Project Report

On topic

Use of MOSFETs as Biosensor

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INTRODUCTION

The Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) is an important building block of electronic devices and digital circuits. It consists of a gate, a source and a drain primarily and current through the channel between source and drain is controlled by the gate voltage (Vgs). Moore's Law predicts that the number of transistors on a microchip will double approximately every two years. As the number of transistors on a chip doubles, the size of each transistor must decrease in order to maintain the same chip size. This has led to a continuous decrease in transistor size over time. However, as the size of MOSFETs has decreased, short channel effects (SCEs) have become increasingly prevalent, leading to significant challenges in their design and optimization.

Short Channel Effects occur when the channel length of MOSFET is reduced. The effects include Drain Induced Barrier Lowering (DIBL), which refers to decrease in effective channel length caused by electric field generated by the drain. This effect can cause a decrease in the threshold voltage, known as Threshold Voltage roll-off. Subthreshold Slope Degradation is another prominent Short Channel Effect, the subthreshold slope is defined as the rate at which the MOSFET turns on as the gate voltage is increased from zero to a small value, ideally it is a steep slope, however it degrades at shorter channel lengths.

In response to the challenges posed by the Short Channel Effects researchers have been exploring techniques to counter them and enhance the performance of a short channel transistor. Some techniques used are use of high-K dielectric at gate oxide, use of FD-SOI MOSFET and MOSFET with Buried Oxide (BOX).

MOSFETS have also found applications in Biosensing, starting with Ion Sensing FET (ISFET) that used to …… further research found use of Dielectric Modulated Field Effect Transistors (DMFET) for label free detection making use of nanogaps in the gate dielectric and changes in transistor characteristics when biomolecule is introduced in the nanogap. Latest discoveries found use of Dielectric Modulated Tunnel Field Effect Transistor (DM-TFET).

MOSFET SCALING AND SHORT CHANNEL EFFECTS

Scaling of MOSFET refers to reducing the physical size while maintaining or improving the performance. Scaling allows for more transistors to be packed on a single chip. Main challenges in scaling is the occurrence of Short Channel Effects at smaller channel lengths.

Drain Induced Barrier Lowering (DIBL) is the reduction of effective channel length due to Drain Voltage (Vd) or electric field at drain. DIBL can also be understood in terms of the height of the potential barrier between the Source and Channel region. The barrier height for channel carriers should ideally be controlled by the gate voltage to maximize transconductance. DIBL effect occurs when the barrier height for channel carriers at the edge of the source reduces due to the influence of drain electric field, upon application of a high drain voltage, which now increases the number of carriers injected into the channel from the source leading to an increased drain off-current. The increased drain off current is undesirable and harmful for the device. This effect also accounts for the decrease in threshold voltage upon decreasing the channel lengths. [2]

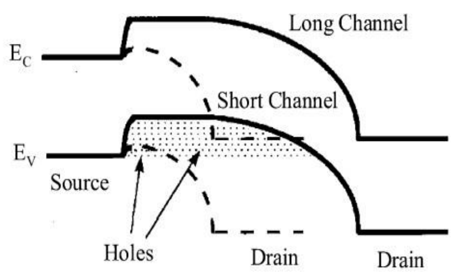
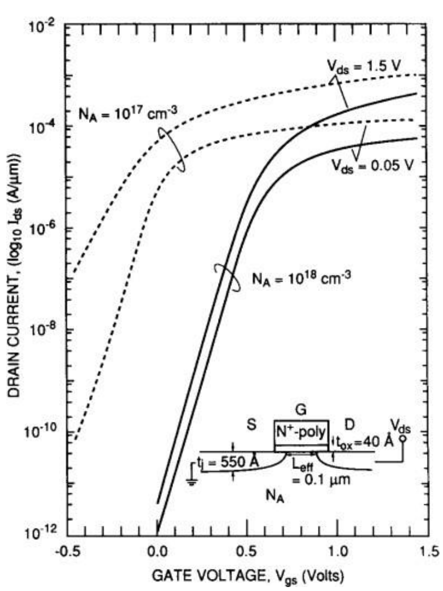
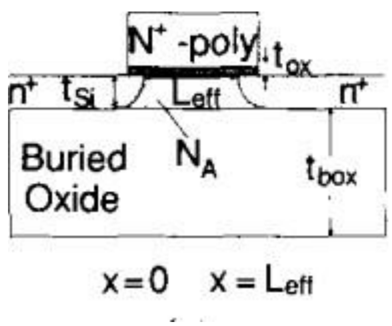


Fig. 3. Comparison of schematic energy band diagrams near the bottom of the body between the long and short-channel FD nMOSFETs [31].

Subthreshold swing (S) is a measure of how steeply the current of a MOSFET changes with respect to the gate voltage in the subthreshold region, it is the inverse slope of the subthreshold drain current versus gate voltage curve and is expressed in units of volts per decade (V/decade). A low subthreshold swing is desirable in MOSFETs, because it allows for better control of the gate voltage and results in lower power consumption(because of low OFF state current).

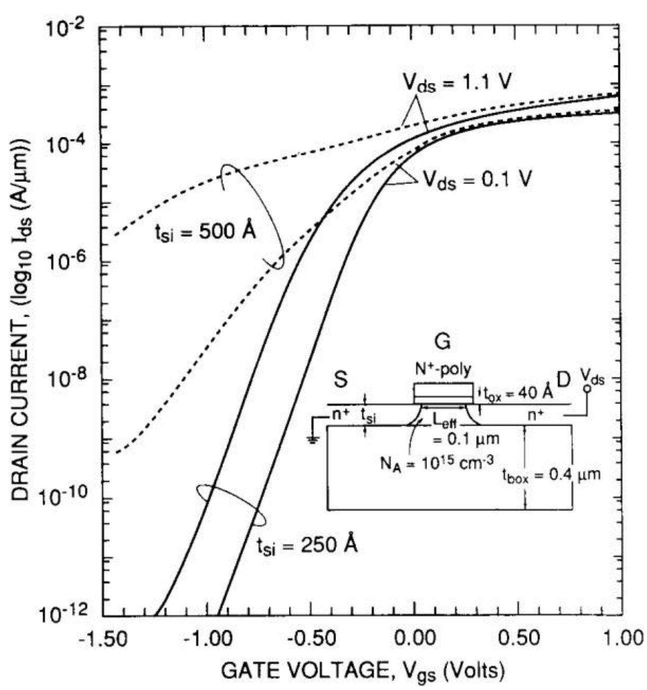


Here we have compared the characteristics of devices with different doping concentrations to try and get better short channel behavior. We observe that the device with higher doping concentration shows less OFF state current, higher Threshold Voltage, and lower value of Subthreshold Swing. Hence increasing the doping concentration gives better short channel behavior. One of the challenges with higher doping is mobility degradation as the number of carriers in a limited space increases, due to higher mobility the device has higher resistance. [1]

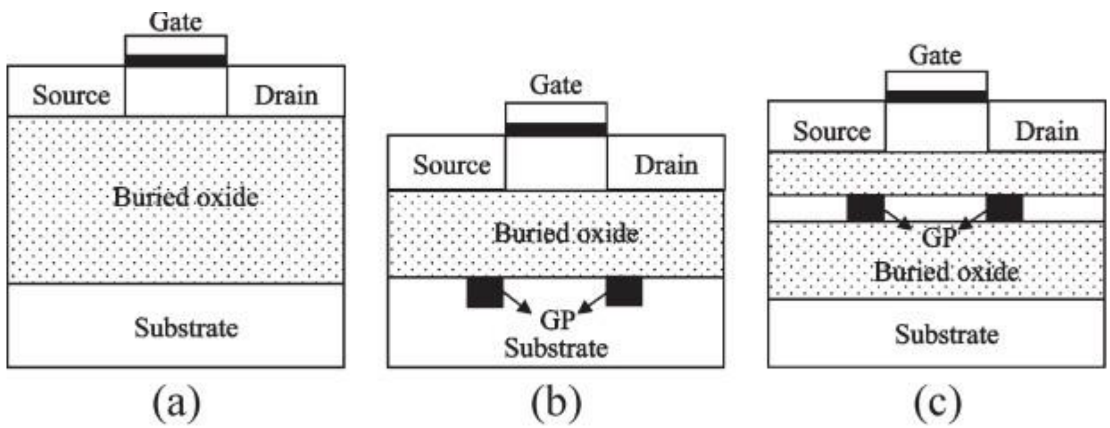


The use of FD-SOI MOSFET for better short channel behavior is studied, FD-SOI is Fully Depleted - Silicon on Insulator, in SOI, a thick buried oxide is introduced in the substrate which forms a quasi-neutral region and reduce the junction capacitance, one of the advantages of using SOI is lesser depletion region, since are below the source and drain region is already occupied by fully depleted Silicon.

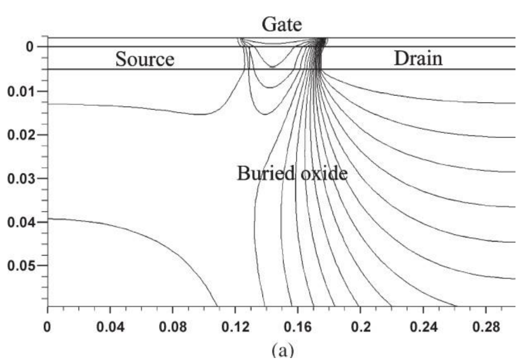
If we compare the behavior of SOI while varying the thickness of buried oxide, we see that the transistor with thinner oxide shows better behavior. Thinner BOX implies higher capacitance between Source/Drain and substrate. the closer the source/drain regions are to the substrate, resulting in reduced parasitic capacitance between the source/drain and the substrate. This can lead to faster switching speeds. A thinner BOX layer can help reduce SCEs, resulting in improved device behavior.



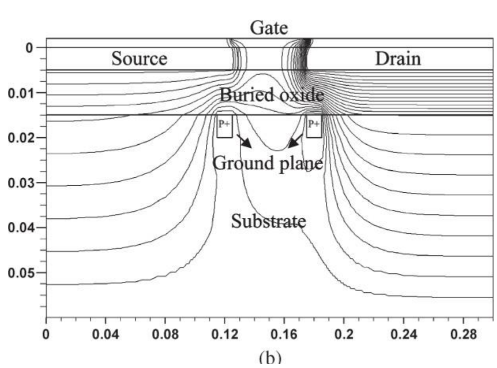
As the device dimensions are scaled down into sub-100-nm regime, the performance of the FD SOI MOSFET-(a) also deteriorates due to short-channel effects. The ground plane (GP) concept is one of the techniques used to reduce the DIBL effect, and it is effective only when the distance between the GP and the drain is small as compared with the channel length. We have discussed



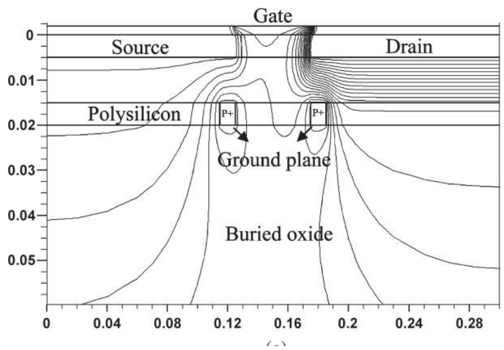
structures with GP in the Substrate (GPS)-(b) and GP in the Buried Oxide (GPB)-(c), GP placed in the BOX, acts as a sink to the drain electric field, leading to a reduced DIBL effect. One of the problems with GPS is that although it counters DIBL, the Subthreshold Slope is still degraded. Which is solved in GPB by increasing the thickness of the BOX (Buried Oxide), which decreases the BOX capacitance. [4]



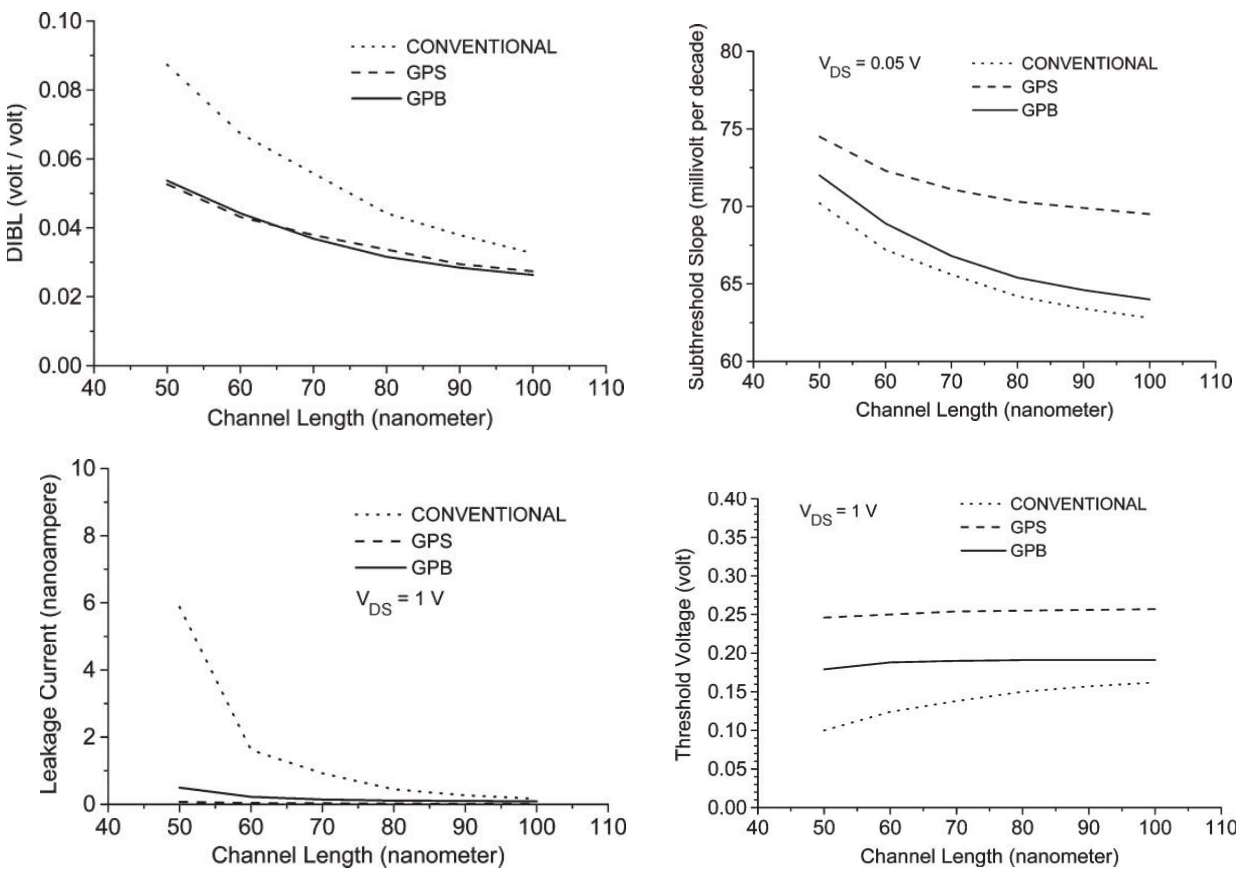
(a) Shows the Potential Contour for a FD-SOI MOSFET, as we can see the field lines are intersecting and disturbing the channel region, weakening gate control.



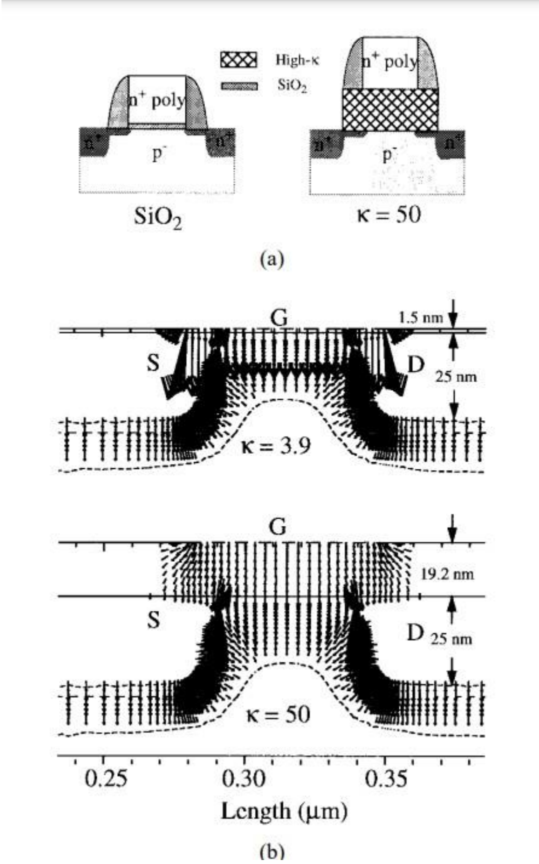
(b) Potential Contour for GPS device structure, we see better behavior than FD-SOI but still there is a significant amount of field in the channel region.



(c) Given is the Potential Contour for GPB structure of the device, here we see that there is minimum interference of field in the channel region hence the best Short Channel behavior

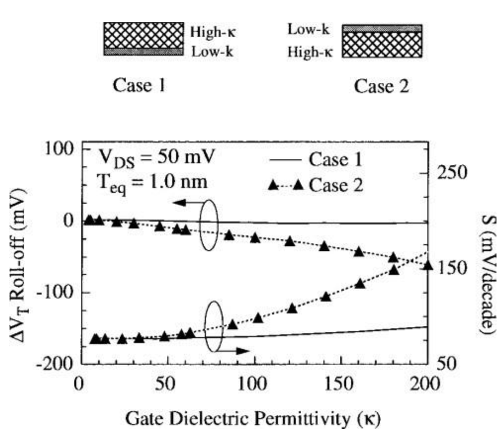


Given above are the ATLAS simulation results for (a) Conventional, (b) GPS and (c) GPB structures, we have studied various characteristics of the varied with channel length, from the results we infer the proposed structure minimizes both the DIBL and the OFF-state leakage current while improving the subthreshold slope compared with the conventional FD SOI MOSFET and the FD SOI MOSFET with the GPS. Thus, the FD SOI MOSFET with the GPB shows promising results for scaling of MOSFETs in sub-100-nm applications. [4]



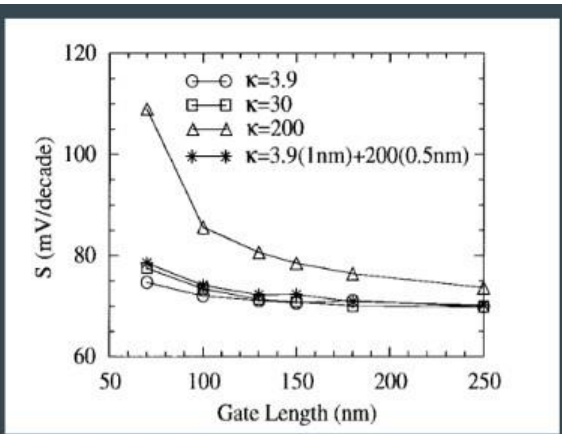
Another solution for improving the behavior of the transistor is use of High-K dielectric at the gate terminal, we analyze the behavior of the devices with varying thickness and dielectric coefficient of the device and the different gate architectures that can be used. When we use a high-K gate dielectric, we can increase its thickness to get the same effective dielectric coefficient by formula, $T_\kappa = \kappa \times T_{SiO_2}/3.9$. One way to understand the benefit of high-K is through studying the fringing fields through source and drain regions, these arise due to non-uniform distribution of electric charges at the edges of these regions. In the given diagram we compare the Fields for a device with SiO2 (K = 3.9) and a device with high-K (K = 50), we see that the device with high-K dielectric has much lesser fringing fields and hence better behavior.

Another way we can experiment with the gate dielectric is by using Multiple-Layer Gate Stack Structure, it means two or more layers of different materials that are deposited on top of each other to form the gate electrode and gate dielectric layers. We compared two cases, Case 1: High-K material over Low-K and Case 2: Low-K material over High-K. We observe that the performance of multiple-layer gate stack structure is better than single layer high-K structure because we can get a thinner device. In these two cases, Case1: High-K material over Low-K shows better short channel behavior due to electric field divergence on the top low k dielectric layer. (Divergence: measure of electric field that flows out of a certain space) [5]

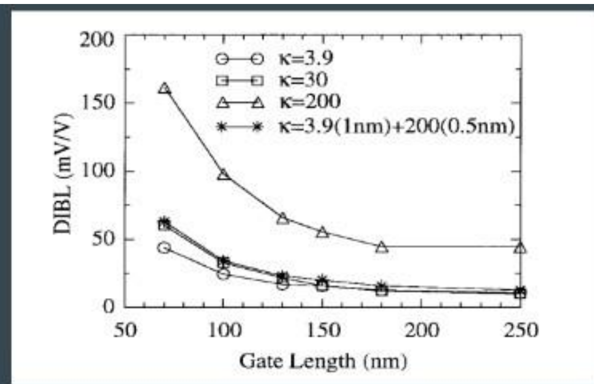


Different configurations at the gate were studied,

a) 1.5nm, k = 3.9
b) 1.5nm, k = 200
c) 1.0nm, k = 3.9 + 0.5 nm, k = 200 (Gate Stack)



Effect of gate length on Subthreshold Swing for different gate stack

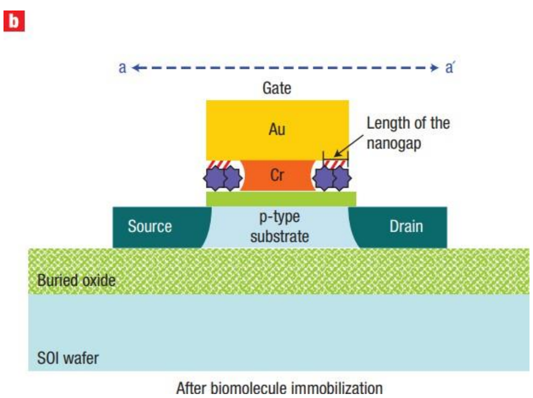


Effect of gate length on DIBL for different gate stack

It can be seen that for sub-100 nm channel MOSFET’s, dielectrics with K=200 degrade the DIBL characteristics by almost a factor of 4 compared to a conventional SiO2 structure, and S by about 50%. On the other hand, the pure high-K structures with K = 30 perform close to the stack structure with a combination of K = 200 and K =3.9. Hence, the gate stack architecture also plays an important role in the device performance. It has been shown that superb short-channel performance can be achieved for a structure with a double-layer gate stack and low- dielectric spacers.

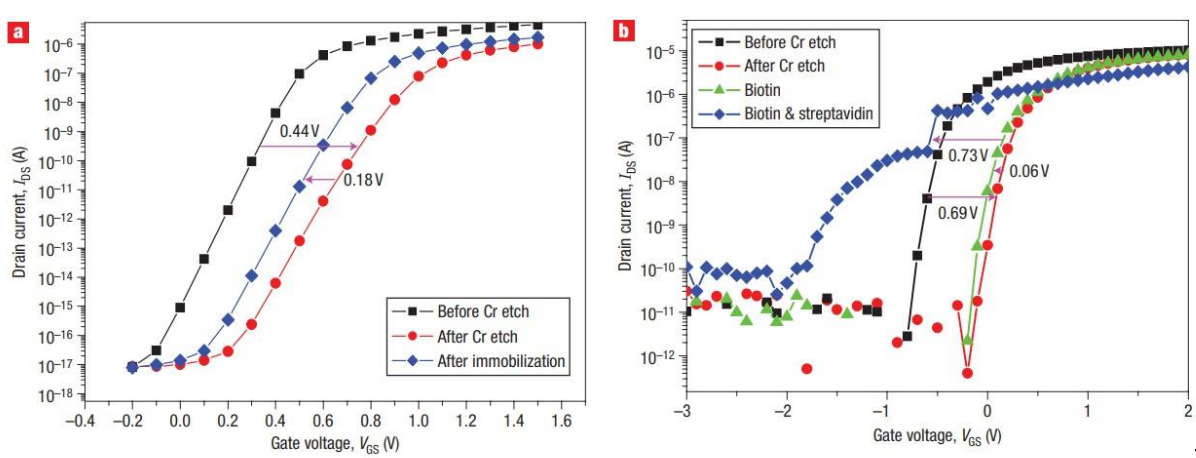
MOSFETS AS BIOSENSORS

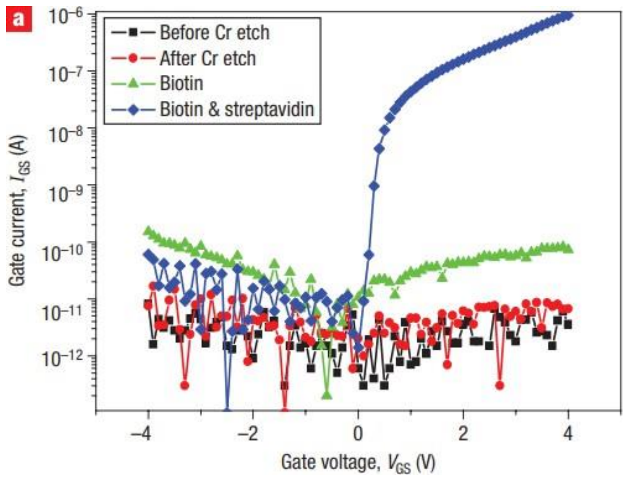
There has been an interest in using MOSFETs as Biosensors. We have studied the use of Dielectric Modulated - Field Effect Transistor (DM-FET) for biosensing purposes; the system to be detected is the Biotin-Streptavidin system. Biotin is a small molecule, it is important for various metabolic processes in living organisms. Biotin is highly specific and has found many uses as a tool in biological applications. Streptavidin is a tetrameric protein, ie, it has four identical subunits, each of which has a strong affinity for Biotin. Binding of Streptavidin with Biotin is one of the strongest non-covalent interactions in nature. Due to strong affinity between Biotin-Streptavidin, it is a popular pair for many biological applications, including protein purification, immunoassays, and biosensors.



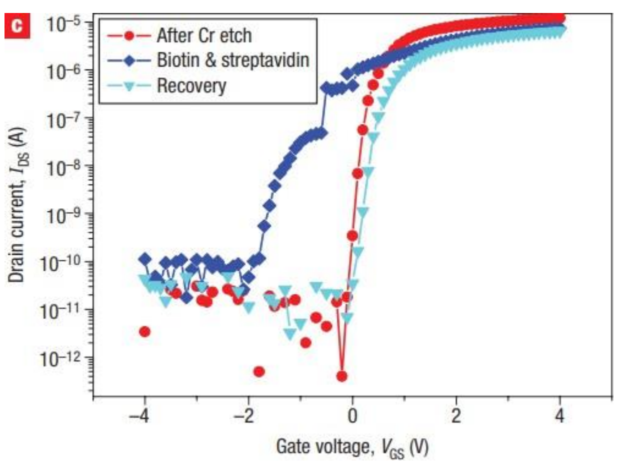
DM-FET biosensors have been used to detect various biomolecules, including Biotin-Streptavidin. We know from previous studies that the Threshold Voltage is dependent on the gate capacitance and the gate capacitance can be modulated by changing the dielectric material or modifying it. One of the ways discussed is by etching the gate dielectric to form nanogaps. (Nanogap: gap left in dielectric for biomolecules to reach and bond) [6]

The given curves (generated by ATLAS simulation) show the Id-Vg characteristics for the device with dielectric material etched and the other with presence of biomolecules.





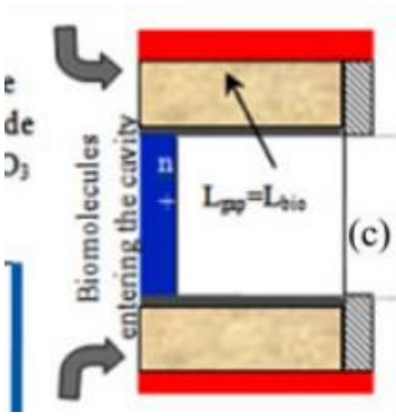
The given curve shows the Igs-Vgs characteristics for different cases under consideration. The sudden jump in Igs in the bound Biotin-Streptavidin case is because the bound molecules provide a current path for electrons to flow to the gate.



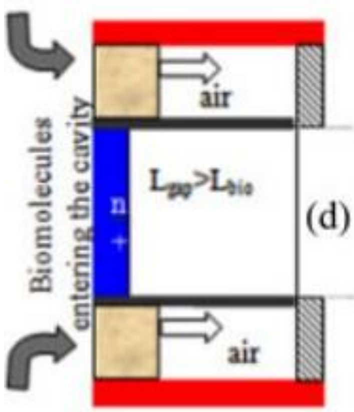
This curve shows the Ids-Vgs characteristics for the cases before, during and after the binding process; we infer that the characteristics of the devices are recovered much precisely, making the device easily reusable.

The problems encountered while using DM-FET are variability in etched cavity length and partial hybridization (PH) of biomolecules due to steric hindrance inside the nanogap. (Steric Hindrance:interference of molecular interactions between the target and the probe due to steric factors) Partial Hybridization occurs when a probe molecule binds to a target molecule incompletely or non-specifically. PH can lead to false positive or false negative results in biosensor measurements and decrease in device sensitivity, because the binding energy between the probe and target is reduced.

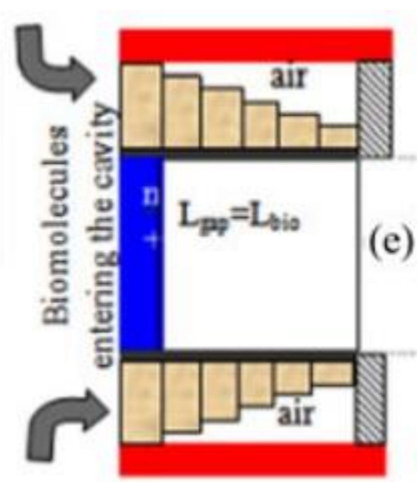
Practically only a part of the cavity gets filled and even the hybridization of target biomolecules starts retarding along the length of the cavity due to the hindrance posed by the already hybridized biomolecules at the cavity entrance.Hence, there are different ways that the cavity can be filled as discussed below,



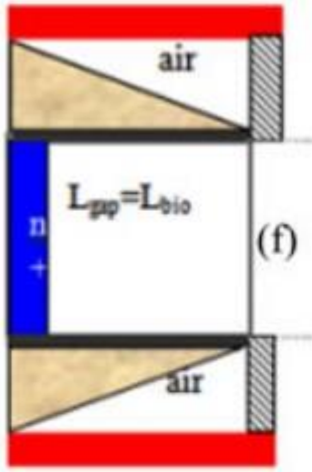
Completely filled Cavity



Uniformly and Partially filled Cavity



Non-Uniform and Partially filled Cavity with Step Profile



Non Uniform and Partially filled Cavity with Slant Profile

Due to steric hindrance the hybridization is more near the cavity entrance and slows down moving inside the cavity. Therefore, to study the effect of PH on the device sensitivity, we define a sensitivity parameter (SBIOTFET /SBIOFET) based on Ion (Ids at Vgs = 2 V and Vds = 1 V) variation due to the presence and absence of biomolecules (using K as a parameter).

$$S_{\mathrm{BIOTFET}}/S_{\mathrm{BIOFET}} = \frac{I_{\mathrm{on}}(\text{biomolecules present},\ k>1)}{I_{\mathrm{on}}(\text{empty cavity},\ k=1)} \quad (1)$$

PH impacts the device by varying the biomolecule spread, PH leads to lower effective gate capacitance and hence lowers the channel potential in the cavity region affecting performance of the device.

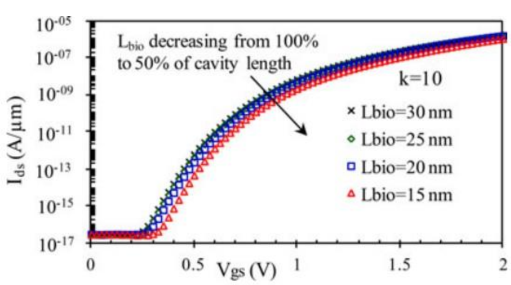
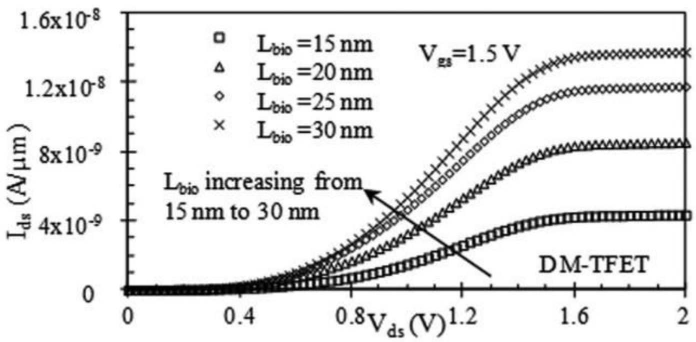


Fig. 4. Impact of uniform PH with increasing L_{bio} on $I_{ds} - V_{gs}$ characteristics of DM-TFET.

From this curve, we observe that the reduction in the current for a 50% filled cavity case to fully filled cavity case is small.

(Lbio > Length of region filled)

To further improve the devices, Dielectric Modulated - Tunnel Field Effect Transistor (DM-TFET) was introduced. TFETs are a type of FET that operate through quantum tunneling of charge carriers across a narrow bandgap material. These are still in early stages of development. In TFETs, the channel region is made of a very thin layer of semiconductor with a narrow bandgap. We also define onset voltage for TFET as the gate voltage at which the tunneling current through the source-channel and channel-drain junctions starts to flow.

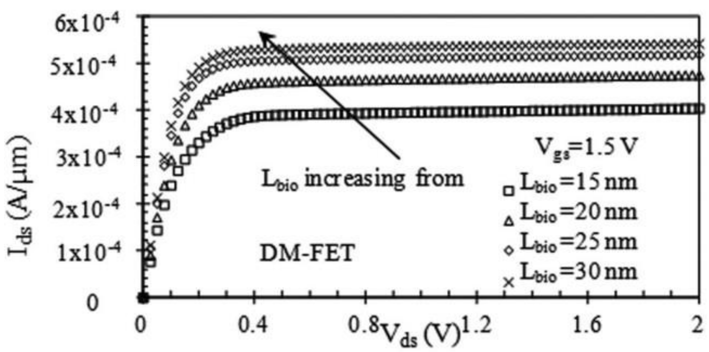


(a)

We compare the Id-Vd characteristics of

a) DM-TFET

b) DM-FET



(b)

We observe that DM-TFET delayed saturation, also the drive current levels are quite low in TFETs as compared to normal FETs, which is a challenge for TFETs.

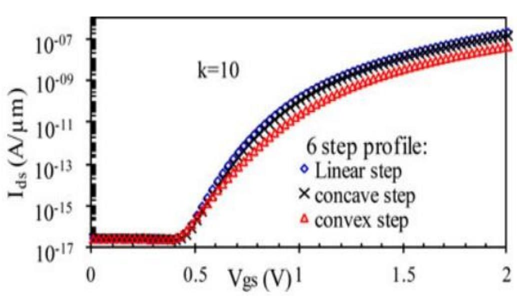
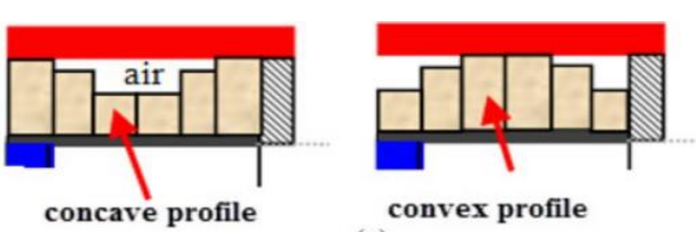
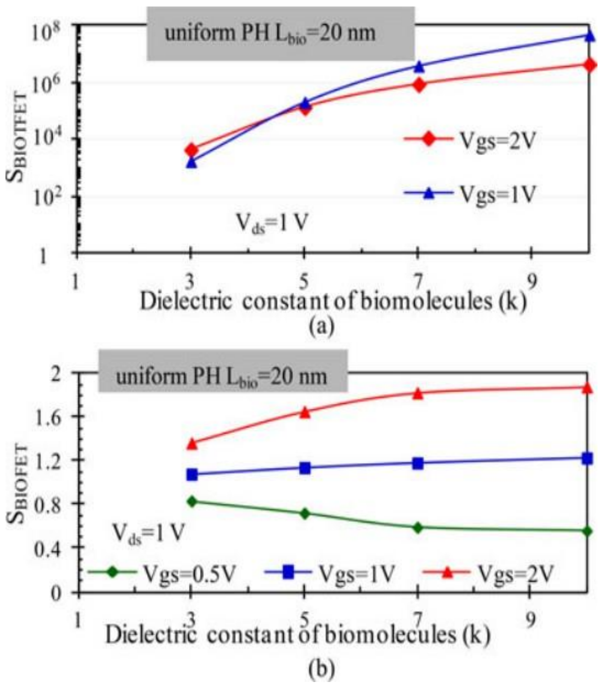


Fig. 7. Effect of non uniform 6 step PH profile (linear step, concave, and convex step) on the drain current characteristic of TFET biosensor.

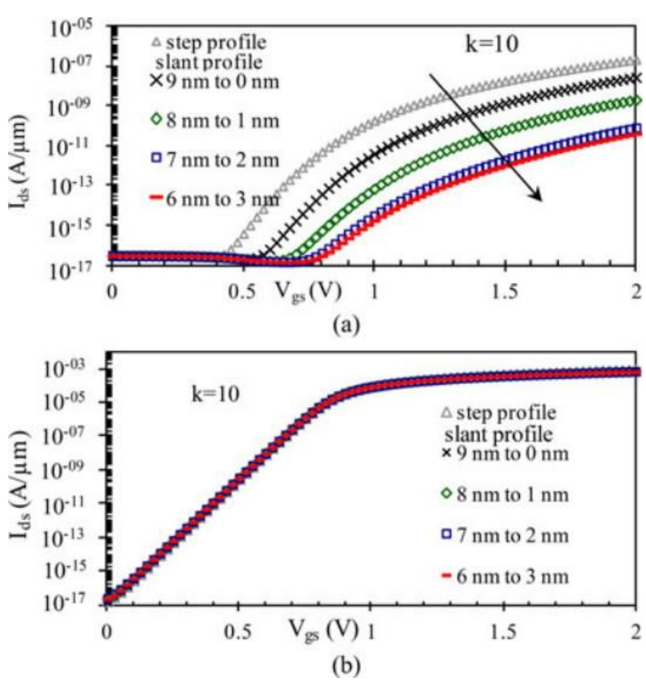
We also studied the effect of non-uniform step profile and the two associated convex and concave profiles on the drain current of TFET based sensor, drain current reduces for the convex profile case because of lower gate capacitance and hence lower effective gate voltage in the vicinity of the tunneling junction. (although the effect is negligible)



(a)



The sensitivity of FET and TFET with bias voltage and dielectric constant (K) is also compared using the parameter SBIOFET. The curves show a) for DM-TFET and b) for DM-FET with cases taken as Subthreshold (0.5V), above threshold (1V) and Saturation (2V) for b) DM-FET and above onset (1V) and in strong inversion (2V) for a) DM-TFET. We didn't take V = 0.5V for the TFET because the device didn't start conducting yet. The curve shows that sensitivity of TFET under any case is greater than conventional FETs and for TFETs although the sensitivity is higher for V = 1V, we still like to operate the device at higher gate voltage because the the drain current value is very low (few nano Amperes) at such low gate bias. And for DM-FETs we see that sensitivity decreases with voltage.

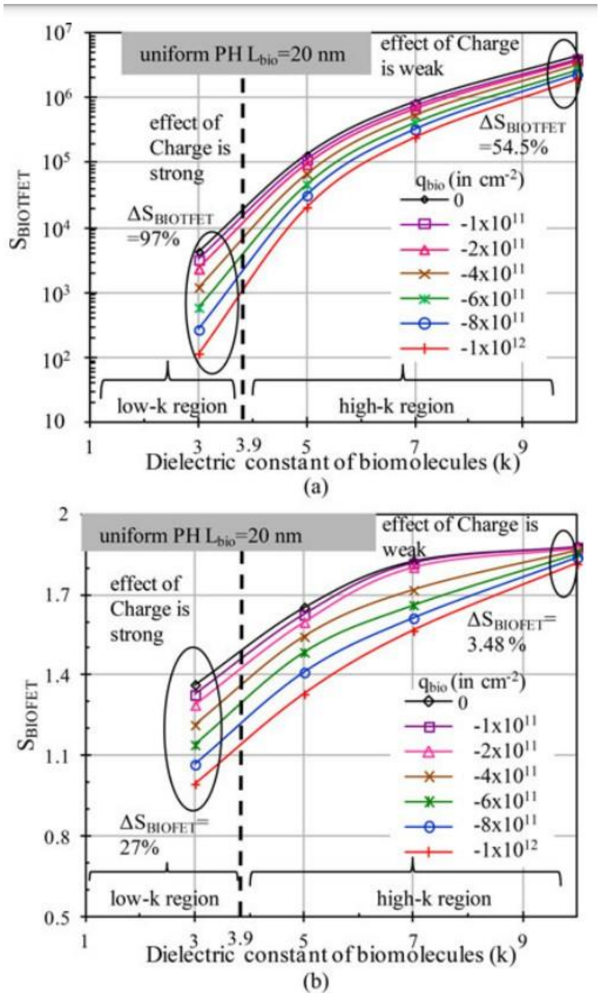


Another interesting observation is change in conduction current by changing the slant profile of biomolecule hybridization. The curves,

a) For DM-TFET

b) For DM-FET

show us that for MOSFET - variation of fill factor due to various slant profiles does not change the drain current & sensitivity is not severely affected, while for TFETs, a large amount of change is seen in the drain current. The reason for such large changes in TFETs is the distance of the thick biomolecule layer from the tunneling junction, although the thickness of the biomolecule layer is increasing simultaneously at the end of the cavity does not influence the drain current from decaying as the increment in the effective gate voltage is far away from the tunneling junction.



Effect of charge of biomolecules on the Sensitivity of the device is studied. The given curve shows variation in sensitivity of both DM-FET and DM-TFET due to the charged (negative) biomolecules having different dielectric constants. In presence of a charged molecule in the cavity, its charge and dielectric constant together affects the sensitivity. When the dielectric constant is low (below 3.9 i.e. of SiO2) the charge effect dominates the dielectric constant, but in case of large dielectric constant the charge effect gets subdued and the effect of dielectric constant is strong. The points depicting the sensitivity towards charge of biomolecules are quite spread out at lower k values as opposed to high-k values where they seem to be compressed. [7]

CONCLUSION

MOSFET scaling has played a significant role in the development of high-performance electronics, however, as devices are scaled down to ever-smaller sizes, they face numerous challenges, such as short-channel effects. Several devices and methods are discussed to address these issues. The solutions discussed are SOI, GP, High-k (elaborate).

The development of these technologies have shown promising results to address the challenges in MOSFET scaling. These technologies offer improved device performance, reduced power consumption, and enhanced scalability, making them promising candidates for the development of high-performance electronics.

Next part of discussion was on Biosensors and Dielectric modulated FETs are a promising candidate for biosensing applications. TFETs, on the other hand, have shown excellent switching characteristics and reduced power consumption compared to traditional MOSFETs.The steep subthreshold slope of TFETs makes them a promising candidate for low-power biosensors. However, further research is needed to improve their performance and reliability. The development of DMFETs and TFETs has provided new opportunities for the design of high-performance biosensors. By leveraging the unique properties of these devices, researchers can develop biosensors capable of detecting a wide range of biological analytes with exceptional accuracy and speed.

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