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Organic light emitting transistors: performance analysis and high performance device

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Abstract

In the field of optoelectronics, Organic Light Emitting Transistors (OLET) symbolise a new era. The OLET is a bifunctional device that combines the switching and amplification capabilities of organic field effect transistors with the electroluminescent capabilities of organic light emitting diodes in a single device. Organic semiconductor materials are important for optoelectronic devices because of their low cost, light weight, and flexible production procedures. OLETs play a vital role in the field of high mobility organic semiconductors and the fabrication of high performance organic optoelectronic devices as organic optoelectronic devices progress. The performance of OLETs with anthracene as an organic semiconductor material is discussed in detail in this research paper. The performance of OLETs is evaluated using a state-of-the-art Atlas Silvaco 2-D Simulator in terms of driving current, mobility, and current-on-off ratio. The device's output properties are also examined, and these values are then compared to the available dataset. The parameter values are as follows: Ids of 17 µA, mobility of $12 \times 10^{-2}\ \mathrm{cm}^2/\mathrm{Vs}$ and on-off ratio of 10^7. We have also calculated power consumption value (0.54 mW). We can see that this device has much higher mobility value and lower power consumption value which makes it the better performance device.

Keywords Organic light-emitting transistors (OLETs) · Organic light-emitting diodes (OLEDs) · Organic field-effect transistors (OFETs) · Organic semiconductors (OSCs)

1 Introduction

During the previous few decades, organic optoelectronics has grown in prominence. Organic semiconducting materials with unique electrical, optical, and magnetic properties have been developed and applied to a wide range of devices. Organic light emitting diodes (OLEDs), organic solar cells (OPVs), organic field effect transistors (OFETs), and organic light emitting transistors (OLETs) are among the devices that play a significant role [1]. OLEDs are one of the most important technological breakthroughs in recent history. OFETs are being developed in the meantime which is an another type of organic electronic component, is still in the experimental phase. They're popular because of their versatility, light weight, and inexpensive cost. OLEDs have recently gained a lot of interest. Nonetheless, circuit complexity is one of the biggest challenges for large-area display applications [2]. A revolutionary concept is offered to merge both optical and electrical functionality in a single device to reduce complexity. An organic light-emitting transistor (OLET) is a thin-film transistor with the ability to generate light [3–5]. It is possible to fabricate electroluminescent displays with simpler driving circuitry using multicolor OLETs. There are active-matrix OLED displays on the market, which is the most advanced technology. Higher penetration conditions affects exciton charge interaction and photon losses, lowering OLED performance 30–35. The goal of OLET research is to enable new display technologies by preventing photon losses and exciton charge interactions [4–7].

An organic light-emitting transistor (OLET) is a bifunctional device made of organic material that possesses both light emission and switching capabilities. OLETs are currently potential devices that exhibit certain intriguing properties of well-known electroluminescent devices. OLETs are being considered as viable candidates in integrated

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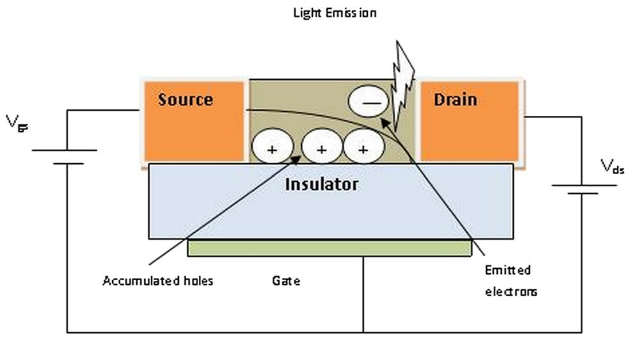


Fig. 1 An OLET structure in bottom contact bottom gate configuration

circuits that process both electrical and optical signals in the future [8]. Electrically pumped organic lasers have recently received a lot of attention in the research community. These devices have the potential to make existing display systems easier to make and to accelerate advancement in new areas like photonic communications and electrically pumped organic lasers [9, 10].

Hepp et al. developed the first organic single BGTC TFT device construction in the year 2003. Here, We're considering of using a unipolar OLET, in which channel can conduct only one type of charge carriers either holes or electrons [11–16]. Figure 1 shows the fundamental operation of an OLET with an organic semiconductor layer of anthracene in a BC/BG (bottom contact/bottom gate) arrangement. The following are the primary components of the device: (1) There are three electrodes. Charge carriers are injected and retrieved into and out of the semiconductor via the source and drain electrodes, (2) an organic semiconductor layer, which are made of either evaporated or deposited material. It is the device's active portion, where charge transfer and light emission take place; and (3) an organic dielectric layer that separates the gate from the source and drain electrodes [17].

2 Organic light emitting transistors: its concept, working principle and fabrication steps, and its device configurations

This section gets into the OLET working principle, fabrication steps, structural dimensions, and device configurations into detail

2.1 OLET working principle and its fabrication steps

In this device, holes are present as majority charge carriers, whereas electrons as minority charge carrier can only enter the channel by tunnelling from the drain electrode near to the drain electrode in the presence of a high electric field. In this device, light emission occurs by the excitons, which are pairs of holes and electrons in a highly excited state that develop near the drain electrode and cause radiative recombination and can emit light. As excitons are present near the drain electrode, non-radiation decay is a strong possibility. It's caused by a charge carrier escaping into the matching metal contact, resulting in an inefficient recombination of holes and electrons. This phenomenon, also known as exciton quenching, causes a reduction in light emission [18].

To improve emission efficiency, the recombination zone should be moved to the center of the channel or distant from the electrodes. The ambipolar OLET structure, as shown in Fig. 2, is one example of this type of structure.

In case of ambipolar OLET structure, charge carriers of source and drain are interchangeable. Radiative recombination occurs in ambipolar OLET structure when opposite charges combine to form an exciton, and the exciton decimates in the form of light radiation and heat. Figure 3 shows the stages involved in fabricating BGTC-OLET.

Fabrication of OLET devices plays a vital part in the device's performance by selecting the appropriate process stage and their materials [19]. Fabrication begins with the selection of the substrate material, which gives the device with mechanical strength. Furthermore, the gate electrode is made of PEDOT: PSS, while the dielectric layer is made of PMMA. Vacuum thermal evaporation is then used to create an organic semiconductor layer. After that, gold (Au) is used to deposit the source and drain electrodes. Table 1 depicts the structural dimensions of the device characteristics that are employed in the analysis of OLET performance.

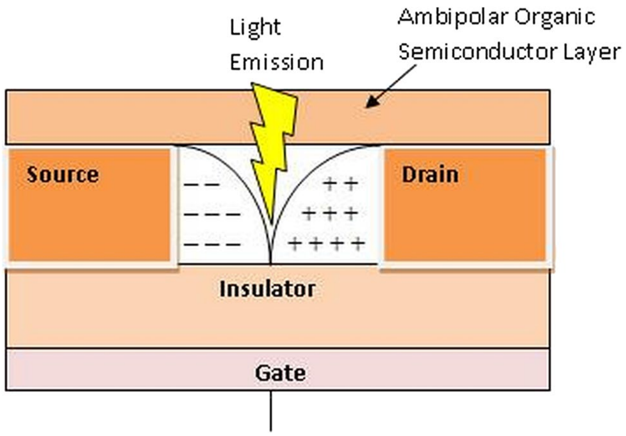


Fig. 2 Ambipolar OLET structure

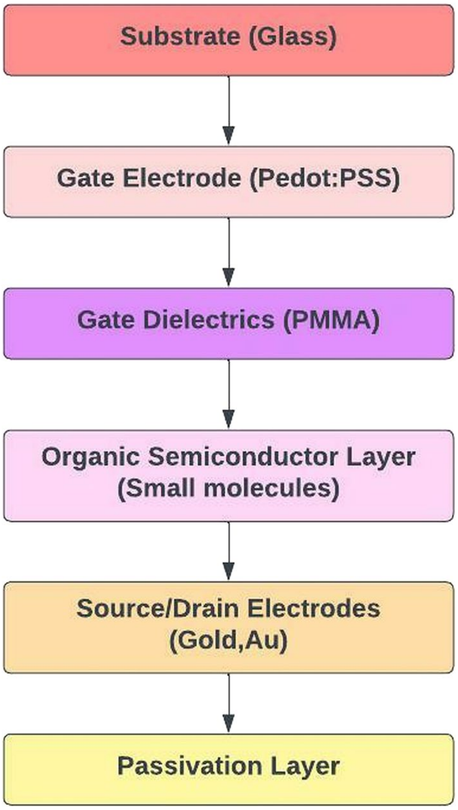


Fig. 3 Fabrication stages in BGTC OLET Structure

Table 1 OLET device parameter dimensions

S. no.	Device parameters	Values (nm)
1.	Length of the channel (L)	20
2.	Width of the channel (W)	1200
3.	Length of the source electrode and the drain electrode (L_S, L_D)	200
4.	OSC thickness (t_{osc})	400
5.	Gate thickness (t_G)	200
6.	Dielectric thickness (t_{ox})	200

3 OLET device configuration

Depending on the location of the device's gate, source, and drain electrodes, different topologies of organic light emitting transistors can be generated, as shown schematically in Figs. 4 and 5. This is especially true in multilayer systems, where the use of appropriate materials and structures is possible. Because top contacts have a greater interface with the underlying semiconductor, they are good for charge injection in field effect transistors. A planar configuration for the source and drain electrodes is not the optimum design when both charges are to be injected, because one of the charges will always be limited, regardless of polarity or transistor working conditions. To maximise charge carrier injection and the in multilayer designs, the energetics of each contact with the suitable semiconductor, non-planar source and drain can be generated. Electrodes in a multi-layer arrangement with a charge transport and emissive layer have been proven to reduce contact resistance and increase electron and hole recombination efficiency, resulting in a significant increase in brightness up to around 800 $\mathrm{cd/m^2}$, an ON/OFF ratio of the device greater than 10^5, EQE about 20 times greater than the reference sample [20–22].

4 OLETs parameters and impact of dielectrics

This section gets into the OLET parameters and importance of dielectrics into detail.

4.1 OLET parameters

The electric switching characteristic of the organic light emitting transistor (OLET) is similar to that of the organic field effect transistor (OFET). Organic light emitting diodes (OLED) electrical luminiscence characteristics [19]. Charge carrier mobility, threshold voltage, and current on-off ratio for electrical characteristics and brightness, as well as other FET and light-emitting OLED attributes [18], all have an impact on OLET parameters.

4.1.1 Mobility of the charge carrier (μ)

Charge carrier mobility is a key performance criterion for Organic semiconductors. In this experiment, an external electric field may be utilised to measure how rapidly a charge carrier can travel through a transistor channel. In highly organised materials, the range of motion is considerable $1\,\mathrm{cm^2/Vs} - 10\,\mathrm{cm^2/Vs}$, whereas disordered materials have lower mobilities ranging from 10^{-3} to $10^{-5}\,\mathrm{cm^2/Vs}$. The following equation can be used to estimate the carrier's mobility

For Unipolar

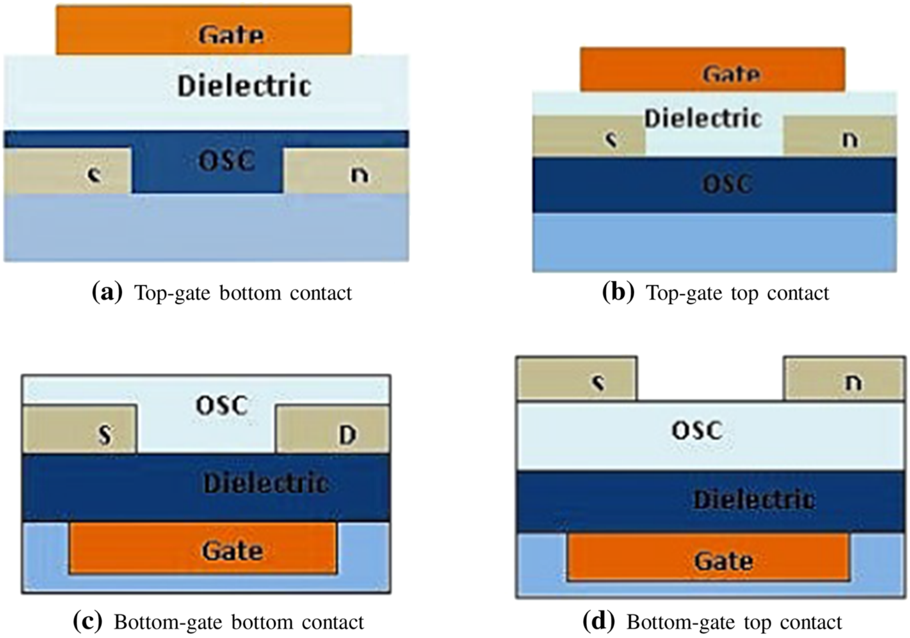
$$I_{ds} = \frac{W}{2L}\mu C_i (V_{gs} - V_{th})^2 \tag{1}$$

For Ambipolar

$$I_{(D,sat)} = \frac{(WC_i)}{2L}\left[\mu_{(e,sat)}(V_G - V_{(th,e)})^2 + \mu_{(h,sat)}(V_D - (V_G - V_{(th,h)})^2\right] \tag{2}$$

where, W denotes width of the channel, L denotes length of the channel, μ denotes mobility, V_{th} denotes threshold

Fig. 4 Planar geometry



(a) Top-gate bottom contact **(b)** Top-gate top contact **(c)** Bottom-gate bottom contact **(d)** Bottom-gate top contact

voltage, C_i denotes gate-dielectric capacitance, and V_{gs} denotes gate-source voltage.

4.2 On to off current ratio $\left(\frac{I_{ON}}{I_{OFF}}\right)$

This is one of the figure of merit which helps in better understanding of the performance of the device. The on-off ratio is the proportion of on-stage to off-stage drain currents.This means that the transistor will be able to more clearly transition between the binary states of on and off as the ratio grows. Using the equation below, the on/off current ratio is a function of the semiconductor and dielectric layer thicknesses.

$$\frac{I_{ON}}{I_{OFF}} = \frac{(C_i\mu(V_{gs} - V_t)^2)}{(t_{osc}V_{ds}\sigma)} \tag{3}$$

$$I_{OFF} = \frac{W}{L}t_{osc}V_{ds}\sigma \tag{4}$$

where, σ denotes channel's conductivity, W denotes its width, L denotes its length, and μ denotes the carrier's mobility. The gate to source voltage is V_{gs}, the drain to source voltage is V_{ds}, the threshold voltage is V_t, the organic semiconducting layer thickness is t_{osc}, and the gate dielectric capacitance is C_i. Dielectric and semiconducting layer thicknesses are reduced which increases the current ratio by increasing I_{on} and decreasing I_{off}, respectively [10].

4.3 Threshold voltage (V_{TH})

At this voltage, between the source and the drain, current will flow. Maintaining power efficiency is a critical scaling factor. Voltage at the Gate Source (V_{gs}), and Voltage at the Drain Source (V_{ds}) Drain-source voltage (V_{DS}) turns on the transistor by applying a voltage to the gate-source (V_{GS}). When using transistors, low V_{DS} and levels are generally required.

5 Impact of dielectrics on OLET

A dielectrics is a materials that inhibits the transport of charges within a layer itself. The capacity of two electrodes increases when a dielectric material is introduced between them by a factor of K, a characteristic of a dielectric material known as dielectric constant. Other important parameters of a dielectric layer are the maximum electrical displacement (D_{max}) that the dielectric layer can sustain and breakdown field (E_B) is given by [17]

$$D_{max} = \epsilon_o K E_B \tag{5}$$

and

$$E_B = \frac{V_B}{d} \tag{6}$$

The organic semiconductors are sandwiched between the dielectric layer of organic devices and the gate electrode. A suitable architecture and geometry can create two interfaces, one static and one dynamic, for certain dielectric materials. As a consequence of charge carrier injection into the dielectric, its threshold voltage declines with time. In the simulation, we have preffered different materials with their dielectric constant and their work function values which are given in Tables 2 and 3.

Table 2 The dielectric constant values of several materials

S. no.	Materials	Dielectric constant
1.	PMMA	3.6
2.	PVA	8.3
3.	PVP	6.4

6 Simulation setup and computation of capacitance and power consumption

The simulation setup utilised to investigate the OLET device, as well as the validation of capacitance and power consumption, is described in this section.

6.1 Simulation setup

The Atlas Silvaco 2-D simulator is used to examine an organic material-based light emitting transistor. In this paper, the channel is created with a tiny molecule of p that is anthracene material. The device's dimensions are listed in Table 1 and are used in the analysis. Poole Frenkel's mobility model is used to investigate field-effect mobility [23–28].

$$\mu = \mu_o\left(\frac{\Delta}{kT}-1\right) - \left(\frac{\beta}{kT}-\gamma\right) \tag{7}$$

where μ denotes mobility. For p-type OSC, μ_o represents zero-field mobility, which is field-dependent, and are defined by Activation-energy(Δ), and Poole Frenkel-constant(β). In the mobility-model, the values of Δ and β are as 1.792×10^{-2} eV and 7.758×10^{-5} eV.

6.2 Calculation of capacitance

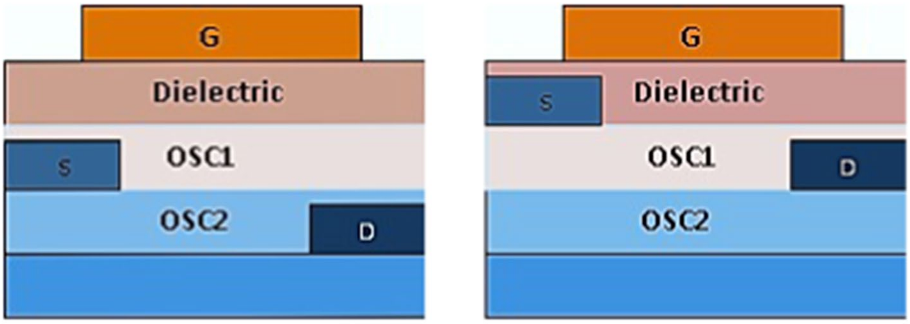
The following are the capacitance values for PMMA and PVA that are used in device simulation and analysis:

$$C_{PMMA} = \frac{\epsilon_o \epsilon_{r1}}{t_{ox}} = \frac{8.854 \times 10^{-12} \times 3.6}{200 \times 10^{-9}} = 159\mu\text{F} \tag{8}$$

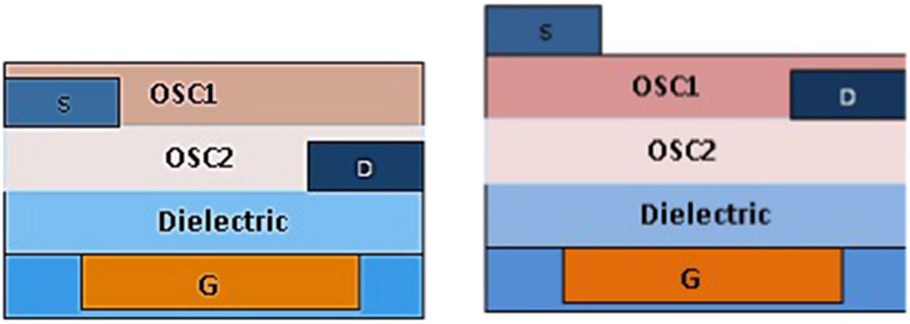
$$C_{PVA} = \frac{\epsilon_o \epsilon_{r2}}{t_{ox}} = \frac{8.854 \times 10^{-12} \times 8.3}{200 \times 10^{-9}} = 366\mu\text{F} \tag{9}$$

Here, ϵ_{r1} and ϵ_{r2} denotes the relative permittivity for PMMA and PVA materials respectively, and ϵ_o denotes the free space permittivity, whose values are given in Table 2, and t_{ox} is oxide thickness (Table 1).

Fig. 5 Non-planar geometry



(a) Top-gate bottom contact **(b)** Top-gate top contact



(c) Bottom-gate bottom contact **(d)** Bottom-gate top contact

Table 3 Materials with their work functions

S. no.	Materials	Work function
1.	Gold (Au)	5.1
2.	Silicon (Si)	4.3
3.	PEDOT: PSS	4.7
4.	PMMA	4.68

Table 4 Comparative table of simulated values and experimental values of OLET performance parameters

S. no.	Parameters	Simulated values	Reported data values [1]
1.	Power	Anthracene 0.051 mW	Tetracene 0.06 mW
2.	Capacitance	159 μF	366 μF
3.	Mobility	$12 \times 10^{-2}\,\mathrm{cm^2/Vs}$	$1.4 \times 10^{-2}\,\mathrm{cm^2/Vs}$
4.	On-off ratio	10^7	10^7
5.	Drive current	17 μA	19.5 μA

6.3 Calculation of power consumption

The International Road Map for Semiconductors (ITRS) recommends that power consumption for portable devices be kept to a bare minimum, despite the fact that this is nearly difficult due to parasitic effects. The total power consumption is given by P = VI, where $P = 3 \times 17 \times 10^{-6} = 0.051\,\mathrm{mWatt}$ is obtained by using – 3 V for V_{gs} and V_{ds}.

7 Results

This section focuses into the performance of OLET device using organic semiconductor as an active layer, and simulated characteristic graphs, where its internal schematic structure is shown in Fig. 6, and its structure which corresponds to the level of doping concentration is shown in Fig. 7, the value for the same is $21 \times 10^{20}/\mathrm{cm}^3$, and its output characteristics is shown in Fig. 8. We investigated the device behaviour with $V_{gs} = -3$ V and $V_{ds} = -3$ V, respectively, are the supply voltages. and comparing its values with the reported data [1] of tetracene as an organic semiconductor of an OLET structure. After validating simulated data, we get $P = 3 \times 17 \times 10^{-6} = 0.051$ mWatt is the entire power consumption of an OSC-based device based on anthracene small molecules. The power consumption of an Anthracene based device is lower than that of a tetracene-based device, according to the results of the analysis. We were able to extract additional data such as mobility, drive current, and current on-off ratio using the 2-D simulation TCAD device. Table 4 has a list of all of these variables. The highest occupied molecular orbit (HOMO) and lowest unoccupied molecular orbit (LUMO) levels of organic semiconductor materials, work function of source, drain, and gate electrodes, dielectric constants of insulators and supply voltages, structural dimensions of devices, and electrical properties of OSCs used in simulation analysis all influence the extracted values of performance parameters.

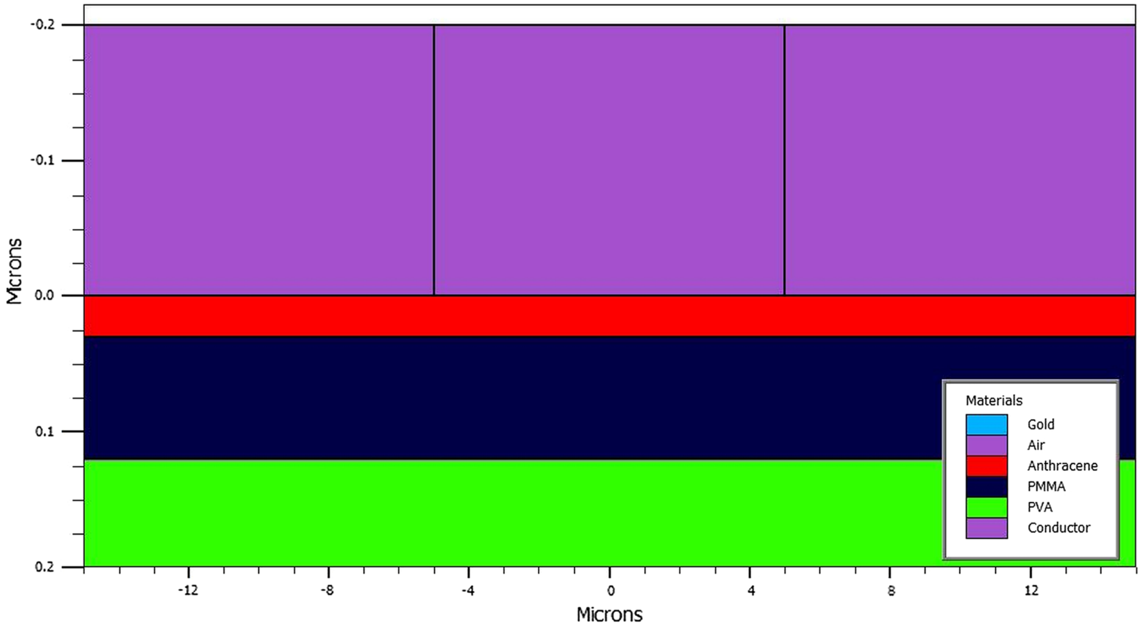


Fig. 6 OLET structure with anthracene as an OSC material

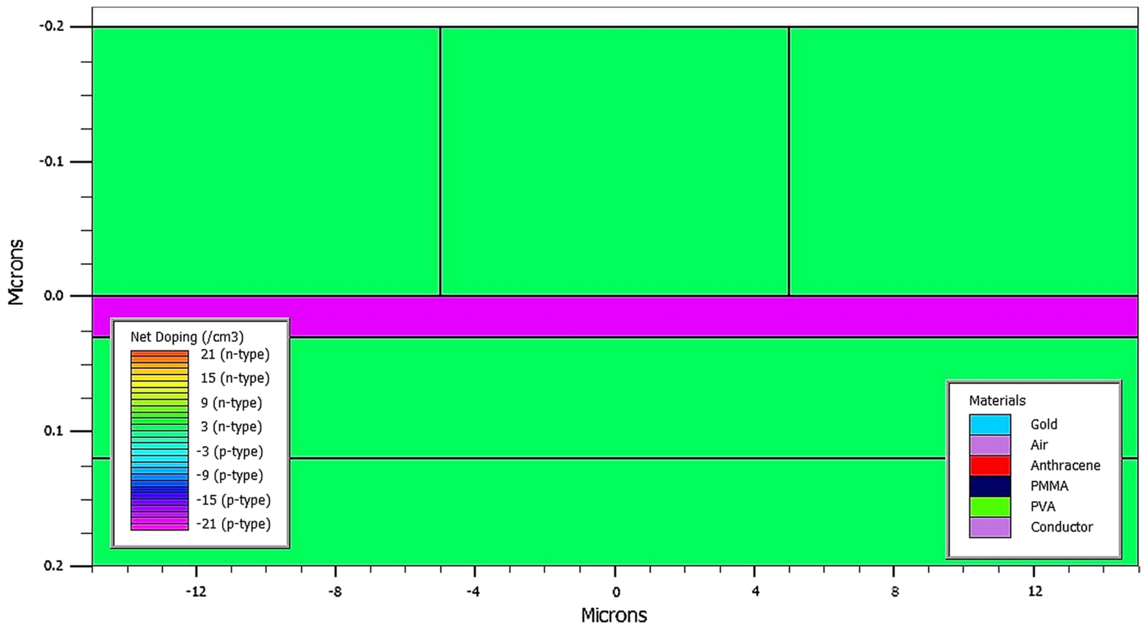


Fig. 7 OLET structure showing doping concentration

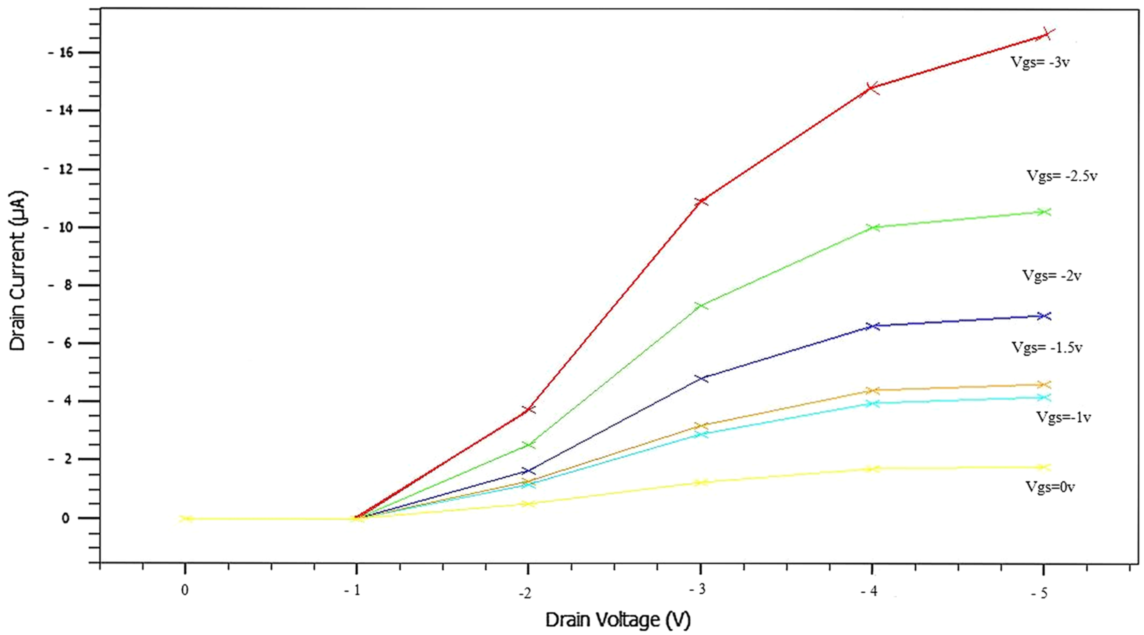


Fig. 8 Output characteristics

8 Conclusion

The performance of an OLET device with anthracene as an organic semiconductor layer is explored in this research work, as well as the simulated values of the OLET device with anthracene as an OSC. is compared with the reported data1 of the OLET device having tetracene as an OSC. Initially, the values of drive-current, on-off ratio and mobility of OLETs are evaluated using 2-D TCAD simulator. After that output characteristics is also analysed. The generated results are then compared to the information provided. The values of performance parameters are as follows: Ids of 17 µA, mobility of $12 \times 10^{-2}\,\mathrm{cm}^2/\mathrm{Vs}$ and on-off ratio of 10^7. It is seen that anthracene based device has much higher mobility value than that of tetracene. It is also seen that power consumption in case of anthracene is lesser than that of tetracene, making it a better performance device. The work provided by this research is assessed using TCAD Silvaco simulation tool that is widely utilised in the microelectronics manufacturing industry. The performance of these devices can be modified by using high performance organic semiconductors as the active channel layer, by changing their structural specifications, their work function values, and dielectric properties.

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