

**FABRICATION OF MICRO/NANO  
DIMENSIONAL SEMICONDUCTOR  
STRUCTURES FOR OPTOELECTRONIC  
DEVICE APPLICATIONS**

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DIMENSIONAL SEMICONDUCTOR  
STRUCTURES FOR OPTOELECTRONIC  
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by

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Department of Physics

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

*to the*



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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*This thesis dissertation is dedicated to my parents.  
For their unconditional love, faith, patience and sacrifices.*

# Certificate

This is to certify that the thesis entitled “**Fabrication of Micro/Nano Dimensional Semiconductor Structures for Optoelectronic Device Applications**”, submitted by **Rangeeta Dhaka**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Department of Physics, is a record of the original, bona fide research work carried out by him under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

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# *Abstract*

Future demand of advanced optoelectronic device for applications i.e. augmented reality, bio-robots, photonic neural networks, automotive lighting and etc. have aroused the researchers to work on ultra-wide band semiconductors materials that also known as 4<sup>th</sup> generation of semiconductor materials e.g. diamond, gallium oxide, hexagonal boron nitride, arsenic oxide, and etc. Unique properties of ultra-wide bandgap materials like high thermal stability, high breakdown electric field, high frequency tolerance, high chemical resistant capability facilitates the fabrication of higher operating speed under harsh environment. Recently, attention has been paid on deep ultraviolet to visible photodetection applications due to uses in different fields i.e. chemical/ biological analysis, medical equipment sterilization, water purification, monitoring of combustion, missile tracking, secure short-range communication, space communication, solar irradiance measurement, ultraviolet astronomy and etc. Photodetectors are optoelectronic devices which includes the transform an optical signal into an electrical signal by involving the complex process of generation, transportation, and recombination of electron-hole pairs.

This thesis delves the fabrication of ultra-wide band gap semiconductor heterostructures for optoelectronic device applications specially focused on photodetection applications. Synthesis techniques focused on flexible and cost-effective way of gallium oxide and arsenic oxide for heterostructures. In recent years, gallium oxide is the most focused ultra-wide band gap semiconductor for optoelectronic devices/power devices whereas beta phase of gallium oxide is preferable due to its high breakdown electric field, thermal and chemical stability, holds tremendous promise for next-generation optoelectronic devices. Arsenic oxide is also a stable ultra-wide band gap materials and have stability under high compression.

Firstly, discusses the synthesis of arsenic oxide microstructures as optical materials useful in ultraviolet and visible range. For synthesis electroless arsenic oxide microstructures, chemical etching of GaAs (100) substrate by nitric acid has been explored as cost-effective approach. Number of polycrystalline octahedron microstructure on the surface increased with etching time with confirmed with structural and morphological analyses. Chemical composition on surface reveals the different oxidation state of arsenic present into microstructures. Static and dynamic nature of

electronic transitions studied using photoluminescence and time-resolved photoluminescence demonstrated the ultraviolet and blue emission with fluorescent nature of arsenic oxide microstructures.

Gallium oxide is preferable choice to work in deep ultraviolet range or solar blind photodetection. Heterostructure/heterointerface of beta-gallium oxide with different semiconductors of appropriate band gap are valuable for broadband photodetection applications from deep ultraviolet to visible wavelength. In this direction, gallium oxide nanostructures fabricated on gallium nitride using combination of cost-effective way of chemical etching and thermal oxidation. Gallium oxide nanostructures exhibits the polycrystalline nature with beta phase. Valance band spectra disclosed the formation of an additional Ga(4s)-O(2p) hybridization energy state. The time-resolved photoluminescence spectra of the samples demonstrated fluorescent transitions of charge carriers from excited state to ground state less than 1 nano-second average career lifetime.

Fabricated  $p - n$  junction configuration devices used to detect the deep ultraviolet wavelength application. The beta-gallium oxide on silicon nanowires fabricated using pulse laser deposition and chemical etching methods. Fabricated  $p - n$  junction configuration shows good photoresponsivity ( $\sim 42$  mA/W) for deep ultraviolet wavelength with external voltage biasing.

For multi-wavelength detection within a single device, beta-gallium oxide – zinc oxide nanowires heterostructures fabricated on silicon using pulse laser deposition and chemical bath deposition. Heterostructures showed the multiple emission peaks from deep ultraviolet to red wavelength that makes it a potential candidate for multi-wavelength detection. The multi-wavelength response (222.85, 133.71 and 44.57 mA/W) of the heterostructure fabricated device is evaluated under three different illuminations (266 nm, 355 nm and 532 nm) using ultraviolet and visible ranges.

The findings reported in this thesis provide the fabrication of ultra-wide band gap semiconductor micro/nano nanodimensional heterostructures have great potential for optoelectronic device applications.

# सारांश

उन्नत ऑप्टोइलेक्ट्रॉनिक डिवाइस अनुप्रयोगों यानी संवर्धित वास्तविकता, बायो-रोबोट, फोटोनिक न्यूरल नेटवर्क, ऑटोमोटिव लाइटिंग आदि की भविष्य की मांग ने शोधकर्ताओं को अल्ट्रा-वाइड बैंड सेमीकंडक्टर सामग्रियों पर काम करने के लिए प्रेरित किया, जिन्हें सेमीकंडक्टर सामग्रियों की चौथी पीढ़ी के रूप में भी जाना जाता है। हीरा, गैलियम ऑक्साइड, हेक्सागोनल बोरोन नाइट्राइड, आर्सेनिक ऑक्साइड, और आदि। उच्च तापीय स्थिरता, उच्च ब्रेकडाउन विद्युत क्षेत्र, उच्च आवृत्ति सहिष्णुता, उच्च रासायनिक प्रतिरोधी क्षमता जैसे अल्ट्रा-वाइड बैंडगैप सामग्रियों के अद्वितीय गुण कठोर परिस्थितियों में उच्च परिचालन गति के निर्माण की सुविधा प्रदान करते हैं। पर्यावरण। हाल ही में, गहरे पराबैंगनी से लेकर दृश्यमान फोटोडिटेक्शन अनुप्रयोगों पर विभिन्न क्षेत्रों में उनके उपयोग के कारण ध्यान दिया गया है, जैसे कि रासायनिक / जैविक विश्लेषण, चिकित्सा उपकरण, जल शोधन, दहन की निगरानी, मिसाइल ट्रैकिंग, सुरक्षित कम दूरी का संचार, अंतरिक्ष संचार, सौर विकिरण माप, पराबैंगनी खगोल विज्ञान और आदि। फोटोडिटेक्टर ऑप्टोइलेक्ट्रॉनिक उपकरण हैं जिनमें इलेक्ट्रॉन-छेद जोड़े के उत्पादन, परिवहन और पुनर्संयोजन की जटिल प्रक्रिया को शामिल करके एक ऑप्टिकल सिग्नल को विद्युत सिग्नल में बदलना शामिल है।

यह थीसिस विशेष रूप से फोटोडिटेक्शन अनुप्रयोगों पर केंद्रित ऑप्टोइलेक्ट्रॉनिक डिवाइस अनुप्रयोगों के लिए अल्ट्रा-वाइड बैंड गैप सेमीकंडक्टर माइक्रो/नैनो नैनोडायमेशनल हेटरोस्ट्रक्चर के निर्माण पर प्रकाश डालती है। संश्लेषण तकनीक गैलियम ऑक्साइड और आर्सेनिक ऑक्साइड के सूक्ष्म/नैनो नैनोआयामी हेटरोस्ट्रक्चर के लिए लचीले और लागत प्रभावी तरीके पर केंद्रित है। आर्सेनिक ऑक्साइड भी एक स्थिर अल्ट्रा-वाइड बैंड गैप सामग्री है और उच्च संपीड़न के तहत स्थिरता रखती है। हाल के वर्षों में, गैलियम ऑक्साइड ऑप्टोइलेक्ट्रॉनिक उपकरणों/बिजली उपकरणों के लिए सबसे केंद्रित अल्ट्रा-वाइड बैंड गैप सेमीकंडक्टर है, जबकि गैलियम ऑक्साइड का बीटा चरण अपने उच्च ब्रेकडाउन इलेक्ट्रिक क्षेत्र, थर्मल और रासायनिक स्थिरता के कारण बेहतर है, जो अगली पीढ़ी के लिए जबरदस्त वादा करता है। ऑप्टोइलेक्ट्रॉनिक उपकरण।

सबसे पहले, पराबैंगनी और दृश्यमान रेंज में उपयोगी ऑप्टिकल सामग्री के रूप में आर्सेनिक ऑक्साइड माइक्रोक्रीस्टल के संश्लेषण पर चर्चा करता है। इलेक्ट्रोलेस आर्सेनिक ऑक्साइड माइक्रोक्रीस्टल के संश्लेषण के लिए, नाइट्रिक एसिड द्वारा गैलियम आर्सेनाइड (100) सबस्ट्रेट की रासायनिक नक्काशी को लागत प्रभावी दृष्टिकोण के रूप में खोजा गया है। सतह पर पॉलीक्रीस्टलाइन ऑक्टाहेड्रोन माइक्रोस्ट्रक्चर की संख्या नक्काशी के समय के साथ बढ़ी और संरचनात्मक और रूपात्मक विश्लेषणों से इसकी पुष्टि हुई। सतह पर रासायनिक संरचना से माइक्रोक्रीस्टल में मौजूद आर्सेनिक की विभिन्न ऑक्सीकरण अवस्था का पता चलता है। फोटोल्यूमिनेसेंस और समय-समाधान फोटोल्यूमिनेसेंस का उपयोग करके अध्ययन किए गए इलेक्ट्रॉनिक संक्रमण और इलेक्ट्रॉनिक संक्रमण की गतिशील प्रकृति ने आर्सेनिक ऑक्साइड माइक्रोक्रीस्टल की फ्लोरोसेंट प्रकृति के साथ पराबैंगनी और नीले उत्सर्जन का प्रदर्शन किया।

गहरे पराबैंगनी रेंज या सौर ब्लाइंड फोटोडिटेक्शन में काम करने के लिए गैलियम ऑक्साइड बेहतर विकल्प है। उपयुक्त बैंड गैप के विभिन्न अर्धचालकों के साथ बीटा-गैलियम ऑक्साइड की हेटरोस्ट्रक्चर/हेटरोइंटरफेस गहरे पराबैंगनी से दृश्यमान तरंग दैर्ध्य तक ब्रॉडबैंड फोटोडिटेक्शन अनुप्रयोगों के लिए मूल्यवान हैं। इस दिशा में, रासायनिक नक्काशी और थर्मल ऑक्सीकरण के लागत प्रभावी तरीके के संयोजन का उपयोग करके गैलियम नाइट्राइड पर गैलियम ऑक्साइड नैनोस्ट्रक्चर का निर्माण किया गया। गैलियम ऑक्साइड नैनोस्ट्रक्चर बीटा चरण के साथ पॉलीक्रिस्टलाइन प्रकृति प्रदर्शित करता है। वैलेंस बैंड स्पेक्ट्रा ने एक अतिरिक्त गैलियम (4 एस)-ऑक्सीजन(2 पी) संकरण ऊर्जा अवस्था के गठन का खुलासा किया। नमूनों के समय-समाधान फोटोल्यूमिनेसेंस स्पेक्ट्रा ने 1 नैनो-सेकंड औसत करियर जीवनकाल से भी कम समय में उत्तेजित अवस्था से जमीनी अवस्था तक आवेश वाहकों के फ्लोरोसेंट संक्रमण का प्रदर्शन किया। गहरे पराबैंगनी तरंग दैर्ध्य अनुप्रयोग का पता लगाने के लिए निर्मित पी-एन जंक्शन कॉन्फिगरेशन डिवाइस का उपयोग किया जाता है। सिलिकॉन नैनोवायर पर बीटा-गैलियम ऑक्साइड पल्स लेजर जमाव और रासायनिक नक्काशी विधियों का उपयोग करके निर्मित किया गया है। फैब्रिकेटेड पी-एन जंक्शन कॉन्फिगरेशन वोल्टेज के बाहरी पूर्वाग्रह के साथ गहरी पराबैंगनी तरंग दैर्ध्य के लिए अच्छी फोटोरिस्पॉन्सिविटी ( $\sim 42$  मिली एम्पीयर/वाट) दिखाता है।

एक ही उपकरण के भीतर बहु-तरंगदैर्ध्य का पता लगाने के लिए, पल्स लेजर जमाव और रासायनिक स्नान जमाव का उपयोग करके सिलिकॉन पर निर्मित बीटा-गैलियम ऑक्साइड - जिंक ऑक्साइड नैनोवायर हेटरोस्ट्रक्चर। हेटरोस्ट्रक्चर ने गहरे पराबैंगनी से लेकर लाल तरंग दैर्ध्य तक कई उत्सर्जन शिखर दिखाए जो इसे बहु-तरंग दैर्ध्य का पता लगाने के लिए एक संभावित उम्मीदवार बनाता है। हेटरोस्ट्रक्चर निर्मित डिवाइस की बहु-तरंग दैर्ध्य प्रतिक्रिया (222.85, 133.71 और 44.57 मिली एम्पीयर/वाट) का मूल्यांकन पराबैंगनी और दृश्यमान श्रेणियों का उपयोग करके तीन अलग-अलग रोशनी (266 नैनोमीटर, 355 नैनोमीटर और नैनोमीटर) के तहत किया जाता है।

इस थीसिस में बताए गए निष्कर्ष अल्ट्रा-वाइड बैंड गैप सेमीकंडक्टर माइक्रो/नैनो नैनोडायमेंशनल हेटरोस्ट्रक्चर के निर्माण को प्रदान करते हैं, जिसमें ऑप्टोइलेक्ट्रॉनिक डिवाइस अनुप्रयोगों के लिए काफी संभावनाएं हैं।

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# Abbreviations

<b>EDS</b>	<b>E</b> nergy <b>D</b> ispersive <b>X</b> -ray <b>S</b> pectroscopy
<b>FESEM</b>	<b>F</b> ield <b>E</b> mission <b>S</b> canning <b>E</b> lectron <b>M</b> icroscope
<b>IPA</b>	<b>I</b> sopropyl <b>A</b> lcohol
<b>CBD</b>	<b>C</b> hemical <b>B</b> ath <b>D</b> eposition
<b>HMTA</b>	<b>H</b> exa <b>M</b> ethyl <b>T</b> etra <b>A</b> mine
<b>MACE</b>	<b>M</b> etal <b>A</b> ssisted <b>C</b> hemical <b>E</b> tching
<b>MSM</b>	<b>M</b> etal <b>S</b> emiconductor <b>M</b> etal
<b>PL</b>	<b>P</b> hotoluminescence
<b>PLD</b>	<b>P</b> ulse <b>L</b> aser <b>D</b> eposition
<b>SiNWs</b>	<b>S</b> ilicon <b>N</b> ano <b>W</b> ires
<b>TEM</b>	<b>T</b> ransmission <b>E</b> lectron <b>M</b> icroscope
<b>TRPL</b>	<b>T</b> ime <b>R</b> esolved <b>P</b> hotoluminescence
<b>XPS</b>	<b>X</b> -Ray <b>P</b> hotoelectron <b>S</b> pectroscopy
<b>XRD</b>	<b>X</b> -Ray <b>D</b> iffraction
<b>ZnONWs</b>	<b>Z</b> inc <b>O</b> xide <b>N</b> ano <b>W</b> ires