sectional View of N-Channel JFET *[17]*

This transistor is made by forming a channel of N-type material in a *P-type substrate*. Three wires are then connected to the device. One at each end of the channel. One connected to the substrate. In a sense, the device is a bit like a PN junction diode, except that there are two wires connected to the N-type side.

JFET is a high-input resistance device, while the BJT is comparatively low. If the channel is doped with a donor impurity, n type material is formed and the channel current will consist of electrons. If the channel is doped with an acceptor impurity, p-type material will be formed and the channel current will consist of holes. N-channel JFET have greater conductivity than p channel types, since electrons have higher mobility than do holes; thus n-channel JFETs are approximately twice as efficient conductors compared to their p-channel counterparts

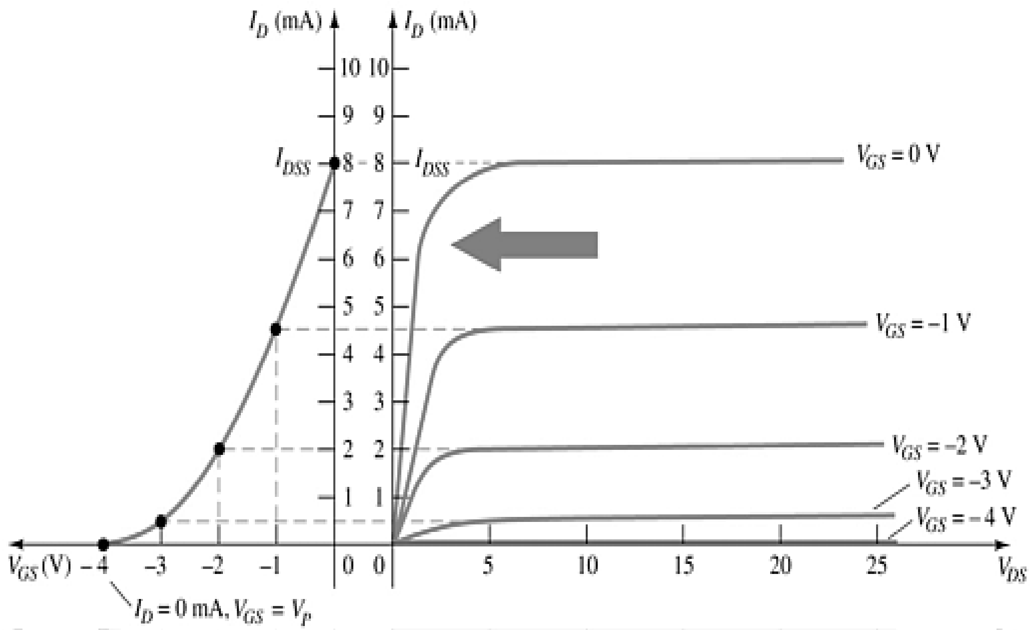

Figure 1-6: JFET Transfer Curve *[18]*

1.3.4 MOSFET

MOSFET Field effect transistor is a unipolar- transistor, which acts as a voltage-controlled current device and is a device in which current at two electrodes drain and source is controlled by the action of an electric field at another electrode gate having in-between semiconductor and metal very a thin metal oxide layer.

Enhancement mode MOSFET based analog switches use the transistor channel as a low resistance to pass analog signals when on, and as a high impedance when off. Signals can flow in either direction across a MOSFET switch. In this application the drain and source of a MOSFET exchange places depending on the voltages of each electrode compared to that of the gate and the direction of current flow-drain currents; exceeding these voltage or current limits will potentially damage the switch.

Almost all electronics and appliances, including personal computers, contain millions of silicon MOSFETs on a thumbnail sized chip. Within a computer most MOSFETs are located on the microprocessor chip, mounted on the motherboard and conspicuously cooled by its own heat sink and cooling fan. The microprocessor chip itself is mounted in an electronic package with hundreds of interconnecting pins and connected to the chip by hundreds of tiny bond wires [19] [20].

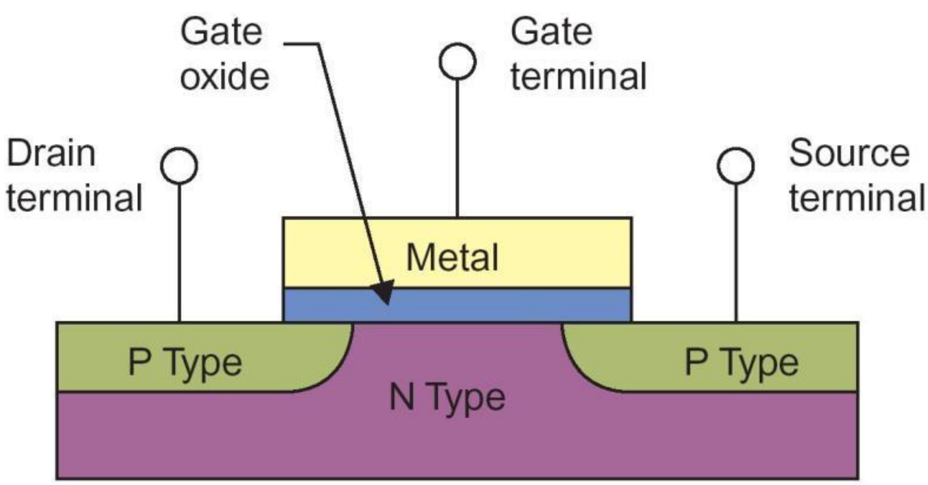

Figure 1-7: Basic Structure of MOSFET *[21]*

1.3.5 MISFET

The most prominent and widely used FET in modern microelectronics is the MOSFET. There are different kinds in this category, such as MISFET (metal–insulator–semiconductor field-effect transistor), and IGFET (insulated-gate FET). A schematic of a MISFET is shown in Figure 1.8. The source and the drain are connected by a semiconductor and the gate is separated from the channel by a layer of insulator. If there is no bias (potential difference) applied on the gate, the band bending is induced due to the energy difference of metal conducting band and the semiconductor Fermi

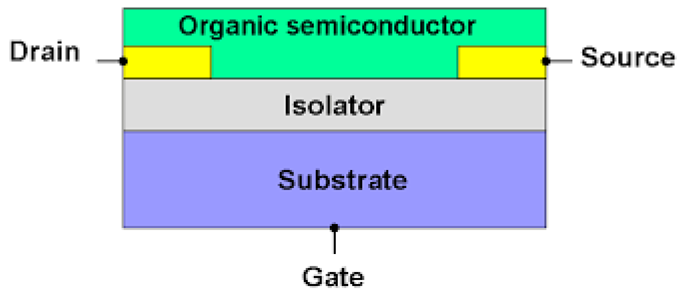

Figure 1-8: Basic Structure of MISFET

level. Therefore a higher concentration of holes is formed on the interface of the semiconductor and the insulator. When an enough positive bias is applied on the gate contact, the bended band becomes flat. If a larger positive bias is applied, the band bending in the opposite direction occurs and the region close to the insulator-semiconductor interface becomes depleted of holes. Then the depleted region is formed. At an even larger positive bias, the band bending becomes so large that the Fermi level at the interface of the semiconductor and the insulator becomes closer to the bottom of the conduction band than to the top of the valence band, therefore, it forms an inversion layer of electrons, providing the conducting channel. Finally, it turns the device on.

1.3.6 FinFET

FinFET technology takes its name from the fact that the FET structure used looks like a set of fins when viewed. The FinFET transistors employ a single gate stacked on top of two vertical gates allowing for essentially three times the surface area for electrons to travel.

The FinFET is a technology that is used within ICs. FinFETs are not available as discrete devices. However FinFET technology is becoming more widespread as feature sizes within integrated circuits fall and there is a growing need to provide very much higher levels of integration with less power consumption within integrated circuits [22]

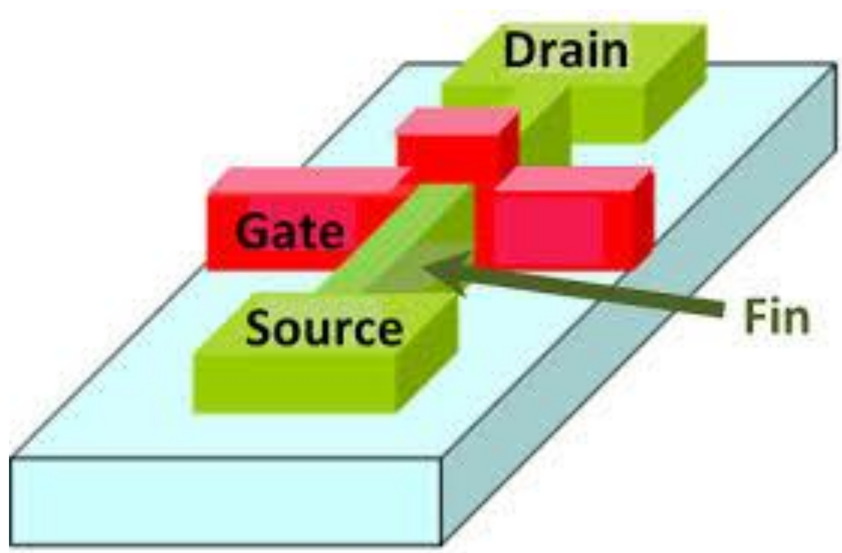

Figure 1-9: Basic Structure of FinFET [23]

1.3.7 TFT (Thin Film Transistor)

The TFT is a field effect transistor (FET). Its structure and operation principles are similar to those of the metal oxide field effect transistor (MOSFET), which is the most critical device component in modern integrated circuits (ICs).

The breakthrough in the field came from a report in 1979 of the first functional TFT made from hydrogenated amorphous silicon (a-Si:H) with a silicon nitride gate dielectric layer. Figure 1.10 shows the different configuration of TFT [24]. The fabrication process is simple and the device is stable at room temperature under atmospheric conditions. The composing films were deposited by plasma-enhanced chemical vapor deposition (PECVD), which can be easily carried out on commercial, large-area, low-temperature glass substrates with high throughput.

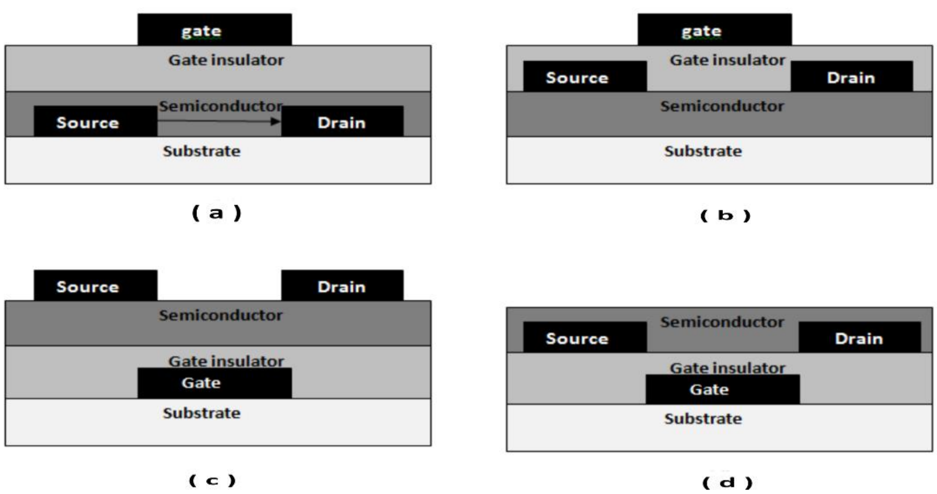

Figure 1-10: TFT configurations: (a) Top-gate bottom-contact and (b) Top-gate top-contact (c) Bottom-gate top-contact; and (d) Bottom-gate bottom-contact. The dashed line indicates charge flow [24]

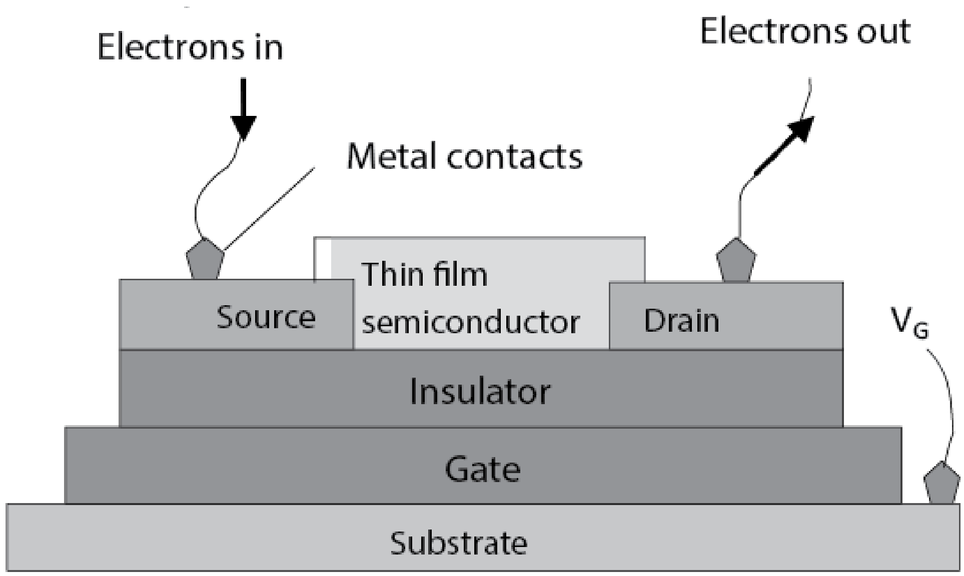

Figure 1-11: Basic Thin Film Transistor Structure

1.3.7.1 Types of TFT

There are different types TFT present in transistor market.

(1) **Amorphous Silicon TFT**

(2) **Poly-silicon TFT**

(3) **Organic TFT**

(4) **Oxide TFT**

1.4 OTFT

Organic TFTs based on organic semiconductors have emerged in the last decade as an alternative technology. Organic thin film transistor (OTFT) performance has improved rapidly over the past several years, especially pentacene TFTs. OTFTs based on pentacene, α,α'-didecyloligothiophenes, et al. with field-effect mobility > 0.5 $cm^2/V\text{-}s$ have been reported, which equals or exceeds that of a-Si:H TFTs [25]. In addition, OTFTs offer the possibility for fabrication on large, cheap, polymeric substrates and processing from solutions. RFIDs and electronic paper are two applications where these merits are of great value.

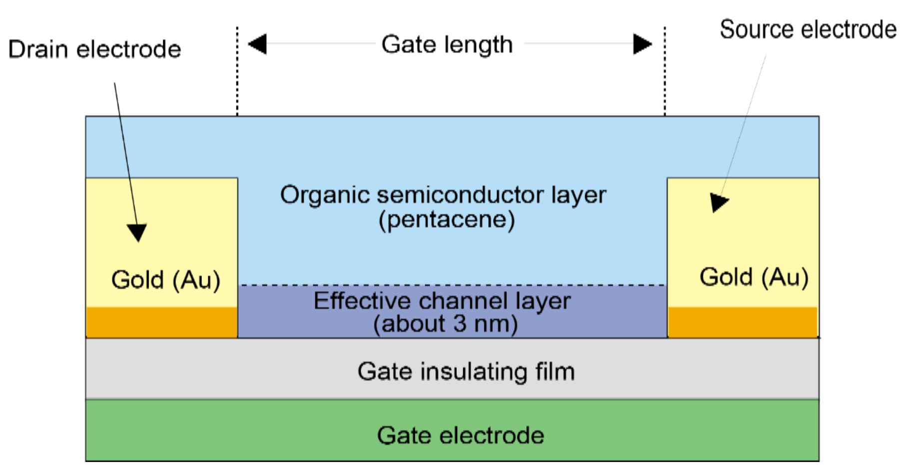

Figure 1-12: Cross sectional view of the OTFT

1.4.1 OTFT Technology

In achieving this, finding an organic semiconductor that meets the criteria for OTFTs, particularly large field-effect mobility, is a crucial step. Since Ebisawa demonstrated polymer TFTs using polyacetylene in 1983, extensive studies have been carried out with many reports of field-effect mobility in semiconducting polymers less than 0.01 cm_2/V-s [26]. The progress made has improved mobility, where today they are about 0.12 cm_2/V-s with the synthesis of regioregular poly-3-hexylthiophene and the refined processing developed in the 1990s. Such device performance is applicable to low-end electronics such as electronic paper and identification tags, and there is much interest in continuing futher research. Other interesting reports of OTFTs using small-molecule organic semiconductors like α-sexithiophene and pentacene have shown larger field-effect mobility (> 0.1 cm2/V-s) than that of semiconducting polymers in the first half decade of the 1990s. Pentacene emerged as the most promising candidate amongst potential materials. Applications based on pentacene OTFTs became very attractive when the field-effect mobility in these OTFTs passed 1.0 cm2/V-s in 1996. The reproducibility of devices was improved by the results presented in this chapter. Pentacene OTFTs with even larger mobilities were also reported, where this level of device performance is comparable to that of a-Si:H TFTs [27]. These advances show pentacene TFTs have the potential for high-end applications such as the backplanes of active matrix displays. In addition, a few new classes of small-molecule organic semiconductors were designed and synthesized to provide more possible improvements. They often consist of one or two aromatic backbones (thiophenes or acenes) similar to those molecules that have been known to have large field-effect mobility. Examples include OTFTs based on soluble functionalized pentacene and anthradithiophene, where recently they have shown some interesting results. Nevertheless, fundamental understanding and improvement of OTFT active materials are still required for further advancement of OTFT technology.

1.4.2 Research on OTFT

Research using organic materials (compounds based on carbon) as the material for transistors began in 1984. Although the research in Japan led the world at that time, the carrier mobility of those materials was nowhere near that of even amorphous silicon and the technology was far from practical. The performance of organic transistors im- proved greatly at the start of the 1990s. Then in 1997, instead of thiophene, the original organic material used in this research, pentacene was used, and a carrier mobility of the order of 1 cm2/Vs, which is comparable to that of amorphous silicon, was reported. Additionally, Bell Laboratories caused an uproar by announcing an organic transistor based on a self-assembled monolayer film, an event that became the catalyst that created a worldwide boom. In recent years, sessions related to organic transistors at international conferences have become standing room only events.

Even if it were the case that characteristics similar to amorphous silicon appeared at the research and development phase, that in itself would not be enough to cause a shift to a new generation. There were still many issues to overcome at the basic research stage to meet the performance requirements for transistors. In the first place, the operating mechanisms of the organic transistor have not yet been fully understood. Although operation of the organic transistor is in principle the same as that of silicon field-effect transistor (FET), how carriers flow in organic materials is not adequately understood. However, Sony's Fusion Domain Laboratory, Materials Laboratories has now explicated one part of those principles, namely the path that carriers pass through. Before we discuss into that explanation, we would first like to summarize why researchers around the world are taking pains to make organic transistors practical. Technological Challenges

1.4.3 Technological Challenges

Organic electronics have reached early stages of commercial viability. Personal electronic devices incorporating small displays based on organic light-emitting diodes (OLEDs) are now available. However, many challenges still remain that are currently hindering the wide adoption of OTFTs in electronic devices. The shortcomings of OTFTs include limited charge carrier mobility, high contact resistance, relatively higher operating voltages, device reliability issues (e.g., stability, shelf-life under operation), and limited availability of robust/mature patterning techniques and fabrication processes that are compatible with organic thin films. These technical challenges can be grouped into two categories: device performance and device manufacture.

1.4.5 Advantages of OTFT over others transistor

These organic transistors have prime advantages over classical inorganic ones. They can be fabricated at a lower temperature which allows them to be made on a low cost plastic substrate, resulting in a flexible device which is unbreakable and very low-weight.

Pentacene-based organic thin-film transistors (OTFTS) are attractive because of their inherit merits of low cost, small weight and visible-light transparency, for potential use in applications such as organic displays, flexible displays and low-cost integrated circuit (IC). The low thermal budget and rapid processing have strong advantages of energy saving and environment friendly.

1.4.6 Disadvantages of OTFT

Conventional OTFTs require a high operating voltage and show a poor sub threshold swing, which are opposite to the low power technology trend and detract from their suitability in IC operation. Besides, the relative low transistor current is difficult to drive the need high operation current of organic light-emitting diode (OLED).

1.4.7 Application of OTFT

OTFTs have already been demonstrated in applications such as electronic paper [28], sensors [24] and memory devices including radio frequency identification cards (RFIDs) [29]. These transistors are especially important as drive elements in niche applications such as the displays of mobile devices and televisions using the Active-Matrix Organic Light-Emitting Diode technology. Sensors, smart labels, solar cells, or smart clothing are other emerging and innovative applications where these transistors work as the main or control element [30].

Although OTFTs are not meant to replace conventional inorganic TFTs because of the upper limit of their switching speed they have great potential for a wide variety of applications, especially for new products that rely on their unique characteristics, such as electronic newspapers, inexpensive smart tags for inventory control, and large area flexible displays.

1.5 Thesis Statement

The potential applications and markets discussed above have attracted great interest in the development of an organic TFT technology. The early work on organic thin film transistors in the last decade has been expanded to cover a broad work on OTFTS. In this work, we have studied contact effects of pentacene p-channel OTFTs, to characterize and model the contact effect in OTFT.

1.6 Literature Review

Interest in organic thin film transistors (OTFTs) has grown rapidly in the last decade. However, the theory of electrical characteristics of OTFTs lags experiments, so it is difficult to provide the required feedback to device designers and technologists. In spite of impressive advances in organic electronic devices, theoretical explanation of their operation is still incomplete. Among other side effects of OFETs, contact effects is decisive.

The electrical characteristics of organic thin film transistors (OTFTs) are frequently affected by contact effects, which can seriously influence the transistor performance. This is because the "parasitic" voltage drop at the contacts reduces the effective drain-source bias voltage applied to the intrinsic channel of the transistor and, consequently, reduces the device current [31]. The contact resistances RC in OTFTs shows a wide range from 10 kΩcm up to 10MΩcm [32]. The strong influence of contact effects on OTFT performance of the source and drain contact metal was observed as early as 1996 by Lin et al [33]. Contact resistance effects are strongly influenced by the device architecture [6]. With decreasing device dimensions, the contact resistance RC will start a dominating part on the channel resistance (R_{CH}) and therefore will play an important part in device operations. The importance of the contact resistance R_C is more relevant at large carrier mobility and small channel length, where its value may become comparable to or larger than the channel resistance R_{CH}. In general, when the channel length is shorter than a critical channel length L_C, the contact effects severely affect the performance of OTFTs [31]. Considering the contact effect a link between a simple resistance model and the linear-regime output characteristics of OTFTs can be established using simple resistance model. A method is proposed to measure Drain–source voltage V_{DS} dependent drain current I_D at a constant gate–source voltage V_{GS} to examine the V_{GS} dependence of the transistor total in the linear regime of OTFTs in [34].

On the other hand, the low-temperature performances of OTFTs have been reported by Yoneya et al. [35] and Nelson et al. [36]. Yoneya et al. found that contact resistance, RC decreases with decreasing temperature. Nelson et al. predicted contact effects is temperature dependent.

As pentacene has become one of the most widely studied and used molecules in both academia and industry, much interest has grown in pentacene for various applications. Ohmic contacts to pentacene are a crucial part of many types of electronic and optoelectronic devices in the pentacene system [34]. Recently several models based on the current crowding mechanism have been published to show the explanation of VG dependence of RC in OFETs [37], [38], [39]. Another DC characteristics model that incorporates a gate-voltage dependent mobility and highly nonlinear drain and source contact series resistances is proposed in [6]. A generic analytical model for extracting I-V curves of OTFTs is proposed in [40], [41]. Some work is done to modeling a comapact model model including both linear and nonlinear behaviors for the contact I–V curves, with its parameters and the injection and transport mechanisms present in the metal-organic contacts and dependence of the I–V curves with the gate voltage and the temperature in [30], [42], [43] recent year.

1.7 Thesis Outline

In Chapter 1 we have discussed the details about OTFT and research on OTFT. Different types of transistor and their details are discussed here. A brief history of OTFT, its technology and its progresses are discussed in this part. This chapter also summarize the previous work of OTFT. The objectives of our works are also stated here.

Chapter 2 reviewed the theoretical overview of OTFT, their structural and electrical characteristics. Here we have discussed the compact model of the OTFT with their parameters.

In chapter 3 we have shown the I_V curve and different output curve extracted using the OTFTs model discussed in this work. A comparison of generic ideal FET model and compact model are shown in this part. We simulate all work with MATLAB software and all work details discussed in this chapter

Chapter 4 has the conclusion and. Future work is proposed in here

Chapter 2

2.1 Organic Semiconductor

Plastics, or polymers, are found throughout everyday life in applications ranging from packaging to videotape. This is because they can be readily shaped and manufactured, and their properties can be tailored to a particular application. Conventional plastics are electrical insulators, but the discovery of a remarkable class of polymers that can conduct electricity has opened a new era of plastics science and technology. Even more significant are the opportunities provided by semiconducting organic materials.

Organic semiconductors have been known since the late 1940s. However, the first transistor based on organic semiconductor was, however, reported in 1986 [44]. The active material used was polythiophene, which belongs to the family of conducting polymers that were discovered in the late

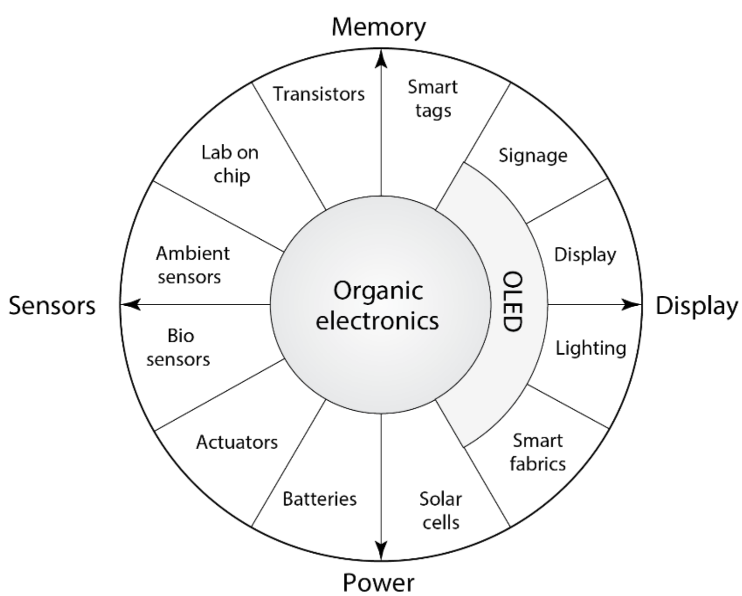

Figure 2-1: A broad range of products and technologies inspired by organic electronics

1970s [45]. Alan Heeger, Alan G. MacDiarmid and Hideki Shirakawa, the inventors of polyacetylene, were awarded the Nobel Prize in chemistry in 2000.

2.2 Types of Organic semiconductor

Organic semiconductor can be either p-type or n-type. In p-type semiconductors, the majority carriers are holes, which in n-type semiconductors, the majority carriers are electrons. Accordingly, the transistors are p-channel transistors or n-channel transistors. Most of the organic semiconductors investigated so far are p-type in their non-doped condition because p-type semiconductors are stable in air and have relatively high carrier mobility when used in organic thin-film transistors (OTFTs). Pentacene is an example of p-type organic semiconductor. Unlike p-type organic semiconductors, most n-type organic semiconductors are sensitive to air and moisture [46] because the organic anions, in particular carbanions, react with oxygen and water under operating conditions. Furthermore, n-type organic semiconductors have relatively low field-effect mobility [47].

Organic conjugated materials used in OTFTs can be categorized into polymers and small molecules. Conjugated polymers present the advantage of being amenable to specific deposition techniques that have been developed for conventional polymers. Their main shortcoming is that their performance is still lower than that of small molecules. Promising performance has been reported for small molecules, which currently offer higher mobility than hydrogenated amorphous silicon. However, high performance requires high ordering, particularly in the vicinity of the insulator-semiconductor interface, a constraint that may be difficult to fulfill when specific deposition methods, such as self-assembled monolayer (SAM), are used.

2.3 Pentacene OTFTs

Pentacene has become one of the most widely studied molecules in both academia and industry. It can be said that pentacene OTFTs are representative of the OTFT technology. Large effort on fabricating organic thin-film transistors using small-molecule organic semiconductors has been reported by Garnier, Jackson, and their collaborators [33]. OTFTs using pentacene as the active material have been of great interest because of their superior device performance compared to other organic semiconductors, particularly their large field-effect mobility typically > 1 cm^2/V-**s** [48]. Such high performance is attributed to the electronic transport of pentacene films due to their high molecular ordering. Many studies point out that the morphology of vapor-deposited pentacene films on various substrates is dependent on deposition conditions and substrate conditions. Examples are the deposition rate, surface roughness, substrate temperature, surface preparation, surface chemistry, and surface energy.

Pentacene, one of the conjugated polyacenes, is a p-type small molecule organic semiconductor consisting of five fused aromatic rings as illustrated in Figure 2.2. It was reported three decades ago that pentacene powders at room temperature show high electrical conductivity, as high as 0.1 ohm-cm under high pressure even though it is insulating under ambient pressure [49] Increased attention to pentacene OTFTs started in mid-1990s when its outstanding device performance was reported [25] [33]. The large potential for pentacene TFTs for electronics was then demonstrated with a variety of logic circuits and flat panel displays.

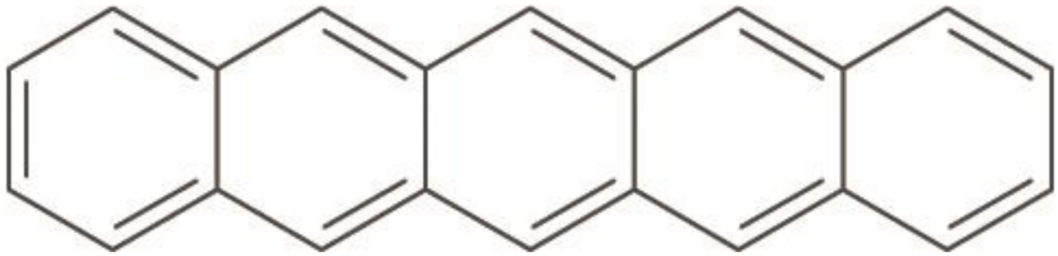

Figure 2-2: Pentacene Molecule [50]

The growth and morphology of pentacene films are greatly related to the properties of the surface on which pentacene molecular crystals nucleate and grow. It was found that the chemical modifications of gate dielectric or source/drain electrodes can improve the carrier transport and injection and thus yielding higher performance.

2.4 Theoretical Overview of Organic TFT

Many impressive advances in the field of organic electronics have proved capable of performing a wide variety of functions. The practical advantages primarily root from the following: (1) Large-area electronics in which the active devices are distributed and embedded over a large area. (2) Low-cost or large volume electronics. Cheap and disposable electronics are increasingly used as the replacement for bar codes and various forms of personal identification. (3) Flexible construction and electronics where ruggedness is necessary. (4) New advances in fabrication methods that may impact the manufacturing of organic electronics and conventional electronics. (5) Novel functionality. In the Center for Thin Film Devices at Penn State, one of the important areas is on the research and development of organic thin film transistors (OTFTs) that perform switching and amplifying functions, like those at a-Si:H TFTs, which are currently used in the pixel control of most active-matrix flat-panel displays.

2.5 Basic Operation of OTFT

A thin film transistor is a special type of field effect transistor formed by placing thin films of the dielectric layer as well as an active semiconductor layer and metallic contacts onto a supporting substrate. OTFT differs from MOSFET in certain ways. Firstly, OTFT works in accumulation layer while MOSFET works under inversion layer. Secondly, OTFT is amorphous in nature as compared to MOSFET, which is crystalline in nature. Thirdly, OTFT is undoped while MOSFET is mostly Si-doped. The working principle for OTFT is as shown in Figure 1.11. The applied gate voltage (VG) controls the electrons flow from source to drain. For positive gate voltage, electrons attract towards the bottom side of the semiconductor layer and conduct a channel. Then, the voltage applied between the two terminals result in current flow. The current flow occurs from drain to source.

OTFT can be operated in depletion mode or enhancement mode depending on whether it requires a gate voltage to induce the channel conduction. When no gate voltage is applied, the channel conductance is low for enhanced mode of operation. Therefore a low carrier density in the channel is essential to achieve this mode. A channel has to be induced in case of enhancement mode. In this mode, channel enhances on increasing the gate source voltage. Then applying voltage between the drain and source terminals causes the drain current to flow. While in case of depletion mode, if we apply the drain source voltage, the drain current will flow for zero gate source voltage. In this type of MOSFET, there is an implanted channel.

2.6 Characteristics of OTFT

An OTFT has drain current characteristics like those of a conventional FET when it is biased by the gate electrode. For small voltages applied between the drain and the source, the drain current I_D varies linearly with drain-to-source voltage V_{DS} as in Figure 2.3. The channel region acts like a resistor. Such a characteristic can be expressed by Eq. 2.3.

$$I_D = g_d V_{DS} \tag{2.1}$$

The channel conductance by Eq. 2.2.

$$g_d = \frac{W}{L} \mu \, |Q| \tag{2.2}$$

Where μ is the carrier mobility in unit of cm2/V-s, |Q| is the sheet density of the charges accumulated at the surface or the inversion layer due to the gate field effect, and W and L are carrier channel width and length, respectively.

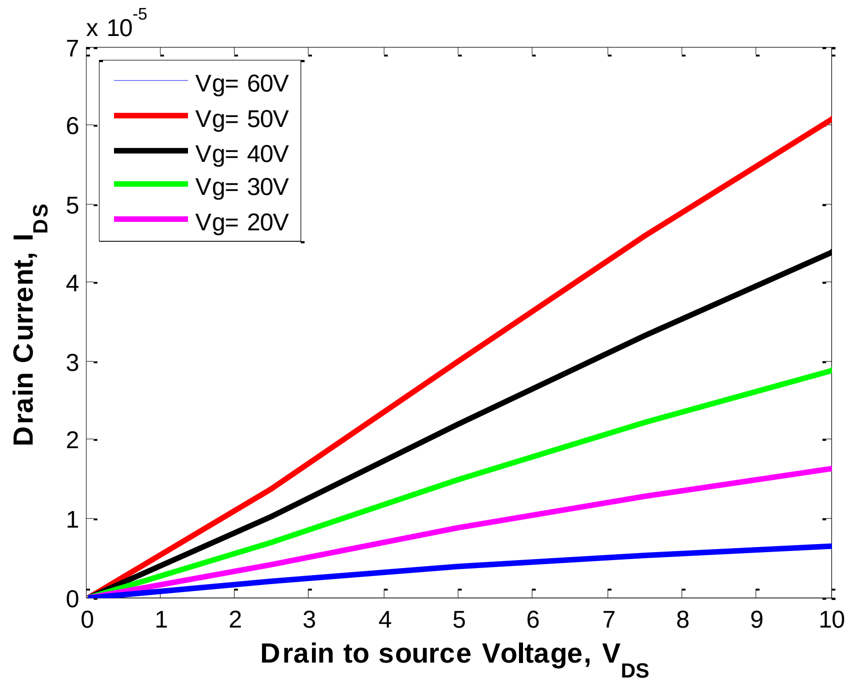

Figure 2-3: A blow-up of the linear region for small VDS

The charge accumulated at the surface or the inversion layer charge is a function of the gate-to-source voltage VGS. The magnitude of the drain current, ID, up to the point where it saturates can be calculated by incremental integration, and the current-voltage relationship is well documented elsewhere [51]. It is shown that for a TFT biased in the linear region of operation, $V_{DS} < V_{GS}-V_T$, I_D varies as in Eq. 2.5.

$$\mathbf{I_D = C\frac{\mathit{W}}{\mathit{L}}\mu\,[(V_{GS} - V_T)V_{DS} - V_{DS}{}^2]} \qquad (2.3)$$

Where V_T is the threshold voltage, $V_T = \frac{\varepsilon_0 \varepsilon}{t}$, $\boldsymbol{\varepsilon_o}$ is the permittivity of free space, $\boldsymbol{\varepsilon}$ is the relative permittivity of the gate insulator, ***t*** is the thickness of the gate insulator, and all other terms remain as previously defined.

We can extract transconductance, $\boldsymbol{g_m}$, and field-effect mobility, $\boldsymbol{\mu}$, in the linear region using the differentiation of Eq. 2.5, and get Eq. 2.4 and 2.5.

$$\mathbf{g_m} = \frac{\partial \mathbf{I_D}}{\partial \mathbf{V_{GS}}} = \mathbf{C}\frac{\mathbf{W}}{\mathbf{L}}\boldsymbol{\mu}(\mathbf{V_{DS}}) \quad (2.4)$$

$$\boldsymbol{\mu} = \mathbf{C}\frac{\mathbf{g_m L}}{\mathbf{W}}\left(\frac{\mathbf{1}}{\mathbf{V_{DS}}}\right) \quad (2.5)$$

Since at the knee (onset of drain current saturation) $V_{DS} = (V_{GS} - V_T)$ and the current remains substantially constant beyond the knee, the saturated drain current is given by Eq. 2.6.

$$\mathbf{I_D} = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{C}\frac{\mathbf{W}}{\mathbf{L}}\boldsymbol{\mu}(\mathbf{V_{GS}} - \mathbf{V_T})^{\mathbf{2}} \quad (2.6)$$

According to Eq. 2.8 we can express the field-effect mobility of carriers in the saturation region as Eq. 2.9. This is a common way of extracting saturation mobility from the slope of the square root of drain current, $\frac{\partial\sqrt{I_D}}{\partial V_{GS}}$, as a function of V_{GS}.

$$\boldsymbol{\mu} = \mathbf{C}\frac{\mathbf{2L}}{\mathbf{W}}\left(\frac{\partial\sqrt{\mathbf{I_D}}}{\partial \mathbf{V_{GS}}}\right)^{\mathbf{2}} \quad (2.7)$$

2.7 Materials of OTFT

Organic semiconductor materials can function either as p-type or n-type. The most widely studied organic semiconductors have been p-type materials. Figure 2.4 show some typical p-type and n-type organic semiconducting materials. The most widely studied organic semiconductor molecules are pentacene and thiophenes due to high mobilities [52]. The mobility of phthalocyanine (Pc) is relatively high (0.02 cm2/Vs) for a p-channel OTFT based on CuPc [52]. Moreover, the high chemical stability of copper phthalocyanine (CuPc) distinguishes this material from other high mobility organic semiconductors, like pentacene or rubrene.

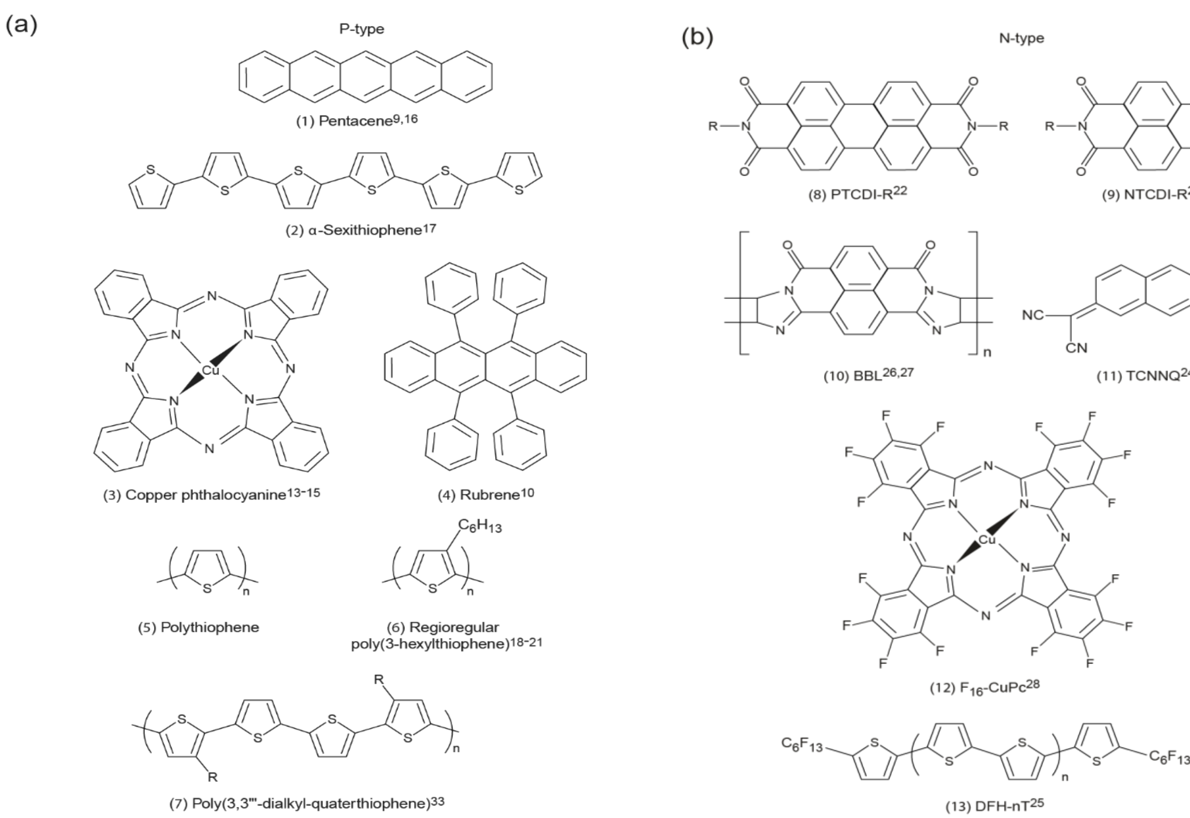

Figure 2-4: Some organic semiconductor (a) P-type (b) n-type [53]

2.8 Electrical Properties of OTFT

OTFTs can be designed in a number of configurations as the active layer is usually deposited onto the gate dielectric. Figure 2.5 shows two typical schematic structures used in OTFTs. Charge carriers are accumulated by the gate capacitor and flow between the source and drain electrodes. The top-contact structure normally shows better performance than those with bottom contact structure due to low contact resistance. However, the top contact structure on Si wafer is difficult to fabricate after deposit organic materials using photolithography process. Therefore, bottom-contact structure is the dominate configuration for OTFTs in literature reports [11] [54] [55] and the bottom contact structure is more suitable for device scaling and chemical sensing studies [9] [56].

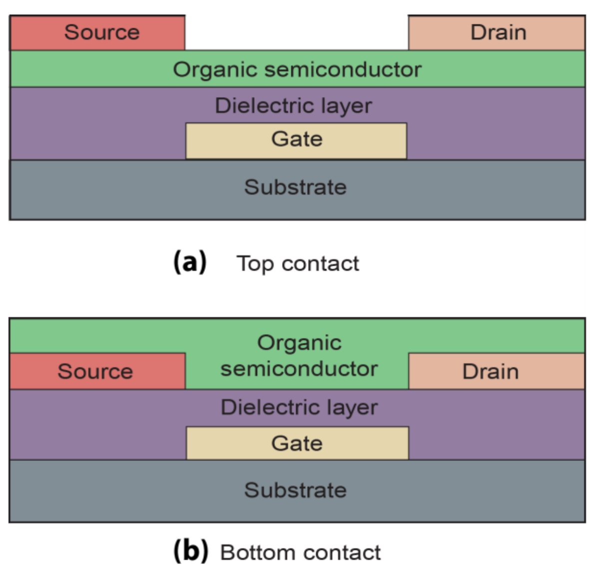

Figure2-5: OTFT architecture (a) Top contact device (b) Bottom contact device

2.8.1 Current and Voltage characteristics of OTFT

The I-V characteristics of OTFTs can be adequately described by models developed for inorganic semiconductors [57] as shown in Equation (2.8) and (2.9). Polycrystalline pentacene OTFTs are used here to demonstrate typical I-V characteristics of OTFTs. Polycrystalline pentacene OTFTs exhibit p-type behavior. Thus, when the gate electrode is biased positively with respect to the grounded source electrode, they operate in the depletion mode, and the channel region is depleted of carriers resulting in high channel resistance (off state). When the gate electrode is biased negatively, they operate in the accumulation mode and a large concentration of carriers is accumulated in the transistor channel, resulting in low channel resistance (on state). For n-type TFT operation, the electrode polarity is reversed and the majority carriers are electrons instead of holes.

$$\mathbf{I_D} = \frac{\mathbf{WC\mu}}{\mathbf{L}}(\mathbf{V_{GS}} - \mathbf{V_T})\boldsymbol{V_{DS}} - \frac{\mathbf{V_{DS}}^2}{2} \qquad \textbf{When } \mathbf{V_{GS}\text{-}V_T > V_{DS}} \qquad (2.8)$$

$$\mathbf{I_D} = \frac{\mathbf{WC\mu}}{\mathbf{L}}\frac{(\mathbf{V_{GS}} - \mathbf{V_T})^2}{2} \qquad \textbf{When } \mathbf{V_{GS} - V_T <= V_{DS}} \qquad (2.9)$$

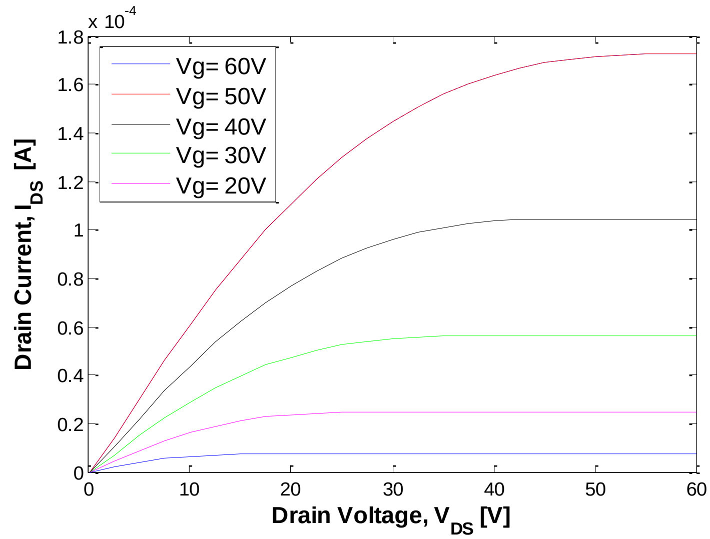

Figure 2-6: **A typical plot of drain current I_D versus drain voltage V_D at various gate voltages V_G**

2.8.2 Contact effect

The contact effects are a result of defects at the interface between the electrodes and the semiconductor, often discussed in literature [9] [10]. They are influenced by the materials, as well as deposition techniques, which affect the homogeneity of the structure. Therefore, the organic transistors exhibit low speed and mobility, as consequence to the fact that the contact resistance is high, and require high operation voltages.

Ohmic contacts to pentacene are a crucial part of many types of electronic and optoelectronic devices in the pentacene system. With decreasing device dimensions, the contact resistance (Rc) as part of the total device resistance will dominate compared with channel resistance (Rch) and therefore will play an important part in device operations. The impact of R_C on the extracted mobility (μ) has been extensively analyzed it showed that for pentacene-based OTFTs with typical dimensions, R_C can be many times greater than R_{Ch} [54]. To improve an OTFT performance it is important to understand the cause of R_C as well as the carrier injection mechanism from S/D electrodes to the channel. Understanding the contact effect is of great technological importance since it limits the OTFT performance.

The classical transistor model cannot give appropriate output characteristics of OTFT because the contact effects interfere in OTFTs with other dependences parameter like bias voltage, temperature, and material parameters. So use a compact model proposed in [30] to reproduction the output characteristics. I_D-V_C curve from equation (2.16), where V_C is the voltage drop in the contact region, and other dependence parameter curves.

Experimental investigations show that the magnitude of $R_{\mathbf{C}}$ is dependent on the gate bias, temperature, and ambient gas environment [58] nonlinear behavior, also observed in the literature, are treated with a drain-voltage-dependent resistance. The slope of the $I_{\mathbf{D}}$–$V_{\mathbf{C}}$ curve increases with $V_{\mathbf{D}}$, thus decreasing the contact resistance, being negligible in the saturation region

2.9 OTFT Models

A suitable OTFT model should incorporate both linear and nonlinear behaviors for the contact I – V curves, with a method that unifies in some of its parameters the injection and transport mechanisms present in the metal-organic contacts and that considers the dependence of the I –V curves with the gate voltage and the temperature. In the following sections, we present such a models.

2.9.1 Classical model

The classical FET model shown in Figure 2.8 represents its I-V characteristics by equation (2.10)

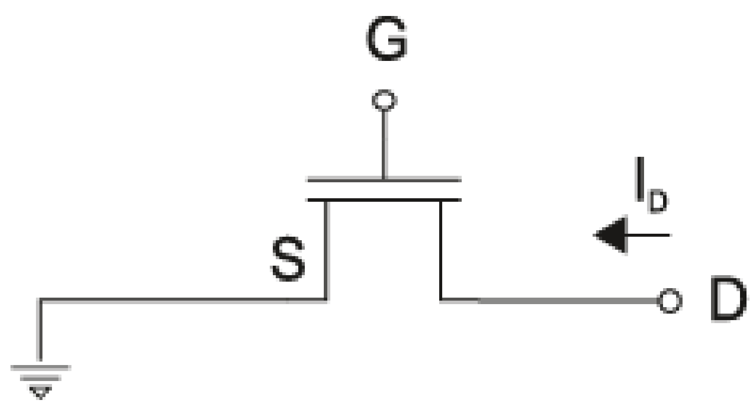

Figure 2-7: Classical model for I-V characteristics of OTFT

When $V_{DS} > (V_{GS} - V_T)$ I_D is given by

$$\mathbf{I_D = \frac{W}{L}\mu C_i \left\{(V_{GS} - V_T)V_{DS} - \frac{{V_{DS}}^2}{2}\right\}} \qquad \textbf{(2.10)}$$

and in the saturation regime, $V_{DS} > (V_{GS} - V_T)$, I_D is given by

$$\mathbf{I_D = \frac{W}{L}\mu C_i\{(V_{GS} - V_T)^2\}} \qquad (2.11)$$

where W is the transistor channel width, L is the transistor channel length, μ is the field-effect mobility, V_T is the threshold voltage, and $C_i = \varepsilon_i/t_i$ is the capacitance per unit area of the gate insulator.

2.8.2 Compact model

To model a compact model for OTFTs considering contacts effects, we use a generic analytical model for the current voltage characteristics of OTFTs [40], [41]. In that work, the authors introduce the drain current I_D and the voltages at the borders of the intrinsic transistor, V_G, V_D, and V_S shown in equation (2.12) and (2.13) and **figure**

$$\mathbf{I_D = \frac{W}{L}\mu_O C_i\left\{\frac{(V_G - V_T - \mathit{V_c})^{\gamma+2} - (V_G - V_T - V_D)^{\gamma+2}}{\gamma+2}\right\}} \qquad (2.12)$$

When V_{GS}-V_T >V_{DS} and

$$\mathbf{I_D = \frac{W}{L}\mu_O C_i\left\{\frac{(V_G - V_T - \mathit{V_c})^{\gamma+2}}{\gamma+2}\right\}} \qquad (2.13)$$

When V_{GS}-V_T <= V_{DS}

where $C_i = \varepsilon_i/t_i$ is the gate insulator capacitance per unit area, ε_i is the insulator dielectric constant, t_i is the insulator thickness, V_T is the threshold voltage, W is the transistor width, and L the channel length. γ is the mobility enhancement factor where, $\gamma = \frac{2To}{T} - 2$, To is the specific equivalent temperature that represents the steepness of the DOS exponential tail, and μ_o is the mobility-related parameter with dimensions cm2/(V1+γ s).

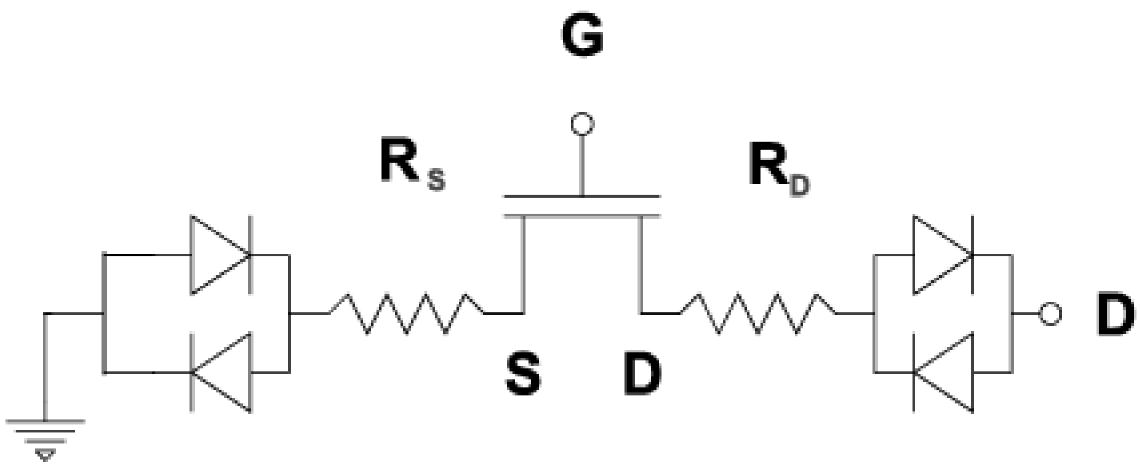

Figure 2-8: nonlinear model for the source and drain contact regions

In this model that the voltage drop at the drain contact is considered as small in comparison to the voltage drop at the source contact [32]. Thus, the contact voltage is reduced to the voltage drop between the external source terminal and the internal source ($V_S = V_C$). To setting of parameters of this compact model to show the dependence of I-V characteristics of OTFT on the contact effects a new parameter, RC (or M) is added. Where

$$\frac{1}{R_C} = \alpha(V_G - V_T)^{\gamma+1} \quad (2.14)$$

Where $\alpha = \frac{WC_i\mu_o}{Kx_c}$, and x_c is the channel length. Many Experiments showed that the parameters I–V curve is dependent on the gate voltage at contact [58], [59], [60] so the parameter Rc and M is expected to be dependent on gate voltage.

As we know the ID and VC relationship [30]

$$I_D = \frac{V_C}{R_C} \tag{2.15}$$

Now from euation (2.13) and (2.14) we can find a equation for VC as

$$V_C = \frac{\sqrt{I_D}}{\sqrt{\alpha(V_G - V_T)}} \tag{2.16}$$

Figure shows the final compact model model which combine combining an intrinsic transistor modeled with the ideal MOS model plus a contact region at the source.

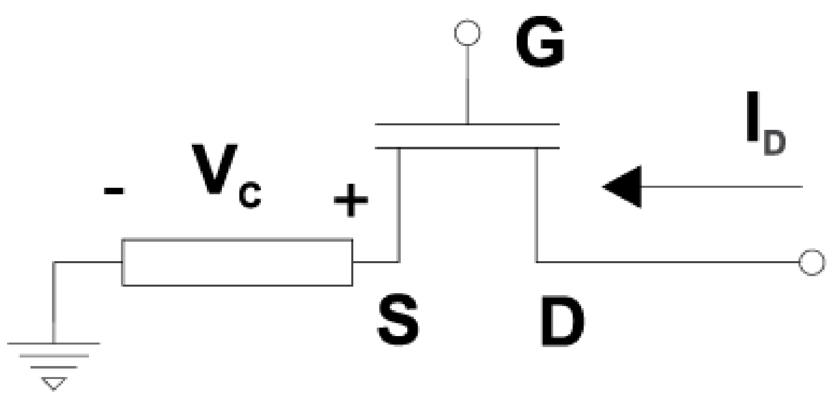

Figure 2-9: Compact model for ID–VC characteristics of OTFT

Chapter 3: Result and Discussion

3.1 I-V Characteristics of OTFT at different structure and drain voltage

We found the effects of the change of channel length with different voltages and lengths and the results are showed in Figure: 3.1 to 3.12. These curve is produced using the classical model equation (2.10) and (2.11) and compact model Equation (2.12) and (2.13) of OTFT with parameters: V_T = −3.14 V, γ = 0.59, μ_o = 0.09 cm2/V1+γ s, and α = 3.9 × 10−8 × (50 nm/x_C) A/V3+γ.

Table 1 Settings of the program for I_{DS} – V_{DS} characteristics curve with different device length

Figure	Device Length L (μm)	Contact Length x_C (μm)	Gate Voltage, V_G (V)	Drain Voltage V_D (V)	Step
3.1	200	50	-60	-60 to 0	2.5
3.2	150	50	-60	-60 to 0	2.5
3.3	100	50	-60	-60 to 0	2.5
3.4	200	50	-40	-60 to 0	2.5
3.5	150	50	-40	-60 to 0	2.5
3.6	100	50	-40	-60 to 0	2.5
3.7	200	50	-20	-60 to 0	2.5
3.8	150	50	-20	-60 to 0	2.5
3.9	100	50	-20	-60 to 0	2.5

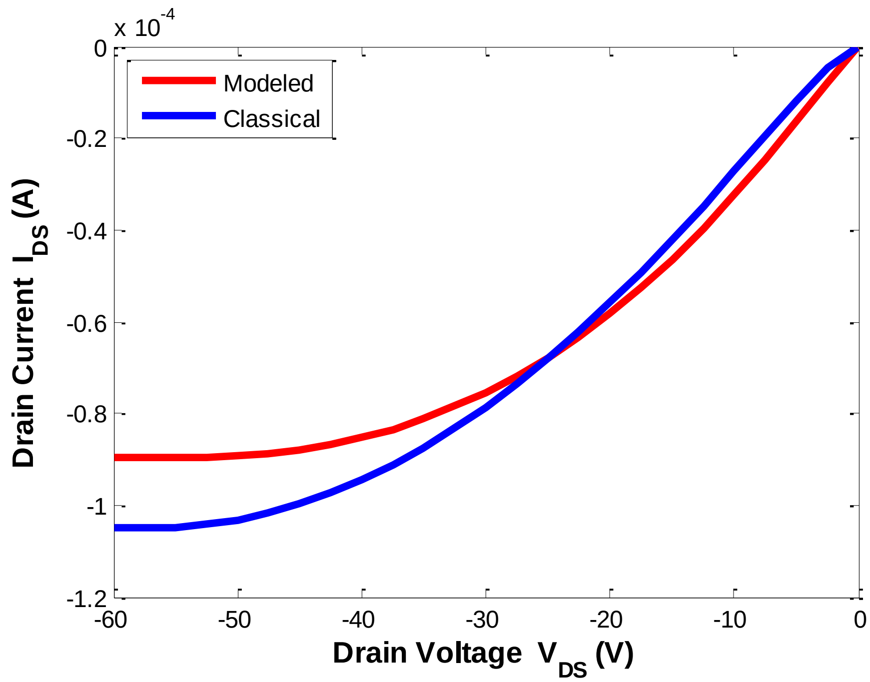

Figure 3-1: Output Characteristics curve with device length 200µm and contact length 5µm at drain voltage -60 V

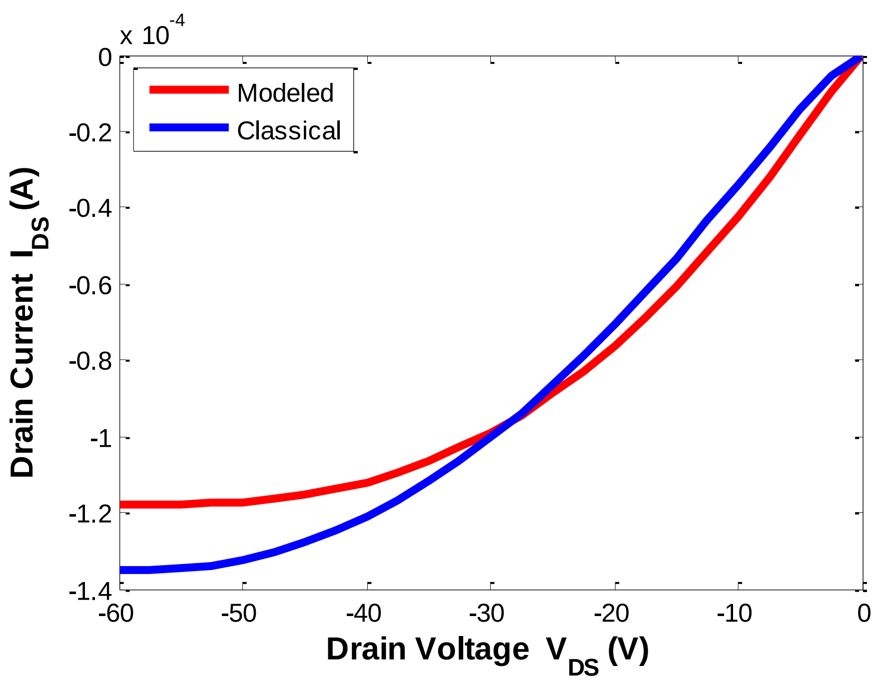

Figure 3-2: Output Characteristics curve with device length 150µm and contact length 5µm at drain voltage -60 V

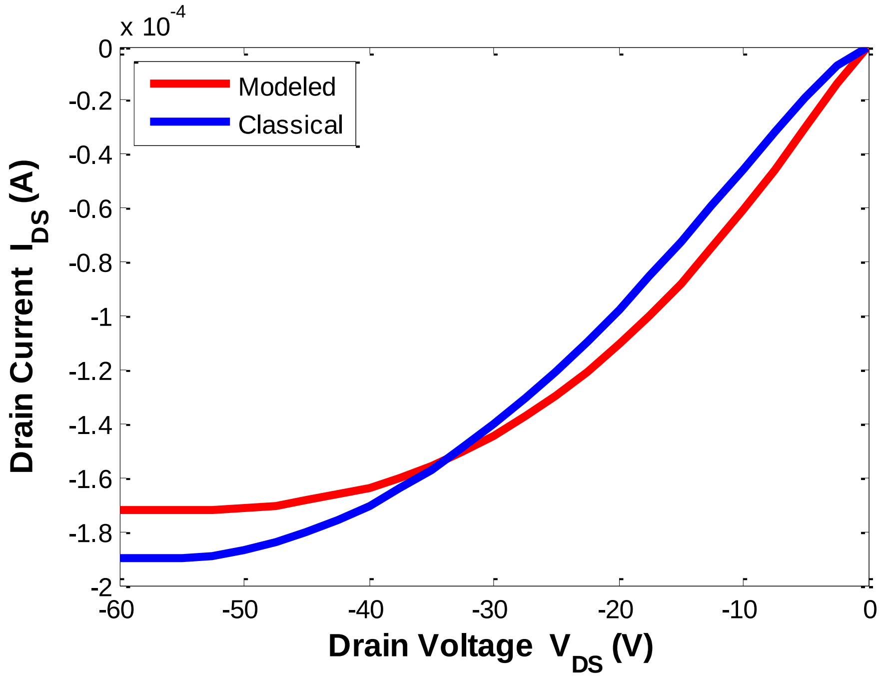

Figure 3-3: Output Characteristics curve with device length 100µm and contact length 5µm at drain voltage -60 V

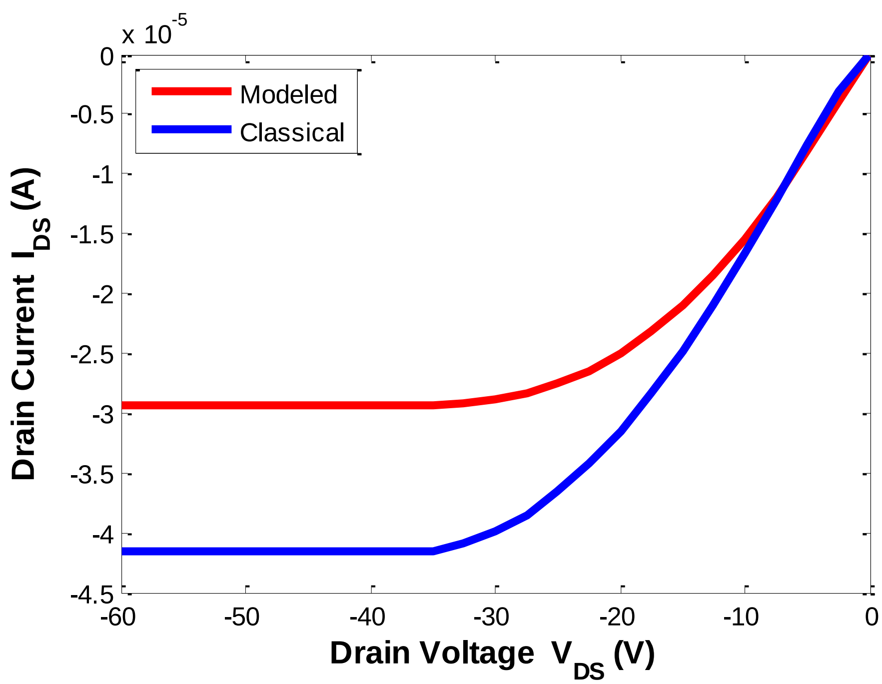

Figure 3-4: **Output Characteristics curve with device length 200µm and contact length 5µm at drain voltage -40 V**

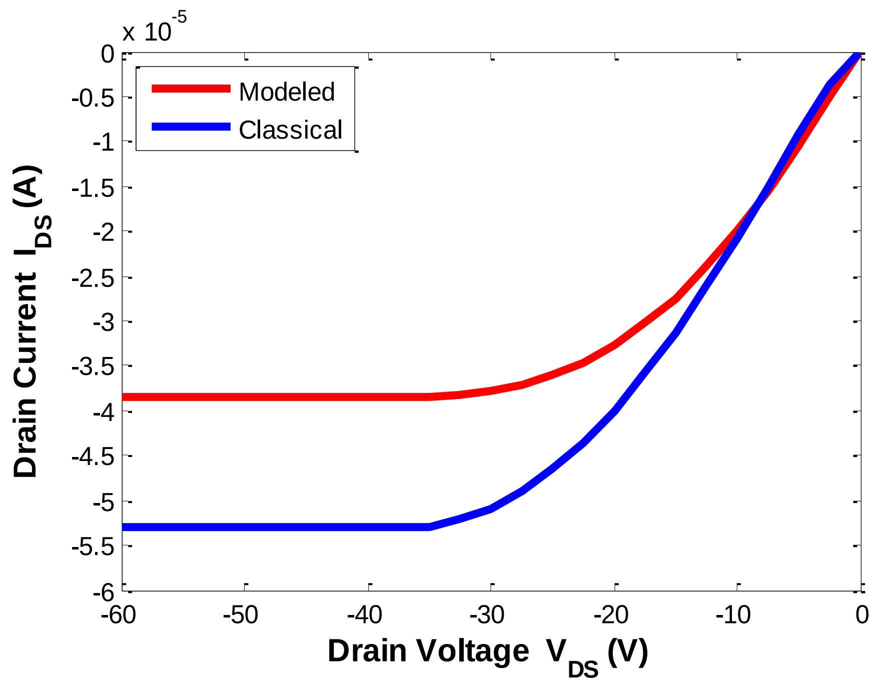

Figure 3-5: **Output Characteristics curve with device length 150µm and contact length 5µm at drain voltage -40 V**

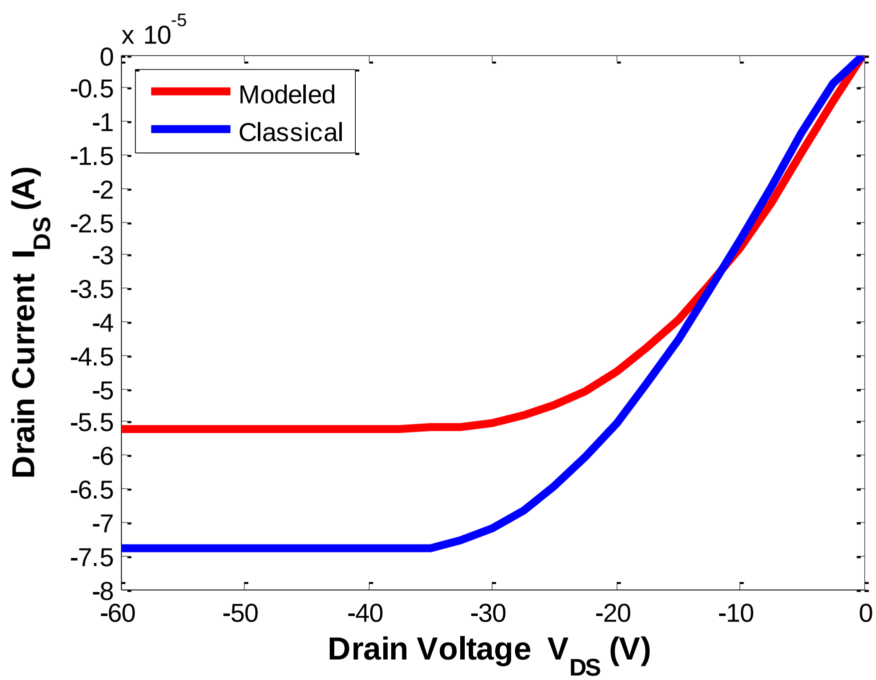

Figure 3-6: **Output Characteristics curve with device length 100µm and contact length 5µm at drain voltage -40 V**

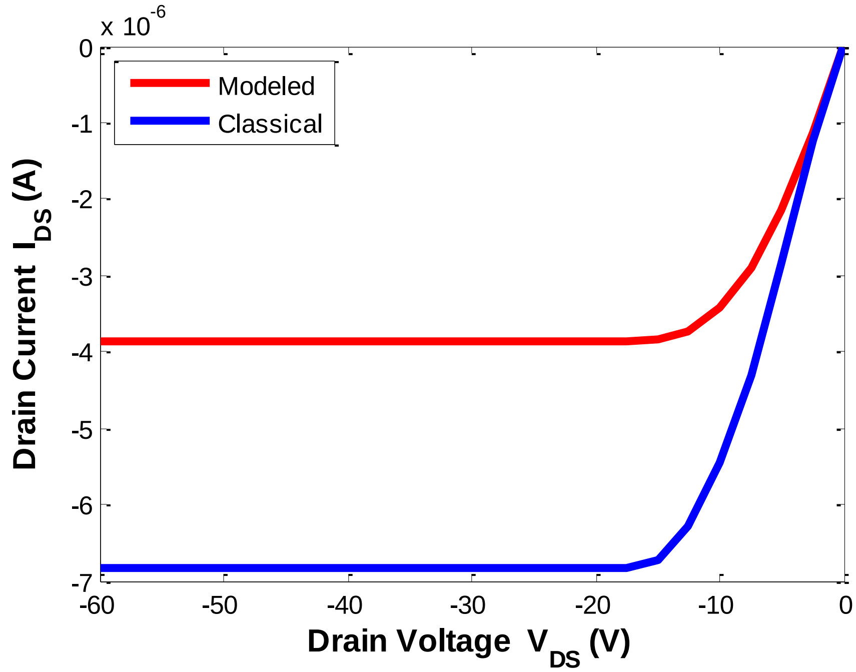

Figure 3-7: **Output Characteristics curve with device length 200µm and contact length 5µm at drain voltage -20 V**

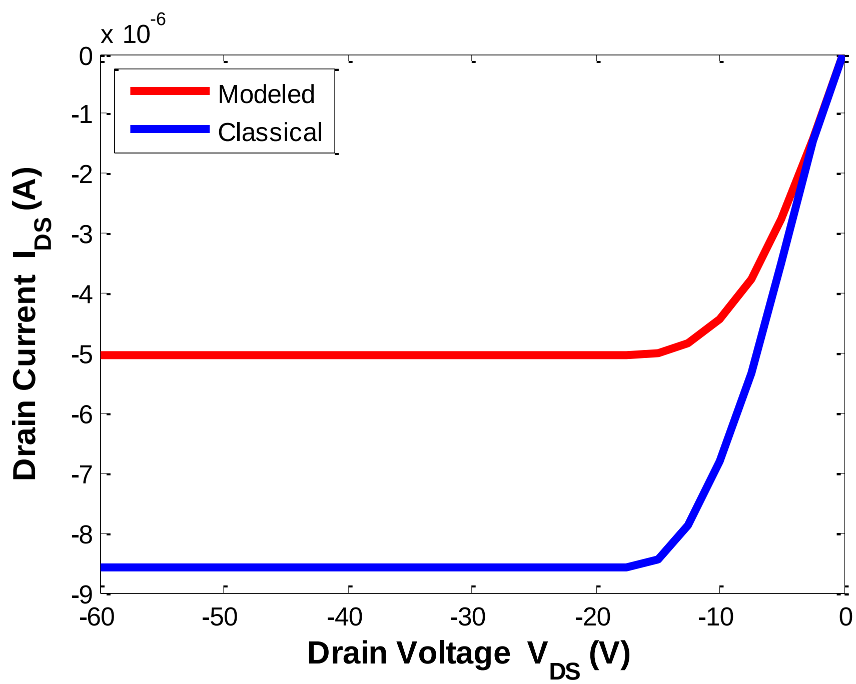

Figure 3-8: **Output Characteristics curve with device length 150µm and contact length 5µm at drain voltage -20 V**

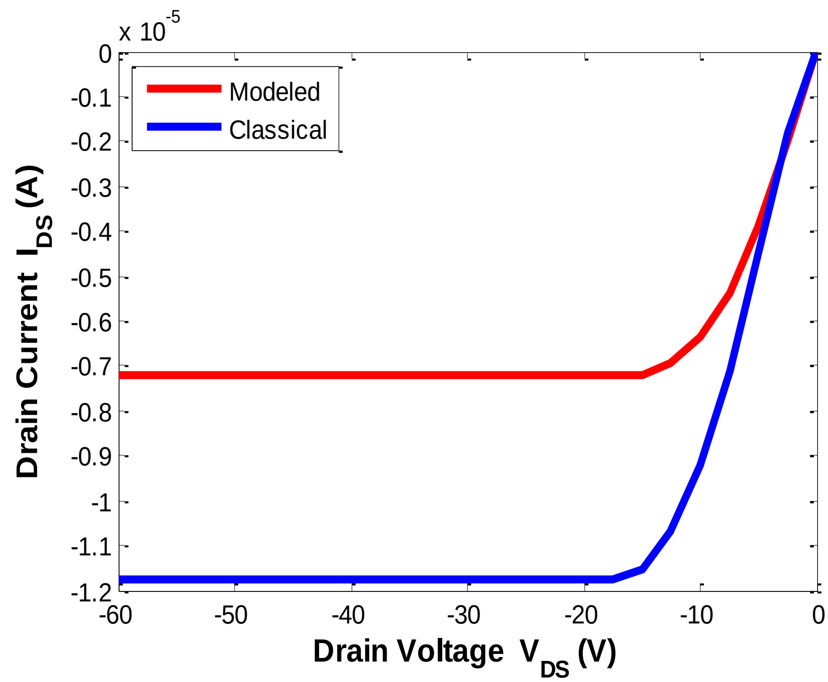

Figure 3-9: **Output Characteristics curve with device length 200µm and contact length 5µm at drain voltage -20 V**

From above curve shows the clear differences between classical model and compact model with various device length and gate voltages. These output curves Figure 3.1-3.9 at different V_{GS} is direct evidence for a nonlinear parasitic contact effect .Hence, it can be predicted that there is nonnegligible contribution of contact resistance R_C to the I-V characteristics of OTFT .

3.1.2 Transfer Characteristics

Transfer Characteristics curve of OTFT produced form Equation (2.5) and (2.6) is shown in figure 3.10

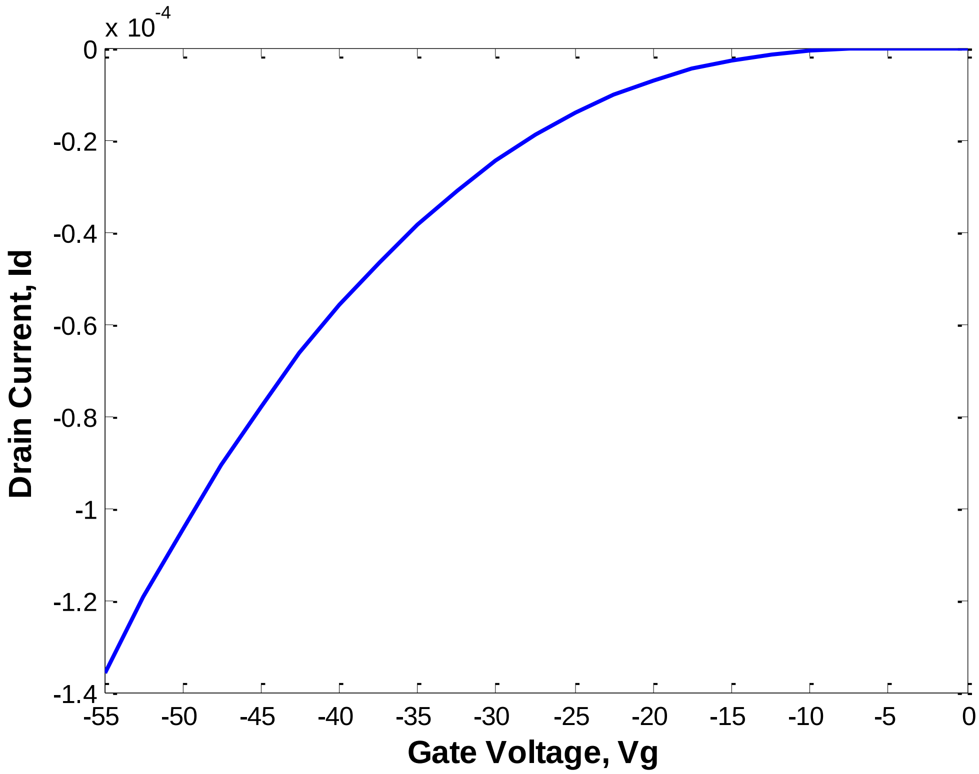

Figure 3-10: **Produced transfer characteristics curve at drain voltage -60V.**

3.1.3 Result of changing Channel length

We produced the I_{DS}-V_{DS} characteristics changing channel length at various gate voltage using equation (2.12) and (2.13) and the results of the output curve shows the contact effect on the OTFT.

Parameters: $V_T = -3.14$ V, $\gamma = 0.59$, $\mu_o = 0.09$ cm2/V1+γ s, and $\alpha = 3.9 \times 10-8 \times (50 \text{ nm}/x_C)$ A/V3+γ.

Table 2: Settings of the program for I_{DS} – V_{DS} characteristics curve at different contact length

Figure	Device Length L (μm)	Contact Length x_C (μm)	Gate Voltage, VG (V)	Drain Voltage V_D (V)	Step
3.11	200	5 to 15	-60	-60 to 0	2.5
3.12	200	5 to 15	-40	-60 to 0	2.5
3.13	200	5 to 15	-20	-60 to 0	2.5
3.14	150	5 to 15	-60	-60 to 0	2.5
3.15	150	5 to 15	-40	-60 to 0	2.5
3.16	150	5 to 15	-40	-60 to 0	2.5
3.17	100	5 to 15	-60	-60 to 0	2.5
3.18	100	5 to 15	-40	-60 to 0	2.5
3.19	100	5 to 15	-20	-60 to 0	2.5

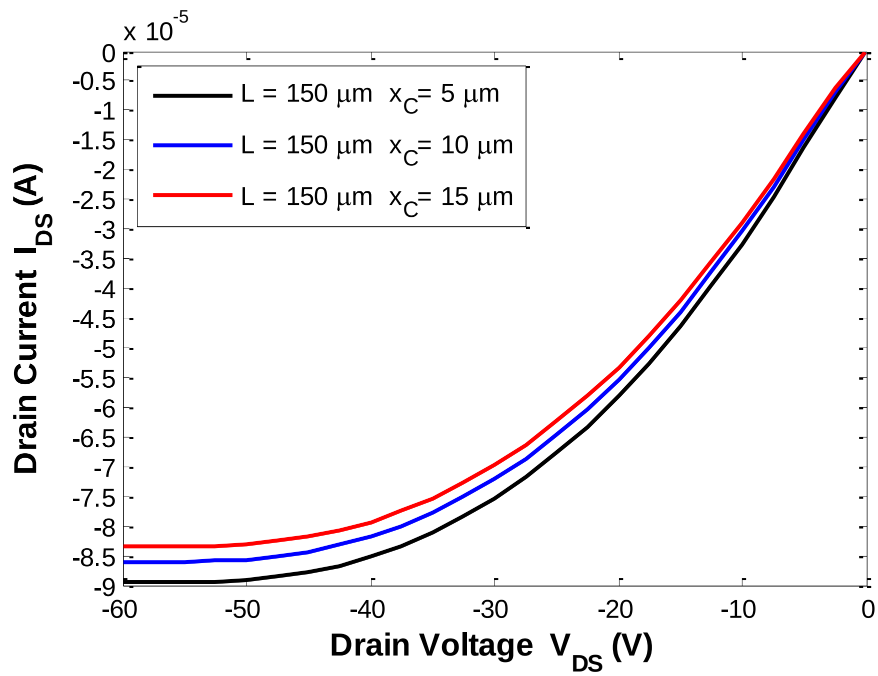

Figure 3-11: **Output Characteristics curve with device length 200µm at drain voltage -60 V**

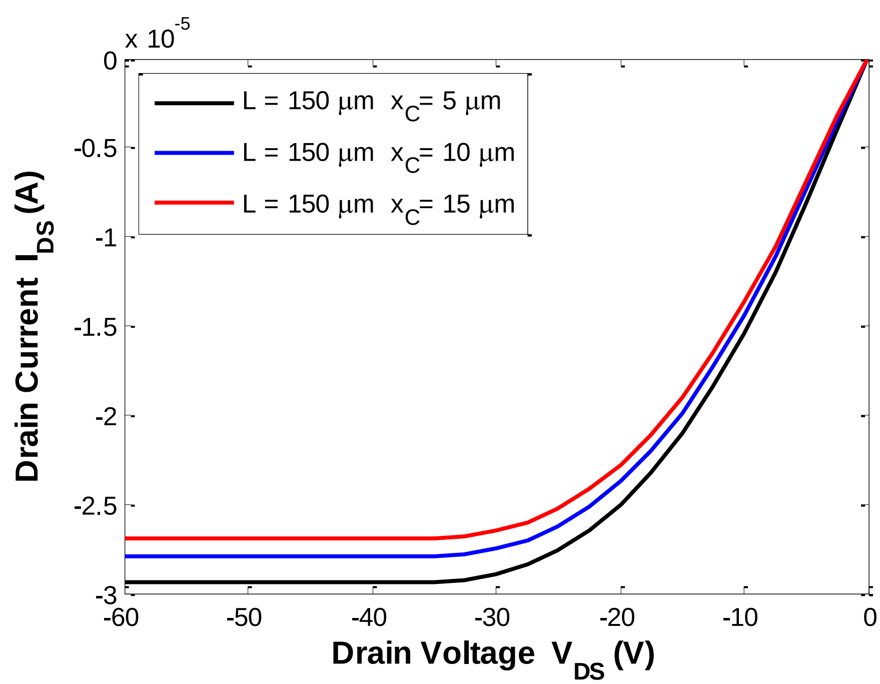

Figure 3-12: **Output Characteristics curve with device length 200µm at drain voltage -40 V**

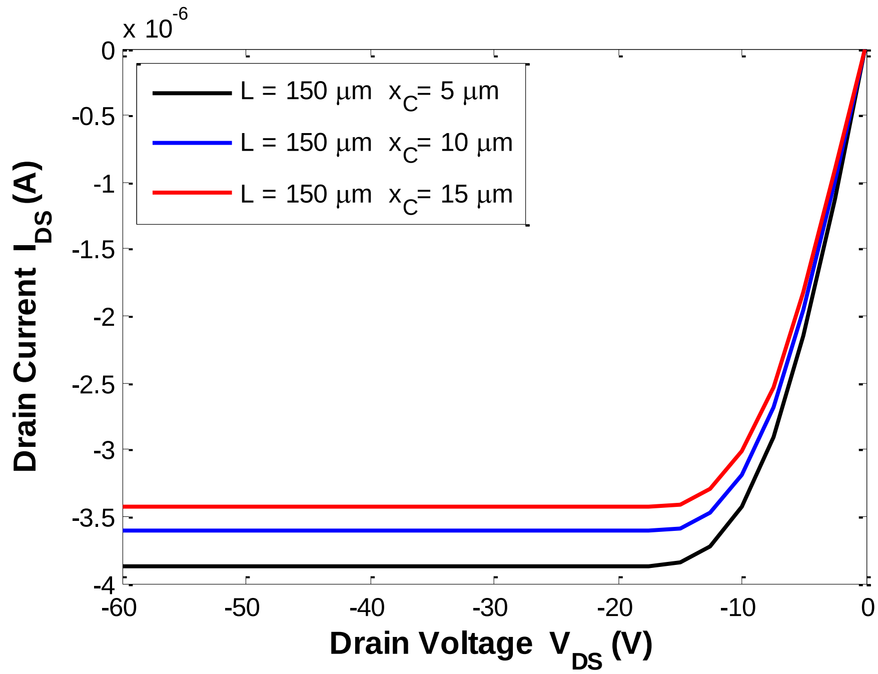

Figure 3-13: **Output Characteristics curve with device length 200µm at drain voltage -20 V**

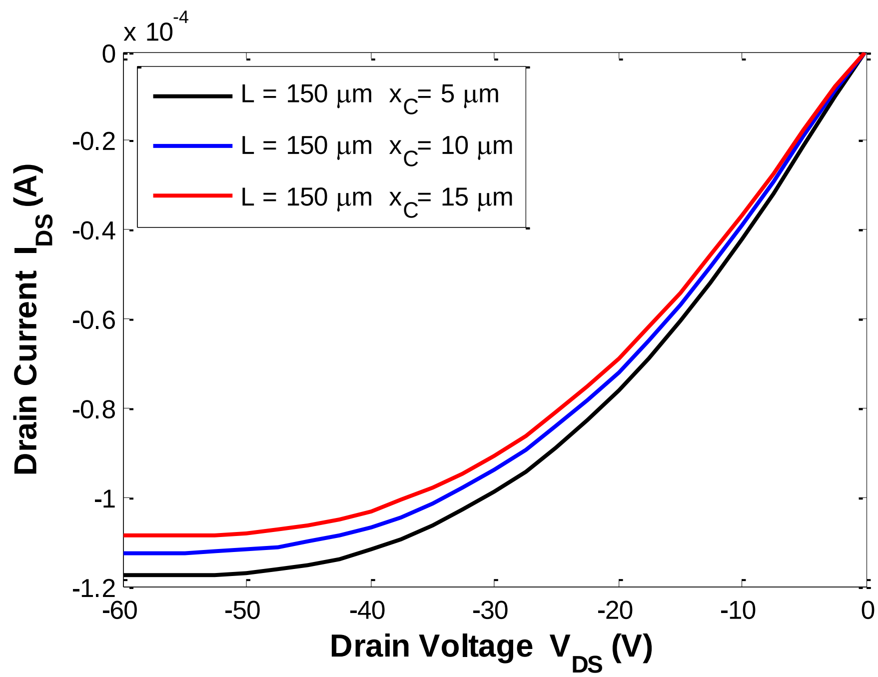

Figure 3-14: **Output Characteristics curve with device length 150µm at drain voltage -60 V**

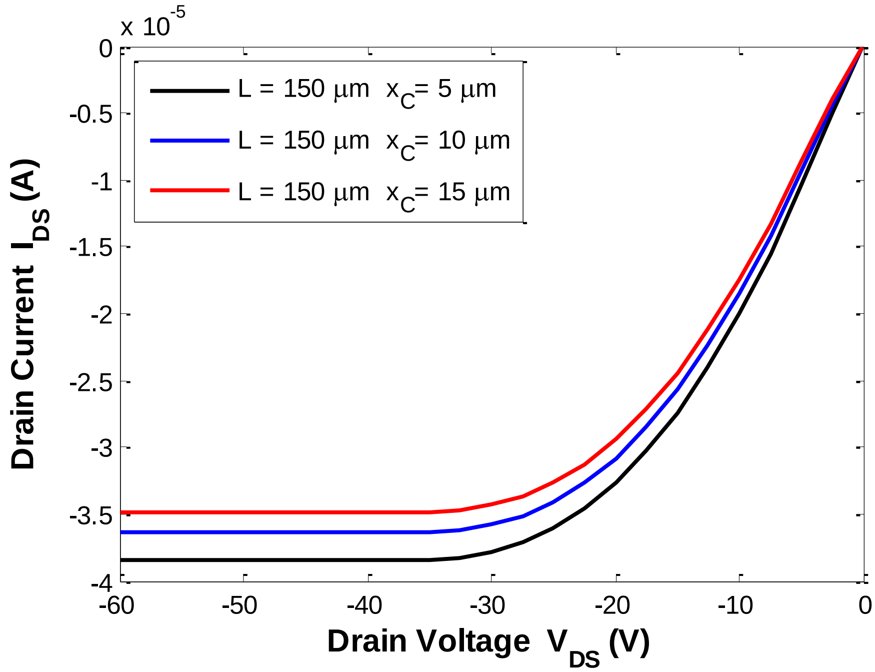

Figure3-15: **Output Characteristics curve with device length 150µm at drain voltage -40 V**

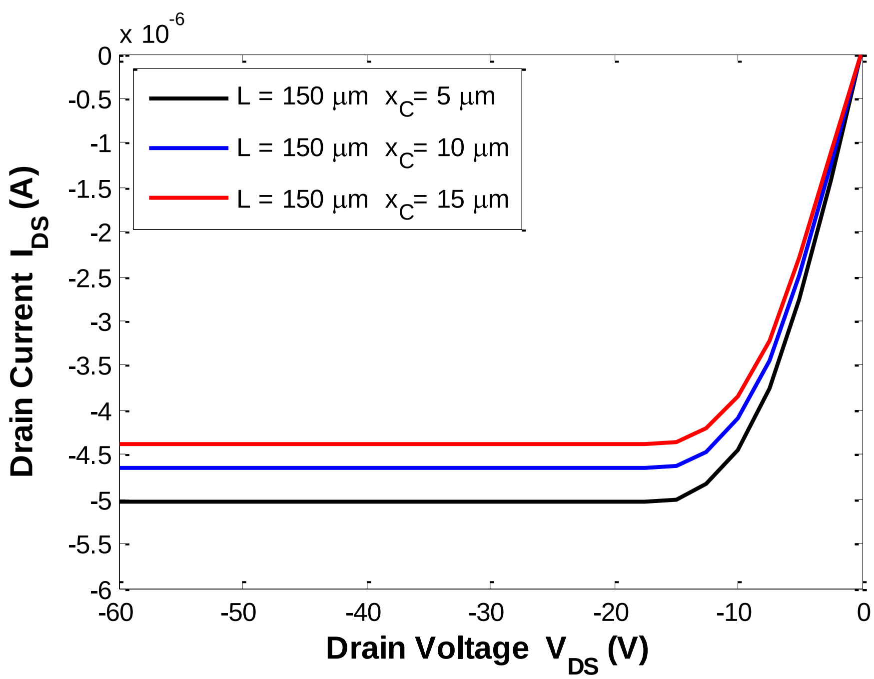

Figure 3-16: **Output Characteristics curve with device length 150µm at drain voltage -20 V**

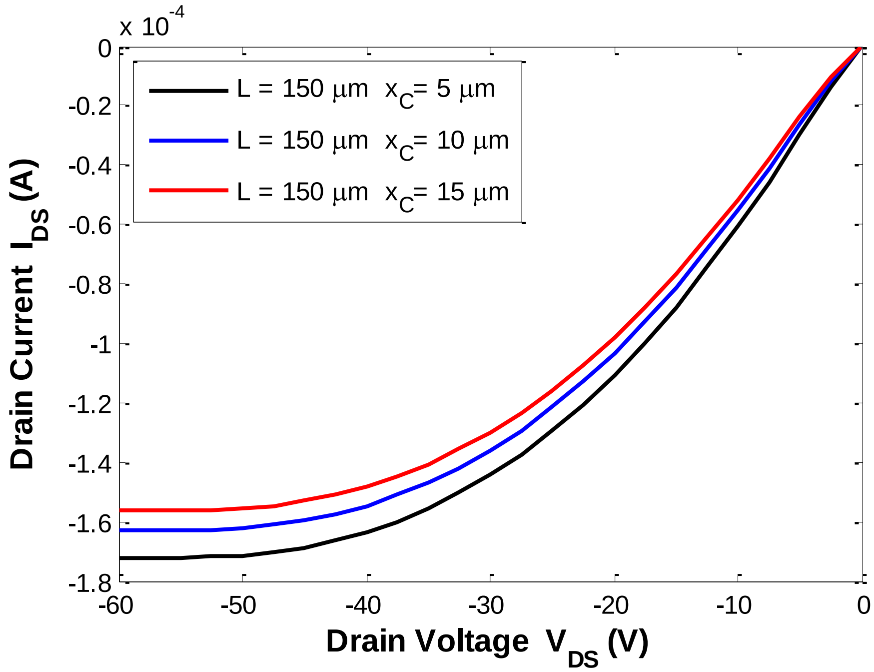

Figure 3-17: **Output Characteristics curve with device length 100µm at drain voltage -60 V**

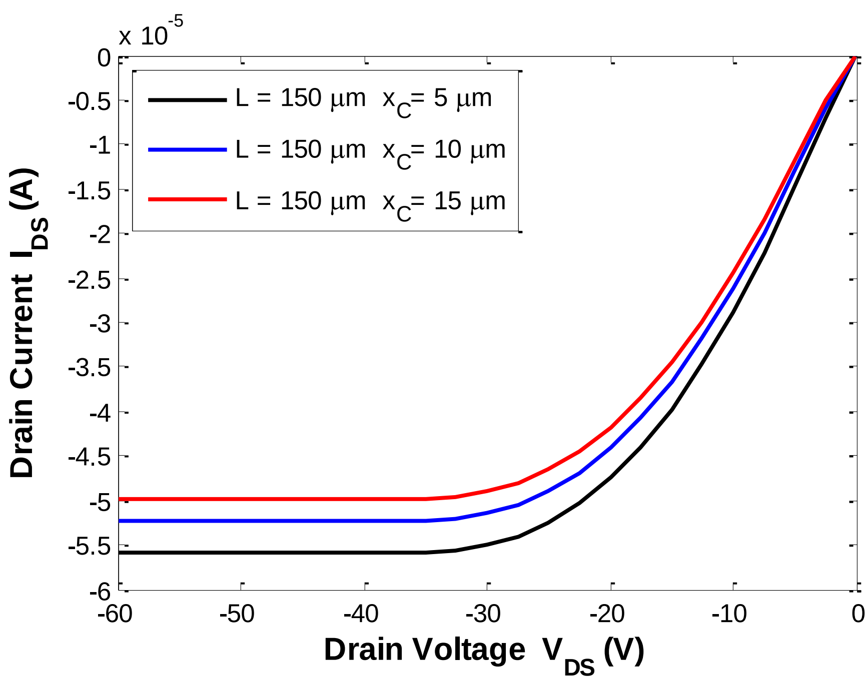

Figure 3-18: **Output Characteristics curve with device length 100µm at drain voltage -40 V**

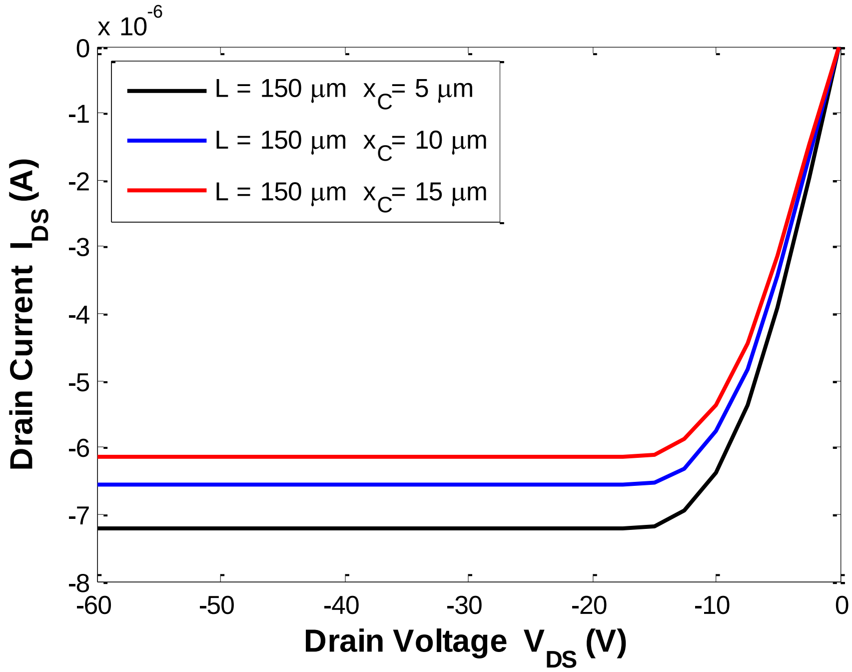

Figure 3-19: **Output Characteristics curve with device length 100µm at drain voltage -20 V**

3.1.4 I_D-V_C Curve

We produced the I_D-V_C curve from equation (2.16) and the setting parameters are given in Table 3. The resultant curves are shown from Figure 3.20 to Figure 3.28

Parameters: $V_T = -3.14$ V, $\gamma = 0.59$, $\mu_o = 0.09$ cm2/V1+γ s, and $\alpha = 3.9 \times 10-8 \times (50\ nm/x_C)$ A/V3+γ.

Table 3: Setting parameters for the I_D-V_C curve

Figure	Device Length L (µm)	Contact Length x_C (µm)	Gate Voltage, V_{GS} (V)	Drain Voltage V_{DS} (V)	Step
3.20	200	15	-60,-40,-20	-60 to 0	2.5
3.21	200	10	-60,-40,-20	-60 to 0	2.5
3.22	200	5	-60,-40,-20	-60 to 0	2.5
3.23	150	15	-60,-40,-20	-60 to 0	2.5
3.24	150	10	-60,-40,-20	-60 to 0	2.5
3.25	150	5	-60,-40,-20	-60 to 0	2.5
3.26	100	15	60,-40,-20	-60 to 0	2.5
3.27	100	10	-60,-40,-20	-60 to 0	2.5
3.28	100	5	-60,-40,-20	-60 to 0	2.5

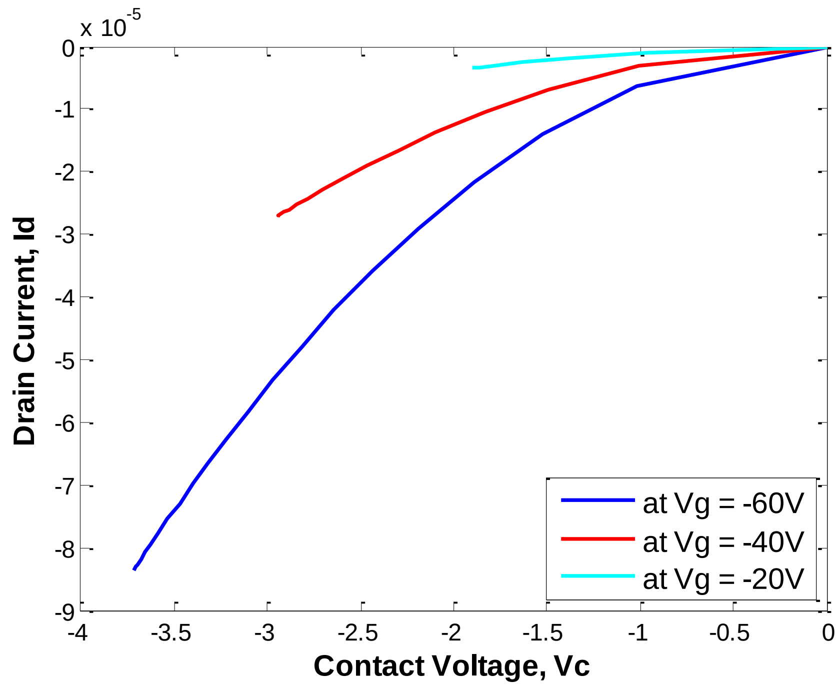

Figure 3-20: **I_D-V_C Curve for L = 200µm and x_C = 15µm**

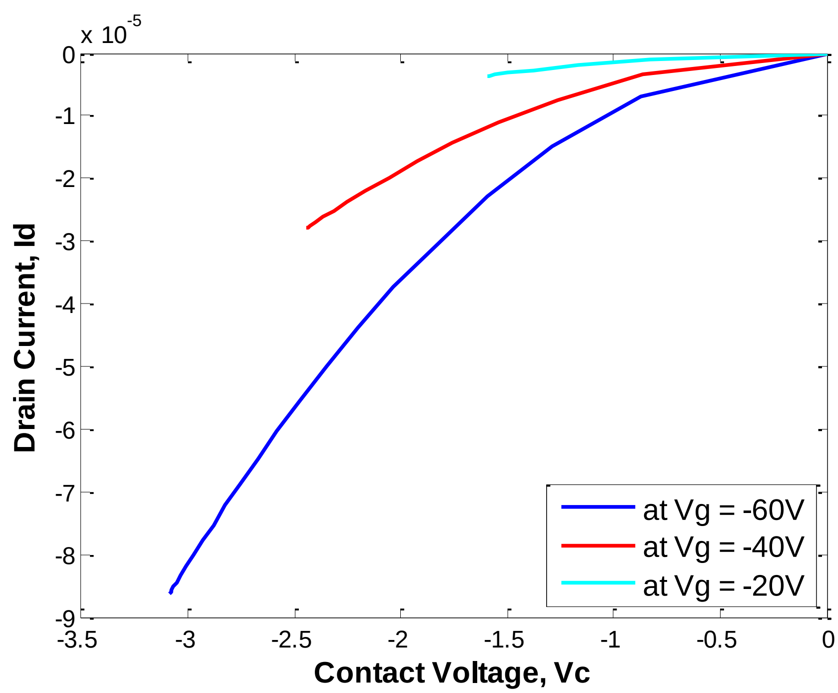

Figure 3-21: **I_D-V_C Curve for L = 200µm and x_C = 10µm**

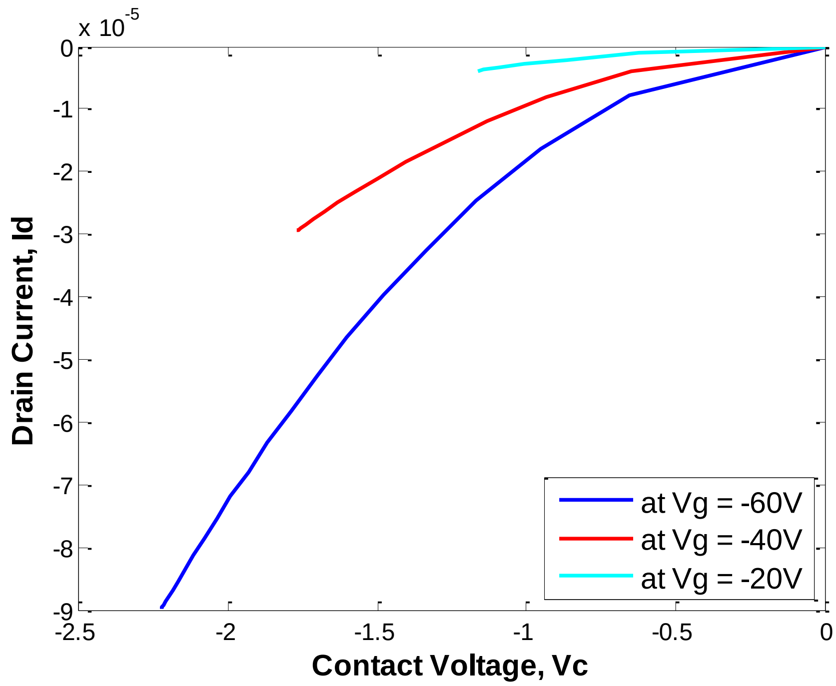

Figure 3-22: I_D-V_C Curve for L = 200µm and x_C = 5µm

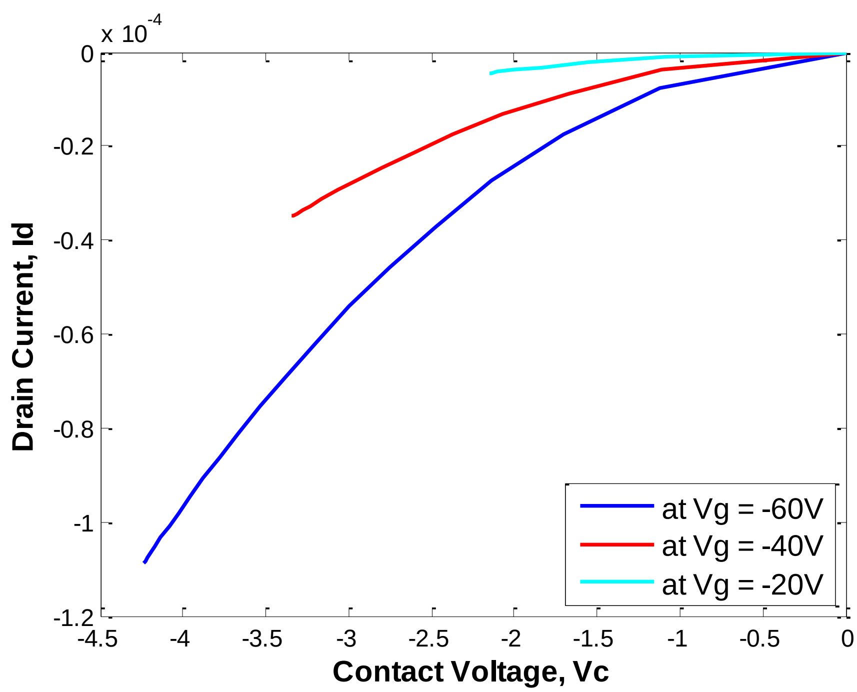

Figure 3-23: I_D-V_C Curve for L = 150µm and x_C = 15µm

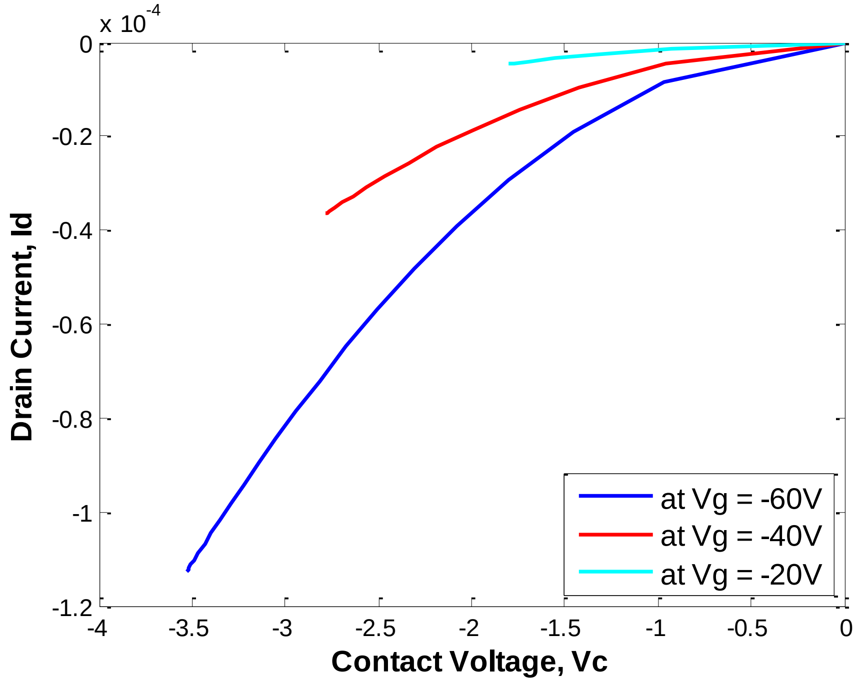

Figure 3-24: I_D-V_C Curve for L = 150µm and x_C = 10µm

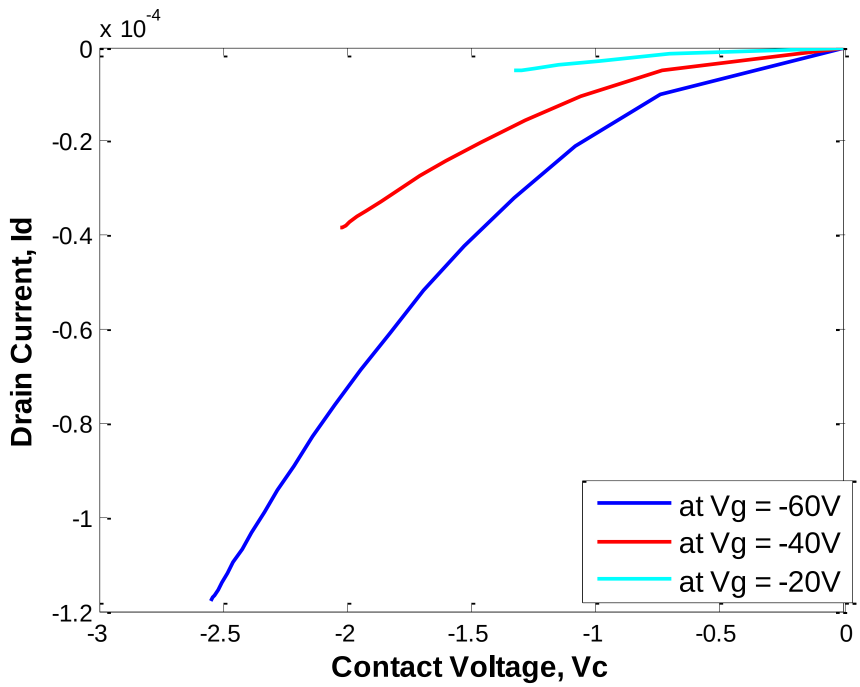

Figure 3-25: I_D-V_C Curve for L = 150µm and x_C = 5µm

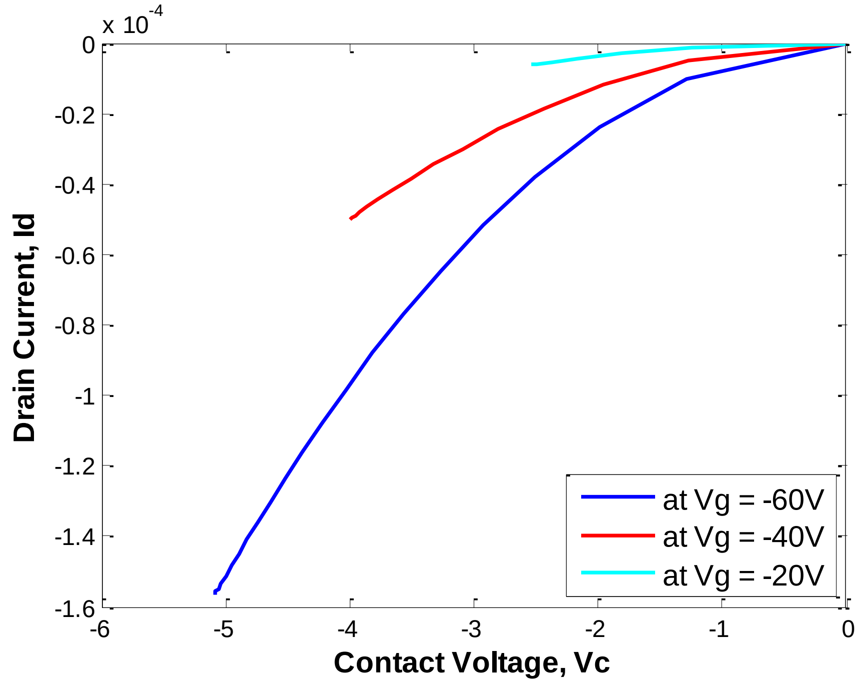

Figure 3-2: I_D-V_C Curve for L = 100µm and x_C = 15µm

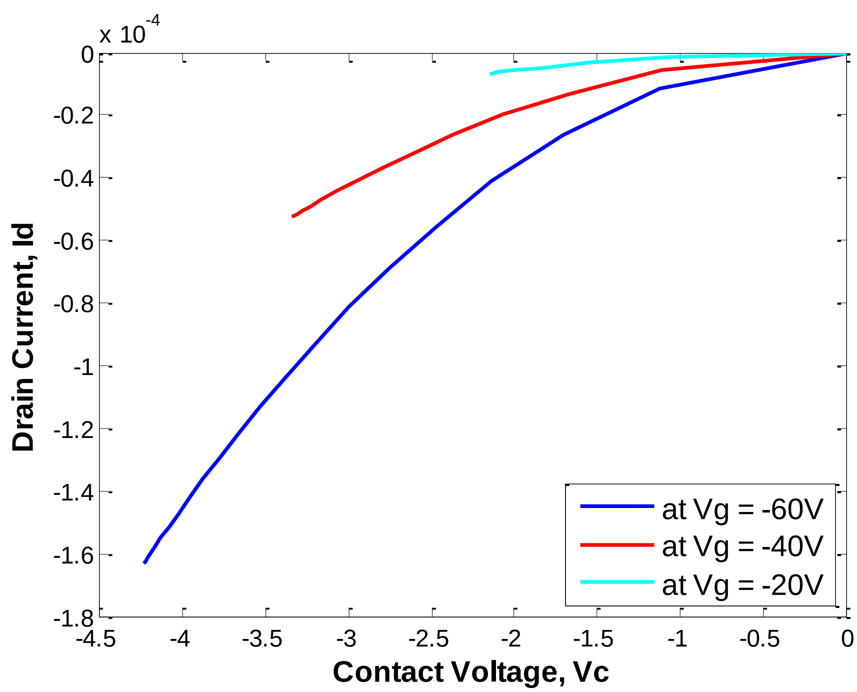

Figure 3-27: I_D-V_C Curve for L = 100µm and x_C = 10µm

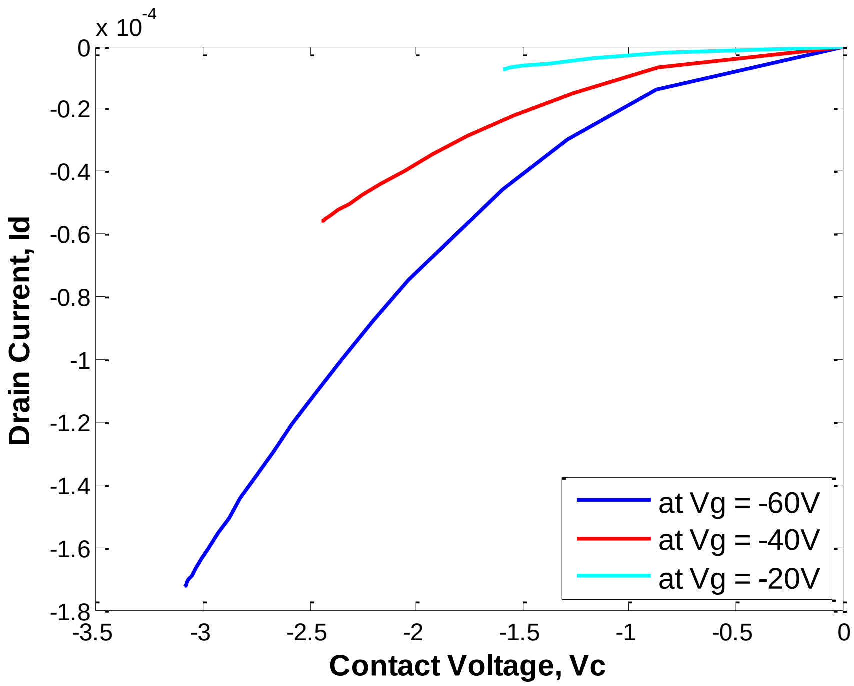

Figure 3-28: I_D-V_C Curve for L = 100µm and x_C = 5µm

3.2 Discussion

- We have made use of a analytical model to interpret contact effects in organic thin film transistors, and we have incorporated it in a generic compact model that describes the output characteristics of OTFTs.

- By carefully inspecting past and current achievements in modeling the contact effects of OTFTs, we have proposed a model for the current–voltage curves at the contact region that unifies different trends found in simulation value

- Using the compact model we captures the essential behavior of transfer characteristics at different channel length, and width and gate voltages at the contact region are varied

- The applicability to OTFTs differs in different structure and morphology.

- Reducing the device length will cause the strong contact effects on the OTFT. So the short-channel devices are strongly affected by the contact regions

- The model is easily reduced to the generic FET model with a constant mobility and no contact effects.

Chapter 4: Conclusion

By carefully inspecting past and current achievements in modeling the contact effects of OTFTs, we have simulated the output characteristics I_D-V_D and input characteristic Id-Vg for the current–voltage curves considering the contact region that unifies different trends. But modeling a OTFT model is difficult task because it does not follow the general FET model. For Characterization of compact modeling, using only one parameter, has been embedded in a generic charge drift model that also includes a gate voltage-dependent mobility. With a constant mobility and no contact effects the model is easily reduced to the generic FET model. We also found from our simulation result that if we reduced the length in the output characteristics equation the contact effect increases which we don't want. We have proposed a characterization procedure to extract the values of the parameters of the OTFT model, which does not need major reassessment as compared to those for crystalline FETs. We have obtained reliable and good fitting of the simulated TFT generic model compare to ideal one. We also try to check the consistency in the bridge between physical origin of the contact effects and the parameters of the model. The proposed simulated model is a powerful tool to describe the large amount of different structures that subjected to same type organic material in an OTFT. This model features the essential behavior of transistors when temperature, channel length, width and different energy barriers at the contact region are varied. It also provides information about the free charge density.

4.1 Future work

P-type OTFTs has resulted in promising carrier mobility and on/off current ratios, there are significant problems requiring further research. One notable issue is the poor electron mobility in OSCs, limiting the effectiveness of n-type OTFTs. Modern circuitry uses both p-type and n-type transistors, so developing an effective n-type OTFT is an important area for future research. Investigating these predictions is a potential area of future research. Previous TFT models assume a heavily doped ohmic contact at the source and drain regions and are inadequate for modeling OTFT characteristics especially at the triode region of operation. The proposed gate voltage dependent resistance model shows a significant improvement, but work still needs to be done to refine the model to make it fit even better. Having such a model is very important, since it will allow more accurate circuit simulation of circuits composed of OTFTs. In conclusion, OFET research over recent decades has led to very promising p-type devices based on a wide selection of OSCs ranging from simple oligomers such as pentacene to complex discotic and functionalized com-pounds. Problems relating to electron mobility, chemical deposition techniques, and anisotropy still limit OFETs. However, if these obstacles are overcome, OFETs could be used to create cost-effective, lightweight and environmentally-friendly circuits.

One of the major problems facing OFETs today is the anisotropy inherent in most of the OSCs due to their linear nature. The conductivity of linear OSCs can change depending on the direction of the applied voltage in relation to the orientation of the molecules. Thus, optimizing the performance of OFETs requires either excellent control of molecule orientation during deposition or an isotropic alternative to linear OSCs. So that a physical advanced model is necessary in order to take into account all the effects that appear in the OTFT.

Bibliography

[1] O. Marinov, M. J. Deen and B. Iniguez, "Charge transport in organic and polymer thin-film transistors: Recent Issues," *IEE Proc.-Circuits Devices and Syst.,* vol. 152, pp. 189-209, 2005.

[2] S. Forrest, "Nature," 2004, pp. 428 , 911.

[3] L. Bürgi, T. Richards, R. Friend and H. Sirringhaus, "Close look at charge carrier injection in polymer field effect transistors," *J. Appl. Phys.,* vol. 94, pp. 6129-6137, Novenber, 2003.

[4] P. L. Bullejos, J. A. J. Tejada, M. J. Deen, O. Marinov and W. R. Datars, "Unified model for the injection and transport of charge in organic diodes," *J.Appl. Phys.,* vol. 103, p. 1−12(064504), March, 2008.

[5] M. J. Deen, O. Marinov, U. Zschieschang and H. Klauk, "Organic thin film transistors: Part II—Parameter extraction," *IEEE Trans. Electron Devices,* vol. 56, p. 2962−2968, December, 2009.

[6] P. Necliudov, M. shur, D. Gundlach and T.N. Jackson, "Modeling of organic thin film transistors of different designs," *J.Appl.Phys.,* vol. 88, p. 6594−6597, December, 2000.

[7] http://whatis.techtarget.com/definition/transistor. [Online].

[8] http://www.transistormuseum.com. [Online].

[9] I. B. Forest, A. Sharoni, C. Colesniuc, J. Park, I. K. Schuller, A. Kummel and W. C. Trogler, "Gas Sensing Mechanism in Chemiresistive Cobalt and Metal-Free Phthalocyanine Thin Films," *J. Am. Chem. Soc.,* vol. 129(17), pp. 5640-5646, 2007.

[10] M. Bouvet, "Phthalocyanine-based field-effect transistors as gas sensors," *Anal Bioanal Chem,* vol. 384(2), pp. 366-373, 2006.

[11] C. Dimitrakopoulos and P. Malenfant, "Organic Thin Film Transistors for Large Area Electronics," *Advanced Materials,* vol. 14, no. 2, pp. 99-117, 2002.

[12] K. Miller, R. Yang, M. Hale, J. Park, B. Fruhberger, R. Colesniuc, L. Schuller, A. Kummel and W. Trogler, "Electrode Independent Chemoresistive Response for Cobalt Phthalocyanine in the Space Charge Limited Conductivity Regime," *J. Phys. Chem.,* vol. 110(1), pp. 361-366, 2006.

[13] R. Yang, B. Fruhberger, J. Park and C. A. Kummel, "Chemical identification using an impedance sensor based on dispersive charge transport," *Applied Physics Letters,* vol. 88(7), p. 074704, 2006.

[14] "http://macao.communications.museum/eng/exhibition/secondfloor/moreinfo/2_10_3_howtransistorworks.html," [Online].

[15] "http://www.electronics-tutorials.ws/transistor/tran_8.html," [Online].

[16] "http://www.electronics-tutorials.ws/transistor/tran_5.html," [Online].

[17] "http://www.electronics-tutorials.ws/transistor/tran_5.html," [Online].

[18] "http://acpce.org/httpdocs/FET-Basics-1.htm#slide0111.htm," [Online].

[19] http://ecee.colorado.edu/~bart/book/movie/movie6.htm. [Online].

[20] http://wiki.analog.com/university/courses/electronics/text/chapter-15. [Online].

[21] "http://berc.berkeley.edu/tunneling-field-effect-transistors-beyond-moores-law/," [Online].

[22] http://www.radio-electronics.com/info/data/semicond/fet-field-effect-transistor/finfet-technology-basics.php. [Online].

[23] "http://en.wikipedia.org/wiki/Multigate_device," [Online].

[24] H. Lars, "Electrolyte-Gated Organic Thin Film Transistors," *Linköping Studies in Science and Technology,* p. 1389, 2011.

[25] Y. Lin, D. Gundlach, S. Nelson and T. Jackson, "Pentacene-Based Organic Thin-film Transistors," *IEEE Transactions on Electron Devices,* vol. 44(8), pp. 1325-1331, 1997.

[26] F. Ebisawa, T. Kurokawa and S. Nara, "Electrical Propertiesof Polyacetylene/Polysiloxane Interface," *J. Appl. Phys,* vol. 54, p. 3255, 1983.

[27] M. Hong, B. Kim, Y. Lee, K. Song, J. Oh and J. Kim, "Recent Progress in Large-Sized High-Performance Organic-TFT Arrays," in *SID International Symposium, Boston, MA,* 2005.

[28] "FinFET Basics and Technology," [Online]. Available: http://www.radio-electronics.com/info/data/semicond/fet-field-effect-transistor/finfet-technology-basics.php.

[29] A. Sharma, C. Madhu and J. Singh, "Performance Evaluation of Thin Film Transistors: History, Technology Development and Comparison: A Review," *International Journal of Computer Applications,* vol. 89(15), p. 0975 – 8887.

[30] J. A. J. Tejada, J. A. L. Villanueva, P. L. Varo and K. M. Awawdeh, "Compact Modeling and Contact Effects in Thin Film Transistors," *IEEE Transasctions on electron devices,* vol. 61, no. 2, FEBRUARY 2014.

[31] A. Valletta, A. Daami, M. Benwadih, R. Coppard, G. Fortunato, M. Rapisarda, F. Torricelli and L. Mariucci, "Contact effects in high performance fully printed p-channel organic thin film transistors," *APPLIED PHYSICS LETTERS,* vol. 99, p. 233309, 2011.

[32] L. Bürgi, T. J. Richards, R. H. Friend and H. Sirringhaus, "Close look at charge carrier injection in polymer field-effect transistors," *JOURNAL OF APPLIED PHYSICS,* vol. 94, no. 9, November 2003.

[33] Y.Y. Lin, D.J. Gundlach and T.N. Jackson, "High-Mobility Pentacene Organic Thin Film Transistors," in *54th Device Research Conference*, 1996.

[34] Y.-J. Lin and B.-C. Huang, "Influence of the contact resistance effect on the output characteristics of pentacene-based organic thin film transistors," *Microelectronic Engineering,* vol. 103, pp. 76-78, 2013.

[35] N. Yoneya, M. Noda, N. Hirai, K. Nomoto, M. Wada and J. Kasahara, "Reduction of contact resistance in pentacene thin-film transistors by direct carrier injection into a-few-molecular-layer channel," *Applied Physics Letter,* vol. 85, p. 4663, 2004.

[36] S. Nelson, Y. Lin, D. Gundlach and T. Jackson, "Temperature-independent transport in high-mobility pentacene transistors," *Applied Physics Letters,* vol. 72, p. 1854, 1998.

[37] S. D. Wang, Y. Yan and K. Tsukagoshi, "Understanding contact behavior in organic thin film transistors," *Applied physics letters,* vol. 97, no. 6, p. 63307, August 2010.

[38] C. Sohn, T. Rim, G.-B. Choi and Y. Jeong, "Analysis of contact effects in inverted-staggered organic thin-film transistors based on anisotropic conduction," *IEEE Trans. Electron Devices,* vol. 57, no. 5, pp. 986-994, May 2010.

[39] V. Vinciguerra, M. L. Rosa, D. Nicolosi, G. Sicurella and L. Occhipinti, "Modeling the gate bias dependence of contact resistance in staggered polycrystalline organic thin film transistors," *Organic Electronics,* vol. 10, no. 6, pp. 1074-1081, September 2009.

[40] O. Marinov, M. J. Deen, U. Zschieschang and H. Klauk, "Organic thinfilm transistors: Part I—Compact DC modeling," *IEEE Trans. Electron Devices,* vol. 56, no. 12, pp. 2962-2968, December 2009.

[41] M. J. Deen, O. Marinov, U. Zschieschang and H. Klauk, "Organic thinfilm transistors: Part II—Parameter extraction," *IEEE Trans. Electron Devices,* vol. 56, no. 12, pp. 2962-2968, December 2009.

[42] C. H. Kim, M. Estrada, A. Cerdeira, G. Horowitz and B. Iñiguez, "compact model for organic field-effect transistors with improved output asymptotic behaviors," *IEEE TRANSACTIONS ON ELECTRON DEVICES,* vol. 60, no. 3, pp. 1136-1141, March 2013.

[43] A. C. Carranza, M. Estrada, J. Nolasco and A. Cerdeira, "Organic thin-film transistor bias-dependent capacitance compact model in accumulation regime," *IET Circ. Dev. Syst.,* vol. 6, no. 2, pp. 130-135, 2012.

[44] T. Minari, T. Nemoto and S. Isoda, "Fabrication and characterization of single-grain organic field-effect transistor of pentacene," *Journal of Applied Physics,* vol. 96, p. 769, 2004.

[45] G. Wang, Yi Luo and P. H. Beton, "High mobility organic transistors fabricated from single pentacene microcrystals grown on a polymerfilm," *Applied Physics Letters,* vol. 83, p. 3108, 2003.

[46] V. Podzorov, S. E. Sysoev, E. Loginova, V. M. Pudalov and M. E. Gershenson, "Single-crystal organic field effect transistors with the hole mobility ~8 cm2/Vs," *Applied Physics Letters,* vol. 83, p. 3504, 2003.

[47] Yanming Sun, Yunqi Liu and Daoben Zhu, "Advances in organic field-effecttransistors," *Journal of Materials Chemistry,* vol. 15, p. 53, 2005.

[48] Y.Y. Lin, D.J. Gundlach, S.F. Nelson and T.N. Jackson, "Pentacene-Based Organic Thin-film Transistors," *IEEE Transactions on Electron Devices,* vol. 44, no. 8, pp. 1325-1331, 1997.

[49] Z. Rang, A. Haraldsson, D.M. Kim, R.J. Chesterfield, C.D. Frisbie and P.P. Ruden, "Hydrostatic Pressure Dependence of the Photoconductivity of Single Crystal Pentacene and Tetracene," *Appl. Phys. Lett,* vol. 79, no. 17, p. 2791, 2001.

[50] "http://wtt-pro.nist.gov/wtt-pro/index.html?cmp=pentacene#pentacene/aa1;100,100,508,418/ compound information," [Online].

[51] H. Borkan and P.K. Weimer, "An analysis of the characteristics of insulated-gate thin-film transistors," *RCA Rev.,* vol. 24, pp. 153-165.

[52] Z. Bao, A.J.Lovinger and A.Dodabalapur, "Organicfield-effecttransistors with high mobility based on copper phthalocyanine," *AppliedPhysicsLetters,* vol. 69, no. 20, pp. 3066-3068, 1996.

[53] C. Reese, M. Roberts, M. Ling and a. ZhenanBao, "Organic thin film," *MaterialstodaySeptember,* September 2004.

[54] G. B. Blanchet, C. R. Fincher, M. Lefenfeld and J. A. Rogers, "Contact resistance in organic thin film transistors," *AppliedPhysicsLetters,* vol. 84, no. 2, pp. 296-298, 2004.

[55] J. Zaumseil, K.W.Baldwin and J.A.Rogers, "Contact resistance inorganic transistors that use source and drain electrodes formed by soft contact lamination," *JournalofAppliedPhysics,* vol. 93, no. 10, pp. 6117-6124, 2003.

[56] R. D. Yang, J. Park, C. N. Colesniuc, I. K. Schuller, W. C. Trogler and A. C. Kummel, "Ultralow drift in organic thin-film transistor chemical sensors by pulsed gating," *Journal of Applied Physics,* vol. 103, no. 3, pp. 34515-7, 2007.

[57] S. M. Sze, Physics of Semiconductor Devices, 2nd ed., New York: Wiley, 1981, pp. 438-453.

[58] D. J. Gundlach, L. Zhou, J. A. Nichols, T. N. Jackson, P. V. Necli-udov and M. S. Shur, "An experimental study of contact effects in organic thin film transistors," *Journal of Applied Physics,* vol. 100, no. 2, pp. 024509-13, 2006.

[59] S. D. Wang, T. Minari, T. Miyadera, K. Tsukagoshi and Y. Aoyagi, "Contact-metal dependent current injection in pentacene thin-film transistor," *Applied Physics Letters*, vol. 91, no. 20, pp. 203508-1–203508-3, 2007.

[60] S. D. Wang, T. Minari, T. Miyadera, K. Tsukagoshi and J. X. Tang, "Contact resistance instability in pentacene thin film transistors induced by ambient gases," *Applied Physics Letters*, vol. 94, no. 8, pp. 083309-1–083309-3, 2009.

Appendix A

A-1 Coder for I_{DS}-V_{DS} Characteristics of OTFT for different device length

```
clear all
clc
clf

IDVDS3=load('-ascii','IDVDS100-20.txt'); % VGS=-20 V
IDS(:,1)=-IDVDS3(:,2)*1e-6; VDS(:,1)=-IDVDS3(:,1);

L = 100e-6; xc = 50e-7; Vg = -20;

Id7 = zeros(1,length(IDS(:,1)));
for n = 2:length(IDS(:,1))
Id7(n) = solvebisection(IDS(n,1),VDS(n,1),Vg,L,xc);
end
plot(VDS(:,1),Id7,'-r','linewidth',3);
hold on

Id7 = zeros(1,length(IDS(:,1)));
for n = 2:length(IDS(:,1))
Id1(n) = solvebisection1(IDS(n,1),VDS(n,1),Vg,L,xc);
end
plot(VDS(:,1),Id1,'-b','linewidth',3);
xlabel('Drain Voltage  V_{DS} (V)','fontweight','bold','FontSize',12);
ylabel('Drain Current  I_{DS} (A)','fontweight','bold','FontSize',12);


hleg=legend('Modeled','Ideal',2);
```

A-2 Coder for transfer characteristics

```
clear all;
clc;
clf;



IDVDS6=load('-ascii','IDVDS100-20.txt'); % VGS=-20 V
IDS(:,6)=-IDVDS6(:,2)*1e-6; VDS(:,6)=-IDVDS6(:,1);

L = 100e-6; xc = 50e-7; Vg = -60:2.5:0; Vd = -60;

Id8 = zeros(1,length(IDS(:,6)));
for n = 2:length(IDS(:,6))
Id8(n) = solvebisection(IDS(n,6),Vd,Vg(n),L,xc);
end
plot(Vg,Id8,'-b','linewidth',2);
xlabel('Gate Voltage, Vg','fontweight','Bold')
ylabel('Drain Current, Id','fontweight','Bold')
xlim([-55 0])
```

A-3 Coder for I_{DS}-V_{DS} Characteristics of OTFT for different channel length

```
clear all;
clc
clf

IDVDS2=load('-ascii','IDVDS150-40.txt');
IDS(:,2)=-IDVDS2(:,2)*1e-6; VDS(:,2)=-IDVDS2(:,1);

L = 100e-6; xc = 50e-7; Vg = -20; Vd1 = -60:.1:0;
Id5 = zeros(1,length(IDS(:,1)));
for n = 2:length(IDS(:,1))
Id5(n) = solvebisection(IDS(n,2),VDS(n,2),Vg,L,xc);
end
plot(VDS(:,2),Id5,'-k','linewidth',2);
hold on

L = 100e-6; xc = 100e-7; Vg = -20; Vd1 = -60:.1:0;
Id5 = zeros(1,length(IDS(:,1)));
```

```
for n = 2:length(IDS(:,1))
Id5(n) = solvebisection(IDS(n,2),VDS(n,2),Vg,L,xc);
end
plot(VDS(:,2),Id5,'-b','linewidth',2);
hold on

L = 100e-6; xc = 150e-7; Vg = -20; Vd1 = -60:.1:0;
Id5 = zeros(1,length(IDS(:,1)));
for n = 2:length(IDS(:,1))
Id5(n) = solvebisection(IDS(n,2),VDS(n,2),Vg,L,xc);
end
plot(VDS(:,2),Id5,'-r','linewidth',2);
xlabel('Drain Voltage  V_{DS} (V)','fontweight','bold','FontSize',12);
ylabel('Drain Current  I_{DS} (A)','fontweight','bold','FontSize',12);


hleg=legend('L = 150 \mum  x_{C}= 50 \mum','L = 150 \mum  x_{C}= 100 \mum','L = 150
\mum  x_{C}= 150 \mum',2)
```

A-4 Coder for I_{DS}-V_C Characteristics of OTFT

```
clear all;
clc;
clf;

IDVDS6=load('-ascii','IDVDS150-60.txt'); % VGS=-20 V
IDS(:,6)=-IDVDS6(:,2)*1e-6; VDS(:,6)=-IDVDS6(:,1);

L = 100e-6; xc = 50e-7; Vg = -60;

Id8 = zeros(1,length(IDS(:,6)));
for n = 2:length(IDS(:,6))
Id8(n) = solvebisection(IDS(n,6),VDS(n,6),Vg,L,xc);
end
```

```
Vc1 = VC(Id8,xc,Vg);
plot(Vc1,Id8,'-b','linewidth',2);
xlabel('Contact Voltage, Vc','fontweight','Bold')
ylabel('Drain Current, Id','fontweight','Bold')
hold on

Vg = -40;

Id8 = zeros(1,length(IDS(:,6)));
for n = 2:length(IDS(:,6))
Id8(n) = solvebisection(IDS(n,6),VDS(n,6),Vg,L,xc);
end

Vc1 = VC(Id8,xc,Vg);
plot(Vc1,Id8,'-r','linewidth',2);
xlabel('Contact Voltage, Vc','fontweight','Bold')
ylabel('Drain Current, Id','fontweight','Bold')
hold on

 Vg = -20;

Id8 = zeros(1,length(IDS(:,6)));
for n = 2:length(IDS(:,6))
Id8(n) = solvebisection(IDS(n,6),VDS(n,6),Vg,L,xc);
end

Vc1 = VC(Id8,xc,Vg);
plot(Vc1,Id8,'-c','linewidth',2);
xlabel('Contact Voltage, Vc','fontweight','Bold','FontSize',12)
ylabel('Drain Current, Id','fontweight','Bold','FontSize',12)
hold off

hleg=legend('at Vg = -60V','at Vg = -40V','at Vg = -20V', 4)
```