



# **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**

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FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
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**Title of Thesis:**

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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  $2.65 \times 10^{-6}$  RIU with gold material, and 1190 nm/RIU with a detection limit of  $4.2 \times 10^{-6}$  RIU with titanium nitride material, which are the highest in the literature to the best of our knowledge.

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## List of Symbols and Abbreviations

### Symbols

$A^e$	Area of element (e)
Ag	Silver
Au	Gold
B	Magnetic flux density
$\text{CaF}_2$	Calcium Fluoride
Cu	Copper
D	Electric flux density
<b>E</b>	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)
$\text{LiNbO}_3$	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
$\text{SiN}_x$	Silicon Nitride

$\text{SiO}_2$	Silicon dioxide
SW	Slot width
T	Temperature
TiN	Titanium Nitride
$t_{\text{plasm}}$	Plasmonic thickness
$V^e$	Volume of the element (e)
$\beta$	Propagation constant
$\varepsilon$	Permittivity
$\varepsilon_r$	Relative Permittivity
$\theta$	Incident angle
$\lambda$	wavelength
$\Phi_0$	Phase constant
$\omega$	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 Polarization
SPR	Surface plasmon resonance
SPW	Surface plasmon wave
ssDNA	Single strand DNA
TE	Transverse electric
TM	Transverse 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  $2.65 \times 10^{-6}$  RIU with gold material, and 1190 nm/RIU with a detection limit of  $4.2 \times 10^{-6}$  RIU with titanium nitride material, which are the highest in the literature to the best of our knowledge.