LABEL-FREE HIGHLY SENSITIVE BIOSENSORS BASED ON SILICON ON INSULATOR

By

Ahmed Samy Saad El-Din Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Engineering Physics

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

LABEL-FREE HIGHLY SENSITIVE BIOSENSORS BASED ON SILICON ON INSULATOR

By
Ahmed Samy Saad El-Din Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Engineering Physics

Under the Supervision of

Dr. Essam M. A. ELKaramany
Associate Professor
Engineering Mathematics and Physics Faculty
of Engineering, Cairo University

Dr. Mohamed Farhat Hameed
Associate Professor
Mathematics and Engineering Physics
Faculty of Engineering, Mansoura
University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

LABEL-FREE HIGHLY SENSITIVE BIOSENSORS BASED ON SILICON ON INSULATOR

By
Ahmed Samy Saad El-Din Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Engineering Physics

Approved by the
Examining Committee

_____
Dr. Essam M. A. Elkaramany, **(Thesis Main Advisor)**

_____
Prof. Dr. Nadia H. Rafat, **(Internal Examiner)**

_____
Prof. Dr. Adel H. Phillips, **(External Examiner)**
- Professor, Faculty of Engineering, Ain Shams university

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

Engineer's Name: Ahmed Samy Saad El-Din Ahmed
Date of Birth: 2/6/1986
Nationality: Egyptian
E-mail: Ahmed_samy2086@yahoo.com
Phone: 01280980888
Address: 7 Eltakafol St., El taawn station, Al Haram

Registration Date: 1/3/2014
Awarding Date: …./…./……..
Degree: Doctor of Philosophy
Department: Engineering Mathematics and Physics

Supervisors:

Dr. Essam M. A. ELKaramany
Dr. Mohamed Farhat O. Hameed
Associate professor, Faculty of Engineering, Mansoura university

Examiners:

Prof. Adel H. Phillips (External examiner)
Professor, Faculty of Engineering, Ain Shams university
Prof. Nadia H. Rafat (Internal examiner)
Dr. Essam M. A. ElKaramany (Thesis main advisor)

Title of Thesis:

LABEL-FREE HIGHLY SENSITIVE BIOSENSORS BASED ON SILICON ON INSULATOR

Key Words:
DNA hybridization; Label-free biosensor; Slot-waveguide; SOI; Surface Plasmon

Summary:

A highly sensitive hybrid plasmonic slot-waveguide (HPSW) biosensors based on silicon-on-insulator (SOI) are proposed and analyzed for DNA hybridization detection. The reported designs are based on increasing the light interaction with the sensing region by using slot-waveguide with plasmonic material.
Due to the high index contrast and plasmonic effect, an ultra-high optical confinement is achieved in the low-index regions which enables the detection of the smallest change in the analyte refractive index with high sensitivity.
In this study, two different plasmonic materials (gold, and titanium nitride) are used for the proposed designs. The simulation results are calculated using full vectorial finite element method (FVFEM). The reported biosensors have high sensitivity of 1890.4 nm/RIU with a detection limit of 2.65×10^{-6} RIU with gold material, and 1190 nm/RIU with a detection limit of 4.2×10^{-6} RIU with titanium nitride material, which are the highest in the literature to the best of our knowledge.

Acknowledgment

First of all I must thank ALLAH for his great mercy supporting me all the way till the end. If it weren't for his help, I wouldn't have reached this point.

My deep gratitude goes to Assoc. Prof. Essam M. A. ELKaramany, my main supervisor, for his patient guidance, encouragement, and support throughout my Ph.D. study. Your invaluable guidance helped me in all the time of research, as well as will keep encouraging me in my future career and life.

I would like especially to thank Assoc. Prof. Mohamed Farhat Hameed, my co-supervisor, for his patient guidance, valuable discussions, and constructive suggestions on the direction of my researches, and scientific writing during the past years, as well as will keep encouraging me in my future career and life. Your immense knowledge, rigorous working attitude and enthusiasm in research always encouraged me to work toward the best.

Many thanks to Prof. Salah S. A. Obayya, Director of Center for Photonics and Smart Materials (CPSM) Zewail City of Science and Technology, for his kind help and guidances in my Ph. D studies, and giving me the opportunity to work in a fruitful research environment.

My deepest gratitude to my parents and parents in law, who are unconditionally loving, supporting and encouraging me. Thanks to my beloved wife, Salma Yehia, thank you for your support and endless love when life was tough; My son, Youssef, you are the best gift for me!

Table of Contents

List of Tables

List of Figures

List of Symbols and Abbreviations

Symbols

A^e	Area of element (e)
Ag	Silver
Au	Gold
B	Magnetic flux density
CaF_2	Calcium Fluoride
Cu	Copper
D	Electric flux density
E	Electric field vector
E_0	Amplitude of the electric field
E_z	z-component of the electric field
GaAs	Gallium Arsenide
Ge	Germanium
GH	Guide height
GW	Guide width
I	intensity
InP	Indium Phosphide
J	Current density
K	wavenumber
L_i^e	Lagrange interpolation polynomial for element (e) and node (i)
$LiNbO_3$	Lithium Niobate
n	Refractive index
N_i^e	Shape function correlated with node (i)
PSW	Plasmonic slot width
P_z	z-component of the power flow
S	sensitivity
S_{21}	Transmission coefficient
S_D	Device sensitivity
Si	Silicon
SiN_x	Silicon Nitride

SiO_2	Silicon dioxide
SW	Slot width
T	Temperature
TiN	Titanium Nitride
t_{plasm}	Plasmonic thickness
V^e	Volume of the element (e)
β	Propagation constant
ε	Permittivity
ε_r	Relative Permittivity
θ	Incident angle
λ	wavelength
Φ_0	Phase constant
ω	Angular frequency

Abbreviations

BESOI	Bond and etched-back silicon on insulator
BOX	Buried oxide layer
BSA	Bovine serum albumin
BSOI	Bond silicon on insulator
CCD	Charge Coupled Device
CMOS	Complementary Metal Oxide-Semiconductor
CMP	Chemical mechanical polishing
DNA	Deoxyribonucleic acid
dsDNA	Double strand DNA
DSP	Digital signal processing
ELTRAN	Epitaxial layer transfer
FEM	Finite Element Method
FV-FEM	Full vectorial Finite element method
HP	Hybrid Plasmonic
HPSW	Hybrid Plasmonic Slot Waveguide
IC	Integrated circuit

IR	Infrared
IUPAC	International Union of Pure and Applied Chemistry
LVIC	Large volume integrated circuit
MEMS	Micro electromechanical system
MZI	Mach-zehnder interferometer
OSA	Optical Spectrum Analyzer
PhC	Photonic crystal
PCF	Photonic crystal fiber
PD	Photodetector
PML	Perfect matched layer
PMT	Photomultiplier Tube
RI	Refractive index
RIU	Refractive index unit
SIMOX	Separation by Implantation oxygen
SOI	Silicon on Insulator
SON	Silicon on nitride
SOS	Silicon on sapphire
SPP	Surface Plasmon Polariation
SPR	Surface plasmon resonance
SPW	Surface plasmon wave
ssDNA	Single strand DNA
TE	Transvers electric
TM	Transvers magnetic

Abstract

Highly sensitive hybrid plasmonic slot-waveguide (HPSW) biosensors based on silicon-on-insulator (SOI) are proposed and analyzed for DNA hybridization detection. The reported designs are based on increasing the light interaction with the sensing region by using slot-waveguide with plasmonic material. Due to the high index contrast and plasmonic effect, an ultra-high optical confinement is achieved in the low-index regions which enables the detection of the smallest change in the analyte refractive index with high sensitivity. The normalized power confinement, power density, effective index of the supported modes by the HPSWs are analyzed to achieve high power confinement through the suggested biosensors and hence high sensitivity can be obtained. The HPSWs are also incorporated with straight slotted resonator to calculate the sensitivity of the proposed design. In this study, two different plasmonic materials (gold, and titanium nitride) are used for the proposed designs. The simulation results are calculated using full vectorial finite element method (FVFEM). The reported biosensors have high sensitivity of 1890.4 nm/RIU (refractive index unit) with a detection limit of 2.65×10^{-6} RIU with gold material, and 1190 nm/RIU with a detection limit of 4.2×10^{-6} RIU with titanium nitride material, which are the highest in the literature to the best of our knowledge.