Synthesis and Characterizations of Plasmonic Nanostructures for Molecular Sensing by Surface Enhanced Raman Scattering (SERS)

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Synthesis and Characterizations of Plasmonic Nanostructures for Molecular Sensing by Surface Enhanced Raman Scattering (SERS)

by

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Submitted

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

to the



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Dedicated to….

….My *Parents & family….*

whose love, patience, and constant encouragement have made this journey possible…

Certificate

This is to certify that the thesis entitled, ***"Synthesis and Characterizations of Plasmonic Nanostructures for Molecular Sensing by Surface Enhanced Raman Scattering (SERS)"****, being submitted by* ***Om Prakash*** *to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of* ***'Doctor of Philosophy'*** *is a record of bonafide research work carried out by him under our supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which, to the best of our knowledge, has reached the requisite standard.*

The material contained in the thesis has not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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Om Prakash

Abstract

Recent advancements in nanotechnology have enabled the development of highly efficient surface-enhanced Raman spectroscopy (SERS) platforms, facilitating rapid, cost-effective, and ultra-sensitive molecular detection. Contemporary SERS substrates consistently achieve enhancement factors up to 10^{10}, facilitating dependable single-molecule detection. These remarkable sensitivities result from localised surface plasmon resonances (LSPRs) produced at the nanoscale, where the electromagnetic field can be amplified by over 10^{11} times. A diverse array of materials has been explored for the fabrication of SERS substrates, with noble metals like gold (Au), silver (Ag), and copper (Cu) being the predominant choices due to their robust plasmonic response in the visible to near-infrared spectrum, chemical stability, and capacity to produce intense hotspots at nanogaps and sharp edges. Silver (Ag) provides the greatest electromagnetic enhancement and minimal losses, rendering it optimal for ultra-trace detection, whereas gold (Au) offers remarkable chemical stability and biocompatibility, facilitating biosensing and in vivo applications. Copper, despite its lower stability, provides an economical option with adjustable plasmonic properties. In addition to noble metals, semiconductor materials such as ZnO, TiO_2, MoS_2, WS_2, and graphene-based hybrids have garnered interest due to their mechanisms of charge transfer enhancement, chemical stability, and capacity to facilitate photocatalytic or synergistic sensing. These materials facilitate detection while concurrently enhancing selective adsorption, controlling molecular orientation, and suppressing fluorescence. Hybrid plasmonic semiconductor platforms, including Au-ZnO, Ag–TiO_2, and Au-MoS_2, have demonstrated significant efficacy by merging robust electromagnetic enhancement with chemical enhancement, facilitating reproducible SERS signals even at parts-per-trillion analyte concentrations. Diverse fabrication techniques, such as electron-beam lithography, chemical vapour deposition, thermal evaporation, laser-induced nanostructuring, colloidal assembly, and nanoparticle self-organisation, facilitate meticulous regulation of

morphology, interparticle spacing, surface roughness, and crystallinity, critical factors influencing hotspot density and SERS reproducibility. These advancements enable SERS to provide molecular fingerprinting in seconds, surpassing traditional analytical methods in sensitivity, speed, portability, and cost-effectiveness. These advancements have broadened the applicability of SERS to areas including pathogen identification, detection of environmental pollutants at ppb -ppt concentrations, monitoring of drug residues, food safety assessments, and early disease diagnostics. This advancement positions SERS as a premier nanotechnology-based analytical instrument for real-time, label-free, and ultra-trace molecular detection.

This thesis presents an in-depth examination of the fabrication and characterisation of advanced nanostructured materials and thin films, with a focus on enhancing optical and spectroscopic performance, particularly in Raman and surface-enhanced Raman scattering (SERS) applications. The study combines experimental synthesis techniques, such as chemical vapour deposition (CVD) and thermal evaporation, with controlled nanostructure engineering, and comprehensive structural, optical, and vibrational characterisation to elucidate the relationships among material morphology, composition, and spectroscopic response. The study begins with a comprehensive examination of conventional Raman spectroscopy, outlining its classical and quantum mechanical principles while highlighting the constraints imposed by weak scattering cross-sections in dilute molecular systems. This thesis investigates rational design principles for plasmonic and semiconductor-based SERS substrates to address these challenges, emphasising the controlled modulation of localised surface plasmon resonances, hotspot formation, and interfacial charge-transfer phenomena. Diverse post-treatment techniques, such as laser modification, plasma processing, ion irradiation, and surface texturing, were utilised to adjust surface roughness, crystallinity, defect density, and electronic structure, facilitating substantial enhancement of Raman signals. Comprehensive characterisation employing SEM, TEM, AFM, UV Vis spectroscopy, Raman spectroscopy, XRD, XPS, RBS, and computational

methods (FDTD and DFT) offers a profound understanding of structure–property correlations. The optimised nanostructured films exhibit significant SERS activity, exceptional sensitivity, reproducibility, and stability for the detection of trace-level analytes. The thesis emphasises the pivotal roles of nanoscale morphology, interparticle gap engineering, and electronic coupling in regulating enhancement mechanisms.

The first study focused on an Au-Ag multilayer system grown on a Si wafer using the thermal evaporation technique and then subjected to 400 keV Krypton irradiation for nanostructure formation. The film deposition and crystalline nature of the samples were confirmed by X-ray diffraction (XRD) and Raman spectroscopy. The surface morphology and microstructural analysis revealed the formation of distinct nanostructures with varying ion fluences, as observed by atomic force microscopy and field-emission scanning electron microscopy (FESEM). Rutherford backscattering spectrometry (RBS) results indicate a considerable change in film thickness after ion irradiation, mainly due to the removal of surface atoms due to sputtering. The Rhodamine 6 G (R6G) molecules were used to study the SERS on ion beam-induced plasmonic nanostructures. The maximum enhancement in Raman intensity of R6G was observed in the Bi-layer Au-Ag substrate compared to other substrates, with an enhancement factor of 4.78×10^{6} corresponding to a 1516 cm^{-1} characteristic peak. A finite-difference time-domain (FDTD) simulation was performed to provide a better understanding of the nanostructure hot-spots formation and support the obtained SERS results. This study presents a viable approach to fabricating a highly uniform SERS substrate over a large area for chemical and biological sensing.

The second study discusses the growth of MoO_3 micro-flakes on SiO_2/Si substrate by the chemical vapour deposition (CVD) technique, and then Ag-Au thin films were deposited over the MoO_3 microflakes via the thermal evaporation method. These prepared substrates were subjected to swift heavy irradiation to alter their morphology under extreme electronic

conditions, thereby creating defects and facilitating nanostructure formation. The phase formation and crystalline nature of the samples are confirmed by X-ray diffraction (XRD) and Raman spectroscopy. The electronic structure and defect analysis were performed using X-ray photoelectron spectroscopy (XPS). The microstructure and purity of the samples are observed by field emission scanning electron microscopy (FESEM). Detailed SERS measurements were taken using different dye molecules to establish the use of the developed substrates in molecular detection. Density functional theory (DFT) based theoretical calculations were in agreement with the experimental results. The finite-difference time-domain (FDTD) simulation was performed to see the electric field distribution over the surface.

The third part focuses on the effect of the size of Au nanoparticles on SERS enhancement, which was studied in detail, and the hybrid system of Au-WS_2 was developed. Small (20nm) and large (80nm) Au nanoparticles were synthesized to investigate their role in electromagnetic field enhancement, and their hybridization with WS_2 nanosheets was formed to examine the synergistic effect of chemical and electromagnetic enhancement. The change in size of Au nanoparticles and the morphology of WS_2 nanosheets were studied through FESEM images. The ultraviolet-visible near-infrared (UV-vis-NIR) spectroscopy was performed to study the shift in the LSPR response with a change in the Au nanoparticle size and to study the intrinsic optical properties of the nanohybrid with Au-WS_2. The FDTD simulation was performed to understand the plasmonic properties and field distribution over the substrate.

The last part includes the highly sensitive Ag wire-based SERS substrates, which were developed using a chemical synthesis procedure. These wires were further treated to develop roughened nanostructures throughout their surface using a single-step chemical synthesis procedure. The roughened nanostructures on the surface of Ag wires were responsible for inducing plasmonic hotspots *via* coupling of inherent surface plasmon oscillations of adjacent nanostructures. These plasmonic hotspots enhanced the Raman scattering signals from analyte

molecules, such as MB, MO, R6G, and the pesticide thiram. The morphology variation was confirmed by AFM, FESEM and HR-TEM. The elemental and structural characteristics was performed by XRD. Field intensity enhancement profiles of plasmonic hotspots were monitored using FDTD simulations. Overall, this thesis offers a comprehensive understanding of material design strategies for efficient spectroscopic platforms and introduces novel methods for producing durable, scalable SERS substrates for chemical sensing, biosensing, environmental monitoring, and optoelectronic applications. The findings of this research provide essential directives for future progress in nanophotonic-based materials and molecular detection technologies.

सारांश

नैनोप्रौद्योगिकी में हालिया प्रगतियों ने अत्यधिक दक्ष सतह-वर्धित रमन स्पेक्ट्रोस्कोपी (SERS) प्लेटफ़ॉर्म के विकास को संभव बनाया है, जो तीव्र, किफ़ायती तथा अति-संवेदनशील आणविक पहचान को सुगम बनाते हैं। समकालीन SERS सब्सट्रेट प्रायः 10^{10}, तक के एन्हांसमेंट फ़ैक्टर प्राप्त करते हैं, जिससे विश्वसनीय एक-अणु (single-molecule) तक पहचान संभव हो पाती है। इन अद्वितीय संवेदनशीलताओं का उद्भव नैनोस्तर पर उत्पन्न स्थानीयकृत सतही प्लाज़मॉन अनुनाद (LSPR) से होता है, जहाँ विद्युतचुंबकीय क्षेत्र को 10^{11} गुना से अधिक तक प्रवर्धित किया जा सकता है। SERS सब्सट्रेटों के निर्माण के लिए अब तक विविध प्रकार की सामग्रियों का अन्वेषण किया गया है, जिनमें स्वर्ण (Au), रजत (Ag) और ताँबा (Cu) जैसे बहुमूल्य धातु प्रमुख रूप से उपयोग किए जाते हैं। इसका कारण दृश्य से निकट-अवरक्त स्पेक्ट्रम में उनकी प्रबल प्लाज़्मॉनिक प्रतिक्रिया, रासायनिक स्थिरता, तथा नैनोगैप और तीक्ष्ण किनारों पर तीव्र हॉटस्पॉट उत्पन्न करने की उनकी क्षमता है।

रजत (Ag) सर्वाधिक विद्युतचुंबकीय प्रवर्धन तथा न्यूनतम हानियाँ प्रदान करता है, जिससे यह अत्यल्प-सांद्रता पहचान (ultra-trace detection) के लिए सर्वोत्तम विकल्प बनता है। इसके विपरीत, स्वर्ण (Au) उत्कृष्ट रासायनिक स्थिरता एवं जैव-संगतता प्रदान करता है, जो बायोसेंसिंग तथा *in vivo* अनुप्रयोगों को सक्षम बनाता है। ताँबा (Cu), यद्यपि अपेक्षाकृत कम स्थिर है, फिर भी समायोज्य प्लाज़्मॉनिक गुणों के साथ एक किफ़ायती विकल्प के रूप में उभरता है। बहुमूल्य धातुओं के अतिरिक्त ZnO, TiO_2, MoS_2, WS_2 तथा ग्रैफीन-आधारित हाइब्रिड जैसी अर्धचालक सामग्रियाँ भी विशेष ध्यान आकर्षित कर रही हैं। इनकी लोकप्रियता का कारण उनके आवेश-हस्तांतरण प्रवर्धन तंत्र, रासायनिक स्थिरता, तथा फोटोकैटलिटिक अथवा सहक्रियात्मक (synergistic) सेंसिंग को सक्षम बनाने की क्षमता है। ये सामग्रियाँ चयनात्मक अवशोषण बढ़ाने, आणविक उन्मुखीकरण को नियंत्रित करने तथा फ्लोरेसेंस दमन करने के साथ-साथ संवेदन (detection) में सहायक होती हैं। संकर (hybrid) प्लाज़्मॉनिक–अर्धचालक प्लेटफ़ॉर्म, जैसे Au-ZnO, Ag-TiO_2 और Au-MoS_2, ने उल्लेखनीय प्रभावशीलता प्रदर्शित की है। ये प्रणालियाँ प्रबल विद्युतचुंबकीय प्रवर्धन को रासायनिक प्रवर्धन के साथ जोड़ती हैं, जिससे पार्ट्स-पर-ट्रिलियन सांद्रता पर भी पुनरुत्पाद्य SERS संकेत प्राप्त करना संभव हो पाता है। विविध निर्माण तकनीकें-जैसे इलेक्ट्रॉन-बीम लिथोग्राफ़ी, केमिकल वेपर डिपोज़िशन, थर्मल एवापोरेशन, लेज़र-प्रेरित नैनोस्ट्रक्चरिंग, कोलॉइडल असेम्बली तथा नैनोकणों की स्व-संगठित व्यवस्था-आकृति-विज्ञान (morphology), इंटरपार्टिकल दूरी, सतही खुरदरापन तथा क्रिस्टैलिनिटी जैसे कारकों पर सूक्ष्म नियंत्रण प्रदान करती हैं, जो हॉटस्पॉट घनत्व और SERS की पुनरुत्पादकता को निर्णायक रूप से प्रभावित करते हैं। इन प्रगतियों ने SERS को कुछ ही सेकंडों में आणविक फिंगरप्रिंटिंग प्रदान करने में सक्षम बनाया है, जिससे यह पारंपरिक विश्लेषणात्मक तकनीकों की तुलना में संवेदनशीलता, गति, पोर्टेबिलिटी और किफ़ायत के मामले में कहीं आगे निकल जाता है। इन उन्नतियों ने SERS के अनुप्रयोग क्षेत्र को भी व्यापक बनाया है, जिसमें रोगजनक (pathogen) पहचान, ppb–ppt स्तर तक पर्यावरणीय प्रदूषकों का पता लगाना, औषधि अवशेषों की निगरानी, खाद्य सुरक्षा मूल्यांकन तथा रोगों के आरंभिक निदान शामिल हैं। इन सभी विकासों के परिणामस्वरूप, SERS वास्तविक-समय, लेबल-मुक्त तथा अति-अल्प सांद्रता आणविक पहचान के लिए एक अग्रणी नैनोप्रौद्योगिकी-आधारित विश्लेषणात्मक उपकरण के रूप में स्थापित हो चुका है।

यह शोधप्रबंध उन्नत नैनोसंरचित सामग्रियों एवं पतली फ़िल्मों के निर्माण तथा उनकी विशेषताओं के विस्तृत अध्ययन को प्रस्तुत करता है, जिसमें विशेष रूप से उनके ऑप्टिकल एवं स्पेक्ट्रोस्कोपिक प्रदर्शन विशेषकर रमन तथा सतह-वर्धित रमन स्कैटरिंग (SERS) को बेहतर बनाने पर केंद्रित किया गया है। इस

अध्ययन में रासायनिक वेपर डिपोज़िशन (CVD) और थर्मल एवापोरेशन जैसी प्रायोगिक संश्लेषण तकनीकों को नियंत्रित नैनोसंरचना अभियांत्रिकी तथा संरचनात्मक, ऑप्टिकल और कंपनात्मक (vibrational) विशेषण के साथ संयोजित किया गया है, ताकि सामग्री की आकृति, संरचना और स्पेक्ट्रोस्कोपिक प्रतिक्रिया के मध्य संबंधों को स्पष्ट किया जा सके। अध्ययन की शुरुआत पारंपरिक रमन स्पेक्ट्रोस्कोपी के विस्तृत विवेचन से की गई है, जिसमें इसके शास्त्रीय एवं क्वांटम-यांत्रिक सिद्धांतों को व्याख्यायित किया गया है तथा दुर्बल स्कैटरिंग क्रॉस-सेक्शनों के कारण विरल आणविक प्रणालियों में उत्पन्न सीमाओं को रेखांकित किया गया है। इन चुनौतियों को संबोधित करने हेतु यह शोधप्रबंध प्लाज़्मॉनिक एवं अर्धचालक-आधारित SERS सब्सट्रेटों के तार्किक डिज़ाइन सिद्धांतों की जाँच करता है, जिसमें स्थानीयकृत सतही प्लाज़्मॉन अनुनाद (LSPR), हॉटस्पॉट गठन तथा अंतरफलीय आवेश-हस्तांतरण प्रक्रियाओं के नियंत्रित विनियमन पर विशेष बल दिया गया है। पश्च-उपचार तकनीकों जैसे लेज़र संशोधन, प्लाज़्मा प्रॉसेसिंग, आयन विकिरण तथा सतह टेक्स्चरिंग का उपयोग सतही खुरदरापन, क्रिस्टैलिनिटी, दोष-सघनता और इलेक्ट्रॉनिक संरचना को समायोजित करने के लिए किया गया, जिसके परिणामस्वरूप रमन संकेतों में उल्लेखनीय प्रवर्धन प्राप्त हुआ। SEM, TEM, AFM, UV-Vis स्पेक्ट्रोस्कोपी, रमन स्पेक्ट्रोस्कोपी, XRD, XPS, RBS तथा FDTD एवं DFT जैसे संगणकीय तरीकों के माध्यम से किए गए विस्तृत विशेषण ने संरचना–गुणधर्म सहसंबंधों की गहन समझ प्रदान की। इष्टतमीकृत नैनोसंरचित फ़िल्मों ने उच्च SERS सक्रियता, उत्कृष्ट संवेदनशीलता, पुनरुत्पादकता और स्थिरता प्रदर्शित की, जिससे अति-अल्प सांद्रता वाले विश्लेष्यों (analytes) का विश्वसनीय पता लगाना संभव हुआ। यह शोधप्रबंध नैनोस्तरीय आकृति-विज्ञान, इंटरपार्टिकल गैप अभियांत्रिकी तथा इलेक्ट्रॉनिक कपलिंग की उन निर्णायक भूमिकाओं को विशेष रूप से रेखांकित करता है, जो SERS प्रवर्धन तंत्रों को नियंत्रित करती हैं।

पहला अध्ययन एक Au-Ag बहुपरत (multilayer) प्रणाली पर केंद्रित है, जिसे थर्मल एवापोरेशन तकनीक द्वारा Si वेफ़र पर विकसित किया गया तथा तत्पश्चात 400 keV क्रिप्टॉन आयन विकिरण के अधीन किया गया, जिससे नैनोसंरचना का निर्माण हो सके। फ़िल्म जमाव और नमूनों की क्रिस्टैलाइन प्रकृति की पुष्टि एक्स-रे विवर्तन (XRD) तथा रमन स्पेक्ट्रोस्कोपी द्वारा की गई। सतही आकृति-विज्ञान और सूक्ष्म-संरचनात्मक विश्लेषण, जिसे एटॉमिक फ़ोर्स माइक्रोस्कोपी (AFM) और फील्ड-एमिशन स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (FESEM) के माध्यम से किया गया, ने आयन फ्लुएन्स के परिवर्तन के साथ विशिष्ट नैनोसंरचनाओं के गठन को स्पष्ट रूप से प्रदर्शित किया। रदरफोर्ड बैकस्कैटरिंग स्पेक्ट्रोमेट्री (RBS) के परिणामों से आयन विकिरण के बाद फ़िल्म की मोटाई में उल्लेखनीय परिवर्तन का पता चला, जिसका मुख्य कारण स्पटरिंग के कारण सतह परमाणुओं का हटना है।

Rhodamine 6G (R6G) अणुओं का उपयोग आयन बीम-प्रेरित प्लाज़्मॉनिक नैनोसंरचनाओं पर SERS अध्ययन के लिए किया गया। द्विपरत Au-Ag सब्सट्रेट में अन्य सब्सट्रेटों की तुलना में R6G की रमन तीव्रता में अधिकतम प्रवर्धन प्राप्त हुआ, जिसमें 1516 cm^{-1} के विशिष्ट पिक के लिए 4.78×10^{6} का एन्हांसमेंट फ़ैक्टर प्राप्त हुआ। नैनोसंरचनाओं में हॉटस्पॉट निर्माण को समझने तथा SERS परिणामों को समर्थन देने के लिए फाइनाइट डिफ़रेंस टाइम-डोमेन (FDTD) सिमुलेशन किया गया। यह अध्ययन रासायनिक एवं जैविक सेंसिंग हेतु बड़े क्षेत्र में अत्यधिक समान SERS सब्सट्रेट के निर्माण की एक व्यावहारिक रणनीति प्रस्तुत करता है।

दूसरे अध्ययन में MoO_3 माइक्रो-फ्लेक्स को SiO_2/Si सब्सट्रेट पर केमिकल वेपर डिपोज़िशन (CVD) द्वारा विकसित किया गया, तथा तत्पश्चात इन माइक्रो-फ्लेक्स पर थर्मल एवापोरेशन तकनीक से Ag-Au पतली फ़िल्मों का जमाव किया गया। तैयार सब्सट्रेटों को स्विफ़्ट हेवी आयन विकिरण के अधीन किया

गया, जिससे अत्यधिक इलेक्ट्रॉनिक उत्तेजना की परिस्थितियों में उनकी आकृति परिवर्तित होकर दोष निर्माण एवं नैनोसंरचना निर्माण संभव हो सके। नमूनों की फेज़ निर्माण एवं क्रिस्टैलाइन संरचना की पुष्टि XRD तथा रमन स्पेक्ट्रोस्कोपी द्वारा की गई। इलेक्ट्रॉनिक संरचना एवं दोष विश्लेषण X-रे फ़ोटोइलेक्ट्रॉन स्पेक्ट्रोस्कोपी (XPS) के माध्यम से किया गया। सूक्ष्म-संरचना एवं शुद्धता की जांच FESEM द्वारा की गई। विकसित सब्सट्रेटों के उपयोग को आणविक पहचान में स्थापित करने हेतु विभिन्न रंगों (dyes) के साथ विस्तृत SERS माप किये गए। डेंसिटी फ़ंक्शनल थ्योरी (DFT) आधारित सैद्धांतिक गणनाएँ प्रायोगिक परिणामों के अनुरूप पाई गईं। सतह पर विद्युत क्षेत्र वितरण का अध्ययन करने के लिए FDTD सिमुलेशन किया गया।

तीसरा भाग SERS प्रवर्धन पर Au नैनोकणों के आकार के प्रभाव पर केंद्रित है, जिसके विस्तृत अध्ययन के पश्चात Au-WS_2 हाइब्रिड प्रणाली विकसित की गई। विद्युतचुंबकीय क्षेत्र प्रवर्धन में नैनोकण आकार की भूमिका का विश्लेषण करने के लिए छोटे (20 nm) तथा बड़े (80 nm) Au नैनोकणों का संश्लेषण किया गया, तथा WS_2 नैनोशीट्स के साथ उनका हाइब्रिडकरण किया गया, ताकि रासायनिक एवं विद्युतचुंबकीय प्रवर्धन के सहक्रियात्मक (synergistic) प्रभाव का आकलन किया जा सके। Au नैनोकणों के आकार तथा WS_2 नैनोशीट्स की आकृति में परिवर्तन का अध्ययन FESEM चित्रों के माध्यम से किया गया। अल्ट्रावॉयलेट-दृश्यमान निकट-अवरक्त (UV-Vis-NIR) स्पेक्ट्रोस्कोपी का उपयोग Au नैनोकण आकार परिवर्तन के साथ LSPR प्रतिक्रिया में होने वाले परिवर्तन तथा Au-WS_2 नैनोहाइब्रिड की अंतर्निहित ऑप्टिकल विशेषताओं के अध्ययन हेतु किया गया। सब्सट्रेट पर प्लाज़्मॉनिक गुणधर्मों एवं क्षेत्र वितरण को समझने हेतु FDTD सिमुलेशन किया गया।

अंतिम भाग में अत्यंत संवेदनशील Ag वायर आधारित SERS सब्सट्रेटों पर चर्चा की गई है, जिन्हें रासायनिक संश्लेषण विधि का उपयोग करके विकसित किया गया। इन तारों को आगे एकल-चरण रासायनिक प्रक्रिया द्वारा उपचारित किया गया, जिससे उनकी सतह पर खुरदरी नैनोसंरचनाओं का निर्माण हुआ। इन खुरदरी नैनोसंरचनाओं ने आसन्न नैनोसंरचनाओं के सतही प्लाज़्मॉन दोलनों के युग्मन के माध्यम से प्लाज़्मॉनिक हॉटस्पॉट उत्पन्न किए। इन हॉटस्पॉट्स ने MB, MO, R6G तथा कृषि-कीटनाशी थिरैम जैसे विश्लेष्य अणुओं से प्राप्त रमन संकेतों में उल्लेखनीय प्रवर्धन प्रदान किया। आकृति-विविधता की पुष्टि AFM, FESEM तथा HR-TEM द्वारा की गई। तत्वीय एवं संरचनात्मक विश्लेषण XRD द्वारा किया गया। प्लाज़्मॉनिक हॉटस्पॉट्स के क्षेत्र-तीव्रता प्रवर्धन प्रोफ़ाइल FDTD सिमुलेशन के माध्यम से मॉनिटर किए गए।

समग्र रूप से, यह शोधप्रबंध प्रभावी स्पेक्ट्रोस्कोपिक प्लेटफ़ॉर्मों के लिए सामग्री डिज़ाइन रणनीतियों की व्यापक समझ प्रदान करता है तथा रासायनिक संवेदन, बायोसेंसिंग, पर्यावरणीय निगरानी और ऑप्टोइलेक्ट्रॉनिक अनुप्रयोगों हेतु टिकाऊ, स्केलेबल SERS सब्सट्रेटों के निर्माण के नवीन तरीकों को प्रस्तुत करता है। इस शोध के निष्कर्ष नैनोफोटोनिक-आधारित सामग्रियों एवं आणविक पहचान प्रौद्योगिकियों में भविष्य की प्रगति के लिए महत्त्वपूर्ण दिशानिर्देश प्रदान करते हैं।

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NOMENCLATURE

Si NW	Silicon Nanowire
UV	Ultraviolet
Nm	Nanometer
R6G	Rhodamine 6g
Al	Aluminium
LSPR	Localised Surface Plasmonic Resonance
SM	Single Molecule
XRD	X-ray Diffraction
Si	Silicon
CFU	Colony Forming Unit
HOMO	Highest Occupied Molecular Orbital
EF	Enhancement Factor
DNA	Deoxyribonucleic Acid
Ag	Silver
a.u.	Arbitrary Unit
E	Electric
μL	Microliter
TSC	Trisodium Citrate
O_2	Oxygen
Cu	Copper
Au	Gold
FDTD	Finite Difference Time Domain
NR	Nanorods
TEM	Transmission Electron Microscopy

TiO_2	Titanium Dioxide
EBL	Electron Beam Lithography
NP / NPs	Nanoparticles
RBS	Rutherford Backscattering Spectrometry
LUMO	Lowest Unoccupied Molecular Orbital
M	Molar
cm^{-1}	$Centimeter^{-1}$
Pt	Platinum
FESEM	Field Emission Scanning Electron Microscopy
SERS	Surface Enhanced Raman Scattering
AFM	Atomic Force Microscopy
B.E.	Binding Energy
CVD	Chemical Vapour Deposition
PVD	Physical Vapour Deposition
FWHM	Full Width at Half Maxima
GIXRD	Glancing Incident x-ray Diffraction
DFT	Density Function Theory
2D	Two Dimensional