Different Materials, Structures and Parameters for Organic Thin Film Transistors

S Gupta, P Mittal and P Juneja

1Department of Electronics and Communication Engineering, Graphic Era (Deemed to be University) Dehradun, Uttarakhand, India-248002
2Department of Electronics and Communication Engineering, Delhi Technological University, New Delhi, India-110042

Email: sakshi.130285@gmail.com; poornimamittal@dtu.ac.in; mailjuneja@gmail.com

Abstract: This paper assesses the topical progressions in the province of organic electronics especially the ones having SM and are made of polymer materials. It shows the analysis of structural disparity between top contact and bottom contact Organic Thin Film Transistors, thus rendering clarity to the conduction mechanism and performance governing parameters. Furthermore, an insight to a variety of materials that can be deployed in making different layers of an OTFT has been presented. In addition to this the parameters that oversee the performance of the device have also been highlighted. An elucidation of a variety of applications, limitations and scope has been reflected in the paper as well.

1. Introduction

Materials comprising hydrocarbon are coined as organic materials. Semiconducting nature of organic materials was identified by Kallmann and Pope through the injection of charge carriers in these using electrodes [1-2]. With the advent of technology, organic transistors are deployed in widely anticipated applications viz-a-viz RFID tags, active matrices [3-5], organic SRAMs, flexible integrated circuits and organic solar cells etc. The fabrication process of organic structures and their performance parameters are hugely affected by factors like electrode thickness, channel length, layer materials and semiconductor & insulator thickness. Progressions in the fabrication techniques using organic materials have aided the research to make use of plastic, glass, paper and fiber as supple substrates [6-10]. Amongst all the carbon-based materials, OTFTs constructed by means of pentacene validate the finest inferences with respect to mobility ($\mu = \text{cm}^2/\text{V s}$) and $I_\text{ON}/I_\text{OFF} (10^8)$ [11, 12]. OTFTs possess certain merits over MOSFETs viz. a) utilization of pliable substrates like cloth, fiber, paper, foil, and plastic, b) reinforcement at temperature that are considerably low, c) use of spin coating to deposit organic materials[13], inkjet printing [14], stamping and inking of polymer [15] etc.

This paper shall concentrate on single and dual gate structures of organic transistors along with an insight to above stated performance influencing factors. This paper is aligned in 6 sections, comprising the current section that focuses on structures and performance parameters of OTFTs. The second section emphasizes on the different organic/inorganic materials used for dielectric, semiconductor and contacts. Section 3 deliberates upon the various structures and their fabrication. On one hand where Section 4 deals with the operating principle of OTFT and insights the performance parameters of various structures of organic TFTs, section 5 talks about the applications of the device with Section 6 concluding the research.
2. Material for Organic TFT

This article elucidates the materials used for making different layers of an OTFT. Different layers of OTFT viz. Semiconductor, Electrode, Gate, and Dielectric may be constructed using a variety of organic/inorganic materials which affect the performance in several ways depending upon their properties listed in Table 1, Table 2, Table 3 and Table 4 respectively [16][17].

| Material | Type | Current ratio ($I_{on}/I_{off}$) | Mobility (cm$^2$/Vs) |
|----------|------|---------------------------------|---------------------|
| P3HT     | p-type CP | $10^{2} - 10^{4}$ | $10^{-2} - 0.13$ |
| PQT-12   | p-type CP | NR | $0.06-0.12$ |
| Pentacene| p-type SM | $10^{-2} - 10^{3}$ | 0.15-5.0 |
| POPP-TNT | p-type SM | $10^{2}$ | 0.42-0.98 |
| DCMT     | n-type CP | $>10^{2}$ | 0.2 |
| BBL      | n-type CP | $2x10^{4}$ | 0.1 |
| NTCDI    | n-type SM | $30-10^{5}$ | $10^{-3}-0.009$ |
| F$_{16}$CuPc | n-type SM | NR | 0.03 |

Table 2. Electrode Materials and their Work Function

| Material       | Work Function (eV) |
|----------------|--------------------|
| Aluminum (Al)  | 4.00-4.28          |
| Nickel (Ni)    | 4.10-5.00          |
| Copper (Cu)    | 4.70               |
| Gold (Au)      | 5.10               |

Table 3. Organic Gate Insulating Materials with their Dielectric Constants

| Material | Dielectric Constant |
|----------|---------------------|
| PI       | 2.60                |
| PVP      | 3.80                |
| PVC      | 4.6                 |
| PVA      | 7.8                 |

Table 4. Inorganic Dielectric Materials with their Dielectric Constants

| Dielectric Material | Dielectric Constant |
|---------------------|---------------------|
| SiO$_{2}$           | 3.50-4.50, 3.90     |
| Al$_{2}$O$_{3}$     | 8.50-9.00           |
| HfO$_{2}$           | 22, 25              |
| MgO                 | 9.80                |

3. OTFT Structures and Fabrication

The channel formation in an OTFT ensues due to the accumulation process which sets them different from the conventional MOSFETs.

3.1 OTFT Structures

Apparently, the classification of OTFT structures is primarily through the lining up of S, D, G and the organic semiconductor layer.

3.1.1 Top gate structures

Such structures have gate aligned on top of the organic semiconductor layer. Moreover, the position of the contacts can either be on top (through shadow masking) or bottom (through Microlithography) of the OSC layer resulting in top gate top contact (TGTC) and top gate bottom contact (BGTC) structures as depicted in Fig. 1a and b, respectively. [18]
3.1.2 Bottom gate structures
At high temperatures, active layer in TG structures undergoes contaminations and flaws due to amassing of gate metal because of which bottom gate (BG) structures as depicted in Fig. 2a and b are favored over these. However, upon increasing the injection area, the resistance of BGTC structures falls prominently [19].

![Fig. 2 BG Organic TFT](a) BGTC (b) BGBC

3.1.3 Dual gate structure
Dual Gate (DG)-OTFTs comprise an extra dielectric material and gate at the top and demonstrate augmented on-current and display improved regulation of threshold voltage in comparison to single gate transistors. SG and DG transistors are represented in Fig. 3a and b respectively [20].

![Fig. 3 Representation of OTFT](a) SG (b) DG

3.1.4 Cylindrical gate structure
Besides showing virtuous bending stability, operation free of hysteresis and elevated packing density, cylindrical gate (CG) structures also deliver reduction in size. [21, 22]. It employs a thin insulating layer encapsulating metallic fiber as gate electrode. The S/D contacts may be constructed by employing metal or conductive polymer after depositing OSC layer on the insulator as shown in Fig. 4.

![Fig. 4 CG-TFT Structure](a) CG-TFT Structure

3.2 OTFT fabrication
Organic material’s purity, substrate cleaning together with the deposition rate govern the performance of the OTFT. In the 1980s, the demonstration of organic transistors on glass and plastic foil was done by numerous researchers, including Tsumura et al.,[23] Kudo et al.,[24] and Ebisawa et al. [25]. Pre-requisites of OTFT fabrication are selection of substrate, deposition of gate using spin-coating or solution processing, growing a dielectric layer and embedding the contacts.

4. Operating Principle and Performance Analysis of OTFTs
An organic thin film transistor is a device in which the organic active layer is a structure with approximately two dimensions, like a thin film. In 1979, Le Comber et al. [26] reported a hydrogenated
amorphous silicon (a-Si: H) based TFT that introduced the achievability of forming a thin film at a relatively lower temperature.

4.1 Operating Principle of OTFT

An OTFT is a layered structure comprising three electrodes named source (S), drain (D), and gate(G), a thin film of organic semiconductor and an insulator as depicted in Fig. 5. The injection and extraction of charge carriers is done by source and drain electrodes, respectively, which are in contact with the active layer. On the contrary, an insulator that controls the conductivity of the channel separates the gate from the semiconductor film.

Radically, the function of an OTFT cognates with that of a capacitor as it induces an electric field in the insulating layer at positive/negative $V_{gs}$ for n/p type OSCs. Consequently, the Fermi level of the metal gets aligned near HOMO (highest occupied molecular orbital) or LUMO (lowest unoccupied molecular orbital) levels of p or n-type semiconductors respectively, thereby resulting in an accumulation of holes/electrons. Owing to the distance of the Fermi level from the LUMO edge; there is an insufficient injection of electrons even after the application of a positive gate bias. Consequently, at positive $V_{gs}$ no current flows through in the OSC layer, only allowing a small leakage current to pass through the insulator [17].

4.2 OTFT-Performance analysis

A few of the significant parameters of OTFTs include threshold voltage ($V_t$), field dependent mobility ($\mu$), on/off current ratio ($I_{ON}/I_{OFF}$) and sub-threshold slope (SS). The value of these factors is dependent on grain size of OSC thin film, device geometry, structural dimensions, grain size of OSC thin film, materials of different layers and morphology of the semiconductor.

This section draws a comparison (Fig. 6) of the performance shown by TG TFT, BG TFT, DG TFT and CG TFT, with pentacene as the organic semiconductor (50 nm), width and length of the channel as 1000 and 30 µm, respectively. The contacts are of Au, each with a thickness of 45 nm
and a heavily doped silicon of 40 nm acting as the gate electrode. The dielectric employed is 200 nm SiO$_2$ with a dielectric of 3.9 and capacitance of the channel set as $1.65 \times 10^{-8}$ F/cm$^2$. [27]

5 Applications of OTFTs

From the very outset, OTFTs have developed as an essential means in the field of electronics. OTFTs have been keeping researchers on the roll with the multifold properties, structural variance and applications. OTFTs as economically viable pliable transistors exemplify for several applications, viz. transparent display, printable electronics, electronic paper, logic circuits, RFID tags, SRAMs and OLEDs. [10] OTFTs also find wide-ranging applications in ring oscillators, organic inverters, memory, organic DNA sensors, integrated circuits, solar cell, and backplane driver assisting in flexible displays. CG-TFT finds extensive application in sensors used in military for sensing the vicinity of the enemy and for sensing the vitals of a patient etc. [16, 17]

6. Conclusion

This paper swotted the developments advancements in conductive polymer/small molecule organic TFTs in relation to device structures, methods employed for fabrication, and applications. Moreover, single gate OTFT structures namely BGTC, BGBC, TGTC and TGB were examined and equated in terms of $\mu$, $I_{on}/I_{off}$, SS, $g_m$ and $V_t$. Certain pivotal applications were also highlighted along with primary limitations and future scope.

References

[1] Kallmann H and Pope M, Nature 186(4718) 31-33 1960
[2] Mittal P et al, Microelectronics Engineering 150 7–18 2016
[3] Kim Y H et al, Jpn. J. Appl. Phys. 43 3605 2004
[4] Nomoto K et al, IEEE Trans. Electron. Devices 52 1519 2005
[5] Mizukami M et al, IEEE Electron Device Lett. 27 249 2006
[6] Negi S et al, IET Circuits Devices and Systems 13(8) 1255-1261 2019
[7] Klauck H et al, Appl. Phys. Lett. 82 4175 2003
[8] Kim Y H et al, IEEE Electron Dev. Lett. 25, 702 (2004)
[9] Mittal P et al Journal of Computational Electronics 14(1) 360–379 2015
[10] Cantatore E et al, IEEE J. Solid-State Circuits 42(4) 84–92 2007
[11] Schon J H, Phys. Stat. Sol. (b) 226 257 2001
[12] Schon J H and Batlogg B J, Appl. Phys. 89 336 2001
[13] Raval H N et al, IEEE Electron Device Lett. 30(5), 484–486 2009
[14] Chen H et al, IEEE/OSA J. Disp. Tech. 5(6) 216–223 2009
[15] Li D and Guo L J, Phys. D: Appl. Phys. 41(10) 105115-1–105115-7 2008
[16] Kumar B et al, J. Mater. Sci: Mater Electron 25(1) 7-10 2013
[17] Kumar B et al Polymer Reviews, 54(1) 33-111 2014
[18] Schon J H, Chem. Soc. Rev. 39 2643 2010
[19] Negi S et al Journal of Electronic Materials 49 4610–4636 2020
[20] Cui T and Liang G, Appl. Phys. Lett. 86 064102 2005
[21] Mittal P Analysis of low-cost single and dual gate organic transistor and their parameters extraction and their performance IEEE International Conference on Signal Processing, Communication, Power and Embedded System, (ICOPES-2016), 1678-1682.
[22] Negi S et al Journal of the Society for Information Display https://doi.org/10.1002/jsid.952 2020
[23] Tsumura A et al, Appl. Phys. Lett. 49(18) 1210–1212 1986
[24] Verma A and Mittal P Performance Analysis of Different Novel Organic Thin Film Transistor Structures IEEE International Conference on Computing Communication and Automation (ICCCA- 2016) 1499-1504, 2016
[25] Ebisawa F et al, J. Appl. Phys. 54(6) 3255–1–3255-6 1983
[26] Mittal P et al Advanced Material Research, Trans. Tech. Publication 622 585–589 2013
[27] Gupta D et al Org. Electron. 10 775 2009