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From the Editor's Desk

The objective of this last edition for the year 2023 is to cater to the importance of β-phase gallium oxide (β-Ga_2O_3) for ultra-violet (UV) photodetection.

The material characteristics of a thermodynamically stable phase of gallium oxide such as ultra-wide band gap, very high breakdown field, intrinsic solar blindness, cost-effectiveness, good chemical and thermal stability etc. make it a promising candidate for various electronics and optoelectronics (detection) devices primarily UV photo-detectors, gas sensors, MOSFET, Schottky barrier Diodes etc.

β-Ga_2O_3 is a promising material for space and military applications too because of its ability to withstand harsh environmental too. Power electronics devices particularly for electric vehicles and UV photo-detection devices are hot topics in our country at present and many industries have launched/will launch their products to take first mover advantage. Considering all that, β-Ga_2O_3 has a potential to give tough competition to other wider bandgap semiconductors such as SiC and GaN.

Hence, in this present issue, a brief article related to UV photodetection is presented. The article includes the limitation of Si, GaAs based technology, other wider band-gap semiconductors constraints and β-Ga_2O_3 as a leading contender w.r.t. UV photodetection.

We request the readers to come forward and share their technical research w.r.t. semiconductor materials, fabrications, measurements, modelling, designing etc.

Have a wonderful year ahead. Enjoy reading

Suggestions for improvement are always welcome.

Editors

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Deep UV Photodetectors: Emrgent of 4th Generation Ultra-Wide Bandgap Semiconductor

Importance of UV radiation study:

UV radiation, while constituting less than 10% of total solar radiation, is a critical component with significant impacts across various domains (**Fig 1**).It serves essential functions such as stimulating vitamin D production in the skin, vital for skeletal development, immune function, and blood cell formation. Moreover, UV radiation is utilized in research and sterilization due to its bactericidal properties, although excessive exposure can lead to harmful effects like skin cancers and cataracts. Therefore, studying UV radiation is crucial for harnessing its benefits while mitigating associated risks.

In recent decades, concern has escalated due to anthropogenic-induced declines in stratospheric ozone, resulting in increased UV radiation levels. This decline, exemplified by the expanding 'ozone hole' over Antarctica, has raised alarms as observed in the correlation between ozone depletion and skin cancer incidences in coral trout. Studies suggest that even a minor decrease in ozone volume correlates with increased UV radiation at ground level, directly impacting skin cancer rates.

The growth in global energy consumption and population has spurred the development of energy-efficient and sustainable optical energy detection systems, emphasizing the significance of UV photodetection.

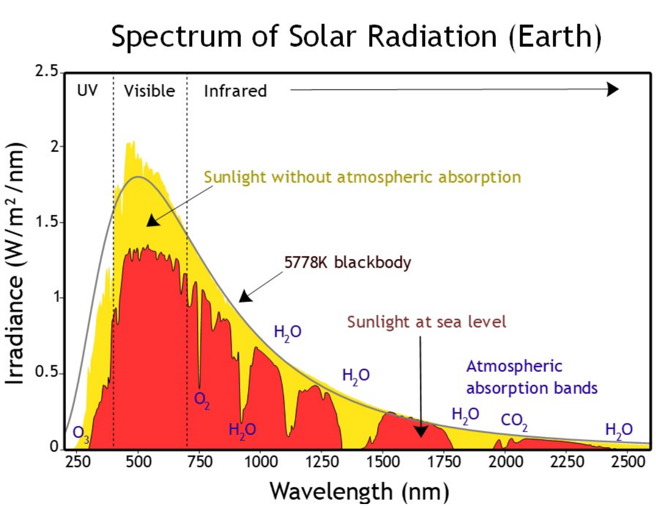

Figure 1. The spectrum of solar radiation.

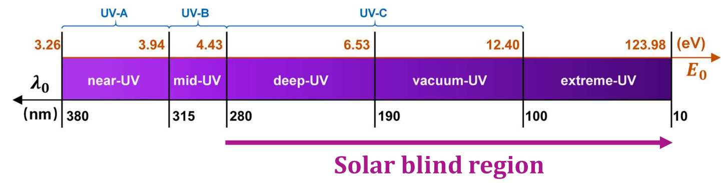

Figure 2. the UV spectral region and its subdivisions in terms of wavelengths and photon energy.

The International Commission on Illumination (CIE) categorizes the UV spectrum into UVA (320-400 nm), UVB (280-320 nm), and UVC (100-280 nm), with deep UV (DUV) wavelengths falling in the solar-blind region, impervious to solar radiation influence (**Fig. 2**).

Despite the Sun being a primary UV source, atmospheric absorption limits the UV spectrum reaching the Earth's surface, rendering the region from 200 to 280 nm "solar blind." Detectors responsive to wavelengths below 280 nm exhibit solar-blind characteristics, crucial for applications like ozone hole monitoring, flame detection, space communication, missile guidance, and biochemical detection.

Recent advancements in solar-blind DUV photodetectors, boasting high sensitivity and reliability, have sparked interest across military, scientific, and civilian sectors. These breakthroughs signify the expanding potential applications of UV photodetection, aligning with the evolving needs of modern society and defence initiatives.

A semiconductor photodetector employs a semiconductor as the primary light-absorbing medium, converting absorbed light signals into measurable electric currents. UV photodetectors operate through the photoconductivity effect,

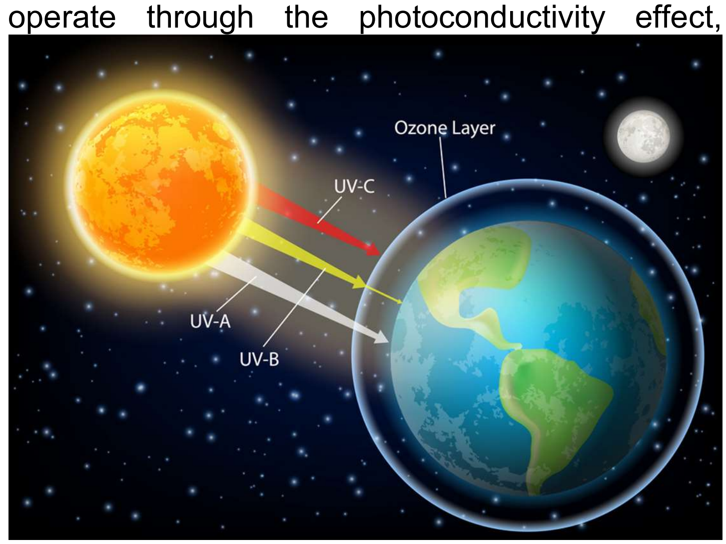

Figure 3. Diagram showing how different types of UV radiation penetrate or interact with the ozone layer.

where UV light absorption by a wide band gap semiconductor generates electron-hole (e-h) pairs when the photon energy (hv) is equal to or exceeds the bandgap (Eg). This process involves three key steps: (i) UV energy absorption and e-h pair generation, (ii) separation of photogenerated e-h pairs via a transportation process, and (iii) collection of electrons and holes as a photocurrent in an external circuit. Photogenerated charges are separated to generate a photocurrent by applying external bias voltage or utilizing an internal built-in electric field.

The fabrication and utilization of photodetectors (PDs) operating across various spectral ranges rely heavily on the properties of the light-absorbing semiconductor materials involved. Currently, silicon (Si)-based technology dominates the market for PDs operational in the visible-to-infrared (IR) spectrum. However, extending the detection capabilities to the ultraviolet (UV) spectrum has presented challenges, primarily due to the complexities associated with incorporating filters into Si-based PDs to achieve UV detection.

Commercially available UV photodetectors and challenges:

Commercially used deep UV photodetectors, such as silicon-based charge-coupled devices (CCDs), complementary metal oxide semiconductor (CMOS) devices, and UV-enhanced silicon photodiodes, are prevalent in UV photodetection applications. However, these devices often require optical filters to reject visible and infrared (IR) wavelengths, adding complexity and weight. Photomultiplier tubes (PMTs) and thermal detectors have also been traditionally employed for solar-blind light detection. PMTs, while blind to photons longer than solar-blind wavelengths, require high voltages (over 100 V) and are bulky, consuming substantial power.

Thermal detectors, serving as absolute radiometric standards, are used for UV light calibration but exhibit slow response times and lack wavelength selectivity for rapid and specific solar-blind radiation detection. Narrow bandgap semiconductor photodiodes and CCDs operate at moderate voltages, offering compactness, lightweight, and affordability compared to older technologies. However, their effective area is reduced due to costly optical filters needed to eliminate visible and IR photons, stemming from the small bandgap of semiconductor materials. Furthermore, exposure to radiation above the semiconductor's bandgap energy can accelerate device aging.

Despite their widespread use, commercially available UV photodetectors face challenges. UV-enhanced Si technology, constrained by silicon's 1.1 eV bandgap energy, requires expensive high-pass optical filters and phosphors to block low-energy photons, resulting in degraded performance at high temperatures. This highlights the need for advancements in UV photodetector technologies to overcome limitations associated with bandgap constraints and optical filtration requirements, improving efficiency and reliability in UV detection applications, and high switching frequency applications. However, it is not efficient at high temperatures. On the other hand, the SiC is the best choice for high voltage, high switching frequency, and high-temperature applications.

Ultrawide bandgap semiconductors for deep UV photodetectors

In recent years, the preference has shifted towards wide-bandgap (WBG) semiconductors such as gallium nitride (GaN), silicon carbide (SiC), zinc oxide (ZnO), and aluminum gallium nitride (AlGaN), among others, for fabricating UV PDs. These materials offer several advantages, including the ability to develop solar-blind PDs and suitability for high-temperature and high-power applications due to their high breakdown field strength compared to Si.

GaN, SiC, and ZnO are suitable for developing visible-UV detectors. Achieving solar-blind detection, with a cutoff below 280 nm, often involves alloying engineering to tune the bandgap or utilizing external filters to eliminate longer wavelengths. AlGaN and magnesium zinc oxide (MgZnO) are examples of WBG ternary semiconductor alloys used to develop solar-blind PDs, albeit with challenges such as epitaxial growth, high-temperature requirements, and phase segregation issues.

Although diamond material shows promise for solar-blind photodetection due to its ultrawide bandgap, challenges in bandgap engineering and the lack of large-area single-crystal diamond bulk material hinder practical application. Alternatively, monoclinic β-phase gallium oxide (β-Ga_2O_3) emerges as a promising candidate for solar-blind deep UV detection. With a bandgap of 4.4 to 4.8 eV, β-Ga_2O_3 exhibits solar-blind sensitivity covering most of the solar-blind UV region. Its availability in large-size bulk single crystals allows for homoepitaxial growth of epitaxial layers with defined doping and bandgap engineering, fulfilling its potential in UV detection.

β-Ga_2O_3, among the fourth-generation semiconductors, is considered one of the most promising candidates for solar-blind UV detectors, offering intrinsic solar blindness and high-efficiency UV photodetection capabilities. Its wide bandgap, good chemical, and thermal stability, and potential for high-efficiency UV detection position it as a leading contender in the field of deep UV photodetection.

Ga_2O_3: Material properties

Gallium Oxide exhibits five distinct crystalline structures, including α, β, γ, δ, and ε. Among these, the β-phase is notable for its thermal (melting point 1730 °C) and chemical stability, distinguishing it from metastable forms that convert to β-phase upon heating (**Fig. 4**). β-Ga_2O_3 is characterized by an impressive breakdown electric field strength of 8 MV/cm and exceptional Baliga figure of merit (BFOM) and Johnson's figure of merit (JFOM), thanks to its ultra-wide bandgap of 4.6 – 4.9 eV, surpassing SiC and GaN. It also boasts a high saturation electron velocity (vs) of 2×10^7 cm/sec, enabling high current density and high-frequency operation.

High-quality native substrates are crucial for producing superior β-Ga_2O_3 epilayers essential for high-performance semiconductor devices. Various melt-growth techniques used for sapphire and other crystals facilitate the cost-effective mass production of high-quality β-Ga_2O_3 bulk single crystals. Edge-defined film-fed (EFG) techniques are mature for producing large-size β-Ga_2O_3 single crystals due to their high growth rate and absence of stacking fault and twin boundary defects.

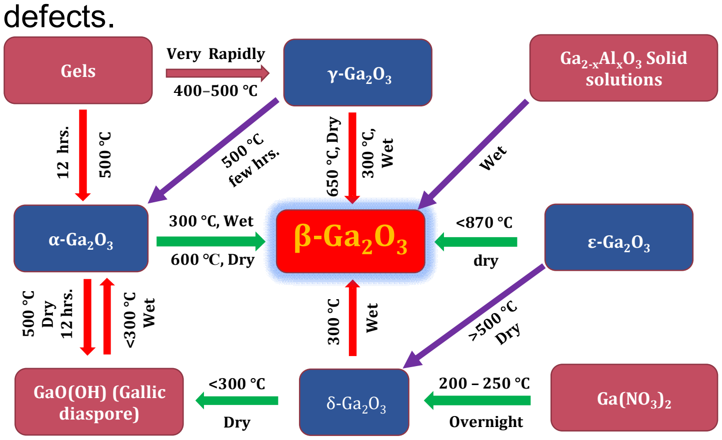

Figure 4. Transformation relationship between beta-phase and other phases and hydrides of gallium oxide.

Furthermore, *n*-type β-Ga_2O_3 epilayers can be grown using metal-organic chemical vapor deposition (MOCVD), halide vapor phase epitaxy (HVPE), and molecular-beam epitaxy (MBE) methods with controllable doping using shallow donors such as Si, Ge, and Sn ranging from 10^{15} to 10^{20} cm^{-3}. Japanese companies like Tamura Corporation and Novel Crystal Technology have successfully commercialized EFG-grown single-crystal substrates and HVPE-grown epilayers, demonstrating advancements in wafer technology up to 6 inches in size.

The unique characteristics and potential applications of Ga_2O_3 have been extensively covered in various review articles, underscoring its significance in the semiconductor industry.

Ga_2O_3: Photodetector

Advanced semiconductor materials with wide bandgaps, such as GaN, AlGaN, diamond, Lu_2O_3, and Ga_2O_3, have emerged as promising candidates for solar-blind photodetectors (PDs) due to their intrinsic solar-blindness resulting from their wide and ultrawide bandgap properties. Unlike conventional UV PDs based on narrow bandgap semiconductor materials like Si and GaAs, these advanced materials eliminate the need for additional optical filters and large cooling systems. Among these materials, β-Ga_2O_3 has garnered significant attention for its outstanding material characteristics, including an ultrawide direct bandgap of approximately 4.9 eV, exceptional radiation hardness, high chemical and thermal stability, and a high absorption coefficient exceeding 10^5 cm^{-1}. By bandgap engineering and alloying Ga_2O_3 with In_2O_3 and Al_2O_3, a complete UV region from near UV to vacuum UV (400-100 nm) could be covered (**Fig. 5**). The growth of high-quality crystalline Ga_2O_3 single crystal substrates, epilayers, and thin films has been achieved using various mature and cost-effective techniques, including edge-defined film-fed (EFG), Czochralski (CZ), metal-organic chemical vapor deposition (MOCVD), halide vapor phase epitaxy (HVPE),

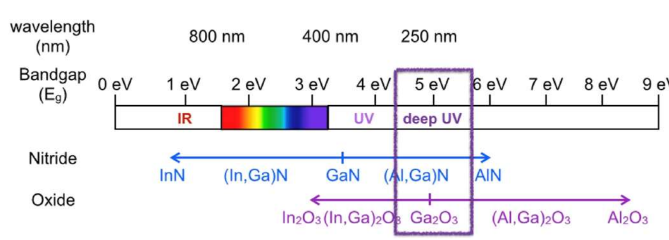

Figure 5. Bandgap and wavelength tuning of nitride and oxide semiconductors adjusting the ratio of Group-III elements (In, Ga, Al).

atomic layer deposition (ALD), pulsed laser deposition (PLD), and molecular beam epitaxy (MBE). Notably, these processes involve minimal doping complexity compared to other wide and ultrawide bandgap semiconductor materials.

In addition to the β-phase, deep ultraviolet (DUV) PDs have also been successfully demonstrated using amorphous and ε-phases of Ga_2O_3, highlighting the versatility and potential of Ga_2O_3-based materials in the development of advanced photodetection technologies.

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Recent News and Concluded Conferences

1. In March 2024, **Honorable Prime Minister Shri Narendra Modi** laid the foundation stone, for three semiconductor projects worth around ₹1.25-lakh crore. The three sites are Dholera Special Investment Region (DSIR) in Dholera, Gujarat; Outsourced Semiconductor Assembly and Test (OSAT) facility at Sanand, Gujarat; and OSAT facility at Morigaon, Assam.

2. "By 2029, India will be among the top five semiconductor manufacturing countries," words of Shri Ashwini Vaishnaw, Minister of Communications and Information Technology, and Railways

3. As per the report recently published by the India Cellular and Electronics Association (ICEA), India has a strategic opportunity due to a global shift in semiconductor manufacturing dynamics, particularly due to US sanctions on China.

4. The XXII International Workshop on Physics of Semiconductor Devices (IWPSD 2023) was jointly organized by the Indian Institute of Technology Madras in collaboration with Society for Semiconductor Devices and Semiconductor Society (India) from 14th to 17th Dec. 2023 at Research Park, Indian Institute of Technology Madras, Tamil Nadu. Various emerging and important topics such as 2D materials/devices, MEMS, NEMS and sensors, Power semiconductor devices, device modeling and simulation etc. were covered in the workshop.

5. 2nd Edition of the IEEE Microwave Antenna and Propagation Conference (MAPCON) was held from 10th to 14th Dec. 2023 at Ahmedabad, Gujarat. Eminent professionals from International Space Agencies, Defence Establishments, National Research Organizations, Academia, and Industries delivered talks during the conference.

6. The annual international conference on "Recent Progress in Graphene and 2D Materials Research" was held from 20th to 23rd Nov. 2023 in Bengaluru, Karnataka. The conference captured the new and impactful developments happening in the research field related to graphene and 2D materials research.

7. Under the visionary leadership of Honorable Prime Minister Shri Narendra Modi, the 'SemiconIndia-2023' was organized by India Semiconductor Mission in partnership with industry and industry associations from 28th July to 30th July 2023 at Gandhinagar, Gujarat. The event aimed to make India a global hub for Semiconductor Design, Manufacturing and Technology Development. The heads of various industries such as SEMI, Foxconn, Micron Technology, IBM Semiconductors, ST Microelectronics etc. delivered a talk at the event.

Forthcoming Conferences/Events

1. ISSMD "*International Symposium on Semiconductor Materials and Devices-2024*" will be held at the University of Kashmir, Jammu and Kashmir, India from 04 to 06th Sep. 2024. It will be jointly organized by the Department of Kashmir, University of Kashmir and Semiconductor Society (India) in cooperation with Society for Semiconductor Devices. The symposium is organized to bring the various researchers working in semiconducting materials and devices on a common platform. Many eminent techno-managerial experts are in advising panel and in the organizing committee. The last date for abstract submission is 30th June 2024. The complete details about ISSMD-2024 are available in Semiconductor Society (India) portal.

2. India's premier semiconductor event, SemiconIndia-2024 will be held from 11th to 13th September 2024 in New Delhi. Since, many semiconductor industry giants such as Micron Technology, Lam Research, AMD, Applied Materials have announced/started investments in the Indian semiconductor ecosystem, and other multinational industries are exploring semiconductor manufacturing opportunities too, so this event is a must-visit event for semiconductor experts, researchers, manufacturers etc.