International Journal of Ethics in Engineering & Management Education
Website: www.ijeee.in (ISSN: 2348-4748, Volume 1, Issue 8, August 2014)

Mechanism of Controlling the Threshold Voltage from Recently Modified Dual Gate Organic Field Effect Transistor Biosensor

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Abstract: **There has been always demand of Thin film Transistors (TFTs) which should not only be environmental friendly (biodegradable) but also economically viable and easily fabricated in branch of microelectronics. Organic Field Effect Transistor (OFET) easily fulfills these criteria thereby providing light weighted electronics equipments. In this paper we describe the mechanism of Dual gate organic field effect transistor (DGOFET) by tuning the threshold voltage and controlling it by gates biasing. The shift depends on the ratio of the capacitances of the two gate dielectrics. The width of the semiconductor layer can be obtained by Time of Flight Secondary Ion Mass Spectroscope (ToF-SIMS) which provides the result of conduction of current through the multi channels. The interface resistance between semiconductor and dielectric layer gets reduced, enhances the effect of biasing and hence increases the charge mobility. Because DGOFET made up of pure organic materials, becomes biodegradable, and no other deposition method is used therefore reduces the cost of fabrication. Even nano-size poly-crystal of semiconductor layer are obtained during the polymerization, therefore extra function to control the size of nano-crystal becomes avoided. Therefore by designing fully-organic FETs, in which all parts of the transistors are composed of organic materials, the potential application, in extremely cheap and flexible circuits, in biosensor is obtained. At the same time the polarity of biomolecules are also determined.**

***Keywords*: Dual gate organic field effect transistor, Threshold voltage, Time of Flight Secondary Ion Mass Spectroscope, Gate dielectric, Biosensor.**

I. INTRODUCTION

There are many applications for field effect devices where fast switching speed is not an issue therefore, the properties of organic materials can be tuned with chemistry, opening a whole new range of possibilities for applications in organic electronics [1-3]. Organic materials can for example be designed to be flexible or soluble in solvents, which allows for flexible electronics and 'ink-based' processing techniques. Opto-electronic properties such as the bandgap can be tuned as well [4-5]. Additionally, when produced in high volumes, production costs are possibly low due to easy processability. In inorganic based electronic circuits, complementary metal-oxide-semiconductor (CMOS) logic is applied, for which both the extrinsic types based transistors are required. The advantages over unipolar logic are low power dissipation and robust operations [6]. Organic semiconductors are mostly unipolar, in the sense (On the base of quantum mechanism) that the hole conduction is larger than electron conduction. As a result most organic transistors are normally-ON unipolar p-type transistors.

For the proper operation of transistor, low power consumption and increasing the noise margin, especially in complicated organic circuitry, by using OFETs, there is the basic requirement to control, the value of threshold voltage (V_t). There are several approaches to obtain the controlled V_t, and some of them are: (i) By modifying the surface of the dielectric with self-assembled monolayers [7], (ii) The amount of doping applied by ion implantation, (iii) The use of a gate metal with a specific work function [8], (iv) By Level shifters in circuits [9]. All of these methods contains some sort of limitations e.g. the implementation of doping in organic films was a really tuff task because again and again doping will not be a convenient method and at the same time the other above mention methods are costly too.

Dual-Gate Organic Field Effect Transistor (DGOFET) is an alternative solution to set V_t. As compared to a conventional thin-film transistor, the layout of a dual-gate transistor contains an additional gate dielectric and electrode, as shown in Fig. 1. The easy implementation of setting threshold voltage provides wide application of DGOFET in branch of electronics. In this paper we emphasis on the modeling of pure organic material based dual gate transistor with comparable data. Carrier mobility is directly proportional to semiconductor conductivity, and is related to the performance of the device. The D.C conductivity at room temperature of poly-(diamino naphthalene) (PDAN)/ poly-(vinyl alcohol) (PVA) film is found to be 2.0408 X 10^{-4} mho m^{-1} which gives the mobility in the range of 0.43 cm^2/Vs. It is a considerably good figure. This value is comparable with known data without considering and calculating the transistor characteristics [10].

The easy adjustment of V_t in DGOFET attracted a lot of attention in chemical and biological sensing [11-12]. At the same time DGOFET individually demonstrated as AND logic gate operation [13]. Normally biomolecules are in ionic form and therefore, for the application purpose, ion/electron coupling plays an important role for the interfacing between the ionic signals and electrical signals in biosensors [14].

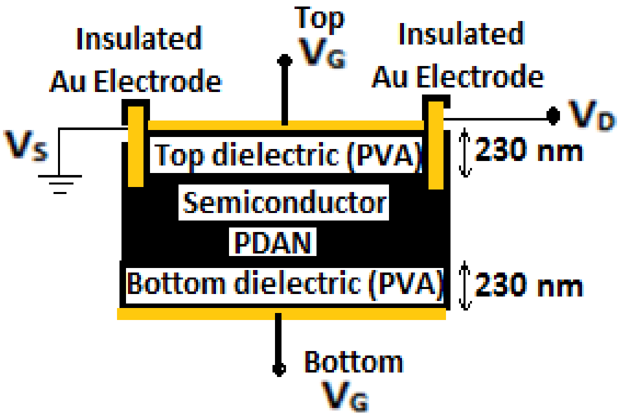


Fig.1 Diagram of Dual Gate Organic Field Effect Transistor

In this paper, by modeling the DGOFET with considering the imposing of biomolecules in the topmost reactive medium at the top dielectric layer, the sensing properties of device has been explain. Because of the ionic nature of biomolecule, the dielectric material changes its capacitive value and therefore, V_t gets shifted which measure the nature of biomolecules.

II. OPERATING MODE

Most OFETs reported in the literature so far show p-type or n-type behavior, meaning that the charge carriers are either holes or electrons respectively. P-type OFETs comprise the majority of these devices, showing the best transport properties [15]. At the same time the operation of an OFET is defined by several parameters like, the spacing between the source and drain electrodes called channel length (L), the width of the source-drain region called channel width (W), the capacitance per unit area of the gate insulator (C_i), and the mobility of charge carriers (μ), neglecting the contact resistance, doping density and short channel effects. Even the mobility is also assumed to be independent of the carrier density. The characteristics of the OFET is described by (i) output characteristics i.e. plotting graph between drain current (I_D), and source-drain voltage (V_D), keeping gate voltages (V_G) constant (ii) transfer characteristics i.e. plotting graph between drain current (I_D), and gate voltages (V_G), keeping constant drain voltage (V_D). If a p-OFET switches ON at $V_G > 0$, this could mean that the sufficient amount of dopants impurity is present producing a large current, even when a $V_D = 0$ [16].

The current in both the linear regime i.e. $|\mathbf{V_D}| \ll |\mathbf{V_G} - \mathbf{V_t}|$ where Vt becomes threshold voltage, and saturation regime i.e. $|\mathbf{V_D}| \gg |\mathbf{V_G} - \mathbf{V_t}|$, can be defined using classical analytically MOS equations [17]. These equations came from gradual channel approximation, which assumes that the field perpendicular to the current, induced by the gate bias, is much larger than the electric field between source and drain [18].

The resulting gradual expression for the drain current ID in accumulation is given by

$$I_D = \frac{WC_i}{L}\mu\,[(V_G - V_t)\,V_D - ½\,V_D^2] \qquad (1)$$

For the linear regime, Eq. (1) can be written as:

$$I_{Dlin} = \frac{WC_i}{L}\mu_{lin}\,(V_G - V_t)\,V_D \qquad (2)$$

and, for saturation regime, Eq. (1) can be written as:

$$I_{Dsat} = \frac{WC_i}{2L}\mu_{sat}\,(V_G - V_t)^2 \qquad (3)$$

It is obvious from the Eq. 3, that, in the saturation regime the mobility can be calculated by finding the slope of the plot between $|\mathbf{I_D}|^{1/2}$ and V_G. The shift in V_t can be measured from the total charge (q_{Total}) induced by the two gates from:

$$q_{Total} = C_{bottom}\,V_{bottom} + C_{top}\,V_{top} \qquad (4)$$

At the threshold voltage of the DGOFET where bottom gate voltage is equal to threshold voltage, the total induced charge (q_{Total}) is zero, which implies that:

$$C_{bottom}\,V_{bottom} = -\,C_{top}\,V_{top} \qquad (5)$$

If the top gate is fixed and the biasing of the bottom gate is varied, the shift in threshold voltage is given by:

$$\Delta V_{t,\,bottom} = -\,\frac{C_{top}}{C_{bottom}}\,\Delta V_{top} \qquad (6)$$

For the other condition in which if the biasing of the top gate is varied and the bottom gate is fixed the Eq.7 becomes:

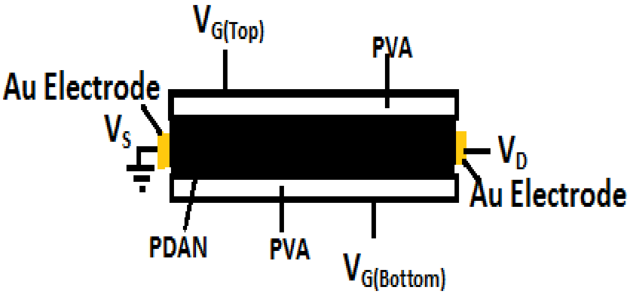
$$\Delta V_{t,\,top} = -\,\frac{C_{bottom}}{C_{top}}\,\Delta V_{bottom} \qquad (7)$$

The factor C_{top} / C_{bottom} is the capacitive coupling, i.e the measure by which the V_t of the bottom gate can be modified as a function of gate bias on the top gate [19].

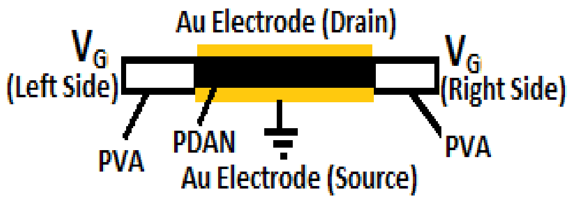
In this chapter, instead of three individual layers of different materials, PDAN/PVA film in which poly-(diamino naphthalene) (PDAN) satisfies the semiconductor layer of OFET and poly-(vinyl alcohol) (PVA) forms the dielectric layers, which serve the two shape of the pure OFET.

(i) Top and bottom gate electrodes, and sidewise two electrodes corresponding to source and drain. In this structure “W” i.e. width of the film is small and the “L” i.e. length of the channel is large. [Figure 2(a)]

(ii) Left and right gate electrodes, and top and bottom electrodes corresponding to source and drain. In this structure “W” i.e. width of the film is large and the “L” i.e. length of the channel is small. [Figure 2(b)]



(a)



(b)

Fig.2 (a) and (b) Two different shapes of pure DGOFET

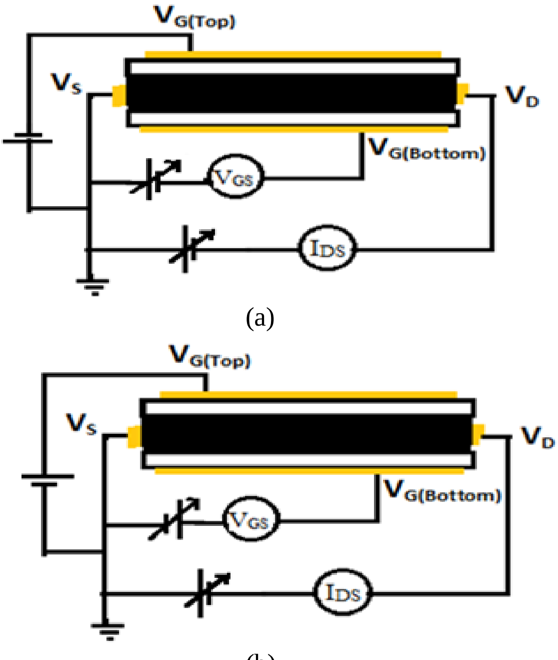
In operating condition there are two assumptions, first, the threshold voltage of the bottom gate V_t, bottom equals to zero when the top gate is floating and the second, the threshold voltage of the top gate V_t, top equals to zero when the bottom gate is floating. Therefore DGOFET may be operated in four different modes [20]:

(i) Double accumulation in which bottom gate voltage (V_G, bottom) and the top gate voltage (V_G, top) are negative.

(ii) Double depletion in which bottom gate voltage (V_G, bottom) and the top gate voltage (V_G, top) are positive.

(iii) Shift of top gate threshold voltage (V_t, top) by bottom gate voltage (V_G, bottom), and

(iv) Shift of bottom gate threshold voltage (V_t, bottom) by top gate voltage (V_G, top).



(a)

(b)

Fig.3 Biasing of the Dual Gate Organic Field Effect Transistor, when (a) V_G, bottom and V_G, top are negative, (b) V_G, bottom and V_G, top are positive

III. APPLICATION OF DGOFET AS BIOSENSOR

A typically DGOFET based biosensor mainly has three parts [21] described in Figure 4. A top layer as bimolecular detector of chemical substance spread over the dielectric layer (PVA), changes the capacitance value when biomolecules exposed on the chemical reactant according to the nature of ions of the species. A transducer, the second part, transforms the signal detected by the biological species (ionic signal) into an electrical signal. A typical pure DGOFET when working as AND gate behaves as transducer. The last part of biosensor is processor that amplifies and/or filters the signal or the computational formula that detect the nature of biomolecules.

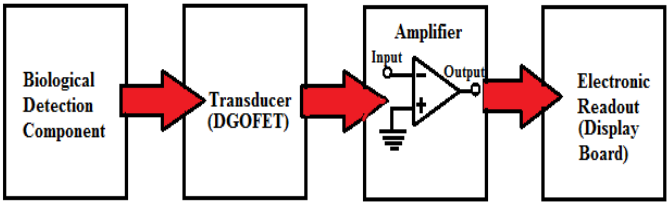


Fig.4 Different parts of Biosensing device [22-23]

According to the Eq. (6) and (7), the factor ‘Capacitive Coupling’ becomes unit due to the same material and same thickness of dielectric material i.e. PVA. The constant value of thickness of dielectric material can be obtained by time of flight secondary ion mass spectroscopy and it becomes 230 nm. During the reaction of biomolecules with the detector, free ion radicals are so obtained are accumulate at the top interphase of the detector and dielectric medium due to the biasing at the top gate electrode. It will change the capacitive value of the top dielectric medium and therefore the value of capacitive coupling will varies, which according to the equation, shifted the value of V_t. The nature of the positive or negative ions so accumulated from the ionic property of biomolecules is also detected with the shifting of threshold voltage either towards negative X-axis or towards positive X-axis. As AND gate operates when both inputs (top gate biasing and bottom gate biasing value) are ON biased say +1V, the output in form of electrical signal are obtained. Initially, bottom gate value is kept logically “1” and the top gate value kept slightly lower value from +1V i.e. logically “0”. In this state, the output of AND gate is in OFF condition. But when biomolecule substance poured into biomolecule detector, it will change the capactive value, which increases the top gate value equal or grater than +1V, therefore both input are logically “1” and DGOFET as AND gate gets come into operating condition, gives result to shift in V_t. It will either calculate with the help of processor in form of amplitude of voltage/current signal or by transistor characteristics curve.

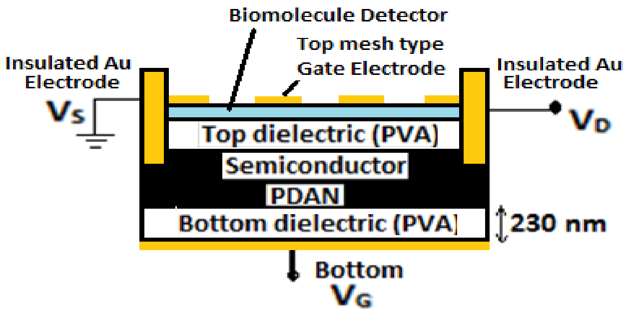


Fig.5 Modeling of DGOFET as biosensor

IV. CONCLUSIONS

The shift in threshold voltage as a function of the capacitive coupling is generally observed in the Eq.6 and Eq.7 confirmed the observation. As the DGOFET formed by the PDAN/PVA films in which p-type semiconductor, PDAN doped inside the PVA film and the obtained film has the top and bottom gate of same material and same width, therefore the value of capacitive coupling becomes unity. It shows that the shift in threshold voltage is only due to, either top voltage biasing (in Eq. 6) or the bottom voltage biasing (in Eq. 7). The mobility of the top channel is a factor of five lower than that of the bottom channel. Because the capacitive coupling is about unity, the accumulated charges in the top channel are immobile and do not contribute to the total current. It results that the tuneability of threshold voltage depends on the semiconductor layer material and biasing on the gate terminals. At the same time the semiconductor layer width so obtained by Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) is about 0.0676 mm, so the mobility of the charge carrier is due to multiple channel of the DGOFET. The interface resistance between semiconductor and dielectric layer gets reduced, enhances the effect of biasing and hence increases the charge mobility. Because DGOFET made up of pure organic materials, becomes biodegradable, and no other deposition method is used therefore reduces the cost of fabrication. Even nano-size poly-crystal of semiconductor layer are obtained during the polymerization, therefore extra function to control the size of nano-crystal becomes avoided.

Because DGOFET acts as self-contained logic gate i.e. AND gate, therefore by changing the capactive value of top dielectric layer, the potential application of biosensor is obtained by easy method. At the same time using DGOFET, the polarity of the biomolecule are also determined.

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