A comprehensive Analysis of Nanoscale Transistor Based Biosensor: A Review

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Imperative introduction of biosensor in the field of medicine, defence, food safety, security and environmental contamination detection acquired paramount attraction. Thus the foundation of the fame of biosensors in detecting wide scope of biomolecules in innumerable fields has driven researchers in advancement of biosensor and enhancing more updates in devices. Among all semiconductor-FET based biosensors grab attraction due to their miniaturization, mass production, ultra-sensitive in nature, improved lifetime, rapid response and reduce thermal budgets. In this review, field effect based biosensors sensitive to ions their principle model along with pros and cons of different structures. Various performance characteristics for semiconductor based biosensor are explored along with detection of label free analytes such as tuberculosis, glucose, antigen 85-B with ISFET. Following with comprehensive detail on MOSFET junction less Silicon based Dual Gate Biosensor with their design parameters for biosensing of neutral and charged analytes with results summarized in table. Drawbacks of dual gate structure introduce cylindrical structures summarized in table with device parameters and respective sensitivity. Role of analytes size in choosing the cavity width and position of analytes influence the sensitivity is recorded. Recent advancement on selectivity, sensitivity and switching results the gate and channel engineering thus compound semiconductor came in picture. In last section challenges with solution and importance of III-V compound channel as scope in biosensor with taking the benefits of fabrication of III-V compound MOSFETs. Semiconductor compound properties are summarized in table for various applications in recent use.

Keywords: ISFET, Junctionless Dual gate Biosensor, Cylindrical/Surrounding Junctionless Biosensor, Semiconductor compound

Introduction

In the recent years, the field of biosensors has experienced a large growth due to technology of semi conductive materials. Biosensors based on a semiconductor can be indicated as one of the fastest developing sensor-technologies. The recent development started in the 1970s with the FET sensors (field-effects-transistors) based on the interaction of biological or chemical elements directly connected to the electric field[1]. They are successfully used as detection of charged analytes but not able to detect neutral biomolecules. Then MOSFET based biosensor comes into picture that used detection without transducers .As the scaling of the technology is in progress there are certain limitations short channel effects (SCE) ,requirement of high doping to gain the sensitivity lowers the utility of junctioned biosensor due to difficulties created in the fabrication of the heavily doped ultra-shallow junctions,

controlling different doping in three regions (source, drain and channel),also limits on scaling .This problem can be overcome by introducing junction less based MOSFETs .Various advantages of junction less are discussed in later section along with different structures recorded in literature. In addition to junction less category the problems associated with non-detection of the neutral biomolecules with ISFET, issues with labled detection techniques, controlling the abrupt junctions and short channel effects are combat by Dual Gate junction less structure based biosensors. Study on various parameters of the biosensor like sensitivity results the advance CMOS techniques are introduced with the scaling feature adapted the sensing arrays in parallel and integrate with circuits and electronic systems. With this solid state biosensors are in completion with other biosensor mechanisms. Fundamental progress in semiconductor materials led to the development of such biosensors to achieve high sensitivity in biological sensors[2.]Moreover, these advances in semiconductors technology have made it possible to

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significantly improve the wide-using capabilities of the biological engineering. At the same time, the market for biosensors based on the electronics material with include the signal processing has significantly expanded. The following section comprises as working principle of ion sensitive field effect (ISFET) biosensor with different structures and applications of ISFET which is the base of all semiconductorbiosensor. Followed by various structures of Semiconductor MOSFET based Biosensor with pros and cons in detail. Design parameters are summarized in table with throughput as sensitivity. Explore the range of analytes size influenced the design of surrounding Gate All Around as biosensor. In last section the recent research scope of III-V compound based biosensor with their challenges and possible solution has discussed. This will lead to further scaling the channel and enhance the performance parameters of biosensors.

1.1 Semiconductor -field effect transistorbased biosensor

Today FET oriented biosensors become an emerging field due to rapid development or advancements in solid state electronics technologies, more often to use semiconductor based FET as biosensor with its adverse advantages like rapid response, lifetime, ultra-sensitive nature *etc*. as discuss in following sections. In nature there are two techniques for detection of bio-analytes are label and label free. Label based method opt the tags or labels act as foreign particle or molecule attached chemically or temporarily as a background of other materials for identification of specific analytes by changing its intrinsic characteristics. As recorded in literature three prominent label relied methods as Chemiluminescence[2, 3] Fluorescence[4-6] and as per[7, 8] is radioactive. In case of isotopic tagging, light and heavy elements are attached to specific analytes for identification of difference .On other hand label free technique utilize the bio physical properties of the analytes such as molecular weight methods are micro-cantilever and mass spectroscopy, for refractive index sensing techniques through surface Plasmon resonance ,localized surface Plasmon resonance[9-11] and dielectric constant along with charge varying threshold voltage results estimation of sensitivity. For point of care biosensor application nanoscale biosensor with low frequency 1- 100kHz ,eliminates the unwanted shielding effect of double electrode layer with low concentration detection of analytes like streptavidin[12]. The main advantage of label free is no requirement of ligads, easy and direct observation relied on characteristics of analytes. Direct along with real time study on interaction and no wastage of preparation of making bonding or attachments. No high cost equipment's for separate preparation and no need of separate technicians unlike in label based techniques. In label free there are two types of biomolecules (analytes) 1) neutral biomolecules (analytes) and 2) charged biomolecules (analytes). The analytes deals with dielectric constant as their properties for detection of molecules called Neutral molecules whereas the analytes properties including charge and dielectric constant for varying the threshold voltage for identification of biomolecules sensitivity termed as charged biomolecules.

1.2 Principle

The various components representing the principle of a biosensor as in Fig. 1. The principle is based on the macromolecules like antigen, cells, antibodies, nucleic acids, enzymes or complex systems such as eukaryotic cells, bacterial cells, plant tissues or slices of mammalian as input and when they interact with the interface between receptor and transducer. After this, the bio component as analytes binds with the receptor to make abound, which results in the output in the measurable form. The transducer sensitive materials are current, voltage, conductance, impedance, optical, fluorescence, colour oriented or surface plasma resonating in order to quantify the concentration of the amino acids, sugar (glucose), lipids, and nucleotide can be identified by biosensors
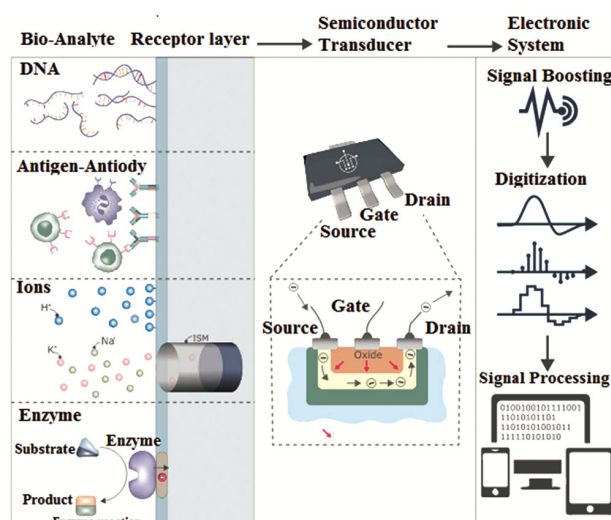

Fig. 1 — Biomolecule Detection using: SEMICONDUCTORFIELD EFFECT TRANSISTOR

The main operation of ISFET is based on solid liquid interface study called double layer model. In this the behavior of ion in solution describes by three different layer, the first layer is called stationary or stern layer which is framed at solid surface[13]. Second layer is termed as diffusion layer, where the diffusion of the ions takes place and change in ion concentration from the interface distance follows as Maxwell-Boltzmann statistics result change in electric potential moving from solid interface towards the solution or liquid interface. *i.e* third layer. The final and third layer is bulk solution layer. At the boundary of diffusion layer and liquid layer, electric potential decreases by e^{-1}. Other parameter as per literature Debye length defined as longest distance between the boundary of diffusion-liquid and sold interface, where the analytes concentration changes may affect the surface (solid interface) characteristics. These three layers are model in its equivalent capacitance as shown in Fig. 2, first and second layer *i.e* stationary layer and diffusion layer is modeled as serial capacitors $Chelm$ and $Cdhelm$ where both terms come from electric double layer (EDL) Helmholtz model. $Chelm$ is fixed interface charge at stern layer and is diffusion capacitance (Cd). Two different theories are present for capacitive equivalent circuit. The first theory is based on tunable diffusion capacitive (Cd) model, in which diffusion capacitance is tuned by redistribution of the ions in diffusion layer.

Potential change is estimated at the sensing surface with the help of charge present at sensing surface represent as ψ. On both sides there is presence of

Fig. 2 — Equivalent model of capacitor of semiconductor FET biosensor[13]

capacitance as CDL double layer (due to electrolyte – diffusion layer and diffusion-stern layer) represented as $Chelm$ and $Cdelm$ respectively and sensor $CFET$ (gate oxide Cox and depletion capacitance CS). Thus surface potential given as:

$$\Delta\psi = \frac{\Delta\zeta}{CDL} + CFET \qquad \ldots (1)$$

For estimating the surface potential, in case of weak inversion depletion capacitance (Cs) is smaller thus included in the above expression. But in case of strong inversion Cs is neglected due to small value, potential strongly influenced by double layer capacitance CDL and Cox is taken[14]. The second theory based on voltage source model, in which (Cd) diffusion capacitance is fixed and electric potential applied on Cd is varying. Be contingent on analytes charge the source voltage is defined as positive or negative. Thus the sensitivity is estimated with analytical model and derivation reported in literature[15]. The model explained three phase operation as (i) interface charge changes with change in the concentration of the analytes a (ii) due to this change in charge at interface results the change in $\left(V_{geff}\right)$ effective gate voltage (iii) drain current change is recorded corresponding to variation in effective gate voltage. Thus overall sensitivity is summed up in this equation $Overall sensitivity$

$$\left(\frac{\partial I}{I}\right) = \underbrace{\left(\partial c.\frac{\partial \sigma}{\partial c}\right)}_{First stage} . \underbrace{\left(\frac{\partial V_{geff}}{\partial \sigma}\right)}_{Second stage} . \underbrace{\left(\frac{\partial I/\partial V_{geff}}{I_0}\right)}_{T\ irdstage} \qquad \ldots (2)$$

1.3 6 Limitation of Semiconductor FET

There are numerous drawbacks associated with Ion sensitive field effect transistor (ISFET) based biosensors. Foremost is electric potential influenced by the ion concentration of the analytes in solution[16]. Secondly as analytes have different layers (bulk solution, diffusion layer and stern layer) with different ion concentration thus may affects the electrical signal[17]. Third problem is maintain and controlling the samples like urine, saliva, blood serum as real human samples is challenging[18]. Fourth ,mostly the modulation in conductance due to high level of ions in buffer solution or electrolyte is partially screened as screening depends upon the Debye screening length shown in Fig. 2 and respective equation .Fifth there is always need to enhance the counter ions with different measures[19] increase the sensor cost and

passivation's layers[20] in different structures recorded that passivation's results additional serial capacitance and affects the overall sensitivity. Sixth controlling the post annealing to avoid hysteresis affects, drift, mobility reduction is challenging. Various compensation methods are included to improve drift as correction algorithms, front end hardware[21] reference probe potential switching[22] Thus there is requirement of the sensors that work under Debye screening free under dry environment over solution or electrolyte based biosensors.

2   Metal Oxide Semiconductor Si Based Junction Less Biosensor

Due to adverse limitations in ISFET explore in above section, it is required to investigate the simultaneous solution for label free detection under dry environment. This investigation also gives birth to scaling of the device design parameters which introduced the Short channel effects (SCE). These effects deteriorate the device performance .To immune the SCE, junction less MOSFET demonstrated by J.P Colinge[23] over the junctioned MOSFET. Junctioned MOSFETS have problems associated at two junctions framed due to different concentration at Source/Drain and channel[24, 25], thus limits the further scaling of the transistor. Junction less structure means no doping concentration gradient *i.e* uniform doping are Single gate junction less (SG JL)[26, 27] double gate junction less (DG JL)[28], nanowire junction less[29, 30], GAA-JL[31] and TFET[32] which are working on to enhance the device operation in nanoscale region. The advantages of junction less over junctioned are less fabrication cost because of uniform doping, scaling approach beyond 22nm[33] improvement in I_{on}/I_{off} ratio,DIBL,Subthreshold voltages[34, 35] *etc.* termed as characteristic parameter for operation of MOSFET explore in later section. Thus JL-MOSFET have more advantages over conventional or junctioned MOSFET, due to which following section focus on exploring the various structures with comparison of the design parameters and improvements in their results in biosensor application for label free detection of molecules. For designing the cavity regions in MOSFETs by etching the insulator layer under the gate material ,split the gate[36], where the molecules are injected and after immobilization between the oxide and analytes, variation in the dielectric constant change the capacitance which results change in threshold voltage and respective drain currents to determine the

sensitivity of the biosensor. The Junction-less Dielectric modulated biosensors is capable of detecting the neutral and compatible with standard CMOS process.

2.1 Observation parameters for Junctionless biosensor

2.1.1. Potential:

a) Surface potential: is define as a f (r, z) ,for cylindrical MOSFET, where r is radius and z is direction along the channel as in Fig. 3. For estimation of surface potential, radius is equal to R, and further electric field is calculated as per boundary conditions and device dimensions along with suitable 1-D or 2-D model. By equating the derivation of the surface potential equal to 0, to find the position of minimum surface potential is expressed as.

$$\frac{\partial(\phi s)}{\partial z} = 0 \qquad \qquad \cdots (3)$$

The surface potential of the device in case of biosensor varies with flat band voltage (ΔVfb), in which by applying charged analytes influence the band bending depends upon qN_f /C, dielectric constant of the analytes and charge of the analytes. The small value of C varies large flat band voltage and current because of fixed charge carriers at interface results increase in sensitivity[37].

b) Centre potential: According to Fig. 3 centre potential define as the f(z) , as r=0, thus centre potential is estimated when radius is zero and electric field at centre is zero due to equal and opposite of the electric lines inside the cylinder. As per literature centre potential estimation is reliable method to calculate the sensitivity of biosensor in case of cylindrical devices[38].

2.1.2. Electric Field:

Electric field varies along the channel and this indicates the immunity towards the short channel effect of the device. This is calculated by
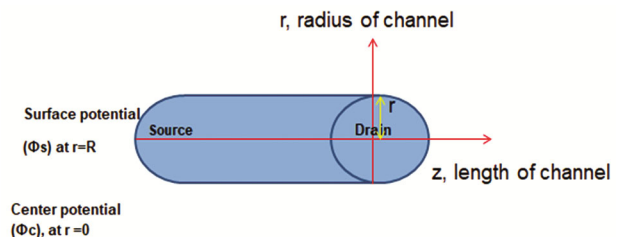

Fig. 3 — Schematic of Cylindrical MOSFET, representing surface and centre potential

differentiating the surface potential for various regions. In case of biosensors[39] literature reflects variation in the magnitude of electric field along with channel with and without biomolecules in cavity. In case of neutral analytes magnitude peak is high in absence of analytes ($K = 1$) as compare to presence of analytes $K > 1$.Similarly for positive charged molecules high magnitude peak that negative due to presence of trap charges increase the Q, thus increase the capacitance thus electric field increases.

Electric field is a significant design parameter that dictates the immunity of the device towards SCEs. The electric-field distribution is considered as a crucial parameter to understand the severity of Drain Induced Barrier Lowering ($DIBL$) effect. The field along the channel length can be determined for the various regions by differentiating the surface potential. The effect of electric field on DG MOSFET as biosensor is shown later in Figure.

$$\frac{\partial \emptyset(r,z)}{\partial r}\bigg|_{r=R} = \frac{C_f}{\in_{si}}[V_{GS} - \emptyset_s(z) - V_{FB}] \qquad \dots (4)$$

2.1.3. Fill in Factor:

This can be observed if the cavity is divided into further smaller section and analysed the sensitivity variation according to the position of the molecule and concentration of the analytes along with dielectric constant in the nanogapcavity. Location of the molecule close to centre of the channel, with higher dielectric constant and large cavity width accept large amount of concentration results increase in sensitivity[40]. This parameter is important for consideration because in real life applications in case of biosensor the position of analytes in cavity may vary the results of detection.

2.1.4 Threshold voltage(V_{TH}):

Is termed as minimum voltage required making device turn on, applied between gate and source (V_{GS}).In case of biosensor the total capacitance increases by factor Kas $C = KC_o$,where $C_o = \varepsilon_o * A/d$with insertion of dielectricmaterial with dielectric constant K and respectively electric field increases due to ($V/K = E.d$) reduction in potential by K. Thus increasing coupling between gate and channel, result decrease in centre channel potential, this indicates the requirement of more threshold voltage to deplete the channel. Change in threshold voltage from ($K = 1\,toK > 1$),the increase the sensitivity of biosensor. Threshold voltage can be modulated by varying various electrical parameters such as gate dielectric constant (K), work function of gate, doping concentration and its device dimensions like length of the channel, cavity width and cavity length. This is estimated from graph between drain current and gate voltage(V_{GS}).at drain current (I_d)value is($Width/Length$) $* ⟦10⟧^{(-7)}$A, that is constant current method. Where$W$ is width and L is length of channel[41]

2.1.5 Drain Current(I_d)

Drain current varies with applied gate voltage at constant V_{DS}. When analytes (charged or neutral) enters into cavity region, immobilization alters threshold voltage corresponding change in dielectric constant of analytes and consequently change in drain current .Drain current measures in term of On current (I_{on})and Off current (I_{off}).In literature the biomolecules used like streptavidin, biotin, APTES, protein, enzymes, cell and DNA ,device shows sufficient change in Off current (Ioff) ,but almost no change in On current (Ion).The reason behind less off current is with increase in dielectric constant in nanogap cavity ,strong control of the gate over the channel ,which makes the device off.

2.1.6 Ion/Ioff ratio:

The sensitivity of a biosensor is measured in terms of On/Off current ratio. When the gate voltage is applied greater the threshold voltage corresponding drain current flows or on current flows, the logarithmic of the drain current ($logId$) when $V_{GS} < V_{TH}$corresponding current flows called off current or leakage current (I_{off}) then log of Ioff current at constantV_{DS}. Ratio should be high for ideal device i:e(I_{on})should be high and (I_{off}) should be low.As per literature the reason for small leakage or off current due to reduction in the tunneling width at the channel and drain interface due to high dielectric constants in the cavity.

2.1.7 Sensitivity:

This represents as figure of merit for sensors. There are two parameters helps to measure the sensitivity by means of change in threshold voltage and the ratio of On/Off current .In former method the alteration in threshold voltage with respect to immobilization of neutral biomolecules in cavity region (by varying the dielectric constant) ($K = 1$) as absence of analytes (treated as air) and any other analytes having

dielectric constant $K > 1$. The sensing metric parameter for neutral analytes is represented mathematical as:

$$S_{NBIO} = \frac{V_{TH(K=1)} - V_{TH(K<1)}}{V_{TH(K=1)}} \qquad \dots (5)$$

The change in threshold voltage with respect to immobilization of the neutral analytes and charged analytes in cavity region .The sensing parameter for charged molecules is represented mathematical as:

$$S_{CBIO} = \frac{V_{TH(NBIO)} - V_{TH(CBIO)}}{V_{TH(NBIO)}} \qquad \dots (6)$$

Where, S_{NBIO} and S_{CBIO} are sensitivity for neutral molecules and charged molecules respectively.

Whereas in On/ Off ratio of current for negative charged biomolecules the depletion near to channel and drain widen due to increase in repulsion of charge carriers from the surface ,thus increase the series resistance which makes the declination of the Off current in turn enhanced the (Ion/Ioff) ration for negative charge deposit in nanocavity. Further structures play a vital role for improving sensitivity. The Structure has more surfaces to volume like in cylindrical makes the strong bond of capacitance around the device negotiates the short channel effects.

2.1.8 Temperature Sensitivity (S_T):

This parameter is indicates the relation of sensitivity with temperature. As the leakage current increases with increase in temperature the sensitivity reduces the main reason behind is the trap charges . These trap charges increase the tunneling between the gate and the drain ,as influence the temperature, thus sensitivity is represented as temperature sensitivity, which is estimated from (I_{off}) off current slope and temperature (T), expressed as:

$$S_T = \left[\frac{\partial \log (I_{off})}{\partial T(K)}\right]^{-1} K/Dec \qquad \dots (7)$$

2.1.9 Sub threshold Slope and Swing (SS):

Sub threshold slope (SS) is used to define the turn on characteristics of device. This is expressed as decades/mV. Sub threshold slope is inversely proportion to the sub threshold swing. Sub threshold swing is expressed as mV/decade. This value should be small which indicates better channel control; further improved $Ion/Ioff$ ratio means short leakage current, less energy.Recorded SS value is 60mV/decade at room temperature.

$$D_{it} = \frac{SS \times C_i \log (e)}{q \times K_B T} \qquad \dots (8)$$

Where C_i denotes the capacitance per unit area, k_B is the Boltzmann's constant, T is the absolute temperature, and q is the electron charge.

2.1.10 Drain Induced Barrier Lowering($DIBL$):

In long channel FET based transistor there is sufficient gap between the gate and drain which makes electrostatically shield between them which makes threshold voltage independent of drain voltage but in short channel the gap reduces and drain conduction starts even when gate voltage is less than minimum voltage required to make transistor on *i.e* threshold voltage. If the gate voltage is lower than the threshold voltage, and after applying drain voltage, potential barriers of the channel declined and current flows from source to drain, this termed as drain induced barrier lowering($DIBL$).The threshold can be measured at two different voltage levels of drain (at 0.1V and 1V) .This signify the $V_{TH(V_{DS}=0.1V)}$ is lower than $V_{TH(V_{DS}=1V)}$ and take mod to express positive. The units are mV/V. This is expressed as

$$DIBL = \left[|\frac{V_{TH(V_{DS}=0.1V)} - V_{TH(V_{DS}=1V)}}{V_{DS(=1V)} - V_{DS(=0.1V)}}|\right] \qquad \dots (9)$$

2.2 Double Gate-Si based junction less biosensor:

There are various limitations arise with scaling like surface scattering, hot carrier, drain induced barrier lowering, velocity saturation, high electric field, impact ionization and heat dissipation recorded in Single gate Si based MOSFET[42]. Thus to improve this drive current capability, reduce the SCE effects mentioned above new structure Multi gate junction less i:e introduction of dual gate at bottom of the single gate structure is with bottom oxide. Further the fringing field effects are reduced and offer high gate control in contrast to SG MOSFET. In following section various structures of semiconductor is based biosensor are explored with their device properties, channel engineering in the form of doping along with formation of cavity for immobilization of analytes. Asymmetric mode (20% to 100% fill-in factor) junction less transistor is used for biomolecules recognition depicts in Fig. 4(a). The main parameters as per shown in Table 1 along with front gate and back gate varying voltages as in symmetric ($Vgf = Vgb$) and $Vgf = -1V$.In asymmetric mode ($Vgb = -0.2\ V$) with $Vgf = -3V$ .The sensitivity
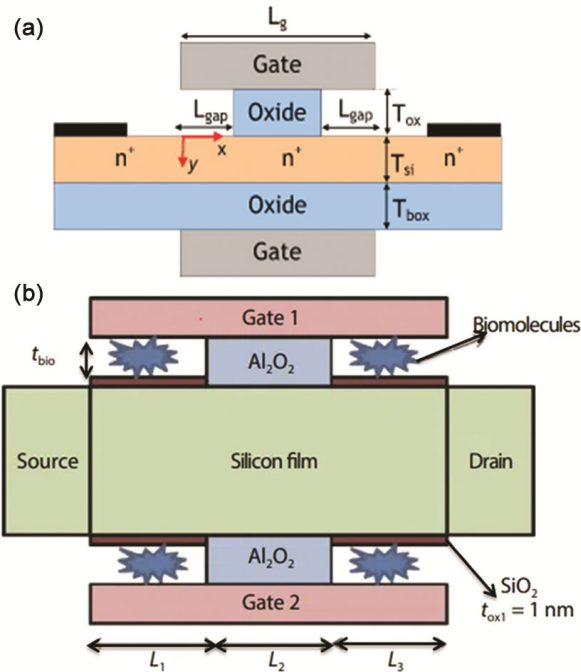
Fig. 4 — (a)Asymmetric cavity Dual Metal Junctionless (DMJL)structure for bio-sensing[43] (b)Schematic structure of n -type Junctionless[61]

improved by $\sim 10^8$ in asymmetric mode for various biomolecules whereas in symmetric mode of operation the sensitivity increase linearly from $\sim 10^4$ to $\sim 10^7$ for different dielectric constant molecules[43]. The further scope of improvement, analysis on fill in factor for long cavities with the charge density consideration for various molecules may results high sensitivity.

Structure shows in Fig. 4(b) that varying dielectric constant insulators are used for forming cavity. Underneath cavities are formed in DM-DG JL for sensing biomolecules ,both n-type and p-type structures are framed for experiments and the surface potential analytical model developed by using 2-D poison's equations and in channel considering parabolic potential profile. Threshold voltages model and respective drain currents shows the sensing parameter of biosensor. Both types of neutral and charges biomolecules are used .As for positively charged molecules , threshold voltage alters for p-type is 103mV whereas n-type molecules reflects weak sensitivity .In contrast for negative molecules for n-type depicts large alteration in threshold voltage about 109mV,comparison with p-type.

Table 1 — Parameters detail of dielectric modulated double gate Biosensor

S. No.	Parameter	[43]	[58]	[48]	[49]	[35]
1	Channel Length	50nm	300 nm	50nm	225nm	100 nm
2	Channel Doping	$5*10^{18}$ cm^{-3}	$1*10^{15}$ cm^{-3}-$1*10^{18}$ cm^{-3}	Nd=$1*10^{24}$m^{-3} and Tsi of channel is 20 nm)	$1*10^{25}$ cm^{-3}	$5*10^{19}$cm^{-3} S/D is 10^{15} cm^{-3}
3	insulator thickness (t$_{ox}$)	10nm	10nm	8.5nm (split form i:e insulator + cavity)	10nm	Cavity thickness is 10-25nm + oxide is 2nm
4	Work function of Gate	-	-	-		P+ 5.25 eV n+ 4.17 eV
5	Fixed trap charges N$_f$	-10^{10}C cm^{-2}	-$5*10^{15}$ m^{-2}	$1*10^{17}$m^{-2} (for positive charge) $-5*10^{17}$m^{-2} for negatively charged biomolecules	1nm	-10x10^{16} to +10x10^{16} C/m^2
6	Nanogap Length	20 nm	20 nm	25nm	175nm	10nm - 25 nm
7	Operating V$_{DS}$ (V)	1.2 V	1V	0.05 V, 0.1 V ,0.5 V and 1V		
8	Biomolecules	Neutral only (Biotin, streptavidin and 3-aminoppropyltriethoxysilane (APTES))	Both(Neutral and charged)	Both(Neutral and charged)		
9	Insulator over the channel with dielectric constant	S$_{io2}$		S$_{io2}$		
10	Reported sensitivity		88mV @ -$5*10^{15}$ m^{-2}			High
11	Remarks		Asymmetric structure and biasing mode			Junctioned with electric field model

In this literature Fig. 5(a), Ajay[43],structure has N-type under lap cavity DM-DG-JL-MOSFET for detection of label free biomolecules .The threshold voltage alters due to immobilization of biomolecules with insulator as SiO_2 represents as the sensing metric for biosensor. The results shows that for n-type the positive charged molecules with charge density 10×10^{15} m^{-2}, enter in cavity region increased the sensitivity factor $S_{(BIO)}$ with 100mVwhereas for negative charge biomolecules having charge density -10×10^{15} m^{-2} improve the bio sensitivity with factor of 340mV.Results also depicts that bio sensitivity factor for neutral biomolecules having dielectric constant 5 reflects low as compare with positive and negative charged biomolecules An important observation that in case of neutral molecules sensitivity is high for high doping , whereas low doping is required for high sensitivity in case of charged molecules detection[44-47]. Secondly for same drain potential when cavity is source side depicts high sensitivity as compare to drain side cavity. To enhance the sensitivity for negatively charged biomolecules, this is suggested that drain bias is increased in order if the cavity is used towards drain side Ajay[48] a symmetric split gate dielectric modulated junction less structure is represents in Fig. 5(b) as per reported literature for biosensor, similarly an analytical model is investigated with 2-D poison's equations and in channel considering parabolic potential profile.

The biomolecules used for identification are neutral like protein, enzyme, DNA, cell, streptavidin, *etc.* Split gate is used as cavity region for immobilization of the neutral and charged species .Important fact observed called neutralization of charged molecules, charge reduces when drying from 20 % to 60% from its initial charge of -5×10^{15}m^{-2}and subsequent change in threshold voltage is from 50mVto143mV is recorded. Surface potential variation is for negatively charge $(-5 \times 10^{15}$m$^{-2})$ is 120mVwhereasfor positive charge $(5 \times 10^{15}$m$^{-2})$ reduces to 23mVall above neutral biomolecule as streptavidin having dielectric constant 2.21 shows higher change in surface potential as compare to negative charged biomolecules as shown in Fig. 6. The effect of fill in factor along with the varying position in the cavity region is represented by Parihar and the observation is recorded here as the sensitivity of the dual gate FET biosensor depends
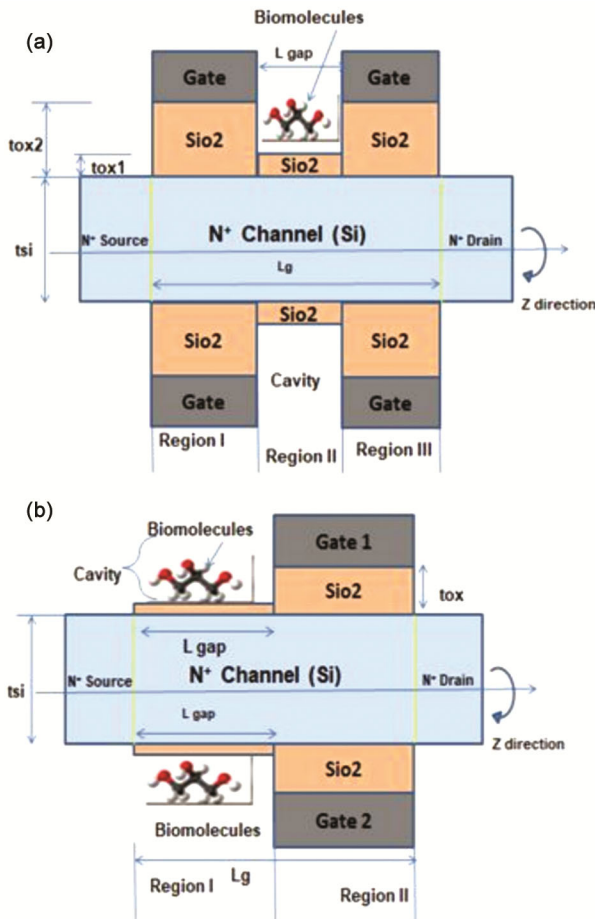

Fig. 5 — a) Different Structure of gate underlap region of JL DG MOSFET Biosensor[58] (b) Schematic structure of n-type split gate JL MOSFET[49].
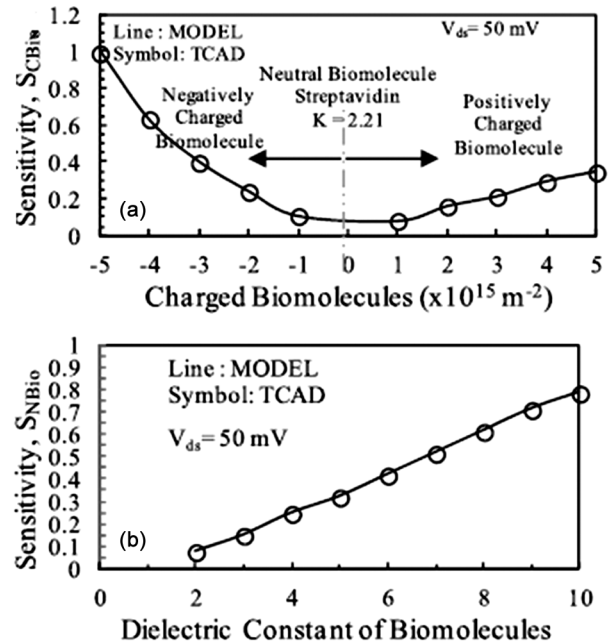

Fig. 6 — Sensitivity with Biomolecules (a) Sensitivity Vs charged biomolecules (b) Sensitivity Vs Neutral biomolecules[48]

upon the size of the fill in factor of a analytes ,as larger in size ,enhanced the sensitivity. Secondly the position of the analytes in the cavity influence the sensitivity, analytes near to the centre, higher the sensitivity and thirdly value of dielectric constants of the analytes has high impact on sensitivity.

There is also literature report by [49] with the length of channel as 225 nm indicate that split gate dielectric modulated JL-transistor for the detection of both neutral and charged biomolecules .The open area between the gates and having High dielectric Hf0$_2$ under gates, the open areas act as cavity, which exist only on one side of gate .The interaction of the biomolecules in this open area effects surface potential, which obtained by using the 2-D Poisson's equation through conformal mapping technique. Thus threshold voltage is varied with the binding of the biomolecules in the underlap gate cavity region.

In Fig. 7 Symmetric structure for embedded nano cavity with dual gate material having different work function for p+ and n+ gates is recorded. Total channel length is 100nm and divided into four regions each of 25nm as shown in Fig. 7. Nano cavity region is used for sensing and it is dual form thus intermolecular interaction is used .Basically electric field study is dominant in this paper to understand the influence of the *DIBL* .Resultant electric field in channel is calculated by differentiating potential in different regions of channel. Dual material with dual gate MOSFET biosensor shows high sensitivity with respect to large length and large thickness of the cavity.

New technique for fabrication of the dual gate FET SiNW is reported ,in which instead of top-down approach or bottom to top approach for fabrication of DG-SiNW FET arrays as conducting channel by (NIL) nano imprint lithography. This fabrication depicts good compatibility with electrical characteristics such as capacitive coupling ratio of 18.0 and under high

temperature stress lower leakage current in Subthres hold region. The sensitivity of SGFET is 56.7mV/pH and DGFET is having 439.3 mV/pH and Dual Gate FET SiNW is 984.1 mV/pH, along with low shift rate of 0.8 percent for pH sensitivity[50].

2.3 Gate All Around (GAA) Si based Junctionless Biosensor:

The surrounding gate MOSFET is rotating structure of single gate with beneath oxide layer over channel. This is different than quadruple gate MOSFETs as with all improved characteristic over dual gate but with limitation of corner effect due to low electrostatic control of gate over channel which is eliminated in cylindrical gate MOSFETs[51]. Also surrounding gate structure helps in further device scaling in contract to dual gate without affecting the device performance. The number of advantages are increasing the integrity *i.e* gate control over channel, thus reduce the leakage currents as gate is covered from all sides. The channel length is reduced as per ITRS by 2023 to 5nm is achievable with cylindrical structure without compromising the silicon body thickness (tsi) and oxide thickness (tox),which increase the packing density of the device on chip and further reduce the cost per chip[52]. The electric field effect either vertical or horizontal both are less as compare to dual gate thus reduce the surface scattering results due to increase in gate voltage, hot carrier effects is reduced caused by increasing gate voltage thus control the impact ionization which results the accumulation of the charges near to substrate results malfunction of the component and reduction in gate current leakage. Cylindrical structure enhances the carrier transport and I_{on}/I_{off} ratio. For increasing sensitivity of sensors more surfaces to volume is required, which is possible with cylindrical structure. The strong bond of capacitance around the device negotiates the short channel effects.
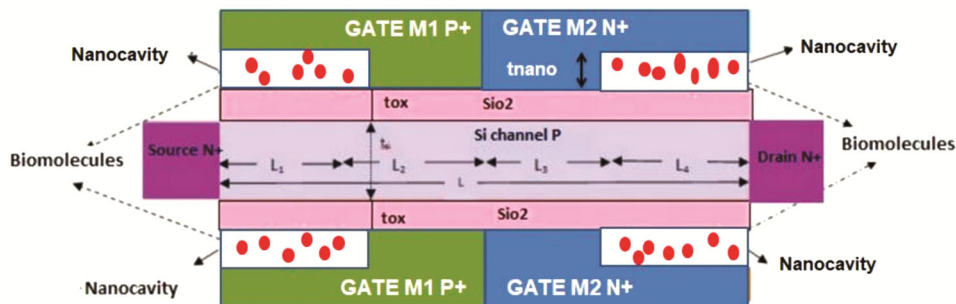

Fig. 7 — Symmetric Dielectric Modulated Dual Gate MOSFET cross-sectional view for biosensor[35]

Control of uniform doping or junction less, a high work function difference between channels and metal gate is used to remove the charge carriers present in the channel[53]. In flat band conditions the complete channel is neutral, thus current flows in bulk instead of surface thus junction less transistor has superior immunity over SCE than inversion mode transistors. To minimize the short channel effects, numerous structure design are invited starting from single gate to four gates or cylindrical design which increases the integrity the gate over the channel. Further to reduce the fabrication cost in terms of minimum steps required and control the thermal budget[54, 55] by shifting the designs from junctioned to junction less means avoid any abrupt source-drain junction formation. The parametersfor various cylindrical structures as per literatureare summarized in Table 2.

The design parameters are channel length is 100nm, length of cavity on both size is 25nm each, radius of silicon is 10nm, cavity thickness is 9nm, S/D doping donor concentration $1\times10^{26}m^{-3}$ and body acceptor doping is $1\times10^{21}m^{-3}$.All the advantages are justified as per results to enhance the sensitivity with increase in silicon radius, with vacuum dielectric operating in sub threshold region depicts high sensitivity towards identification of charged and neutral biomolecules. Charge analytes change in band

Table 2 — Size of biomolecules for electrical detection[62]

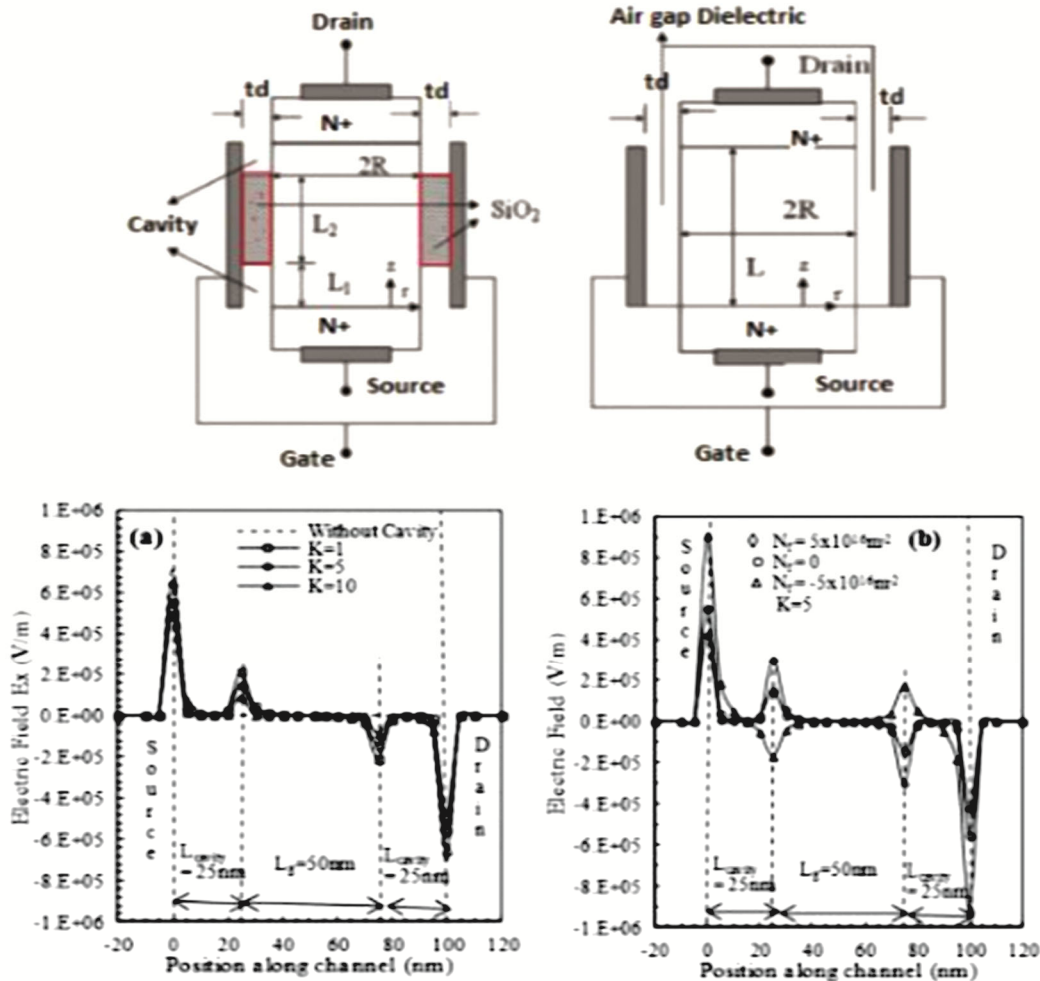| S.no	Range in mm,μm and nm	Analytes
1	10^{-3} to $10^{-5.9}$	1mm-1 μm RBC, and Bacteria
2	10^{-6} to $10^{-8.9}$	10nm to 100nm Virus
		10nm Proteins
3	10^{-9} and above	1nm DNA

Fig. 8 (i) — Structure of Gate All Around MOSFET (a) with nanogap cavities at source and drain sides and (b) with air gap or vacuum dielectric[56], (ii) Magnitude of Electric Field with respect to channel length.(a) For Neutral biomolecules (b) For charged biomolecules. For T_{si} = 20nm, V_{GS}= 0V and V_{DS} = 0V[42]

bending reflects Fermi level ending is equal to N_f/Cd, N_f is interface trap charges. For huge radius and Cd is small thus due to N_f, larger change in flatband voltage and current which increase the sensitivity. The cavity thickness and length depends upon size of analytes, filling position and immobilization kinetics between insulator and the analytes of different K This design is a promising structure for ultra-sensitive, low power, prone to damage and stable biosensor[56]. Figure 8(ii) represents the variation of the electric filed with respect to neutral and charged biomolecules. When cavity is empty, $(K = 1)$ then highest peaks magnitude of electric field are shown in Fig. 8(ii).a with dotted lines and after entering neutral biomolecules$(K > 1)$, magnitude of electric field peak reduces .In contrast Fig. 8 (ii).b depicts that charged analytes increase and decrease the magnitudes of peaks ,positive analytes increase the magnitude in comparison with negative molecules. Positive molecules shows superior effect on magnitude of electric filed as compare to neutral analytes with $K = 5$.

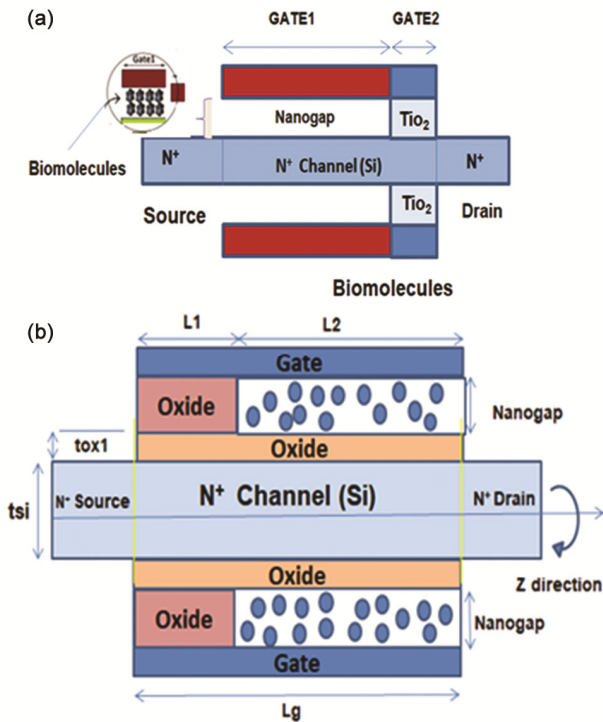New structure in Fig. 9(i) proposed by Ahangari[57] design for enhanced sensitivity and low power is SiNW MOSFET, Dielectric Modulated Dual Material Gate (DM-DMG) nanowire junction less MOSFET. The basic design depends upon the adjusting the work function of different material gates between the cavity area and the rest region of the channel. Results shows the optimized value of work function is $0.5eV$ along with doping concentration of $3 - 5 * (10^{18} cm^{-3})$ to obtain maximum sensitivity to avoid the contradiction of leakage current (off state current) and sensitivity. As this is common phenomenon that change in capacitance alters the threshold voltage due to accumulation of analytes in cavity. Thus there is inverse relationship between the permittivity of the molecules and the threshold voltage, which in turn indicates the sensitivity enhancement with respect to change in threshold voltage.

$$\Delta V_{TH} \alpha \frac{1}{K_{BIO}}$$

1.   In Fig. 10 Dielectric modulated stack based JL GAA MOSFET design for biosensor .The parameters defined as length of channel as 50nm, cavity length is 20nm on both side and cavity width is 10nm with Si thickness is 20nm and concentration is $3 * (10^{18} cm^{-3})$ the design is for both neutral and charged biomolecules detection. Ahangari[58, 59] is $150mV$ for dielectric constant of the analytes is $K = 10$.By using V_{DS} 1V the sensitivity obtained is 192mV[60] which is high in comparison to published reports as design is dual material JL MOSFET having cavity dimensions as 35nm length and width is 10nm . Similarly Narang[61] reported the sensitivity of $-90mV$ with DG-JL MOSFET having dimensions as $25nm * 10nm$ for dielectric constant is $K = 10$.On the other hand same results are recorded by[62] for label free

Fig. 9(a) — Cross section view of 3D Structure of DM gate SiNW MOSFET[57] (b) cross-sectional view of 3D Structure of GAA-JNT with nanogap cavity[62]
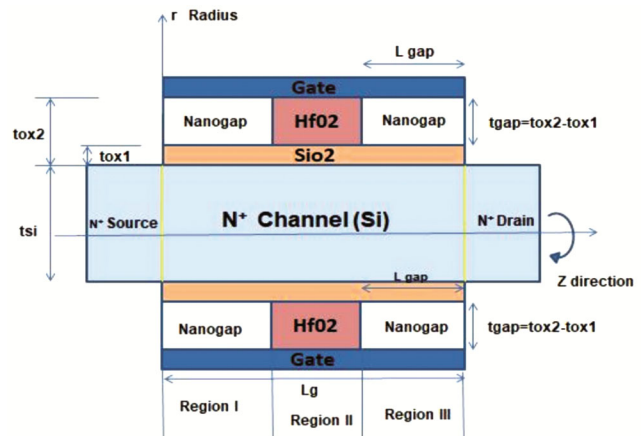

Fig. 10 — 2D Structure of JL Gate Stack Surrounding Gate MOSFET biosensor[60]

detection of both neutral and charged biomolecules by using structure shown in Fig. 9(ii), change in capacitance due to immobilization of the various biomolecules in the cavity region by variation dielectric constant thus shift in threshold voltage and current. Thus new parameter for sensitivity is termed as $S_{I_{OFF}}$ based on off current, defined as:

$$S_{I_{OFF}} = \left| \frac{I_{OFF_{Withbiomolecules}}}{I_{OFF_{Withoutbiomolecules}}} \right|_{V_{GS}=0V} \qquad \dots (10)$$

Sensitivity influenced with cavity dimensions as recorded in literature. The size of the biomolecules for detection decides the thickness of cavity region, thus following Table 3 is summarized the range from mm to nm as per analytes.

2.4. III-V Compound Semiconductor Based Sensor

In past few years scaling is challenged in conventional MOSFETs due to increase in leakage currents, high power consumption because of supply voltage is saturated when scaled at around 0.8 or 0.9 V[63-65].Thus new technologies, strategies are framed in the form of structure innovations, material *i.e* gate engineering or channel engineering[66-68] without the loss of operation .One section is channel engineering in which symmetric ,asymmetric doping along with junctioned and junction less above all working on different materials as compounds to

achieve high current, SS in less than 60 $mV/decade$ at room temperature.There is demand of low power consumption in electronic gadgets results the usage of less supply voltage, along with compact architecture, channel engineering with new materials ,doping profile *etc.* without compromising the device operation. The key figure of merit in electronic devices; Sub threshold swing (*SS*), at best, has a value of 60 $mV/decade$ at normal temperature[69, 70]. On current is calculated from injection velocity and interfacial density of state[71, 72], thus in this regard III-V compounds as shown in table 4 having high injection velocity and adequate electron density of sates. In GaAs is having more than double injection velocity as compare than Si based FETs.

3 Challenges:

i. The heart of the MOSFET is the stacking. Stacking is combination of the high K dielectric along with metal gate build on top the channel to modulate the surface potential of the channel[73, 74]. But with III-V compound channel creates interface trap charges, impurities at the interface or interface imperfections also results in stability, to avoid this high dielectric stacks required and with appropriate thickness. As similar bonds and Ga-As drooping bonds, bestow to the interface defects asstate density, that degrades device operation[75]. An interface density state occur at the interface of semiconductor-dielectric

Table 3 — Parameters detail of dielectric modulated Cylindrical Biosensor

S. No.	Parameter	[58]	[59]	[60]	[42]
1.	Channel Length	100 nm	40nm	50nm	40nm
2.	Channel Doping	Source/drain (N_D)=1* 10^{26} m^{-3} and channel (N_A) =1* 10^{21} m^{-3}	1* 10^{18} cm^{-3}	1* 10^{18} cm^{-3}-1* 10^{20} cm^{-3}	5* 10^{18} cm^{-3}
3.	Silicon thickness(t_{si})	9 nm Channel radius =5nm	-	20nm	10nm
4.	Work function of Gate		4-5eV	5.5eV	Gate1 (4,4.25,4.5,4.75 and 5eV) and gate 2(5eV) difference is 0.5eV
5.	SiO$_2$ thickness Over detecting region(t_{ox})	Nf1=−6×10cm^{-2},Nf2=−1×10^{11}cm^{-2},andNf3=−1×10^{10}cm^{-2}		1nm	-1*10^{12}C cm^{-2}
6.	Nanogap Length	20 nm Both side	5nm-35nm	L$_{gap}$	5 nm to 35 nm (from gate 1) channel length from gate 2 varies from (35 nm to 5 nm)
7	Operating V$_{DS}$	0V to .05V		1V-1.5V	50mV or (0.5V)
8.	Biomolecules	Both(Neutral and charged)		Both(Neutral and charged)	Both(Neutral and charged)
9	insulator over the channel with dielectric constant	S$_{io2}$ and vacuum			50(T$_{iO2}$)
10	Reported sensitivity			172mV	

Table 4 — Physical properties of compound semiconductors

Physical properties	Si	Ge	InSb	InAs	InP	InN	In$_{.53}$Ga$_{.47}$As	GaAs	GaSb	GaN
Energy Band(eV)	1.11	0.67	0.18	0.36	1.35	0.7 to 1.97	0.75	1.42	.70	3.39
Energy gap	Indirect	indirect	direct	direct	direct			direct		direct
Electron Mobility (Cm^2/Vs)	1350	3900	8*10^4	3*10^4	5400	<3200	7800		5000	1500
Hole mobility(Cm^2/Vs)	480	1900	850	500	200	<80	300	400	1000	
Electron saturation velocity (*10^{7}cm/s)			4.0	4.0	1.0		0.8	1.0	-	2.7
Electron mean free path length/nm	28		226	194	-		106	80	-	-
Effective mass g/mol					145.792	128.83	.041			82.929 g/mol
Thermal conductivity W/cmK	1.3	0.58	0.15	0.27	0.7	0.45		0.5	0.4	1.3
Dielectric constant			17.9	15.1	12.5			12.8	15.7	9
Applications					Optical, telecom, photovolativ	Solar cells, high speed elctronics	Electronics and photonics			

due to mediocre bonding in both semiconductor and dielectric. Results to degrades the channel mobility, change the threshold voltage, increase the swing and reduction in Ion with respect to Ioff, also cause of instability[74, 76]. Gate Dielectric thickness is appropriately choose effective oxide thickness ($EOT < 1nm$) to get high electrostatic integrity.

ii. Choosing the accurate molar fraction of the compounds egIn$_{.53}$Ga$_{.47}$As[77, 78].Using buried layer of In P, but limits the EOT scalability.

iii. Gate stacks results the coulomb scattering, interface imperfection scattering, phonon scattering[79, 80].

iv. Parasitic resistance: along with the contact resistance there is parasitic resistance between source and drain contacts with gate.

v. Substrate based on III-V compound is expensive and fragile. Other issues are compatibility, manufacturing infrastructure requirement etc[81].

vi. Compounds do not have superior hole mobility.

4 Solutions available in Literature:

Literature post the number of solutions foremost for stacking, investigating the approach from fabrication point of view by using the deposition of the high k like Al$_2$O$_3$, H$_f$O$_3$ with atomic layer deposition (ALD) on In GaAs substrate[82]. Other methods like pre deposition cleaning treatments[83], buried layers or Box to supress interfacial traps as charge leakage[84, 85], changes in deposition chemistry[86, 87] using post deposition therapy[83, 88, 89] are investigated. Thus to reduce parasitic resistance, self-aligned structure are preferred because ohmic contacts are separated with

less distance. Other method is precision etching or in situ doped S/D regions results enhancing the drive current and transconductance or gain. Thus for P-type MOSFETS Ge based substrate is preferred over Si as Ge has high hole mobility>$1000cm^2$/Vs. Other method is using bi-axial strain to improve the hole mobility Moreover the GaAs are highly lattice matched with Ge[90]. There is usage of buffer layer Inp as InGaAs-InP combination provide little mismatch with improvement in current and other potential characteristics.

Recently[91, 92] junction less DG-TFET with narrow band gap material with the pocket area of Si0:7 Ge:0:3, reflects agreeable characteristics as sharp sub threshold, increased band to band tunneling that meets the low power and high speed digital and memory application.

5 Benefits of Semiconductor compound:

i).low power consumption as controlled on leakage current caused by quantum tunnelling. ii) High switching speed because of high mobility and small effective mass. iii) Advance techniques available for fabrication like quantum wires and dots by molecular beam epitaxy (MBE) and molecular vapour(MVPE) epitaxy. Higher reverse breakdown voltage approx.$100V$.III-V compound with cylindrical structure and stack of high –k improves the off state control. For various application like low power analog, chemical and biochemical sensors, smart chips for sensor networks, quantum computers etc. are benefitted by using semiconductor compound as channel.

6 Summary and outlook:

In the nutshell the MOSFET measurements have constantly been downsized offering ascend to short channel impacts (SCEs), truly influence gadget conduct. At nanoscale level, the effect of narrow channel on attributes customary MOSFETs can't overlook. So as to decrease nanoscale effects, various device structures explored in literature, for example, Double Gate (DG) MOSFET, Surrounding-Gate/Gate All Around (SG/GAA) MOSFET and nanowire, this can smother the SCEs and enhance entryway controllability.The label free technique reflects an alternative and supportive method in contrast to label based analytes. The monitoring of the label free analytes (charged or neutral) is more important because of numerous advantages such as analytical quality, less cost, easy procedure to follow, the target analytes need not to alter as in the case of label based where requirement of ligads .Thus direct and real time observation with no wastage of preparation of attachments as in Ion Sensitive Field Effect Transistor (ISFETs). In this review various label free techniques and their types charged and neutral biomolecule based on various structures are concluded. The effect of cavity length and width along with the cavity position on sensitivity is explored. The observational parameters that have influence on sensitivity are collected as per literature. In any case, acknowledgment of ultrasharp doping profile between n-or p-type source/Drain (S/D) district and p-or n-type body locale represents an incredible trouble in the creation of short channel gadgets. Colinge introduced Junction less MOSFET having lower *DIBL*,enhanced on current and more better attributes than ordinary MOSFETs. Semiconductor based Biosensor drawn tremendous attention as a strong candidate for ultra-sensitivity, selectivity, signal to noise ratioand real time analysis along with reduce power dissipation. Review is based on dual gate and cylindrical structure based biosensor with summarizing their electrical and physical parameters in Tables 1 & 4. This article also focus on the scope of the material engineering as III-V compound as channel instead of Si/Ge due to their tremendous advantages as high carrier mobility ,high temperature stability, and ease in fabrication. Certain challenges and their solution as per literature are discussed in this article. In the last as per the growth market of biosensor the applications expands from biomedical and diagnostics to chemical analysis of food and beverages in connection with miniaturization of the biosensor dimensions to the nano-scale results point of care and wearable applications increase the demand of the novel and more efficient methods for designing the biosensors.

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