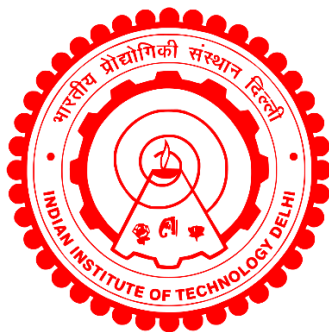


**TAILORING OF STRUCTURAL AND OPTICAL
PROPERTIES OF SILICON NITRIDE THIN FILMS FOR
PHOTOVOLTAIC AND PLASMONIC APPLICATIONS**

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JULY-2024**

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by

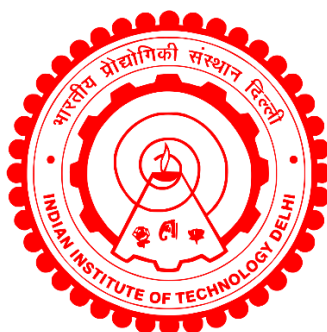
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Submitted

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

to the



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Dedicated to....

.... Parents & Friends....
who always wanted me to be a doctor

“Research is what I'm doing when I don't know what I'm doing.”

—Wernher Von Braun

Certificate

*This is to certify that the thesis entitled, “**Tailoring of Structural and Optical Properties of Silicon Nitride Thin Films for Photovoltaic and Plasmonic Applications**”, being submitted by **Ms. Pariksha Malik** to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of **Doctor of Philosophy in Physics** is a record of bonafide research work carried out by her under our supervision and guidance. She 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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Pariksha Malik

Abstract

Silicon nitride thin films have been used in numerous fields since the beginning of the microelectronics revolution. These films have been utilized in optical and microelectronic devices due to their excellent optical, chemical, and mechanical properties. Applications also include surface passivation, device encapsulation, impurity barriers, dielectric gate material, and optical coatings. With its stability and suitability for photonics, the non-stoichiometric amorphous SiN_x:H has several benefits, including composition tunability (from Si-rich to N-rich), which leads to a wide range of optical and electrical characteristics, and a wide spectrum operation band from visible to infrared frequencies. These properties are mostly determined by material composition and microstructure of the films, which are controlled by the conditions and methods of deposition. The technique commonly used to produce silicon nitride thin films, typically *a*-SiN_x:H, involves plasma-enhanced chemical vapor deposition (PECVD) due to the hydrogen introduced during the process. The optical and electrical properties of these films are strongly influenced by their hydrogen content. This thesis investigates the optical, microstructural, and electrical properties of stoichiometric and non-stoichiometric *a*-SiN_x:H thin films for photovoltaic and plasmonic applications. Furthermore, the thesis investigates the impact of different post-treatments, such as laser texturing, plasma treatment, and rapid heavy ion irradiation, with a focus on utilizing optoelectrical characteristics.

The first research problem described in the thesis deals with the optical characteristics of single- and double-layer *a*-SiN_x:H thin films with varying stoichiometry grown using the PECVD method that are pertinent for photovoltaic applications. Over a broad range of wavelengths, it was found that the double layer SiN_x exhibits superior anti-reflection properties than a single layer. Furthermore, Fourier-transform infrared spectroscopy is used

to validate that hydrogen is present in the films were formed under carefully chosen processing conditions. The study also examines the short circuit current density (J_{sc}) values and measures the minority carrier lifetime for both single- and double-layer a -SiNx:H. The a -SiNx:H double layer can be used as an antireflection coating (ARC) for solar cells because it can produce high absorptivity in many optoelectronic devices. This is shown by the measured carrier lifetime, J_{sc} values, and higher efficiency (about 21% more than the bare solar cell).

The second research problem explores the use of simple ultrafast laser writing as a post-deposition treatment for the creation of hierarchical a -SiNx:H microstructures to make an efficient anti-reflection coating. The PECVD technique is used to manufacture a broad range of Si-rich to N-rich a -SiNx:H thin films with varying optical bandgap (2.32 to 5.94 eV) and refractive index (2.8 to 1.7) of wavelength-ordered ($\sim\lambda/4$) thickness. Nonlinear light-matter interactions gave rise to a variety of nano- and microstructures with systematic breadth and depth when a high-intensity femtosecond laser (800 nm, 120 fs, 1 kHz) interacted with a -SiNx:H films. These micro-nanostructures, which are highly disordered, were shown experimentally over a vast area of around 1 cm², and they show strong light absorption and trapping capabilities throughout a broad spectral band of 200–1000 nm. Broadband anti-reflective coatings are well suited for improving light harvesting from prefabricated solar systems when reflection losses are significantly reduced from 30% to 2.8% from pre- to post-laser texturing.

Recent years have seen a surge in research on metallic nanostructures due to the emergence of several important applications utilizing localized surface plasmon resonance (LSPR), a special optical property of nanocomposite films containing embedded metallic nanoparticles (NPs) within insulating media in the UV-Vis and NIR ranges. Surface-

enhanced Raman spectroscopy (SERS) is a highly effective analytical technique with applications in fields like analytical chemistry, food safety, and forensic science. It capitalizes on the LSPR phenomenon occurring at metal surfaces and interfaces. These surfaces generate an amplified electromagnetic field, significantly boosting SERS signals. High surface area further enhances this effect by providing more active sites for analyte molecules to interact with metal nanoparticles, significantly increasing signal enhancement.

The third research problem addresses the tuning of the LSPR of gold nanoparticles (Au NPs) by varying incident ion fluences during Swift Heavy Ion (SHI) irradiation. Increasing incident ion fluence initially caused a blue shift in LSPR, but beyond a certain dose, it diminished. The annealed Au NPs (diameter ~ 12 nm), embedded in a thin Si_3N_4 matrix deposited by PECVD, were exposed to various 120 MeV Au^{+9} fluences to engineer shape and interparticle distance. The main objectives were to explore how SHI-induced morphological changes tune optical characteristics. Optical reflection spectra for pre- and post-irradiated samples were measured using UV-Vis spectroscopy. The characterizations using high-resolution cross-sectional Transmission Electron Microscopy (TEM) and synchrotron radiation-based Grazing-Incidence Small-Angle X-ray Scattering (GI-SAXS) confirmed the influence of mean inter-particle distance and anisotropic shape deformation on the optical response. Finite Domain Time Difference (FDTD) simulations validated our understanding, while Grazing-Incidence X-ray Diffraction (GI-XRD) and GI-Wide-Angle X-ray Scattering (GI-WAXS) confirmed the crystalline nature of NPs. The dependence of shape deformation on initial NP dimensions and ion fluence was analyzed through GI-XRD/GI-WAXS, supported by X-TEM data. Correlation with a thermal spike model-based analysis elucidated the process of shape deformation and discussed the impact of irradiation

on structural and optical characteristics, emphasizing LSPR tuning. An important application demonstrated was the SERS of LSPR in a metal-dielectric (Au-Si₃N₄) nanocomposite in the visible wavelength region.

Having employed Si₃N₄ in various configurations and subjected it to diverse post-treatment methods, the final research problem of the present thesis addresses the use of Si₃N₄ as a substrate in hybrid structures combined with 2D semiconducting materials. The aim is to create heterostructures, assessing the capability of this combination and its potential application in optoelectronic devices. Among 2D semiconducting materials, two-dimensional transition metal oxide materials, particularly α -MoO₃, have garnered significant attention due to their excellent structural, chemical, electrical, catalytic, and optical properties. A semiconductor with an indirect wide band gap is intrinsic α -MoO₃. They possess a perovskite-like structure, which makes them a suitable candidate for optoelectronic and photocatalytic applications. Several studies in past literature were carried out to know more about the superior optoelectrical, structural, and morphological properties of MoO₃ depending on post-treatment methods such as annealing, hydrogenation, oxygen plasma, etc. Although there have been few reports addressing defect-induced luminescence processes for these flakes, there has been a lack of studies addressing the impact of the plasma treatment on the α -MoO₃'s microstructure and optical properties, which greatly affect their use in device applications. As an alternative post-treatment method, the final chapter aimed to show that by adjusting the exposure duration of plasma treatment, one can controllably tune the structural and optical properties of as-deposited α -MoO₃ flakes via defect engineering of oxygen vacancies (V_o), a technology that can even be further adopted for several other TMOs such as VO_x and WO_x.

Layered MoO₃ flakes were deposited on a Si₃N₄/Si substrate through Chemical Vapor

Deposition (CVD), which were subjected to varying durations of Ar plasma treatment. The cold plasma treatment proves effective in modifying the optical and structural attributes of MoO_3 . This chapter examines how different durations of ex-situ plasma treatment, ranging from 15 to 45 minutes, impact the structural, luminescent, and optical properties, as well as the surface morphology of both pristine and treated samples. Utilizing XRD, Raman, FTIR, EPMA, and UV-Visible-NIR spectroscopy measurements, we assess the influence of plasma exposure duration on the optical, morphological, and structural characteristics of MoO_3 . Surface morphology displays diverse appearances depending on the duration of plasma exposure after treatment, as evidenced by optical and structural analyses, which are further verified through SEM measurements. The room-temperature photoluminescence (PL) investigation reveals that plasma-induced oxygen vacancies contribute to the observed effects. These findings, elucidating the opto-luminescent characteristics of MoO_3 flakes, represent a significant advancement with implications for various applications in optoelectronics, energy storage, and sensing devices. This dissertation emphasizes the importance of applying post-treatment methods to $\alpha\text{-SiN}_x\text{:H}$ films and nanocomposites, specifically in diverse setups, including dielectric matrices, ARCs, and substrates in hybrid structures. The proposed approach suggests that post-treatment can significantly enhance the characteristics of Si_3N_4 films, rendering them more suitable for applications in dielectrics, multilayer structures, hybrid materials, and optical coatings.

माइक्रोइलेक्ट्रॉनिक क्रांति की शुरुआत के बाद से सिलिकॉन नाइट्राइड पतली फिल्मों का उपयोग कई क्षेत्रों में किया गया है। इन फिल्मों का उपयोग उनके उत्कृष्ट प्रकाशिक, रासायनिक, और यांत्रिक गुणों के कारण प्रकाशिक और माइक्रोइलेक्ट्रॉनिक उपकरणों में किया गया है। अनुप्रयोगों में सतह निष्क्रियता, उपकरण एनकैप्सुलेशन, अशुद्धता बाधाएं, असंवाहक द्वार सामग्री और प्रकाशिक लेपन भी शामिल हैं। फोटोनिक्स के लिए इसकी स्थिरता और उपयुक्तता के साथ, गैर-स्टोइकोमेट्रिक अनाकार $\text{SiN}_x\text{:H}$ के कई लाभ हैं, जिसमें संघटन ट्यूनेबिलिटी (Si- आधिक्य से N- आधिक्य तक) शामिल है, जो ऑप्टिकल और इलेक्ट्रिकल विशेषताओं की एक विस्तृत श्रृंखला और दृश्यमान से अवरक्त आवृत्तियों तक एक विस्तृत संचालन स्पेक्ट्रम पट्टी की ओर ले जाती है। ये गुण अधिकतर फिल्मों की सामग्री संरचना और सूक्ष्म संरचना द्वारा निर्धारित होते हैं, जो जमाव की स्थितियों और तरीकों से नियंत्रित होते हैं। आमतौर पर सिलिकॉन नाइट्राइड (सामान्यतय: a- $\text{SiN}_x\text{:H}$) पतली फिल्में बनाने के लिए इस्तेमाल की जाने वाली तकनीक में, प्रक्रिया के दौरान समाविष्ट किए गए हाइड्रोजन के कारण प्लाज्मा-संवर्धित रासायनिक वाष्प जमाव (PECVD) शामिल होती है। इन फिल्मों के प्रकाशिक और वैद्युत गुण उनकी हाइड्रोजन की मात्रा से काफी प्रभावित होते हैं। यह थीसिस फोटोवोल्टिक और प्लास्मोनिक अनुप्रयोगों के लिए स्टोइकोमेट्रिक और गैर-स्टोइकोमेट्रिक a- $\text{SiN}_x\text{:H}$ पतली फिल्मों के प्रकाशिक, सूक्ष्म संरचना और वैद्युत गुणों की जांच करती है। इसके अलावा, थीसिस प्रकाश वैद्युत विशेषताओं के उपयोग पर ध्यान देने के साथ, लेजर टेक्सचरिंग, प्लाज्मा उपचार और तेजी से भारी आयन विकिरण जैसे विभिन्न उपचार के बाद के प्रभाव की जांच करती है।

थीसिस में वर्णित पहली शोध समस्या PECVD विधि का उपयोग करके विकसित की गई अलग-अलग स्टोइकोमेट्री वाली एकल और द्विपरत $a\text{-SiN}_x\text{:H}$ पतली फिल्मों की प्रकाशिक विशेषताओं से संबंधित है जो फोटोवोल्टिक अनुप्रयोगों के लिए प्रासंगिक हैं। तरंग दैर्ध्य की एक विस्तृत श्रृंखला में, यह पाया गया कि दोहरी परत SiN_x एकल परत की तुलना में बेहतर विरोधी-प्रतिबिंब गुण प्रदर्शित करती है।

इसके अलावा, फूरियर-ट्रांसफॉर्म इन्फ्रारेड स्पेक्ट्रोस्कोपी का उपयोग यह सत्यापित करने के लिए किया जाता है कि सावधानीपूर्वक चुनी गई प्रसंस्करण स्थितियों के तहत बनाई गई फिल्मों में हाइड्रोजन मौजूद है। अध्ययन शॉर्ट सर्किट करंट डेंसिटी (J_{sc}) मूल्यों की भी जांच करता है और सिंगल और डबल-लेयर $a\text{-SiN}_x\text{:H}$ दोनों के लिए अल्पसंख्यक वाहक जीवनकाल को मापता है। $a\text{-SiN}_x\text{:H}$ डबल परत का उपयोग सौर कोशिकाओं के लिए एंटीरिफ्लेक्शन कोटिंग (ARC) के रूप में किया जा सकता है क्योंकि यह कई ऑप्टोइलेक्ट्रॉनिक उपकरणों में उच्च अवशोषण क्षमता उत्पन्न कर सकता है। यह मापे गए वाहक जीवनकाल, जेएससी मूल्यों और उच्च दक्षता (अनावृत सौर सेल से लगभग 21% अधिक) द्वारा दिखाया गया है।

दूसरी शोध समस्या एक कुशल प्रवर्तन विरोधी लेप बनाने के लिए पदानुक्रमित $a\text{-SiN}_x\text{:H}$ सूक्ष्म संरचना के निर्माण के लिए अवक्षेपण के बाद उपचार के रूप में सरल अल्ट्राफास्ट लेजर लेखन के उपयोग की पड़ताल करती है। PECVD तकनीक का उपयोग Si- आधिक्य से N- आधिक्य $a\text{-SiN}_x\text{:H}$ की अलग-अलग प्रकाशिक ऊर्जा अंतराल (2.32 से 5.94 eV) और अपवर्तक सूचकांक (2.8 से 1.7) की तरंग दैर्ध्य ($\sim \lambda$)/4 के क्रम की मोटाई की पतली फिल्मों की एक विस्तृत श्रृंखला के निर्माण के लिए किया जाता है, । जब एक उच्च तीव्रता वाले फेम्टोसेकंड लेजर (800 nm, 120 fs, 1 kHz) ने $a\text{-SiN}_x\text{:H}$ फिल्मों के साथ बातचीत की, तो नॉनलाइनियर लाइट-मैटर इंटरैक्शन ने व्यवस्थित चौड़ाई

और गहराई के साथ विभिन्न प्रकार के नैनो और माइक्रोस्ट्रक्चर को जन्म दिया। ये माइक्रो-नैनोस्ट्रक्चर, जो अत्यधिक अव्यवस्थित हैं, प्रयोगात्मक रूप से लगभग 1 सेमी² के विशाल क्षेत्र में दिखाए गए थे, और वे 200-1000 nm के व्यापक वर्णक्रमीय बैंड में मजबूत प्रकाश अवशोषण और फँसाने की क्षमता दिखाते हैं। प्रीफैब्रिकेटेड सौर प्रणालियों से प्रकाश संचयन में सुधार के लिए ब्रॉडबैंड प्रवर्तन विरोधी लेपन अच्छी तरह से अनुकूल हैं, जब प्री-लेजर टेक्सचरिंग से लेकर पोस्ट-लेजर टेक्सचर तक प्रतिबिंब हानि 30% से घटकर 2.8% हो जाती है।

हाल के वर्षों में स्थानीय सतह प्लास्मोन अनुनाद (एलएसपीआर) का उपयोग करने वाले कई महत्वपूर्ण अनुप्रयोगों के उद्भव के कारण धातु नैनोस्ट्रक्चर पर शोध में वृद्धि देखी गई है, जो यूवी-विज़ और एनआईआर रेंज में इन्सुलेटिंग मीडिया के भीतर एम्बेडेड धातु नैनोकणों (एनपी) युक्त नैनोकम्पोजिट फिल्मों की एक विशेष प्रकाशिक संपत्ति है। । सतह-संवर्धित रमन स्पेक्ट्रोस्कोपी (SERS) विश्लेषणात्मक रसायन विज्ञान, खाद्य सुरक्षा और फोरेंसिक विज्ञान जैसे क्षेत्रों में अनुप्रयोगों के साथ एक अत्यधिक प्रभावी विश्लेषणात्मक तकनीक है। यह धातु की सतहों और इंटरफेस पर होने वाली LSPR घटना का लाभ उठाता है। ये सतहें एक प्रवर्धित विद्युत चुम्बकीय क्षेत्र उत्पन्न करती हैं, जो SERS संकेतों को महत्वपूर्ण रूप से बढ़ाती हैं। उच्च सतह क्षेत्र धातु नैनोकणों के साथ बातचीत करने के लिए विश्लेषण अणुओं के लिए अधिक सक्रिय साइट प्रदान करके इस प्रभाव को और बढ़ाता है, जिससे सिग्नल वृद्धि में काफी सुधार होता है।

तीसरी शोध समस्या स्विफ्ट हेवी आयन (एसएचआई) विकिरण के दौरान अलग-अलग घटना आयन प्रवाह द्वारा सोने के नैनोकणों (Au NPs) के LSPR की ट्यूनिंग को संबोधित करती है। बढ़ती घटना आयन प्रवाह के कारण शुरू में LSPR में नीला बदलाव आया, लेकिन एक निश्चित खुराक से परे, यह कम हो गया। PECVD द्वारा अवक्षेपित पतले Si₃N₄ मैट्रिक्स में एम्बेडेड एनील्ड Au NP (व्यास ~ 12

nm), इंजीनियर आकार और इंटरपार्टिकल दूरी के लिए विभिन्न 120 MeV Au +9 प्रवाह के संपर्क में थे। मुख्य उद्देश्य यह पता लगाना था कि SHI-प्रेरित रूपात्मक परिवर्तन प्रकाशिक विशेषताओं को कैसे समायोजित करते हैं। पूर्व और बाद के विकिरणित नमूनों के लिए प्रकाशिक प्रतिबिंब स्पेक्ट्रा को यूवी-विज़ स्पेक्ट्रोस्कोपी का उपयोग करके मापा गया था। उच्च-रिज़ॉल्यूशन क्रॉस-सेक्शनल ट्रांसमिशन इलेक्ट्रॉन माइक्रोस्कोपी (TEM) और सिंक्रोट्रॉन विकिरण-आधारित ग्राज़िंग-इंसिडेंस स्मॉल-एंगल एक्स-रे स्कैटरिंग (GI-SAXS) का उपयोग करते हुए लक्षण वर्णन ने माध्य अंतर-कण दूरी और अनिसोट्रोपिक आकार विरूपण के प्रभाव की पुष्टि की। प्रकाशिक प्रतिक्रिया, परिमित डोमेन समय अंतर (एफडीटीडी) सिमुलेशन ने हमारी समझ को मान्य किया, जबकि GISAXS और जीआई-वाइड-एंगल एक्स-रे स्कैटरिंग (GIWAXS) ने NP की क्रिस्टलीय प्रकृति की पुष्टि की। प्रारंभिक NP आयामों और आयन प्रवाह पर आकार विरूपण की निर्भरता का विश्लेषण X-TEM डेटा द्वारा समर्थित GI-XRD/GI-WAXS के माध्यम से किया गया था। थर्मल स्पाइक मॉडल-आधारित विश्लेषण के साथ सहसंबंध ने आकार विरूपण की प्रक्रिया को स्पष्ट किया और LSPR ट्यूनिंग पर जोर देते हुए संरचनात्मक और प्रकाशिक विशेषताओं पर विकिरण के प्रभाव पर चर्चा की। दृश्य तरंग दैर्ध्य क्षेत्र में धातु-असंवाहक (Au-Si₃N₄) नैनोकम्पोजिट में LSPR का SERS एक महत्वपूर्ण अनुप्रयोग प्रदर्शित किया गया था।

विभिन्न विन्यासों में Si₃N₄ को नियोजित करने और इसे विभिन्न उपचार के बाद के तरीकों के अधीन करने के बाद, वर्तमान थीसिस की अंतिम शोध समस्या द्विविमीय (2D) अर्धचालक सामग्रियों के साथ संयुक्त संकर संरचनाओं में एक सबस्ट्रेट के रूप में Si₃N₄ के उपयोग को संबोधित करती है। इसका उद्देश्य हेटरोस्ट्रक्चर बनाना, इस संयोजन की क्षमता और ऑप्टोइलेक्ट्रॉनिक उपकरणों में इसके संभावित अनुप्रयोग का आकलन करना है। 2D अर्धचालक सामग्रियों में, द्वि-आयामी संक्रमण धातु ऑक्साइड सामग्री, विशेष रूप से α -MoO₃, ने अपने उत्कृष्ट संरचनात्मक, रासायनिक, विद्युत,

उत्प्रेरक और प्रकाशिक गुणों के कारण महत्वपूर्ण ध्यान आकर्षित किया है। अप्रत्यक्ष वृहत ऊर्जा अंतराल वाला अर्धचालक आंतरिक $\alpha\text{-MoO}_3$ है। उनके पास पेरोव्स्काइट जैसी संरचना है, जो उन्हें ऑप्टोइलेक्ट्रॉनिक और फोटोकैटलिटिक अनुप्रयोगों के लिए उपयुक्त उम्मीदवार बनाती है। एनीलिंग, हाइड्रोजनीकरण, ऑक्सीजन प्लाज्मा आदि जैसे उपचार के बाद के तरीकों के आधार पर MoO_3 के बेहतर ऑप्टोइलेक्ट्रिकल, संरचनात्मक और रूपात्मक गुणों के बारे में अधिक जानने के लिए पिछले साहित्य में कई अध्ययन किए गए थे। हालांकि दोष-प्रेरित को संबोधित करने वाली कुछ रिपोर्टें आई हैं इन गुणों के लिए ल्यूमिनेसेंस प्रक्रियाओं के कारण, $\alpha\text{-MoO}_3$ के माइक्रोस्ट्रक्चर और प्रकाशिक गुणों पर प्लाज्मा उपचार के प्रभाव को संबोधित करने वाले अध्ययनों की कमी रही है, जो डिवाइस अनुप्रयोगों में उनके उपयोग को बहुत प्रभावित करते हैं। वैकल्पिक उपचार के बाद की विधि के रूप में, अंतिम अध्याय का उद्देश्य यह दिखाना है कि प्लाज्मा उपचार की एक्सपोज़र अवधि को समायोजित करके, ऑक्सीजन रिक्तियों (वीओ) की दोष इंजीनियरिंग के माध्यम से जमा किए गए $\alpha\text{-MoO}_3$ फ्लेक्स के संरचनात्मक और प्रकाशिक गुणों को नियंत्रित रूप से ट्यून किया जा सकता है। एक ऐसी तकनीक जिसे VO_x और WO_x जैसे कई अन्य TMOs के लिए भी अपनाया जा सकता है।

स्तरित MoO_3 गुच्छे को रासायनिक वाष्प जमाव (CVD) के माध्यम से $\text{Si}_3\text{N}_4/\text{Si}$ सब्सट्रेट पर जमा किया गया था, जो Ar प्लाज्मा उपचार की अलग-अलग अवधि के अधीन थे। शीत प्लाज्मा उपचार MoO_3 की ऑप्टिकल और संरचनात्मक विशेषताओं को संशोधित करने में प्रभावी साबित होता है। यह अध्याय जांच करता है कि एक्स-सीटू प्लाज्मा उपचार की विभिन्न अवधि, 15 से 45 मिनट तक, संरचनात्मक, ल्यूमिनेसेंस और प्रकाशिक गुणों के साथ-साथ प्राचीन और उपचारित नमूनों की सतह आकृति विज्ञान को कैसे प्रभावित करती है। एक्सआरडी, रमन, एफटीआईआर, ईपीएमए और यूवी-विज़िबल-एनआईआर स्पेक्ट्रोस्कोपी माप का उपयोग करते हुए, हम MoO_3 की ऑप्टिकल, रूपात्मक और संरचनात्मक विशेषताओं पर प्लाज्मा एक्सपोज़र अवधि के प्रभाव का आकलन करते हैं। सतह

आकारिकी उपचार के बाद प्लाज्मा एक्सपोजर की अवधि के आधार पर विविध उपस्थिति प्रदर्शित करती है, जैसा कि प्रकाशिक और संरचनात्मक विश्लेषणों से प्रमाणित होता है, जिसे SEM माप के माध्यम से आगे सत्यापित किया जाता है। कमरे के तापमान फोटोलुमिनसेंस (PL) जांच से पता चलता है कि प्लाज्मा-प्रेरित ऑक्सीजन रिक्तियां देखे गए प्रभावों में योगदान करती हैं। ये निष्कर्ष, MoO_3 फ्लेक्स की ऑप्टो-ल्यूमिनसेंट विशेषताओं को स्पष्ट करते हुए, ऑप्टोइलेक्ट्रॉनिक्स, ऊर्जा भंडारण और सेंसिंग उपकरणों में विभिन्न अनुप्रयोगों के लिए निहितार्थ के साथ एक महत्वपूर्ण प्रगति का प्रतिनिधित्व करते हैं। यह शोध प्रबंध $\alpha\text{-SiN}_x\text{:H}$ फिल्मों और नैनोकम्पोजिट्स में उपचार के बाद के तरीकों को लागू करने के महत्व पर जोर देता है, विशेष रूप से विभिन्न सेटअपों में, जिसमें असंवाहक मैट्रिक्स, ARC और हाइब्रिड संरचनाओं में सबस्ट्रेट शामिल हैं। प्रस्तावित दृष्टिकोण से पता चलता है कि उपचार के बाद Si_3N_4 फिल्मों की विशेषताओं में काफी वृद्धि हो सकती है, जो उन्हें असंवाहक, मल्टीलेयर संरचनाओं, हाइब्रिड सामग्री और प्रकाशिक लेपन में अनुप्रयोगों के लिए अधिक उपयुक्त बनाती है।

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