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Modelling and Development of 4H-SiC Nanowire/Nanoribbon Biosensing FET Structures

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Abstract. A SiCNWFET device serving as a biosensor was designed and simulated using Silvaco ATLAS device simulation software. The performance of the designed device in charges sensing was investigated. The device shows the ability to recognize different interface charge values ranging from $-1.10E11$ to $-5.10E12$ cm^{-2} applied on the surface of the silicon carbide nanowire channel to simulate target charge biomolecules that are bound to the biosensor. A significant change in the output current is observed due to the presence of different values of fixed interface charge densities. An optimum, according to the TCAD simulation, the 4H-SiC epitaxial structure has been grown. The designed device was fully fabricated on this structure and it exhibited acceptable electrical characteristics.

Introduction

Field-effect transistors based on Silicon nanowires (SiNWFET) have been intensely developed over the last decades and have proved major promise in label-free, real-time, selective and highly sensitive electrical measurements for biosensing applications [1]. However, problems in terms of result reproducibility still exist. Notably, SiNWs suffer from a lack of long-term chemical stability in physiological environments resulting in drastic signal drift and changes in the signal-noise ratio [2]–[4]. In this regard, SiC semiconductor is the complete alternative material of choice. SiC is particularly attractive for highly sensitive devices owing to its chemical inertness in harsh environments and its biocompatibility. To show the utility of these devices as a biosensor, this paper focuses first on the wafer design and the TCAD Silvaco simulation results in terms of electrical characteristics as a SiCNWFET and then as a biosensor detecting charged molecules. The second part comprises the device process fabrication and the electrical characterisation results. In the conclusion, the characteristics of the device are discussed and the results are summarized.

Biosensor Layout

The layout of the 2×2 cm^2 biosensor is shown in Figure 1. For reasons of statistical investigations of the biosensor performances, many identical FET devices are needed to be incorporated. The device is divided into four separated microwires groups. Each group contains eighteen microwires of different width sizes ($0.8 \mu\text{m}$, $1 \mu\text{m}$ and $1.3 \mu\text{m}$) (Figure 1). We choose to fabricate microwires instead of nanowires as it is based on conventional lithography which is non-time consuming, non-expensive and the most accessible technique. Later on, different SiC micro and nanowires will be

fabricated to experimentally reveal the effect of the nanowire size, number and shape parameters on the sensitivity of our developed SiC-based biosensor. Biosensors with this design have been fabricated with Si core/a-SiC shell [5] as FET material. In the present paper, 4H-SiC is considered as material for the FET fabrication. Source and drain contacts are localized on each SiC microwire extremity and the corresponding metal lines are extended to the device edges as metal pads.

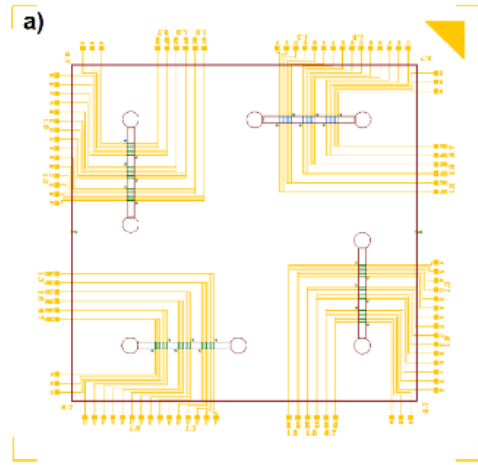


Figure 1: Top view schematic of a $2 \times 2 \text{ cm}^2$ device with identical SiC-NR/NW biosensing FETs

Wafer Design and the TCAD Silvaco Simulation

Epitaxial Structure

The 4H-SiC polytype has been chosen for the development of the devices. The 4H-SiC is one of the most readily grown and can be easily purchased on the market. Furthermore, the bare SiC surface and not the SiO_2/SiC one has been adopted as a sensing surface mainly due to the poor quality of the SiC/ SiO_2 interface. Figure 2 shows the schematic of the designed SiC epitaxial wafer, the doping concentration (cm^{-3})

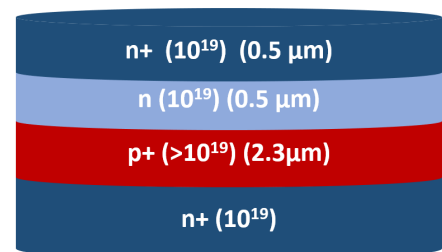


Figure 2: Schematic of the designed full SiC epitaxial wafer

and the thickness of each epitaxial layer. The structure design has been based on SiC MESFET bibliography, on basic

analytical calculations by taking into account charge density to be detected and on the verification of analytical calculation results by TCAD simulations. A p-type buffer layer is introduced on the top of the n-type conductive substrate to shield the substrate and thus measure the current in the active region of the device (channel). The channel is fabricated from an n-type 4H-SiC epitaxial layer. The topmost layer of the structure is heavy-doped n for ohmic contact formation purposes.

TCAD simulation

Before proceeding to the device fabrication, the TCAD-Silvaco-ATLAS tool was used to design the 4H-SiC-nanoribbon/nanowire NR/NW biosensing FET. The size of the simulated SiC microwire is as follow: $3 \mu\text{m}$ in length, $1 \mu\text{m}$ in width and thickness of $0.5 \mu\text{m}$. The device was simulated to observe and validate the electrical characteristics before and after its configuration as a biosensor for negatively charged species detection. Figure 3 shows a schematic of the simulated device structure. According to the simulations, the applied negative V_{GS} (to the back-gate or substrate) results in a

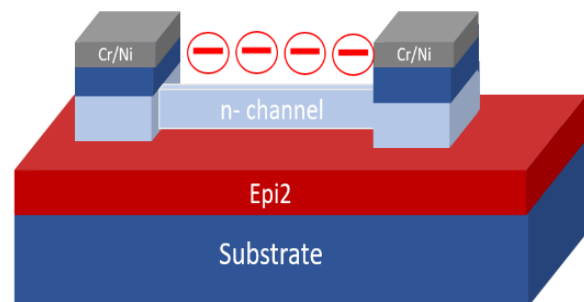


Figure 3: 3D structure of the simulated device showing the negative fixed charges equivalent to the bounded DNA molecules on the top of the SiC microwire. the latter forms a "pseudo-gate".

depletion layer formation at the interface between the n- SiCNW channel and the p+ epi-layer, resulting in a controlled magnitude of the output I_D current. Then, several negative interface charge densities Q_F (-1.1×10^{11} , -5.10×10^{11} , -1.1×10^{12} , $-5.1 \times 10^{12} \text{ cm}^{-2}$) were introduced on the surface of the n-type SiC-NW/NR to mimic the targeted deoxyribonucleic acid (DNA) captured by the biosensor (Figure 4). Figure 4 shows the simulated IDS versus V_{DS} characteristic before and after the introduction of the Q_F . The back gate voltage was fixed at -1V , the minimum value to lightly deplete the n- channel in a way to let a sufficient amount of the majority electron carriers interact with the pseudo front gate (the target charged molecules).

Based on the results shown in Figure 4, the negatively Q_F repulsed the electron carriers below the n-type SiC-NR/NW to form a depletion layer inside the channel, causing a decrease in drain current I_D . The increase of the applied negative charge density had allowed for less drain current I_D to flow across the channel between source and drain region. Thus, the sensitivity as defined $I_{\text{norm}}=(I-I_0)/I_0$ [6] (where I and I_0 are respectively the drain current value with and without target charged molecules on the channel surface) is validated (Figure 4, right).

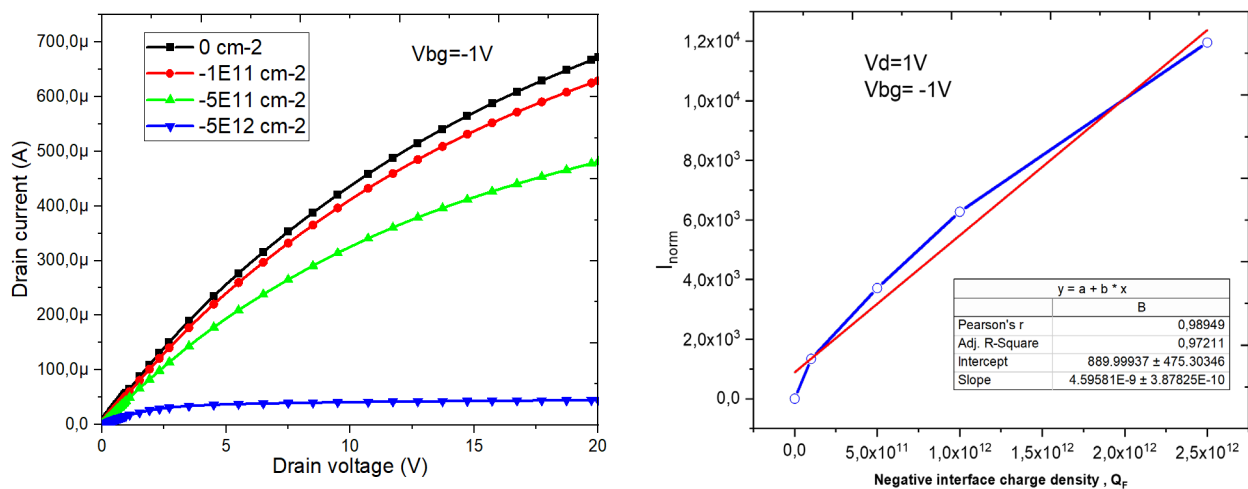


Figure 4: (left) Electrical characteristics in terms of I_D versus V_{DS} for SiC-NW/NR-FET biosensor at fixed back-gate voltage -1V and when applied different surface charge density (Q_F) values of 0 , -1.1×10^{11} , -5.10×10^{11} , -1.1×10^{12} and $-5.1 \times 10^{12} \text{ cm}^{-2}$, (right) sensitivity curve of the simulated biosensor in terms of normalized current $(I-I_0)/I_0$ versus negative interface charge densities Q_F

Biosensor Processing

Only two mask steps (source and drain regions and contacts, SiC microwires) are used to fabricate the SiC-NR/NW biosensing FET device. The source and drain regions were etched from the top n+ SiC layer using RIE and Cr/Ni mask. The Cr/Ni mask was kept for forming ohmic contacts on the source and drain. The SiC microwires were etched from the n- SiC layer under an Al mask using RIE. At the end of the process, the Al mask is etched selectively with respect to the Cr/Ni contacts using a 5% KOH solution. The contacts were annealed at $950 \text{ }^\circ\text{C}$ for 2 min inside a rapid thermal annealing chamber RTA.

Electrical Characterisation

The initial electrical characterisation of the as-fabricated devices was performed under ambient conditions using a manual probe station. First, in Figure 5 (left) the transfer characteristic (logarithmic scale) in terms of $I_{DS}-V_{GS}$ of a device was measured at a fixed $V_{DS}=0.1\text{V}$. The device shows typical FET device electrical characteristics, good control of the channel conductivity through the back gate and low leakage current (I_g). Figure 5 (right) shows $I_{DS}-V_{DS}$ characteristics at different negative V_{GS} . The off-current of the device is in the order of pA which yields a good I_{on}/I_{off} ratio of approximately 4 orders of magnitude.

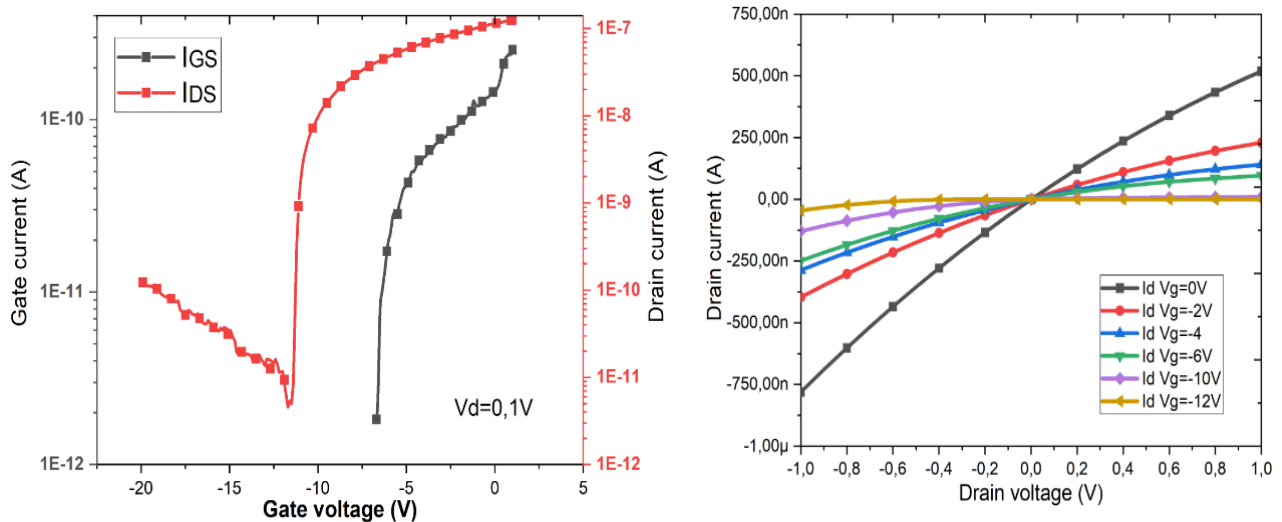


Figure 5: (left) Transfer characteristic I_D (axis 1) and I_G (axis 2) versus back-gate voltage V_{BG} for $V_{DS}=0.1V$, (right) Output characteristic drain current I_{DS} versus drain voltage V_{DS} for different negative values of V_{GS} , (SiC wire dimensions/SiC channel: $L=300\mu m$, $W=1.3\mu m$, $H=0.5\mu m$)

Conclusion

We have demonstrated the design, fabrication and operation of a 4H-SiC-microwire FET based biosensing device. The device was simulated as a biosensor showing its ability to perform biomolecules detection where charged molecules (DNA) bound on the SiC surface can control the device channel conduction. A simplified fabrication process of the device was implemented. The fabricated device shows proper electrical characteristics.

In conclusion, the designed and fabricated 4H-SiC-NR/NW FET device is introduced as a biosensor. We take advantage of the excellent SiC properties, such as biocompatibility, its semiconducting characteristics and its compatibility with the CMOS technology fabrication processes to realize this innovative application. This, together with the fact that the 4H-SiC wafers are commercially available, shows that the SiC is an excellent candidate for the development of highly reliable nanosensing devices for environmental and emerging biochemical sensing applications.

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