

# Group III-nitride semiconductor Schottky barrier photodiodes for radiometric use in the UV and VUV regions

Terubumi Saito<sup>1</sup>, Toshimi Hitora<sup>2,3</sup>, Hideaki Ishihara<sup>4</sup>,  
Mikihiko Matsuoka<sup>4</sup>, Hisako Hitora<sup>2</sup>, Hiroji Kawai<sup>5</sup>, Ichiro Saito<sup>1</sup> and  
Eiichi Yamaguchi<sup>2,3,5</sup>

<sup>1</sup> National Metrology Institute of Japan, AIST, Umezono 1-1-1, Tsukuba, Ibaraki 305-8568, Japan

<sup>2</sup> ALGAN K.K., ASTEM Bldg. 202, Chudojiminami-cho 134, Shimogyo-ku, Kyoto 600-8813, Japan

<sup>3</sup> Graduate School of Policy and Management, Doshisha University, Karasuma-Imadegawa, Kamigyo-ku, Kyoto 602-8580, Japan

<sup>4</sup> Iwasaki Electric Co, Ltd., Gyoda, Saitama 361-0021, Japan

<sup>5</sup> Powdec K.K., Hagizono 2500, Chigasaki, Kanagawa 253-0071, Japan

E-mail: [t.saito@aist.go.jp](mailto:t.saito@aist.go.jp)

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## Abstract

We have developed Schottky barrier photodiodes of AlN,  $\text{Al}_x\text{Ga}_{1-x}\text{N}$ , GaN and  $\text{In}_y\text{Ga}_{1-y}\text{N}$  grown on n-SiC. Spectral responsivity measurements demonstrate that the devices fabricated have sharp cut-offs with a rejection ratio of over 3 decades and the cut-off wavelength can be varied by changing the alloy or the composition of the alloys. The internal quantum efficiency of an  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  photodiode is estimated to reach 64% around 300 nm. It is also confirmed that the photodiodes do not notably degrade in responsivity to the UV radiant exposure of  $5 \text{ kJ cm}^{-2}$  in contrast to Si photodiodes. Characterization on uniformity, temperature dependence and angular response is also conducted and gives satisfactory results for all items. In conclusion, the Schottky barrier photodiodes of AlN,  $\text{Al}_x\text{Ga}_{1-x}\text{N}$ , GaN and  $\text{In}_y\text{Ga}_{1-y}\text{N}$  work properly as expected and look very promising for precise measurements in the VUV and UV regions.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

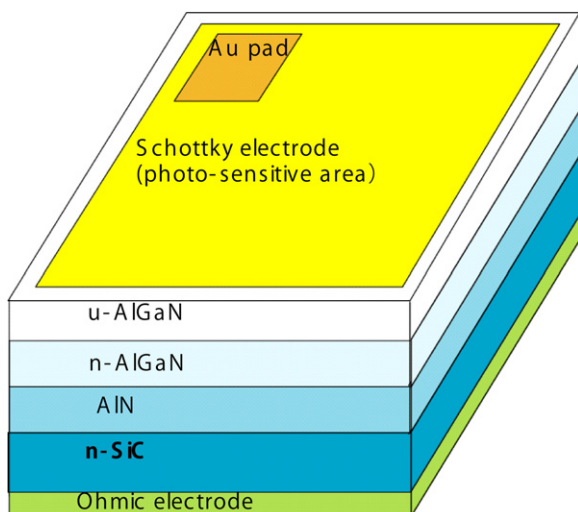
Applications using UV/VUV radiation sources are expanding rapidly in many fields such as sterilization, curing and ashing etc, utilizing the UV characteristics of strong absorption/interaction with any materials. However, strong absorption in this region causes many difficulties especially for photodetectors, such as degradation [1] in responsivity by UV photons and poor uniformity in the UV.

The absorption length (the inverse of the absorption coefficient) of silicon has, over the entire spectral range, the shortest value of about 4 nm [2] at the wavelength of 285 nm. For p–n junction type photodiodes, since the depletion region is located far deeper inside, photogenerated carriers need to reach the depletion region mostly by diffusion to produce the signal.

Therefore, it is known for Si photodiodes that the spectral responsivity steeply decreases below about 400 nm with the increase in the surface recombination velocity [3], which is often caused by intense UV irradiation. This not only requires stronger materials than Si but also makes photodetectors with a shallower sensing region such as Schottky barrier photodiodes more attractive than p–n junction photodiodes.

Another drawback of the use of silicon photodiodes for the measurements in the UV and VUV regions is an unnecessary high and wide responsivity to longer wavelength radiation, which often results in a false signal due to possible stray radiation.

To overcome such problems in the UV and VUV regions, group III-nitride semiconductor [4–6] Schottky barrier photodiodes are considered to be highly promising as wide



**Figure 1.** Structure of the group III-nitride semiconductor Schottky barrier photodiodes fabricated.

bandgap semiconductor devices owing to their potential advantages of solar blindness (insensitivity to visible radiation) and radiation hardness.

For this purpose, we have fabricated Schottky barrier photodiodes based on AlN,  $\text{Al}_x\text{Ga}_{1-x}\text{N}$ , GaN and  $\text{In}_y\text{Ga}_{1-y}\text{N}$  with different compositions aiming to have different cut-off wavelengths. Although Dahal *et al* already reported on the successful fabrication of Schottky barrier photodiodes of AlN grown on n-SiC [7], detailed characterization of radiometric use in a wider spectral range including the VUV has not been reported.

In this paper, we present characterization results on stability to UV radiation, spectral responsivity, its temperature dependence, spatial uniformity and angular response for group III-nitride semiconductor Schottky barrier photodiodes to check whether the detectors meet the requirements for radiometric purposes.

## 2. Schottky barrier nitride photodiodes

Devices under test were group III-nitride semiconductor based photodiodes basically composed of a semitransparent metallic (gold or platinum) Schottky barrier electrode and a photon absorbing semiconductor layer of AlN,  $\text{Al}_x\text{Ga}_{1-x}\text{N}$ , GaN or  $\text{In}_y\text{Ga}_{1-y}\text{N}$ . The detailed structure of our Schottky barrier photodiodes is shown in figure 1. The devices were fabricated by ALGAN K.K. and Doshisha University with collaborative supply of these kinds of semiconductors from Powdec K.K. The total detector area was  $0.5\text{ mm} \times 0.5\text{ mm}$  unless otherwise noted. Exceptionally, we also successfully fabricated Schottky barrier photodiodes of AlN and  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  as large as  $10\text{ mm} \times 10\text{ mm}$  (see sections 3.1 and 3.2 for the results).

All undoped  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  or  $\text{In}_y\text{Ga}_{1-y}\text{N}$  Schottky barrier photodiodes investigated were grown by metal-organic vapour phase epitaxy (MOVPE) on n-SiC. We used AlN thin layers as a buffer layer. For ohmic contacts, Ti/Au layers were evaporated to 280 nm thickness on the back side of the SiC surface. Schottky contacts of Ni/Au or Pt were deposited to a thickness

of 5 nm on the front side of the MOVPE grown  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  or  $\text{In}_y\text{Ga}_{1-y}\text{N}$  to make well-defined Schottky barriers. For  $\text{Al}_x\text{Ga}_{1-x}\text{N}$ , we have succeeded in varying the Al content  $x$  from 0 to 1 and found from photoluminescence measurement that  $E_g$  is equal to 3.4 eV for  $x = 1$  and 3.85 eV for  $x = 0.19$ . We also fabricated  $\text{In}_y\text{Ga}_{1-y}\text{N}$  with  $y$  being 0.05 and found that  $E_g$  is equal to 3.13 eV.

## 3. Characterization methods and results

### 3.1. Spectral responsivity

**3.1.1. Measurement instruments and method.** The devices were characterized in their spectral responsivity in the wavelength range from 120 nm to 500 nm at National Metrology Institute of Japan (NMIJ) and National Institute of Advanced Industrial Science and Technology (AIST).

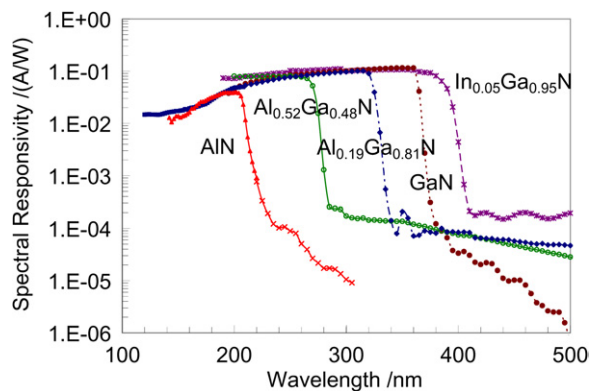
Two measurement instruments were used depending on the measurement spectral range. One is a vacuum system for the VUV region (wavelengths from 120 nm to 300 nm) consisting of a 50 cm focal-length Seya-Namioka type grating monochromator and a deuterium lamp. The spectral full bandwidth at half maximum of the optical beam is approximately 3.5 nm and its half apex angle is 50 mrad.

The other is a system for the wavelength range above 200 nm, which consists of deuterium/halogen lamps, pre-focusing mirror optics, a filter wheel, a Czerny–Turner double grating monochromator having a focal length of 25 cm, post-focusing mirror optics, monitor detectors and a computer-controlled detector stage. The spectral full bandwidth at half maximum of the optical beam is approximately 5 nm and its half apex angle is 10 mrad.

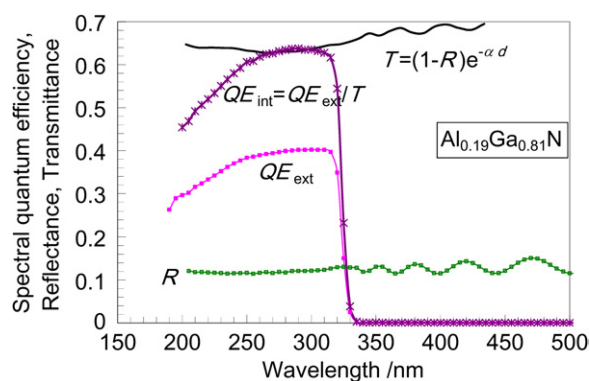
The measurements were carried out by using NMIJ spectral responsivity standard PtSi and Si photodiodes, whose scale had been established based on the NMIJ cryogenic radiometer and spectral extent using a thermopile as a non-selective detector. The scale was cross-checked with another scale that had been realized using an electrical substitution radiometer [8]. The relative combined expanded uncertainty ( $k = 2$ ) in an underfill measurement condition is as follows: 10% to 5.7% for 120 nm to 160 nm, 5.7% to 4.8% for 160 nm to 200 nm, 4.8% to 1.6% for 200 nm to 250 nm, 1.6% for 250 nm to 450 nm and 0.88% for 450 nm to 650 nm.

For all measurements here, the photocurrents were measured in a condition that no bias voltage was applied to the photodiodes and the front side electrode (Schottky electrode) was always grounded to avoid possible photoemission contribution [9, 10].

**3.1.2. Results (external spectral responsivity).** Figure 2 shows the spectral responsivity spectra of AlN,  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$ ,  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$ , GaN and  $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$  in the wavelength range from 120 nm to 500 nm. It is demonstrated that the fabricated devices have sharp cut-offs, and the cut-off wavelength can be changed by changing the alloy or the composition of the alloys. The rejection ratio in the responsivity of the sensitive UV region to the longer wavelengths above the cut-off reaches at least 3 decades for all the photodiodes measured, which



**Figure 2.** Measured spectral responsivity for Schottky barrier photodiodes of AlN,  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$ ,  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$ , GaN and  $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$ .



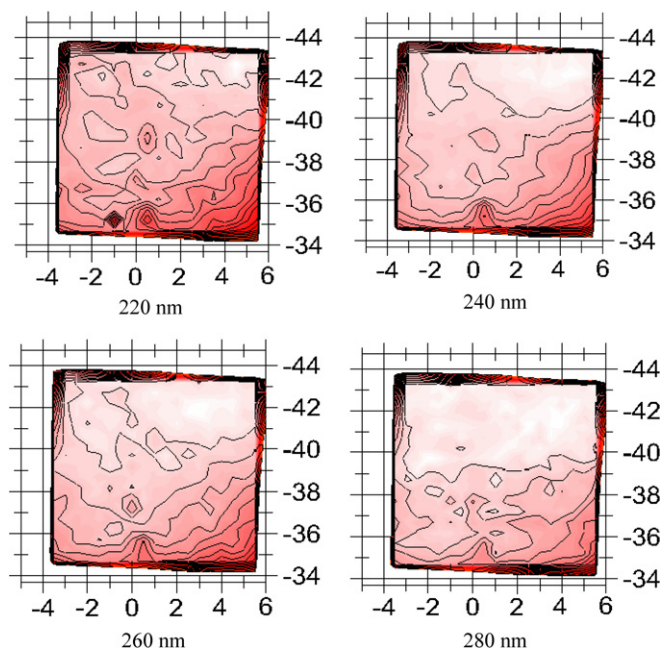
**Figure 3.** Measured external quantum efficiency ( $\text{QE}_{\text{ext}}$ ) and reflectance ( $R$ ) of the  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  Schottky barrier photodiode. Also shown are the estimated transmittance ( $T$ ) and the internal quantum efficiency ( $\text{QE}_{\text{int}}$ ). The transmittance was estimated from the equation using the measured reflectance and the absorption calculated for the 4 nm thick gold overlayer. See the text for details.

shows that the carrier trap density is satisfactorily low, in contrast to the case of highly oriented diamond film based photoconductive detectors [11, 12] although single crystal based diamond detectors [13, 14] were reported to achieve much better performance in the rejection ratio.

**3.1.3. Results (internal quantum efficiency).** To estimate the internal quantum efficiency, measurements for the external quantum efficiency and the reflectance were conducted on an  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  photodiode with the active area size of  $10\text{ mm} \times 10\text{ mm}$ . The results are shown in figure 3. The reflectance spectrum,  $R$ , exhibits oscillating characteristics above the cut-off wavelength corresponding to the bandgap energy due to the interference effect in the AlGaIn layer. We assume that the transmittance,  $T$ , of the Schottky electrode (4 nm thick Au), or the absorption of the AlGaIn substrate, which should be proportional to the spectral responsivity, can be given by

$$T = (1 - R) \exp(-\alpha d),$$

where  $R$  is the measured reflectance,  $\alpha$  the absorption coefficient of Au [2] and  $d$  the thickness of the Au film. Although the equation neglects the interference in the gold



**Figure 4.** Spatial non-uniformity indicated by equi-responsivity contours in 1% steps as a function of the wavelength. The horizontal and vertical axes represent the two-dimensional lateral positions of the device sensing area expressed in millimetres.

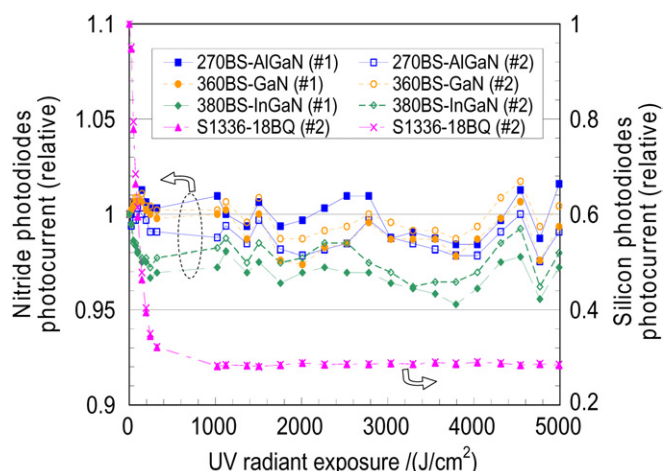
film, it is expected to give a good approximation since the Schottky electrode (4 nm thick Au) is absorptive.

The internal quantum efficiency reaches 64% around 300 nm and decreases as the wavelength decreases. It is highly likely that the deficiency from the unity quantum efficiency can be mainly attributed to surface recombination loss as reported for GaAsP Schottky barrier photodiodes [12, 15, 16]. The high internal quantum efficiency is very promising even in the current situation where the crystal quality of AlGaIn is still poorer than that of Si.

### 3.2. Spatial uniformity

**3.2.1. Method.** For the spatial uniformity measurements, a monochromatized beam from the UV/VIS/IR spectral responsivity calibration instrument at NMIJ was used additionally with the use of an aperture stop and a computer-controlled detector stage. The aperture having a diameter of 1 mm was set 2 mm in front of the detector so that the diameter of the optical beam at the test detector surface was almost the same as 1 mm. The uniformity measurements were carried out by taking photocurrent data as a function of the position in a plane perpendicular to the optical beam axis by controlling the two orthogonal axes of the detector stage.

**3.2.2. Results.** Figure 4 shows the spatial uniformity measurements for the same  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  photodiode also used for the internal quantum efficiency measurements in section 3.1.3 at wavelengths of 220 nm, 240 nm, 260 nm and 280 nm. Each uniformity figure is normalized with respect to the peak responsivity and is shown by equi-responsivity contours at 1% intervals.



**Figure 5.** Stability test results for  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  (denoted by 270BS-AlGaN), GaN (360BS-GaN),  $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$  (380BS-InGaN) Schottky barrier photodiodes and Si photodiodes under irradiation by a low pressure mercury lamp in nitrogen ambient (residual oxygen density: 360 ppm) with a UV irradiance level of about  $14 \text{ mW cm}^{-2}$ . Note that the curves for the Si photodiodes refer to the right ordinate while the others refer to the left one.

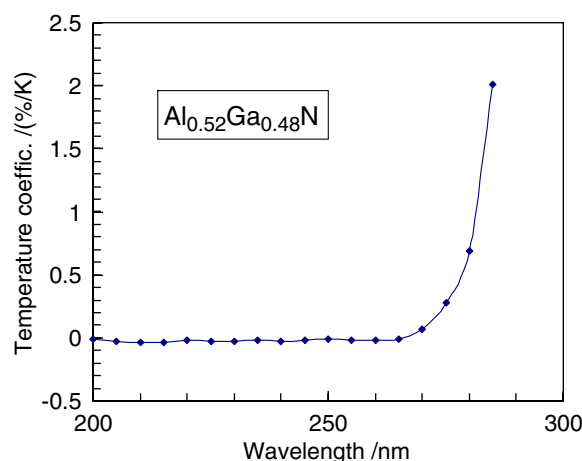
The uniformities at all wavelengths are within  $\pm 3\%$  (peak-to-peak) for more than 90% area, which is reasonably satisfactory although small dips are observed. There is a tendency for the uniformity to become worse as the wavelength decreases. It is likely as a general phenomenon that this tendency correlates with the increase in the absorption coefficient of AlGaIn at the shorter wavelengths.

### 3.3. Stability to UV radiation

**3.3.1. Method.** To test the stability of the photodiodes under UV irradiation, an intense irradiation system using a low pressure mercury lamp installed at Iwasaki Electric Corporation was used. The lamp discharge tube is housed in an aluminium chamber that is filled with nitrogen. The radiation was directly (no window and not monochromatized) irradiated in the flow of nitrogen gas, at the same time, to multiple photodiodes under test which were aligned along the mercury discharge tube.

The irradiances at major emission lines at 185 nm, 254 nm, 365 nm and 436 nm were measured at the beginning of the test to be  $1.97 \text{ mW cm}^{-2}$ ,  $11.2 \text{ mW cm}^{-2}$ ,  $0.38 \text{ mW cm}^{-2}$  and  $1.61 \text{ mW cm}^{-2}$ , respectively, using commercially available UV irradiance meters (Iwasaki EVUV-200 for 185 nm, ORC UV-MO2 for the remaining lines). During the irradiation test for 100 h, outputs of detectors under test and the 185 nm emission monitor detector were recorded in a defined time interval.

**3.3.2. Results.** The measurement results are shown in figure 5. The UV radiant exposure (horizontal axis) was defined as the time integral of the sum ( $14 \text{ mW cm}^{-2}$ ) of the irradiances at 185 nm, 254 nm and 365 nm. During the 100 h irradiation test, the reading of the 185 nm emission monitor (diamond based) was almost kept constant but fluctuated



**Figure 6.** Measured temperature coefficients of the spectral responsivity for the  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  Schottky barrier photodiode as a function of the wavelength.

within  $\pm 1.8\%$ . Although all the tested detector outputs were normalized by this monitor detector, it is highly likely that the source intensity fluctuation was not fully corrected because data sampling was conducted in a serial manner. Considering this, it can be said that all the nitride photodiodes were stable during the test without notable changes. In contrast, silicon photodiodes, which are widely used for precise measurements typically above the wavelength of 250 nm, exhibit steep degradation. The remaining outputs of the Si photodiodes after about  $500 \text{ J cm}^{-2}$  are mostly due to the visible components of the mercury lamp.

### 3.4. Temperature dependence

The dependence of spectral responsivity on temperature was investigated at ALGAN Corporation in the temperature range from  $27^\circ\text{C}$  to  $130^\circ\text{C}$  by using a Peltier device-based temperature controller for some AlGaIn photodiodes. Spectroscopic measurements for the spectral responsivity were carried out in the wavelength range from 200 nm to 350 nm at each temperature.

The temperature coefficient,  $c$  ( $\% \text{ K}^{-1}$ ), was derived according to the following equation:

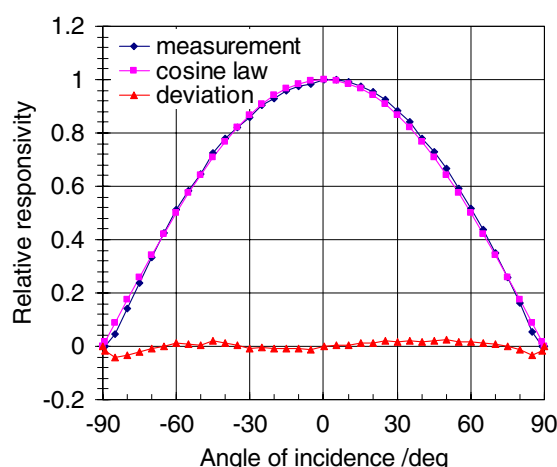
$$c = 100 \times (A_2 - A_1) / (t_2 - t_1),$$

where  $t_1$  is the lower end of the temperature range,  $t_2$  the upper end,  $A_1$  the test detector output at  $t_1$  and  $A_2$  the test detector output at  $t_2$ .

A typical measurement result is shown in figure 6 for the  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  photodiode. Note that the device becomes insensitive above about 290 nm as shown in figure 2. The results show that the temperature coefficients are very small (about  $-3 \times 10^{-4} \text{ K}^{-1}$ ) for the wavelengths equal to or less than 265 nm.

The temperature coefficient becomes positive and rapidly increases as the photon energy approaches the bandgap energy. It can be interpreted that the band gap energy decreases as the temperature increases, thus resulting in the increase in





**Figure 7.** Angular dependence at 260 nm for the  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  Schottky barrier photodiode. Also shown are the ideal cosine-law response and the deviation of the measured response from the ideal one.

responsivity due to the red-shift (to longer wavelengths) of the cut-off wavelength.

### 3.5. Angular response

The angular response was tested at ALGAN Corporation to check if the detector satisfies the cosine law, which is ideally required for irradiance meters. The photocurrent of a test detector was measured under an overfill condition irradiated by a monochromatized beam as a function of the angle of incidence.

Figure 7 shows the result for the  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  Schottky barrier photodiode at the wavelength of 260 nm. The experimental result is very close to the cosine law and this could be explained by the low reflectance as already shown in figure 3. This performance is very satisfactory for irradiance meter applications.

## 4. Conclusions

We have successfully fabricated a wide variety of group III-nitride Schottky barrier photodiodes with cut-off wavelengths from 210 nm (AlN) to 390 nm ( $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$ ).

The spectral responsivity measurements have shown that the out-of-band rejection ratio is over three orders of magnitude for all the photodiodes fabricated. Measurements of the external quantum efficiency and the reflectance have shown that the internal quantum efficiency of an  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N}$  photodiode has been estimated to reach 64% around 300 nm.

The photodiodes have been proven to be very stable and not to degrade during the UV radiant exposure of  $5.0 \text{ kJ cm}^{-2}$  by a low pressure mercury lamp.

The measurements show that the spatial uniformity is less than  $\pm 3\%$  for more than 90% of the active area and improves as the wavelength increases.

The temperature coefficient for the  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  photodiode has been determined to be about  $-3 \times 10^{-4} \text{ K}^{-1}$  at a wavelength equal to or less than 265 nm and rapidly increases with positive sign as the photon energy approaches the bandgap energy.

The angular response of an  $\text{Al}_{0.52}\text{Ga}_{0.48}\text{N}$  Schottky barrier photodiode has been measured at the wavelength of 260 nm. The result is very close to the cosine law and this could be explained by the low reflectance at any angle of incidence.

In summary, the group III-nitride semiconductor Schottky barrier photodiodes have been demonstrated to exhibit a satisfactory solar blindness and an outstanding radiation hardness suitable for radiometric purposes such as irradiance meters, radiant power evaluation of the line spectrum, and so on.

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