

**DESIGN AND SIMULATION OF NANOSCALE
FIELD EFFECT TRANSISTORS FOR
BIOSENSING APPLICATIONS**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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DESIGN AND SIMULATION OF NANOSCALE FIELD EFFECT TRANSISTORS FOR BIOSENSING APPLICATIONS

by

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*Dedicated to Mum, Guru, and God
who gave me life and pointed towards knowledge*

Certificate

This is to certify that the thesis entitled “*Design and Simulation of Nanoscale Field Effect Transistors for Biosensing Applications*” being submitted by **Ms. Sumeet Kalra** for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi is a record of bonafide work done by her under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

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“No man’s life can be encompassed in one telling. There is no way to give each year its allotted weight, to include each event, each person who helped to shape a lifetime.

What can be done is to be faithful in spirit and record...”

–Internet

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Sumeet

Abstract

The necessity of early disease detection and advanced therapeutic approaches have motivated the development of analysis tools that provide a better diagnosis in a rapid and cost-effective manner. Therefore, the next generation of biosensing platforms, especially for the point-of-care applications, require small, inexpensive, multifunctional, portable and reliable devices characterized with the metrics of direct, label-free detection, rapid response, high detection sensitivity for low sample concentrations and easy fabrication with a low associated cost. Endowed with a potential to meet these requirements, nanoscale Field Effect Transistors (FETs) are highly suitable for the development of future high-performance and integrated bioanalytical systems. Accordingly, the recent years have seen many efforts utilizing nanoscale FETs for a host of such biosensing applications. Despite notable progress, the development of such devices into robust commercial tools is still challenging. Further developments require careful designs combining the advances in the understanding of molecular interactions, engineered functionalization schemes, alternate and facile device fabrication routes and novel device structures with enhanced sensing capabilities.

Given the limitation of conventional charge based FET biosensors for the detection of neutral and very small concentrations of target molecules, dielectric modulated field effect transistor (DMFET) biosensors have been demonstrated in the recent past. Such devices have shown to exhibit advantages of higher detection sensitivity and small required sample volumes. Nevertheless, to thoroughly understand their sensing mechanisms and the role of factors affecting their sensing

performance, this work provides an insight into the importance of DNA orientation effects on the functioning principles of DMFET biosensors. Using 2D simulations, the work provides a correct explanation for the reason of lower sensitivity of n-channel DMFET biosensors than their counterpart p-channel devices.

For the development of reliable portable sensors and point-of-care analyzers, device miniaturization and reduced costs are the two key concerns. Although the use of nanoscale structures and materials facilitate small device sizes, the controlled doping of such scaled-down devices is technologically challenging and results in reliability concerns in their performance. To address these concerns, the work proposes an approach to electrostatically induce doping in the nanowire based DMFET and DM Tunnel FET (DM TFET) biosensors by exploiting the dielectric properties of biomolecules. With reduced thermal budget requirements, these designs offer improved manufacturability and can be easily fabricated on glass or plastic substrates, hence, offering prospects for low cost mass production.

Although most of the works on FET biosensors have been based on ohmic contacted devices, the Schottky contacted FET biosensors are potentially more advantageous for their simple, dopant-free processing and an enhanced sensitivity due to longer Debye screening lengths. Capitalizing on these features, this work also presents a highly sensitive Schottky Barrier FET (SB FET) biosensor with dual polarity sensing capability. Further, the work elucidates a strategy of electrically reconfiguring the device to deliver multiple functionalities with different sensing responses. The design is also recognized to achieve a significantly wide and tunable Dynamic range, without considerable structural or chemical modification overhead.

सार

प्रारंभिक रोग का पता लगाने और उन्नत चिकित्सीय दृष्टिकोण की आवश्यकता ने ऐसे विश्लेषण उपकरणों के विकास को प्रेरित किया है जो तेजी से और लागत प्रभावी तरीके से बेहतर निदान प्रदान करते हैं। इसलिए, अगली पीढ़ी के बायोसिंग प्लेटफार्मों, विशेष रूप से पॉइंट-ऑफ-केयर (POC) अनुप्रयोगों के लिए, प्रत्यक्ष, लेबल-मुक्त पहचान, तेजी से प्रतिक्रिया, कम के लिए उच्च पहचान संवेदनशीलता, नमूना सांद्रता और कम संबद्ध लागत से आसान निर्माण के मैट्रिक्स के साथ छोटे, सस्ती, बहुक्रियाशील, पोर्टेबल और विश्वसनीय डिवाइस की आवश्यकता है। इन आवश्यकताओं को पूरा करने की क्षमता के साथ संपन्न, नैनोस्केल फील्ड इफेक्ट ट्रांजिस्टर (FET) भविष्य के उच्च-प्रदर्शन और एकीकृत बायोएनालिटिक सिस्टम के विकास के लिए अत्यधिक उपयुक्त हैं। तदनुसार, हाल के वर्षों में इस तरह के बायोसिंग अनुप्रयोगों की मेजबानी के लिए नैनोस्केल FET का उपयोग करने के कई प्रयास देखे गए हैं। उल्लेखनीय प्रगति के बावजूद, ऐसे उपकरणों का मजबूत वाणिज्यिक उपकरणों में विकास अभी भी चुनौतीपूर्ण है। आगे के विकास के लिए सावधानीपूर्वक डिजाइन के साथ आणविक इंटरैक्शन की समझ में प्रगति, इंजीनियर की हुई कार्यात्मककरण योजनाएं, वैकल्पिक और सुगम उपकरण निर्माण मार्गों और उन्नत संवेदन क्षमताओं के साथ उपन्यास उपकरण संरचनाओं की आवश्यकता है।

लक्ष्य अणुओं की तटस्थ और बहुत कम सांद्रता का पता लगाने के लिए पारंपरिक चार्ज आधारित FET बायोसेंसर की सीमा को देखते हुए, हाल के दिनों में डार्डइलेक्ट्रिक फील्ड इफेक्ट ट्रांजिस्टर (DMFET) बायोसेंसर का प्रदर्शन किया गया है। इस तरह के उपकरणों ने उच्च पहचान संवेदनशीलता और छोटे आवश्यक नमूना संस्करणों के फायदे प्रदर्शित किए हैं।

फिर भी, उनके संवेदन तंत्र और उनके संवेदन प्रदर्शन को प्रभावित करने वाले कारकों की भूमिका को अच्छी तरह से समझने के लिए, यह कार्य DMFET बायोसेंसर के कार्य सिद्धांतों पर डीएनए अभिविन्यास प्रभाव के महत्व को एक अंतर्दृष्टि प्रदान करता है। 2D सिमुलेशन का उपयोग करते हुए, यह काम उनके समकक्ष पी-चैनल उपकरणों की तुलना में एन-चैनल DMFET बायोसेंसर की कम संवेदनशीलता के कारण के लिए एक सही स्पष्टीकरण प्रदान करता है।

विश्वसनीय पोर्टेबल सेंसर और POC एनालिसिस के विकास के लिए, उपकरण लघुकरण और कम लागत दो प्रमुख चिंताएं हैं। यद्यपि नैनोस्केल संरचनाओं और सामग्रियों के उपयोग से छोटे उपकरण आकार की सुविधा होती है, ऐसे स्केल-डाउन उपकरणों का नियंत्रित डोपिंग तकनीकी रूप से चुनौतीपूर्ण है जो उनके प्रदर्शन में विश्वसनीयता की चिंता का परिणाम है। इन चिंताओं को दूर करने के लिए, यह कार्य जैव-अणु के dielectric गुणों का उपयोग करके नैनोवायर (NW) आधारित DMFET और डीएम टनलएफईटी (DMTFET) बायोसेंसर में इलेक्ट्रोस्टैटिक रूप से प्रेरित डोपिंग के लिए एक दृष्टिकोण का प्रस्ताव करता है। कम थर्मल बजट आवश्यकताओं के साथ, ये डिज़ाइन बेहतर ढंग से विनिर्माण क्षमता प्रदान करते हैं और आसानी से कांच या प्लास्टिक सबस्ट्रेट पर गढ़े जा सकते हैं, इसलिए, कम लागत वाले बड़े पैमाने पर उत्पादन की संभावनाएं प्रदान करते हैं।

यद्यपि FET बायोसेंसर के अधिकांश कार्य ओमिक (ohmic) लॉजिक डिवाइसेस पर आधारित हैं, शोट्की (Schottky) लॉजिक FET बायोसेंसर संभावित रूप से अपने सरल, डोपेंट-मुक्त प्रसंस्करण और लम्बी Debye स्क्रीनिंग के कारण एक बढ़ी संवेदनशीलता के लिए फायदेमंद हैं। इन विशेषताओं का उपयोग करते हुए, यह कार्य दोहरी ध्रुवीय संवेदन क्षमता के साथ एक अत्यधिक संवेदनशील शोट्की बैरियर FET (SB FET) बायोसेंसर भी प्रस्तुत करता

है। इसके अलावा, यह कार्य विभिन्न संवेदनशीलता प्रतिक्रियाओं के साथ कई कार्यात्मकताओं को वितरित करने के लिए विद्युत रूप से पुनः कॉन्फ़िगर करने की रणनीति को स्पष्ट करता है। महत्वपूर्ण संरचनात्मक या रासायनिक संशोधन ओवरहेड के बिना, काफी व्यापक और ट्यून किए गए गतिशील रेंज को प्राप्त करने के लिए डिज़ाइन को भी मान्यता दी गई है। यह डिज़ाइन, संरचनात्मक या रासायनिक संशोधन ओवरहेड के बिना, काफी विस्तृत और ट्यून करने योग्य पहचान सीमा को प्राप्त करता है ।

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List of Acronyms

BGN	Band Gap Narrowing
BTBT	Band To Band Tunneling
CMOS	Complementary Metal Oxide Semiconductor
cTnI	Cardiac Troponin I
DNA	Deoxyribonucleic Acid
DMFET	Dielectric Modulated Field Effect Transistor
DM-TFET	Dielectric Modulated Tunnel Field Effect Transistor
DR	Dynamic Range
dsDNA	Double-Stranded DNA
FET	Field Effect Transistor
IMOS	Impact Ionization MOSFET
ISFET	Ion-Sensitive Field Effect Transistor
LoC	Lab-on-Chip
LLOD	Lower Limit of Detection
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NW	Nanowire
pI	Isoelectric Point
PNA	Peptide Nucleic Acid
PoC	Point-of-Care
pH	Potential of Hydrogen

qLOD	Lower Limit of Charge Detection
qUOD	Upper Limit of Charge Detection
SAM	Self-Assembled Monolayer
SB	Schottky Barrier
SB FET	Schottky Barrier Field Effect Transistor
SCE	Saturated Calomel Electrode
SiNW	Silicon Nanowire
SJ	Schottky Junction
SOI	Silicon-on-Insulator
SS	Subthreshold Swing
ssDNA	Single-Stranded DNA
TCAD	Technology Computer Aided Design
TCCT	Thin Capacitively-Coupled Thyristor
TFET	Tunnel Field Effect Transistor
ULOD	Upper Limit of Detection