Physica B 407 (2012) 1529–1532

Contents lists available at SciVerse ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

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

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ARTICLE INFO

Available online 24 September 2011

Keywords:
AlGaN
Solar-blind
Ultraviolet
Iridium oxide
Schottky
Photodiode
Optoelectronic

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}.

1. Introduction

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

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 (280–200 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 tunability 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 μΩ cm) and high 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

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doi:10.1016/j.physb.2011.09.078

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, Chapter 3].

Spectral characterization in the UV region was done using a 30 W deuterium lamp, mounted directly onto a Digikröm DK240 1/4-m 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, Chapter 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

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

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

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

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 referred 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 after each of the fabrication steps and after He-ion irradiation. Typical dark *I–V* characteristics of a good Ir Schottky photodiode is 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].

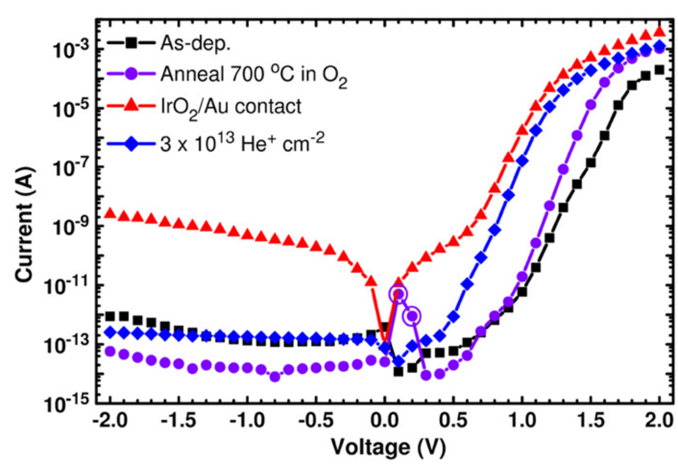

Fig. 1. *I–V* characteristics of the Ir Schottky photodiodes for each of the fabrication steps and after 5.4 MeV He-ion irradiation. Circled data points were negative current readings obtained during forward bias measurements.

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.

Fabrication step	n	$\phi_B \pm 15\%$ (eV)	J_R at -1 V (nA/cm^2)	$R_S \pm 25\%$ (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