Characterization of AlGaN-based metal-semiconductor solar-blind UV photodiodes with IrO_2 Schottky contacts

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Abstract

Intrinsically solar-blind ultraviolet (UV) AlGaN-based Schottky photodiodes were fabricated using Iridium oxide (IrO_2) as the Schottky barrier material. The Ir Schottky contacts were annealed at 700 °C under O_2 ambient and the photodiodes characterized with an optoelectronic system. The main parameters extracted from I–V measurements were an average ideality factor of 1.38, a Schottky barrier height of 1.52 eV, a reverse leakage current density at −1 V bias of 5.2 nA/cm^2 and series resistance of 250 Ω. After spectral characterization, it was found that annealing, alone, of the Ir contact to form the more UV transmissive IrO_2 does not always improve the responsivity. The deposition of a Au probe contact on the IrO_2 contact increased the responsivity from 40 mA/W to 52 mA/W at 275 nm with respect to the annealed Ir contact. However, the ideality factor degraded to 1.57, Schottky barrier height lowered to 1.19 eV, reverse leakage current density increased to 49 nA/cm^2 and series resistance decreased to 100 Ω with the addition of the Au contact. The radiation hardness of AlGaN was also confirmed after studying the effects of 5.4 MeV He-ion irradiation using ^{241}Am for a total fluence of 3×10^{13} cm^{-2}.

Keywords: AlGaN, solar-blind, ultraviolet, Iridium oxide, Schottky, photodiode, optoelectronic
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1. Introduction

$Al_xGa_{1-x}N$ is one of the promising photonic materials for use in tuneable intrinsically solar-blind ultraviolet (UV) detectors. These detectors have numerous applications in the scientific, industrial and military fields [1, 2, 3].

The UV spectrum is commonly defined as light with a wavelength ranging from 10 nm to 400 nm [1]. Although the Sun radiates over the entire UV spectrum, the Earth's atmosphere absorbs strongly in some regions of the UV spectrum. Specifically, wavelengths between 200 nm and 300 nm are mainly absorbed by ozone [1, 2]. Photodiodes sensitive only to wavelengths in the UV-C region (280 nm to 200 nm) are referred to as solar-blind UV photodiodes. These photodiodes will therefore only respond to terrestrial sources radiating in the UV-C region.

$Al_xGa_{1-x}N$ is a ternary semiconductor, of which the bandgap can be varied by changing the Al mole fraction, x. This allows for tuneability of the range of wavelengths to which Schottky photodiodes manufactured on the AlGaN are sensitive [4]. Schottky photodiodes are of particular interest because of their advantages over p-n junction photodiodes, such as higher short-wavelength sensitivity and faster response [1, 2]. However, some disadvantages are lower breakdown voltages and large reverse leakage currents [2]. Through electrical and spectral characterization of AlGaN-based Schottky photodiodes the effects of varying parameters, such as metallization, metallization technique, metal thickness and annealing can be investigated in order to optimize the photodiodes for a specific application.

In this paper, front illuminated AlGaN-based metal-semiconductor solar-blind UV photodiodes will be considered. For these types of photodiodes it is essential to make use of materials with high optical transmittance in the UV region as Schottky barrier contacts. Iridium oxide (IrO_2) has been effectively used as a Schottky barrier material for GaN metal-semiconductor-metal UV photodetectors [5]. Being one of the conducting metal oxides, IrO_2 has advantages such as a high work function (> 5 eV), low resistivity (approx. 50 $\mu\Omega$·cm) and high

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optical transmittance in the UV region [5]. Therefore, in this study we investigate the electrical and spectral characteristics of Ir Schottky contacts on AlGaN.

2. Experimental procedure

We used $Al_{0.35}Ga_{0.65}N$-based (4.2 eV bandgap [4]) samples obtained from Technologies and Devices International, Inc. for this study. These samples were prepared in the same manner as GaN-based samples. Sample preparation consisted of chemical degreasing, followed by wet chemical etching [6, 7]. A layered ohmic structure of Ti/Al/Ni/Au (150/2000/450/500 Å) was deposited. The ohmic contacts were annealed under an argon ambient for 5 min at both 500 °C and then at 700 °C. Circular 0.65 mm-diameter 50 Å-thick Ir contacts were deposited through a metal contact mask as Schottky contacts. The Schottky photodiodes were annealed in O_2 ambient for 20 min at 700 °C to form the more UV transmissive IrO_2 Schottky contacts. Thereafter, 0.3 mm-diameter 1000 Å-thick circular Au probe contacts were deposited on the Schottky contacts. This was done to investigate the effect of future wire bonding on the Schottky photodiodes.

Electrical and spectral characterization were done after each of the fabrication steps. Finally, the effects of 5.4 MeV He-ion irradiation using ^{241}Am for a total fluence of 3×10^{13} cm^{-2} were studied.

Characterization of the Schottky photodiodes was done with an optoelectronic system. For electrical characterization a programmable HP4140B pA meter/ DC source for current-voltage (I–V) measurements and a HP4192A Low Frequency Impedance Analyzer for capacitance-voltage (C–V) measurements were used. Parameters were extracted from the I–V and C–V characteristics as discussed in Sze and Ng [8, Chap. 3].

Spectral characterization in the UV region was done using a 30 W deuterium lamp, mounted directly onto a Digikröm DK240 ¼-meter Czerny-Turner type monochromator. An optical fibre led the light from the monochromator to the photodiode, which was placed inside a light-tight shielded enclosure that eliminates electromagnetic interference from external noise sources. The irradiance (W/cm^2) of the monochromatic light incident on the photodiode was calibrated using Gamma Scientific's flexOptometer with a Si-based detector.

The photodetector substitution method was followed for the calibration of the UV source [9, Chap. 3]. The optical fibre was placed perpendicular to the calibration detector such that the photosensitive area was overfilled. The constant spectral resolution function of the monochromator was enabled to provide a constant bandwidth of 1.5 nm throughout the calibration and measurement procedure. The UV source irradiance was calibrated for wavelengths ranging from 200 nm to 350 nm. The optical fibre was then placed perpendicular and closer to the photodiode under investigation such that the photosensitive area was still overfilled. Hence, the sample subtended a similar solid angle as the detector used for calibration.

Using radiometry and assuming a point source, it can be shown that the irradiance (W/cm^2) at the photodiode can be calculated from:

$$E_\lambda^{\mathrm{PD}} = E_\lambda^{\mathrm{CD}} \left(\frac{R_{\mathrm{CD}}}{R_{\mathrm{PD}}}\right)^2 \quad (1)$$

where, E_λ^{CD} is the irradiance (W/cm^2) at a specific wavelength as measured by the calibration detector at a distance R_{CD} from the optical fibre end, and R_{PD} the distance of the photodiode to the optical fibre end.

The two main parameters studied from the spectral characterization is the current responsivity and quantum efficiency. Current responsivity (A/W) is the ratio between the short-circuit photocurrent density (A/cm^2) and the irradiance of the light source [1]. The current responsivity (A/W) at a specific wavelength was calculated from:

$$\mathcal{R}_\lambda = \frac{J_\lambda^{\mathrm{ph}}}{E_\lambda^{\mathrm{PD}}} \quad (2)$$

where J_λ^{ph} is the photocurrent density (A/cm^2) during illumination at a specific wavelength of monochromatic light. The photocurrent generated during the illumination of the photodiode was measured with the HP4140B pA meter at zero bias.

The number of electron-hole pairs generated (photocurrent) per incident photon is refered to as the quantum efficiency [1]. The quantum efficiency is related to the current responsivity as follows:

$$\eta_\lambda = \mathcal{R}_\lambda \frac{hc}{\lambda} \quad (3)$$

where λ is the wavelength, c the speed of light and h the Planck constant [1].

3. Results and discussion

3.1. Electrical Characterization

Dark I–V and C–V measurements were made before any UV illumination for after each of the fabrication steps and after He-ion irradiation. Typical dark I–V characteristics of a good Ir Schottky photodiode is

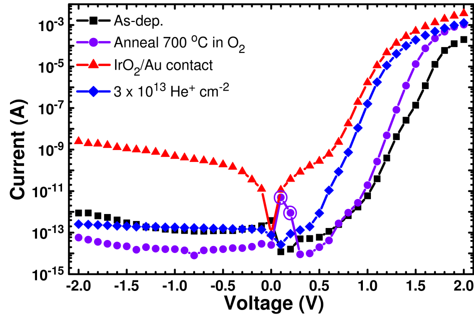

Figure 1: I–V characteristics of the Ir Schottky photodiodes for each of the fabrication steps and after 5.4 MeV He-ion irradiation. Circled data points were negative current readings obtained during forward bias measurements.

shown in Fig. 1. The average values of the parameters extracted from the I–V characteristics of the samples are listed in Table 1.

For the Ir Schottky photodiodes, the average ideality factor (n) improved after annealing from 1.63 to 1.38 with respect to the as-deposited state, this can also be seen in Fig. 1. The Schottky barrier height (ϕ_B) was 1.34 eV at the as-deposited state, but increased to 1.52 eV after annealing with a 15% standard deviation. Jeon and Lee [10] observed the same effect of Schottky barrier height increase after annealing. They had an increase from 0.68 eV to 1.07 eV for the Ir contact on their sample. The series resistance (R_S) also decreased significantly from 1200 Ω to 250 Ω after annealing with a 25% standard deviation. The average reverse leakage current density (J_R) has increased by a factor of approx. 30, but in some cases the reverse leakage current actually decreased, as seen in Fig. 1 and also found by Jeon and Lee [10].

The deposition of the Au probe contact on the IrO_2 Schottky photodiode resulted in an even lower series resistance of 100 Ω. The Schottky barrier height lowered to 1.19 eV in comparison with the as-deposited and annealed states. This value for the Schottky barrier height was also more comparable to the 1.07 eV obtained by Jeon and Lee [10]. The ideality factor however degraded to 1.57, but was still better than the as-deposited state. A difference in the reverse leakage current density was also observed. It increased further by a factor of approx. 10 on average, or as seen in Fig. 1 by a factor of 30 000 for one of the samples. Fluctuations in the small reverse leakage currents ($< 10^{-10}$ A) measured, resulted in the large standard deviations of the averages.

After the He-ion irradiation the average ideality factor degraded for most of the samples even more to 1.86, but the ideality factor for the one sample presented in Fig. 1 improved to that obtained after annealing. The Schottky barrier height did not change significantly compared to that of the deposited Au contact. The series resistance increased to 310 Ω, which was somewhat greater than after annealing. The reverse leakage current density has however improved significantly on average, as seen in Fig. 1. The Au probe contacts started to flake off and this reduction in Au probe contact definitely contributed to the increase in series resistance, lower reverse leakage current measurements and degraded ideality factor.

Table 1: Average ideality factor, Schottky barrier height, reverse leakage current density and series resistance of the Ir Schottky photodiodes for each of the fabrication steps and after He-ion irradiation.

	n	ϕ_B ±15% (eV)	J_R at −1 V (nA/cm^2)	R_S ±25% (Ω)
As-dep.	1.63	1.34	0.18 ± 0.23	1200
Annealed	1.38	1.52	5.2 ± 8.4	250
IrO_2/Au	1.57	1.19	49 ± 84	100
He^+	1.86	1.17	0.08 ± 0.04	310

The free carrier concentration was found to be approx. 1.4×10^{18} cm^{-3} from C–V measurements. After He-ion irradiation it has decreased by at least 30% to 1.0×10^{18} cm^{-3}.

3.2. *Spectral Characterization*

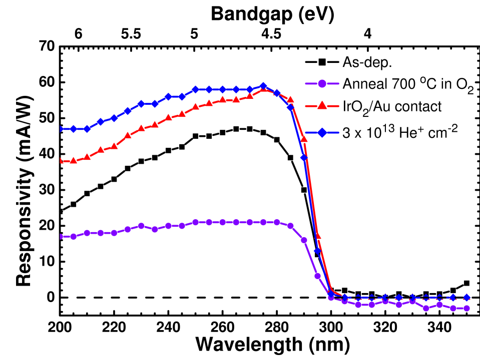

Figure 2: Spectral responsivities of the Ir Schottky photodiodes for each of the fabrication steps and after 5.4 MeV He-ion irradiation at zero biasing.

After each dark I–V and C–V measurement, the measurement probes were left in place and the optical fibre was positioned. Fig. 2 shows the spectral responsivities measured at zero bias for a photosensitive area of 0.33 mm^2 of the same photodiode used for Fig. 1.

A clear cut-off at approx. 295 nm (4.2 eV) was observed for all the photodiodes as seen in Fig. 2

which corresponded well with the absorption edge of $Al_{0.35}Ga_{0.65}N$. Considering the responsivity at 275 nm ($\mathcal{R}_{275}$) the as-deposited Ir Schottky photodiodes gave an average of (48 ± 16) mA/W and a quantum efficiency (η_{275}) of (23 ± 6)%.

To obtain the more UV transmissive IrO_2 the photodiodes were annnealed, but the $\mathcal{R}_{275}$ and η_{275} decreased to (40 ± 26) mA/W and (18 ± 12)% respectively, which was not expected. The deposition of the Au probe contact resulted in a smaller photosensitive area of 0.261 mm^2, but the $\mathcal{R}_{275}$ and η_{275} increased to (52 ± 17) mA/W and (23 ± 7)% respectively.

After the He-ion irradiation there was an unexpected improvement on the $\mathcal{R}_{275}$ and η_{275} to (64 ± 8) mA/W and (29 ± 3)% respectively. This was again attributed to the reduction in Au probe contact as the Au flaked off, which led to parts where the UV light could pass through. Because of this, the photosensitive area of 0.261 mm^2 used in the calculations was not valid and could have been larger.

4. Conclusions

Electrical characterization indicated that, after annealing the series resistance decreased significantly for all photodiodes. The addition of a Au probe contact on the IrO_2 brought a further reduction in series resistance. On average, the series resistance of the 0.65 mm Schottky photodiodes decreased from 1200 Ω for the as-deposited Ir, to 250 Ω after annealing and to 100 Ω after the addition of Au probe contacts.

Annealing improved the average ideality factor and the reverse leakage current densities were still of reasonable order. The average reverse leakage current density at -1 V bias was larger after the deposition of the Au probe contacts, increasing from 5.2 nA/cm^2 to 49 nA/cm^2. An average Schottky barrier height of 1.52 eV and 1.19 eV was calculated from I–V measurements, after annealing and the addition of Au probe contacts, respectively.

Spectral characterization showed that, in all cases the cut-off wavelength was at approx. 295 nm (4.20 eV) which corresponded well to the bandgap as predicted when using 35% mole fraction Al. Wavelengths shorter than the cut-off wavelength successfully generated electron-hole pairs per incident photon.

However, annealing did not improve the average responsivity and quantum efficiencies as compared to both the as-deposited Ir and addition of Au probe contacts. It is suggested that the thin 50 Å-thick Ir Schottky contact does not make sufficient contact with the probe used to measure the small photocurrent after annealing, compared to when the Au probe contact was deposited. Therefore it is not only important to use materials with high optical transmittance in the UV region, but the photocurrent must also be effectively conducted. Hence, future wire bonding to the Schottky photodiodes can further improve responsivities.

The III-V nitrides are known to be very radiation hard [2]. Apart from the 30% decrease in the free carrier concentration, the effects observed after a total fluence of 3×10^{13} He^+ cm^{-2} were not significant and are inconclusive, because of the loss in the Au probe contacts. To obtain more reasonable results in the future, the Au probe contacts should be annealed and the sample subjected to higher fluences of He-ion irradiation.

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