Influence of Gate Dielectrics, Electrodes and Channel Width on OFET Characteristics

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Abstract. Organic Field Effect Transistors (OFET) possess wide applications in large area electronics owing to their attractive features like easy fabrication process, light weight, flexibility, cost effectiveness etc. But instability, high operational voltages and low carrier mobility act as inhibitors to commercialization of OFETs and various approaches were tried on a regular basis so as to make it viable. In this work, Poly 3-hexylthiophene-2,5diyl (P3HT) based OFETs with bottom-contact top-gate configuration using Poly vinyl alcohol (PVA) and Poly (methyl methacrylate) (PMMA) as gate dielectrics, aluminium and copper as source-drain electrodes are investigated. An effort is made to compare the effect of these dielectric materials and electrodes on the performance of OFET. Also, an attempt has been made to optimize the channel width of the device. These devices are characterised with mobility (μ), threshold voltage (V_T), on-off ratio (I_{on}/I_{off}) and their comparative analysis is reported.

1. Introduction

Organic Electronics has attracted a lot of attention lately as organic polymers mainly aromatic derivatives like thiophene [1] revealed moderate conductivity and mobility ($\sim 10^{-3} cm^2V^{-1}s^{-1}$) due to their inherent optical and electrical properties which make them competent candidates in semiconductor industry. However, they still require improvement in manifolds to outperform silicon's ($\mu \sim 10^2$-$10^3 cm^2V^{-1}s^{-1}$) legacy as semiconductor material.

OFET has been undergoing incessant and intensive research to enhance performance which is expected to be attained by the rightful combination of all its components and interfaces. Gate dielectrics and electrodes are the elements that are under study and a total of three transistors with a permuted combination are built by employing solution based thin film technology. OFETs are fabricated with bottom contact top-gate. Regioregular Poly (3-hexylthiophene-2,5diyl) (P3HT), a popularly used organic semiconductor (p-type) is used as active layer as it is shown to have comparably good mobility ($\mu = 10^{-4}$-$10^{-1} cm^2V^{-1}s^{-1}$) [2] of its charge carriers.

This study involves assessment of prevalent materials and their comparison. For the same reason, Poly vinyl alcohol (PVA) (K=2) and Poly (methyl methacrylate) (PMMA) (K=3.5), a water soluble material and a non-polar solvent based material, respectively formed the two dielectric choices that are investigated in this study. Similarly, two commonly used and readily available metal contacts, namely aluminium and copper are tested for their compatibility with the semiconductor in use.

2. Materials and Methods

P3HT is dissolved in toluene without further purification to prepare a solution. Glass slides are used as substrates. Source-drain metallic layers are then coated on the substrate in a bell jar evacuated to a pressure under 1.5×10^{-5} mbar. Two devices are fabricated with aluminium (b.p. ~1,080 K) and one device with copper (b.p. ~1,600 K) as source/drain electrodes. RR-P3HT (degree of regioregularity ~ 99%) with a weight percentage of 10 mg/ml is drop cast onto the electrode with the help of a micro syringe in the dark to prevent decomposition. They are left undisturbed and screened from light to facilitate the alignment of the semiconductor between the electrodes. PVA (Mol. Wt 125,000 $gmol^{-1}$) with dielectric constant 2 is dissolved in water and PMMA (Mol. Wt 12,000 $gmol^{-1}$) with dielectric constant 3.5 is dissolved in acetate to obtain a clear solution. Both of these solutions were dispersed over the already prepared component films, employing the same procedure formerly adopted. The device with 4 mm channel width and aluminium electrode was coated with PMMA as dielectric and the rest are built with PVA. The final layer of gate was deposited with the same metals applying the same methods used earlier.

The OFET characterization is conducted in air at room conditions using Keithley 2400 Source Meter and Keithley 6517B Electrometer/High Resistance Meter. Electrical characterization is made by biasing the gate with a constant voltage (V_g), and a voltage is applied across drain and source (V_{sd}) with the latter grounded. V_{sd} is swept over a range of 60 V and the corresponding drain-source current (I_{sd}) is noted for the voltage range -20 V and 20 V of V_g in steps of 10 V.

3. Results and Discussion

The recorded values of I_{sd} are plotted against V_{sd} and V_g to obtain the transfer characteristics and transconductance (g_m) curve respectively. Further, $I_{sd}^{1/2}$ is also annotated on the g_m curve against V_g. The value g_m of is the slope of I_{sd} vs V_g curve. Charge carrier mobility μ ($cm^2\, V^{-1}s^{-1}$) is calculated from the slope of transconductance curve and the following relations [3].

$$\mu = (g_m L)/(WC_p V_{sd}) \qquad (1)$$

From SEM images, the channel length (L) and thickness of the dielectric (t) are found to be 19 μm and 25 μm respectively. Threshold voltage (V_T) can be obtained by using the simple current equation in the linear regime.

$$I_{sd} = (\mu C_p W/L)\,((V_g - V_T)\,V_{sd} - V_{sd}^2/2) \qquad (2)$$

3.1. Effect of Dielectric Materials

For gate dielectrics comparison, the devices with aluminium electrodes and dimensions as mentioned in table 1 are prepared with dielectric layer as PVA and PMMA for two separate devices. The transfer curve and the transconductance curve of the two devices are shown in figures 1(a), 2(a) and 1(b), 2(b) respectively.

In the case of FET when positive gate voltage increases, source drain current decreases which is due to the negative charges induced in the active channel with the help of positive gate bias voltages indicating p-type of FET operation in depletion mode.

Table 1. Various parameters of the two devices under study for dielectric comparison.

Parameters	Device 1 (PVA)	Device 2 (PMMA)
Channel Width, W (mm)	5	4
Mobility, μ(m2V-1s-1)	4.802x10-7	2.297x10-5
Threshold Voltage, VT (V)	9.968	-4.43
On-Off Ratio, Ion/Ioff	1.1785	6.348

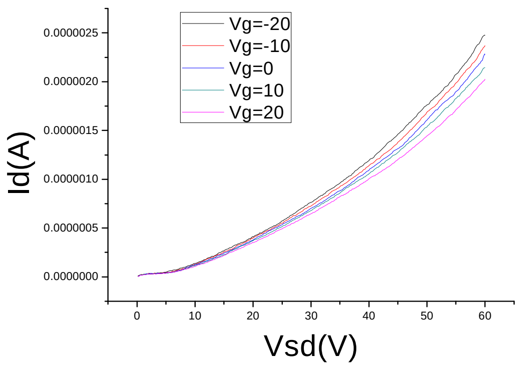

Figure 1(a). Relationship between Isd and Vsd

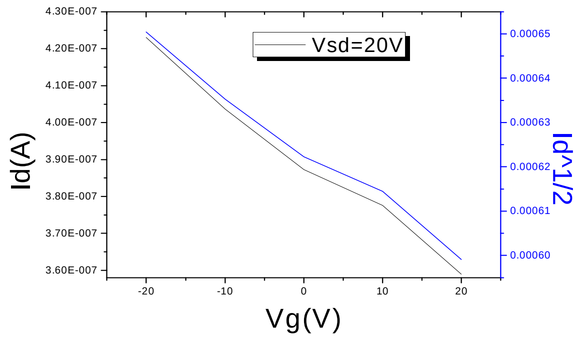

Figure 1(b). Transconductance curve

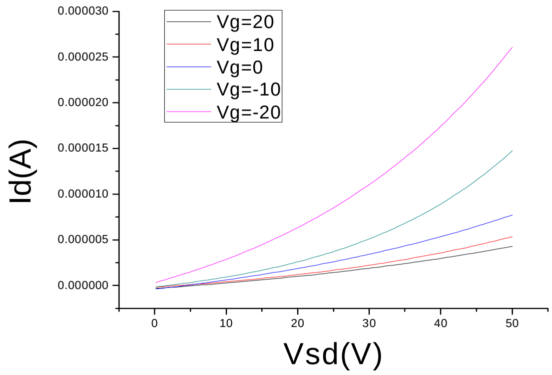

Figure 2(a). Relationship between Isd and Vsd

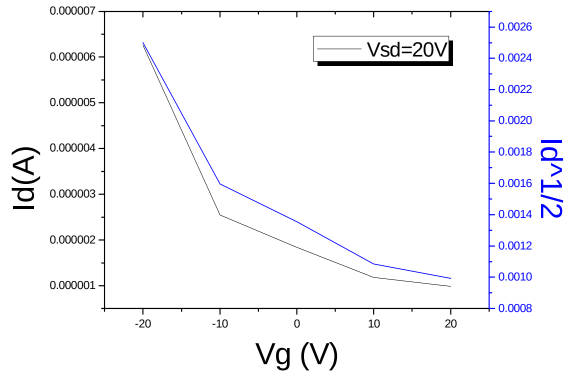

Figure 2(b). Transconductance curve

It can be seen from table 1 that performance of PMMA over PVA as a gate dielectric is discernible, as the corresponding device exhibited better OFET characteristics. The mobility of PMMA (μ=2.297x10^{5} $m^2V^{-1}s^{-1}$) exceeds that of PVA (μ=4.802x10^{-7} $m^2V^{-1}s^{-1}$) by a power of two. PMMA has intrinsic properties due to its molecular structure which makes it a good dielectric with insulating properties compared to its counterpart PVA. PMMA possesses better molecular packing than PVA. This results in the proximity of the functional groups which is essential for higher dipole moment. This in turn contributes to its higher dielectric constant, making it as a high capacitance dielectric (C_p= 1.239 $\mu F/m^2$) which is vital for a lower operating voltage. A reduction in operational voltage increases the mobile charge carrier density which improves the effective mobility ultimately leading to an increased current drive even at low voltage. Enhanced performance of device 2 also indicates that smaller channel width or a low aspect ratio enhances the performance of OFET and yields better output.

3.2. Effect of Electrode Material

Aluminium and Copper electrode devices fabricated having PVA as dielectric material is used for comparing the electrodes.

Table 2. Various parameters of the two devices for electrode study.

Parameters	Device 1 (Al)	Device 3 (Cu)
Channel Width, W (mm)	5	5
Mobility, μ ($m^2V^{-1}s^{-1}$)	4.802x10^{-7}	4.5167x10^{-4}
Threshold Voltage, V_T (V)	9.968	-86.435
On-Off Ratio, I_{on}/I_{off}	1.1785	1.3647

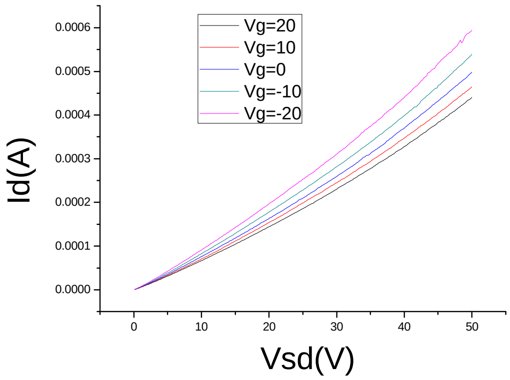

Figure 3(a). Relationship between I_{sd} and V_{sd}

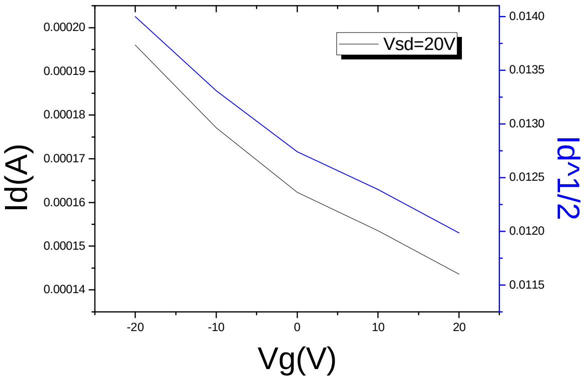

Figure 3(b). Transconductance curve of device

Referring to table 2, the results indicate that copper is better for electrode application in P3HT based OFET as this gives carrier mobility nearly 1000 times higher than aluminium. This will mean better compatibility of copper with the P3HT which again means better band alignment between the HOMO & LUMO (Highest Occupied Molecular Orbital and Lowest Unoccupied Molecular Orbital) of the organic semiconductor with the work function of the metal as illustrated in figure 4. Shift in energy levels of both the materials results in the formation of dipole barrier at the metal-semiconductor interface. The work function of copper (~4.7 eV) lies closer to the HOMO level of P3HT (~5.2 eV) [4] than aluminium (~4.08 eV) and is in concurrence with the observed results and provides a convincing explanation for the same. When gate source terminal is applied a negative bias voltage, I_{sd} would increase as shown in the transconductance curves in figure 3(b) and 1(b). Transfer curves are given in figure 3(a) and 1(a) for the two devices.

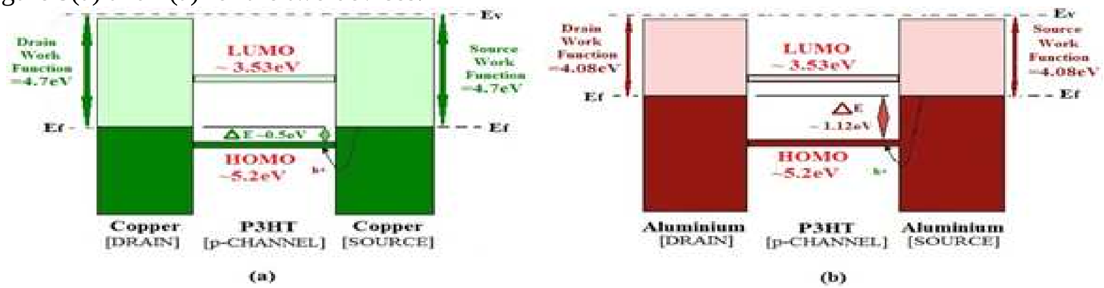

Figure 4. Energy level diagram of metal contact and semiconductor interface.

4. Conclusion

By the fabrication of hole conducting OFETs it is demonstrated that gate dielectric and electrodes have an effect on the performance of P3HT based OFET. It can be concluded that when P3HT is the semiconducting material, gate dielectric using PMMA shows better performance than PVA since former is showing 100 times better mobility and V_T, I_{on}/I_{off} are also in the preferred range.

References

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