FABRICATION AND CHARACTERIZATION OF Ga_2O_3 BASED SCHOTTKY DIODES AND SOLAR-BLIND PHOTODETECTORS FOR POWER ELECTRONICS AND OPTOELECTRONICS APPLICATIONS

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Fabrication and Characterization of Ga_2O_3 based Schottky Barrier Diodes and Solar-Blind Photodetectors for Power Electronics and Optoelectronics Applications

by

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This Thesis is dedicated to my Parents and Gurus.

Certificate

This is to certify that the thesis entitled "***Fabrication and Characterization of Ga_2O_3 based Schottky Barrier Diodes and Solar-Blind Photodetectors for Power Electronics and Optoelectronics Applications***" being submitted by ***Mr. Hardhyan*** to the ***Indian Institute of Technology Delhi***, ***India*** 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 our 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.

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Hardhyan Sheoran

Abstract

With superior material properties, availability, and ease of growth of high crystalline wafers and epitaxial thin films, β-Ga_2O_3 emerged as a viable candidate for power semiconductor devices, especially Schottky barrier diodes (SBDs), Field-effect transistors (FETs) and deep ultraviolet (DUV) photodetectors for harsh environmental conditions. Very high values of breakdown electric field strength ~8 MV/cm and Baliga`s figure of merit (BFOM) of 3444 due to ultrawide bandgap ~4.5 – 4.9 eV, along with high thermal and chemical stability make β-Ga_2O_3 a promising semiconductor material of power semiconductor devices. Also, due to its UWBG, β-Ga_2O_3 has intrinsic solar blindness and a very high absorption coefficient (>10^5 cm^{-1}), making β-Ga_2O_3 a potential contender for DUV photodetectors. With the achievement of controllable n-type conductivity using Si, Sn as a dopant with doping density in the 10^{15} – 10^{20} cm^{-3} range, high-power SBDs can be fabricated on β-Ga_2O_3. Metal-semiconductor (MS) contacts are critical for any semiconductor device to achieve high performance. The quality of MS contacts significantly affects the device characteristics. The reproducibility and thermal stability of MS contacts are essential for the high performance of Schottky diodes.

In this direction, at the beginning of this work, a meticulous examination of the temperature-dependent current transport mechanism in Ni/β-Ga_2O_3 Schottky Barrier Diodes (SBDs) on halide vapor phase epitaxy (HVPE)-grown β-Ga_2O_3 epilayer through current-voltage (I-V) and capacitance-voltage (C-V) characterization techniques across a broad temperature range (78–350 K) was carried out. The study reveals a strong temperature dependency of the Schottky barrier height and ideality factor, with values of 1.27 eV, 1.12, and high rectification ratio (RR) of the order of $10^{12,}$ respectively, at room temperature. The temperature dependency of SBH and ideality factor revealed the barrier inhomogeneity at the Ni/β-Ga_2O_3 interface and was analyzed by using the Werner-Güttler barrier inhomogeneity model, which further indicated the presence of defects at the interface or within the semiconductor material.

Following this work, in the next step, a high-quality Pt-based SBDs was fabricated on HVPE-grown β-Ga_2O_3 epilayer, and a detailed investigation of repeatability and thermal stability was done by performing the temperature-dependent electrical measurements over a wide temperature range (80–525 K) multiple times on several SBDs. A high Schottky barrier height (SBH) exceeding 1 eV with a near unity ideality factor at 300 K with superior thermal stability was obtained. The temperature dependence of SBH indicates barrier inhomogeneity at the Pt/β-

Ga_2O_3 interface. The persistence of a very high RR of the order of 10^7 even at a high temperature of 525 K, near unity ideality factors above 300 K, and high values of SBHs across the entire temperature range further underscore the potential of these Pt/β-Ga_2O_3 SBDs for advanced power electronic devices.

In the quest for cost-effective alternatives to Ni and Pt, the thesis explores the use of copper for Schottky contact. The fabricated Cu/β-Ga_2O_3 SBDs exhibit remarkable properties, including high Schottky barrier heights (SBHs) exceeding 1.0 eV, near-unity ideality factors, and a substantial RR of 10^{12} at 300 K. Temperature-dependent current-voltage and temperature-dependent capacitance-voltage measurements up to 500 K were performed multiple times on many diodes. Cu/β-Ga_2O_3 SBDs showed excellent thermal stability. The decrease of SBH above 410 K indicated the homogeneous Schottky barrier at high temperatures. The superb performance and thermal stability attributed to the formation of a high-work-function copper oxide thin film at the Cu-Ga_2O_3 interface. This study opens avenues for low-cost mass production of power semiconductor devices, highlighting the potential of copper as a viable alternative for Schottky contacts in oxide semiconductor devices.

These findings contribute to the fundamental understanding of β-Ga_2O_3-based Schottky diodes and offer practical implications for developing advanced power electronic devices with enhanced thermal stability, endurance, and cost-effectiveness. Exploring alternative materials like copper further extends the potential for scalable and economical production of future semiconductor devices based on oxide semiconductors.

Various defects at metal-semiconductor interfaces or within the semiconductors significantly affect power device performance and reliability. Most defects are introduced in semiconductors during the growth, and external factors such as ion implantation, irradiation, and fabrication process produce the defects at the MS interface and inside the semiconductor below the interface. Therefore, it is utmost to characterize the defects spectrum within the energy bandgap to address critical issues like carrier compensation, trapping-detrapping, generation, recombination, scattering, etc.

In this scenario in the 2nd part of the thesis, a detailed examination of electrically active defects in Si-doped HVPE-grown β-Ga_2O_3 epilayers was conducted through deep-level transient spectroscopy (DLTS). Notable traps were identified, providing insights into their origin and behavior. The traps were generated during the growth of semiconductors and affected or introduced due to metallization and chemical mechanical polishing (CMP). This highlighted the importance of understanding and mitigating defects in β-Ga_2O_3-based devices.

Good crystalline quality of β-Ga_2O_3 epitaxial thin films is necessary for high-performance DUV photodetectors. The DUV photodetectors must be stable even in harsh environmental conditions such as temperature, high-energy photons from the sun, and high radiation levels for defense and space applications. Self-powered photodetectors are critical for future technologies.

In the last part of this work, high-performance DUV photodetectors are fabricated on high crystalline quality metal-organic chemical vapor deposition (MOCVD) grown β-Ga_2O_3 thin films. The thermal stability of these PDs was also tested up to 125 °C. The fabricated exhibited self-powered behaviour with a high photo-to-dark current ratio (PDCR) value greater than 10^5 and an ultra-low dark current of 1.75 *f*A at zero bias. Very high values of specific detectivity of the order of 10^{11} and greater than 10^{14} Jones were obtained at zero, and higher biases indicated the very high capability of our fabricated to detect weak signals from background noise even at zero bias. Fabricated PDs exhibited stable behaviour up to 125 °C with constant ultralow dark current values, increasing UV to visible rejection ratio over the entire temperature range.

सार

β-Ga_2O_3, बेहतर सामग्री गुणों, उच्च क्रिस्टलीय वेफर्स, एपिटैक्सियल पतली फिल्मों के विकास और उपलब्धता में आसानी के साथ, कठोर पर्यावरणीय परिस्थितियों में एक व्यवहार्य उम्मीदवार के रूप में उभरा है। विशेष रूप से शक्ति अर्धचालक उपकरणों जैसे शोट्की अवरोध डायोड (SBD), विद्युत प्रभाव ट्रांजिस्टर (FET) और गहरी पराबैंगनी (DUV) फोटोडिटेक्टर। β-Ga_2O_3 अपने गहरा ऊर्जा अंतराल (UWBG) ~4.5 - 4.9 eV के कारण विद्युत क्षेत्र सामर्थ्य के बहुत उच्च मान ~8 MV/cm और बालिगा दक्षताँक (BFOM) ~ 3444, साथ ही उच्च तापीय और रासायनिक स्थिरता के कारण, शक्ति अर्धचालक उपकरणों के लिये एक आशाजनक अर्धचालक सामग्री है।

अपने UWBG के कारण, β-Ga_2O_3 में आंतरिक सौरअंधता और बहुत उच्च अवशोषण गुणांक ($>10^5$ cm^{-1}) है, जो β-Ga_2O_3 को DUV फोटोडिटेक्टरों के लिए एक संभावित दावेदार बनाता है। 10^{15} - 10^{20} cm^{-3} रेंज में डोपिंग घनत्व के साथ डोपेंट के रूप में Si, Sn का उपयोग करके नियंत्रणीय n-प्रकार की चालकता की उपलब्धि के साथ, उच्च-शक्ति SBD को β-Ga_2O_3 पर निर्मित किया जा सकता है। उच्च प्रदर्शन प्राप्त करने के लिए किसी भी अर्धचालक उपकरण के लिए धातु-अर्धचालक (MS) संपर्क महत्वपूर्ण हैं। MS संपर्कों की गुणवत्ता उपकरण की विशेषताओं को महत्वपूर्ण रूप से प्रभावित करती है। शोट्की डायोड के उच्च प्रदर्शन के लिए एमएस संपर्कों की पुनरुत्पादकता और ऊष्मीय स्थिरता आवश्यक है।

शोध कार्य की शुरुआत में, हैलाइड वेपर फेज एपिटैक्सी (HVPE) द्वारा निर्मित β-Ga_2O_3 एपिलेयर पर Ni/β-Ga_2O_3 Schottky बैरियर डायोड्स (SBDs) बनाये गए और ताप अनुभागीय विद्युत संधारिता की बहुविधात्मक जाँच की गई। इसके लिए विद्युत धारा- वोल्टेज (I-V) और संधारित्र धारिता -वोल्टेज (C-V) लक्षण वर्णन तकनीकों का उपयोग एक व्यापक तापमान रेंज (78–350 K) में किया गया। अध्ययन ने स्थायी तापमान पर Schottky बैरियर ऊचाई और आदर्शता कारक की एक मजबूत तापमान निर्भरता का खुलासा किया, जिसमें कमरा तापमान पर Schottky बैरियर ऊचाई = 1.27 eV, आदर्शता कारक = 1.12 और उच्च दिष्टकारी अनुपात (RR) = 10^{12} प्राप्त हुआ। SBH और आदर्शता कारक की तापमान निर्भरता ने Ni/β-Ga_2O_3 इंटरफ़ेस पर Schottky बैरियर असमानता का खुलासा किया और वर्नर - गटलर बैरियर असमरूपता मॉडल का उपयोग करके विश्लेषण किया गया, जिसने इंटरफ़ेस पर या अर्धचालक पदार्थ के भीतर दोषों की उपस्थिति का संकेत दिया।

इस काम के बाद, अगले चरण में, एक उच्च गुणवत्ता वाले Pt-आधारित SBDs को HVPE-द्वारा निर्मित β-Ga_2O_3 इपिलेयर पर बनाया गया और और विभिन्न SBDs पर कई बार एक विस्तृत तापमान रेंज (80 - 525 K) पर तापमान - निर्भर विद्युत माप करके पुनरुत्पादकता और ऊष्मीय स्थिरता की विस्तृत जांच की गई। 300 K पर, एक उच्च Schottky बैरियर ऊंचाई (SBH) बेहतर ऊष्मीय स्थिरता के साथ एक निकट एकता आदर्शता कारक के साथ 1 ईवी से अधिक प्राप्त किया गया । SBH की तापमान निर्भरता Pt/β-Ga_2O_3 इंटरफ़ेस पर बैरियर असमानता को इंगित करती है। 525 K के उच्च तापमान पर भी एक बहुत ही 10^7 के दिष्टकारी अनुपात की दृढ़ता, 300 K से ऊपर निकट एकता आदर्शता कारकों, और पूरे तापमान सीमा में SBHs के उच्च मान आगे उन्नत बिजली इलेक्ट्रॉनिक उपकरणों के लिए इन Pt/β-Ga_2O_3 SBDs की क्षमता को रेखांकित करते हैं ।

निकल धातु और प्लैटिनम धातु के सस्ते विकल्पों की खोज में, यह शोध, Schottky संपर्क के लिए तांबे के उपयोग की पड़ताल करती है । निर्मित Cu/β-Ga_2O_3 SBDs उल्लेखनीय गुणों का प्रदर्शन करते हैं , जिनमें 1.0 eV से अधिक उच्च Schottky बैरियर ऊंचाई (SBHs), निकट - एकता आदर्शता कारक और 300 K पर 10^{12} की दिष्टकारी अनुपात शामिल है । तापमान - निर्भर विद्युत धारा - वोल्टेज और तापमान - निर्भर संधारित्र धारिता - वोल्टेज माप, 500 K तक विभिन्न डायोड पर कई बार किए गए थे । Cu/β-Ga_2O_3 SBD ने उत्कृष्ट ऊष्मीय स्थिरता दिखाई । 410 K से ऊपर उच्च तापमान पर SBH के कम होने ने समरूप Schottky बैरियर का संकेत दिया। शानदार प्रदर्शन और ऊष्मीय स्थिरता के लिए Cu-Ga_2O_3 इंटरफ़ेस पर एक उच्च कार्यक्रिया कॉपर ऑक्साइड पतली फिल्म के गठन को श्रेय जाता है। यह अध्ययन बिजली अर्धचालक उपकरणों के कम लागत वाले बड़े पैमाने पर उत्पादन के लिए रास्ते खोलता है और ऑक्साइड अर्धचालक उपकरणों में Schottky संपर्कों के लिए एक व्यवहार्य विकल्प के रूप में तांबे की क्षमता को प्रदर्शित करता है।

ये निष्कर्ष β-Ga_2O_3 आधारित Schottky डायोड की मौलिक समझ में योगदान करते हैं और उन्नत ऊष्मीय स्थिरता, टिकाव और लागत-प्रभावशीलता के साथ उन्नत बिजली इलेक्ट्रॉनिक उपकरणों के विकास के लिए व्यावहारिक निहितार्थ प्रदान करते हैं। तांबे जैसी वैकल्पिक सामग्रियों की खोज आगे ऑक्साइड अर्धचालक पर आधारित भविष्य के अर्धचालक उपकरणों के मापनीय और किफायती उत्पादन की क्षमता को बढ़ाती है।

धातु-अर्धचालक (MS) इंटरफेस या अर्धचालक के भीतर विभिन्न दोष बिजली-शक्ति डिवाइस के प्रदर्शन और विश्वसनीयता को काफी प्रभावित करते हैं। अधिकांश दोष अर्धचालक के निर्माण के दौरान विकसित हो जाते हैं और बाहरी कारक जैसे आयन आरोपण, विकिरण और फैब्रिकेशन प्रक्रिया आदि MS इंटरफ़ेस

पर और इंटरफ़ेस के नीचे अर्धचालक के अंदर दोष उत्पन्न करते हैं। इसलिए वाहक क्षतिपूर्ति, ट्रैपिंग - डिट्रैपिंग, पुनर्संयोजन, बिखरने आदि जैसे महत्वपूर्ण मुद्दों को हल करने के लिए ऊर्जा बैंडगैप के भीतर दोष स्पेक्ट्रम को चिह्नित करना अत्यंत आवश्यक है।

इस कार्य के दूसरे हिस्से में, डीप-लेवल ट्रांसिएंट स्पेक्ट्रोस्कोपी (DLTS) के माध्यम से Si-doped HVPE-β-Ga_2O_3 एपिलेयर में विद्युत सक्रिय दोषों की एक विस्तृत जांच की गई। उल्लेखनीय traps की पहचान की गई, जिससे उनकी उत्पत्ति और व्यवहार के बारे में जानकारी मिली। ये traps, semiconductor के विकास के दौरान उत्पन्न हुए और मेटलाइजेशन और केमिकल मैकेनिकल पॉलिशिंग (CMP) के कारण प्रभावित या उत्पन्न हुए। इसने β-Ga_2O_3 आधारित डिवाइसेज़ में traps को समझने और उन्हें कम करने के महत्व को उजागर करता है।

उच्च प्रदर्शन DUV फोटोडिटेक्टर के लिए β-Ga_2O_3 एपिटैक्सियल पतली फिल्मों की अच्छी क्रिस्टलीय गुणवत्ता आवश्यक है। DUV फोटोडिटेक्टर कठोर पर्यावरणीय परिस्थितियों जैसे तापमान, सूर्य से उच्च ऊर्जा फोटॉन और रक्षा और अंतरिक्ष अनुप्रयोगों के लिए उच्च विकिरण स्तर में भी स्थिर होना चाहिए। स्व-संचालित फोटोडिटेक्टर भविष्य की प्रौद्योगिकियों के लिए महत्वपूर्ण हैं।

इस परिदृश्य में थीसिस के अंतिम भाग में, उच्च क्रिस्टलीन गुणवत्ता वाले मेटल-आर्गेनिक केमिकल वेपोर डिपोजिशन (MOCVD) से उत्पन्न β-Ga_2O_3 पतली फिल्मों पर उच्च प्रदर्शन DUV फोटोडिटेक्टर्स बनाए गए। इन PDs की ऊष्मीय स्थिरता को 125 °C तक भी जांचा किया गया था। बनाए गए फोटोडिटेक्टर्स ने अपनी स्वयं संचालित व्यवहार को प्रदर्शित किया, जिसमें शून्य विभव पर एक उच्च फोटो-टू-डार्क करंट अनुपात (PDCR) मान 10^5 से अधिक और 1.75 *f*A की अत्यंत - निम्न डार्क करंट शामिल थी। शून्य पर, और उच्च विभव पर 10^{11} और 10^{14} Jones के क्रम में विशेष डिटेक्टिविटी के बहुत उच्च मान प्राप्त किए गए, जिससे हमारे बनाए गए फोटोडिटेक्टर्स की बहुत उच्च क्षमता सुझाई गई कि वे शून्य विभव पर भी पृष्ठभूमि शोर से कमज़ोर सिग्नल्स की पहचान कर सकते हैं। निर्मित PDs ने 125 °C तक स्थिर व्यवहार प्रदर्शित किया, जिसमें पूरे तापमान सीमा पर स्थिर अल्ट्रा-लो डार्क करंट मान, बढ़ती UV-visible अस्वीकृति अनुपात है।

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Symbols

$\overline{\Phi_{B0}}$	Mean Schottky barrier height
$\dot{\sigma}_S$	Capture cross-section
$\Delta\phi_{IL}$	Induced image force potential lowering
μ	Electron mobility
α^*	Optical absorption coefficient
A	Ampere
$A^{`}$	Absorbance
A^*	Effective Richardson's constant
$B, b1$	proportionality constant
b_2	Empirical coefficient
C	Capacitance
c	Speed of light
C_0	Capacitance of diode at fix reverse bias
d	Thickness
D_i	Interface states density
e	Emission rate
E_{br}	Breakdown field
E_C	Conduction band edge
E_{Fi}	Intrinsic Fermi energy level
E_{fm}	Fermi energy position in metal
E_{fs}	Fermi energy position in semiconductor
E_g	Bandgap
E_{MS}	Electric field strength at MS interface
E_T	Trap energy
E_V	Valance band edge
E_F	Fermi level
f	Femto
G	Gain of photodetector
h	Planck's constant

hυ	Photons energy
I	Current
I_0	Saturation photocurrent
I_d	Dark current
I_p	Photocurrent
I_r	Reverse leakage current
I_s	Reverse saturation current
J	Current density
K	Kelvin
k_b	Boltzmann's constant
m_0	Free electron mass
m^*	Effective electron mass
D^*	Specific detectivity
η	Ideality factor
N_C	Effective density of states in the conduction band
N_d	Doping density
n_i	Intrinsic carrier concentration
N_T	Trap density
p	Pico
Φ_{ap}	Apparent Schottky barrier height
P_λ	Illuminated power density at wavelength λ
q	Electronic charge
R_C	Contact resistance
R_{on}	Turn on-resistance
R_S	Series resistance
R_λ	Responsivity of the photodetector
S	Contact area
S_λ	Photosensitivity of photodetector
T	Temperature
V	Voltage
V_{bi}	Built-in potential

V_{on}	Turn on-voltage
V_{th}	Mean thermal velocity
W	Depletion width
x	Distance from the MS interface
α	Temperature coefficient
δ	Interfacial layer width
ε	Dielectric constant
ε_i	Intrinsic dielectric constant
ε_S	Relative permittivity
ζ	Voltage dependent positive coefficient of SBH
Λ	Potential drop across the interfacial layer
ρ_2	Voltage-deformation coefficients of mean SBH $\overline{\phi_{B0}}$
ρ_3	Voltage-deformation coefficients of standard deviation
ρ_C	Specific contact resistance
σ_S	Standard deviation of Gaussian distribution of SBH
τ_e	Emission time constant
τ_p	Pulse width
$\tau_{r1}, \tau_{r2}, \tau_d, \tau_r$	Time constants
υ	Frequency
v_S	Saturation velocity
ϕ_0	Charge neutrality level
ϕ_B	Schottky barrier height
ϕ_{hom}	Homogeneous barrier height
ϕ_m	Metal work function
χ_S	Electron affinity
ψ	External quantum efficiency
d	Interplanar spacing between the crystal planes
θ	Angle
λ	Wavelength

Abbreviations

AFM	Atomic force microscopy
ALD	Atomic layer deposition
AS	Admittance spectroscopy
BFOM	Baliga`s figure of merit
CIE	International Commission on Illumination
CL	Cathodoluminescence
CMP	Chemical mechanical polishing
CV	Capacitance voltage
CVT	Temperature-dependent capacitance-voltage
CZ	Czochralski
DC	Direct-current
DDLTS	Double correlated DLTS
DI	Deionized water
DLTS	Deep level transient spectroscopy
DMD	Digital-mirror-display
DOLS	Deep level optical spectroscopy
DUT	Device under test
DUV	Deep ultraviolet
E-beam	Electron-beam
EFG	Edge-defined film-fed growth
E-field	Electric-field
EHP	Electron-hole pair
FE	Field emission
FET	Field-effect transistor
FOM	Figure of merit
FZ	Floating zone
G-R	Generation-recombination
HVPE	Halide vapor phase epitaxy
IPA	Isopropyl alcohol
ISL	Intermediate semiconductor layer
I-V	Current voltage

IVT	Temperature-dependent current-voltage
JFOM	Johnson’s figure of merit
KITE	Keithley Test Environment
LED	Light-emitting diode
LSPR	Localized surface plasmon resonance
MBE	Molecular-beam epitaxy
MESFET	Metal-semiconductor field-effect transistor
MOCVD	Metal-organic chemical vapor deposition
MOS	Metal oxide semiconductor
MOSFET	Metal-oxide-semiconductor field-effect transistor
MS	Metal-semiconductor
MSM	Metal-semiconductor-metal
NEP	Noise equivalent power
PD	Photodetector
PDCR	Photo-to-dark current ratio
PFE	Poole-Frenkel effect
PL	Photoluminescence
PLD	Pulsed laser deposition
PPC	Persistent photoconductivity
RMS	Root-mean-square
rpm	Rotations per minute
RR	Rectification ratio
RRAM	Resistance random access memory
RT	Room temperature
SB	Solar-blind
SBD	Schottky barrier diode
SBH	Schottky barrier height
SC	Schottky contact
SCS	Semiconductor characterization system
SNR	Signal-to-noise ratio
SOG	Spin-on-glass
SPM	Scanning probe microscopy
TE	Thermionic emission

TEGa	Triethylgallium
TFE	Thermionic field emission
TLM	Transmission line method
TSC	Thermally stimulated capacitance
UID	Unintentionally doped
UV	Ultraviolet
UWBG	Ultra-wide bandgap
WBG	Wide bandgap
WG	Werner and Güttler
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction