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Design and Performance Analysis of Dielectrically Modulated Doping-less Tunnel FET based Label Free Biosensor

Sunny Anand, Amrita Singh, S. Intekhab Amin, and Asmita Thool

Abstract— **In this work, we have proposed a charge plasma based doping less double gated tunnel FET (DLDGTFET) based biosensor using dielectric modulation with a cavity introduced at the source side for the label free sensing of the biomolecules. These biomolecules are immobilized in the cavity region to induce drain current. The sensing of the biomolecules is based on the drain current of the device while the drain current is based on the dielectric constant and the interfacing charges of the biomolecules. The cavity length is varied between 25 nm and 30 nm and different dielectric constants have been used. The expansion of the cavity length results in slight reduction of the drain current due to lowering of the capacitance. Higher dielectric constants result in better drain current values which leads to an increase in the sensitivity of the device. The maximum sensitivity attained was as high as $1.0x10^{10}$. As compared to other transistors, DLDGTFET provides better sensitivity as a biosensor and also the leakage current is low.**

***Index Terms*— Charge plasma, Dielectric Modulation Tunnel FET, Biosensor, Biomolecule Sensitivity.**

I. Introduction

LATELY, the field of biosensors has been growing due to its wide range of applications ranging from medical [1] to environmental and agricultural fields. Biosensors based on FETs have been studied due to their various advantages such as low cost and their ability to detect charged biomolecules. FET-based biosensors were popular due to their performance in label-free detection of the biomolecules [2]. Despite being a low cost device, FET based biosensor did not had much applications due to their inability of detecting neutral charged particles. Later on, the dielectrically modulated FET based biosensors were imported to detect both charged and non-charged biomolecules [3]. A cavity was introduced under the gate to immobilize the biomolecules and determine the outcome on the basis of dielectric constant and drain current [4]. The immobilization of the biomolecules causes the electrical parameters to modulate and form a biosensor. However, it has some drawbacks such as scaling, power supply, short channel effects (SCEs) [5, 6], etc.

Later on, biosensors based on metal oxide semiconductors FETs (MOSFETs) were introduced because of their better performance with respect to the drain current as compared to the conventional FETs. Due to its limitations such as the inability of the sub-threshold swing to reduce below 60mV/dec [7, 8] and higher leakage current, MOSFET based biosensors did not find much attention. To overcome these issues, a TFET based biosensor was proposed [9]. TFET based biosensor is one of the most promising device which helps to overcome the difficulties faced by the conventional FETs. The performance of TFET devices are improved due to Band-to-Band tunneling [10, 11] at the source and channel interface which results in higher sensitivity for biosensing purpose as compared to the thermionic emission in MOSFETs.

We have proposed a charge plasma [12] based DLDGTFET (Doping-less [13] double gate tunnel FET) biosensor for the detection of biomolecules. The random dopant fluctuation (RDFs) is a major issue in doped nanoscale devices [14]. However, achieving physical doping with the help of thermal annealing process at source and drain region is complex and to achieve uniform doping in required region with the help of diffusion or ion implantation is also a challenge. Therefore, charge plasma technique is used in DLDGTFET to achieve source (p+) and drain (n+) regions over the silicon body to avoid physical doping and reduce the cost for annealing process [12]. In this device, the p+ region and n+ region are formed by applying suitable metal work functions at the source and drain sides [12]. This results in the absence of abrupt junctions admist the source-channel and drain-channel regions which further simplifies the fabrication process of DLDGTFET. Biosensors are used to detect the biological elements present in the environment by converting the biological response into electrical signal [15]. This is achieved by introducing cavities at the top and bottom regions of the device towards the source side underneath the gates. The cavities help in the detection of biomolecule charges (both positive and negative) in terms of dielectric constant and their respective currents. Due to the presence of biomolecules, the

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electrical parameters of the device get modulated due to which the detection of biomolecules becomes easy. The double gate metals have been used for better gate controllability [13] and also to control the threshold voltage with the help of the gate work function. The high-k dielectric [16] present as gate oxide will increase the DLDGTFET drain current because ON current is directly proportional to the gate dielectric constant. Hence, HfO_2 has been used as a dielectric [17].

This paper focuses on label free sensing [2] by studying the impact of different biomolecules on the performance of DLDGTFET device. In this work, the comparison of drain current for different cavity lengths (25nm and 30nm) has been studied in detail with different biomolecules such as Protein, Biotion, Aminopropyltrithoxysilane, etc. for biosensing application. The comparison is done for different biomolecules as well as interfacing charges (both positive and negative) to study their effect on the drain current.

II. Device Structure

For the simulation of DLDGTFET based Biosensor, the device parameters with their respective values are: thickness of silicon film (T_{si}= 10 nm), channel length (L= 50 nm), gate oxide thickness (t_{ox}= 5nm), intrinsic carrier concentration (n_i= 1×10^{15} cm^{-3}). In the charge plasma based DLDGTFET, the source and drain regions are formed by using suitable metal work functions. The P^+ region is formed by introducing platinum (WF=5.93 eV) at the source side while hafnium (WF=3.9 eV) is used to form the N^+ region at the drain side. Cavities formed underneath the gates are introduced with different biomolecules to get the device modulated to detect the biomolecules. In Figure 1, it can be seen that the channel is parted into two regions. The first region is the cavity length taken as 25 and 30 nm and the second region is gate oxide (HfO_2) whose length is taken as 25 and 20 nm. The metal work function of both the gates is 4.5 eV. The spacer between the gate and source (L_{gs}) is 3 nm and between gate and drain (L_{gd}) is 15 nm [18]. As shown in Figure 1, the spacer between gate and source is set to be lesser than that between drain and gate because it determines the electron tunneling probability from source to the channel [19]. To avoid the formation of silicide, 3 nm thick silicon dioxide between silicon substrate and drain electrode and 0.5 nm thick silicon dioxide between source electrode and silicon film are introduced respectively [19].

Silvaco Atlas tool is used to obtain the simulation results of above mentioned device [20]. In the simulations, drift diffusion current transport model is contemplated for the tunneling of electrons and holes. By using Lombardi mobility (CVT) model and concentration dependent Shockley-Read-Hall recombination and generation model, the effect of leakage current and mobility are accounted. The model, Non-local BTBT, is considered to account for the distinct separation of holes generated in valance band, electrons originated in the conduction band and also to model the tunneling process more precisely [20].

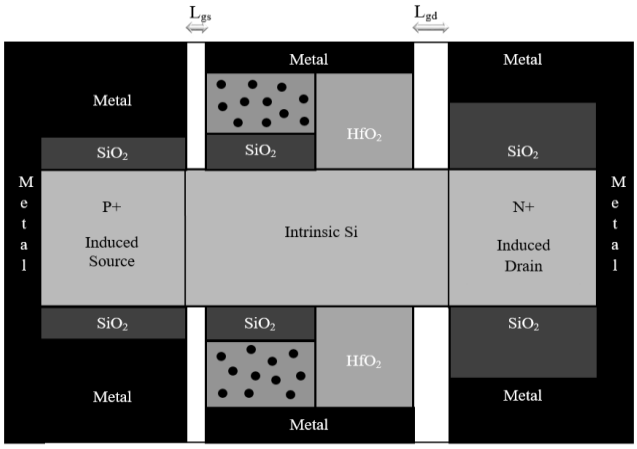

Fig. 1 2D Structure of DLDGTFET Biosensor.

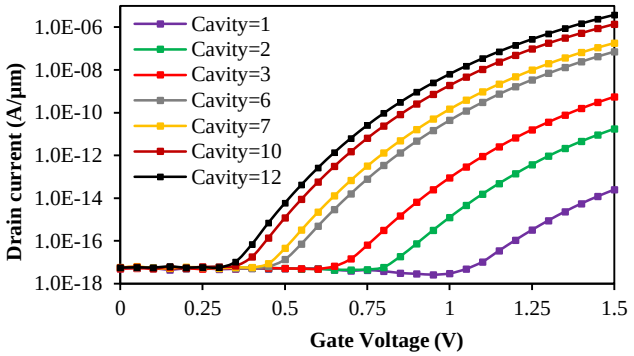

Fig. 2 Transfer characteristics of DLDGTFET with different value of cavity for cavity length=25nm.

III. Results And Discussions

Different biomolecules have different dielectric constants. There exists two kinds of biomolecules – neutral and charged. The simulations of neutral biomolecules are based on their dielectric constants while the charged biomolecules are simulated by considering the dielectric constant as well as the charge density. The immobilization of the biomolecules induces BTBT procedure from source to channel region for different dielectric constants and interfacing charges.

As length of the cavity is varied, there is a variation in drain current due to immobilization of biomolecules in the cavity region with different dielectric constants and with cavity length 25 nm at V_{DS} =1.0V as shown in Figure 2. The notation 'cavity=1' represents that the cavity consists of air. Similarly, 'cavity=2' represents that the cavity is filled with biomolecules having a dielectric value as 2 and so on. Since, the tunneling barrier width increases when cavities are introduced under the gate, the possibility of low electron tunnelling arises. After introducing biomolecules, the tunnelling barrier width reduces with an increase in the dielectric constant as seen in Figure 3. Whereas, the OFF current remains constant due to an increase in the curve of the energy band which leads to the depletion of the barrier width. More curving of the energy band will lead to more tunneling of electrons due to reduced tunneling barrier between the conduction band of channel and valence band of source.

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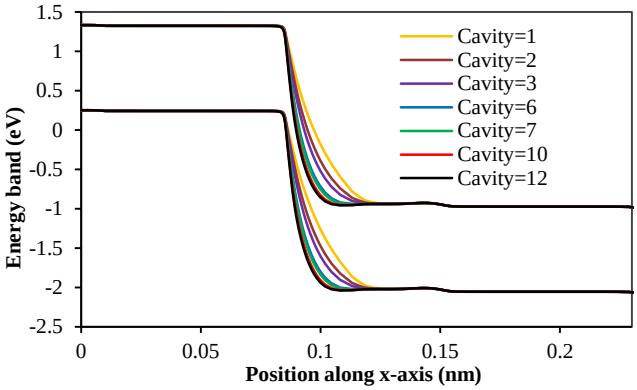

Fig. 3 Energy band diagram for DLDGTFET with different value of cavity for cavity length= 25nm.

For the charged biomolecules, both dielectric constants and interfacing charges (ID_NF) are taken into account. Figure 4(a) shows the variation in drain current when positively charged biomolecules are immobilized under the gates. It is known that voltage is directly proportional to current and also, $q = cv$, where q is the charge, c is the capacitance and v is the voltage. Hence, charge is directly proportional to the current. Therefore, the drain current increases with an increase in the interfacing charges because it decreases the barrier width between the conduction band and the valence band of channel and source respectively. Figure 4(b) shows the plot of drain current when negatively charged biomolecules are introduced in the cavity. The drain current obtained for negatively charged particles is low as compared to that of the positively charged particles because for the negatively charged particles, the charge density becomes low when compared to the positively charged particles, however, the current increases with an increase in the interfacing charges of the biomolecules while the OFF state current remains the same. The explanation for increase in the current is same as for positively charged biomolecules, i.e. the current increases with an increase in the charge.

Figure 5 shows the variation in drain current due to immobilization of biomolecules in the cavity region by taking different dielectric constants with a cavity length of 30 nm at V_{DS} =1.0V. It is observed that there is a slight change in the drain current when the cavity length is increased from 25nm to 30 nm. It occurs due to the fact that in DLDGTFET the current is obtained by the tunneling principle. Increase in length widens the tunnelling barrier which leads to a lower probability of tunneling. Capacitance is inversely proportional to length l, which can be shown by the relation, $C = \frac{\varepsilon A}{l}$, where C is the capacitance, ε is the permittivity and A denotes the area. As we increase the length of the cavity, it decreases the capacitance between the gate and the channel region. Therefore, increase in cavity length decreases the drain current.

Figure 6 shows the electric field variation for different dielectric constants of biomolecules. We can see that the biomolecules with higher dielectric constants provide a higher

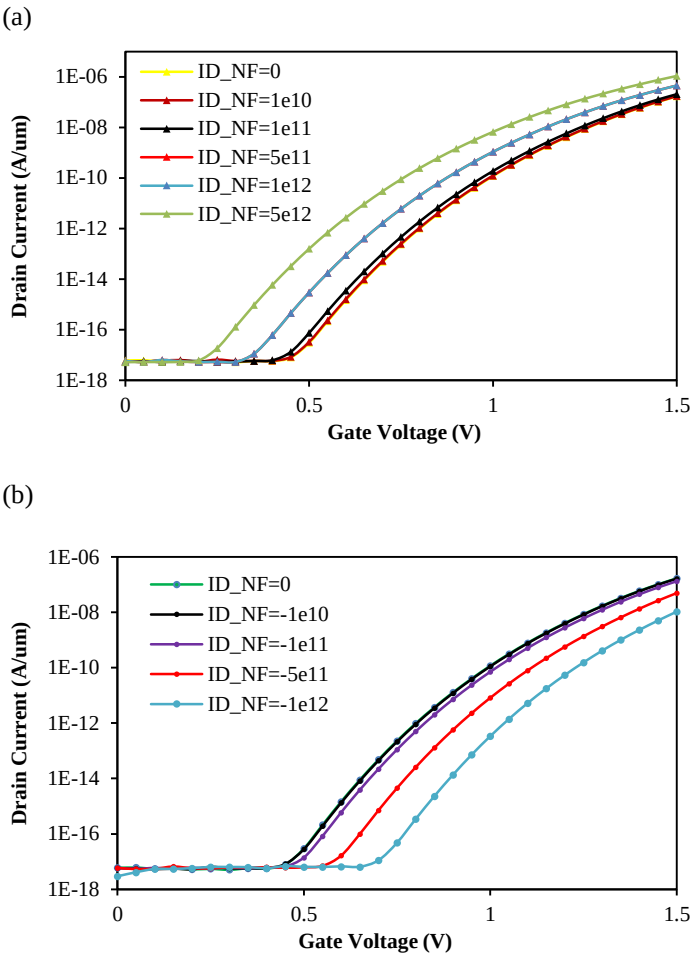

Fig. 4 Drain Current for DLDGTFET with cavity length=25nm with cavity=7 for different (a) positive interfacing charges and (b) negative interfacing charges.

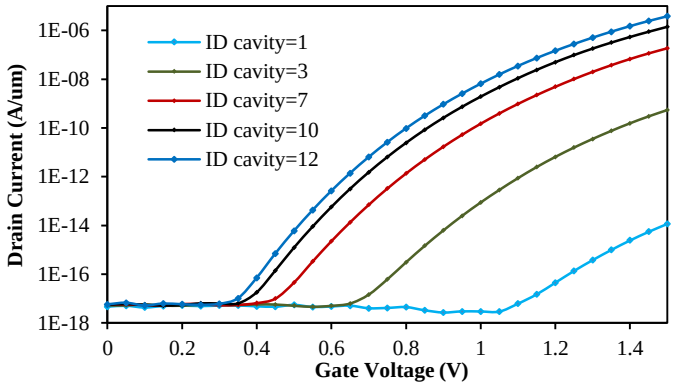

Fig. 5 Transfer characteristics of DLDGTFET with different value of cavity for cavity length=30nm.

value of electric field. It takes place due to the fact that when gate voltage is applied, it induces electric field. We know that electric filed is inversely proportional to the length of the cavity. In Figure 6, it can be seen that the higher the dielectric, the higher is the electric field and more electric field indicates more tunneling of electrons which in turn means higher drain current.

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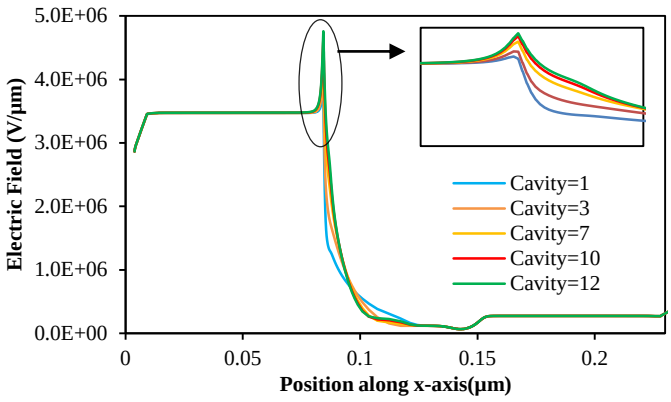

Fig.6 Effective Electric Field at cavity length=30 nm with different cavity.

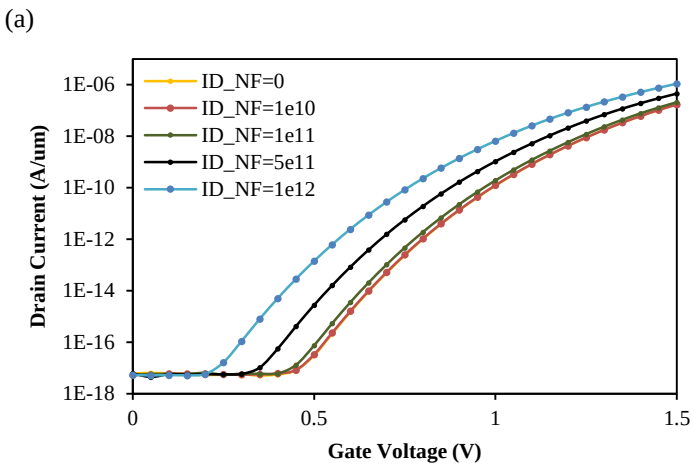

Fig. 7 (a) Drain Current for DLDGTFET and (b) Energy band diagram for different positive interfacing charges with cavity length=30nm with cavity =7.

Figure 7(a) holds the same explanation for the increased cavity length i.e. 30nm as it was for the charged biomolecules for cavity length 25nm. It is observed that an increase in the positive interfacing charges will increase the drain current. This happens due to lowering of the tunneling barrier between

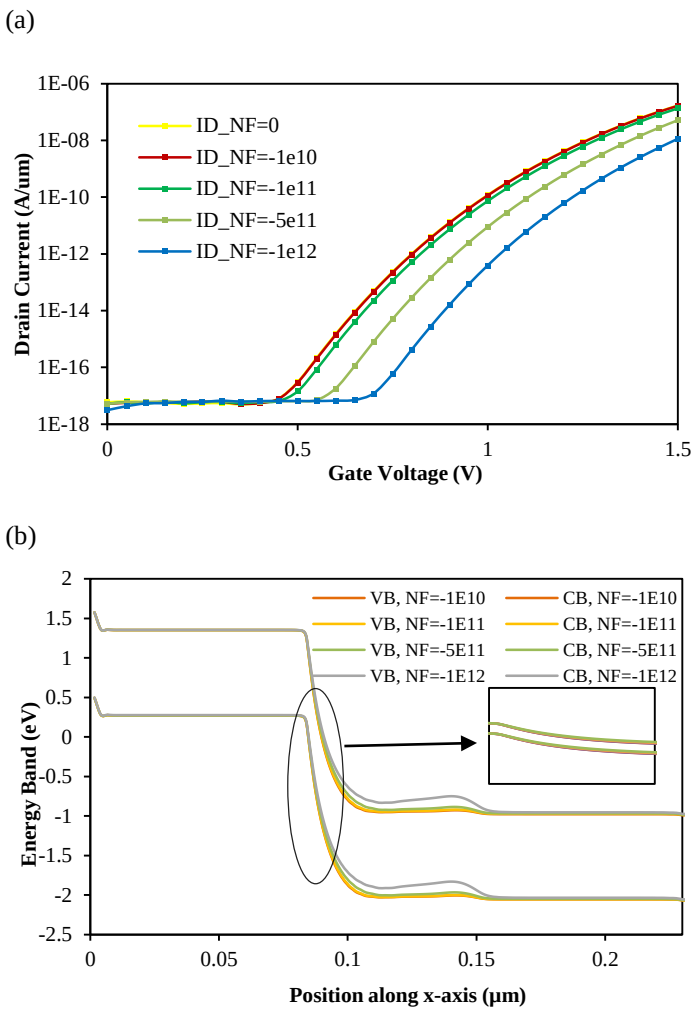

Fig. 8 (a) Drain Current for DLDGTFET and (b) Energy band diagram for different negative interfacing charges with cavity length=30nm with cavity =7.

the conduction and the valence band as shown in Figure 7(b).

Positively charged biomolecules produce more drain current than the negatively charged biomolecules which leads to depletion of the barrier width. Figure 8(a) shows an increase in the drain current because the charge density of the negatively charged biomolecules increases due to the same fact that the tunneling barrier reduces and the tunneling probability of the electrons increases which leads to a higher drain current as seen in Figure 8(b). In spite of all, the OFF state current remains constant throughout.

The drain current sensitivity is considered to be the main factor while measuring the performance of a biosensor.

$$Sensitivity = \frac{I_d(bio) - I_d(air)}{I_d(air)}$$

where I_d(bio)= drain current with biomolecules and I_d(air)= drain current without biomolecules.

Figure 9 (a) and (b) shows the drain current sensitivity characteristics of the DLDGTFET with cavity length 25nm and 30nm respectively at V_{DS}=1.0V. The notation 'SS_k=2vs1' denotes the sensitivity factor when biomolecule

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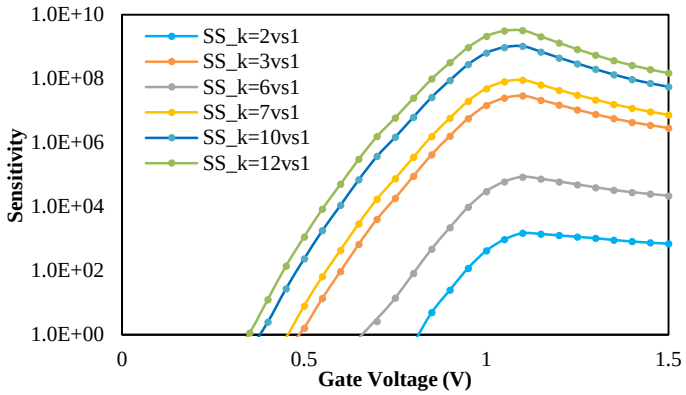
(a)



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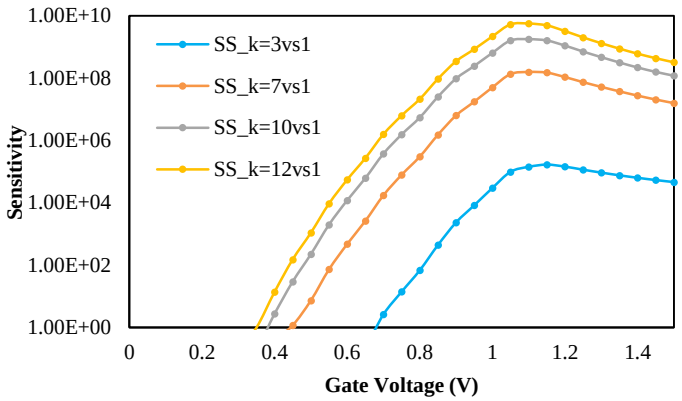

Fig. 9 Sensitivity plot of cavity length (a) 25 nm and (b) 30 nm.

with dielectric value 2 is taken into account for the calculations with respect to air and so on. The sensitivity increases with the drain current which in turn is associated with the dielectric constant. Whenever there is a moderate change in the dielectric value, it is observed that the sensitivity increases with the drain current. The ability of DLDGTFET to sense the biomolecules is directly proportional to the drain current sensitivity.

IV. CONCLUSION

It is observed that since the immobilization of biomolecules takes place under the gate, TFET proves to be a better device for sensing biomolecules. The proposed structure DLDGTFET is obtained using charge plasma technique which eliminates the need for the formation of junctions. Biosensors have several applications which requires high sensitivity and DGDLTFET poses the ability to fulfill the requirements. Thus, taking cost and performance into consideration, a charge plasma based DLDGTFET exhibits surpassing qualities with respect to cavity length and different charged and neutral biomolecules. It provides better drain current sensitivity and also, the leakage current remains constant throughout with a minimum value, making it a highly desirable structure.

REFERENCES

1. Bergveld, Piet. "The development and application of FET-based biosensors." *Biosensors* vol. 2, no. 1, pp. 15-33, 1986.
2. Sarkar, Deblina, and Kaustav Banerjee. "Proposal for tunnel-field-effect-transistor as ultra-sensitive and label-free biosensors." *Applied Physics Letters*, vol. 100, no. 14, pp.143108, 2012.
3. Im, Hyungsoon, Xing-Jiu Huang, Bonsang Gu, and Yang-Kyu Choi. "A dielectric-modulated field-effect transistor for biosensing." *Nature nanotechnology*, vol. 2, no. 7, pp. 430, 2007.
4. Gu, Bonsang, Tae Jung Park, Jae-Hyuk Ahn, Xing-Jiu Huang, Sang Yup Lee, and Yang-Kyu Choi. "Nanogap field-effect transistor biosensors for electrical detection of avian influenza." *small*, vol. 5, no. 21, pp. 2407-2412, 2009.
5. Kataoka-Hamai, Chiho, and Yuji Miyahara. "Label-free detection of DNA by field-effect devices." *IEEE Sensors Journal*, vol. 11, no. 12, pp. 3153-3160, 2011.
6. Colinge, Jean-Pierre, Chi-Woo Lee, Aryan Afzalian, Nima Dehdashti Akhavan, Ran Yan, Isabelle Ferain, Pedram Razavi et al. "Nanowire transistors without junctions." *Nature nanotechnology*, vol. 5, no. 3, pp. 225, 2010.
7. Bhuwalka, Krishna K., Jörg Schulze, and Ignaz Eisele. "Scaling the vertical tunnel FET with tunnel bandgap modulation and gate workfunction engineering." *IEEE transactions on electron devices*, vol. 52, no. 5, pp. 909-917, 2005.
8. Nirschl, T., Fischer, J., Fulde, M., Bargagli-Stoffi, A., Sterkel, M., Sedlmeir, J., Weber, C., Heinrich, R., Schaper, U., Einfeld, J. and Neubert, R. "Scaling properties of the tunneling field effect transistor (TFET): device and circuit". *Solid-state electronics*, vol. 50, no. 1, pp.44-51, 2006.
9. Narang, Rakhi, Manoj Saxena, R. S. Gupta, and Mridula Gupta. "Dielectric modulated tunnel field-effect transistor-a biomolecule sensor." *IEEE Electron Device Letters*, vol. 33, no. 2, pp. 266-268, 2012.
10. Choi, Woo Young, Byung-Gook Park, Jong Duk Lee, and Tsu-Jae King Liu. "Tunneling field-effect transistors (TFETs) with subthreshold swing (SS) less than 60 mV/dec." *IEEE Electron Device Letters*, vol. 28, no. 8, pp. 743-745, 2007.
11. Boucart, Kathy, and Adrian Mihai Ionescu. "Length scaling of the double gate tunnel FET with a high-k gate dielectric." *Solid-State Electronics*, vol. 51, no. 11-12, pp. 1500-1507, 2007.
12. Anand, Sunny, S. Intekhab Amin, and R. K. Sarin. "Performance analysis of charge plasma based dual electrode tunnel FET." *Journal of Semiconductors*, vol. 37, no. 5, pp. 054003, 2016.
13. Anand, Sunny, S. Intekhab Amin, and R. K. Sarin. "Analog performance investigation of dual electrode based doping-less tunnel FET." Journal of Computational Electronics, vol. 15, no. 1, pp. 94-103, 2016.
14. Leung, Greg, and Chi On Chui. "Variability impact of random dopant fluctuation on nanoscale junctionless FinFETs." *IEEE Electron Device Letters*, vol. 33, no. 6, pp. 767-769, 2012.
15. Narang, Rakhi, KV Sasidhar Reddy, Manoj Saxena, R. S. Gupta, and Mridula Gupta. "A dielectric-modulated tunnel-FET-based biosensor for label-free detection: Analytical modeling study and sensitivity analysis." *IEEE Transactions on Electron Devices*, vol. 59, no. 10, pp. 2809-2817, 2012.
16. Boucart, Kathy, and Adrian Mihai Ionescu. "Double-Gate Tunnel FET With High-$\kappa $ Gate Dielectric." *IEEE Transactions on Electron Devices*, vol. 54, no. 7, pp. 1725-1733, 2007.
17. Wang, Hao, Sheng Chang, Jin He, Qijun Huang, and Feng Liu. "The dual effects of gate dielectric constant in tunnel FETs." *IEEE J. Electron Dev. Soc*, vol. 4, pp. 445-450, 2016.

18. Anand, Sunny, and R. K. Sarin. "An Analysis on Ambipolar Reduction Techniques for Charge Plasma Based Tunnel Field Effect Transistors." *Journal of Nanoelectronics and Optoelectronics*, vol. 11, no. 4, pp. 543-550, 2016.
19. Kumar, M. Jagadesh, and Sindhu Janardhanan. "Doping-less tunnel field effect transistor: Design and investigation." *IEEE transactions on Electron Devices*, vol. 60, no. 10, pp. 3285-3290, 2013.
20. ATLAS Device Simulation Software, Silvaco Int., Santa Clara, CA, USA, 2012.

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