

Fabrication and Characterization of Self-Biased MSM UV Photodetectors with β -Ga₂O₃ Thin Films

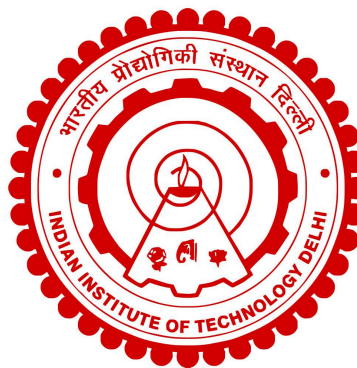
A project report submitted
in Partial Fulfillment of the requirements of

Summer Internship

by

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Dated: **July 20, 2024**

Declaration

I solemnly declare that this summer internship report, titled "Fabrication and Characterization of Zero-Power MSM UV Photodetectors with β -Ga₂O₃ Thin Films," represents my original work and has been conducted solely by me during my internship under the supervision of Prof. Rajendra Singh at the Advanced Semiconductor Materials and Devices (ASMD) group, Department of Physics, IIT Delhi.

To the best of my knowledge, it is an original work, both in terms of research content and narrative, and has not been submitted elsewhere, in whole or in parts, for the award of a degree or diploma.

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Table of Contents

1. Introduction	5
2. Material Characterization	7
a. Atomic Force Microscopy	8
b. X-ray diffraction	11
c. UV-Visible spectroscopy	15
d. Raman spectroscopy	19
3. Fabrication of the MSM Photodetector	23
a. E-beam evaporation	24
4. Electrical Measurements	26
a. I-V characteristics	27
b. Photo-to-Dark Current Ratio (PDCR)	29
c. Responsivity	30
d. UV-visible rejection ratio	33
e. Detectivity (D^*), Noise Equivalent Power (NEP)	34
f. Temporal measurements	36
5. Conclusion	39
6. References	41

Introduction

Why Gallium Oxide?

Deep ultraviolet photodetectors (DUV PDs), which operate at wavelengths below 280 nm and are often referred to as solar-blind photodetectors, have garnered significant attention due to their diverse applications in fields such as defense, space communication, civil sectors, agriculture, healthcare, UV astronomy, high-temperature flame detection, solar-blind imaging for missile tracking, and ozone hole monitoring. Materials with wide-band-gap and ultrawide-band-gap properties, such as GaN, AlGaN, diamond, Lu₂O₃, and Ga₂O₃, have been identified as promising candidates for these devices due to their intrinsic solar-blindness. Unlike UV photodetectors made from narrow-band-gap semiconductors like Si and GaAs, these materials do not require additional optical filters or extensive cooling systems. Among these materials, β -Ga₂O₃ has attracted significant interest due to its ultrawide direct band gap of approximately 4.9 eV, excellent radiation hardness, high chemical and thermal stability, and high absorption coefficient. Additionally, Ga₂O₃ can be grown with high crystalline quality and cost-effectiveness using various melt growth and thin-film techniques, such as edge-defined film-fed growth (EFG), Czochralski (CZ) method, MOCVD, halide vapor-phase epitaxy (HVPE), atomic layer deposition (ALD), pulsed laser deposition (PLD), and molecular beam epitaxy (MBE), without complex doping requirements.[1], [2]

The metal-semiconductor-metal (MSM) structure is preferred for photodetector designs due to its ease of fabrication, device isolation, doping, and superior speed compared to photodiodes. Ti-based ohmic and Ni- and Pt-based Schottky contacts are commonly used for the electrodes. To enhance light transmission and reduce reflectivity, transparent conductive electrodes such as ITO and graphene have been employed. Schottky contact-based MSM electrodes are favored for their low dark currents, achieved through back-to-back Schottky contacts, offering superior photodetector performance without significant loss in photoresponsivity. In contrast, MSM-structured photodetectors with ohmic contacts tend to exhibit photoconductive behavior, which can lead to persistent photoconductivity (PPC) that lowers response speed and increases dark current. Alongside performance parameters like spectral selectivity, responsivity, detectivity, noise equivalent power (NEP), and temporal response, the development of self-powered photodetectors is crucial for reducing power consumption in future electronic devices. Although several self-powered DUV PDs based on β -Ga₂O₃ have been demonstrated, those utilizing p-n heterojunctions with n-type Ga₂O₃ and asymmetrical Schottky contacts face fabrication challenges and often suffer from high dark currents. Additionally, p-n heterojunctions are limited by photosensitivity due to their narrow band gaps and the difficulty of growing high-quality epitaxial films due to lattice mismatch with non-solar-blind materials.

[3]

Material Characterization

Method followed for cleaning the sample (for result reproducibility):

The sample was placed successively in acetone, isopropyl alcohol, deionized (DI) water, and ultrasonicated in each solvent for 5 minutes. We then left it to air-dry and sprayed it with a nitrogen gun to remove the residual humidity.

This cleaning was performed twice before the initial characterization and e-beam deposition.

Characterisation Techniques

As mentioned, the sample received was a beta-gallium Oxide ($\beta - Ga_2O_3$) thin film coated epitaxially on a sapphire substrate (Al_2O_3).

We determined the quality and composition of the film through four techniques:

- X-ray diffraction (XRD)
- Raman spectroscopy
- UV-Vis spectroscopy
- Atomic Force Microscopy (AFM)

The basic principles behind the techniques are displayed below.

Atomic Force Microscopy

Principle and Operation

Atomic Force Microscopy (AFM) is a high-resolution imaging technique used to analyze surface characteristics at the nanometer scale. It operates by scanning a sharp tip over the surface of a sample. The tip is attached to a flexible cantilever, and interactions between the tip and the sample surface cause the cantilever to deflect. A laser beam reflects off the cantilever into a photodetector, measuring these deflections to produce an image of the surface. This measurement is achieved through laser interferometry, which accurately detects cantilever movements.[4], [5]

Imaging modes

- **Contact Mode:** The tip remains constantly in contact with the surface, mapping topography.
- **Tapping Mode:** The tip oscillates near its resonant frequency and intermittently touches the surface. This mode minimizes damage to delicate samples while providing high-resolution topographical images. Our experiments used tapping mode to ensure precise imaging with minimal sample disturbance.
- **Non-Contact Mode:** The tip hovers above the surface, detecting forces without touching, ideal for soft or fragile materials.

Sample Preparation and Measurement:

Samples for AFM analysis must be clean and securely mounted on the AFM stage. In tapping mode, the cantilever oscillates, and the tip makes intermittent contact with the surface. This mode is handy for analyzing samples that are soft or have loosely bound surfaces.

Specific application to the study

This study employed AFM to characterize the surface morphology and roughness of the beta-gallium Oxide thin film grown on a sapphire substrate. We obtained high-resolution images of the film's surface using tapping mode, providing detailed topographical information. The AFM analysis revealed crucial insights into the film's uniformity and surface texture, essential for its performance in MSM photodetectors.

Benefits

AFM offers several advantages:

- **High Resolution:** Achieves atomic-scale resolution.
- **Versatility:** Works on conductive and non-conductive samples.

Results and Analysis:

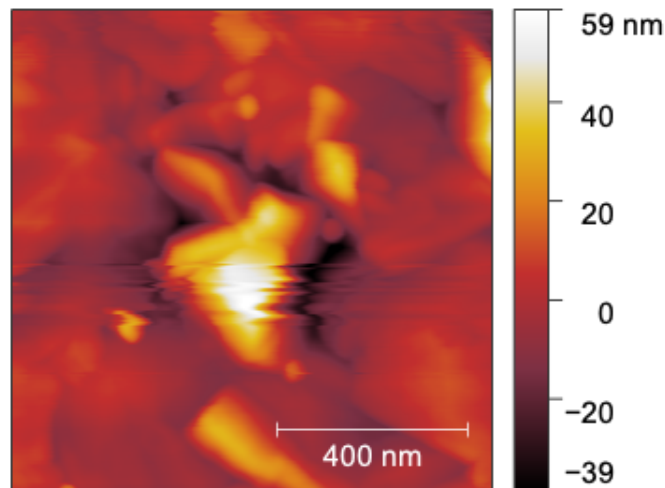


Fig 1: 1 X 1 micron AFM graphic of Gallium Oxide sample

We performed the analysis and produced the attached images using the open-source Gwyddion software.[6]

We obtained an RMS surface roughness of 1.002 nm for the thin film, which is considered reasonable but has room for further improvement. For further improvement, the sample should be comprehensively cleaned before taking the AFM measurement, which would remove most dust particles and other impurities accumulated on the surface.

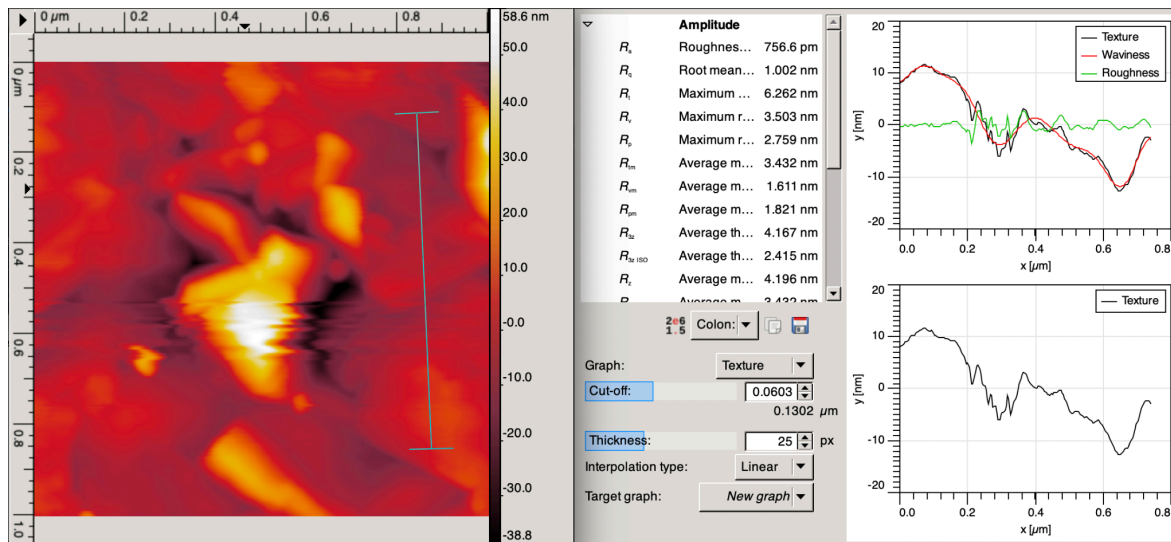


Fig 2: Surface profile of the sample, analyzed by Gwyddion

X-Ray Diffraction

X-ray diffraction (XRD) is a versatile, non-destructive analytical technique used to analyze the physical properties of materials, such as phase composition, crystal structure, and orientation.

Key Principles:

1. X-rays interact with the atoms in a crystalline material, causing the X-rays to "bounce" off at specific angles (diffraction).
2. Constructive interference occurs when the diffracted X-rays have a path difference that is an integer multiple of the wavelength, as described by Bragg's law ($n\lambda = 2d\sin\theta$)

3. The angle of diffraction θ is related to the spacing between atomic planes (d) in the crystal structure, allowing determination of the material's composition and structure[7], [8].

XRD Instrumentation:

Key components include the X-ray source, detector, incident/diffracted beam optics, and goniometer (sample stage).

Various configurations are used for applications such as powder diffraction, single-crystal diffraction, and thin film analysis.

Applications of XRD:

- Qualitative and quantitative phase analysis of pure substances and mixtures.
- Analysis of phase changes under different conditions (temperature, pressure, etc.).
- Determination of physical properties like crystallite size, crystal orientation, and residual stress.
- Characterization of polycrystalline layered materials like coatings and thin films.[9]

Data Analysis:

- The intensity of diffraction peaks is related to the amount of each phase present.
- The width of the peaks is inversely proportional to the crystal size - broader peaks indicate smaller crystals or defects.

- A comparison of the measured diffraction patterns with reference databases allows for the identification of unknown materials.

Results and Analysis:

The measurements were performed on the *Empyrean, Malvern Panalytical* instrument in the physics department, using the GONIO configuration. [9]

The goal was to determine the crystalline quality of the thin film of Gallium oxide. We ran the GONIO scan from 10° to 90° to account for all the expected peaks. A diffraction peak was also expected due to the sapphire substrate.

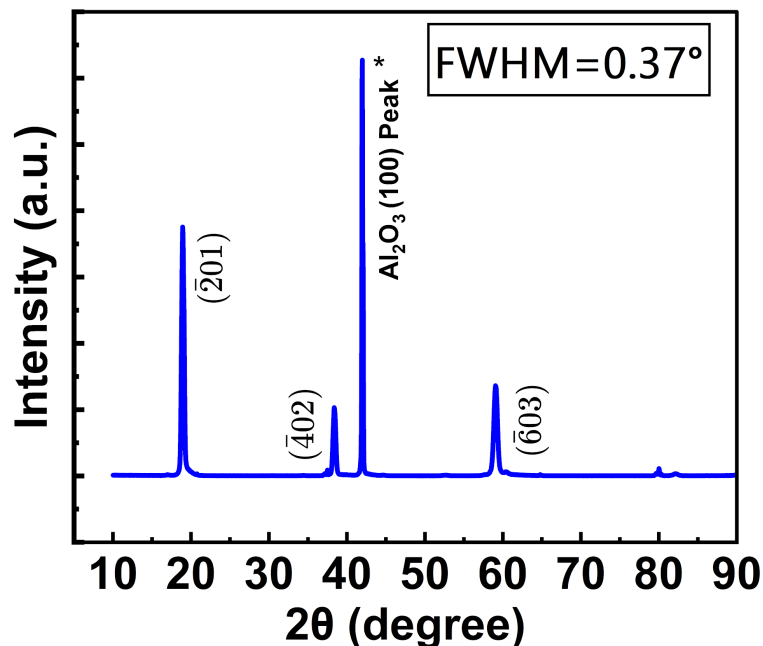


Fig 3: Observed XRD spectra of sample

Observed peak positions in the XRD data

S. No.	2θ	Crystal plane (hkl)
1	18.94	$(\bar{2}01)$
2	38.38	$(\bar{4}02)$
3	41.98	(100)
4	59.06	$(\bar{6}03)$

The peak numbers 1, 2, and 4 correspond to the $(\bar{2}04)$, $(\bar{4}02)$, and $(\bar{6}03)$ peaks of $\beta - Ga_2O_3$ as are detailed in the literature.

The peak 3 (which is the most intense in the spectrum) corresponds to the sapphire substrate. Since the substrate is a single-crystal, it produces a sharp but intense peak. The Gaussian-fitted XRD- 2θ plot corresponding to the $(\bar{2}01)$ peak has a full-width half-maximum of 0.37° , indicating the high crystallinity of the monoclinic $\beta - Ga_2O_3$ film.

The sharp and well-defined peaks observed suggest the high crystallinity of the sample.[10]

UV Vis spectroscopy

Principle and Operation:

Ultraviolet-visible (UV-Vis) Spectroscopy is a technique used to measure a sample's absorption of ultraviolet or visible light. When light passes through a sample, specific wavelengths are absorbed by the material, causing electronic transitions. By measuring the intensity of light before and after it passes through the sample, an absorption spectrum is obtained, which provides information about the electronic structure and concentration of the sample.[11]

Measurement Technique:

The basic setup for UV-Vis spectroscopy includes a light source, a sample holder, a monochromator to select specific wavelengths and a detector. The light source emits a broad spectrum of UV and visible light directed through the monochromator. The monochromator isolates particular wavelengths of light, which then pass through the sample. The detector measures the intensity of the transmitted light, and the data is used to generate an absorption spectrum.

Applications:

UV-Vis spectroscopy is widely used in various fields, including:

- **Chemical Analysis:** Determining the concentration of solutions and identifying substances based on their absorption characteristics.

- **Biochemistry:** Studying protein and nucleic acid concentrations, enzyme kinetics, and molecular interactions.
- **Materials Science:** Characterizing optical properties of materials, thin films, and nanoparticles. [11]

Sample Preparation and Measurement:

Samples for UV-Vis spectroscopy can be in liquid or solid form. Fluid samples are typically placed in quartz cuvettes, while thin films and solid samples are mounted on appropriate holders. The sample should be free of particles and bubbles to avoid scattering and interference.

Specific Application to the study:

This study utilized UV-Vis spectroscopy to characterize the optical properties of the beta-gallium Oxide thin film grown on a sapphire substrate. By measuring the absorbance and transmittance of the film, we obtained critical information about its bandgap and optical transparency. These optical properties are essential for understanding the film's suitability for deep UV photodetectors. The UV-Vis spectra provided insights into the electronic transitions and helped optimize the thin film for better performance in optoelectronic applications.

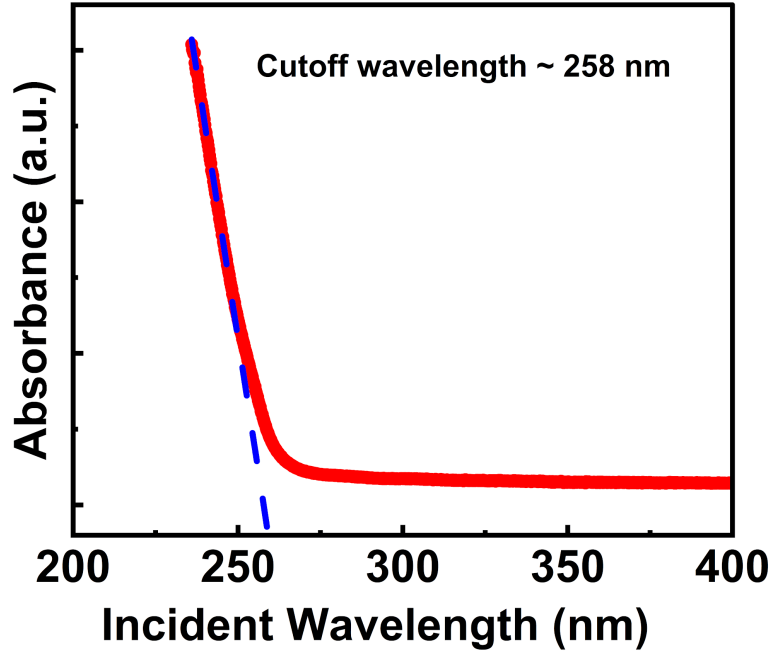


Fig 4: Absorbance v/s Wavelength plot determined by UV-Vis spectroscopy

We can see that the cutoff wavelength is around 258 nm, i.e., the wavelength before which the absorbance increases sharply, translating to a bandgap of 4.81 eV.

The *Tauc plot* is a graphical method used to determine the optical band gap of a material.[12] By plotting $(\alpha h\nu)^n$ versus $h\nu$, where α is the absorption coefficient, h is Planck's constant, and ν is the frequency of light, the band gap can be estimated from the x-intercept of the linear portion of the plot. For β -Ga₂O₃, which has a direct band gap, n is taken as 2, and the plot is $(\alpha h\nu)^2$ versus $h\nu$. We took the thickness of the β -Ga₂O₃ film to be 100 nm.

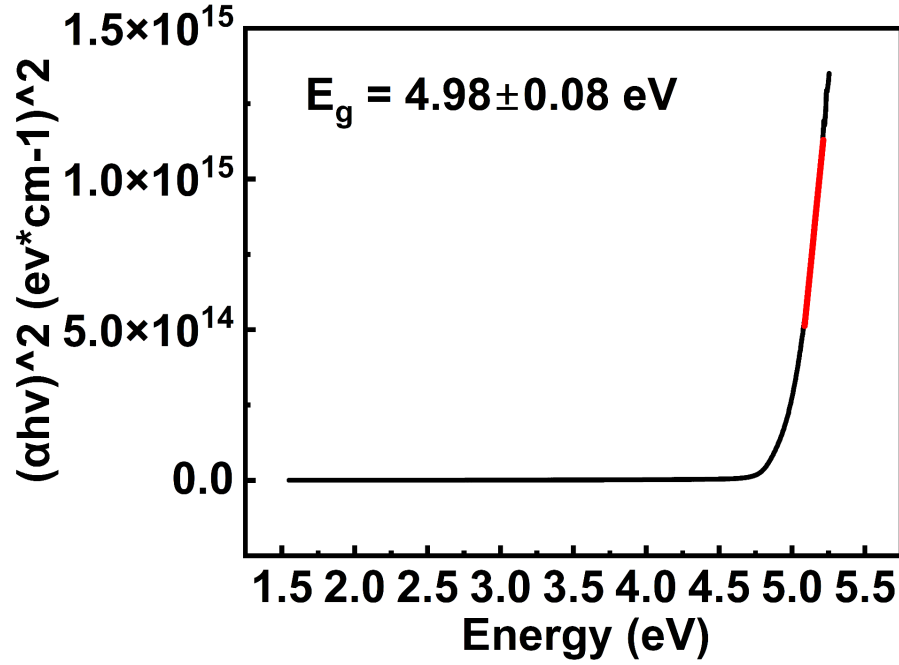


Fig 5: Tauc plot of the UV-Vis data. The red line segment represents the linear fit of the data, extrapolated to give the bandgap energy.

From extrapolating the linear region of the Tauc plot, we can see that the bandgap of $\beta - Ga_2O_3$ has come to be $4.98 \pm 0.08 \text{ eV}$, which shows that the Gallium Oxide film is of good quality, since the bandgap is close to the theoretically expected range.

Raman spectroscopy

Principle and Operation:

Raman Spectroscopy is a non-destructive technique used to study a system's vibrational, rotational, and other low-frequency modes. It is based on the inelastic scattering of monochromatic light, usually from a laser. When light interacts with the molecular vibrations or phonons in the sample, most photons are elastically scattered (Rayleigh scattering). However, a small fraction of the light is scattered at different frequencies, corresponding to the energy of vibrational modes (Raman scattering). The frequency shift gives information about the vibrational modes of the molecules.[13]

Measurement Technique:

The basic setup for Raman spectroscopy includes a laser light source, a sample holder, a spectrometer, and a detector. The laser light is directed onto the sample, and the spectrometer collects and analyzes the scattered light. The sensor records the intensity of the scattered light as a function of its frequency shift from the incident laser light.[14]



Fig 6: Apparatus used for Raman measurement

Cosmic Ray Noise and Removal:

One challenge in Raman spectroscopy is cosmic ray noise, which can cause spikes in the recorded spectra. These spikes are due to high-energy particles hitting the detector, resulting in random, intense signals unrelated to the sample's Raman signal. We take multiple accumulations of the spectrum to identify and deal with the noise due to cosmic rays. The random noise from cosmic rays is minimized by averaging these accumulations, while the consistent Raman signal is retained. This process ensures a cleaner, more accurate spectrum.

Applications:

Raman spectroscopy is widely used in various fields, including:

- **Chemical Analysis:** Identifying molecular compositions and structures.
- **Materials Science:** Characterizing crystal structures, phase transitions, and stress/strain in materials.
- **Biology:** Studying biological tissues, cells, and biomolecules.

Sample Preparation and Measurement:

Samples for Raman spectroscopy can be in solid, liquid, or gaseous form. Solid samples should be placed on a clean substrate, while liquid samples are typically analyzed in glass or quartz cuvettes. Proper alignment of the laser and careful calibration of the spectrometer are crucial for accurate measurements.

Specific Application to the study:

This study employed Raman spectroscopy to characterize the beta-gallium Oxide thin film grown on a sapphire substrate. Analyzing the Raman spectra, we identified the vibrational modes specific to beta-gallium Oxide, confirming its crystalline quality and phase composition. This information was essential for understanding the material's properties and potential performance in MSM photodetectors. Identifying and removing cosmic ray noise through accumulations ensured high-quality spectra, providing reliable data for our analysis.

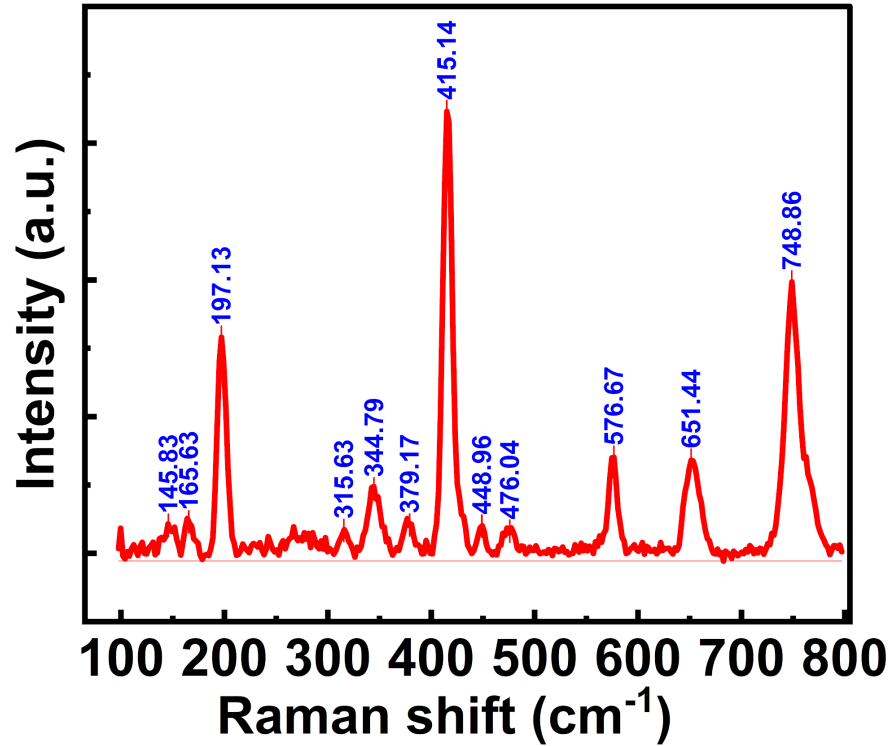


Fig 7: Raman spectra of the MOCVD grown $\beta - Ga_2O_3$ thin film

Analysis

Most Raman active modes corresponding to $\beta - Ga_2O_3$ were observed, and the excellent crystallinity of the thin film was confirmed. The intensities of Raman modes at 197.13 cm^{-1} , 415.14 cm^{-1} , and 748.86 cm^{-1} are very high compared to those of the others, and the spectra have sharp and narrow peaks.

Fabrication of the MSM Photodetector

The interdigitated electrodes for MSM PDs on the $\beta - Ga_2O_3$ thin film were created using e-beam physical vapor deposition using a hard mask.

Device design:

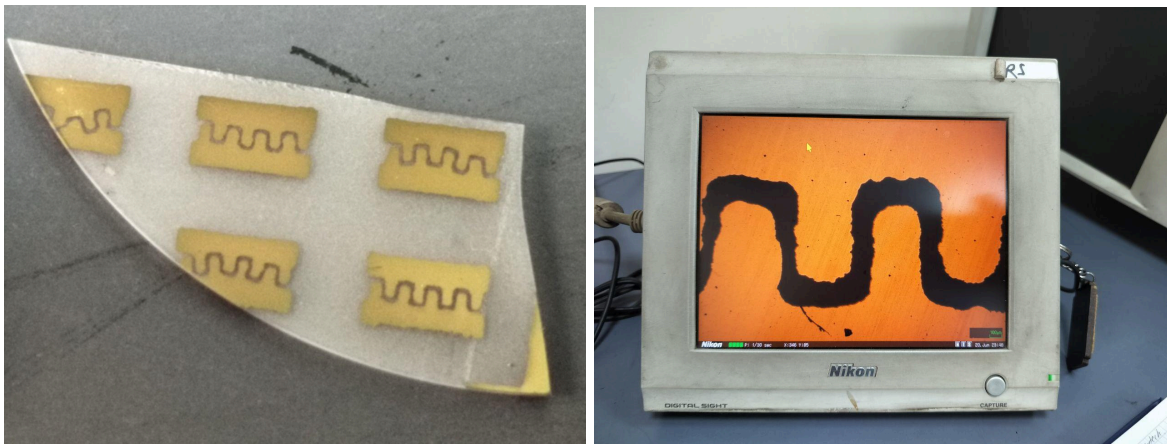


Fig 8: Left-Photo of fabricated devices; Right-Measurements being made in an optical microscope

Before device fabrication, the sample was ultrasonically cleaned for 10 min each in acetone, isopropyl alcohol (IPA), deionized (DI) water, and then dried in dry N_2 gas. The fabrication process involved the deposition of metal Ni (40 nm) and Au (50 nm)[3] using an e-beam evaporation system (Hind High Vacuum Company) [10]. E-beam evaporation was used instead of thermal evaporation because it offers more control. In the latter, the entire material is melted and evaporated at once. The deposition rate may be controlled only by using the temperature of the resistive heater.

E-Beam evaporation

E-beam evaporation is a physical vapor deposition (PVD) method that uses a high-energy electron beam to evaporate a source material, condensing onto a substrate to form a thin film.

Key Points:

- An electron gun generates a high-energy electron beam (5-10 kV) focused onto the source material in a water-cooled crucible.
- The electron beam's kinetic energy is converted to thermal energy, causing the source material to evaporate.
- The vaporized atoms travel through the high-vacuum chamber and condense onto the substrate, forming a thin film.
- E-beam evaporation enables the deposition of materials with very high melting points and provides high deposition rates (0.1-100 nm/min)[15].

System Components:

- Electron gun, crucible, substrate holder, and high-vacuum chamber.

Applications:

- Aerospace, automotive, cutting tools, optics, and electronics industries. E-beam evaporation is a versatile PVD technique that deposits high-purity, uniform, thin films using a high-energy electron beam.



Fig 9: Top-Gold being evaporated in the e-beam apparatus; Bottom-Operating the E-beam evaporator

In the e-beam case, while the entire material may be melted, only the spot where the beam is concentrated is evaporated. This results in a much greater degree of control.

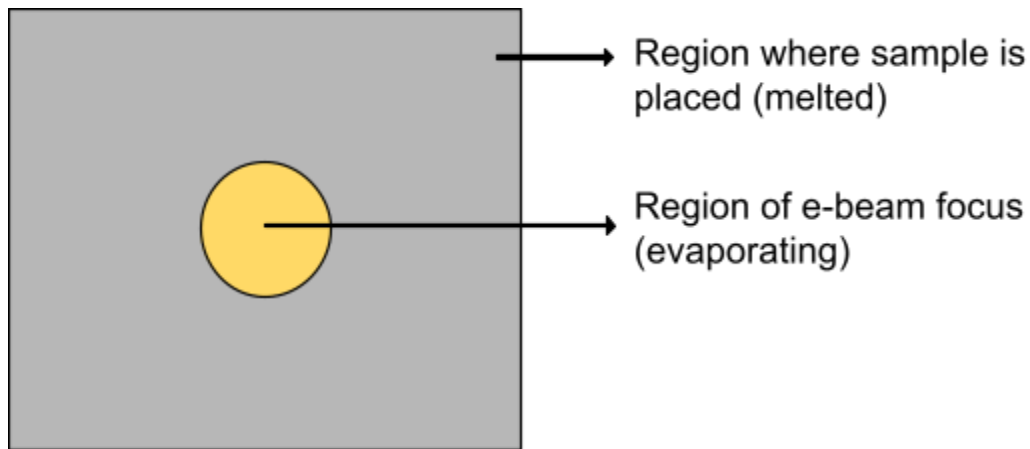


Fig 10: Schematic depicting E-beam evaporation

The optoelectronic and electrical measurements were carried out with the help of a nitrogen-purged Xenon lamp (75 W) in conjunction with a computer-interfaced monochromator (Bentham TMC-300V), an optical UV fiber (PCU-1000), and a Keithley semiconductor parameter analyzer (SCS-4200). All measurements were taken in the presence of air.

Electrical Measurements

Photocurrent measurements on the MSM Photodetector were obtained under different illumination conditions.

The room temperature I-V measurements were taken using a probe station and a semiconductor parameter analyzer. These were taken under dark (no illumination) conditions and then subject to illumination with wavelengths of both the UV and visible regions. We wish to study the electrical characteristics of the photodetector,

like its dark current, to determine quantities like the *Photo-to-Dark Current Ratio* (PDCR), the *UV-to-visible rejection ratio*, and so on.

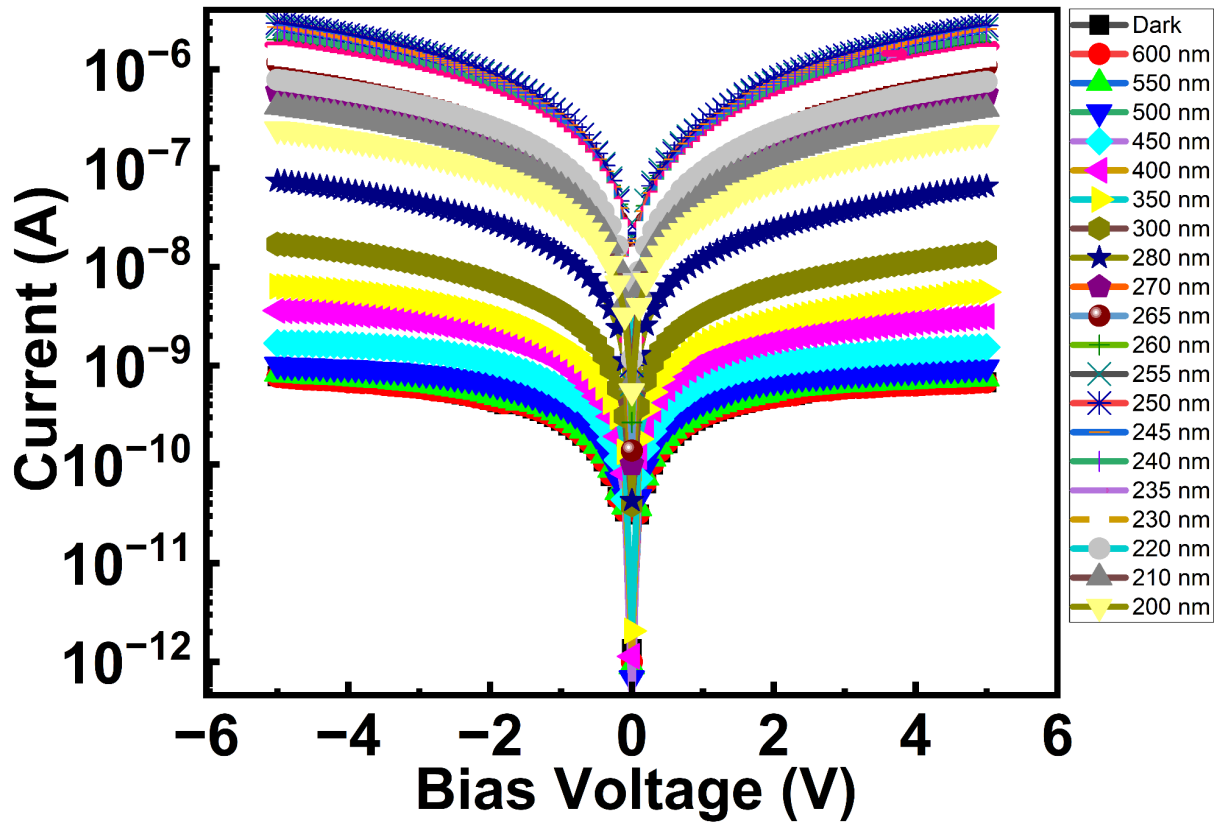


Fig 11: Log-linear plot of the I-V characteristics of the photodetector at room temperature

From the above figure, we can see that the maximum photocurrent was observed at 250 nm illumination. Consequently, we will measure many quantities at this wavelength in the paper further.

Also, we can see that the current continues to rise from 600 nm up to 250 nm and then starts dropping again as we decrease the wavelength further.

For greater clarity, we can plot just the dark current and the current observed at 250 nm across the range of voltages.

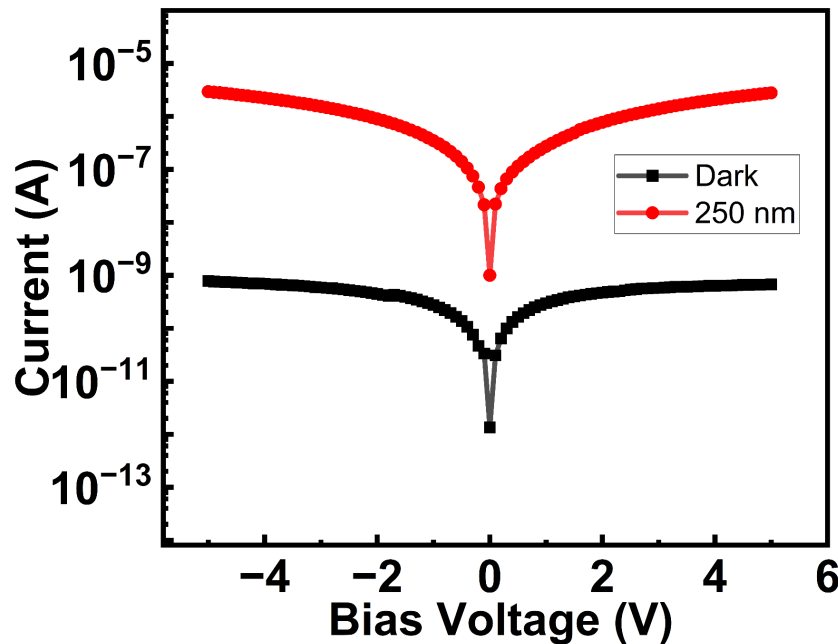


Fig 12: Semilog plot of the Current v/s voltage characteristics for no illumination and 250 nm illumination

An approximate increase of more than 10^3 can be observed from dark current in the case of 250 nm illumination. To see this more quantitatively, we can use a quantity called the *Photo-to-Dark Current Ratio (PDCR)* and how it changes over the bias voltages.

The photo-to-dark current ratio (PDCR) of a photodetector is defined as:

$$PDCR = \frac{I_p - I_d}{I_d}$$

Where I_p is the net photocurrent and I_d is the dark current at a fixed bias voltage.
[10]

Table showing PDCR at no bias and 2V and 5 V bias

Bias Voltage (V)	Net Photocurrent (250 nm) (A)	Dark current (A)	PDCR
5	2.93E-06	7.82E-10	3.74E+3
2	8.97E-07	4.46E-10	2.01E+3
0	1.00E-09	1.35E-12	7.41E+2

A shallow dark current in pico-amperes was observed at zero bias, while the photocurrent was found to be in the order of nano-amperes. Thus, the PDCR of 7.412×10^2 was observed, demonstrating that these MOCVD-grown $\beta - Ga_2O_3$ PDs are self-powered.

Spectral selectivity and responsivity are primary figures of merit (FOMs) for photodetectors. Concisely, they are defined as:

Spectral Selectivity: Refers to the ability of a photodetector to preferentially respond to specific wavelengths of light while minimizing the response to others. It indicates how selectively the detector can sense light from a particular part of the spectrum.

In our device, we want the photodetector to be highly selective towards UV light while largely ignoring the visible part of the spectrum. So, our FOM for spectral selectivity will be the *UV-visible rejection ratio*, which will be evaluated later in the study.

Responsivity: Responsivity is a measure of the electrical output (current or voltage) generated by a photodetector per unit of incident optical power, typically expressed in amperes per watt (A/W) or volts per watt (V/W).

The responsivity of the photodetector is defined as:

$$R_{\lambda} = \frac{I_p - I_d}{P_{\lambda}S}$$

Where P_{λ} denotes the illuminated power density at wavelength λ , and S represents the effective active device area of 2.0858 mm^2 for the device under test. The plots showing the photodetector's responsivity behavior, as wavelength functions, are displayed below.

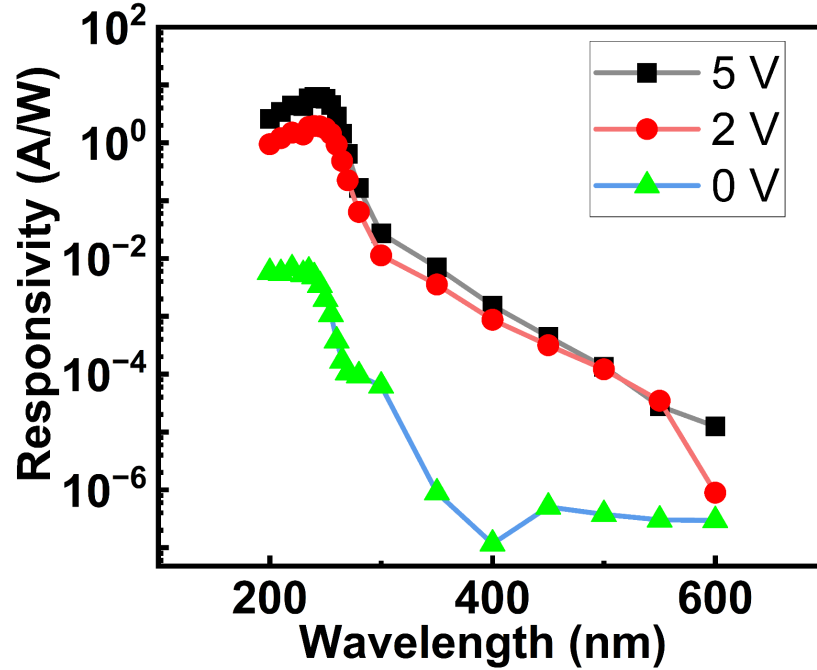


Fig 13: Log-linear plot of the responsivity of the photodetector

The spectral responsivity of photodetectors is crucial for selecting appropriate wavelengths. The responsivity versus wavelength plots of the photodetector at room temperature under zero and higher biases show that the peak responsivity occurs at 250 nm, which falls within the solar-blind range (100–280 nm) of the electromagnetic spectrum. Under 250 nm illumination, electron-hole pairs (EHPs) are generated in β -Ga₂O₃ thin films and contribute to the photocurrent. There was no response under UV-A (280–320 nm) and UV-B (320–400 nm) illumination, as β -Ga₂O₃ is transparent to these wavelengths. The high responsivity at 250 nm indicates that the photocurrent is primarily generated by EHPs created by photons with energy greater than the band gap of β -Ga₂O₃. At wavelengths shorter than 250 nm, responsivity decreases abruptly due to enhanced absorption of high-energy

photons near the surface and a higher recombination rate of EHPs near the surface than the bulk of the material.

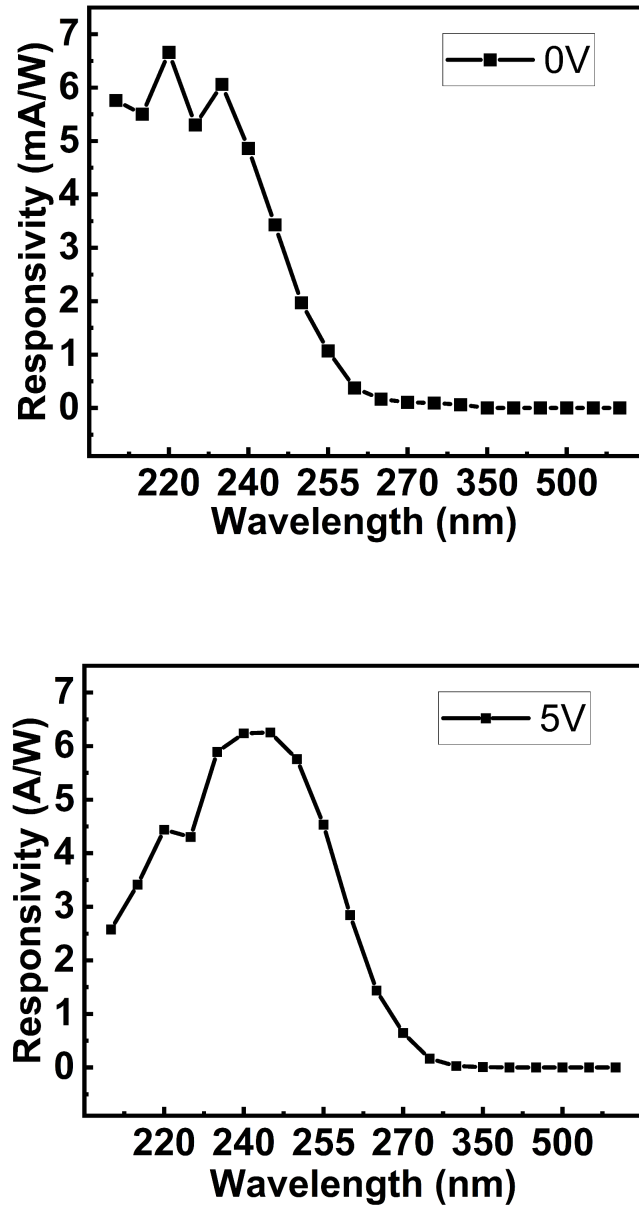


Fig 14: Linear plot of the responsivity of PD at 0V and 5V, respectively

If the photon energy is below the band gap, there is insufficient energy to excite an electron to the conduction band, which is not absorbed. Photons with energy equal to or greater than the band gap are strongly absorbed within the semiconductor material. The absorption coefficient ($\alpha' = 4\pi k/\lambda$) of any semiconductor material depends on its optical properties (extinction coefficient (k) and the wavelength (λ) of the incident photon. The absorption coefficient determines how deeply light of a particular wavelength penetrates the semiconductor before being absorbed. The absorption depth, the inverse of the absorption coefficient, indicates the distance at which the light intensity drops by a factor of $1/e$ in the semiconductor material. Ga₂O₃ has a very high absorption coefficient, so light is more readily absorbed, creating EHPs. We observed a higher response at 250 nm. The absorption coefficient increases abruptly at shorter wavelengths, and the absorption depth decreases dramatically. Consequently, more light is absorbed near the surface of Ga₂O₃ than the bulk material, leading to a more prevalent recombination of EHPs and an abrupt decrease in responsivity.[10]

For the Device Under Test, the room temperature responsivity (at 250 nm) was observed to be 5.75782 A/W for a bias of 5V, 1.7647 A/W for a bias of 2V, and 1.97 mA/W for no bias.

The UV-visible rejection ratio is a crucial parameter of PDs; in this case, we define it as

$$\text{UV-Visible rejection ratio} = \frac{R_{\lambda}(250nm)}{R_{\lambda}(500nm)}$$

It denotes the spectral selectivity of the photodetector, in this case, preferentially for the UV region around 250 nm.

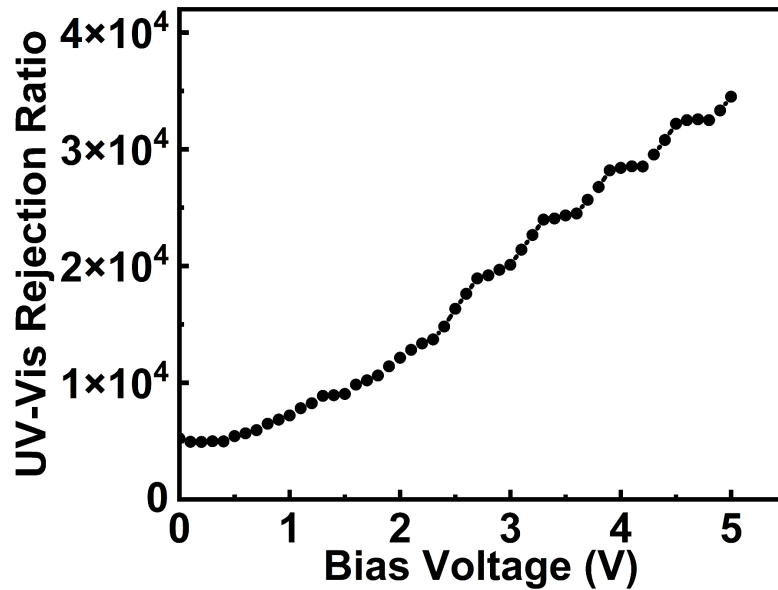


Fig 15: UV-visible rejection ratio v/s Bias voltage at 250 nm illumination

The RT UV-Vis ratio of 5.230×10^3 , 1.46×10^4 , and 4.3042×10^4 for bias voltages of 0V, 2V, and 5V were observed. These high values indicate that the MOCVD-grown $\beta - Ga_2O_3$ PDs have a very high SNR (Signal-to-Noise ratio).

Additional important FOMs, such as specific detectivity (D^*) and NEP, can be used to evaluate the performance of PDs.

The detectivity of a photodetector (PD) reflects its ability to identify weak signals. Noise Equivalent Power (NEP) is the smallest incident power needed to achieve a signal-to-noise ratio (SNR) of one at a 1 Hz bandwidth. The specific detectivity and NEP of the PD, which are influenced by various types of background noise,

including thermal, shot, flicker, and generation-recombination noise, can be determined using the following equations.

$$D^* = \sqrt{\frac{A}{2eI_d}} R_\lambda$$

$$NEP = \frac{\sqrt{S}}{D^*}$$

Where e is the electronic charge, $e = 1.6 \times 10^{-19} C$.

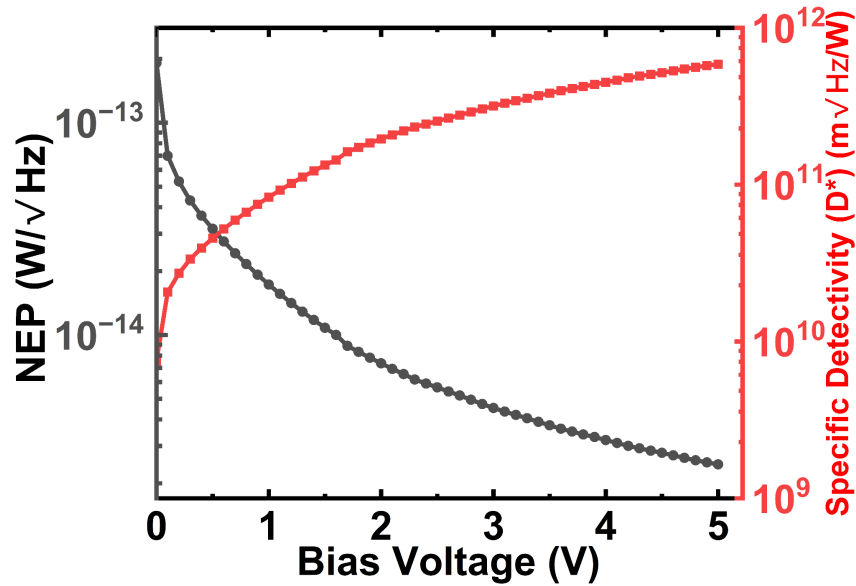


Fig 16: Variation of specific detectivity and NEP under the applied bias of the photodetector at RT

The high specific detectivity of $5.074 \times 10^{11} m\sqrt{Hz}W^{-1}$ at 5V bias, $2.32 \times 10^{11} m\sqrt{Hz}W^{-1}$ at 2V bias, and $7.532 \times 10^9 m\sqrt{Hz}W^{-1}$ at no bias was observed at room temperature. D^* increased with increasing bias, which can be attributed to the increased responsivity with applied bias.

The very low NEP of $2.525 \times 10^{-15} \text{ W Hz}^{-1/2}$ at a bias of 5V, $6.216 \times 10^{-15} \text{ W Hz}^{-1/2}$ at a bias of 2V, and $1.912 \times 10^{-13} \text{ W Hz}^{-1/2}$ at 0V bias was observed. These values indicate a very high sensitivity of the PDs to illumination in the solar-blind region of the solar spectrum.

At room temperature, the fabricated Ni/ β -Ga₂O₃/Ni MSM photodetectors on MOCVD-grown β -Ga₂O₃ exhibit good dark current, high PDCR, high responsivity, excellent spectral selectivity, high detectivity, low NEP, quite good photosensitivity, and self-powered behavior. These characteristics suggest that photodetectors are sensitive and efficient within the solar-blind spectrum.

Evaluating the Temporal Response

Time-dependent photocurrent measurements were performed at different biases and temperatures to evaluate the temporal response of PDs. During the measurements, light at 250 nm with a power density of 6.89 $\mu\text{W}/\text{cm}^2$ was manually turned on and off periodically at an interval of 30 s. Photocurrent rapidly increases and becomes saturated under deep UV 260 nm wavelength illumination, then abruptly decreases and returns to its initial value when UV illumination is turned off.[10]

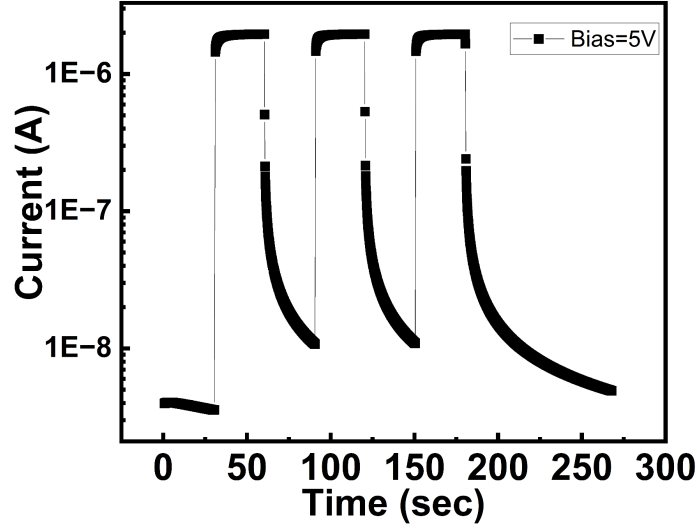


Fig 17: Current-time (I-t) characteristics of the fabricated DUV MOCVD

$\beta - Ga_2O_3$ PD in semi-log scale, under 5V applied bias

The rise and decay components of the temporal response were fitted using the *rise time gadget* in the *OriginLab* software. The average rise and decay times at ambient conditions are shown as follows:

- 1. Rise Time:** 1.609 sec
- 2. Decay Time:** 0.394 sec

The rise time is in the order of seconds, and the decay time in the order of 100 milliseconds was observed, which indicates that the device does not possess severe persistent photoconductivity (PPC).

PPC is a phenomenon where a material's conductivity remains elevated for an extended period after exposure to light has ceased. This occurs because electron-hole pairs generated by light recombine very slowly, maintaining increased conductivity even after removing the light source. This causes a problem

in PDs, which are intended for fast-switching applications. However, our fabricated MSM PD performed adequately in this measurement.

Conclusion

We started with a sapphire substrate with an MOCVD-grown $\beta - Ga_2O_3$ thin film on one side. The sample was cleaned, and we analyzed the quality of the thin film using various material characterization techniques. We then measured the surface roughness using Atomic Force Microscopy (AFM). We analyzed the crystalline quality of the film using Raman spectroscopy and X-ray diffraction (XRD). At the same time, the material's bandgap was calculated using UV-visible spectroscopy using the Tauc plot method.

We used a prefabricated hard mask in E-beam lithography to deposit nickel and gold metal to create the interdigitated structure for the MSM PDs. The device's electrical characteristics were then measured using a semiconductor parameter analyzer. The channel length was also measured using an optical microscope to determine the channel length and the active device area.

The exceptional performance and self-powered functionality indicate that the DUV photodetectors made from MOCVD $\beta - Ga_2O_3$ are highly effective solar-blind photodetectors. They promise future applications in defense, civil, and space communication.

Scope for future improvement

The PD was fabricated using a rudimentary wire-based hard mask, which may have caused deviations from the ideal performances. The effects of this were seen while measuring the channel area of the device with the optical microscope, where the metal electrodes were seen to be deposited haphazardly and not in clean straight lines as was intended, which may adversely impact the reproducibility of data. We could use photolithography to make photodetectors with higher precision for further improvement, which may improve device performance.

Furthermore, electrical characterization of the device should be performed at other temperatures to study the impact on its performance. Additionally, since $\beta - Ga_2O_3$ is a wide-bandgap semiconductor with possible military and space applications, the effect of radiation on the devices should be studied, and potential techniques for radiation hardening may be investigated.

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