

LSPR- and SERS-based PLASMONIC SENSORS

ABHIJIT KUMAR DAS



DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2022

LSPR- and SERS-based PLASMONIC SENSORS

by

ABHIJIT KUMAR DAS

Department of Electrical Engineering

submitted

in fulfillment of the requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2022

CERTIFICATE

This is to certify that this thesis entitled “**LSPR- and SERS-based Plasmonic Sensors**” being submitted by **Abhijit Kumar Das** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements, which to my knowledge, have reached the requisite standard for the submission of the thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.



Prof. Anuj Dhawan
Department of Electrical Engineering
Indian Institute of Technology Delhi

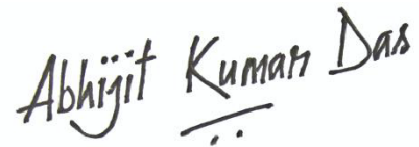
ACKNOWLEDGEMENTS

I thank my supervisor, Prof. Anuj Dhawan, for the opportunity to carry out my research work and for providing encouragement and guidance.

I also extend my sincere thanks to the members of my SRC, Prof. Manan Suri, Prof. Swades De, and Prof. Shantanu Ghosh, for their support.

To my fellow lab members at Nano-Photonics and Plasmonics Laboratory, my heartiest appreciation for fruitful suggestions and sharing with me their knowledge and ideas. I would like to express my gratitude to the Nanoscale Research Facility at IIT Delhi and the Indian Nanoelectronics Users' Programme at IIT Bombay for providing the experimental facility for my research.

Finally, I am thankful to my family for their unwavering support throughout my career and beyond.

A handwritten signature in black ink that reads "Abhijit Kumar Das". The signature is written in a cursive style, with "Abhijit" and "Kumar" on the first line and "Das" on the second line. There are some small dots and a horizontal line under "Kumar".

Abhijit Kumar Das

February 2022

ABSTRACT

There is significant interest in the development of plasmonic nanostructures for the detection of chemicals or biomarkers based on Localized Surface Plasmon Resonance (LSPR). The large electric-field enhancement due to the excitation of LSPR or SPR also enables surface-enhanced Raman scattering (SERS), which is used for the specific and sensitive detection of chemicals and biological molecules of interest. This thesis details the research work carried out in the development of plasmonic nanostructures and nanoparticles for LSPR- and SERS-based applications.

The design and numerical simulations of a nanostructure geometry consisting of arrays of nanocrosses interspaced between triangular bowties for LSPR-based refractive index sensing have been presented. Various parameters of the geometry were varied, and their effect studied. The geometry was suitably tuned to maximize bulk and localized sensing performance in different regimes of operation.

The process for the formation of gold nanoparticles (AuNPs) by evaporation on substrates at a high temperature has been thoroughly studied. Highly crystalline AuNPs have been successfully formed for film thicknesses up to 40 nm at a comparatively lower temperature of 500 °C. The bulk and localized sensitivity of the fabricated AuNPs were evaluated.

A novel method for developing large-area SERS substrates based on gold-coated nanostructured surfaces has been presented. The SERS substrates were optimized by variation in the fabrication process parameters. The substrates were tested using a SERS active molecule (pMBA) and subsequently used for the detection of organophosphorous pesticides — Paraoxon-Methyl and Paraoxon-Ethyl.

The growth of silver nanowires performed (AgNWs) on flexible substrates – plain weave fabric and Kapton was studied and their performance compared with AgNWs grown on a rigid substrate – silicon. The substrates were assessed with the SERS active molecule pMBA and also employed for the label-free detection of DNA nucleobases adenine (A) and cytosine (C).

सारांश

स्थानीयकृत सतह प्लास्मोन रेजोनेंस (एलएसपीआर) पर आधारित रसायनों या बायोमार्करों का पता लगाने के लिए प्लास्मोनिक नैनोस्ट्रक्चर के विकास में महत्वपूर्ण रुचि है। एलएसपीआर या एसपीआर की उत्तेजना के कारण बड़े विद्युत-क्षेत्र में वृद्धि सतह-वर्धित रमन स्कैटरिंग (एसईआरएस) को भी सक्षम बनाती है, जिसका उपयोग रसायनों और जैविक अणुओं की विशिष्ट और संवेदनशील पहचान के लिए किया जाता है। यह थीसिस एलएसपीआर- और SERS-आधारित अनुप्रयोगों के लिए प्लास्मोनिक नैनोस्ट्रक्चर और नैनोकणों के विकास में किए गए शोध कार्य का विवरण देती है।

एलएसपीआर-आधारित अपवर्तक सूचकांक संवेदन के लिए त्रिकोणीय आकृति के बीच प्रतिच्छेदित नैनोकॉस से युक्त एक नैनोस्ट्रक्चर ज्यामिति के डिजाइन और सिमुलेशन प्रस्तुत किए गए हैं, और उनके प्रभाव का अध्ययन किया गया है।

उच्च तापमान पर सबस्ट्रेट पर वाष्पीकरण द्वारा सोने के नैनोकणों (AuNPs) के निर्माण की प्रक्रिया का गहन अध्ययन किया गया है। 500 डिग्री सेल्सियस के तुलनात्मक रूप से कम तापमान पर 40 nm तक की फिल्म मोटाई के लिए अत्यधिक क्रिस्टलीय AuNP का सफलतापूर्वक गठन किया गया है। AuNPs की बल्क और स्थानीय संवेदनशीलता का मूल्यांकन किया गया है।

गोल्ड-कोटेड नैनोस्ट्रक्चर्ड सतहों पर आधारित बड़े क्षेत्र के SERS सेंसर चिप्स विकसित करने के लिए एक नई विधि प्रस्तुत की गई है। SERS सेंसर चिप्स को निर्माण प्रक्रिया मापदंडों में भिन्नता द्वारा अनुकूलित किया गया है। सबस्ट्रेट्स का एक SERS सक्रिय अणु (pMBA) का उपयोग करके परीक्षण किया गया और बाद में ऑर्गनोफॉस्फोरस कीटनाशकों - पैराऑक्सन-मिथाइल और पैराऑक्सन-एथिल का पता लगाने के लिए उपयोग किया गया है।

लचीले सबस्ट्रेट - सादे बुनाई के कपड़े और कैप्टन पर सिल्वर नैनोवायर्स के प्रदर्शन (AgNWs) की वृद्धि का अध्ययन किया गया और कठोर सबस्ट्रेट - सिलिकॉन पर उगाए गए AgNW की तुलना में उनके प्रदर्शन का अध्ययन किया गया। सबस्ट्रेट्स का मूल्यांकन SERS सक्रिय अणु pMBA के साथ किया गया है और डीएनए न्यूक्लियोबेस एडेनिन (A) और साइटोसिन (C) के लेबल-मुक्त पता लगाने के लिए भी नियोजित किया गया है।

Table of Contents

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
Table of Contents	ix
List of Figures	xi
List of Tables.....	xvii
List of Abbreviations.....	xix
1. Introduction	1
2. Fundamentals of Plasmonics.....	5
2.1 Optical Properties of Metals	5
2.2 Plasmons, Plasmon-Polaritons, and Surface Plasmon-Polaritons	6
2.3 Suitable Metals for Plasmonics	8
2.4 Localized Surface Plasmons.....	9
2.5 Surface Enhanced Raman Spectroscopy (SERS)	12
2.6 Finite-Difference Time-Domain Method	14
2.7 Experimental Methods.....	16
3. Nanocrosses interspaced between crossed-bowties for LSPR-based sensing.....	25
3.1. Introduction	25
3.2. Structure and Simulation Details.....	27
3.3. Results and Discussion	29
3.4. Conclusions	40
4. LSPR sensor chips based on crystalline gold nanoparticles on silica	49
4.1. Introduction	49
4.2. Experimental Methods.....	51

4.3. Results and Discussion	53
4.4. Conclusions	67
5. Large-area gold-coated nanostructured surface as a SERS substrate	75
5.1. Introduction	75
5.2. Experimental Methods.....	77
5.3. Results and Discussion	80
5.4. Conclusions	85
6. Conformal, large-area, and low-cost SERS substrates using GLAD.....	93
6.1. Introduction	93
6.2. Experimental Methods.....	96
6.3. Results and Discussion	98
6.4. Conclusions	103
7. Conclusions	109
List of Publications	111
Biodata	113

List of Figures

Chapter 2

Figure 2.1. Interface between a metal and dielectric for surface plasmon propagation [1]..	7
Figure 2.2. (a) The Kretschmann coupling method. (b) The Otto coupling method.	8
Figure 2.3. The grating coupling method.....	8
Figure 2.4. Real and Imaginary parts of the dielectric constants of various metals [2].....	9
Figure 2.5. A single metallic nanosphere in a homogenous electric field [1].....	10
Figure 2.6. (a) Bulk LSPR sensing and (b) Localized LSPR sensing using gold (Au) nanoparticles.	12
Figure 2.7. Simplified energy-level diagram illustrating the states involved in Rayleigh Scattering, Stokes Raman Scattering, and Anti-Stokes Raman Scattering [6].....	13
Figure 2.8. Schematic for (a) a thermal evaporator and (b) an electron-beam evaporator.	17
Figure 2.9. Schematic of an RIE vacuum chamber [25].	18
Figure 2.10. Principle of X-ray Diffraction – Bragg’s Law.....	21

Chapter 3

Figure 3.1. Schematics showing: (a) Plasmonic nanostructures consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses on a SiO₂ substrate, with a top view inset; (b) bulk LSPR sensing arrangement using the plasmonic nanostructures; and (c) localized LSPR sensing arrangement. Here, ‘W’ is the nanocross pillar width, and ‘d’ is the edge-to-edge gap distance between all the pillars. The side length of the right-angled triangular pillars is given by ‘L’. The height of the nanopillars is 50 nm.27

Figure 3.2. Reflectance spectra of plasmonic nanostructures, consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses, for different values of nanocross pillar width, ‘W’. The triangular pillar side length, ‘L’ and the edge-to-edge gap distance, ‘d’, were kept constant at 100 nm and 6 nm, respectively. Ambient refractive index, n was taken to be 1.33. The height of the Au nanopillars was taken to be 50 nm.....30

Figure 3.3. (a) Schematic showing the plasmonic nanostructures consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses employed for carrying out bulk refractive index sensing. (b) Shift in the reflectance spectra due to a change in ambient refractive index for the plasmonic nanostructures with nanocross pillar width ‘W’ = 50 nm. Shift in dip wavelength as a function of ambient refractive index for (c) Mode 1 resonance and (d) Mode 2 resonance with different nanocross pillar widths ‘W’. The

triangular pillar side length, 'L' and the edge-to-edge gap distance, 'd', were kept constant at 100 nm and 6 nm, respectively. The height of the Au nanopillars was taken to be 50 nm.31

Figure 3.4. Reflectance spectra of plasmonic nanostructures, consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses, for different values of the triangular pillar side length, 'L'. The nanocross pillar width, 'W' and the gap distance, 'd' were kept constant at 100 nm and 6 nm, respectively. Ambient refractive index, n was taken to be 1.33. The height of the Au nanopillars was taken to be 50 nm.....33

Figure 3.5. Shift in dip wavelength as a function of ambient refractive index around plasmonic nanostructures consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses for (a) Mode 1 resonance and (b) Mode 2 resonance with different values of triangular pillar side length 'L'. The nanocross pillar width, 'W' and the edge-to-edge gap distance, 'd' were 100 nm and 6 nm, respectively. The height of the Au nanopillars was taken to be 50 nm.34

Figure 3.6. Reflectance spectra of plasmonic nanostructures, consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses, for a change in edge-to-edge gap distance, 'd'. The nanocross pillar width, 'W', and the triangular pillar side length, 'L' were kept constant at 100 nm and 100 nm, respectively. The ambient refractive index, n, was taken to be 1.33. The height of the Au nanopillars was taken to be 50 nm.35

Figure 3.7. Shift in dip wavelength as a function of ambient refractive index around plasmonic nanostructures consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses for (a) Mode 1 resonance and (b) Mode 2 resonance with different values of edge-to-edge gap distance 'd'. The nanocross pillar width, 'W', and the triangular pillar side length, 'L', were 100 nm and 100 nm, respectively. The height of the Au nanopillars was taken to be 50 nm.36

Figure 3.8. Spatial distribution of the electric-field enhancements around the plasmonic nanostructures, consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses, with 'W' = 100 nm, 'L' = 100 nm, 'd' = 6 nm, and the ambient refractive index, n = 1.33 for: (a) Mode 2 plasmon resonance dip at $\lambda = 1400$ nm, (b) Off-resonance dip at $\lambda = 1530$ nm, (c) Mode 1 resonance dip at $\lambda = 1700$ nm, and (d) Off-resonance tail at $\lambda = 2000$ nm.37

Figure 3.9. (a) Schematic showing the plasmonic nanostructures consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses employed for localized sensing. Shift in the reflectance spectra due to the addition of a 2 nm biomolecule layer having a refractive index of 1.53 over the plasmonic nanostructures, for different values

of the triangular pillar side length 'L': (b) 'L' = 80 nm, (c) 'L' = 90 nm, and (d) 'L' = 120 nm. The nanocross pillar width, 'W' and the edge-to-edge gap distance, 'd' were taken to be 100 nm and 6 nm, respectively. Ambient refractive index, n was taken to be 1.33. The height of the Au nanopillars was taken to be 50 nm.....39

Chapter 4

Figure 4.1. (a) Schematic showing the plasmonic AuNPs grown on silica; (b) bulk LSPR sensing, and (c) localized LSPR sensing using the grown plasmonic AuNPs. Process schematic and FESEM image of (d) AuNPs grown by thermal evaporation on a heated substrate; and (e) AuNPs formed via post-deposition annealing.....52

Figure 4.2. (a) Schematic of a thermal evaporation chamber used for the growth of the AuNPs. FESEM images of AuNPs grown on silica at different substrate temperatures, T: (b) 100 °C, (c) 200 °C, (d) 300 °C, (e) 400 °C, and (f) 500 °C. QCM film thickness, t, of 10 nm Au was deposited at a rate, r, of 0.5 Å/s.54

Figure 4.3. Absorbance spectra obtained from UV-Vis spectrophotometer in (a) air, and (c) water of AuNPs grown on silica at different substrate temperatures, T. (b) Corresponding LSPR wavelength and FWHM obtained from curves in (a). (d) Bulk sensitivity and FOM obtained from curves in (a) and (c). QCM film thickness, t, of 10 nm Au was deposited at a rate, r, of 0.5 Å/s.55

Figure 4.4. FESEM images of AuNPs grown on silica at different deposition rates, r: (a) 0.1 Å/s, (b) 0.2 Å/s, (c) 0.5 Å/s, and (d) 1.0 Å/s. QCM film thickness, t of 10 nm Au was deposited at a substrate temperature, T of 500 °C.56

Figure 4.5. Absorbance spectra obtained from UV-Vis spectrophotometer in (a) air and (c) water of AuNPs grown on silica at different deposition rates, r. (b) Corresponding LSPR wavelength and FWHM obtained from curves in (a). (d) Bulk sensitivity and FOM obtained from curves in (a) and (c). QCM film thickness, t of 10 nm Au was deposited at a substrate temperature, T of 500 °C.57

Figure 4.6. FESEM images of AuNPs grown on silica for different QCM film thickness values, t: (a) 5 nm, (b) 10 nm, (c) 15 nm, (d) 20 nm, (e) 25 nm, (f) & (h) 30 nm, (g) & (i) 40 nm. Deposition was carried out at a substrate temperature, T, of 500 °C, with a rate, r, of 0.1 Å/s.58

Figure 4.7. Absorbance spectra obtained from UV-Vis spectrophotometer in (a) air and (c) water of AuNPs grown on silica for different QCM film thickness values, t. (b) Corresponding LSPR wavelength and FWHM obtained from curves in (a). (d) Bulk

sensitivity and FOM obtained from curves in (a) and (c). The deposition was carried out at a substrate temperature, T , of 500 °C, with rate, r , of 0.1 Å/s.....59

Figure 4.8. (a) Normalized absorbance spectra obtained from UV-Vis spectrophotometer in different solvents for AuNPs grown on silica for QCM film thickness, $t = 25$ nm; at substrate temperature, T , of 500 °C; with rate, r , of 0.1 Å/s. (b) Shift in the LSPR wavelength of the AuNPs grown on silica as a function of ambient refractive index.60

Figure 4.9. (a) Normalized absorbance spectra obtained from UV-Vis spectrophotometer from AuNPs over-coated with incremental thicknesses of Al₂O₃ thin films via ALD. (b) Shift in the LSPR wavelength of the AuNPs grown on silica as a function of over-coated film thickness. AuNPs were grown on silica for QCM film thickness, $t = 25$ nm; at substrate temperature, T , of 500 °C; with rate, r , of 0.1 Å/s.61

Figure 4.10. (a) XRD patterns of AuNPs, either grown or annealed after deposition, on a silica substrate. (b)-(e) FESEM images of the equivalent AuNPs for $t = 10$ nm.....63

Figure 4.11. XRD patterns of AuNPs grown on silica for different QCM film thicknesses. FESEM images of the equivalent AuNPs are also presented.63

Figure 4.12. FESEM images of annealed AuNPs on silica for different QCM film thickness values, t : (a) 3 nm, (b) 5 nm, (c) 8 nm, and (d) 10 nm. Post deposition, annealing was carried out in the evaporation vacuum chamber at a temperature of 500 °C for 30 minutes.....64

Figure 4.13. Absorbance spectra obtained from UV-Vis spectrophotometer in (a) air and (c) water of annealed AuNPs on silica for different QCM film thickness values. (b) Corresponding LSPR wavelength and FWHM obtained from curves in (a). (d) Bulk sensitivity and FOM obtained from curves in (a) and (c). Post deposition, annealing was carried out in the evaporation vacuum chamber at a temperature of 500 °C for 30 minutes. .65

Figure 4.S1. Real (n) and imaginary (k) part of the refractive index of the Al₂O₃ thin film — as a function of wavelength.68

Chapter 5

Figure 5.1. (a) 3” silicon wafer with 1000 nm SiO₂. (b) SERS substrates and (c) SEM images of the gold-coated nanostructured surface formed with 2000 s CHF₃ plasma exposure, followed by 400 s O₂ plasma exposure and 60 nm Au overcoating. (d) Raman signals of 10⁻³ M pMBA on the gold-coated nanostructured surface obtained with increasing CHF₃ plasma

exposure followed by 400 s O ₂ plasma exposure and 60 nm Au overcoating. (e) Process schematic for the fabrication of large-area gold-coated nanostructured surface.	79
Figure 5.2. SEM images of the gold-coated nanostructured surface formed with CHF ₃ plasma exposure, followed by O ₂ plasma exposure and 60 nm Au over-coating.....	80
Figure 5.3. Raman signals of 10 ⁻³ M pMBA on the gold-coated nanostructured surface obtained with CHF ₃ plasma exposure – (a) 500 s, (b) 1000 s, and (c) 2000 s followed by O ₂ plasma exposure (0 s, 200 s, and 400 s) along z-axis.	81
Figure 5.4. Raman signals of varying concentrations of pMBA on the gold-coated nanostructured surface-based SERS substrates.	82
Figure 5.5. Raman signal peak counts at 1080 cm ⁻¹ of varying concentrations of pMBA on gold-coated nanostructured surface-based SERS substrates.....	83
Figure 5.6. Raman signal peak maps of 10 ⁻³ M pMBA at (a) 1080 cm ⁻¹ , and (b) 1592 cm ⁻¹ on gold-coated nanostructured surface-based SERS substrates.....	83
Figure 5.7. Raman signal peak counts of 10 ⁻³ M pMBA on gold-coated nanostructured surface-based SERS substrates: (a) at different locations on one sample, and (b) on different substrates.....	84
Figure 5.8. Raman signals of 10 ⁻³ M (a) Paraoxon-Ethyl and (b) Paraoxon-Methyl on gold-coated nanostructured surface-based SERS substrates.	84

Chapter 6

Figure 6.1. (a) Schematic of the thermal evaporator system employed for the glancing angle deposition of silver nanowires (AgNWs) on a woven textile fabric; (b) Schematic showing a plain weave fabric made from multifilament yarns, with inset showing the FESEM image of the multifilament yarns (warp yarns and weft yarns) woven into a plain weave; (c) Schematic of a close-up of a crossover point of warp and weft yarns in a woven fabric, with inset showing the FESEM image of the individual fibers (or filaments) in a multifilament yarn; and (d) Schematic showing AgNWs on the fiber of the multifilament yarns (warp and weft yarns) that are woven into a fabric.....	95
Figure 6.2. Photographs and FESEM images of AgNWs grown on different substrates — (a) silicon; (b) Kapton; and (c) plain weave fabric.	97
Figure 6.3. FESEM images of AgNWs grown on the plain weave fabric.	99
Figure 6.4. (a) Raman signals of 10 ⁻³ M pMBA on AgNWs grown on different substrates. Measurement parameters: 785 nm laser, 10 s acquisition, 25 mW power. (b) Raman signals of 10 ⁻³ M pMBA from different lasers incident on AgNWs grown on the plain weave fabric.	

Measurement parameters: 532 nm laser — 10 s acquisition, 0.25 mW power; 633 nm laser — 10 s acquisition, 0.17 mW power; and 785 nm laser — 10 s acquisition, 0.25 mW power. . 100

Figure 6.5. Raman signals of varying concentrations of pMBA on AgNWs grown on the fabric. Measurement parameters were – 785 nm laser, 10 s acquisition, 25 mW power. 100

Figure 6.6. Raman signal peak counts at (a) 1084 cm^{-1} , and (b) 1593 cm^{-1} of varying concentrations of pMBA on AgNWs grown on the fabric. Measurement parameters were – 785 nm laser, 10 s acquisition, 25 mW power. 101

Figure 6.7. Raman signal peak counts of 10^{-3} M pMBA on AgNWs grown on the fabric (a) at different locations on one sample and (b) on different substrates. Measurement parameters were – 785 nm laser, 10 s acquisition, 25 mW power. 102

Figure 6.8. Raman signals of 10^{-3} M aqueous solution of (a) adenine and (b) cytosine on AgNWs grown on the fabric. Measurement parameters were – 785 nm laser, 10 s acquisition, 25 mW power. 103

List of Tables

Chapter 3

Table 3.1. Bulk sensing performance characteristics of the plasmonic nanostructures — consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses — employed to detect changes in the ambient refractive index, for different values of nanocross pillar width ‘W’. The triangular pillar side length, ‘L’ and the edge-to-edge gap distance, ‘d’ were taken to be 100 nm and 6 nm. The height of the Au nanopillars was taken to be 50 nm.....32

Table 3.2. Bulk sensing performance characteristics of the plasmonic nanostructures — consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses — employed to detect changes in the ambient refractive index, for different values of triangular pillar side length ‘L’. The nanocross pillar width, ‘W’ and the edge-to-edge gap distance, ‘d’ were taken to be 100 nm and 6 nm. The height of the Au nanopillars was taken to be 50 nm.....34

Table 3.3. Bulk sensing performance characteristics of the plasmonic nanostructures — consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses — employed to detect changes in the ambient refractive index, for different values of edge-to-edge gap distance ‘d’. The nanocross pillar width, ‘W’ and triangular pillar side length, ‘L’, were taken to be 100 nm and 100 nm, respectively. The height of the Au nanopillars was taken to be 50 nm.....36

Table 3.4. Localized sensing performance characteristics of the plasmonic nanostructures — consisting of a periodic array of Au crossed-bowtie nanostructures interspaced with Au nanocrosses — employed to detect localized changes in the refractive index caused by the addition of a 2 nm biomolecule layer of $n = 1.53$ over the nanopillars, for different values of triangular pillar side length ‘L’. The nanocross pillar width, ‘W’ and the edge-to-edge gap distance, ‘d’ were taken to be 100 nm and 6 nm. Ambient refractive index, n was taken to be 1.33. Height of the Au nanopillars was 50 nm.39

Table 3.5. Characteristics of published plasmonic sensors40

Chapter 4

Table 4.1. Bulk sensing performance characteristics of AuNP-based sensors.66

Table 4.2. Surface sensitivity characteristics of plasmonic nanostructure-based sensors. .66

List of Abbreviations

AFM: Atomic Force Microscopy
AgNWs: Silver Nanowires
ALD: Atomic Layer Deposition
AuNPs: Gold Nanoparticles
DNA: Deoxyribonucleic Acid
EBL: Electron-Beam Lithography
EF: Enhancement Factor
EM: Electromagnetics
FDFD: Finite-Difference Frequency-Domain
FDTD: Finite-Difference Time-Domain
FEM: Finite Element Method
FESEM: Field Emission Scanning Electron Microscope
FIB: Focused Ion Beam
FOM: Figure of Merit
FMM: Fast Multipole Method
FWHM: Full Width Half Maximum
GLAD: Glancing Angle Deposition
HeFIB: Helium Focused Ion Beam
LSP: Localized Surface Plasmon
LSPR: Localized Surface Plasmon Resonance
MoM: Method of Moments
MPTES: (3-mercaptopropyl) triethoxy-silane
NN: Neural Network
PCA: Principal Component Analysis
PLD: Pulsed Laser Deposition
pMBA: 4-Mercaptobenzoic Acid
PML: Perfectly Matched Layer
QCM: Quartz Crystal Monitor
RIE: Reactive Ion Etching
RIU: Refractive Index Unit
SERS: Surface-Enhanced Raman Spectroscopy

SPP: Surface Plasmon Polariton

TEBAL: Transmission Electron Beam Ablation Lithography

TEM: Transmission Electron Microscopy

TLM: Transmission Line Method

UV-Vis: Ultraviolet-Visible Spectrophotometer

XRD: X-Ray Diffraction