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Silicon Nanotube Tunnel FET as a Label Free Biosensor

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ABSTRACT

In this paper, we propose a Silicon Nanotube Tunnel FET-based biosensor in which ambipolar current is used as the sensitivity parameter. For low power consumption and steeper sub-threshold slope for the fast switching, aluminum (Al) is utilized as a source. A nanogap cavity-based tunnel FET biosensor is already demonstrated but Silicon nanotube-based TFET biosensor is proposed for the first time. The result shows better sensitivity concerning the two different effects i.e., dielectric constant (k)and the charge of the biomolecules (positive or negative). For the practical realization of the band to band tunneling, the Kane model is employed in this work. The length of the cavity region is the main parameter to optimize the sensitivity. It shows superior results in dielectric modulation effects and higher ambipolar sensitivity even at lower concentrations of biomolecules. Band diagrams and electric field lines are analyzed to observe the performance of the biosensor. On increasing the value of the dielectric constant (k) from 5 to 20, the sensitivity of the biosensor is reduced by 3 times. It could be used in array-type screening and for DNA-based bio genre diagnostics. It has been observed that when we use the TFET as a biosensor then the leakage is minimum and the sensitivity is maximum.

Keywords: - Silicon Nanotube FET, tunnel FET, biosensor, ambipolar**.**

1. INTRODUCTION

Nowadays, researchers are very much interested in the field of Metal Oxide Semiconductor Field Effect transistor (MOSFET) based biosensors for the detection of biomolecules because of their number of advantages like better sensitivity, low-cost production, and compatibility with Complementary Metal Oxide Semiconductor (CMOS) process. These types of biosensors are working on the principle of variation of electrical property due to the fluctuation in conductivity in the presence of the biomolecules. There are a large number of nanogap embedded-based field-effect transistors have been reported as label-free sensors cause of their several advantages over other types of biosensors. In the last few decades, worldwide researchers proposed a plethora of device structures as a prominent substitute to replace the conventional MOSFET for low power and high-speed applications[1]. The International technology roadmap of semiconductors (ITRS) 2015 document "Beyond CMOS" proclaimed that the new devices are based on the material or structure and non-charge/charge entity. The number of devices is included in this category like nanowire Field-Effect Transistor(FET) [2], carbon nanotube FET [3], TFET [4], Graphene FET[5], and

negative capacitance FET[6]. Tunnel FET is emerging as the most suitable candidate to replace the traditional MOSFET in CMOS applications due to its capacity to show the lower subthreshold swing (SS) below 60 mV/decade, ability to work on lower supply voltage, and also has very low I_{off} current [7]. In recent times many architectures related to TFET are proposed to improve the performance in terms of On-state current[8]and low SS. Some such type of devices are Nanowire tunnel FET[9], heterojunction tunnel FET[10], III-V tunnel FET[11], Triple material gate Tunnel FET [12], SOI TFET, cylindrical TFET[13] these are some widely used structures. TFETs are widely used or the low power based memory and other applications[14]. Recently TFET emergent as potential candidate for the FET based biosensors, works on dielectric modulation in which the dielectric constant (k) accompanying with the charge of the biomolecules decides the device drain current[15].
The process of doping of ultra-thin Source /Drain region in FET devices requires a complex thermal annealing procedure, which introduces the random dopant fluctuations (RDFs) which tend to the impossible formation of an anatomically abrupt junction. The above abrupt junction issue, Source/ drain parasitic resistance, power dissipation, and leakage current in TFET were improved by using metal source-based tunnel FET as reported by shih et.al.[16-[17].

Moreover, the packaging density of the device is bounded through parametric variability. As we know the driving capability is dependent on the mobility of the device, therefore the speed is not increasing linearly with scaling and the device performance is also degraded because of high electric field stress[18]. In this paper, the first time we are proposing the aluminum (metal) source, Silicon nanotube Tunnel FET (SI_NT_FET) device has two gates due to which it has more Surface to volume (S/V) ratio, which helps in covering the larger area for the detection of the bio-molecules [8][19]. By using this Tunnel FET structure, it is feasible to enhance the drive capability while constraining the drain supply voltage and aspect ratio of the device. Generally, at low ionic concentration, we are detecting the bio-molecules in tubular type biosensors. This is because of their wide detecting contact area [20]. In this paper, the ambipolar current is considered as the sensitivity parameter for the Tunnel FET. The ambipolar describes the device flow of electrons in twain directions i.e., negative as well as for positive voltages. Ambipolar conduction mechanism is because of the deviating of tunneling junction from channel source to drain channel. This is the cause of gate voltage is lesser than zero (V_{gs}<0) for P-type source, channel-Intrinsic, and N-type drain(P-I-N) Tunnel FET structures. It has been reported, ambipolar transport of TFET structure shall be bettered by incorporating the Schottky barrier junction of TFET. On increasing the value of the dielectric constant the overlapped capacitance coupling increases due to which the value of the ambipolar current is also decreased [21].This is the reason that ambipolar current has been found as one of the options of sensitivity parameter for sensing the biomolecules which are immobilized at the contactable surface of the FET device.

The remaining work of this work is summarized as: Section 2 defines the TFET device description and simulation method with some model description. Discussion regarding the results is given in section 3. Section 4 concluded the paper.

2. DEVICE DESCRIPTION

The inner view and perpendicular cross-section of embedded nano dimension gap Silicon nanotube Tunnel FET are depicted in Fig. 1 (a) and (b). The Parameters which are used for simulation are given as, detecting gate length (L_d) = 40 nm; controlling gate length (L_g) = 40 nm; tube thickness (t_{tube}) = 5 nm; source and drain regions length = 30 nm; oxide (gate) thickness(t_{OX}) = 1nm, drain doping (N_d) =1 x 10^{19} $cm^{-3,}$ Nano gap length

=40 nm, nanogap width is 10nm. Instead of semiconductor material aluminum (metal) is taken as the source material[22]. While fixing the ambipolar current at higher values and for adequate channel-drain sideband profile and also to improve the ambipolar conduction, the most preferable value of the doping for the drain region is considered as 1 x 10^{19} cm^{-3}. The parameters of the biosensors are well defined in table 1.

There are two types of techniques to detect the biomolecules i.e., gating effect and dielectric modulation [23] Gating effect is generally used in the scenario where the gate dielectric material with receptors is there on the surface for the immobilization of the bio-molecules [20]. Gating effect-based biosensors are used for the detection of the charged biomolecules [23]on another part dielectric modulation based can detect both, charged and neutral biomolecules [20].

Table 1 Device Specifications

Parameter	**Value**
Detecting Gate Length (L_g)	40 nm
Controlling Gate Length (L_d)	40 nm
Tube thickness (T_{tube})	5 nm
Nano Gap Length (L_{gap})	40 nm
Source/Drain Length	30 nm
Nano Gap Width (W_{gap})	10 nm
Oxide thickness (t_{ox})	1 nm
Channel doping	10^{17} cm^{-3}
Drain region doping (cm^{-3})	1 x 10^{19} cm^{-3}

In the proposed device, the ambipolar current is taken as the main sensing parameter. When biomolecules of different dielectric values (proteins, enzymes, etc.,) are immobilized at the observing gate, the ambipolar current (I_A) of the TFET device changed[24]. In Fig. 2 (a) and 2 (b) quasi-Fermi energy level of the electrons and holes at the negative gate voltage (Ambipolar) and the zero-gate voltage (OFF state).

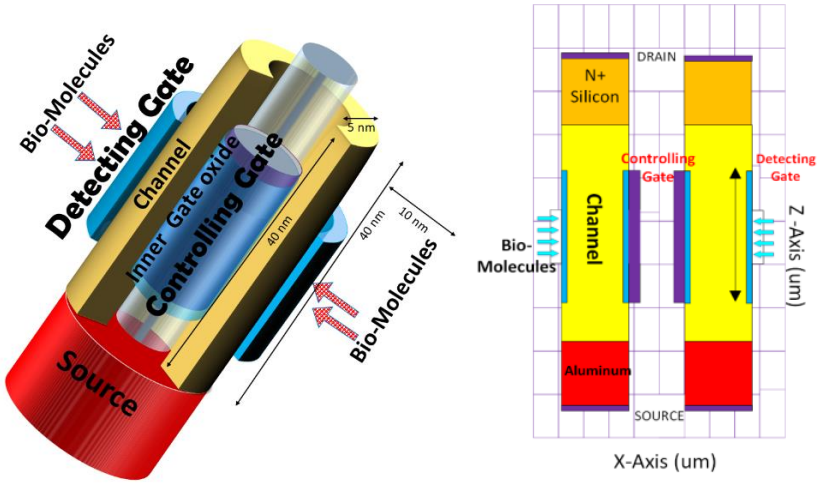

Fig 1 Silicon nanotube tunnel TFET biosensor illustration (a) 3D Inner and (b) Vertical cross-sectional

It is found in an ambipolar state, the tunneling barrier width is the least in contrast with the OFF state. It is conceivable because of the moving of energy bands on the utilization of negative voltages. In the phenomenon of displacing, the valance energy band of the channel directly occurs before the drain's conduction energy band, the flow of current starts. In this paper, all the estimations of I_A were taken for V_{gs} = -0.5V. All the simulations were completed in 3D ATLAS simulator of SILCVACO TCAD[25]. For tunnel FET realization KANE model for BTBT is incorporated in the work. The existence of bio-molecules in nanogap has been shown by employ material of dielectric constant (k>1) (such as protein= 2.50, streptavidin = 2.1, APTES 3.57, and biotin=2.63). A filled nanogap has been considered. After all the effect of charged biomolecules has been realized by introducing the fixed oxide charge, i.e., positive or negative, at the interface of dielectric and gate oxide [26].

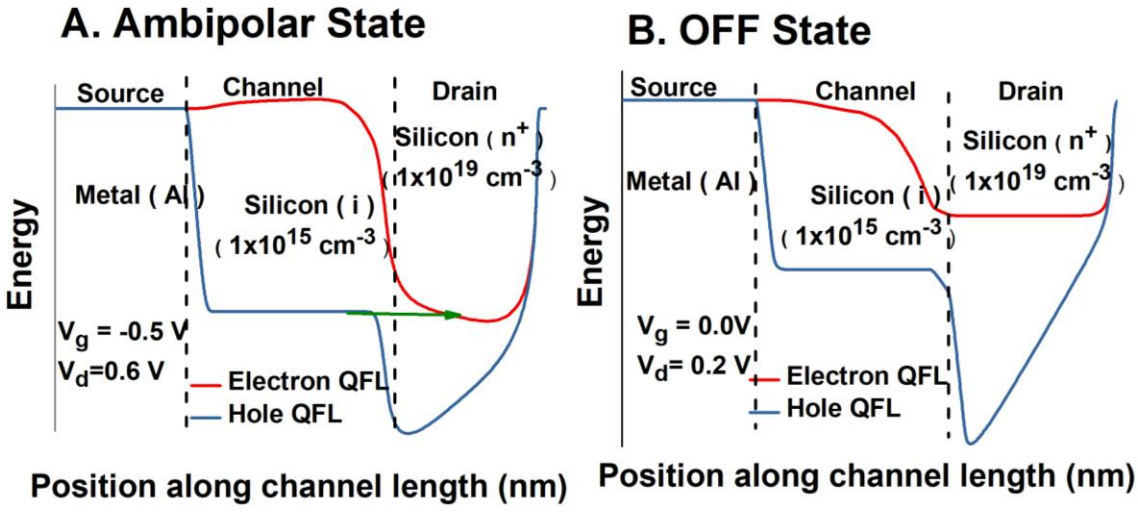

Fig 2. Quasi Fermi level for drain valance and channel conduction band at (A) Ambipolar state and (B) OFF state

3. RESULT AND DISCUSSION

The most suited adaptive method to analyze, biosensor, based on simulation platform in which we are applying the analytical models to investigate the device performance in terms of ON state, OFF state, and ambipolar current. To comprehend the operation of the Tunnel FET device as a biosensing device is necessary to explain the band to band tunneling (BTBT) process at the source-channel junction by varying the dielectric constant (k) value and alter the value of bio-molecules charge density. The change in the electric field of SI_NT_TFET with various dielectric constant (k) and variation of density of charged bio-molecules with channel length is depicted in Fig. 3 (a) and (b). A huge decrease in the electric field lines has been seen as the dielectric constant value of the nanogap increments. If there should be an occurrence of positively charged biomolecules, the electric field lines are expanding in the gap region with the increasing charge of the biomolecules while in the case of negatively bio-molecules charge on enhancing the intensity of the charge the electric field value is reduced [28].

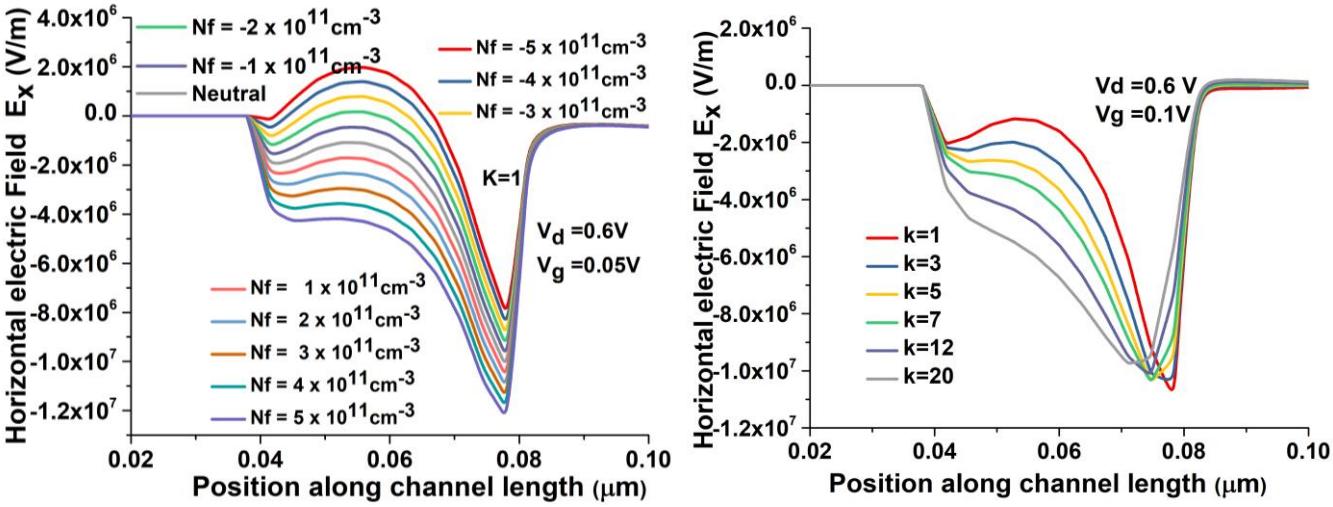

***Fig 3**. Electric Field lines of SI_NT_TFET for various (a) Dielectric Constant(k) (b) charged biomolecule (N_f)*

It tends to be investigated that as a greater number of negative charges are incrementing in the cavity locale, the width of the tunneling barrier in the cavity region increments. As the electric field lessens, the quantity of tunneling electrons from the Source to the drain region utilizing the channel reduces. The channel flow is likewise expanding with expanding electric field. As the dielectric constant value of bio-molecules is charged at the observing gate the on-state current is changing respectively[15].

Fig. 4 denotes the effect of varying dielectric constant values on the Ambipolar current (I_A) corresponding to charge bio-molecules. The ambipolar current increases (decreases) when the number of positively (negatively) charged bio-molecules increase in the nano gap region. If the total number of bio-molecules infused are increase and the depth of the cavity region is increased, ambipolar current (I_A) is reduced in both the cases negative as well as positive charges.

In this work, we follow the ambipolar current as sensing parameter, the sensitivity parameter is given as:

$$S_{ADielectric} = \frac{I_A(k>1) - I_A(k=1)}{I_A(k=1)} \quad \text{(I)}$$

$$S_{Acharge} = \frac{I_A(charged) - I_A(neutral)}{I_A(neutral)} \quad \text{(II)}$$

In equations I and II I_A is ambipolar current and k define as a dielectric constant value. The graph between the sensitivity and biomolecules with different charge values (fig 5 a) and dielectric constant values (fig 5 b) are shown in Fig 5.

It is found that the sensitivity of biomolecule reduce (enhances) with decreasing charge of negative (positive) charged bio-molecules in the nanocavity area[27]. I_A sensitivity reduces when the dielectric constant (k) of the bio-molecules are increased in the nano-gap region. The relevant changes in sensitivity of the SI_NT_TFET depict the sensitivity potential to find the height of charge in the gap region. Sufficient change in sensitivity proves the capability of tube-based TFET for bio-sensing applications. For K=5 the ambipolar sensitivity is about 0.54 and for K=20 it reaches 0.16 so here the sensitivity is decreased by 3 times.

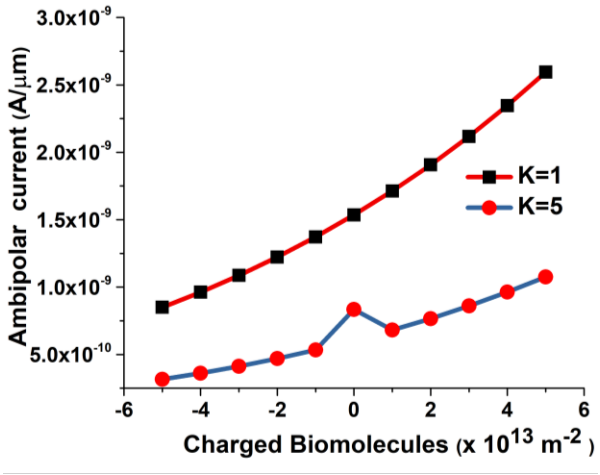

Fig. 4 Varying *ambipolar current corresponding to charged biomolecules at K=1 and K=5*

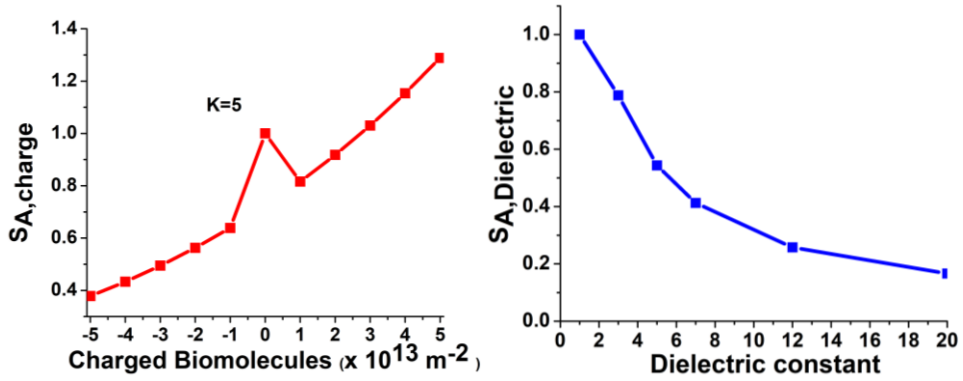

Fig. 5 Varying *Ambipolar sensitivity corresponding to (a) Charged bio-molecules and (b) Dielectric Constant*

4. Conclusion:

In this paper, a silicon nanotube-based tunnel field-effect biosensor has been considered as a label-free biosensor. Hence, the ambipolar current has been considered as the main sensing parameter, which will change in presence of neutral and charged biomolecules. Significant variations of the ambipolar current have been observed in presence of charged and neutral biomolecules. The proposed device is more sensitive in presence of charged bio-molecules compared to the neutral one. So, the proposed silicon nanotube-based TFET can be a promising candidate for the label-free biosensing process

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