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Testing and Calibration of an Ultraviolet-A Radiation Sensor Based on GaN Photodiode

(Pengujian dan Penentukuran Sensor Sinaran Ultra Lembayung-A Berasaskan Fotodiod GaN)

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ABSTRACT

An ultraviolet A (UVA) radiation intensity sensor with responsivity in the wavelength range of 320-360 nm was developed based on a gallium nitride (GaN) photodiode. In this sensor system, a GaN photodiode in reverse-biased mode converts the radiation intensity into current, which was then converted and amplified into an output voltage by a transimpedance amplifier (TIA), or current-voltage converter, consisting of an operational amplifier and a feedback resistor. For a narrowband UV source, the radiation intensity could be calculated from the values of the output voltage, feedback resistor, photodiode responsivity and photodiode effective area. The sensor was tested by performing measurements over different values of UV source wavelength, source distance, ambient temperature and sampling time. For calibration with a broadband UV source, the GaN-UVA sensor was used simultaneously with a standard Si-UVA sensor to measure solar radiation. The observed linear relationship between the sensors' outputs enables us to convert the output voltage of the GaN-UVA sensor to UVA intensity. Thus, we have successfully developed, tested and calibrated an ultraviolet A radiation sensor based on the GaN photodiode.

Keywords: GaN photodiode; radiation sensor; transimpedance amplifier; ultraviolet A

ABSTRAK

Sebuah sensor keamatan sinaran ultra lembayung A (ULA) dengan responsiviti dalam julat panjang gelombang 320-360 nm telah dibangunkan berasaskan fotodiod galium nitrida (GaN). Dalam sistem sensor ini, fotodiod GaN dalam keadaan pincang-balikan menukarkan keamatan sinaran kepada arus, yang kemudiannya ditukar dan diperbesarkan kepada voltan output oleh amplifier transimpedans (ATI), atau penukar arus-voltan, yang mengandungi amplifier operasian dan perintang suapbalik. Bagi sumber UL berjalur sempit, keamatan sinaran dapat ditentukan daripada nilai-nilai voltan output, rintangan suapbalik, responsiviti fotodiod dan keluasan berkesan fotodiod. Sensor ini diuji dengan melakukan pengukuran ke atas nilai-nilai berbeza bagi panjang gelombang sumber UL, jarak sumber, suhu ambien dan masa persampelan. Bagi penentukuran dengan sumber UL berjalur lebar, sensor GaN-ULA digunakan secara serentak dengan sensor Si-ULA piawai untuk mengukur sinaran suria. Cerapan hubungan linear antara kedua-dua output sensor membolehkan kita menukar voltan output sensor GaN-ULA kepada keamatan sinaran ULA. Dengan itu, sensor sinaran ultra lembayung A berasaskan fotodiod GaN telah berjaya dibangunkan, diuji dan ditentukurkan dalam kajian ini.

Kata kunci: Amplifier transimpedans; fotodiod GaN; sensor sinaran; ultra lembayung A

INTRODUCTION

The new III-nitride compounds of gallium-nitride (GaN), aluminium-nitride (AlN) and alloy of AlGaN with band gaps of 3.4 – 6.1 eV (corresponding wavelengths of 203 – 365 nm) are potentially attractive materials for the detection of ultraviolet (UV) radiation in the respective wavelengths of 315 – 400 nm (UVA), 280 – 315 nm (UVB) and 100 – 280 nm (UVC) (Chow et al. 2000; Diffey 2002; Dupuis et al. 2008; Monroy et al. 2003; Sandvik et al. 2001; Vasquez & Hanslmeier 2006). Presently, the established silicon-based UV photodetectors and photomultiplier tubes use complex and expensive filters to remove unwanted signals from the visible and infrared spectra. The wider band gaps of the III-nitride compounds and alloys make them intrinsically solar- and visible-blind; and thus do not require filters for the visible and infrared regions. Hence, III-nitride based UV sensors are well suited to the extreme temperature and harsh environments of space, flame and engine monitoring, and military applications (Chow et al. 2000; Sandvik et al. 2001).

Here we describe a newly designed and constructed ultraviolet A (UVA) radiation sensor based on a GaN photodiode. This GaN-UVA sensor is tested by performing measurements for several parameters and calibrated using a standard Si-UVA sensor and solar radiation.

MATERIAL AND METHOD

Our developed UVA radiation sensor consists of a broadband Schottky-type GaN GUVA-T10GD photodiode (PD) supplied by Roithner Laser-Technik, a JFET TL071 operational amplifier (OA) and a feedback resistor R_F (Figure 1). The photodiode of effective area A = 0.076 mm^2 operates in reverse-biased mode and converts the incident UV radiation intensity I_λ of wavelength λ into photocurrent i_λ (Kasap 2001). This setup of OA and R_F defines a current-voltage converter, or transimpedance amplifier (TIA) (Nashelsky & Boylestad 2006), which amplifies and converts i_λ into an output voltage, $V_\lambda = i_\lambda R_F$. The spectral responsivity of the GUVA-T10GD photodiode, $S_\lambda = i_\lambda / P_\lambda$, is at least 0.13 A W^{-1} for λ in the UVA spectrum of 320 – 360 nm, with $P_\lambda = I_\lambda A$ the incident UV power for λ. Thus, for a narrowband UV source, the incident I_λ can be determined by $I_\lambda = V_\lambda/(R_F S_\lambda A)$. However, for a broadband UV source of wider spectrum, the output voltage of the developed GaN-UVA sensor needs to be calibrated to the output of a standard UVA sensor.

To test the developed GaN-UVA sensor in the laboratory, we use a Raytech SE-7228 mercury-type UV lamp as a narrowband UV source emitting λ of 365 nm (UVA) and 254 nm (UVC), with R_F = 15 ± 5% MΩ for the TIA stage. Here V_λ is measured for different UV source wavelength λ, source distance x = 5 – 45 cm, ambient temperature T = 18 – 26°C and sampling time t = 0 – 600 s (10 minutes); with t = 0 when the UV lamp is switched on.

For calibration in broadband UV measurements, i.e. to relate the output voltage to the incident intensity of the UV radiation, the GaN-UVA sensor is used simultaneously with a standard UVA sensor to measure daytime solar radiation, producing respective outputs of V_λ and I_λ. Our standard UVA sensor is a silicon-based PASCO PS-2149 UVA Light Sensor having spectral response at 315 – 400 nm when used with a Schott UG-1 glass filter; and attached to a PASCO GLX Xplorer datalogger. If a linear relationship exists between V_λ and I_λ, then V_λ could be inferred from I_λ. Sensor calibration with solar radiation was performed at Bangi (2.92 °N, 101.78 °E and altitude 50 m) in Malaysia over two time periods – four days of February 2009 and 16 days of May-June 2009. Samplings were made every hour throughout the day from 8 am to 6 pm; and by pointing both UVA sensors either to the sun (for direct radiation) or other parts of the sky (for indirect radiation).

RESULT AND DISCUSSION

Measurement results performed with the developed GaN-UVA sensor are shown in Figure 2. Figures 2(a) and 2(b) show how V_λ varies with T and x with sampling time of t = 0 - 60 s for the respective narrowband UVA and UVC lamp sources of wavelengths 365 and 254 nm. It is seen that V_λ, and thus source radiation intensity I_λ, are not significantly affected by T within the applied range for both UV wavelengths. For this range of T, we observe a power law relationship, $V_\lambda = k/x^n$, with constants k = 35 – 50 and n = 1.81 – 1.92 for λ = 365 nm; and k = 47 – 55 and n = 1.86 – 1.92 for λ = 254 nm. Thus, the GaN-UVA sensor shows that the narrowband UV lamp approximates a radiation point source with an inverse square law, n = 2 (Budde 1983). Figures 2(c) and 2(d) show the variation of V_λ with λ, x, and T when t is extended to 600 s (10 minutes). In general, it is observed that V_λ increases within the first minute of sampling, then reaches a peak at around two minutes and decreases or stabilizes thereafter. This trend is due to the initial warming up of the mercury-type UV lamp and after a while it heats up emitting more infrared radiation and less UV radiation (Zhang & Boyd 2000). Thus, the GaN-UVA sensor is able to monitor the time dependence of the narrowband UV lamp; showing that the UV lamp is a stable UV source within 1 – 2 minutes of it being switched on. Therefore, we are able to characterize a UV source using the developed GaN-UVA sensor in the laboratory controlled condition.

The broadband solar radiation measurements of I_λ for the standard Si-UVA sensor and V_λ of the developed GaN-UVA sensor are plotted in Figure 2(e) for four days of sampling in February 2009 and Figure 2(f) for 16 days of sampling in May-June 2009; with their sample sizes of N and R_F given in Table 1.

For both sampling periods, I_λ is observed to be linearly related to V_λ by $I_\lambda = mV_\lambda + c$. The least squares

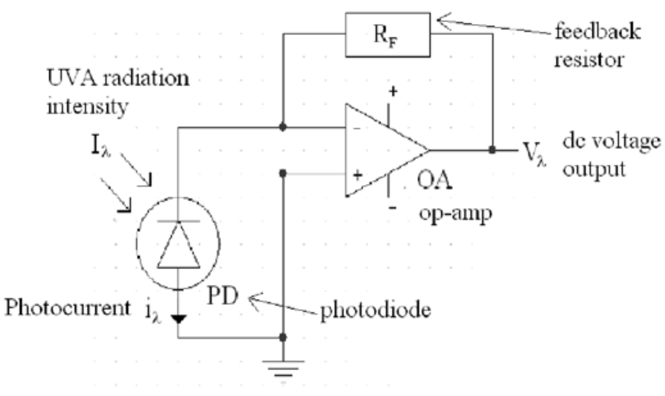

FIGURE 1. Schematic diagram of the developed GaN-UVA radiation sensor

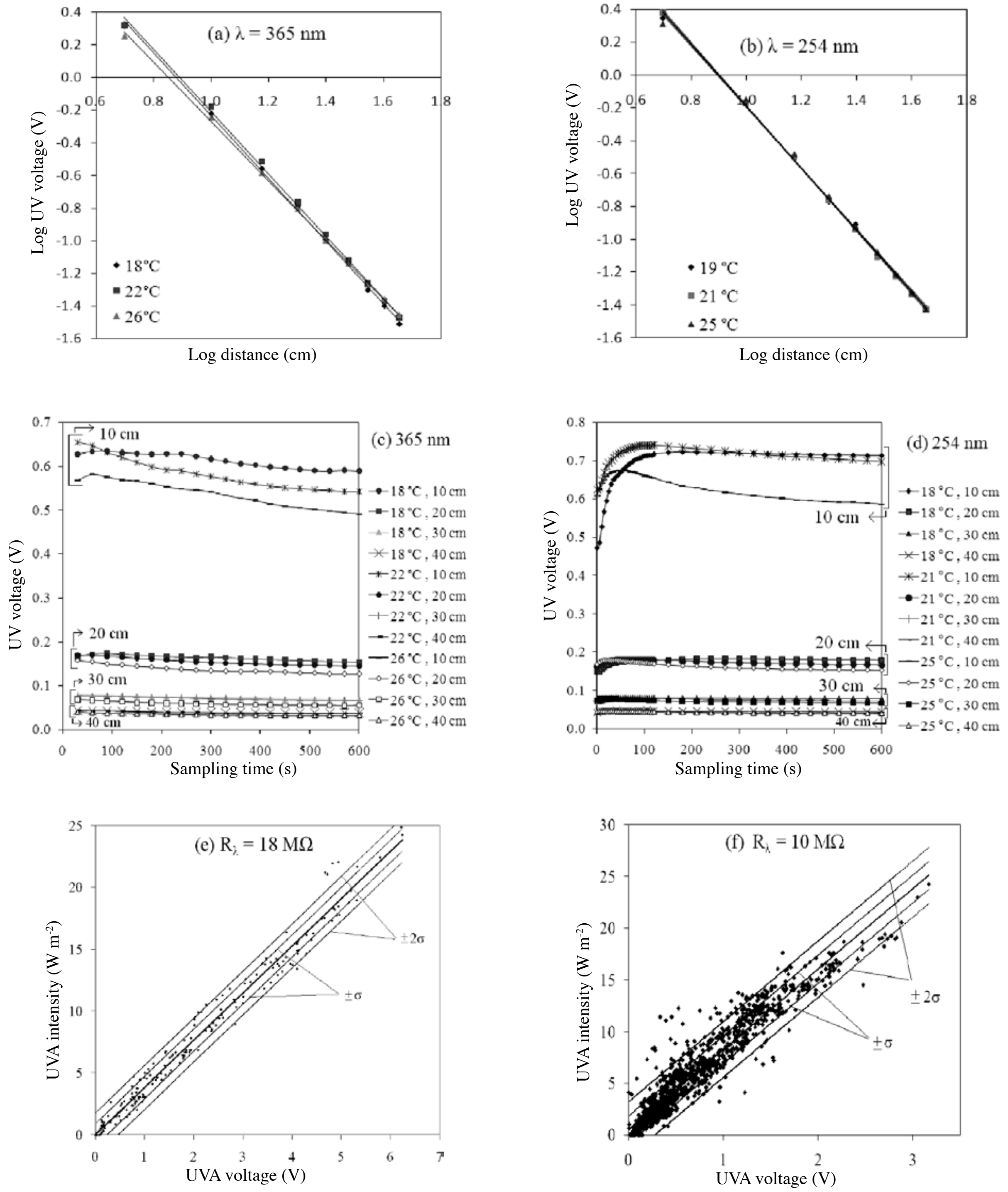

FIGURE 2. Log UV voltage output of developed GaN-UVA sensor, V_λ, versus log source distance, x, for narrowband UV source with wavelengths λ of (a) 365 nm (UVA) and (b) 254 nm (UVC) at ambient temperature, T. The V_λ versus sampling time, t, for λ of (c) 365 nm and (d) 254 nm for varying T and x. Broadband solar UVA radiation intensity of standard Si-UVA sensor, I_λ, versus V_λ of GaN-UVA sensor using feedback resistor R_F of (e) 18 MΩ for February 2009 and (f) 10 MΩ for May-June 2009

fitted regression lines for these relationships are plotted in the figures together with the estimated I_λ error bands of ±σ and ±2σ. The calculated gradient m and intercept c with their uncertainties (standard errors); and correlation coefficient r for the regression lines are listed in Table 1. Here, (e) and (f) refer to the sampling sets of Figure 2(e) and Figure 2(f), respectively; and $I_{\lambda,max}$ and $V_{\lambda,max}$ are the maximum values of I_λ and V_λ. It is seen that c is practically zero; indicating that I_λ is directly proportional to V_λ, or $I_\lambda = mV_\lambda = V_\lambda/(R_F S_\lambda A)$, with $m = 1/R_F S_\lambda A$. We obtain m = 3.82 ± 0.04 W m^{-2} V^{-1} for R_F = 18 MΩ and m = 7.76 ± 0.07 W m^{-2} V^{-1} for R_F = 10 MΩ for the two periods of sampling in

TABLE 1. Linear regression parameters of gradient m, intercept c and correlation coefficient r for the sampling periods of (e) and (f), corresponding to Figures 2e-f. Here N is sample size, R_F is feedback resistor; and $V_{\lambda,max}$ and $I_{\lambda,max}$ are the respective maximum I_λ and V_λ values

	Period (days)	N	R_F (MΩ)	$m \pm \Delta m$ (W m^{-2} V^{-1})	$c \pm \Delta c$ (W m^{-2})	r	$V_{\lambda,max}$ (± 0.001 V)	$I_{\lambda,max}$ (± 0.01 W m^{-2})
(e)	4	191	18 ± 5 %	3.82 ± 0.04	0.0 ± 0.1	0.99	6.244	24.24
(f)	16	1296	10 ± 5 %	7.76 ± 0.07	0.53 ± 0.06	0.95	3.169	24.27

the direct and indirect solar UVA radiation. If only direct solar UVA radiation is considered, the value of m is 7.4 ± 0.2 W m^{-2} V^{-1} for R_F = 10 MΩ (Theyirakumar et al. 2009). By using $I_\lambda = m'(V_\lambda /R_F)= V_\lambda/(R_F S_\lambda A)$, we obtain $m' = 1/S_\lambda A = mR_F$, defined as the inverse responsivity-area, with values of 69 ± 4 and 78 ± 5 MW m^{-2} A^{-1} for the sampling periods of 4 days in February 2009 and 16 days in May-June 2009, respectively. More measurements will be made in future to refine the value of m' and show that this parameter is dependent only on the photodiode parameters of responsivity and effective area. Thus, the observed linear relationship between the standard Si-based UVA sensor intensity and the developed GaN-UVA sensor voltage enables the developed GaN-UVA sensor to be calibrated and used for the intensity measurement of the broadband solar UVA radiation.

Additionally, our measurements show that the peak noon UVA intensities at the tropical location of Bangi are in the range of 20 – 22 W m^{-2}, with a number of instances reaching $I_{\lambda,max}$ of 24 W m^{-2}. These values are comparable to the peak noon UVA intensity of 20.67 W m^{-2} measured in 1994-1995 for nearby Penang in Malaysia (Ilyas et al. 2001).

CONCLUSION

We have constructed an ultraviolet A (UVA) radiation sensor based on a GaN photodiode. The developed GaN-UVA sensor is tested in the laboratory by measuring its voltage output for a narrowband UV source under different parametric conditions of source wavelength, source distance, ambient temperature and sampling time. These measurements show that different UV wavelengths produce different relative intensities, ambient temperature of applied range does not significantly affect the source UV intensity, source UV intensity versus distance follows a power law and source UV intensity changes with time. The developed GaN-UVA sensor is calibrated by performing simultaneous measurement of solar radiation with a standard Si-UVA sensor. A linear relationship between the outputs of these UVA sensors enables us to perform the calibration and thereafter use the developed UVA sensor to measure the intensity of a broadband UVA source such as solar radiation. Hence, an ultraviolet A intensity sensor based on a GaN photodiode has been developed, tested and calibrated.

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