DESIGN AND SIMULATION OF STEEP SUBTHRESHOLD SLOPE TRANSISTORS FOR BIOSENSING APPLICATIONS

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DESIGN AND SIMULATION OF STEEP SUBTHRESHOLD SLOPE TRANSISTORS FOR BIOSENSING APPLICATIONS

by

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Certificate

This is to certify that the thesis entitled **"*Design and Simulation of Steep Subthreshold Slope Transistors for Biosensing Applications"*** being submitted by **Mr. N. Kannan** 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 bona fide work done by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

Date:

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Dedicated to Amma & Appa (my parents) whose examples and guidance have inspired me to work with commitment and integrity, and to my wife Mani for her support and encouragement.

கற்க கசடறக் கற்பவை கற்றபின்

நிற்க அதற்குத் தக

Learn well without blemishes that which is worthy of being learned; having learnt,

may your conduct be worthy of it

(Tirukkural Chapter 40:1)

विद्वान् सर्वत्र पूज्यते…

The learned one is honored everywhere…

(A Sanskrit proverb)

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Date: N. Kannan

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Abstract

Electronic devices are finding increasing application as biosensors for the real-time, label-free detection of biomolecules. The ion-sensitive field-effect transistor (ISFET) was the precursor to the application of the FET based biosensors. Subsequent developments have resulted in the application of planar, nanowire and nanotube-based field effect transistors (FETs) as biosensors. FET based biosensors have been developed for the detection of biomolecules like DNA, various other proteins as well as pathogens like bacteria and viruses. The FET based biosensors can achieve very low detection limits for the analyte concentration and offer the advantage of fast detection and compatibility with existing CMOS processes. These features of the FET based biosensors enable the possibility of rapid commercialization for "lab-on-a-chip" systems - constituting of a sensor array to detect a wide range of biomolecules, and the readout circuitry and signal processor.

One of the main factor determining a biosensor's performance is its sensitivity. The FET based biosensor, when biased in the subthreshold regime will have a sharp turn-ON due to the immobilization of biomolecules, resulting in a high sensitivity of detection. The ideal FET based biosensor should have a subthreshold swing (SS) = 0 mV/decade to achieve the maximum possible sensitivity. However, the conventional MOSFET (metal oxide semiconductor FET) has a theoretical lower limit of SS = 60 mV/decade at 300 K. There is a significant focus on the development of steep

subthreshold slope transistors with SS < 60 mV/decade to enable substantial reduction in the OFF-state current for the future generations of logic circuits. The low value of SS for the steep subthreshold slope transistors offers the possibility of application of these devices as label-free biosensors thereby achieving very high sensitivity of detection.

In this thesis, the application of steep subthreshold transistors like the impact ionization MOS (I-MOS) is extensively studied for application as a label-free biosensor. Using 2D TCAD simulations, the I-MOS is explored as a dielectric-modulated as well as charge-modulated biosensor using different gate electrode configurations. The TCAD simulations include detailed modeling of the dry and wet measurement environments for dielectric-modulated and charge-modulated biosensor study, respectively. The I-MOS based dielectric-modulated biosensor is demonstrated to be an extremely sensitive biosensor for charge-neutral or low charge biomolecules, with a V_T shift of around 90% (~14 V) for biomolecules with dielectric constant K = 12. For the proposed charge-modulated I-MOS biosensors, the gate structure is modified to introduce an underlap region for immobilization by biomolecules. The charges on the biomolecules modulate the channel carrier concentration resulting in changes in the electrical characteristics of the device. Two different underlap configurations viz. embedded underlap gate and drain-side gate underlap are studied and current sensitivities of the order of ~10^7 are reported. In addition, the bipolar I-MOS concept is used to propose a low-power underlap gate biosensor with current sensitivity two orders of magnitude greater than the FET based underlap sensor, and power consumption two orders of magnitude lower than the conventional I-MOS based underlap biosensor. Hence, the bipolar I-MOS underlap biosensor combines the

advantages of low-power consumption of conventional FET based biosensors and the high sensitivity of I-MOS based biosensors. The bipolar I-MOS concept is further extended to a Schottky bipolar I-MOS with Schottky contacts replacing the source and drain regions. The Schottky bipolar I-MOS based underlap gate biosensor shows an operating voltage as low as 0.5 V, enabling the use of the I-MOS concept with latest generation of logic circuits.

Finally, the thin capacitively-coupled thyristor (TCCT) is proposed to be used as a label-free dielectric-modulated and charge-modulated biosensor. A very high sensitivity of the order of 10^{11} to 10^{12} is demonstrated for the TCCT based biosensors. The sensitivity of the TCCT based biosensors is around two to four magnitudes higher than the sensitivities seen with other steep subthreshold slope transistors. The high sensitivity is observed for a large range of gate voltage (~800 mV) making the TCCT based biosensor's sensitivity relatively immune to power supply noise or variation making the device very attractive for application as a label-free biosensor.

सार

बायोमॉलिक्यूल्स के रियल-टाइम, लेबल-फ्री डिटेक्शन (पता लगाने) में इलेक्ट्रॉनिक डिवाइसस के उपयोग मे वृद्धि हो रही है| आयन-सेंसिटिव फील्ड-इफ़ेक्ट ट्रांजिस्टर (ISFET), FET आधारित बायोसेंसर का अग्रगामी है | नयी शोध के परिणामस्वरूप प्लैनर, नैनोवायर तथा नैनोट्यूब पर आधारित फील्ड इफ़ेक्ट ट्रांसिस्टर्स (FETs) का बायोसेंसर्स के रूप मे उपयोग हो रहा है | FET आधारित बायोसेंसरों को डीएनए, विभिन्न अन्य प्रोटीन के साथ-साथ बैक्टीरिया और वायरस जैसे रोगजनकों के बायोमॉलिक्यूल्स के पता लगाने के लिए विकसित किया गया है । FET आधारित बायोसेंसर्स एनालाइट कोन्संट्रेशन की बहुत छोटी पहचान सीमा (लिमिट-ऑफ़-डिटेक्शन) प्राप्त कर सकते हैं | FET आधारित बायोसेंसर्स एनालाइट के त्वरित पहचान एवं मौजूदा CMOS निर्माण प्रक्रिया से अनुकूलता के कारण आकर्षक सिद्ध हो रहें हें | FET आधारित बायोसेंसरों की ये विशेषताएं "लैब-ऑन-ए-चिप" सिस्टम के लिए तेजी से व्यावसायीकरण की संभावना को सक्षम करती हैं | "लैब-ऑन-ए-चिप" सिस्टम में विभिन्न बायोम्योल्यूल्स के पता लगाने के लिए एक सेंसर सरणी का गठन, रीडआउट सर्किट्री और सिग्नल प्रोसेसर शामिल होते हैं।

बायोसेंसर के प्रदर्शन को निर्धारित करने वाले मुख्य कारक में से एक इसकी संवेदनशीलता (सेन्सिटिवटी) है । FET आधारित बायोसेंसर, जब सबथ्रेशहोल्ड क्षेत्र में बायस होती है तो बायोमॉलिक्यूल्स के इम्मोबिलिज़ेशन के कारण त्वरित रूप से चालू होती है, जिसके परिणामस्वरूप एनालाइट के पहचान की उच्च संवेदनशीलता होती है । एक आदर्श FET आधारित बायोसेंसर में अधिकतम संभावित संवेदनशीलता प्राप्त करने के लिए सबथ्रेशहोल्ड स्विंग

(SS) = 0 mV/decade होना चाहिए। पारंपरिक MOSFET (मेटल ऑक्साइड सेमीकंडक्टर FET) में 300 केल्विन के तापमान पर SS = 60 mV/decade की सैद्धांतिक निचली सीमा ही संभव है | लॉजिक सर्किट की भविष्य की पीढ़ियों के लिए ऑफ-स्टेट करेंट (विद्युत प्रवाह) में पर्याप्त कमी को सक्षम करने के लिए SS < 60 mV/decade वाले स्टीप सबथ्रेशहोल्ड स्लोप ट्रांजिस्टर के विकास पर शोद केंद्रित है। स्टीप सबथ्रेशहोल्ड स्लोप ट्रांजिस्टर के लिए SS का कम मूल्य होना इन डिवाइसस के बहुत अधिक संवेदनशीलता युक्त लेबल-फ्री बायोसेंसर के रूप में उपयोग होने की संभावना प्रदान करता है।

इस शोध प्रभंद (थीसिस) में, इम्पैक्ट आईओनैज़ेशन MOS (I-MOS) जैसे स्टीप सबथ्रेशहोल्ड स्लोप ट्रांसिस्टर्स का लेबल-फ्री बायोसेंसर के रूप में प्रयोग पर विस्तृत अध्ययन किया गया है। 2डी TCAD सिमुलेशन का उपयोग करके, I-MOS का डाईइलेक्ट्रिक-मॉड्यूलेटेड बायोसेंसर के साथ-साथ विभिन्न गेट इलेक्ट्रोड कॉन्फ़िगरेशन का उपयोग करके चार्ज-मॉड्यूलेटेड बायोसेंसर के रूप में अन्वेषण किया गया है। TCAD सिमुलेशन व्यवस्था में डाईइलेक्ट्रिक-मॉड्यूलेटेड और चार्ज-मॉड्यूलेटेड बायोसेंसर के अध्ययन के लिए क्रमशः शुष्क और गीले मापक व्यवस्था का विस्तृत मॉडलिंग शामिल है। इस शोध द्वारा I-MOS आधारित डाईइलेक्ट्रिक-मॉड्यूलेटेड बायोसेंसर को चार्ज-मुक्त अथवा निम्न-चार्ज बायोम्योल्यूल्स के लिए अति संवेदनशील बायोसेंसर सिद्ध किया गया है | I-MOS आधारित डाईइलेक्ट्रिक-मॉड्यूलेटेड बायोसेंसर द्वारा डाइलेक्ट्रिक स्तर, K = 12 वाले बायोम्योल्यूल्स के लिए 90% V_T शिफ्ट (~ 14 V) प्राप्त हुआ है। बायोमॉलिक्यूल्स मे प्रस्तुत चार्जेस के कारण चैनल की वाहक (कैर्रिएर) मात्रा परिवर्तित होती है जिसके परिणामस्वरूप डिवाइस की विद्युतिया गुणों में परिवर्तन होता है। चार्ज-मॉड्यूलेटेड बायोसेंसर के दो अलग अंडरलैप कॉन्फ़िगरेशन - एम्बेडेड अंडरलैप गेट और ड्रेन-साइड गेट अंडरलैप का अध्ययन किया गया और कर्रेंट सेन्सिटिवटी की मात्रा लगभग ~ 10^7 प्रदर्षित करी गयी है। इसके अलावा, बाइपोलर I-MOS सिद्धांत पर आधारित एक लो-पावर (कम ऊर्जा खपत की दर) बायोसेंसर प्रस्तावित किया गया है | प्रस्तावित बाइपोलर I-MOS

बायोसेंसर की करेंट संवेदनशीलता पारंपरिक FET अंडरलैप गेट बायोसेंसर की तुलना में दो दशक अधिक है | तथापि बाइपोलर I-MOS बायोसेंसर की पावर (ऊर्जा खपत की दर) पारंपरिक I-MOS अंडरलैप गेट बायोसेंसर की तुलना में दो दशक काम पाई गयी | इसलिए, बाइपोलर I-MOS बायोसेन्सर पारंपरिक अंडरलैप FET आधारित बायोसेंसरों की कम ऊर्जा खपत की दर और I-MOS आधारित बायोसेंसरों की उच्च संवेदनशीलता के लाभ को जोड़ती है। बाइपोलर I-MOS सिद्धांत को शॉट्की बाइपोलर I-MOS के रूप मैं आगे बढ़ाया गया है | शॉट्की बाइपोलर I-MOS में शॉट्की कांटैक्ट्स सोर्स एवं ड्रेन क्षेत्रों की जगह लेते हैं। शॉट्की बाइपोलर I-MOS आधारित अंडरलैप गेट बायोसेंसर द्वारा ऑपरेटिंग वोल्टेज की निचली सीमा 0.5 V तक दर्शायी गयी है | यह अविष्कार I-MOS सिद्धांत को नवीनतम पीढ़ी के लॉजिक सर्किट मे उपयोग के लिए योग्य बनाता है।

अंत में, थिन कैपेसिटिवली-कपल्ड थाइरिस्टर (TCCT) को लेबल-फ्री डाईइलेक्ट्रिक-मॉड्यूलेटेड और चार्ज-मॉड्यूलेटेड बायोसेंसर के रूप में उपयोग करने का प्रस्ताव रखा गया है। TCCT आधारित बायोसेंसरस की करेंट सेन्सिटिवटी की मात्रा लगभग ~ 10^{11} - 10^{12} प्रदर्षित करी गयी है, जो इन डिवाइसस को अत्यधिक संवेदनशील सिद्ध करता है | TCCT आधारित बायोसेंसरों की संवेदनशीलता अन्य स्टीप सबथ्रेशहोल्ड स्लोप ट्रांसिस्टर्स के साथ देखी गई संवेदनशीलताओं की तुलना में लगभग दो से चार दशक अधिक है | यह उच्च संवेदनशीलता गेट वोल्टेज के मूल्यों की एक बड़ी श्रृंखला के लिए देखी जाती है (~ 800 mV) | परिणामस्वरूप, TCCT बायोसेंसर की संवेदनशीलता पावर सप्लाई नॉइज़ या वेरिएशन के द्वारा बहुत कम प्रभावित होती है | यहाँ डिवाइस को लेबल-फ्री बायोसेंसर के रूप में उपयोग के लिए बहुत आकर्षक बनाता है।

Table of Contents

Certificate i

Acknowledgements iv

Abstract vii

List of Figures xiv

List of Symbols xxiii

Chapter 1 1

Introduction 1

1.1. The Field Effect Transistor as a Sensor 1

1.2. Field Effect Transistors for Biosensing Applications 3

1.3. Motivation for the Research Work 10

1.3.1. The Case for Application of Steep Subthreshold Transistors as Biosensors 11

1.4. Objectives and Outline of the Thesis 14

References 15

Chapter 2 21

Steep Subthreshold Slope Transistors: An Overview 21

2.1. Introduction 21

2.2. Subthreshold Swing of the MOSFET 22

2.3. Steep Subthreshold Slope Transistors 24

2.3.1 Tunnel Field Effect Transistors (TFETs) 25

2.3.2 The Impact-ionization MOS (I-MOS) Transistor 28

2.3.3 Thin Capacitively Coupled Thyristor (TCCT) 32

2.3.4. Energy Band-modulated Sharp Switching Transistors 34

2.4. Conclusion 37

References 38

Chapter 3 46

A Dielectric-Modulated Impact-Ionization MOS Transistor as a Label-Free Biosensor 46

3.1. Introduction 46

3.2. Device Structure and Biosensing Action 47

3.3 Simulation Results and Discussion 49

3.3.1. Effect of Gate Length (L_G) Change at a Fixed Cr Gate Length (L_{Cr}) 52

3.3.2 Impact of Chromium Gate Length (L_{Cr}) Change 53

3.3.3 Impact of Biomolecular Charges 54

3.4 Amorphous Silicon based Dielectric-Modulated I-MOS transistor as a label-free biosensor 55

3.4.1 Simulation Results and Discussions 58

3.5. Conclusion 61

References 62

Chapter 4 65

Charge-Modulated Impact Ionization MOS Transistor as Label-Free Biosensors 65

4.1 Introduction 65

4.2. Embedded Underlap I-MOS Transistor as a Charge-modulated Label-free biosensor 68

4.2.1. Device Structure and Biosensing Action 68

4.2.2 Simulation Setup 69

4.2.3 Results and Discussions 72

4.3. Drain-side Gate-underlap I-MOS (DGI-MOS) Transistor as a Label-free Biosensor for Detection of Charged Biomolecules 82

4.3.1. Device Structure and Simulation Parameters 82

4.3.2 DGIMOS Biosensor TCAD Analysis 83

4.4. Conclusion 90

References 91

Chapter 5 94

The Bipolar I-MOS as a Label-Free Biosensor: A Highly Sensitive, Low Power Sensing Device 94

5.1. Introduction 94

5.2 Device Structure and Parameters for the Bipolar I-MOS biosensor 98

5.2.1 Biomolecule Detection and Sensing Parameters 101

5.2.2 Simulation Setup and Electrolyte Modelling 101

5.2.3 Simulation Results and Discussion 103

5.3 Schottky Bipolar I-MOS: A Bipolar I-MOS with Schottky Electrodes for Reduced Operating Voltage 111

5.3.1 Device Structure 112

5.3.2 Simulation Setup 114

5.3.3 Simulation Results and Discussion 115

5.3.4 Schottky Bipolar Underlap I-MOS Biosensor 120

5.4 Conclusion 124

References 126

Chapter 6 131

Thin Capacitively-Coupled Thyristor (TCCT) as an Ultra-Sensitive Label-Free Biosensor: Proposal and Investigation 131

6.1 Introduction 131

6.2 Nanogap TCCT Dielectric-modulated Biosensor 133

6.2.1 Device Structure and Simulation Setup 133

6.2.2 Results and Biosensing Action 135

6.3 Underlap TCCT Charge-Modulated Biosensor 143

6.4 Conclusion 146

References 147

Chapter 7 151

Conclusion 151

7.1. Summary of Contributions.....151
7.2. Concluding Remarks.....154
Appendix A.....156
Sample Atlas Input File 156
Appendix B.....160
Tcl based automation script for ATLAS IN file creation 160
Example of parameter values definition script 164
Curriculum Vitae 165

List of Figures

Figure 1.1: Cross sectional view of (a) the MOSFET and (b) the ISFET [5].....2

Figure 1.2: Schematic setup and functional principle of a bio-chemical sensor based on the ISFET [18] 5

Figure 1.3: Schematic structure of an ImmunoFET with immobilized antibody (Ab) molecules with the antigen (Ag) molecules to be detected present in the electrolyte [18] 6

Figure 1.4: Schematic representation of a dielectric-modulated nanogap FET biosensor [25].....8

Figure 1.5: Schematic representation of the change of *K* due to nanogap formation and immobilization of the biomolecule inside the nanogap of DMFET [31].....9

Figure 1.6: Illustration of the impact of subthreshold swing on the current sensitivity, $S_{current}$ of a FET based biosensor for different values of change in channel surface potential due to biomolecule binding or conjugation. The value of I_{OFF} for all the cases is assumed to be 10 nA. 13

Figure 2.1: Plot of I_D vs. V_G for a MOSFET to illustrate the concept of subthreshold swing.....22

Figure 2.2: Schematic of a lateral BTBT N-type TFET. 26

Figure 2.4: I_D vs. V_G characteristics of: (a) N-channel I-MOS and (b) N-Channel MOSFET. 29

Figure 2.5: Schematic of the N-channel bipolar I-MOS with the equivalent circuit on top 31

Figure 2.6: Schematic of the TCCT with the equivalent circuit on top 33

Figure 2.7: I_A vs. V_G characteristics of the TCCT 34

Figure 2.8: Schematic of the FED 35

Figure 2.9: Schematic of the N-type Z^2-FET 36

Figure 2.10: Schematic of the N-type Z^3-FET (from [70]) 37

Figure 3.1: Cross sectional view of (a) the conventional I-MOS and (b) The DMIMOS. 48

Figure 3.2: I_D vs. V_G characteristics of the P-channel DMIMOS and the conventional P-channel I-MOS for V_{SD} = 7.8 V. 50

Figure 3.3: Horizontal electric field (E_X) profile along the x-axis of the channel, 1 nm below the gate oxide and silicon film interface, for the DMIMOS for V_{SD} = 7.8 Vand V_G = -6 V. 51

Figure 3.4: ΔV_T and ΔI_{ON} for the DMIMOS as a function of L_G with V_{SD} = 7.8 V and L = 200 nm 52

Figure 3.5: ΔV_T and ΔI_{ON} of the P-channel DMIMOS as a function of Cr Gate Length (L_{Cr}) with V_{SD} = 7.8 V and K = 12. 53

Figure 3.6: ΔV_T and ΔI_{ON} of the P-channel DMIMOS for negatively charged biomolecules with V_{SD} = 7.8 V.....54

Figure 3.7: Cross-sectional view of the P-channel amorphous DMIMOS. 56

Figure 3.8: I_D vs. V_G characteristics of the P-channel amorphous DMIMOS for V_{SD} = 7.8 V.....58

Figure 3.9: ΔV_G and ΔI_{ON} of the amorphous DMIMOS, with L = 200 nm, as a function of: (a) Gate Length (L_G) with L_{Cr} = 40 nm and (b) Cr Gate Length (L_{Cr}) for L_G= 125 nm and 140 nm.....60

Figure 3.10: ΔV_G and ΔI_{ON} of the amorphous DMIMOS as a function of: (a) T_{GAP} and (b) Negative biomolecular charge density. 61

Figure 4.1: Schematic view of (a) the conventional I-MOS and (b) the embedded underlap I-MOS (UIMOS).....69

Figure 4.2: Reproduction of the simulated I_D vs. V_G plot of a conventional P-channel I-MOS transistor in Fig. 2 of [18] for calibrating the TCAD setup used for analysis of the UIMOS transistor. The device is simulated at V_S = 7.8 V and V_D = 0 V.....70

Figure 4.3: P-Channel embedded UIMOS biosensor I_D vs. V_G characteristics for channel length L = 150 nm, V_S = 7.0 V and V_D = 0 V showing the impact of charged biomolecules present in the underlap region. 73

Figure 4.4: (a) Energy Band diagram in the embedded UIMOS silicon film, measured 1 nm below the SiO_2-Silicon interface, along the x-axis in the presence and absence of negatively charged biomolecules for V_G = -1 V, V_S = 7.0 V and V_D = 0 V. The drain,

gate, intrinsic and source regions are marked in the figure. (b) Energy Band diagram in the underlap region marked in Fig. 4.4(a) to highlight the steep transition at the edge of the underlap region in presence of charged biomolecules. 75

Figure 4.5: Hole concentration for V_G = - 3.2 V, V_S = 7.0 V and V_D = 0 V, measured 1 nm below the SiO_2-Silicon interface, in the underlap region along the x-axis for different negative biomolecular charge densities. The x-axis origin is located at the start of the drain region. 76

Figure 4.6: $S_{current}$ as a function of V_G for V_S = 7.0 V and V_D = 0 V due to increasing biomolecular charge densities in underlap region. 76

Figure 4.7: ΔV_G and the peak value of $S_{current}$ for increasing biomolecular charge density in the underlap region of the P-channel embedded UIMOS. 78

Figure 4.8: ΔV_G and the peak value of $S_{current}$ of the P-channel embedded UIMOS as a function of T_{OX}, with immobilized biomolecular charge density of -1.0×10^{13} cm^{-2} and V_S = 7.0 V and V_D = 0 V. 79

Figure 4.9: Hole concentration for V_G = - 3.2 V, V_S = 7.0 V and V_D = 0 V along the Silicon film thickness (y-axis), measured from the SiO_2-Silicon interface, in the middle of the underlap region along the x-axis for increasing negative biomolecular charge density. 80

Figure 4.10: ΔV_G and the peak value of $S_{current}$ at V_S = 7.0 V and V_D = 0 V versus (a) L_G and (b) L_U/L_G ratio, keeping L (150 nm) and T_{OX} (10 nm) as constant. 81

Figure 4.11: Cross sectional view of (a) the conventional I-MOS and (b) the DGIMOS biosensor with an underlap region for immobilization of biomolecules. 83

Figure 4.12: I_D vs. V_G characteristics of the P-channel DGIMOS biosensor with V_S = 7.0 V and V_D = 0 V for a channel length L = 150 nm. 84

Figure 4.13: Hole concentration for V_G = - 3.4 V, V_S = 7.0 V and V_D = 0 V, measured 1 nm below the SiO_2-Silicon interface, in the underlap region along the x-axis for different negative biomolecular charge densities. 85

Figure 4.14: $S_{current}$ as a function of V_G for V_S = 7.0 V and V_D = 0 V due to increasing biomolecular charge densities in underlap region. 86

Figure 4.15: The values of ΔV_T and Peak $S_{current}$ of the P-channel DGIMOS biosensor versus increasing biomolecular charge density with V_S = 7.0 V and V_D = 0 V. 87

Figure 4.16: The values of ΔV_T and Peak $S_{current}$ of the P-channel DGIMOS biosensor versus L_G for a biomolecular charge density of -1.0×10^{13} $cm^{-2}$and channel length L = 150 nm, with V_S = 7.0 V and V_D = 0 V. 87

Figure 4.17: The values of ΔV_T and Peak $S_{current}$ of the P-channel DGIMOS biosensor versus underlap length L_U for a biomolecular charge density of -1.0×10^{13} cm^{-2} with V_S = 7.0 V and V_D = 0 V.....88

Figure 4.18: The values of ΔV_T and Peak $S_{current}$ of the P-channel DGIMOS biosensor versus gate oxide thickness T_{OX} for a biomolecular charge density of -1.0×10^{13} cm^{-2} with V_S = 7.0 V and V_D = 0 V. 89

Figure 4.19: Comparison of $S_{current}$ values of the UIMOS and the DGIMOS as a function of V_G for V_S = 7.0 V and V_D = 0 V due to increasing biomolecular charge densities in underlap region. 90

Figure 5.1: Cross sectional view of (a) the n-Channel Bipolar I-MOS, (b) the Bipolar underlap I-MOS (UIMOS) biosensor, (c) the n-Channel PIN I-MOS biosensor, (d) the PIN underlap I-MOS (UIMOS) biosensor, (e) the n-Channel FET and (f) the underlap FET (U-FET) biosensor. 99

Figure 5.2: I_D vs. V_G characteristics with L = 150 nm, L_G = 90 nm, L_U = 63 nm and T_{OX} = 10 nm for: (a) the conventional bipolar I-MOS and the bipolar UIMOS with no charge in the underlap and a positive biomolecular charge of 1×10^{12} cm^{-2} in the underlap for V_{DS} = 1.4 V (b) the conventional PIN I-MOS and the PIN UIMOS with no charge in the underlap and a positive biomolecular charge of 1×10^{12} cm^{-2} in the underlap for V_{SD} = -7 V (c) the conventional FET and the U-FET with no charge in the underlap and a positive biomolecular charge of 1×10^{12} cm^{-2} in the underlap for V_{DS} = 0.8 V..... 105

Figure 5.3: Sensitivity and power consumption comparison between the bipolar UIMOS, PIN UIMOS and U-FET with L = 150 nm, L_G = 90 nm, L_U = 63 nm and T_{OX} = 10 nm at V_{DS} = 1.4 V (bipolar UIMOS) and 0.8 V (U-FET) and V_{SD} = -7 V (PIN UIMOS): (a) $S_{current}$ vs. V_G for a positive biomolecular charge of 1×10^{12} cm^{-2} in the underlap region (b) P_{Device} (= $I_D \times V_{DS}$) vs. V_G for a positive biomolecular charge of 1×10^{12} cm^{-2} (c) Values of $S_{current}$ and $S_{current}/P_{Device}$ when $I_D = I_{D,Ref}$ = 1.0 μA for a biomolecular charge of 1×10^{12} cm^{-2} and (d) ΔV_G vs. biomolecular charge. 107

Figure 5.4: Sensitivity and power consumption comparison for the bipolar UIMOS and PIN UIMOS as a function of L_G and L_U with L = 150 nm and T_{OX} = 10 nm for a positive biomolecular charge of 1×10^{12} cm^{-2} in the underlap region and V_{DS} = 1.4 V (bipolar UIMOS) and V_{SD} = -7 V (PIN UIMOS): (a) The peak value of $S_{current}$ across the range

of V_G and the value of ΔV_G vs. L_G with L_U / L_G fixed at 0.7 (b) P_{Device} at the point of peak $S_{current}$ vs. L_G and (c) Peak $S_{current}$ across the range of V_G and the value of ΔV_G vs. L_U with L_G fixed at 90 nm. 110

Figure 5.5: Cross sectional view of (a) the n-Channel Schottky bipolar I-MOS and (b) the conventional n-Channel p-i-n I-MOS. 113

Figure 5.6: N-channel Schottky bipolar I-MOS and PIN I-MOS breakdown characteristics: (a) I_D vs. $|V_{DS}|$ characteristics for V_{GS} or V_{GD} = 0 V and L = 100 nm. (b) Breakdown voltage, V_{BD} of the Schottky bipolar I-MOS at two different channel doping levels for different values of channel length L. The length of the gate is taken as 50% of the channel length. 116

Figure 5.7: N-channel Schottky bipolar I-MOS transfer characteristics for L = 100 nm and L_G = 50 nm: (a) I_D vs. V_{GS} characteristics for different values of V_{DS}. (b) Energy band diagram and Impact Ionization Rate in the channel region of the n-channel Schottky bipolar I-MOS at V_{DS} = 1.06 V for V_{GS} = 0 V and 0.13 V.....118

Figure 5.8: Horizontal electric field, measured 1 nm below the gate oxide, across the channel length for the Schottky bipolar I-MOS and the p-i-n I-MOS of channel length L = 100 nm.....119

Figure 5.9: Cross-sectional view of the Schottky bipolar UIMOS biosensor.....121

Figure 5.10: Transfer characteristics of the Schottky bipolar UIMOS biosensor with L_G = 70 nm, L_U = 28 nm, and T_{OX} = 5 nm at V_{DS} = 0.5 V and biomolecules in the underlap with different values of charge density: (a) I_D vs. V_G for increasing biomolecular charge

density (b) Current sensitivity $S_{current}$ vs. V_G for increasing biomolecular charge density. 122

Figure 6.1: Cross sectional view of the nanogap TCCT dielectric-modulated biosensor. 134

Figure 6.2: Transfer characteristics of the nanogap TCCT biosensor with L_G = 50 nm, L_{GAP} = 15 nm, T_{GAP} = 10 nm and T_{OX} = 3 nm at V_{AK} = 2.5 V and biomolecules in the nanogap with different values of *K*, where *K* = 1 represents the characteristics in the absence of biomolecules (Air in the nanogap): (a) I_A vs. V_G for increasing *K* of the biomolecules (b) Current sensitivity $S_{current}$ vs. V_G for low (*K* = 2) and high (*K* =12) biomolecular dielectric constant. 136

Figure 6.3: Equivalent Representation of the TCCT as the combination of a pnp and npn biploar junction transistor. 137

Figure 6.4: Energy band diagram along the x-axis of the nanogap TCCT biosensor 1 nm below the gate-oxide and inside the silicon film with L_G = 50 nm, L_{GAP} = 15 nm, T_{GAP} = 10 nm and T_{OX} = 3 nm, for various bias conditions: (a) Equilibrium state (V_G = V_{AK} = 0 V), OFF state (V_G = 0 V and V_{AK} = 2.5 V), and ON state (V_G = 2 V and V_{AK} = 2.5 V) with *K* = 1 (Air) (b) V_{AK} = 2.5 V, V_G = 1.5 V with *K* = 1 (Air) and *K* = 2 and 12 (biomolecules).....138

Figure 6.5: Peak value of current sensitivity $S_{current}$ of the nanogap TCCT calculated for values of V_G between 0 V to 2 V as a function of L_{GAP} and T_{GAP} with L_G = 50 nm, V_{AK} = 2.5 V and *K* = 12: (a) Peak $S_{current}$ vs. L_{GAP} for T_{OX} = 2 and 3 nm (b) Peak $S_{current}$ vs. T_{GAP} for L_{GAP} = 10 nm and 15 nm and T_{OX} = 2 nm. 140

Figure 6.6: Peak value of current sensitivity $S_{current}$ of the nanogap TCCT calculated for values of V_G between 0 V to 2 V for charged biomolecules with L_G = 50 nm, L_{GAP} = 15 nm, T_{GAP} = 10 nm, T_{OX} = 2nm and V_{AK} = 2.5 V: (a) Peak $S_{current}$ for increasing charge density of positively charged biomolecules with K = 2 and 12 (b) Peak $S_{current}$ for increasing charge density of negatively charged biomolecules with K = 2 and 12. 142

Figure 6.7: Cross sectional view of the underlap TCCT Charge-modulated biosensor. 143

Figure 6.8: Transfer characteristics of the underlap TCCT biosensor with L = 100 nm, L_G = 50 nm, L_U = 25 nm and T_{OX} = 1 nm at V_{SD} = 1.5 V and biomolecules in the underlap with different values of charge density Q_{bio} (cm^{-2}): (a) I_D vs. V_G (b) Current sensitivity $S_{current}$ vs. V_G. 145

List of Symbols

α_{npn}	DC common-base current gain for an npn bipolar junction transistor
α_{pnp}	DC common-base current gain for a pnp bipolar junction transistor
BGN	Band Gap Narrowing
BJT	Bipolar Junction Transistor
BTBT	Band to Band Tunneling
CMOS	Complementary Metal Oxide Semiconductor
c_{elec}	Electrolyte Ion concentration
δ	Debye length
DGIMOS	Drain-side Gate-underlap Impact-ionization Metal Oxide Semiconductor
DMIMOS	Dielectric-modulated Impact-ionization Metal Oxide Semiconductor
DMFET	Dielectric-modulated Field-effect transistor
DNA	Deoxyribonucleic acid
DRAM	Dynamic Random Access Memory
ΔV_G	Change in the required gate voltage of a biosensor, due to immobilization of biomolecules, for attaining a reference drain current value
ΔV_T	Change in the biosensor threshold voltage due to immobilization of biomolecules
ΔI_{ON}	Change in the ON-state current of biosensor due to immobilization of biomolecules
E_g	Energy band gap of the material
FET	Field-effect Transistor
FED	Field-effect Diode

FD-SOI	Fully Depleted Silicon On Insulator
I-MOS	Impact-ionization Metal Oxide Semiconductor
IUPAC	International Union of Pure and Applied Chemistry
ISFET	Ion-Sensitive Field-Effect Transistor
I_A	Anode current
I_{A0}	Anode current of biosensor in the absence of biomolecules
I_{Abio}	Anode current of biosensor after the immobilization of biomolecules
I_{C0npn}	Collector-base reverse saturation current of an npn BJT
I_{C0pnp}	Collector-base reverse saturation current of a pnp BJT
I_D	Drain current
I_{D0}	Drain current of a biosensor in the absence of biomolecules
I_{Dbio}	Drain current of a biosensor after the immobilization of biomolecules
$I_{D,Ref}$	Reference drain current used for comparison of the gate voltage shift or the current sensitivity parameter of the biosensor
I_{OFF}	OFF-State current
I_{ON}	ON-State current
K	Dielectric constant
K_{elec}	Electrolyte dielectric const.
K_{EDL}	Electric Double layer (EDL) dielectric const.
L_G	Length of the gate electrode
L_{UG}	Length of the ungated region of the channel

L_U	Length of the gate underlap region for underlap biosensors
L_{IN}	Length of the intrinsic region of the I-MOS
L_S	Length of the source region
L_D	Length of the drain region
L_{GAP}	Length of the nanogap region
L_{Cr}	Length of the chromium gate electrode in the DMIMOS
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
N_A	Acceptor doping concentration in a P-region
N_D	Donor doping concentration in an N-region
P_{Device}	Power (product of current and voltage) of biosensing device
PIN	Denotes a device consisting of P-type and N-type regions with an intrinsic semiconductor region separating them
Φ_M	Work function of the gate electrode
Q_{bio}	Charge density on the immobilized biomolecules
SOI	Silicon On Insulator
SS	Subthreshold Swing
$S_{current}$	Current sensitivity of a biosensor, denoting relative change in current due to the immobilization and conjugation of biomolecules over the gate insulator surface
SRAM	Static Random Access Memory
SRH	Shockley–Read–Hall recombination model
TCAD	Technology Computer-aided Design
TFET	Tunnel Field Effect Transistor
TCCT	Thin Capacitively Coupled Thyristor
T_{OX}	Gate oxide thickness

T_{Si}	Silicon body thickness
T_{BOX}	Thickness of the buried oxide
T_{GAP}	Thickness of the nanogap region
T_{EDL}	Electric Double layer (EDL) thickness
U-FET	Underlap Field-effect Transistor
V_{BD}	Device breakdown voltage
V_{BF}	Forward break over voltage for a TCCT
V_{DD}	Supply voltage
V_D	Drain voltage
V_S	Source voltage
V_{DS}/V_{SD}	Drain to source or Source to drain voltage
V_{AK}	Anode to cathode voltage
V_G	Gate voltage
V_{GS}	Gate to source voltage
V_{G0}	Gate voltage required to achieve $I_{D,Ref}$ in the absence of biomolecules
V_{Gbio}	Gate voltage required to achieve $I_{D,Ref}$ in the presence of biomolecules
V_T	Threshold voltage
V_{T0}	Threshold voltage in the absence of biomolecules
V_{Tbio}	Threshold voltage in the presence of biomolecules
Z^2-FET	Zero subthreshold swing Zero impact ionization FET
Z^3-FET	Zero gate Zero subthreshold swing Zero impact ionization FET