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Performance Characterization of GaN-Based Ultraviolet Detectors

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ABSTRACT
In ultraviolet calibration applications, specific broadband detectors capable of covering the UVA, UVB, and UVC bands are essential to achieve full-spectrum response without the need for filter changes, thereby providing critical support for establishing a unified, traceable ultraviolet radiation calibration system. This paper reports on a GaN broadband Schottky ultraviolet detector based on a vertical "NiAu/i-GaN/n-GaN/sapphire" structure. An independent microcontroller-based calibration system for the ultraviolet detector was developed. The detector exhibits dual-peak responsivity at 250 nm and 365 nm, with a peak responsivity of 0.12 A/W. The device demonstrates a dark current density of only 0.35 μA/cm² at 0 V bias and shows no hard breakdown even at -5 V, indicating effective surface passivation and isolation from the substrate. Under zero-bias operation, thermal noise dominates, yielding a measured R_0A product of 2.6×10^2 Ω·cm², corresponding to a relative detection efficiency (D*) of approximately 1.5×10^{10} cm $\cdot Hz^{0.5}$/W. This structure enables simultaneous monitoring of the solar-blind and UVA bands without requiring visible light filtering, making it suitable for applications such as broad-spectrum UV index monitoring, curing light feedback, and flame detection.

KEYWORDS
GaN; UV detection, Low-noise amplification; Photodiode; Single chip microcomputer

1 Introduction

Ultraviolet (UV) radiation is routinely monitored in environmental metrology, phototherapy dosage control, and high-power UV curing, all of which demand a single sensor that can be traced to national standards across the full UVA (315–400 nm), UVB (280–315 nm) and UVC (200–280 nm) windows [1]. Conventional silicon radiometers require a set of narrow-band filters and frequent interchange, increasing calibration complexity, stray-light uncertainty and maintenance cost. Wide-bandgap GaN offers an intrinsic visible-blind response and tailorable cut-off through Al-composition tuning, making it an ideal platform for a filter-free, broadband UV detector [2]. However, the photocurrent generated by solar-blind photodetectors is typically in the nanoampere level, which is below the resolution of conventional read-out electronics, therefore a preamplifier must be used to amplify this weak current signal and convert it into an electrical signal that is easier to process [3]. In this work, we designed a GaN-based vertical-structure ultraviolet photodiode and developed a microcontroller-based calibration system comprising: bias voltage, sensor, microcurrent amplification, analog-to-digital converter (ADC), microcontroller unit (MCU), and host computer. The bias voltage sets the operating point, while the sensor converts sunlight into picoampere-level currents. After current-to-voltage (I/V) amplification and filtering, the ADC samples the signal, which is then digitally filtered by the MCU and transmitted to the host computer. Testing revealed a significant response from 250 nm to 365 nm, coupled with low dark current at 0 V bias. The device integrates the solar-blind and UVA regions without spectral discontinuities, enabling measurements of UVA, UVB, and UVC radiation. This provides a compact, solid-state alternative to existing filter-based standards and paves the way for field-deployable broadband UV irradiance calibration, reducing system footprint while enhancing measurement repeatability.

2 System Design and Experimental Flow

Photodetection systems convert the measurand into optical flux, transduce this flux into an electrical signal, and, by integrating transmission and processing stages, deliver the desired physical quantity [4]. The UV photodetector calibration and measurement system described herein comprises a daylight-blind UV photodetector under test, a bias voltage module, a preamplifier circuit, a microcomputer-based signal processing unit, and a host interface. As shown in Figure 1, this configuration enables the application of a bias voltage to the detector under test, conditioning and amplifying the weak current generated by the detector. The amplified signal is then acquired via an ADC and transmitted through the microcontroller's serial port to the host computer for analysis. The overall system configuration is illustrated in Figure 1.

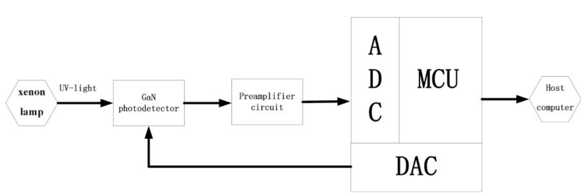

Figure 1 Structure of Photoelectric Detection System

In optoelectronic detection systems, a light source serves as the carrier to transmit the information to be detected. The MEXE series mercury-xenon lamp is employed for this purpose. This lamp combines the spectral characteristics of both xenon and mercury lamps, covering a spectral range from 200 to 2000 nm. The system features continuously adjustable light intensity and offers selectable output modes, including point light source, parallel light (with adjustable diameter), and fiber optic output. It also incorporates multiple filters for spectral selection and utilizes a highly stable power supply to ensure consistent experimental conditions effectively.

GaN-based wide-bandgap semiconductors have emerged as the leading material system for ultraviolet (UV) photodetection, primarily due to their inherent solar-blind operation and tunable bandgap [5]. The device fabricated in this study is a Schottky photodiode designed to leverage these properties. Its architecture begins with a sapphire substrate, chosen for its optical transparency in the UV range and excellent lattice matching with GaN, which promotes high-quality epitaxial growth.

The heterostructure was synthesized by metal-organic chemical vapor deposition (MOCVD), ensuring precise control over layer thickness and doping concentration. As depicted in Figure 2, the growth process initiated with the deposition of a 2-μm-thick, Si-doped n-type GaN layer. This layer serves a dual purpose: it provides a low-resistance path for carrier transport and forms a non-rectifying ohmic contact with the underlying n-electrode, thereby facilitating efficient electron collection. Subsequently, a critical 0.4-μm-thick undoped, intrinsic (i-) GaN layer was grown. This layer functions as the primary photo-absorption region, where incident UV photons with energy exceeding the GaN bandgap are absorbed, generating electron-hole pairs. The device's active region was defined using standard photolithography to create a mesa structure, followed by reactive ion etching (RIE) for anisotropic pattern transfer, which minimizes device leakage current. For the Schottky contact, a Ni/Au bilayer metal stack was deposited on the intrinsic GaN layer. The nickel (Ni) layer, in direct contact with the intrinsic semiconductor, forms the requisite Schottky barrier, which is pivotal for separating the photo-generated carriers under an applied electric field. The overlying gold (Au) layer enhances electrical conductivity and provides resistance to oxidation. Conversely, the n-type ohmic contact was realized using a Ti/Au/Ti/Au multilayer metallization scheme, where titanium (Ti) ensures low contact resistance with the n-GaN layer. Finally, a silicon dioxide (SiO_2) passivation layer was deposited over the etched sidewalls and the device surface to suppress surface recombination and further minimize leakage currents, thereby significantly improving the overall detectivity and stability of the photodiode.

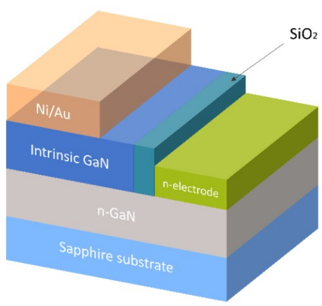

Figure 2 Schematic diagram of GaN Schottky Barrier Photodiode

Calibration of GaN ultraviolet photodetectors requires measuring photocurrent under a controlled bias voltage. Although the microcontroller's built-in DAC allows precise bias voltage setting, its high output impedance and limited load-driving capability prevent it from directly driving the sensor. Therefore, a voltage follower stage is added downstream of the DAC to reduce output impedance and improve load-driving capability, thereby providing a stable bias voltage to the detector, as illustrated in Figure 3.

The amplified weak electrical signal from the detector is first conditioned by signal conditioning circuitry, which typically includes a preamplifier, analog-to-digital conversion. This process converts the initial signal into a standardized level or digital format suitable for further use. Subsequently, the processed data is routed to a microcomputer or control

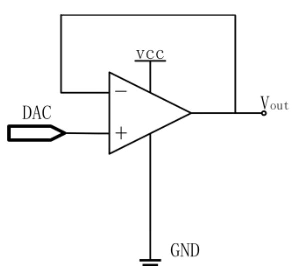

Figure 3 Bias volt module

system for analysis and interpretation, and can also be sent to a display system for real-time visualization. Figure 4 shows the amplification circuit for the faint light signals of a solar-blind ultraviolet GaN Schottky barrier detector. To enhance circuit performance, capacitors are connected in parallel to stabilize voltage, suppress harmonics, mitigate interference, and prevent self-oscillation [6]. The photodiode operates under zero bias (photovoltaic mode), outputting a weak current signal proportional to light intensity. The transimpedance amplifier converts this current into voltage, with its ideal transimpedance gain formula shown in Equation 1. The selection of an operational amplifier for a transimpedance amplifier (TIA) circuit is critically governed by the imperative to minimize both input bias current and input offset voltage. A sufficiently low input bias current is essential, as this parameter, when amplified by the feedback resistor, introduces a non-negligible total output error by superimposing itself onto the weak photocurrent signal. Concurrently, a minimal input offset voltage is crucial for mitigating DC output offset, which fundamentally compromises signal fidelity at the quiescent point and severely constrains the system's available dynamic range and signal-to-noise ratio. The pursuit of exemplary performance in both of these parameters is therefore a fundamental prerequisite for the realization of high-precision, high-sensitivity photoelectric conversion systems.

$$V_{out} = -I_{pd} \times R_f \tag{1}$$

Finally, the amplified output voltage signal is recorded and stored by the data acquisition module via the microcontroller's internal ADC, then transmitted through the serial port for further analysis by the test computer.

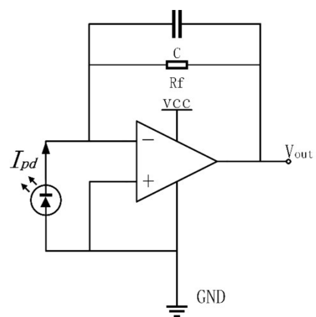

Figure 4 Weak Photocurrent Amplifier Circuit

3 Analysis and discussion

The spectral responsivity R(λ), external quantum efficiency EQE(λ), dark current I_dand specific detectivity D* are the key performance metrics used to evaluate the quality of solar-blind ultraviolet photodetectors.

Figure 5(a) shows the spectral response curves of the GaN-based broadband ultraviolet photodetector without an external bias voltage source in the 200−400 nm range. A secondary peak response of 0.058 $A \cdot W^{-1}$ was observed at 250 nm, corresponding to an external quantum efficiency (EQE) of approximately 60%. The primary peak response occurred at 350 nm, with a responsivity of approximately 0.12 $A \cdot W^{-1}$. At 400 nm, the responsivity was less than 10^{-4} $A \cdot W^{-1}$. This device exhibits distinct responses across the ultraviolet UVA, UVB, and UVC bands, with an ultraviolet-to-visible light suppression ratio greater than 10^3, meeting the requirements for ultraviolet band irradiance calibration. These results demonstrate the device's capability for effective ultraviolet photon detection without the application of reverse bias voltage. The current-voltage (I-V) characteristic curve of the sample device, measured under dark conditions at room temperature, is shown in Figure 5(b). It exhibits clear Schottky diode rectification behavior with a low turn-on voltage. Linear fitting of the forward bias region yields a turn-on voltage of approximately 0.2 V and a turn-on resistance of approximately 2.87 kΩ. This behavior can be attributed to the formation of an effective Schottky contact between the metal electrode and the GaN film. Figure 5(c) presents the logarithmic representation of the I-V characteristic curve of the GaN-based ultraviolet photodetector under dark conditions. Differentiating this curve produces the result shown in Figure 5(d), where the differential resistance of the device at 0 V bias is approximately 1.8 MΩ. In practice, under zero-bias operation, the noise in the photodetector is primarily caused by thermally excited carriers. Its magnitude can be estimated from the I-V characteristic curve, with the corresponding relative detection efficiency expressed as shown in Equation 2.

$$D^* = R_\lambda \left(\frac{R_0 A}{4KT} \right)^{1/2} \tag{2}$$

In the equation, R_λ represents the 0 bias responsivity, R_0denotes the differential resistance, A indicates the device area (the photosensitive surface of this sample is a 1.2 mm × 1.2 mm square), K is the Boltzmann constant, and T is the absolute temperature. From the I-V curve in Figure 4(d), the differential resistance is determined to be 1.8×10^5 Ω. Calculations based on Equation (3) yield a relative detection efficiency of 1.5×10^{10} cm $\cdot Hz^{0.5}$/W at 0 V bias voltage.

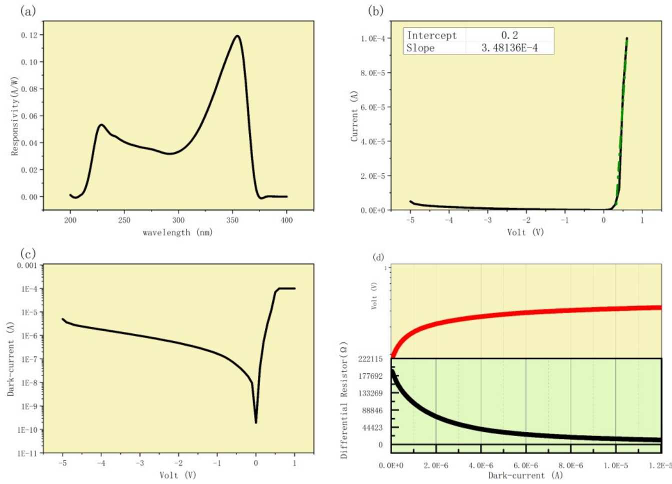

Figure 5 (a) Spectral responsivity curves of GaN-based solar-blind photodetectors under different bias voltages in the 200–400 nm range. (b) I-V characteristic curve (liner) of a GaN-based photodetector in the dark at room temperature. (c) I-V characteristic curve (logarithmic scale) of GaN-based photodetectors in dark conditions. (d) Differential Resistance Curve of GaN-Based solar-blind Photodetector

4 Conclusions

This study established a calibration system for a self-developed GaN ultraviolet detector and conducted a comprehensive performance characterization. At 0 V bias, the device exhibited a dark current density of only 0.35 μA/cm^2 and remained non-breakdown even at -5 V, demonstrating excellent junction quality and surface passivation. The spectral response spans 250 – 365 nm, with a peak responsivity of 0.12 A/W, enabling seamless detection across the entire UVA, UVB, and UVC spectrum. The zero-bias R_0A product reached 2.6 × 10^2 Ω·cm^2, corresponding to a relative detection efficiency (D*) of approximately 1.5 × 10^{10} cm ·Hz$^{0.5}$/W, meeting the demands for high-speed, low-light detection. In summary, this detector combines broad spectral coverage, high sensitivity, low noise, and low cost, providing a reliable solution for UV radiation calibration, light source monitoring, and portable UV meters.

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