High-Sensitivity Visible-Blind AlGaN Photodiodes and Photodiode Arrays

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ABSTRACT

Visible-blind UV cameras based on a 32 x 32 array of backside-illuminated GaN/AlGaN p-i-n photodiodes have been successfully demonstrated. The photodiode arrays were hybridized to silicon readout integrated circuits (ROICs) using In bump bonds. Output from the UV cameras were recorded at room temperature at frame rates of 30-240 Hz. These new visible-blind digital cameras are sensitive to radiation from 285-365 nm in the UV spectral region.

INTRODUCTION

The III-V nitrides have developed rapidly over the past five years. This has lead to the commercialization of blue and green light emitting diodes, along with demonstrations of violet laser diodes and a variety of electronic devices [1-2]. In addition, a number of photodetectors based on photoconductive elements and arrays [3-6] along with junction devices have also recently been reported [7-9].

This paper reports new images from the first successful demonstration of ultraviolet (UV) digital cameras [8] based on an array of GaN/AlGaN heterostructure p-i-n photodiodes. These new (32 x 32 pixel) digital imagers are designed to sense radiation in the 285-365 nm wavelength band in the UV spectral region. Thus, the digital camera is visible-blind but is not solar-blind (250-280 nm). A discussion of photodiode properties is followed by a description of the experimental procedures employed to synthesize, process and study discrete photodiodes and photodiode arrays, and then by the experimental results obtained.

EXPERIMENTAL DETAILS

The photodiode structure employed in the present work is shown schematically in Figure 1. It consists of a base layer of n-AlGaN (~20% Al) followed by an undoped GaN layer and a p-GaN layer. The photodiode structure is deposited by MOVPE onto a

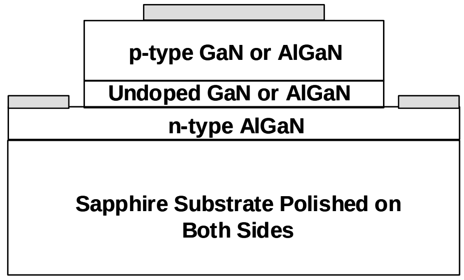

Figure 1 Schematic of p-i-n photodiode structure.

polished sapphire wafer to permit illumination of the device through the substrate. The photodiode structure employed in our initial experiments responds to UV light in the wavelength band from about 320 nm to 365 nm. At wavelengths shorter than 320 nm, the incoming light is absorbed in the thick AlGaN base layer (~20% Al) and the junction is not illuminated. Likewise, the diode does not respond to wavelengths greater than 365 nm, since this corresponds to the optical absorption edge of GaN at 300K. By increasing the Al content of the base layer it is possible to increase the optical bandwidth of the diode's UV responsivity. Likewise, by adding Al to the top layers, it is possible to change the diode UV responsivity band to other wavelength regions in the UV. Thus, UV detectors that sense different UV "colors" are possible.

Diode structures of the type shown were prepared by MOVPE both at North Carolina State University (NCSU) and at the Honeywell Technology Center using low-pressure, vertical-flow MOVPE reactors that employ high speed substrate rotation during film growth. The photodiode structures were deposited onto 2 in diameter c-plane sapphire substrates. The growth was initiated by depositing a thin AlN buffer layer at 500-650 ^{o}C; all subsequent layers were grown at 1050-1080 ^{o}C.

All device processing was completed at NCSU using standard semiconductor processing techniques which included photolithography using appropriately-designed masks, reactive ion etching to define mesa structures, and metallizations to provide ohmic contacts to the n-type and p-type layers of the device.

Spectral responsivity measurements [8] were completed at NCSU on selected discrete photodiodes. The 300K dynamic resistance of the photodiode at zero-bias, R_0, was measured for selected devices using a shielded low-noise enclosure and shielded probe tips. These measurements were combined with the device area A to obtain the R_0A product which was then used to obtain an estimate of the detector detectivity D* [8].
In order to use the GaN/AlGaN photodiodes as the basis for a new visible-blind UV digital camera it is necessary to employ flip-chip bonding techniques to hybridize an appropriately sized photodiode array to a silicon readout integrated circuit (ROIC). In the present case, NCSU designed and purchased a mask set for a photodiode array that matched a 32 x 32 ROIC chip provided by the Night Vision Laboratory (NVL) at Ft. Belvoir. Prior to hybridization at NVL, In bumps were deposited onto each of the mesas and n-contact layers of the photodiode array and onto the corresponding areas of the ROIC using NCSU facilities. Each 32 x 32 GaN/AlGaN photodiode array was hybridized to the silicon ROIC using facilities at NVL and then cemented onto a leadless

chip carrier. Gold wire bonds were then used to link the various input/output channels from the ROIC to the leadless chip carrier. A closeup of a hybridized UV photodiode array is shown in Figure 2 mounted onto a printed circuit board in preparation for testing.

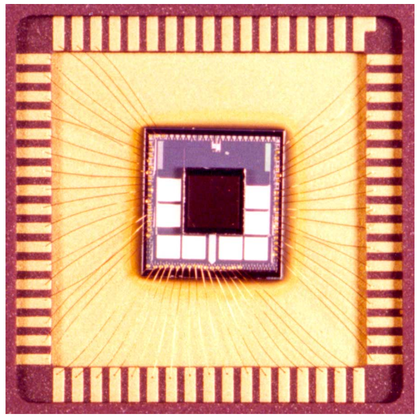

Figure 2 *Photograph of a hybridized UV focal plane array(FPA). The dark square in the middle is the GaN/AlGaN photodiode array which is In bump bonded to the larger ROIC chip. Wire bonds connect the ROIC outputs to the leadless chip carrier.*

The experimental setup used for testing the GaN/AlGaN UV FPAs is shown in Figure 3 below. It consists of an alphanumeric UV source, a quartz focusing lens, the UV digital

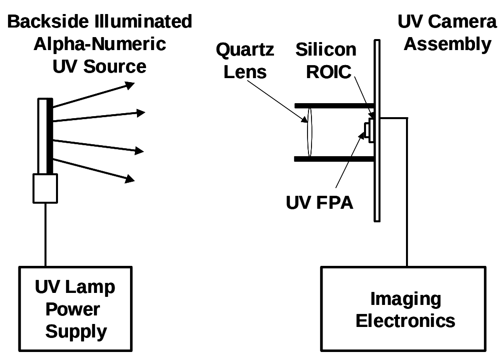

Figure 3 *Experimental setup for testing the UV digital camera.*

camera, and a computerized imaging system [8]. A UV Hg lamp fitted with a fluorescent filter was used as a UV light source. This produced a UV output centered at about 350 nm with a FWHM of ~40 nm. A computer-generated template was then attached to the front of the UV source generating a UV back-lighted scene. A fused quartz lens of focal length 25 mm was used to focus the UV scene onto the AlGaN FPA as shown in Figure 3.

RESULTS AND DISCUSSION

The room temperature spectral responsivity of two discrete AlGaN p-i-n photodiodes is shown in Figure 4. The first device consists of a base n-type layer of $Al_{0.2}Ga_{0.8}N$, an undoped GaN layer, and a p-type GaN:Mg layer. The device has a sharp cut-on beginning at about 365 nm, which corresponds to the optical absorption edge of GaN at room temperature. The responsivity reaches its maximum value of 0.2 A/W at a wavelength of 358 nm, corresponding to an internal quantum efficiency of ~82% [8]. $D^* = 6.3 \times 10^{13}$ cm $Hz^{1/2}W^{-1}$ for this type of UV photodiode. This is one of the largest D* values ever obtained for any semiconductor photodiode at any temperature.

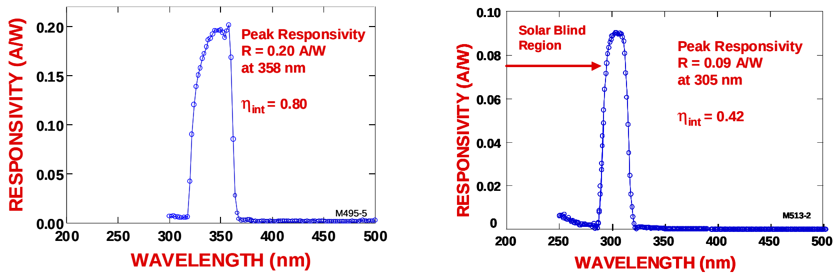

Figure 4. Spectral responsivities for two different p-i-n photodiodes.

The second device consists of a base n-type layer of $Al_{0.33}Ga_{0.67}N$, an undoped $Al_{0.16}Ga_{0.84}N$ layer, and a p-type $Al_{0.16}Ga_{0.84}N$ layer. This photodiode has a sharp cut on at ~320 nm and displays a peak responsivity of 0.09 A/W at 305 nm, corresponding an internal quantum efficiency of ~42%. Its responsivity band covers the region 285-320 nm. $D^* = 2.1 \times 10^{13}$ cm $Hz^{1/2}W^{-1}$ for this type of AlGaN heterostructure p-i-n photodiode.

Photodiode arrays have been successfully fabricated and tested for both of these types of devices. In addition, we have subjected selected devices to light pulses from a xenon lamp and have measured their transient response using an oscilloscope. From these measurements we estimate that the risetime of the nitride photodiodes is about 1 ns and the falltime is less that 1 µs. Thus, they are quite suitable for UV imaging applications.

Initial images from the 32 x 32 UV digital camera have already been reported [8] and will not be reproduced here. Rather, we will report new images obtained from several new UV scenes. The first set of UV images obtained from one of the 32x32 UV camera chips is shown below in Figure 5.

***Figure 5**. Alpha/Numeric images from visible-blind UV digital camera.*

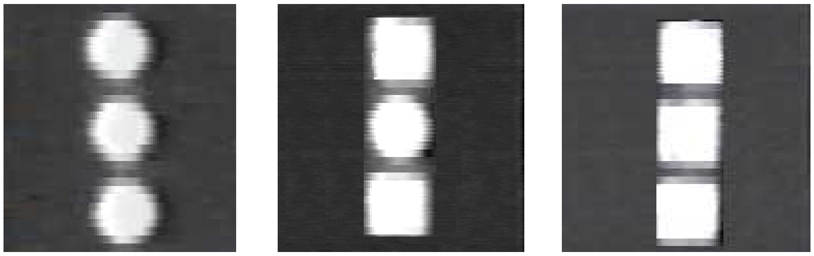

Figure 6 UV images of selected geometric shapes.

In Figure 6, UV images of several sets of geometric objects are shown. It is seen that the squares image reasonably well, but the circles suffer from the coarseness of the 32x32 pixel format.

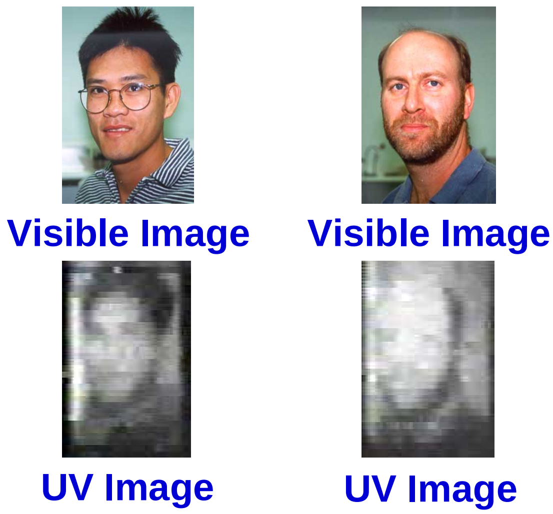

Figure 7 UV images of Dr. Dang (left) and Dr. Benson (right) of NVL

Figure 7 shows images of Drs. Dang and Benson, the UV images are produced with the back-lighting method described earlier. The quality of the UV images are similar to those obtainable from 32x32 pixel arrays of silicon photodiodes. Although the image resolution would greatly improve with the use of UV imagers based on larger 128x128 arrays of photodiodes, the two subjects are readily discernable using the 32x32 arrays.

SUMMARY AND CONCLUSIONS

These UV camera demonstrations represent another historical advancement in opto-electronic devices based on III-V nitride materials. When fully developed into large-format photodiode arrays, this new type of UV digital camera may be used in many wide-ranging applications including biological agent detection, missile and shellfire detection, atmospheric ozone-level detection, welding imagery, and flame sensing. In addition, large-format UV staring FPAs based on nitride photodiodes may play an important role in obtaining UV images of the stars and other astronomical objects of importance in understanding the creation and evolution of the universe.

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