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# Wavelength-Specific Ultraviolet Photodetectors based on AlGaN Multiple Quantum Wells

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***Abstract*—The detection of a specific spectral line in the ultraviolet in presence of broadband ambient lighting is necessary for many applications. We report wavelength-selective photodetection using AlGaN Multiple Quantum Wells grown by Molecular Beam Epitaxy. A near-Gaussian photoresponse peak at 300nm with a width of 17nm was achieved in the lateral photocurrent, along with a much faster transient response compared to devices based on bulk AlGaN. The wavelength selectivity, controlled by the formation and subsequent splitting of excitons, was achieved by optimization of the alloy properties of the barrier layers, reducing the leakage of photogenerated carriers into the active region.**

***Index Terms*—Optoelectronic devices, Semiconductor growth, Photoconductivity, Quantum wells**

## I. INTRODUCTION

The detection of Ultraviolet (UV) light is important for a large number of applications in both civilian and military domain. Limiting the photodetection within a narrow UV spectral range is necessary for selectively sensing relatively weak spectral lines in presence of broadband ambient illumination. This is useful in various fields such as environmental monitoring, fluorescence imaging and identification of chemical and biological agents, and detection of high temperature flames. Photomultiplier tubes show sensitivity in the UV but are relatively bulky and vulnerable to mechanical shocks. Silicon based photodetectors show a drastically reduced sensitivity below 300nm due to the presence of surface states. Furthermore, all of these detectors are broadband, and can be made wavelength specific only in conjunction with complex multilayer optical filters.

Detectors based on wide band-gap semiconductors can be made to specifically detect UV radiation by careful tuning of the energy band-gaps. Solar blind photodetectors based on AlGaN alloys have been reported by a number of groups [1, 2], with detectivity specific to the wavelength range around 280nm. These structures typically are in the p-i-n configuration with the layer initially deposited on the substrate (typically n-AlGaN) acting as a window layer designed to absorb higher energy photons before they reach the active region. Since the wavelength selectivity of these detectors are controlled by the absorption edge of the window layer and the active (intrinsic) layer, the width of the window of sensitivity cannot be made very narrow due to the presence of strong band-tails observed in AlGaN alloys.

In this paper we report on the development of sharply wavelength specific ultraviolet detectors based on lateral transport in AlGaN based quantum wells.

## II. EXPERIMENTAL METHODS

We have employed Molecular Beam Epitaxy method, using a VEECO Gen 930 system for the growth of all AlGaN Multiple Quantum Well (MQW) structures. Standard effusion cells were employed for the generation of molecular beams of Ga, Al and In, and an RF plasma source was used for the generation of active nitrogen. The growths were carried out on single side polished c-plane sapphire substrates using an AlN buffer layer. Prior to deposition the substrates were outgassed at 500°C at a vacuum level of $10^{-9}$ T. For all growths, a three step process was used. Initially the substrate was nitridated at 800°C, i.e. the $Al_2O_3$ surface was exposed to the nitrogen plasma (400 Watt) till the Reflection High Energy Electron Diffraction (RHEED) pattern corresponding to AlN was observed. Subsequently, an AlN buffer layer was deposited at a substrate temperature of 800°C, using a plasma power of 350 Watts. A modified version of the Migration Enhanced Epitaxy (MEE) process was employed, where the arrival rates of Al and Nitrogen are modulated to control the diffusion speed of the adatoms on the growth surface [3, 4].

Two types of photodetector structures based on bulk AlGaN films and AlGaN MQWs, were investigated in this work.

TABLE I
SAMPLE DESCRIPTION

| Sample ID | Active Region is based on: |
|---|---|
| *B1* | $Al_{0.35}Ga_{0.65}N$ film 200nm thick |
| *MQW1* | Wells: $Al_{0.35}Ga_{0.65}N$ (1.5nm),<br>Barrier: $Al_{0.55}Ga_{0.45}N$(2nm), 20 pairs |
| *MQW2* | Wells: $Al_{0.35}Ga_{0.65}N$ (1.5nm),<br>Barrier: $Al_{0.55}Ga_{0.45}N$ (2nm), 20 pairs<br>Indium flux was present during growth |

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Their growth conditions were identical except for the configuration of the active region, as shown in Table I.

The deposited structures consist of a bulk $Al_{0.35}Ga_{0.65}N$ layer ~320nm thick, onto which a set of 20 quantum wells were grown, with well composition identical to that of the underlying bulk film, and barrier containing nominally 55% AlN mole fraction. During the growth (at 800°C) of some of the quantum well structures (MQW 2), a flux of Indium was made incident on the growth surface. However, as Indium has a very high vapor pressure at 800°C, it is expected to have minimal sticking probability and will only modify the surface diffusivity of Al and Ga adatoms [5,6]. The growth rate of these samples has been calculated to be 45 Å/min.

Post growth the samples were characterized by X-Ray Diffraction (XRD), Transmission Electron Microscopy (TEM), optical transmission, room and low temperature photocurrent measurements. Tecnai 20 G2 (200 keV) analytical TEM instrument was used to carry out cross-sectional TEM studies. Electrical contacts were formed for lateral transport using Indium that was deposited on to the top surface. No further annealing or passivation steps were carried out in order to lessen the degree of complexity of the system and thereby promote a clear understanding of the underlying physical processes. The samples were illuminated by a 30W De lamp dispersed by a 0.5m Monochromator, and the photocurrent was measured under constant DC bias. The temperature-dependent photocurrent measurements were carried out in a closed cycle cryogenic workstation, operating between 10 and 300 K.

The schematic of the detector device is shown in Figure 1(a). It indicates the various layers employed and Indium contacts were employed as metal-semiconductor contacts. After the deposition of the nucleation layers that are highly defective due to large lattice mismatch, a thicker AlGaN layer is deposited to spatially separate it from the active layer that will determine device properties such as sensitivity and speed. For some of the samples, the deposition process was terminated at the bulk AlGaN layer to be used as benchmarks, and for the rest a set of quantum wells were deposited on top. The active region consists of 20 pairs of quantum wells, where the well and barrier compositions were $Al_{0.35}Ga_{0.65}N$ and $Al_{0.55}Ga_{0.45}N$ respectively. Their thicknesses were nominally 1.5nm and 2nm respectively.

## III. RESULTS AND DISCUSSION

Fig. 1(b) shows a cross sectional transmission electron micrograph of the sample whose schematic is shown in Fig. 1(a). As expected, we can observe a large number of threading dislocations in the nucleation layers which then propagate vertically. It should be noted that while there is a reduction of the dislocation density during the deposition of the bulk AlGaN film, the starting of the MQW deposition further reduces the dislocation density strongly by bending them away from the vertical and hence causing them to annihilate through recombination with other dislocations. This makes the active region relatively defect free.

The TEM image (Fig. 1(c)) shows the quantum wells in higher magnification. As can be observed, the interface quality is quite high and all the 20 pairs can be clearly discerned. Also, the thickness of the well and barrier material is close to the target values, which indicate the robustness and precision of the deposition system.

The photodetector devices based on bulk AlGaN film and the MQW samples grown with or without the presence of Indium flux were tested for their spectral response. The device based on the bulk AlGaN film with 35% AlN mole fraction showed a response given in Fig. 2(a). A sharp absorption edge can be clearly observed. More importantly, a sharp peak can also be observed near 300nm, which is due to excitonic transitions in the material. This peak is red-shifted by ~210meV from the absorption edge measured by optical transmission measurements. A band tail extending up to 360nm is also observed, which can be attributed to either alloy disorder [7,8] or due to the Urbach edge from the excitonic transition. The photoresponse from the devices based on MQWs grown with and without an Indium flux show a significantly enhanced excitonic peak as shown in Fig. 2(c) and 2(b) respectively. This is because of the higher probability of formation of the exciton due to quantum confinement in the wells.

The excitonic peak in the MQW samples is broader, due to the small variation of the eigen energy states of the 20 individual quantum wells. This happens as the alloy composition of the well and barrier materials show

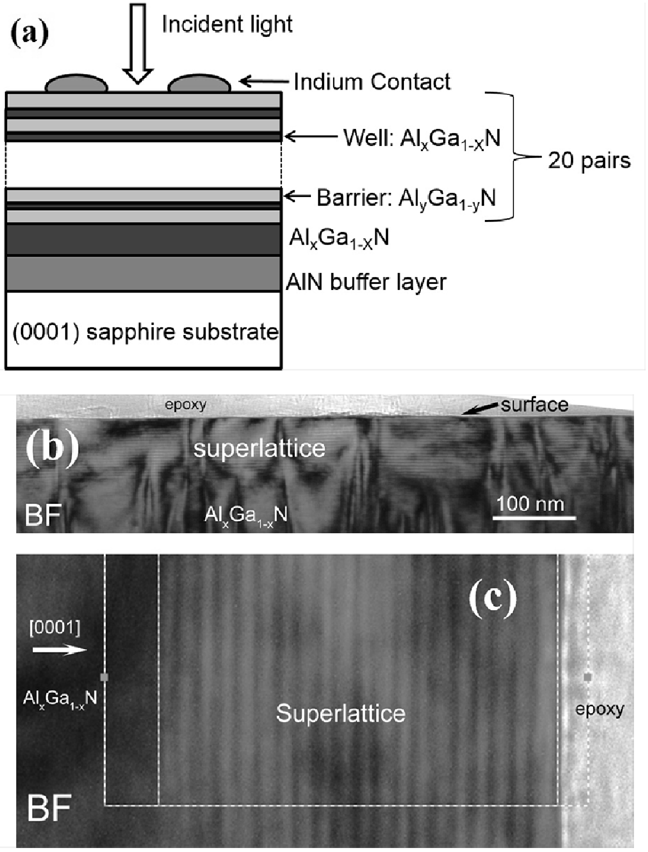

Fig. 1. (a) Schematic of the photodetector, (b) Cross sectional TEM image of the entire structure, (c) TEM microscope image of the MQW region.

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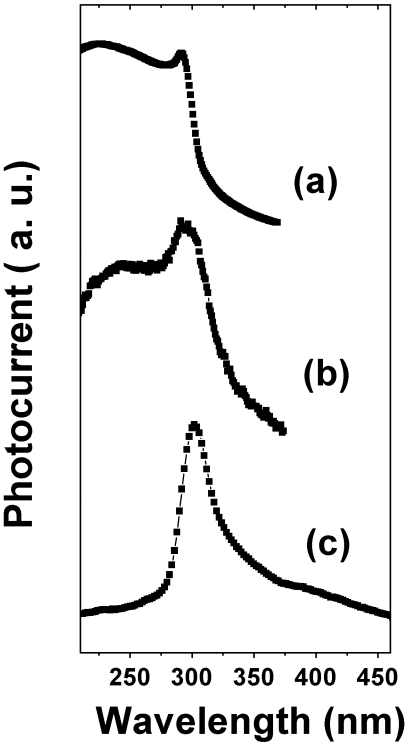

Fig. 2. Photocurrent spectrum of photodetectors based on (a) bulk AlGaN (B1) and AlGaN/AlGaN MQWs grown with (MQW2) (c) and without (MQW1) (b) an Indium flux.

inhomogeneity as has been reported extensively in the literature [9]. In addition, interface roughness of the order of one monolayer may be present even though the TEM data shows nearly uniform thicknesses. All of this broadens the excitonic transition energy compared to a bulk material as shown in Fig. 2(a). A high energy shoulder is also observed in the spectra of the MQW sample grown without Indium flux (MQW1) in addition to the excitonic peak (Fig. 2(b)), and we attribute it to carriers photogenerated in the bulk AlGaN underneath the MQW that may leak into the active region and thus contribute to the photocurrent. As shown in the device schematic, the total thickness of the well and barrier region is only 70nm, which is too thin to completely absorb the entire incident light. Therefore photogeneration of carriers also occur in the bulk AlGaN underneath; and these carriers can diffuse back into the well region where they get swept away by the electric field to add to the photocurrent. The leakage of carriers is facilitated by the alloy fluctuations in the barrier layer which reduces the carrier confinement. The higher Al-content of the barrier layer (50% AlN mole fraction) makes it more prone to exhibit potential fluctuations. This has been attributed to the lower mobility of Al adatoms on the growth surface [10] or due to statistical fluctuations [8].

For the quantum wells grown with an Indium flux in the active region (MQW2), a single peak can be observed in the UV photoresponse spectrum, as shown in Fig. 2(c). This peak, which is centered at 300nm, shows little photoresponse at higher or lower energies. It has been shown that the presence of Indium during growth reduces amplitude of the alloy fluctuations by affecting the surface mobility of Ga and Al during deposition [6,11]. Thus, the high energy shoulder in the photocurrent spectrum due to leakage of carriers from the bulk material is absent as the electron-hole pairs that are generated in the bulk AlGaN are unable to penetrate the barrier layer separating the bulk from the MQWs, which in this sample have a reduced compositional fluctuation. The peak position is determined by the energy of transition between the quantum states of the MQW, modified by the formation of exciton, which red-shifts the peak. It should be noted that the photoresponse spectra can be fitted to a Gaussian curve with FWHM of around 17nm. There is a slight asymmetry in the peak, and a weak longer-wavelength shoulder can also be observed, probably arising from point defects associated with threading dislocations. This can be minimized by employing a thicker underlying AlGaN layer, thereby reducing dislocation densities.

The photoresponse of the Metal-Semiconductor-Metal (MSM) detector over a wider wavelength range is shown in Fig. 3. As indicated in the figure, a single sharp peak is observed throughout the entire range indicating its importance in various applications where detection of a specific spectral line in the UV is necessary in the presence of a broad energy spectrum. The inset shows the I-V characteristics of the MSM diode with and without incident UV radiation. From the nature of the curve (which is symmetric, and only the first quadrant is shown), we can see a typical back-to-back diode behavior.

The arresting of carriers photogenerated in the bulk AlGaN layer away from the well region and thereby nullifying their contribution to the photocurrent is also corroborated by a significant improvement of the transient response of these devices (MQW2). The bulk AlGaN layer has been studied by low magnification Bright Field and Weak Beam Dark Field (WBDF) TEM, and the images show a density of threading dislocations of around $2x10^{10}$ $cm^{-2}$ close to the buffer layer.

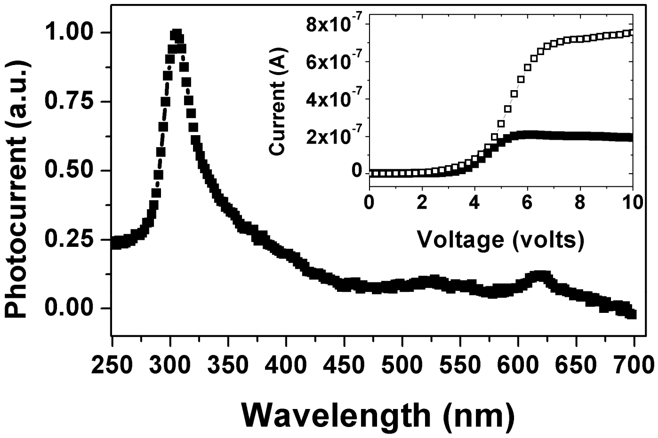

Fig. 3. Full-range Photoresponse of photodetector MQW2; (Inset: I-V characteristics with and without UV excitation).

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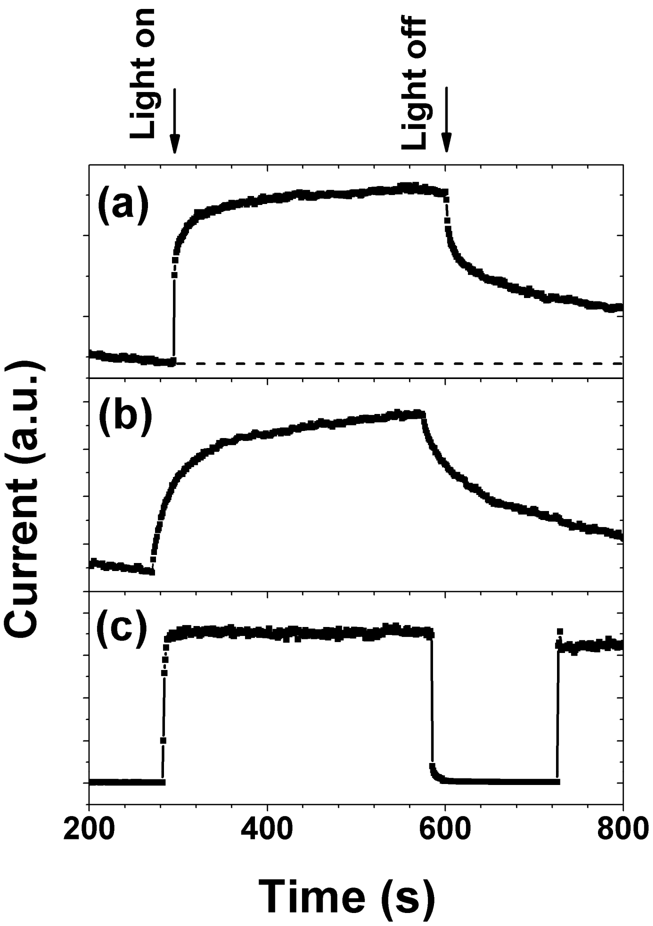

Fig. 4. Transient photocurrent of photodetectors on (a) bulk AlGaN (B1) and AlGaN/AlGaN MQWs grown with (MQW2) (c) and without (MQW1) (b) an Indium flux.

A large number of point defects are associated with these threading dislocations, which trap the photogenerated carriers and can lead to photocurrent transients lasting several hours even at room temperature [12,13]. Long persistence can be observed in devices based on AlGaN bulk films (B1), as shown in Fig. 4(a), where the region near the buffer layer is highly defective and thus prone to trapping of charges. Similar results are also evident in Fig. 4(b) for MQWs grown without the presence of an Indium flux, where carriers thermally detrapped from the bulk AlGaN can diffuse back into the well region, leaking through barriers that show strong potential fluctuations. These carriers can be further trapped at well-barrier interfaces which make the initial decay even slower for the MQW1 sample compared to the bulk.

For MQWs grown with an Indium flux we can see a significantly improved transient response with a sharp turn on and turn off behavior, as the carriers in the underlying bulk AlGaN region, when de-trapped, are not allowed to leak into the well region because of reduced alloy fluctuation in the barrier layer as evident from Fig. 4(c).

It may be relevant to note here that the formation of 2D electron and hole gases due to spontaneous and piezoelectric polarization effects may play a role. The generated electric fields would tend to cause a lateral segregation of the electrons and holes to the two ends of the MQW, but this effect is not expected to be significant given the thinness of the well layers [14]. More studies are however required to come to any specific conclusion.

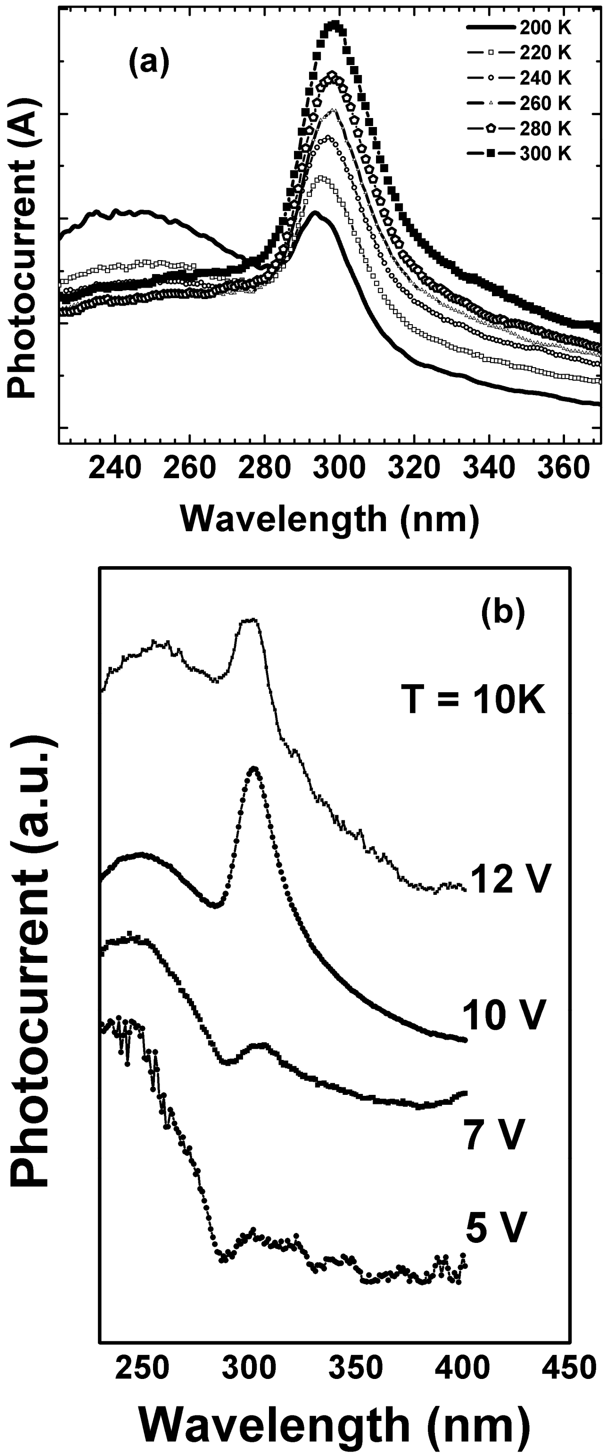

Fig. 5. (a) Temperature dependent PC spectra of photodetector MQW2 taken with bias voltage of 12V, (b) PC spectra of MQW2 for different bias at 10K.

The generation of lateral photocurrent in the MQWs is linked to three major processes- the creation of electron-hole pairs, the formation of excitons, and the subsequent splitting of the excitons by the applied electric field to allow the transport of carriers. The excitonic processes play a strong role in the generation of the narrow peak in the spectral response of these devices. In order to establish the role of excitons, we have carried out photoresponse measurements at low temperatures and the results are presented in Fig. 5(a). We can see that the peak intensity of the photoresponse at a fixed bias of 12V decreases significantly with reduction in temperature. This is due to the reduced probability of the splitting of the exciton which is necessary for the formation of photocurrent. This is complimentary to photoluminescence measurements in these structures, which show a strong increase in intensity and increased stability of the exciton at cryogenic temperatures. At low temperatures, the photocurrent from the bulk AlGaN dominates, showing a distinct hump at ~250nm. For shorter wavelengths the photocurrent decays due to surface recombination.

The splitting of the excitons by the applied voltage is further established by our photocurrent measurements at 10K. It can be observed in Fig. 5(b) that the peak of the photoresponse is absent for lower voltages where the field is not strong enough to split the exciton. With the increase of applied bias from 5 to 10 Volts, the intensity of the peak is strongly increased. This effect saturates for higher applied voltages.

## IV. CONCLUSIONS

Wavelength specific ultraviolet photodetectors have been developed with a narrow band sensitivity peaked at ~300nm with a nearly Gaussian sensitivity profile and an FWHM of 17nm. The detectors are based on lateral transport in AlGaN MQWs, which has been specially designed to reduce the compositional inhomogeneities in the barrier layer to arrest diffusion of carriers from the bulk AlGaN underneath. This process also enhances the switching speed in the device, significantly reducing long transients that are typically observed in these materials.

In addition, the photodetectors developed are designed for illumination from the epitaxial side, in contrast to solar-blind PIN photodetectors which depend on the use of a transparent substrate for their wavelength selectivity. This will allow the growth to be carried out on to low cost and large area substrates like Silicon, thereby making these devices appropriate for commercial production.

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