

Carrier Dynamics In Ga_2O_3 UV Photodetectors

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Abstract— This report delves into the carrier dynamics within Ga_2O_3 , highlighting their role in determining the performance of UV photodetectors. Through a combination of experimental investigations and theoretical modeling, several processes are examined. Including carrier recombination, trapping, and transport mechanisms. The findings underscore the importance of optimizing carrier dynamics to achieve high-performance UV photodetectors capable of operating in harsh environments.

Index Terms— Carrier Dynamics, Gallium Oxide (Ga_2O_3), Photodetector Efficiency, Solar-Blind Applications, Device Performance, UV Photodetectors

I. INTRODUCTION

Recently, Ga_2O_3 -based photodetectors have garnered considerable research interest as potential alternatives to traditional semiconductor materials. Understanding carrier dynamics in these materials is important for improving the performance of optoelectronic devices. Gallium Oxide (Ga_2O_3) is especially notable for ultraviolet (UV) optoelectronics, offering substantial potential for solar-blind deep UV photodetectors. The concept of solar blind UV detection involves detecting UV-C radiation without interference from longer wavelengths. Ga_2O_3 exists in multiple crystalline forms or polymorphs, including α , β , γ , ϵ , and δ , with the β phase being the most stable and extensively studied. With an ultra-wide bandgap of 4.8-5.0 eV, β - Ga_2O_3 is intrinsically solar blind, enabling the detection of UV-C radiation. The material's high chemical and thermal stability ensures its effectiveness in challenging environments.

II. MOTIVATION

The study of carrier dynamics in β - Ga_2O_3 is motivated by the fundamental need to improve UV photodetector performance. Understanding how carriers are generated, transported, and recombined is essential for enhancing key device metrics such as responsivity, detectivity, and response time.

III. KEY SCIENTIFIC TOPICS

a. Crystal Structure

As described in Reference [1], β - Ga_2O_3 exhibits a monoclinic crystal structure characterized by a complex, low-symmetry arrangement of atoms. Reference [3] discusses how the monoclinic structure leads to direction-dependent carrier transport properties. This anisotropy is evident in electron mobility, which varies significantly along different crystallographic axes. As noted in Reference [2], this anisotropy can be exploited in device design to enhance performance. For instance, by aligning the device structure with the high-mobility directions, one can potentially achieve faster response times and higher sensitivity in β - Ga_2O_3 based UV photodetectors.

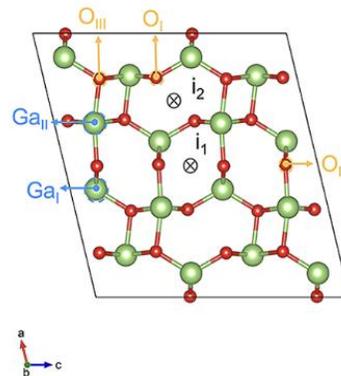


Fig. 1. Crystal structure of β - Ga_2O_3 .

In Fig. 1, the green spheres represent gallium atoms, while the red spheres are oxygen atoms. This

structure contains two distinct types of gallium sites: Ga(I) atoms surrounded by four oxygen atoms in a tetrahedral arrangement, and Ga(II) atoms surrounded by six oxygen atoms in an octahedral arrangement. The oxygen atoms in β -Ga₂O₃ also occupy three different sites, labeled O(I), O(II), and O(III). Reference [3] highlights that O(I) and O(II) are connected to three gallium atoms, while O(III) is connected to four. This variety in oxygen positions is particularly important because it allows for different types of oxygen vacancies, which can significantly affect carrier dynamics and device performance.

b. Device Structure of β -Ga₂O₃ Photodetectors

Photodetector devices consist of a β -Ga₂O₃ thin film grown on a suitable substrate, with metal contacts for electrical connections. The choice of substrate and any intermediate layers can affect the quality of the β -Ga₂O₃ film, and consequently, the device's optoelectronic properties.

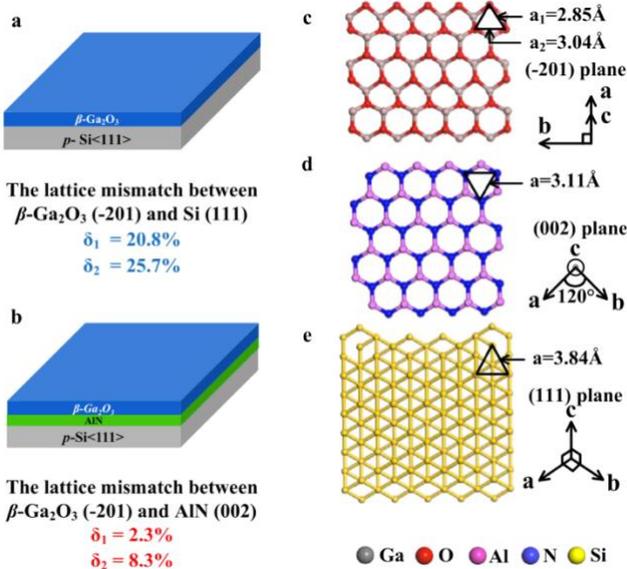


Fig. 2. Structure of β -Ga₂O₃ Photodetectors

Fig 2 illustrates the structure and lattice relationships in β -Ga₂O₃ photodetectors grown on p-Si(111) substrates. The top left shows a basic β -Ga₂O₃/p-Si(111) structure, while the bottom left depicts an improved design incorporating an AlN buffer layer. The right side of the image details the atomic arrangements and lattice parameters of the β -Ga₂O₃ (-201) plane, AlN (002) plane, and Si (111) plane. Without the AlN buffer, there is a significant lattice mismatch between β -Ga₂O₃ and Si, with mismatches of 20.8% and 25.7% along different axes. This large mismatch can lead to

structural defects and strain in β -Ga₂O₃ film. In contrast, the introduction of an AlN buffer layer reduces the lattice mismatch between β -Ga₂O₃ and the underlying structure to 2.3% and 8.3%. This reduction in lattice mismatch is expected to improve the crystalline quality of the β -Ga₂O₃ film. The atomic models show how the hexagonal structure of the AlN (002) plane provides a better template for β -Ga₂O₃ growth compared to the Si (111) plane.

c. Fundamentals of Carrier Dynamics

As outlined in Reference [2], carrier dynamics in β -Ga₂O₃ encompass three key processes: carrier generation, transport, and recombination. The interplay between these processes determines the overall efficiency of the photodetector and its ability to convert incident UV photons into measurable electrical signals.

d. Carrier Generation

Carrier generation in β -Ga₂O₃ primarily occurs through band-to-band absorption, as described in Reference [2]. When a UV photon with energy exceeding the bandgap (4.8-5.0 eV) is absorbed, it excites an electron from the valence band to the conduction band, creating an electron-hole pair. The absorption process is characterized by the absorption coefficient (α), which describes how strongly light is absorbed at different energies.

$$(\alpha h\nu)^2 = A(h\nu - E_g)$$

An important concept related to carrier generation is the penetration depth, which is the inverse of the absorption coefficient.

$$\delta = \frac{1}{\alpha}$$

Reference [4] notes that for UV-C light in β -Ga₂O₃, this depth is typically just 10-100 nanometers. This shallow absorption depth means that most carrier generation occurs near the material's surface.

e. Carrier Transport

Once carriers are generated, they must be transported and collected to produce a photocurrent. Reference [2] describes two main mechanisms governing carrier transport in β -Ga₂O₃: drift and diffusion. Drift is the motion of carriers under an

electric field, characterized by the drift velocity equation:

$$v_d = \mu_n \mathcal{E}$$

where μ is the carrier mobility and \mathcal{E} is the electric field. Diffusion is the movement due to carrier concentration gradients, described by the diffusion coefficient D :

$$D_n = \left(\frac{k_B T}{q} \right) \mu_n \quad \text{and} \quad D_p = \left(\frac{k_B T}{q} \right) \mu_p.$$

An important feature of β -Ga₂O₃, highlighted in Reference [3], is its anisotropic transport properties. Electron mobility along different crystallographic directions can vary significantly, which can be exploited in device design to enhance photodetector performance. Additionally, Reference [5] notes that in β -Ga₂O₃, electron mobility is much higher than hole mobility due to the band structure, resulting in electron-dominated transport in photodetectors.

f. Recombination Processes

Recombination processes in β -Ga₂O₃ are significant as they determine the lifetime of photogenerated carriers and significantly impact device performance. Reference [1] outlines several recombination mechanisms in β -Ga₂O₃, including radiative recombination, Shockley-Read-Hall (SRH) recombination, Auger recombination, and surface recombination. Among these, SRH recombination, which is trap-assisted recombination often mediated by defects, is typically dominant in β -Ga₂O₃, as noted in Reference [4]. Surface recombination is also particularly important due to the shallow absorption depth of UV light in β -Ga₂O₃. Reference [2] emphasizes that understanding and controlling these recombination processes is key to optimizing photodetector performance, as reducing recombination can increase carrier lifetime and improve detector sensitivity.

g. Interface Effects in Gallium Oxide Heterostructures

Ga₂O₃ heterostructures play a role in enhancing the performance of UV photodetectors. As discussed in Reference [2], the interface between Ga₂O₃ and other materials significantly influences carrier dynamics. One of the primary effects at these interfaces is band alignment, which

determines how carriers are confined or transferred across the interface. Charge transfer and band bending at the interface play a role in carrier separation, as highlighted in Reference [3]. When two materials with different Fermi levels come into contact, charge redistribution occurs to achieve equilibrium, resulting in band bending near the interface. This band bending creates built-in electric fields that can aid in separating photogenerated carriers, enhancing the efficiency of the photodetector. Interface states and traps, as noted in Reference [1], can significantly impact carrier transport and recombination. These states, often caused by lattice mismatch or defects at the interface, can act as recombination centers, reducing device efficiency. Reference [4] emphasizes that proper design of heterostructures, taking into account these interface effects, can lead to enhanced carrier separation and collection.

h. Modulating Carrier Dynamics

One key strategy, as discussed in Reference [5], is doping. By introducing specific impurities into the Ga₂O₃ lattice, researchers can control carrier concentrations and modify transport properties. For instance, Si doping can increase electron concentration, potentially enhancing conductivity, but it may also introduce additional scattering centers that affect mobility. Reference [2] highlights how carefully designed heterostructures enable band engineering for optimal carrier separation and collection. By combining Ga₂O₃ with materials of different bandgaps and electron affinities, researchers can create potential wells or barriers that guide the flow of photogenerated carriers. Surface treatments and defect engineering have a major impact on modulating carrier dynamics. As noted in Reference [4], surface treatments can reduce surface recombination, which is particularly important for Ga₂O₃ due to its shallow UV absorption depth. Defect engineering, discussed in Reference [1], allows researchers to tailor trap states for desired characteristics. For example, oxygen vacancies in Ga₂O₃ can act as donor states and significantly influence carrier transport. By controlling the concentration and distribution of these defects, researchers can fine-tune the electrical and optical properties of Ga₂O₃ devices.

i. Characterization of Carrier Dynamics

Understanding carrier dynamics in Ga₂O₃ UV photodetectors requires specialized characterization techniques. Time-resolved photoluminescence (TRPL) is a tool for measuring carrier lifetimes in Ga₂O₃, as discussed in Reference [3]. Transient absorption spectroscopy, highlighted in Reference [5], allows researchers to probe ultrafast carrier processes in Ga₂O₃. By measuring changes in absorption after photoexcitation, this technique can reveal details about carrier generation, relaxation, and recombination on timescales as short as femtoseconds. This information is valuable for understanding the initial stages of the photodetection process. Deep-level transient spectroscopy (DLTS), as noted in Reference [1], provides information about defect levels and captures cross-sections in Ga₂O₃. This technique is important for defect levels and captures cross-sections in Ga₂O₃. This technique is fundamental given the significant role that defects, especially oxygen vacancies, play in Ga₂O₃ carrier dynamics. By characterizing these defects, researchers can better understand their impact on device performance to mitigate their negative effects or explore their beneficial properties.

j. Photodetector Performance Metrics

The carrier dynamics in Ga₂O₃ UV photodetectors directly influence key performance metrics, as discussed in Reference [2]. One of the most important metrics is responsivity (R), which measures the photocurrent generated per incident optical power:

$$R = \frac{I_{ph}}{P_{in}} = \frac{\eta \lambda (\mu m)}{1.24} \quad A/W$$

Where I_{ph} is the dark current, P is the incident power density, and A is the active area. As noted in Reference [4], high responsivity is essential for detecting weak UV signals and is directly related to the efficiency of carrier generation and collection processes in the device.

External Quantum Efficiency (EQE) is another metric, representing the ratio of collected charge carriers to incident photons. It can be calculated as:

$$EQE = \frac{hc}{q\lambda} R$$

Where h is Planck's constant, c is the speed of light, q is the elementary charge and λ is the wavelength

of incident light. Reference [5] highlights that EQE provides insight into the overall efficiency of the photodetection process. A high EQE indicates that a large proportion of incident photons are successfully converted into measurable electrical signals.

Detectivity and response time are two additional metrics necessary for evaluating photodetector performance. Detectivity, as discussed in Reference [1], indicates the signal-to-noise ratio and is a measure of the device's ability to detect weak optical signals. Response time, influenced by carrier transit time and recombination lifetime, determines the speed of photodetection. Reference [3] emphasizes the importance of fast response times for applications requiring high-speed UV detection, such as UV communications.

k. Comparison

Property	Ga ₂ O ₃	Si	SiC	GaN
Bandgap (ev)	24.8 - 5.0	1.1	3.3	3.4
Solar-blindness	Intrinsic	Requires filters	Near solar-blind	Near solar-blind
Crystal Growth	Melt growth possible	Well-established	Challenging	Challenging
Relative Cost	Moderate	Low	High	High
Radiation Hardness	Excellent	Poor	Good	Good

Fig. 3. Comparison Table of Materials

Ga₂O₃ offers several advantages when compared to other materials commonly used for UV photodetectors. As noted in Reference [6], the wide bandgap makes it intrinsically solar-blind, a significant advantage over materials like silicon, silicon carbide, and gallium nitride. This intrinsic solar-blindness eliminates the need for additional filters, which are often required for silicon-based detectors and can degrade over time. The crystal growth and cost aspects of Ga₂O₃ also present advantages. Reference [7] discusses how high-quality Ga₂O₃ crystals can be grown from the melt, like silicon, potentially allowing for larger wafers and lower production costs compared to SiC or GaN. Radiation hardness is another area where Ga₂O₃ excels. Reference [8] highlights the excellent radiation hardness of Ga₂O₃, comparable to or better than SiC and GaN. This property makes Ga₂O₃ particularly promising for space-based UV detection and other high-radiation environments. However, it is important to note that Ga₂O₃ also faces challenges, such as difficulties in p-type doping and lower thermal conductivity compared to some competing materials.

IV. KEY EXPERIMENTAL RESULTS

The carrier dynamics in Ga_2O_3 photodetectors are influenced by crystal defects, particularly oxygen vacancies. As described in Reference [1], these defects can introduce energy levels within the bandgap and modify the vibrational properties of the crystal, both of which impact carrier behavior.

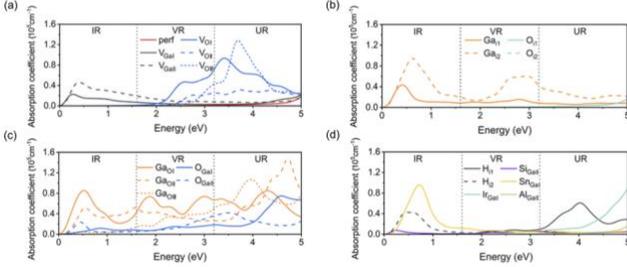


Fig. 4. Spectra of $\beta\text{-Ga}_2\text{O}_3$ with and without vacancies

The above figure illustrates the Fourier transform spectra of phonon-induced fluctuations in $\beta\text{-Ga}_2\text{O}_3$ with and without oxygen vacancies. The introduction of oxygen vacancies leads to new peaks, particularly in the 140-150 cm^{-1} range, corresponding to a collective transverse vibrational mode of oxygen atoms. These enhanced vibrational modes affect electron-phonon interactions, influencing carrier transport and recombination processes in $\beta\text{-Ga}_2\text{O}_3$ UV photodetectors.

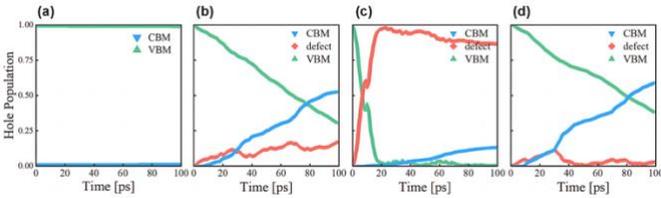


Fig. 5. Time-Dependent Electron Population of $\beta\text{-Ga}_2\text{O}_3$

The impact of oxygen vacancies on carrier dynamics is further elucidated in Fig. 5. This figure shows the time-dependent electron population in pristine $\beta\text{-Ga}_2\text{O}_3$ and $\beta\text{-Ga}_2\text{O}_3$ with different types of oxygen vacancies ($\text{Vo}1$, $\text{Vo}2$, and $\text{Vo}3$). In pristine $\beta\text{-Ga}_2\text{O}_3$, the conduction band minimum (CBM) population remains very low over time, indicating a long carrier lifetime. However, the introduction of oxygen vacancies significantly alters this behavior. For instance, $\text{Vo}1$ and $\text{Vo}3$ create pathways for electrons to move from the valence band to the conduction band via defect states, while $\text{Vo}2$ creates a “trap” state that captures and holds electrons, potentially leading to persistent photoconductivity.

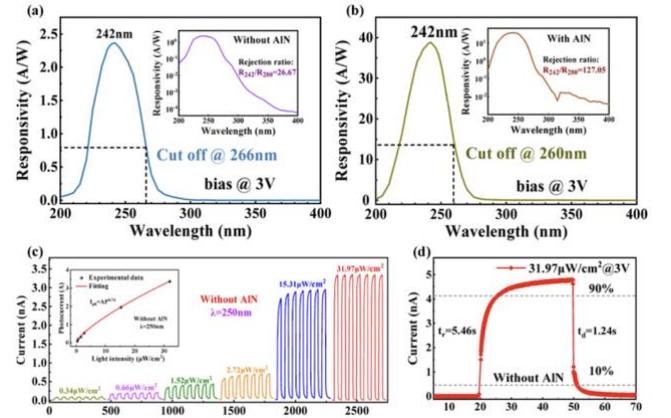


Fig. 6. Photoresponse of Ga_2O_3 UV Photodetectors

The performance characteristics of $\beta\text{-Ga}_2\text{O}_3$ UV photodetectors are demonstrated in Fig. 6. This figure shows key metrics such as spectral responsivity, temporal Photoresponse, and response speed. The photodetector exhibits a peak responsivity of about 2.4 A/W at 242 nm and a sharp cut off at 266 nm, demonstrating excellent solar-blind characteristics. The temporal photoresponse under various light intensities follows a sub-linear power law relationship, suggesting the presence of trap states affecting carrier dynamics. The response speed, with rise and decay times of 5.46 s and 1.24 s respectively, is influenced by carrier transit time and recombination lifetime.

These experimental results highlight the complex interplay between material properties, defects, and device performance in Ga_2O_3 UV photodetectors.

V. APPLICATIONS/FUTURE

Ga_2O_3 photodetectors show great promise for UV-C detection in applications ranging from environmental monitoring to space-based sensing. Future research directions include improving material quality through buffer layers and developing heterostructures to extend spectral range. The potential for solar-blind imaging arrays opens up possibilities in both materials and civilian sectors.

VI. PLAN OF CONTRIBUTION

This literature review on carrier dynamics in Ga_2O_3 UV photodetectors has identified key challenges in the field. Primary among these is the need to improve carrier lifetime and reduce defects in Ga_2O_3 films. While not directly related to my

current research activities, this exploration has provided valuable insight into wide bandgap semiconductor physics.

VII. CONCLUSION

Gaining insight into carrier dynamics in Ga₂O₃ has become essential for advancing high-performance UV photodetectors, especially for solar-blind applications. While challenges remain in fully controlling carrier behavior, such as improving hole transport and minimizing undesirable recombination processes, continued research into carrier dynamics promises exciting developments. Strategies such as defect engineering, heterostructure design, and strain modulation offer pathways to optimize carrier generation, transport, and collection. As the understanding of carrier dynamics in Ga₂O₃ deepens, innovative device designs that leverage these insights can be expected, leading to UV photodetectors with enhanced responsivity, faster response times, and improved overall performance.

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