A Novel GAA Hollow Cavity FinFET based biosensor for Cancer protein marker sensing.

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Abstract*—In this work we have proposed and simulated a novel GAA FinFET with a hollow fin that could be used for sensing proteins and other biological molecules that show high values of dielectric constant (k) compared to free space. This device may also be used to detect biological as well bio-chemical processes that involve structural changes in the biomolecules that may alter its dielectric properties. This can be used in the detection of various cancers cell line proteins that have dielectric constants in the range of 40 to 80 as solutions in water. The principle of the device is based on the variation of the various device parameters associated with the device such as threshold voltage (V_{th}), ON-State Drain current (I_{ds}), Voltage gain (g_m/g_d), switching ratio (I_{on}/I_{off}) and sensitivity in the presence of a protein due to its dielectric properties. The variation of the dielectric constant is done from 1 to 80 in steps of 20. It is seen from the results of the simulation that the device shows a deviation in the threshold voltage (V_{th}) of 0.371 V when k=80. The device also shows an average value of 4 x 10^{-3}V for average V_{th} shift ($\Delta V_{th}/\Delta k$). The ON-State Drain current of the device also increases from 2.85 x 10^{-7}A to 1.6 x 10^{-5}A at k=80. The switching ratio of the device also decreases from 1.95 x 10^{4} at k=1 to 0.71 x 10^{3} at k=80 as the value of k increases. The sensitivity of the device calculated as "$S=I_{on(k>1)}/I_{on(k=1)}$" also increases from 6.3 at k=20 to56 at k=80. The average sensitivity defined as (S/k), increases from 0.315 at k=20 to 0.7 at k=80.

Keywords*— Gate All Around, FinFET, Bio-Sensor, Proteins, Dielectric

I. Introduction

Due to its potential for miniaturization, real-time sensing, rapid response time, and smooth integration with existing electronics production systems, sensing based on field effect transistors (FETs) has gathered attention among various electronic sensing techniques [1]. There are many sensor architectures, active materials, along with various target molecules, that result in a lot of different combinations of device sensors [1].

We intentionally apply a gate voltage in traditional MOSFET to invert the channel ($V_{gs} > V_{th}$) and turn the transistor on. Similarly, in the presence of a biomolecule, other factors such as pH or bio-molecular charge can influence the gate potential. Such factors influence the status of channel carriers and make a positive or negative shift in the characteristics of the system. Then the change in the characteristics appears as a threshold voltage (V_{th}) shift. The difference in threshold voltages (ΔV_{th}) can therefore be determined as a sensitivity measure [2].

Biosensors are defined as an analytical tool for monitoring biological activity and interactions. It transfers the monitoring data to electrical signals. A basic biosensor consists of three major components: bio-recognition system, a transducer and a signal processing module. The pathway of signal transmission begins with different physical quantities that are changed by the biomolecules are detected. These physical changes are then detected by transducers and translated to an observable electrical signal. It amplifies and processes the signals [2]. The data obtained from the sample corresponds either to the target molecule's concentration, activity, presence or quantity of a biomolecule which is translated into an electrical signal through the Bio-sensing device [1].

Proteins are macromolecules many of which are charged. These molecules could be detected by means of surface-charge sensing devices, in view of their intrinsic charge [1]. Protein macromolecules are known to be a low dielectric medium while water is seen as a medium with a uniform dielectric constant of 80 so a dielectric constant of about 80 is ideal for the classification of dielectric properties of proteins in wet systems [3].

Proteins have intramolecular forces, such as Van-der-Waals forces, Hydrogen bonds, Covalent bonds, and Hydrophobic and Hydrophilic interactions, which play an important role in determining the protein's spatial and structural orientation in both dry and wet state. These forces not only stabilize the protein structure, but also contribute to the protein's electric and dielectric properties, performing a vital role in the structure's stability. These give rise to interactions such as polarization of the interfaces, strong dipole-dipole interactions, which are the sharing of electron pairs between atoms (atomic interactions) [4].

In this work, we propose to use a GAA FinFET with its fin modified to include a hollow cavity for the detection of proteins and potentially other biomolecules that show variation in properties such as dielectric constant.

Fig 1

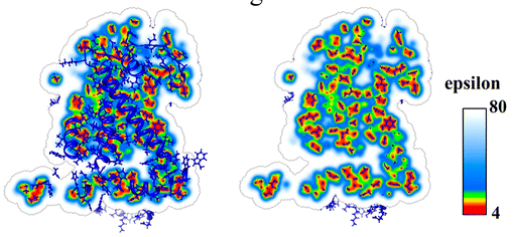


Fig. 1. Variation of the dielectric constant inside a protein within its structure in water. This diagram has been taken from reference [3]

II. Device Structure

The Device structure as shown in Fig 2 with parameters given in Table I was simulated using DEVEDIT 3D Structure and Mesh Editor by SILVACO [6]. The simulated device is a GAA FinFET with a tube like fin that is partially filled with SiO_2 on the drain side.

The tube like structure of the fin allows the target biomolecules that need to be detected to lodge themselves inside the hole on the fin thus allowing them to be detected. This enables the device to act as a Bio-sensor that can be used to selectively detect only those molecules that can fit inside the hole in the fin of the device.

The device simulated here has an 80 nm long fin that is covered on all sides externally by SiO_2 that is 3 nm thick. The gate length was taken as 40 nm and an Aluminium gate with a work function of 4.26 eV was used. The width of the Silicon fin was 20 nm and the height was 45 nm. The dimensions of the hole were 10 nm x 35 nm as shown in Fig 2. The tubular fin was filled with SiO_2 on the drain side to enable the capture and retention of the biomolecules on the Bio-Sensor FET. The fin was doped with a uniform n-type doping of 10^{18} cm^{-3}. The source and drain were doped with n-type doping of 10^{21} cm^{-3}.

The characteristics of the device were simulated using SILVACO ATLAS Device Simulator [7]. The models used in the device simulation were Concentration Dependent SHR Recombination Model, Concentration Dependent Arora Mobility Model and Fermi-Dirac Statistics. [7].

TABLE I

Parameter	*Value*
Channel Length (L_g)	40 *nm*
Fin Height (H_f)	45 *nm*
Fin Width (W_f)	20 *nm*
Thickness Oxide (t_{ox})	3 *nm*
Hole Height	35 *nm*
Hole Width	20 *nm*
Hole Depth	60 *nm*
Source and Drain Length	20 *nm*
Source and Drain Doping Concentration	10^{21} cm^{-3}
Gate Work function	4.26 *eV*

Fig 2

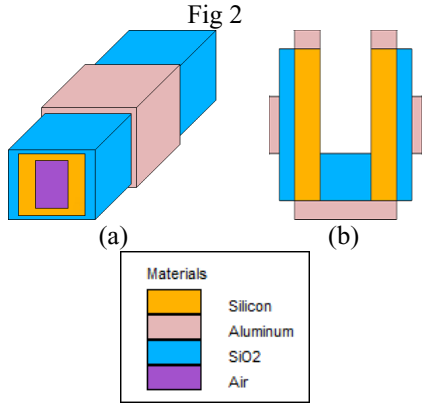


Fig. 2. (a) 3D Structure of the simulated device. **(b)** Lateral cross section of the device.

III. Methodology

The analysis methodology used in this work is the variation of the dielectric constant in the space inside the hollow cavity in the structure and studying the variation of the device parameters. This methodology is used to simulate the presence of biomolecules inside the cavity thus enabling the device's action as a biosensor. This variation is done using SILVACO DEVEDIT 3D Structure and Mesh Editor.

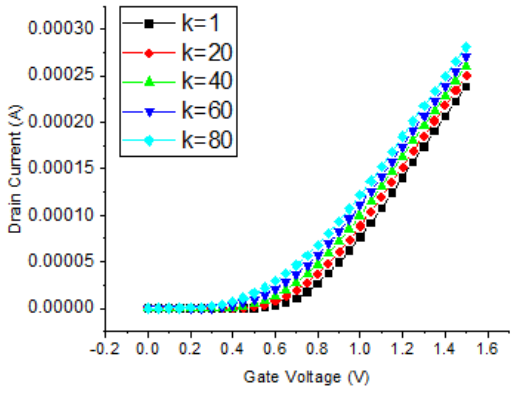
The dielectric constant is varied from 1 to 80 in steps of 20. It is known that the dielectric constant of water is 78.9 [3]. And decreases with the presence of biomolecules in the solution and in the cavity, this is due to decrease in the number of water molecules in the cavity. This in turn causes a change in the effective dielectric constant of the analyte that is detected by the device.

IV. Results and Discussion

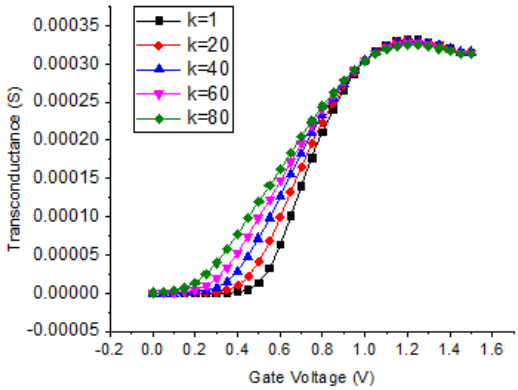
A. Transfer Charectarestics and Threshold Voltage Shift.

The I_{ds} *vs* V_{gs} curves for {k=1,20,40,60,80} were simulated at $V_{ds}=0.5V$ and the shift in the V_{th} from k=1 is calculated and are shown in Fig 3.

Fig 3



(a)



(b)

Fig. 3. (a) Transfer characteristics of the device at different values of k at $V_{ds}=0.5V$. **(b)** g_m of the device at different values of k at $V_{ds}=0.5V$.

TABLE II

Dielectric Constant	ΔV_{th} (V)	(I_{on}/I_{off})	Sensitivity
20	0.107	1.95×10^4	6.3
40	0.2	0.77×10^4	17.2
60	0.286	2.35×10^3	34.6
80	0.371	0.71×10^3	56.9

The increase in the Drain Current *(I_{ds})* is attributed to the fact that the Electric Field applied to the fin by the gate is able to permeate more into the fin due to the presence of the biomolecule simulated by the dielectric material in the hollow cavity. The increase in the dielectric constant of the cavity causes the effective thickness of the fin to decrease thus increasing the capacitance between the gate and the fin. This in turn increases the Electric Field in the fin thus resulting in better channel formation at higher values of dielectric constant.

The increase in the current density in the interior surface of the fin is also aided by the gate acting as the back gate for the opposite wall of the cavity. This coupled with the above reason results in the backward shift in the Threshold Voltage of the device at higher values of dielectric constant.

B. Output Charecterestics and Sensitivity

The I_{ds} *vs* V_{ds} curves for the device were simulated for {k=1,20,40,60,80} at V_{gs}=*0.*5V as shown in Fig 4. The switching ratio and the sensitivity were calculated from the curves. The sensitivity of the device is defined as shown in Equation (1).

$$S = \frac{I_{on(k>1)}}{I_{on(k=1)})}$$

It is seen that the Drain Current *(I_{ds})* increases with the increase in the dielectric constant ***(k)*** this is due to the increase in the effective Electric Field inside the fin that causes better channel formation as dielectric constant increases. The sensitivity of the device also increases as the dielectric constant increases. This is due to the increase in the Drain Current with increase in dielectric constant ***(k)***.

C. Tansverse Electric field Distribution

The Transverse Electric Field Distribution at the middle of the gate is shown in Fig 5. It can be seen that the Electric Field in the Cavity increases with the increase in dielectric constant keeping the applied gate voltage ***(V_{gs})*** constant. This is due to the decrease in the effective width of the fin when a biomolecule is inside the hollow cavity.

The increase in the dielectric constant of the cavity causes the effective thickness of the fin to decrease thus increasing the capacitance between the gate and the fin. This in turn increases the Electric Field in the fin thus resulting in better channel formation at higher values of dielectric constant.

Fig 4

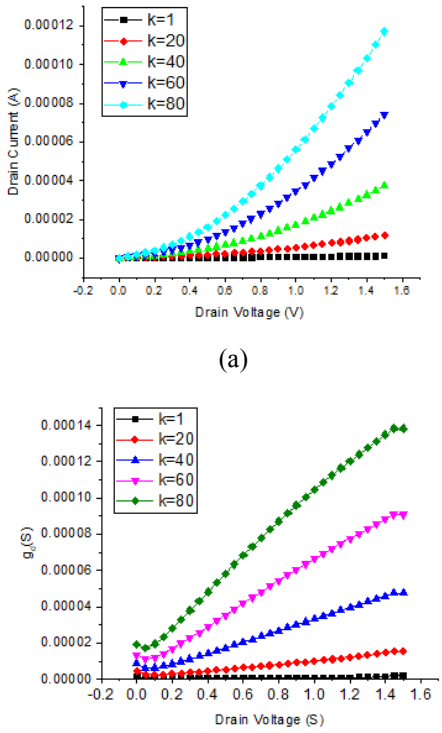


Fig. 4. (a) Output characteristics of the device at different values of k at V_{gs}=*0.5V*. **(b)** g_d of the device at different values of k at V_{gs}=*0.5V*.

Fig 5

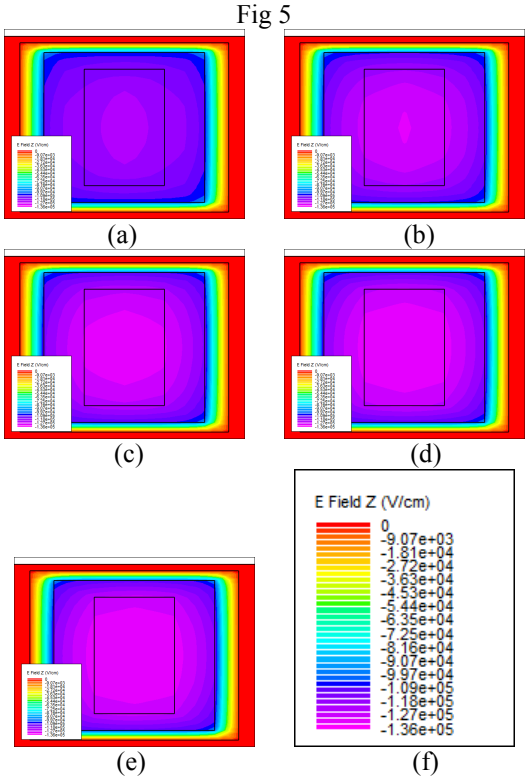


Fig. 5. Electric Field in the Transverse direction **(a)**k=1 **(b)**k=20 **(c)**k=40 **(d)**k=60 **(e)**k=80 **(f)** scale

Fig 6

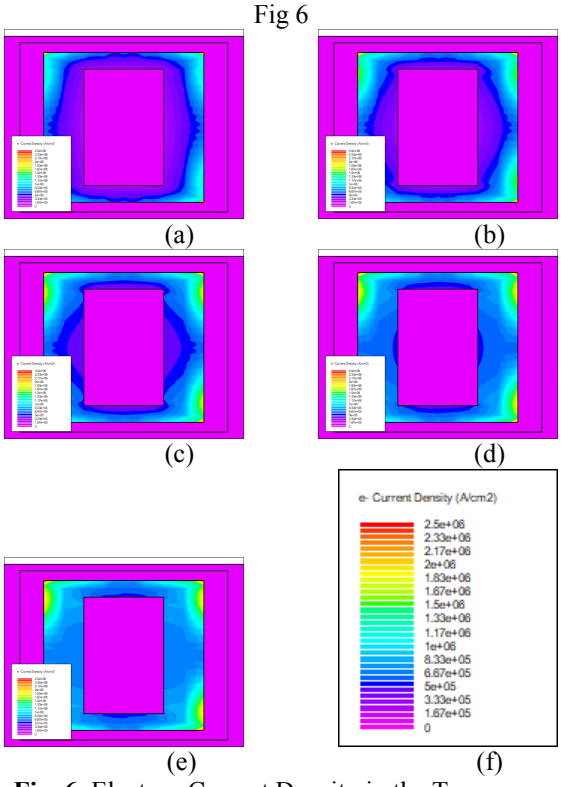


Fig. 6. Electron Current Density in the Transverse direction **(a)**k=1 **(b)**k=20 **(c)**k=40 **(d)**k=60 **(e)**k=80 **(f)** scale

D. Electron Current Density Distribution

The Electron Current Density in the Z direction is shown in Fig 6. It can be observed that the current density increases with the increase in the dielectric constant inside the hollow cavity. This increase can be attributed to the increase in the Electric Field that can permeate into the fin with the dielectric constant as shown in Fig 5.

It is also seen that the channel depth on the surface of the fin increase and moves towards the inner surface of the fin thus increasing the Drain Current at higher dielectric constants ***(I_{on} (k>1)).*** This causes an increase in sensitivity with increase in dielectric constant that is evidenced in Table II.

The increase in current density also causes an increase in the subthreshold current of the device ***(I_{off}).*** This in turn causes the Switching Ratio ***(I_{on}/I_{off})*** to decrease with an increase in dielectric constant.

V. Conclusion

We have simulated a novel hollow cavity GAA FinFET for potential detection of cancer protein markers. The methodology of the study involves the response of the device and the change in the parameters of the device when it is swung from the dielectric constant of pure water ***(k=80)*** to the dielectric constant of free space ***(k=1)*** in steps of 20.The threshold voltage shift *(ΔV_{th})* follows an increasing trend with dielectric constant and maximum shift in the threshold voltage of *0.371 V* is seen at *k=80*. The ON-StateDrain current of the device also increases from 2.85 x 10^{-7} A at *k=1* to 1.6 x 10^{-5}A at *k=80*. The switching ratio of the device also decreases from 1.95 x 10^{4} at *k=1* to 0.71 x 10_3 at *k=80* as the value of k increases. The Electric field and Current Density in the fin also increases with dielectric constant which are identified as the primary causes of the changes in the physical parameters that are observed in the device and act as the basis of it acting as a biosensor.

VI. ACKNOWLEGEMENTS

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