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Ultraviolet Photodetectors Based on $Al_xGa_{1-x}N$ Schottky Barriers

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Schottky barrier photovoltaic detectors based on Si-doped $Al_xGa_{1-x}N$ ($0 \le x \le 0.22$) have been fabricated and characterized. Samples were grown on basal plane sapphire by LP-MOVPE. Schottky contacts were made with Au. Responsivities are independent of the diode size and of the incident power in the range measured (10mW/m^2 to 2KW/m^2). The spectral response shows an abrupt cutoff that shifts linearly to higher energy with increasing Al content. A visible rejection of 3 to 4 orders of magnitude is observed in $Al_xGa_{1-x}N$ Schottky photodiodes. Device time response is RC-limited, and a minimum decay time as short as 15ns have been estimated in unbiased $Al_{0.22}Ga_{0.28}N$ diodes. This time response can be further reduced by reverse biasing.

1 Introduction

$Al_xGa_{1-x}N$ alloys, with a bandgap tunable from 365 nm (x=0) to 200 nm (x=1), are extremely attractive for optoelectronic applications such as visible-blind ultraviolet (UV) photodetectors [1]. These materials are remarkably tolerant to aggressive environments, due to its thermal stability and radiation hardness. Applications range from flame detection to space communications or solar UV monitoring systems [2].

High responsivity $Al_xGa_{1-x}N$ photoconductors have already been demonstrated [3] [4] [5]. However, the persistent photoconductivity (PPC) [5] [6] present in these devices results in a very slow non-exponential response which makes them unsuitable for most applications. GaN photovoltaic diodes have proven to be a better approach than photoconductive devices in applications requiring fast response or a high UV/visible contrast [2] [7]. Schottky barrier GaN photodetectors were first reported by Khan et al. [8], who demonstrated a Ti Schottky diode on p-type GaN. This devices showed a RC-limited time response of 1 µs (time for the signal to fall from maximum to 1/*e*), and a zero-bias responsivity of 130 mA/W illuminating through the sapphire. The inconvenience of backside illumination was analyzed by Binet et al. [9], who calculated a hole diffusion length of 0.1 µm which limited the device response. This problem was overcome by a semitransparent Schottky electrode, as used by Chen et al [10], who reported a 50 Å Pd Schottky barrier on n-type GaN, with a responsivity of 180 mA/W and a RC-limited time response of 118 ns on a 50 Ω resistance. $Al_{0.26}Ga_{0.74}N$ photodiodes based on 50 Å Pd Schottky barriers have been recently demonstrated [11], showing a responsivity of 70 mA/W with a minimum time response of 1.6 µs. In this work, we report on the fabrication and characterization of Schottky barrier photovoltaic detectors based on Si-doped $Al_xGa_{1-x}N$ samples with different Al content ($0 \le x \le 0.22$), aiming to increase the time response.

2 Devices and experimental

The $Al_xGa_{1-x}N$ epilayers were grown on basal plane sapphire in an AIX200RF horizontal LP-MOVPE reactor. Trimethylgallium (TMG), trimethylaluminum (TMA) and ammonia (NH_3) served as precursors, and H_2 was used as carrier gas. Growth temperature was fixed at 1170°C, with a V/III partial ratio of 3500, and a growth rate of 1 µm/h. A 250 Å thick GaN buffer layer was grown at 525°C. N-type doping has been achieved using silane (SiH_4). The aluminum fraction in the solid phase was determined by energy dispersion spectroscopy (EDS) in a scanning electron microscope. AlGaN epilayers show a FWHM of 670 arc-sec for the (0002)

X-ray double diffraction peak in the Ω-configuration [12]. Typical electron mobilities of 75-90 cm^2/Vs and 140 cm^2/Vs are obtained at room temperature in 2×10^{18} cm^{-3} n-type doped AlGaN and GaN respectively. Doping levels as determined by C-V measurements ranged from 5×10^{17} cm^{-3} to 2×10^{18} cm^{-3}.

For the fabrication of Schottky barriers, samples were diced into 4 × 4 mm squares and cleaned in acids. A semitransparent 100Å thick Au layer was deposited by Joule evaporation. The transmittance of this layer was found to be rather flat in the ultraviolet region, with a mean value of 30%. The pattern of the metallization was defined with standard photolithography. Detector diameters ranged from ϕ = 240 µm to ϕ = 1 mm. A second metallization was performed to deposit a gold pad, whose pattern was defined using a lift-off technique. Ohmic contacts were made with indium.

The photodiode current-voltage (I-V) characteristics were measured with a Hewlett Packard HP4155A semiconductor parameter analyzer. Capacitance vs. bias voltage were obtained using a Hewlett Packard HP4284A LCR-meter. Photodetector responsivity and its dependence on the incident optical power were determined with a non-focused cw He-Cd laser (325 nm). Spectral responsivity studies were performed by using a 150W xenon arc lamp and a Jobin-Yvon H-25 monochromator with a holographic grating that ensures good transmission down to 200 nm. The optical system was calibrated using a Molectron PR200 pyroelectric detector. Time response was measured using the fourth frequency of a Nd-YAG laser (266 nm), whose pulses were gaussian with a FWHM of 10 ns. Low frequency noise studies were performed with a PARC 113 low noise preamplifier and a FFT analyzer. The system has a background level of ~10^{-21} A^2/Hz.

3 Results and discussion

Figure 12 shows a typical I-V curve of $Al_{0.22}Ga_{0.78}N$ Schottky diodes. Devices present an ideality factor of 1 to 2, a leakage resistance above 500 MΩ, and a typical forward resistance of 100 Ω. Capacitance-voltage (C-V) characteristics are shown in the inset for diodes with different sizes. In GaN diodes a barrier height of about 1 eV is estimated from the C-V curve. However, in $Al_xGa_{1-x}N$ higher values are obtained (~2 eV), probably due to the presence of oxide in the surface.

The room temperature spectral responsivity of the photodiodes is depicted in Figure 2. Photocurrent increases linearly with optical power from 10 mW/m^2 to 2 KW/m^2, as shown in the inset. Responsivity remains quite flat for photons with energy over the bandgap, with values of 70 mA/W, 45 mA/W and 29mA/W for $Al_xGa_{1-x}N$ with x = 0, 0.15 and 0.22 respectively. These low values are due to the metal thickness (100 Å). A rejection of the visible radiation of more than three orders of magnitude is measured in all the devices, independent of diode size. The cutoff wavelength shifts with Al content from 362 nm (x = 0) to 320 nm (x = 0.22), which implies a linear variation of the energy bandgap as a function of aluminum concentration. This dependence has been checked by transmission measurements [12], and agrees with the data published by Wickenden et al. [13], although it is in contradiction with the downward bowing parameter recently reported by Brunner et al. [14].

Exponential photocurrent decays have been found when switching off the illumination, as shown in Figure 3 for $Al_{0.22}Ga_{0.78}N$ diodes operating with a 2 KΩ load resistance. Detectors are RC limited, where R is the sum of the load resistance, R_L, and the series resistance of the device, R_S, and C is the sum of the load capacitance, C_L, and the capacitance related to the diode space-charge-region, C_{SCR}.

The dependence of photocurrent decay time on the load resistance has been analyzed (see Figure 4) and confirms the RC behavior. By extrapolating the results in figure 3 to zero load resistance, a minimum time constant of 15 ns is estimated for 240 µm $Al_{0.22}Ga_{0.78}N$ Schottky diodes. This value is shorter than the values previously reported for similar size AlGaN Schottky photodiodes [11]. The observed time response decreases with diode size due to the reduction of its internal capacitance. Time response is further reduced by reverse biasing, as diode capacitance decreases with the square root of the reverse bias voltage (see Figure 5).

The bandwidth of the devices, BW, can be estimated by:

$$BW = \frac{1}{2\pi R_S C_{SCR}} \tag{1}$$

For diodes with the same geometry and polarization, C_{SCR} and R_S are proportional to $N_D^{1/2}$ and $(\mu N_D)^{-1}$ respectively, where µ is the electron mobility and N_D is the doping level. Therefore, the bandwidth of these devices would be optimized by increasing $\mu N_D^{1/2}$. Under this assumption, Si-doping should improve the time response of Schottky photodiodes, provided that mobility does not decrease drastically and Schottky barrier is not much lowered by tunnel transport.

Low frequency noise is 1/f limited, satisfying the relationship:

$$S_n = S_0 \frac{I_d^2}{f^\gamma} \tag{2}$$

where I_d is the dark current, and S_0 and γ are fitting parameters, with $1 \le \gamma \le 1.2$. A noise equivalent power (NEP) of 13 nW has been obtained in ϕ = 1mm $Al_{0.22}Ga_{0.78}N$ diodes at -1.35 V bias, which implies a normalized detectivity as high as 3.5×10^7 $Hz^{1/2}W^{-1}m$.

4 Conclusions

Schottky barrier photovoltaic detectors have been fabricated on Si-doped $Al_xGa_{1-x}N$ ($0 \le x \le 0.22$) samples grown on sapphire by MOVPE. Schottky contacts were made with Au. Responsivities are independent of the diode size and of the incident power in the range measured (10 mW/m^2 to 2 KW/m^2). The spectral response shows an abrupt cutoff that shifts linearly to higher energy with increasing Al content. A visible rejection of 3 to 4 orders of magnitude is observed in $Al_xGa_{1-x}N$ Schottky photodiodes. Device time response is RC-limited, and a minimum decay time as short as 15ns have been estimated in unbiased $Al_{0.22}Ga_{0.28}N$ diodes. This time response can be further reduced by reverse biasing. Low frequency noise is 1/f limited, and detectivities as high as 3.5×10^7 $Hz^{1/2}W^{-1}m$ have been obtained in ϕ = 1mm $Al_{0.22}Ga_{0.78}N$ diodes at -1.35 V.

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FIGURES

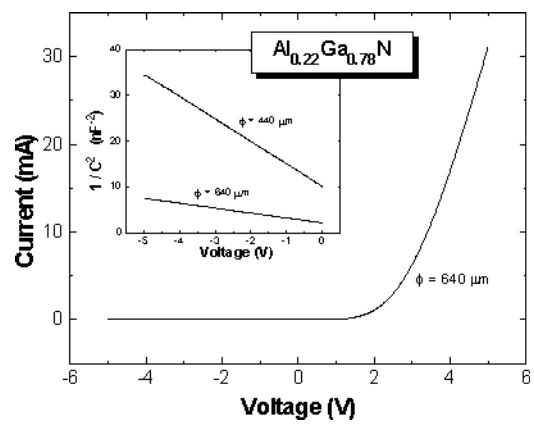

Figure 1. Current vs. voltage (I-V) characteristic of an $Al_{0.22}Ga_{0.78}N$/Au Schottky photodiode. In the inset, 1 / C^2 vs. voltage relation.

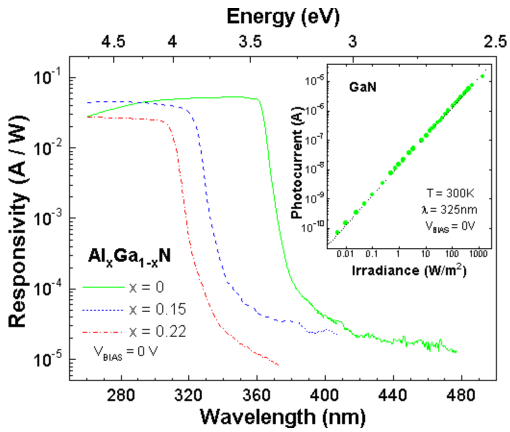

Figure 2. Zero-bias spectral response of $Al_xGa_{1-x}N$ Schottky photodetectors at room temperature. In the inset, variation of photocurrent with irradiance in a GaN Schottky diode.

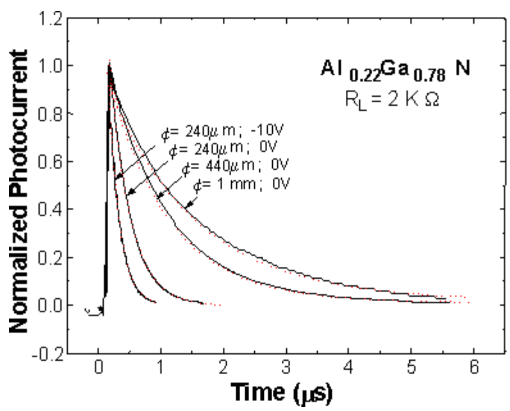

Figure 3. Photocurrent decays observed in $Al_{0.22}Ga_{0.78}N$/Au Schottky photodiodes with different sizes and bias. Red dotted lines correspond to exponential fits.

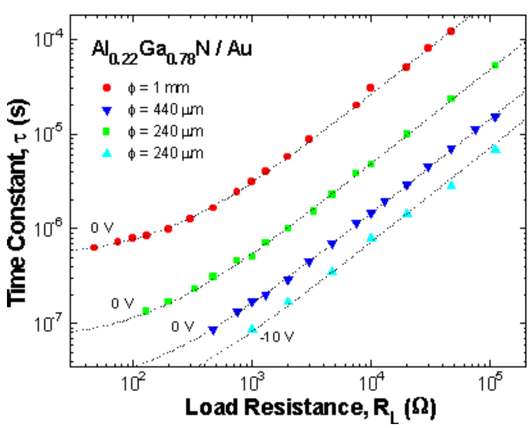

Figure 4. Photocurrent decay time constant vs. load resistance measured in $Al_{0.22}Ga_{0.78}N$/Au Schottky photodiodes with different sizes and bias voltage. Black dotted lines correspond to linear fits.

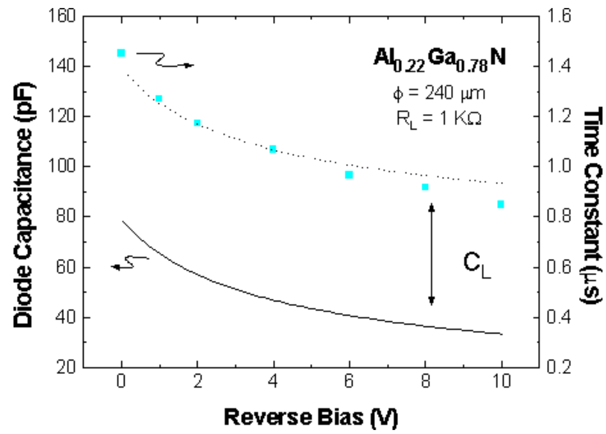

Figure 5. Variation of diode capacitance with reverse bias. Dotted line represents the sum of the diode internal capacitance and the load capacitance, C_L. The decay time constant dependence on reverse bias (blue dots) is also shown.

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