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Characterization and Modeling of Photoconductive GaN Ultraviolet Detectors

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Abstract

In this work high gain GaN photoconductive UV detectors have been fabricated and characterized, and a novel gain mechanism, dominant in these detectors, is described. DC responsivities higher than 10^3A/W have been measured for an incident power of lW/m^2 at room temperature. The photoconductive gain depends directly on the bias voltage and scales with incident power as P^{-k} ($k \approx$ 0.9) for more than five decades. A decrease of both gain and *k* parameter with temperature has also been observed. As a consequence of the slow non-exponential transient response, AC gain measurements result in lower values for gain and *k* parameter, which are frequency dependent. The high responsivity, non-linear behavior and slow non-exponential transient response, are all modeled taking into account a modulation mechanism of the layer conductive volume. Such spatial modulation is due to the photovoltaic response of the potential barriers related to the surface and charged dislocations arrays.

1. Introduction

Considering current advances in nitride technology, GaN is the most promising semiconductor for photodetection in the ultraviolet (UV) region of the spectrum [1]. Its direct wide bandgap makes it suitable to develop efficient visible blind sensors [2]. Taking into account its superior radiation hardness and high temperature resistance, this material is suitable for devices working in extreme conditions. Moreover, the $Al_xGa_{x-1}N$ system should enable to develop UV detectors with a cut-off wavelength tunable from 366nm to 200nm [3] [4]. Applications range from space communications to ozone layer monitoring or flame detection.

Photocoductive GaN detectors have early attracted a significant interest [5] [6] [7] [8] [9]. For their simplicity, they are candidates as low cost UV detectors in consumer and environmental applications. Their high responsivity would enable their use without any preamplifier stage. Some of the characteristics of GaN photoconductors have been reported. There is a general agreement on the presence of an abnormally high responsivity [5] [6] [9] and persistent photoconductivity [7] [10] [11], which have been tentatively attributed either to deep levels [9] or to Mg-doping related centers [8]. A frequency dependence of the responsivity has also been detected [7] [11]. Reported data also indicate a very non-linear behavior, with a photoconductive gain decreasing with the optical power [5] [7]. In this work we present a study of the physical mechanism of photoconductive gain in GaN epitaxial layers, and the computer implementation of a novel model that matches our experimental results quite precisely.

The photocurrent (I_{ph}) in semiconductor photoconductive detectors is described by the equation [2]:

$$I_{ph} = \frac{q\lambda}{hc} GP$$

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where q is the electron charge, P is the incident power and G is the photoconductive gain (number of electrons detected per incident photon). This last parameter is determined by the characteristics of the material and the configuration of the detector. The detector current responsivity is defined as $R = I_{ph} / P$.

2. Devices and experimental

Our devices consist of non-intentionally-doped wurtzite GaN epitaxial layers grown on sapphire by MOVPE [12] and on Si(111) substrates by gas-source MBE [13]. AlN buffer layers were used in both cases. Ti/Al or In contacts were deposited, leaving a free surface between contacts of about $1mm^2$. The measurement circuit consists of a DC voltage source connected to the photoconductor in series with a small sense resistor. The photocurrent induced in the device is obtained by measuring the variation of the voltage drop in the resistor under illumination conditions. In all the measurements the bias voltage was held at 5V, unless indicated.

The characterization of the DC responsivity with incident optical power has been performed by using a non focused He-Cd laser (325nm) as excitation source. Special care was taken to determine the dark current, waiting for long periods of time (hours). For spectral responsivity studies the sample was illuminated using a 600W globar (quartz-tungsten) lamp and a Jobin-Yvon H-25 monochromator. The optical system was calibrated using detectors with known spectral responsivities and the photocurrent was normalized to allow for the lamp emission intensity variation as a function of wavelength. The normalization was performed taking into account the dependence of the sample response on incident power, previously analyzed.

3. Results

Responsivities higher than 10^3A/W were obtained for an incident irradiance of $1W/m^2$ at room temperature. The photoresponse follows a non-linear behavior, with a photoconductive gain that decreases with incident power as P^{-k} ($k \approx 0.9$) for more than five decades, as it is shown in figure 1. The same dependence is observed when illuminating with photon energies below the gap; this result has been confirmed by performing the same study with the 514nm and 488nm lines of an Ar laser (see inset of Figure 1). A decrease of both gain and *k* parameter with temperature has also been observed.

Figure 2 shows the spectral responsivity of the detector at room temperature. The responsivity starts to rise for photon energies of about 2.5eV, and reaches its maximum at 3.42eV. The response to illumination below gap is justified by the photoionization of defect levels located 1eV over the valence band [14]. The sharp peak at 3.42eV is attributed to the free exciton A, which domines the photoluminescence spectra of these samples at room temperature (see inset of Figure 2). This excitonic peak was previously detected by Manasreh [15] in optical absorption studies, and its presence in current responsivity spectra is reported for the first time.

On the other hand, all the samples show a non-exponential transient response, which is specially slow when switching off the illumination (see Figure 3). In this sense, our experimental data agree with the studies performed by Kung [7] and Qiu [10] [11]. As a consequence of this long recovery time, AC gain measurements result in lower values of both gain and *k* parameter, as shown in figure 4. Therefore, there is a dependence of photoconductive gain on frequency which prevents obtaining information about the gain mechanism from AC measurements. These results explain the data reported by Kung [7] and by Binet [9] on similar GaN devices.

4. Model and discussions

Classical models define the photoconductive gain as

$$G = \frac{\tau}{t_t} \eta$$

where η is the quantum efficiency, τ is the excess carrier lifetime and t_t is the transit time of electrons between the ohmic contacts. This transit time can be calculated as:

$$t_t = \frac{L^2}{\mu_e V}$$

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where L is the detector length, μ_e is the electron mobility and V is the voltage drop between contacts. Thus, the photoconductive gain should be linearly dependent on bias voltage, which is in perfect agreement with our measurements. However, the dependence of the photocurrent on the incident power (figure 1) can hardly be explained with such a simple model. For this reason, a novel gain mechanism based on a modulation of the GaN layer conduction volume is proposed to explain such results.

The high responsivity, non-linear behavior with incident power and the slow non-exponential transient response observed in GaN photoconductors have been successfully modeled taking into account the modulation of the device effective conduction area by the space charge regions related to surface and dislocations. Photons above the gap generate electron-hole pairs, and these holes are trapped by surface or dislocation related states. Illumination below gap photoionizes electrons from these defect levels, which are separated from the localized capture centers by the electric fields involved. Once in the dark, the extra free electrons have to cross the potential barrier that separates them from their capture centers, what implies a very slow transient response. During this process, the height of the potential barriers is a function of the remaining free carrier concentration, which results in a time-dependent lifetime and a non-exponential behavior. The proposed model has been implemented in detail by computer simulation, achieving a good fitting with the experimental photoconductance decays (see Figure 3).

The slowness of the change of these space charge regions has also been checked by analyzing the variation of the capacitance of GaN Schottky diodes with illumination. Au Schottky contacts were deposited on the same samples used for photoconductors, and the variation of the capacitance was studied when switching on and off the light for wavelengths above and below gap. As a result, slow non-exponential transient responses were recorded, showing the same characteristics than the current transient response of photoconductors. This data support the idea of considering the width modulation of the space charge regions as responsible for the slowness of GaN photoconductors.

The effect on the value of the photocurrent is shown in the following equation:

$$\Delta I = I_{light} - I_{dark} = V\frac{q\mu_e}{L}\left[(n+\Delta n)(A+\Delta A) - nA\right]$$

where Δn is the excess of free electrons and ΔA is the variation of the conduction area. Under conditions of low injection ($\Delta n << n$), as it is the case, the photocurrent is given by:

$$\Delta I \approx V\frac{q\mu_e}{L} n\Delta A$$

Applying this approximation we obtain values of gain similar to the ones measured. The calculated dependence of gain with irradiance and temperature are shown in figure 5.

The importance of these surface band-bendings in photoconductance spectroscopy of thin layers has recently been reported by Izpura et al. [16]. These photovoltaic effects can be dominant and, in some cases, responsible for the persistent photoconductivity effect observed in n.i.d. and Mg-compensated GaN samples [7] [10] [11].

5. Conclusions

We report a detailed characterization of GaN photoconductive detectors, together with a novel model which is able to describe the basic behavior of these devices. The high responsivity, slow non-transient responses and the dependence of gain on incident power, temperature and frequency can all be explained by taking into account the modulation of the sample conductive volume by the space charge regions related to surface and dislocations.

Acknowledgments

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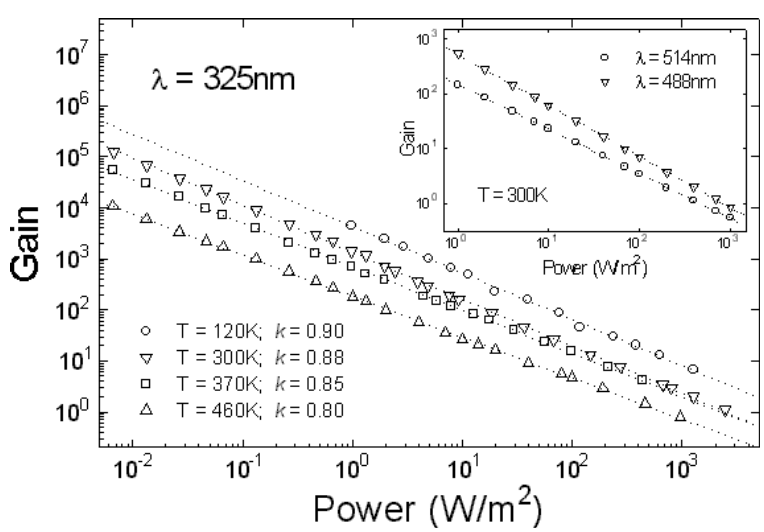

Figure 1. Photoconductive gain as function of the incident power and temperature.

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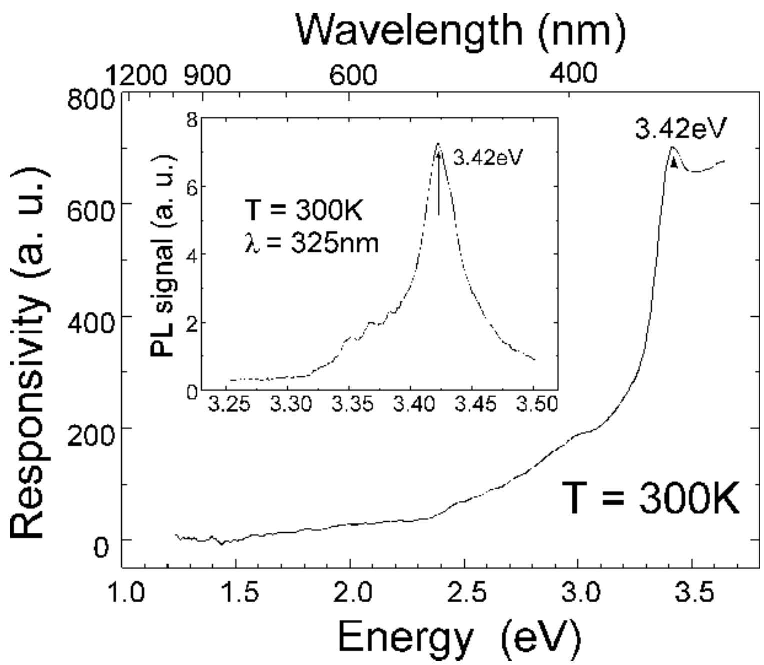

Figure 2. Spectral response of the photodetector at room temperature. The peak at 3.42eV is attributed to the free exciton A. The inset shows the photoluminescence spectrum of the sample at room temperature.

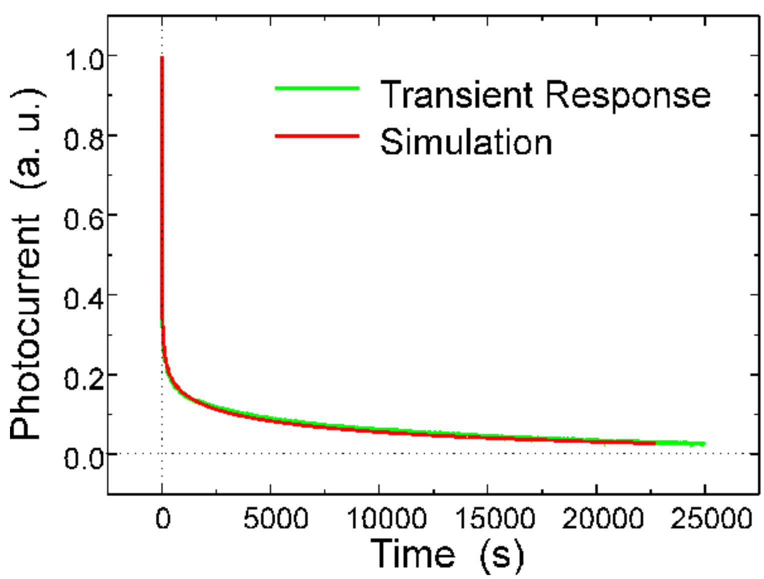

Figure 3. Temporal response of the photodetectors and its computer simulation.

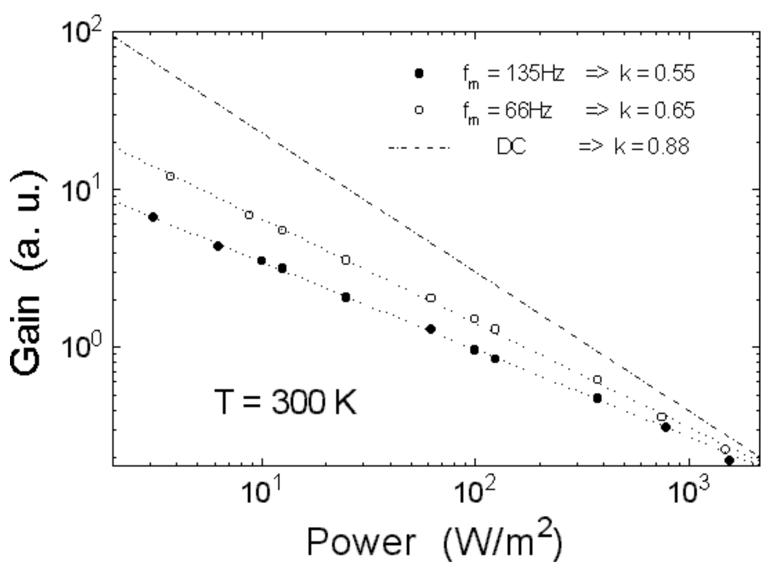

Figure 4. Effect of frequency on the gain vs. incident power curve.

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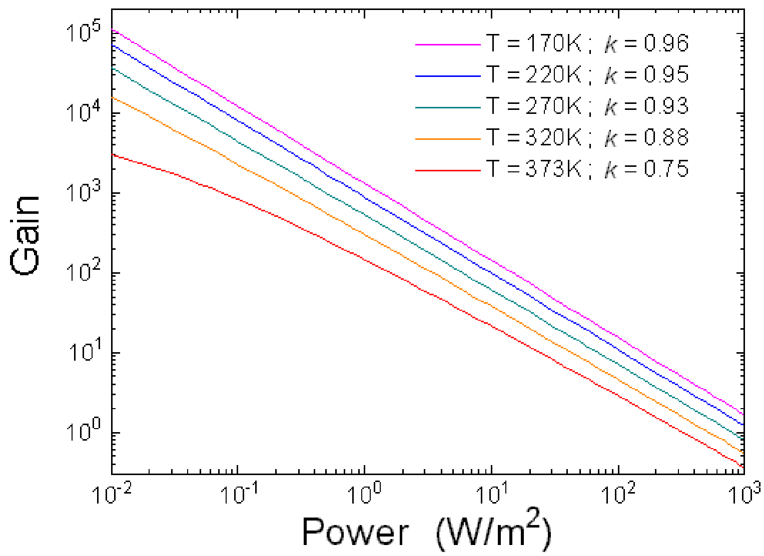

Figure 5. Dependence of gain on incident power and temperature obtained by computer simulation.

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