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Comparative Study of Materials for Low Voltage Organic and Inorganic Dielectric for OFET

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Abstract - *This paper presents comparative analysis of various for Organic field effect transistor (OFET) design. With the aim of creating active channel layers in OFETs to increase their selectivity and sensitivity, extensive research has been done on various organic semiconductors (OSCs) in small molecules and polymers. However, stalled OFET devices must be amplified in order to demonstrate reliable performance at the device level and in application detection. Beginning with OFETs, this analysis will concentrate on their device geometry, operating principle, materials (OSC), parameters, and OFET-based sensors. The electrical scattering of the OFET can no longer be treated improperly due to the ongoing rise in charge carrier mobility and OFET operating frequency. To create Organic field effect transistors and their compatible circuits with low power consumption, comparative study has been conducted.*

Key Words: Organic field effect transistor (OFET), Dielectric Materials, Low Power Consumption, OFET based Sensors, Material for OFET.

1. INTRODUCTION

For the past twenty years, organic field effect transistors (OFETs) have focused on application research sensing. Organic field effect transistors have many advantages over their inorganic counterparts, including easy assembly, low power consumption, wide coverage, low cost, flexibility, and easily tuneable electronic material properties. Due to its printing, and low power capabilities, organic field effect transistors (OFET) have evolved over the past several years into vehicles for many electronic technologies, such as robotic skin and wearable electronics. The organic semiconductor is used in the channels of field-effect transistors (FETs) called OFETs. Small molecules can be vacuum evaporated, small molecules or polymers can be solution cast, or an open single-crystalline organic layer can be applied over a substrate to create an organic field effect transistor. These tools were created to distinguish between low-priced, low-volume, and biodegradable electronics. Different device geometries are used for designing OFETs.The top drain and bottom gate with the source electrode is the most common device shape, and it is identical to that of thin film silicon transistors (TFT), which use thermally developed SiO_2 as the gate dielectric. The organic polymers, such as the widely used insulator poly (methyl-methacrylate) (PMMA)[1].

1.1 Device Structure of OFET

Organic field effect transistors are essentially a three terminal device, source drain and gateit is able to be defined as a sandwich structure together with a capacitor with one plate as a gate and the other plate as a semiconductor layer. The semiconductor layer interfaces electronically with the other two electrodes (source and drain). Fig- 1 shows the simple diagram of OFETs. A gate electrode is made from a highly doped silicon or gold, silver or platinum conductive material deposited on an insulating substrate which includes glass. All different layers are very thin, vaporized or printed films which give a dual reason of the structural base of the gate device and the carrier gate terminal, as they cannot structurally support themselves. [2]

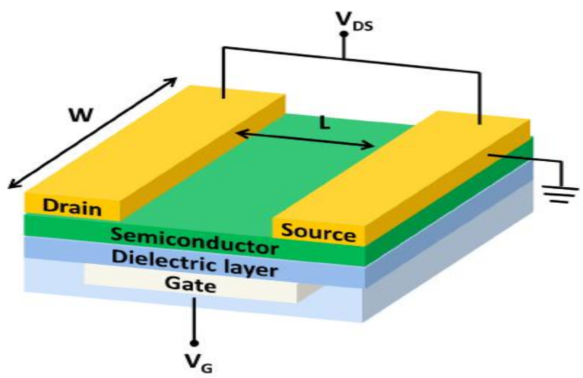

Fig -1: Schematic structure of an OFET

Silicon Gate Material Silicon dioxide is generallyfavored as a dielectric materials, but printable insulate polymers- for examples, polystyrene, poly (methyl methacrylate) (PMMA) and polyurethane and PVV are used to make flexible devices. Organic semiconductor layers may be printed or deposited the use of physical vapour deposition which includes poly (3-hexildiophene-2,5-diol) (P3HT) or pentacene are used. The source electrode and the drain electrodes are made of conductive material such as polymer or metal.[3]

2. Electrical Characteristic OFET devices

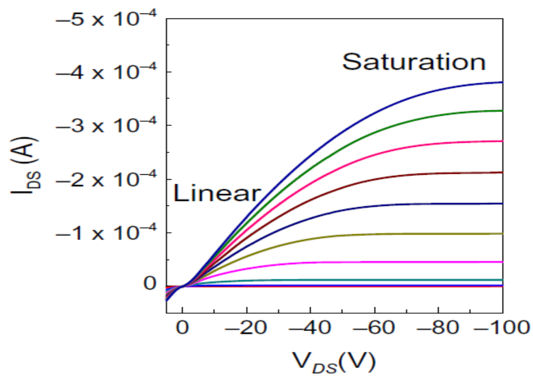

Fig -2: (a) Output characteristic of an OFETS

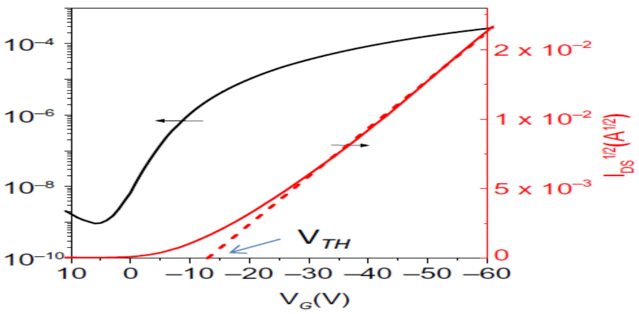

Fig -2: (b) Transfer characteristic an OFETS

3. OFET Parameter

3.1 Field-Effect Mobility

For a small drain to source voltage, the Transconductance (gm), which is the change in source to drain current with gate to source voltage, can be used to derive the carrier field-effect mobility (μ) in the linear area (VDS). For Transconductance(g_m) is given by

$$g_m = -\frac{\partial I_{DS}}{\partial V_{GS}}\Big|_{V_{DS}=\text{small const.}} = \frac{W \mu C_{OX}}{L} V_{DS}$$

Therefore, the linear mobility

$$\mu = -g_m \frac{L}{W}\frac{1}{C_{OX}}\frac{1}{V_{DS}}\Big|\ V_{DS} = \text{small const.}$$

Similarly, the biased device's transfer curve (IDS / VGS) yields the field-effect mobility (μ) in the saturation state as [$V_{DS} \geq V_{GS} - V_T$]. The field effect mobility demonstrates that the saturated current's square root is only dependent on gate voltage. The slope of the curve that depicts the square root of the saturated current as a function of the gate voltage between the source and gate is where the field-effect dynamics curve is retrieved from (Vgs). [6]

Mobility can be given by,

,

$$\mu = 2\frac{L}{W}\frac{1}{C_{OX}}\left(\frac{\partial\sqrt{I_{DS}}}{\partial V_{GS}}\right)^2$$

3.2 Threshold voltage

Threshold voltage is the result of much effect and is powerfully dependent on the organic semiconductor and using dielectric. Normally, threshold voltage can be caused by charge traps, interface states, impurities inherent dipoles etc. And this can be reducing by increase the gate capacitance, which produces a higher charge at a lesser applied voltage. In maximum of instances, the input voltage isn't a given device is always constant. It is called the bias stress performance and it has an important impact at the application of organic transistors in electric circuits. It is therefore currently under intense scrutiny. A change in the input voltage might cause current hysteresis on the time scale of the current-voltage measurement.[5]

3.3 Current ON/OFF Ratio

Any other important Field Effect Transistor (FET) parameter that can be subtracted from the transfer property is the present on/off ratio. It is determined by the drainage current to on-state and off-state ratio. This value needs to be as high as it can be for the transistor to operate at its best. The current on state also depends on the gate dielectric potential and on the mobility of the semiconductor when the contact resistance property at the source electrode and drain electrodes is disregarded. The gate leakage current also affects the current off state. Due to the conduction channel on the substrate boundary and the semiconductor's bulk conductivity, this is extended for semiconductor layers and non-pattern gate electrodes. Additionally, accidental doping can boost current off state. [7]

3.4 Sub threshold Swing

Subthreshold swing/subthreshold slope regulates the voltage needed for the transistor to change from the on-state to the off-state. To further reduce the operation voltages, the sub threshold slope (SS), which specifies the gate voltage quantity necessary to increase the drain-source current by an order of magnitude in the sub threshold region, should be steep. This is how the Subthreshold Slop is defined-

Here,

$$SS = SS_{\text{theoretical}}\left(1 + \frac{q^2 D_t}{C}\right)$$

$$SS_{\text{theoretical}} = \ln(10) v_{th} = 59.6 \frac{mV}{decade} \quad \text{(at T = 300K)}$$

D_t - Trap density

v_{th} - Thermal voltage

C - Gate dielectric's Capacitance.

For a perfect Organic FET, the subthreshold swing at room temperature (T = 300 K) is around 59.6 mV dec^{-1}.[23]

3.5 Contact Resistance

Contact resistance, which restricts device performance, is the resistance present between the contact electrode and the semiconductor interface. Numerous factors, including trap concentration, temperature, the work function between the contact electrode and the semiconductor material, doping levels, and device shape, have an impact on it. The barrier height is lowered as a result of increasing the work function of the contact electrode, which also lowers contact resistance. Reduced carrier mobility due to high resistance drains current. By include an optimally constructed acceptor layer and an appropriate active layer thickness, it can be decreased.

4. Materials of OFET

Basically, organic semiconductors fall into two categories: 1. Small molecules Polymers 2. A smaller molecule has fewer conjugated monomer units than a polymer, which has numerous conjugated monomer units and often forms longer chains with more complicated structures. The efficiency of the process and the qualities of the polymers are essentially determined by the configuration of repeated monomer units. These materials may be sub classified as semiconductors, which require n-type semiconductor, p-type semiconductor, and ambipolar transportation channels while being included in OFET, depending on the kind of charge carriers they primarily transport in equipment.[7]

4.1 P type semiconductor

Over the past 2 decades, The P-type semiconductor material has made great strides due to their easy design and artificial approach. P-type organic semiconductor consist mainly of acins, heterosines, theophanes, and their corresponding polymers and oligomers with two-dimensional (2D) disc-like molecule.[6]

4.1.1 Chemical structures of P-type small molecule-

4.1.1.1 Pentacene –Pentacene was first reported as a benchmark for organic semiconductors in the 1970s, although many OFET applications have been conducted recently. [6]The pentacene is a P-type small molecule and it is a polycyclic aromatic hydrocarbon with five linear linked Benzene rings. It is highly composite compound is the organic semiconductors. Excitation is produced by this chemical when ultraviolet or visible light is absorbed. It is extremely vulnerable to oxidation. Therefore this molecule is a purple color powder, decomposes gradually when exposed to light and air. [9] Pentacene molecules are known to have high carrier mobility in compared with many other organic compounds. The electrical performance of the pentacene transistors (normally organic transistors) is limited in carrier mobility, operating voltage and power consumption.

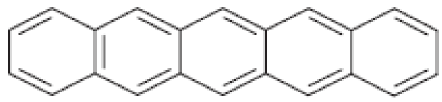

Fig -3: Chemical structure of Pentacene

4.1.1.2 Rubrene – The Rubrene (5,6,11,12-tetrafenyltetrazine) molecule is the red polycyclic aromatic hydrocarbon. Rubren is use as a sensitizer in chemistry and also as a yellow light source in light sticks. [10] Rubren is a molecule with a tetracycline spine and four attached phenyl ring. It has high charge mobility. Specifically, room-temperature hole mobility is measured for rubbers in a single-crystal OFET of the order 20-40 $cm^2V^{-1}s^{-1}$ [1]. Rubrene is broadly use in organic electronics, mainly organic field-effect transistors and organic light-emitting diodes (OLEDs).[8]

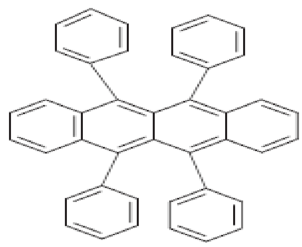

Fig -4: Chemical structure of Rubrene

4.1.1.3 TIPS-Pentacene – TheTIPS-Pentacene is a high purity molecule for used in OFET. It is generally used as a small molecule for OFETs application and it has high performance, excellent solubility and good ambient stability in the range of common organic solvents - making it easy to process in equipment.[9]

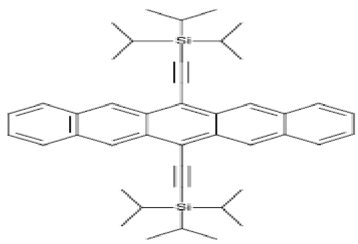

Fig -5: Chemical structure of TIPS-Pentacene

4.1.1.4 DNTT –The Dinaphthothienothiophene (DNTT) is a semiconducting polymer that has π-extended heteroarenes with six fused aromatic rings. It is a thermally stable crystal that has a hole mobility of 1 $cm^2V^{-1}s^{-1}$ which can be used for a majority of electronic applications. It is mainly use in the fabrication of organic field effect transistor (OFET) for a variety of applications such as implantable electronics, large-area sensitive catheters, and light emitting diodes (LEDs).[10]

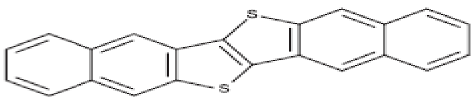

Fig -6: Chemical structure of DNTT

4.1.1.5 BTBT -A conjugating polymer, BTBT stands for benzothienobenzothiophene. It could be a spin-coated TFT. Its charge mobility is 43 $cm^2V^{-1}s^{-1}$, making it is suitable for usage as p-type semiconductors. High field-effect mobility in solution-processed OFETs is 5.5 to 5.7 cm2/Vs, and an excessive On/Off ratio of 109 is present. The organic light emitting diode (OLED), organic photovoltaic cell (OPV), and organic thin film transistor are some examples of organic electronic applications in which it might be used (OTFT).[11]

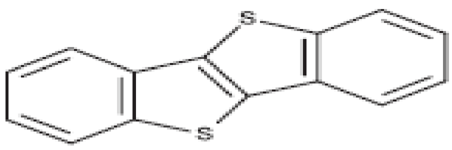

Fig -7: Chemical structure of BTBT

4.1.2 Chemical structures of p-type polymers

4.1.2.1 P3HT –The Regioregular poly(3-hexylthiophene-2,5-diyl) is also called as P3HT.It is a trendy low band gap polymers donor with applications in OFET, OLED, polymer solar cells and OPV. The highest P3HT polymers produce vastly crystalline film and are suggested for OFET. The regioregularity P3HT and lower molecular weight is recommended for inkjet and drying deposition techniques for large area where gelling/aggregation and surface roughness should to be avoid. The fabrication report has mobility measurement value is 0.12 cm2/Vs.[12]

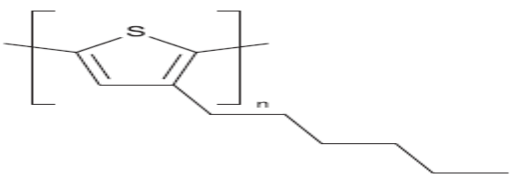

Fig -8: Chemical structure of P3HT

4.1.2.2 PBTTT -PBTTT-C14 is a semiconducting material which is used as a hole transporting material (HTM). It has crystal orientation and ordered structure gives the result in a high performance conducting material.[1] PBTTT-C14 based conjugated polymers can potentially be used in combination with fullerenes and P3HT for the manufacture of a wide range of devices like organic field effect transistor (OFET), organic photovoltaics (OPVs), solar cells (SCs) and photodiodes. It has high charge-carrier mobility is approx~1 $cm^2/(V\ s)$ in TFT. The electron affinity (EA) and ionization energy (IE) of PBTTT is −3.2 eV and −5.1 eV .[13]

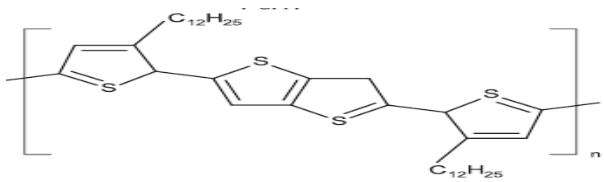

Fig -9: Chemical structure of PBTTT

4.2 N type semiconductor

Because of their high lowest unoccupied molecular orbital (LUMO) energy levels, N-type organic semiconductors nevertheless exhibit air instability under ambient conditions despite having much higher mobility than p-type semiconductors. For OFETS, stable n-type semiconductor materials with high charge carrier mobility are the optimal choice.

4.2.1 Chemical structures of n-type small molecules

4.2.1.1 Fullerene -In 1985, the Fullerene tiny molecule was discovered in the sooty residue that remained after carbon was vaporised in a helium environment. They were given the name "buckminsterfullerenes" in honour of the discoverers who thought that the icosahedral geometry, which contains exactly 60 unsaturated carbon atoms, resembled the geodesic domes made famous by architect Buckminster Fuller. [14] Although the word has been shortened to "fullerene," they are also known as "buckyballs." Twelve pentagons and twenty hexagons make up the truncated icosahedral shape of fullerene C60. Every vertex and edge of the polygons are joined by bonds made up of one carbon atom. Fullerene C60 has a nucleus-to-nucleus diameter of around 0.71 nm and a van der Waals diameter of about 1.1 nm.[14]

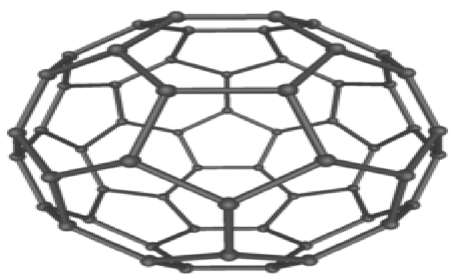

Fig -10: Chemical structure of Fullerene

4.2.1.2PCBM -The fullerene derivative of C60 buckyball, PCBM, was created for the first time in the 1990s. In flexible electronics, it is frequently combined with P3HT, organic solar cells (plastic solar cells), or electron donor materials like P3HT or other conductive polymers since it is an electron-accepting substance. [16] It combines with p-type conjugated polymer to produce thin film organic field effect transistors and photovoltaic (PV) components (OFET). It facilitates heterojunction PV cell and organic field effect transistor solution processes as well as composites planning. In a thin-film organic field effect transistor, PCBM has the strongest affinity for effective photo-induced electron transfer from p-type polymers as well as metal electrodes. Bulk energy conversion efficiency of 4.4% have been reported.[15]

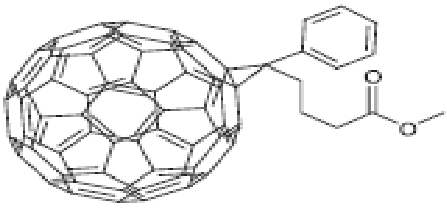

Fig -11: Chemical structure of PCBM

4.2.1.3 NTCDI –The Naphthalene tetracarboxylicdiamide (NTCDI) is a solid organic compound and simple naphthalene diamides (NDIs). The intermediate compound from NTCDI parent naphthalene is produced by naphthaleneetracarboxylicdionehydride. NTCDI Redox-Active forms a stable radical ion at -1.10 V against FC / Fc +. [5] The ability to accept electrons showcase an extended coupling ring system and the presence of electron withdrawal groups (carbonyl centers). Because of its tendency to form charge-transfer complexes with crown ethers NDI is used in supermolecular chemistry, for example, to give rotaxanes and catechins.[16]

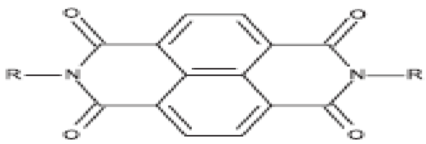

Fig -12: Chemical structure of NTCDI

4.2.1.4 PTCDI – Due to its brilliant colour, fluorescence, and strong absorption as well as excellent thermal and photochemical stability, the perylenetetracarboxylicdiimide, often known as PTCDI, is frequently used as a commercial pigment [14]. Powerful n-type organic semiconductors with several uses include PTCDI and its derivatives. For instance, they are used as optoelectronic devices such molecular switches, tunable laser dyes, solar cells, light-emitting diodes, and transistors due to their unique optical and electrochemical capabilities. Due to their significant intermolecular aggregation, derivatives of peryleneetrocarboxylic acid show warning indicators that they are suitable for charge transfer, which results in the generation of charge transfer exciton.[17]

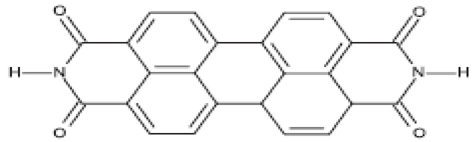

Fig -13: Chemical structure of PTCDI

4.2.2 Chemical structures of n-type polymers

4.2.2.1 P (NDI2OD-T2) –Researchers have studied the P(NDI2OD-T2) copolymer comprising naphthalene diimide (NDI) and bithiophene units for usage as an electron acceptor in polymer solar cells. The polymer exhibits high electron affinity, high light absorption, and excessive electron mobility. All polymer solar cells with J51 as a donor (fullerene-free) and P(NDI2OD-T2) as an acceptor have demonstrated an energy conversion efficiency of over 8%. Another name for the P(NDI2OD-T2) is high-mobility n-type polymer semiconductors. Based on organic field effect devices, P(NDI2OD-T2) has electron mobility ranging from 0.45 to 0.85 cm2V-1 s-1.·[18]

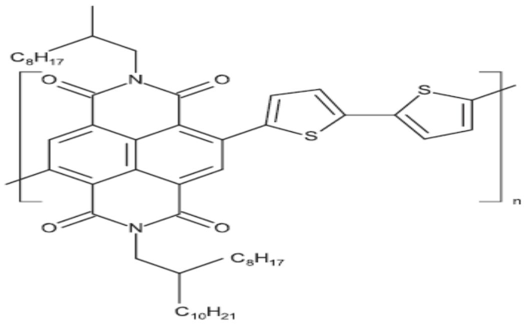

Fig -14: Chemical structure of P(NDI2OD-T2)

4.2.2.2 BBL -ThePoly(benzimidazobenzophenanthroline) Polymer is a semiconductor with *n*-type behaviour in photovoltaic cells (PVs) and organic field-effect transistors (OFETs). This Processed from solutions in methanesulfonic acid. The chemical formula of BBL is $(C_{20}H_6N_4O_2)_n$, and Band gap is1.9 eV. This material has Orbital energy LUMO -4.0 eV and HOMO -5.9 eV .The properties of N-type semiconductor mobility is 0.1 cm^2/V·s and P-type semiconductor mobility is 0.4 cm^2/V·s [19]

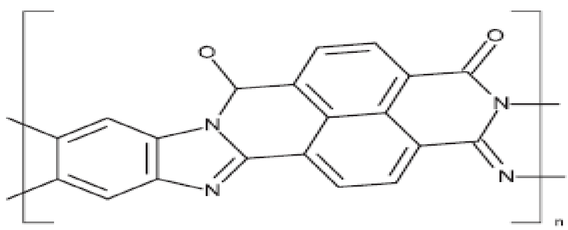

Fig -15: Chemical structure of BBL

5. Comparative Material for Low Voltage using organic and inorganic dielectric

Dielectric	Semiconductor	Method	Reference
Al_2O_3	Pentacene	Spin coating	[25]
Al_2O_3	ZNO	D.C. Sputtering	[26]
Al_2O_3	IGZO	Anodization	[27]
Ta_2O_5	P3HT	e-Beam	[28]
HfO_x	PTCDI-C_{13}	Sol-gel	[29]
PVA	P3HT	Spin-coating	[30]
SBA	Pentacene	Sol-gel	[31]
TiO2/SAM	DNTT	Anodization	[32]

Conclusion-

In this paper work has been carryout materials study for OFET. Organic field effect transistors are the most important technology with the use of organic semiconductor and also polymer. Organic field effect transistor device provided high flexibility and low manufacturing cost and also large area coverage transistor. Various OFET based device using p-type materials which includes pentacene because of higher carrier mobility in comparative to n-type materials. It can be treated at low temperatures compatible with plastic substrate, while high temperature is needed for different Si based FET. For Low power OFET design reducing Sub threshold Swing and Contact resistance is also decreased. High-k dielectric material should be used to reduce the operating voltage. Organic semiconductors based sensor show great bio compatibility and selectivity and also more sensitivity in comparison to conventional sensing devices.

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