Sensors and Materials, Vol. 38, No. 3 (2026) 1625–1635
MYU Tokyo

S & M 4397

Fabrication and Characterization of NiO-doped Ga_2O_3 films and Applications in Deep-ultraviolet Photodetectors

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(Received January 26, 2026; accepted March 9, 2026)

Keywords: Ga_2O_3 film, deep-ultraviolet photodetectors, electron-beam evaporation technique, structural properties, optical properties, electrical properties

Ga_2O_3 has emerged as a promising material for deep-ultraviolet (DUV) photodetectors owing to its ultrawide bandgap, intrinsic solar-blind response, low dark current, and high breakdown electric field, making it highly suitable for high-sensitivity DUV sensing applications. However, despite these advantages, several challenges remain in Ga_2O_3-based DUV photodetectors, including limited carrier transport efficiency, defect-related trap states, and the need for simplified and scalable fabrication routes for doped conductive films. However, the relatively low electron mobility and limited intrinsic carrier transport capability of pristine Ga_2O_3 restrict further improvements in device performance. To address these limitations, impurity doping has been recognized as an effective strategy to modulate the electrical properties and enhance carrier transport in Ga_2O_3-based devices. In this work, NiO-doped Ga_2O_3 films were developed and systematically investigated for application in DUV photodetectors. NiO was introduced as a functional dopant with a fixed atomic ratio of Ga:Ni = 100:12 (12 at%), and NiO-doped Ga_2O_3 films were deposited using an electron-beam evaporation technique. This approach aims to provide a simplified fabrication pathway while simultaneously improving electrical transport properties without compromising the intrinsic solar-blind characteristics of Ga_2O_3. The structural, optical, and electrical properties of the doped films were characterized to evaluate the effects of NiO incorporation on material quality and carrier transport behavior. The results demonstrate that NiO doping effectively modifies the electronic characteristics of Ga_2O_3 while preserving its ultrawide bandgap and solar-blind detection capability. The fabricated photodetectors exhibit reduced dark current and enhanced photoresponse under DUV illumination. Although the present study demonstrates improved photoresponse and stable device performance, further optimization of dopant concentration, defect control, and long-term operational stability remains necessary to fully realize the potential of NiO-doped Ga_2O_3 for practical large-scale DUV sensing applications. These findings indicate that NiO-doped Ga_2O_3

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https://doi.org/10.18494/SAM6227

ISSN 0914-4935
https://myukk.org/

films are a promising material platform for high-performance DUV photodetectors and provide valuable insights into the dopant-assisted performance optimization of ultrawide-bandgap oxide semiconductors.

1. Introduction

Deep-ultraviolet (DUV) photodetectors, operating at wavelengths below 280 nm, have attracted significant attention owing to their intrinsic solar-blind capability, which effectively suppresses interference from visible and near-ultraviolet radiation.[1] This unique characteristic enables reliable operation under strong ambient illumination, making DUV photodetectors indispensable in a wide range of safety-critical and high-precision applications. One of the most established applications is flame and combustion monitoring, where hydrocarbon flames emit strong UV-C radiation while background solar radiation in this spectral region is negligible. As a result, DUV photodetectors are widely deployed in industrial safety systems, gas turbines, aerospace propulsion, and fire detection equipment. In recent years, the rapid expansion of UV-C-based sterilization and disinfection technologies has further increased the demand for DUV photodetectors. These devices are essential for monitoring UV dose and ensuring the effectiveness and safety of UV-C light sources used in medical facilities, water purification systems, and public environments.

Additionally, DUV photodetectors play an important role in environmental and atmospheric monitoring, such as ozone sensing and ultraviolet radiation measurement, where high spectral selectivity and signal-to-noise ratio are required.[2,3] In more demanding fields, including space exploration, national defense, and nuclear instrumentation, DUV photodetectors must operate reliably under extreme conditions involving high temperatures, strong radiation, and harsh environments. To meet these diverse requirements, extensive research has focused on wide and ultrawide-bandgap semiconductor materials capable of providing intrinsic solar blindness, low dark current, and long-term stability. Among them, diamond,[4,5] AlGaN,[6,7] and Ga_2O_3[8,9] have emerged as the most representative material systems. Diamond offers exceptional robustness under extreme conditions, AlGaN provides bandgap tunability and technological maturity, and Ga_2O_3 has recently attracted attention owing to its ultrawide bandgap and favorable material properties. Together, these materials form the foundation of current DUV photodetector research and development.

Diamond, AlGaN, and Ga_2O_3 represent three major material platforms for DUV photodetectors, each possessing distinct advantages and limitations. Diamond features an ultrawide bandgap of approximately 5.5 eV, enabling intrinsic solar-blind detection with extremely low dark current and outstanding resistance to high temperatures and radiation damage. These properties make diamond-based photodetectors highly suitable for space, nuclear, and high-energy physics applications. However, their broader adoption is limited by the high cost of single-crystal diamond substrates, restricted wafer size, and complex fabrication processes, which significantly hinder large-area and low-cost device integration. AlGaN-based photodetectors constitute the most technologically mature DUV platform. By adjusting the aluminum composition, the bandgap of AlGaN can be tailored to cover the entire UV-C range,

enabling wavelength-selective detection. Moreover, AlGaN benefits from compatibility with established III-nitride semiconductor technologies. Nevertheless, high-aluminum-content AlGaN suffers from degraded crystalline quality due to lattice mismatch and strain, leading to increased defect densities. In addition, reliable p-type doping in Al-rich AlGaN remains challenging, complicating device design and limiting performance optimization.

In comparison, Ga_2O_3 has emerged as a promising alternative ultrawide-bandgap semiconductor for DUV photodetectors. With a bandgap of approximately 4.8–4.9 eV, Ga_2O_3 inherently supports solar-blind operation while offering several practical advantages. Ga_2O_3 films can be grown using various scalable and cost-effective deposition techniques, enabling large-area fabrication and flexible substrate selection. Furthermore, Ga_2O_3 exhibits excellent thermal and chemical stability, along with a high breakdown electric field, which is beneficial for low-noise and reliable photodetector operation. Although achieving stable p-type conductivity remains challenging, recent advances in doping strategies and heterojunction engineering have significantly enhanced the versatility of Ga_2O_3-based devices. Consequently, Ga_2O_3 is increasingly regarded as a strong candidate for next-generation DUV photodetectors, balancing performance, manufacturability, and cost.

Building on the above discussion of material selection and application requirements for DUV photodetectors, in this study, we focus on the development and characterization of NiO-doped Ga_2O_3 films as a promising material platform for solar-blind DUV sensing.[10] Although Ga_2O_3-based materials and Ni-related modifications have been explored in previous studies, reports on directly deposited NiO-doped Ga_2O_3 films remain relatively limited. More importantly, in many earlier approaches, Ni incorporation was achieved through postdeposition treatments, multistep doping processes, or complex cosputtering systems, often requiring additional annealing or strict process control to obtain conductive Ga_2O_3 films. In contrast, in the present work, we demonstrate a simplified and scalable fabrication strategy in which NiO-doped Ga_2O_3 films are directly deposited using a single-step electron-beam evaporation process. By employing a presintered composite target with a controlled Ga:Ni atomic ratio, conductive NiO-doped Ga_2O_3 films were obtained without additional postannealing treatments, representing a practical advancement in fabrication methodology.

The primary aim of this work is to mitigate the limited carrier transport capability of pristine Ga_2O_3 through controlled NiO doping while preserving its intrinsic ultrawide bandgap and low dark current characteristics. The structural and compositional properties of the deposited films were investigated by field-emission scanning electron microscopy (FESEM) and secondary ion mass spectrometry (SIMS) depth profiling to confirm film uniformity and successful Ni incorporation. Energy band structure calculations were further performed to elucidate the effect of NiO doping on carrier transport modulation. On the basis of the investigated semiconductive NiO-doped Ga_2O_3 films, DUV photodetector devices with an interdigitated electrode configuration were fabricated and evaluated under monochromatic illumination from 200 to 400 nm. The wavelength-dependent photoresponse demonstrates a clear solar-blind behavior and an enhanced DUV sensitivity, highlighting the strong potential of the proposed single-step NiO-doped Ga_2O_3 platform for high-performance DUV photodetector applications.

2. Methodology

A p-type Si wafer with (100) orientation was used as the substrate for film deposition. Prior to target preparation, Ga_2O_3 powder was thermally treated at 950 ℃ for 1 h to improve material stability. Stoichiometric amounts of Ga_2O_3 and NiO powders, corresponding to a Ga:Ni atomic ratio of 100:12 (12 at% NiO), were subsequently mixed by ball milling to ensure homogeneous blending. The mixed powders were then pressed into green compacts and sintered at 500 ℃ for 1 h to form NiO-doped Ga_2O_3 evaporation targets. The sintered targets were placed in an electron-beam evaporation crucible, and the deposition chamber was evacuated to a base pressure of 7.5×10^{-6} torr. NiO-doped Ga_2O_3 films were deposited at room temperature for 6 min. During deposition, only the deposition rate was controlled, while the chamber pressure was not actively regulated. As a result, uniform and smooth NiO-doped Ga_2O_3 films with an average thickness of approximately 65 nm were obtained, as confirmed by surface observation shown in Fig. 1(a) and cross-sectional observation shown in Fig. 1(b).

The structural, optical, and electrical properties of the films were systematically characterized. FESEM was employed to examine surface morphology and film thickness. Optical bandgap values were extracted from UV–Vis transmission spectra measured on films deposited on transparent sapphire substrates. The elemental distribution and chemical composition across the film cross section were analyzed by X-ray photoelectron spectroscopy (XPS). Electrical current–voltage (*I–V*) characteristics were measured using an Agilent B1500A semiconductor parameter analyzer over a voltage range of −2 to 2 V. For device fabrication, interdigitated electrodes were deposited onto the NiO-doped Ga_2O_3 films to form DUV photodetectors. Photoresponse measurements were carried out under monochromatic ultraviolet illumination in the wavelength range of 200–400 nm. During measurement, the devices were biased at a constant voltage while the photocurrent was recorded by periodically switching the UV light source on and off, allowing the evaluation of wavelength-dependent responsivity and solar-blind detection behavior.

3. Results and Discussion

Figure 2(a) shows the XPS depth profiles of Ga, Ni, O, and Si in the NiO-doped Ga_2O_3 films, which were obtained from the SIMS analyses. As the sputtering depth approaches approximately

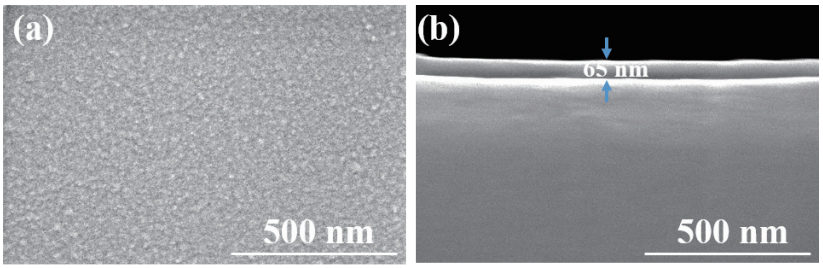

Fig. 1. (Color online) FESEM images for (a) surface and (b) cross-sectional observations.

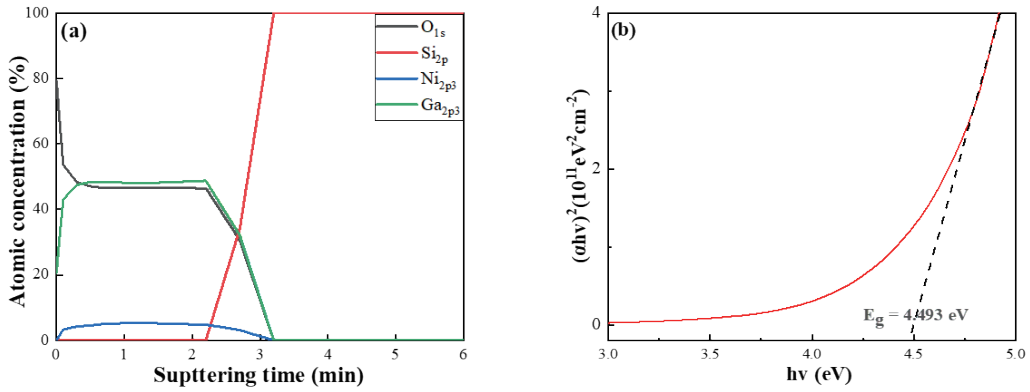

Fig. 2. (Color online) (a) XPS depth profiles of Ga, Ni, O, and Si. Because XPS depth profiling obtained from SIMS analyses controls the penetration depth of the electron beam by adjusting the sputtering time, the horizontal axis represents time. (b) E_g of the deposited NiO-doped Ga_2O_3 films.

65 nm, the concentrations of Ga, Ni, and O gradually decrease rather than exhibit an abrupt drop. This gradual transition suggests the presence of a compositional gradient near the film–substrate interface, indicating partial interfacial mixing or diffusion effects between the NiO-doped Ga_2O_3 layer and the underlying Si substrate. Such behavior is commonly observed in ultrathin oxide films deposited on Si, particularly when room-temperature deposition is employed. Simultaneously, the Si signal increases markedly at depths beyond ~65 nm, confirming that the sputtering process has reached the Si substrate. This observation further verifies the film thickness estimated by cross-sectional FESEM analysis (not shown here), demonstrating good consistency between morphological and compositional characterization results. The absence of a sharp compositional boundary implies that the interface is not ideally abrupt, which may affect carrier transport and interfacial electrical behavior in the fabricated photodetector devices. From a device perspective, the gradual elemental transition at the interface can contribute to reduced interfacial defects and improved carrier injection under bias, which is beneficial for photodetector performance. Overall, the SIMS results confirm the successful incorporation of NiO within the Ga_2O_3 matrix, validate the film thickness of approximately 65 nm, and provide insight into the interfacial characteristics of the NiO-doped Ga_2O_3/Si system.

The optical transmittance characteristics of the NiO-doped Ga_2O_3 films provide important insight into their electronic band structure and light–matter interactions. In this study, optical transmittance spectra were analyzed using the Tauc method to determine the optical bandgap (E_g), and the corresponding results are summarized in Fig. 2(b). The extracted Eg value for NiO-doped Ga_2O_3 films deposited without thermal treatment at 950 °C was 3.885 eV (not shown), whereas the investigated NiO-doped Ga_2O_3 films exhibited an increased bandgap of 4.493 eV when using the Ga_2O_3 powder thermally treated at 950 °C. This represents a notable bandgap widening of approximately 0.608 eV. The observed increase in Eg can be attributed to the effects of the high-temperature pretreatment on the structural properties of the Ga_2O_3 source material. The Ga_2O_3 powder was pretreated by sintering at 950 °C, which promoted the formation of the crystalline β-Ga_2O_3 phase, as confirmed by X-ray diffraction analysis.[11] During the subsequent

electron-beam evaporation process, this crystalline phase characteristic was effectively transferred or "induced" into the deposited thin films, leading to improved structural ordering compared with films deposited using untreated Ga_2O_3 powder. Improved crystallinity and reduced structural disorder are known to suppress defect-related localized states near the band edges, resulting in an apparent widening of the optical bandgap. Therefore, the increase in Eg observed in the NiO-doped Ga_2O_3 films can be reasonably attributed to the combined effects of phase stabilization and enhanced short-range ordering associated with the β-Ga_2O_3 structure.

In previously reported Ni-modified or doped Ga_2O_3 systems, bandgap variations are often associated primarily with impurity-induced states or defect-related band tailing effects, which may either slightly narrow or only marginally modify the optical bandgap. In contrast, the bandgap widening observed in this study is mainly attributed to the phase stabilization of β-Ga_2O_3 induced by the high-temperature pretreatment of the source material, rather than solely to the presence of Ni-related impurity levels. This distinction suggests that the optical improvement is structurally driven, reflecting enhanced crystallinity rather than defect-mediated band modification. Compared with untreated Ga_2O_3 films commonly reported in the literature, which frequently exhibit lower apparent bandgap values due to structural disorder or sub-bandgap absorption, the present films demonstrate a clearer and wider bandgap characteristic, supporting a stronger intrinsic solar-blind behavior. These results indicate that the 950 °C pretreatment of the Ga_2O_3 source material plays a crucial role in tailoring the optical properties of NiO-doped Ga_2O_3 films, which is advantageous for achieving high selectivity and solar-blind operation in DUV photodetector applications.

The dark current (I_d) is defined as the current measured when the photodetector is placed in a light-tight enclosure, ensuring a completely dark environment, and a constant bias voltage is applied to the device. This current mainly originates from intrinsic noise or leakage pathways within the device. For practical photodetector operation, a low dark current is highly desirable, as it directly contributes to an improved signal-to-noise performance. In contrast, the photocurrent (I_{ph}) is generated when the device is biased and illuminated with light of a specific wavelength. The resulting increase in current relative to the dark condition corresponds to the photoinduced carrier generation. The key performance parameter of the fabricated NiO-doped Ga_2O_3 photodetector is responsivity (R), which quantifies the efficiency of converting incident optical power into an electrical signal. Responsivity is defined as the generated photocurrent per unit incident optical power and expressed as $R = (I_{ph} - I_d) / (P_\lambda \times S)$, where P_λ is the incident optical power density and S is the effective illuminated area of the device. Figure 3(a) illustrates the wavelength-dependent R of the fabricated NiO-doped Ga_2O_3 photodetector under monochromatic illumination.

As shown in Fig. 3(a), R initially increases as the incident wavelength increases from 200 nm and reaches a maximum at approximately 280 nm. With further increase in wavelength, R gradually decreases and eventually saturates at around 380 nm. It exhibits a pronounced peak in the DUV region between 260 and 280 nm, which corresponds to the intrinsic absorption range of Ga_2O_3. Figure 3(a) further confirms that the fabricated device is suitable for DUV photodetection. In addition to the primary peak, two minor responsivity features are observed at approximately 370 and 430 nm. On the basis of these spectral characteristics, subsequent

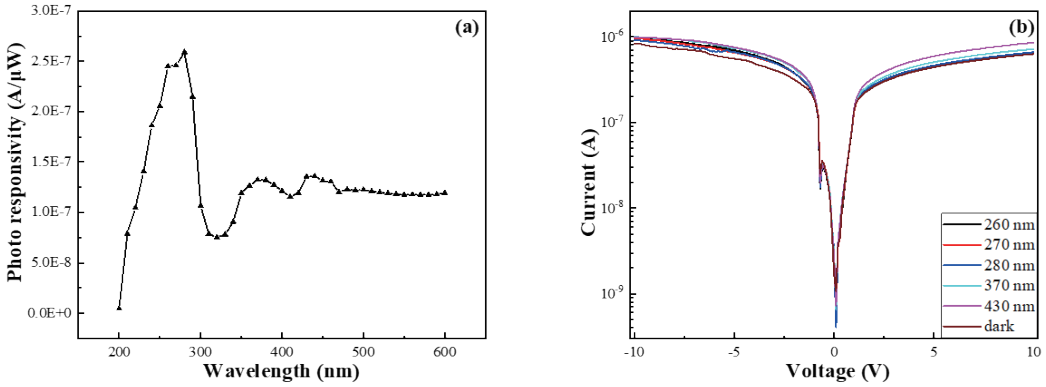

Fig. 3. (Color online) (a) Variations in (a) *R* values and (b) *I–V* curves as a function of wavelength.

analyses were conducted under dark conditions and at selected illumination wavelengths of 260, 270, 280, 370, and 430 nm to further investigate the device's photoresponse behavior. Figure 3(b) presents the *I–V* characteristics of the device measured under dark conditions and under illumination at different wavelengths while a bias voltage was applied. The results show that the *I–V* curves obtained under these conditions are nearly identical, indicating minimal variation in current response with respect to wavelength-dependent illumination.

This behavior can be attributed to the intrinsic solar-blind nature of the NiO-doped Ga_2O_3 photodetector. Owing to its ultrawide bandgap, photons with energies below the bandgap are insufficient to generate significant photoinduced carriers, resulting in negligible changes in the measured current. In addition, the low intrinsic carrier concentration and suppressed leakage current of Ga_2O_3 further limit photoresponse outside the DUV region. Compared with previously reported Ga_2O_3-based photodetectors, where sub-bandgap response or notable current fluctuation under near-UV illumination has occasionally been observed owing to defect-related states, the present device exhibits highly stable *I–V* characteristics across the measured wavelength range. This indicates that NiO doping combined with the adopted fabrication process does not introduce excessive defect-assisted conduction pathways that would degrade wavelength selectivity. The nearly unchanged *I–V* curves under different illumination conditions therefore highlight an improved suppression of unintended photoresponse outside the DUV region, demonstrating a clearer solar-blind behavior than that typically reported for untreated or defect-rich Ga_2O_3 films. As a result, the electrical transport characteristics remain largely unchanged under illumination at non-DUV wavelengths, confirming the strong wavelength selectivity and stable electrical behavior of the fabricated device.

The photoresponse time is an important parameter that describes how quickly a photodetector responds to optical illumination under a fixed incident power. In this study, the response time is characterized by the rise time (T_r) and fall time (T_f). The rise time is defined as the time required for the photocurrent to increase from 10 to 90% of its maximum upon illumination, whereas the fall time corresponds to the time for the photocurrent to decay from 90 to 10% of its maximum after the light source is turned off. For many practical applications, rapid response is essential; therefore, reducing the response time of photodetectors has become an important research focus.

In metal–semiconductor–metal (MSM) structured photodetectors, the response time is affected by several factors, including carrier recombination dynamics, carrier transport pathways, defect density within the thin film, hole trapping mechanisms, and oxygen-related surface sensitization effects. These processes collectively govern the generation, transport, and recombination of photoinduced carriers. Figures 4(a)–4(e) present the transient photoresponse of the NiO-doped Ga_2O_3 photodetector under illumination at different wavelengths. The results indicate that both the rise and fall times are relatively short for all excitation wavelengths. Except for the fall time measured at 270 nm, which is approximately 1.55 s, all rise and fall times are below 0.8 s. The fast response behavior can be attributed to the ultrawide bandgap of Ga_2O_3, which suppresses

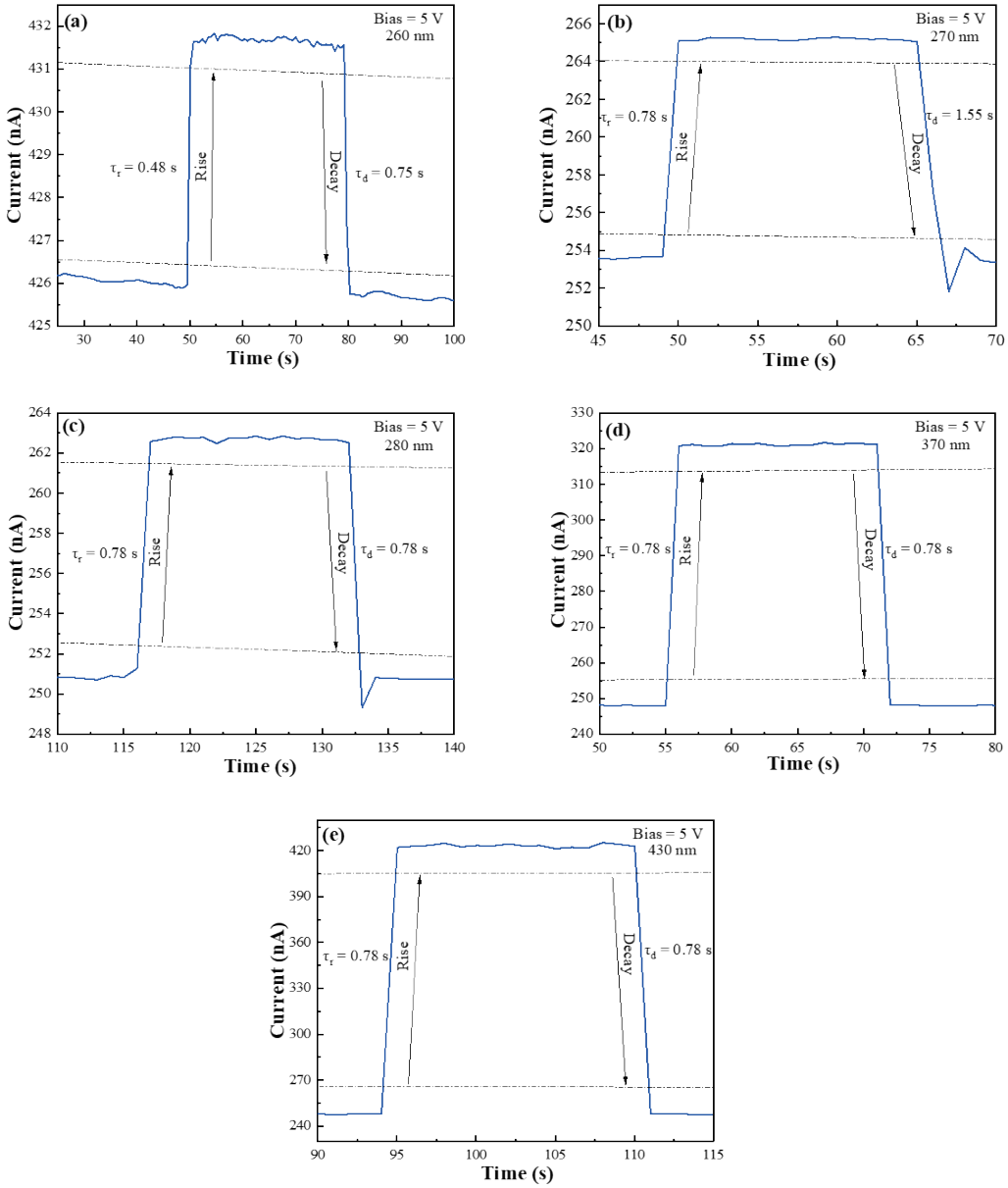

Fig. 4. (Color online) Response time of fabricated DUV photodetector under illumination at different wavelengths: (a) 260, (b) 270, (c) 280, (d) 370, and (e) 430 nm.

persistent photoconductivity, as well as the reduced defect-assisted carrier trapping in the NiO-doped Ga_2O_3 films. These characteristics enable efficient carrier generation and recombination, resulting in rapid and stable photoresponse suitable for DUV photodetector applications.

Finally, cyclic stability measurements were performed to evaluate the repeatability and operational reliability of the fabricated DUV photodetector. Figures 5(a)–5(e) present the photocurrent responses of the device under five consecutive on–off illumination cycles at different wavelengths. As shown in Figs. 5(a)–5(e), the photocurrent response remains highly consistent throughout the cycling tests. Notably, for all tested wavelengths, the current modulation amplitude observed during the first illumination cycle is nearly identical to that of

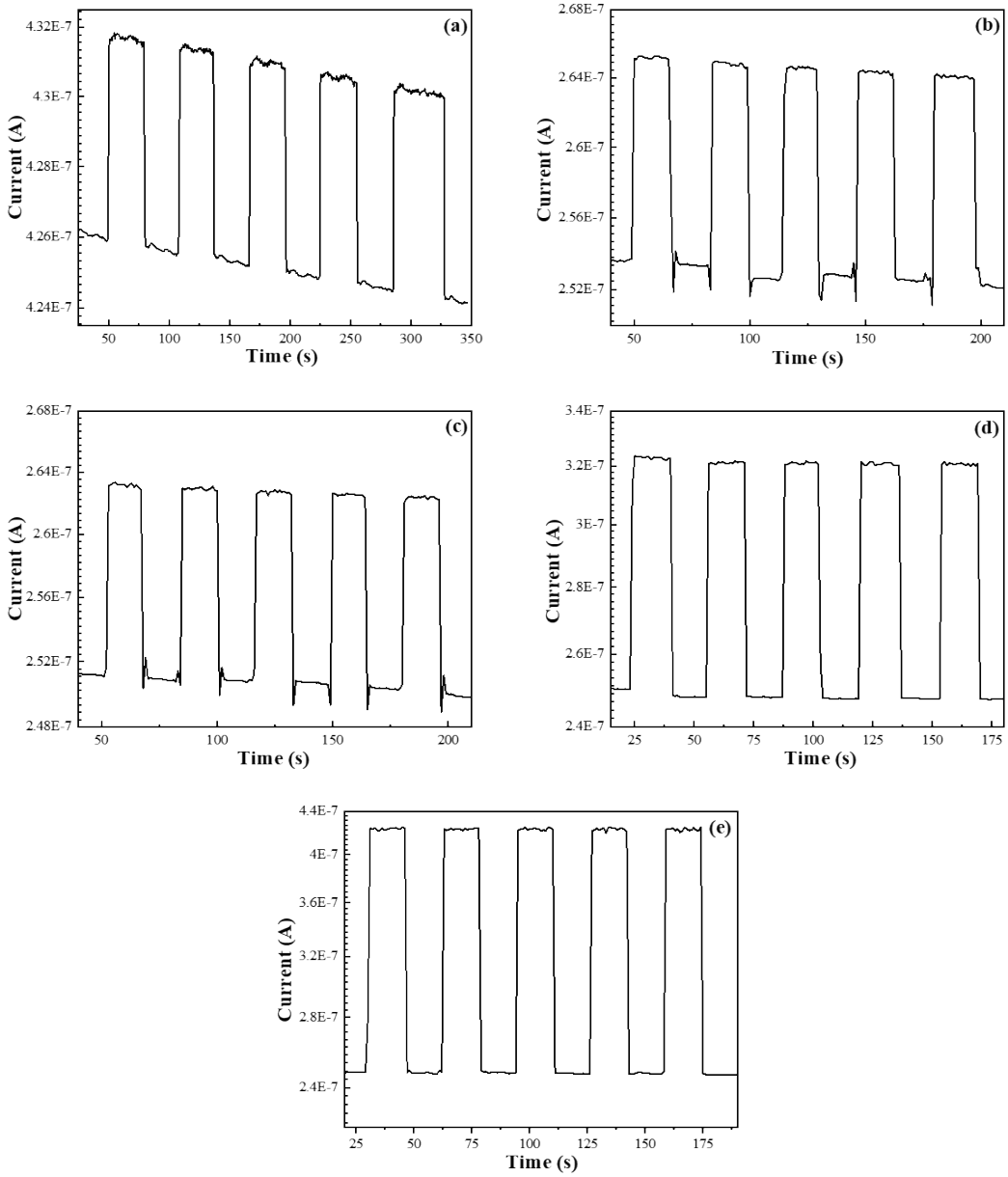

Fig. 5. (Color online) Cyclic stability measurements of fabricated DUV photodetector under illumination at different wavelengths: (a) 260, (b) 270, (c) 280, (d) 370, and (e) 430 nm.

the fifth cycle, indicating negligible degradation in photoresponse intensity. This stable behavior demonstrates the excellent repeatability and reproducibility of the device under repeated optical excitation. The absence of notable photocurrent decay or baseline drift suggests that the NiO-doped Ga_2O_3 photodetector exhibits robust material stability, minimal carrier trapping effects, and suppressed photoinduced degradation. These results highlight a key advantage of the proposed device: reliable and repeatable DUV sensing performance without performance deterioration over multiple operation cycles. Such stability is essential for practical photodetector applications, particularly in continuous monitoring and real-time sensing systems, further confirming the suitability of the NiO-doped Ga_2O_3 photodetector for DUV detection.

4. Conclusions

In this study, NiO-doped Ga_2O_3 films were successfully developed and systematically investigated for DUV photodetector applications. Although Ga_2O_3 has been widely recognized as a promising ultrawide-bandgap semiconductor, challenges such as limited carrier transport efficiency, defect-related recombination, and the lack of simplified fabrication routes for conductive doped films remain unresolved in current research. The films in this work were deposited using a single-step electron-beam evaporation technique with a fixed Ga:Ni atomic ratio of 100:12, enabling controlled composition and uniform film formation without additional complex post-treatment processes. This approach addresses the need for a more practical and scalable method to fabricate NiO-doped Ga_2O_3 films while improving electrical transport characteristics. Structural and compositional analyses confirmed the formation of smooth and uniform films with an average thickness of approximately 65 nm, while SIMS depth profiling verified the effective incorporation and spatial distribution of Ni within the Ga_2O_3 matrix. Optical characterization revealed a widened optical bandgap of 4.493 eV, which is attributed to the β-Ga_2O_3 phase characteristics induced by the high-temperature pretreatment of the Ga_2O_3 source material, supporting intrinsic solar-blind operation. On the basis of the optimized NiO-doped Ga_2O_3 films, interdigitated electrode photodetectors were fabricated and evaluated over a wavelength range of 200–400 nm. The devices exhibited pronounced responsivity in the DUV region, with a clear response peak between 260 and 280 nm, confirming their suitability for DUV sensing. In addition, the photodetectors demonstrated low dark current, fast photoresponse with rise and fall times mostly below 0.8 s, and excellent wavelength selectivity. Cyclic stability measurements further revealed a highly repeatable photoresponse behavior with negligible degradation over multiple illumination cycles, indicating robust operational reliability and reusability. While the present results demonstrate an improved photoresponse behavior and a stable device operation, further optimization of dopant concentration, interface engineering, and long-term environmental reliability remains necessary for large-scale practical deployment. Overall, this work demonstrates that NiO doping is an effective approach for tailoring the optical and electrical properties of Ga_2O_3 films. The combination of stable material characteristics, rapid response, and reliable solar-blind detection highlights the strong potential of NiO-doped Ga_2O_3 as a promising material platform for next-generation DUV photodetectors.

Acknowledgments

This work was supported by the postsubsidy project for the industry education research of Xiamen Science and Technology Bureau, Fujian Province, China (Grant No. 2023CXY0322). This work was also supported by Summit-Tech Resource Corp. and by projects under Nos. NSTC 113-2221-E-390-011 and NSTC 114-2622-E-390-001.

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