Optoelectronic characterization of Au/Ni/n-AlGaN photodiodes after annealing at different temperatures

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Abstract

The optoelectronic characteristics of Ni/Au Schottky photodiodes based on $Al_{0.35}Ga_{0.65}N$ were investigated. The transmission of the Ni (50 Å) /Au (50 Å) layer was determined by evaporating it on a quartz substrate. As evaporated, the transmission coefficient in the 200 to 350 nm wavelength range was found to be 43 to 48 %. Annealing at temperatures of up to 400 °C did not influence the transmission coefficient. After annealing at 500 °C, the transmission coefficient increased from 50 to 68 % over the 200 to 350 nm range. The reverse bias current was optimised in terms of annealing temperature and was found to be as low as 1.94×10^{-13} A after annealing at 400 °C for a 0.6 mm diameter contact. The Schottky barrier heights increased with annealing temperature reaching as high as 1.46 eV and 1.89 eV for *I-V* and *C-V* measurements, respectively. The quantum efficiency was measured to be 20.5 % and the responsivity reached its peak of 0.046 A/W at 275 nm. The cut-off wavelength was 292 nm.

Keywords: Annealing, Schottky photodiode, AlGaN

1. Introduction

Wide bandgap materials have been of interest recently because of their suitability for use in industrial, scientific and military applications. Aluminium gallium nitride ($Al_xGa_{1-x}N$) is such a material and has attracted a lot of attention for ultraviolet (UV) detection. This is because $Al_xGa_{1-x}N$ based photodiodes have an adjustable cut-off wavelength which can be varied by changing the Al composition. Another contributing factor is that AlGaN is a direct bandgap semiconductor. For the right choice of Al mole fraction, these detectors are intrinsically solar

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blind, thus eliminating the need for filters and thereby decreasing the size and cost of the complete system. The applications of UV sensitive photodetectors include missile plume sensing, flame detection, and chemical sensing. For front illuminated diodes, a transparent/ semi-transparent non reflective Schottky contact needs to be produced. This can be done by a number of methods such as depositing a very thin Schottky layer and/or annealing the diode under different conducive conditions to form a transparent conductive metal layer. Careful steps must be taken however to ensure that the transparency is achieved without degrading the electrical characteristics of the diode. The properties of Ni/Au have been investigated for different applications and by various methods. Miaru et al. investigated thermal annealing effects on Ni/Au and found them to be quite small [5]. Chang et al also performed thermal annealing studies for Ni/Au contacts on AlGaN for MSM photodiodes [6]. In this paper we endeavour to study the thermal annealing effects of a Ni/Au on $Al_{0.35}Ga_{0.65}N$ Schottky contact by investigating the optical and electronic characteristics after annealing at different temperatures in Ar gas.

2. Experimental

The AlGaN sample used in this study was grown by hydride vapour phase epitaxy (HVPE) at Technologies and Devices International, Inc. (TDI). The structure of the sample, as per specification from TDI, is as follows (from the top layer): 0.7 μm $Al_{0.35}Ga_{0.65}N$, 0.2 μm Si doped $Al_{0.35}Ga_{0.65}N$, 1.2 μm Si doped GaN, 0.8 μm undoped GaN and a sapphire substrate (polished on one side). For the cleaning process, the AlGaN wafer was degreased in trichloroethylene and in isopropanol respectively for 3 minutes. It was then etched in boiling aqua regia for 10 minutes and dipped in $HCl:H_20$ (1:1) for a minute. In between all the chemical cleaning processes, de-ionised water was used to rinse the chemicals from the sample. The sample was then blow-dried with N_2. Ti (150 Å) /Al (2200 Å) /Ni (400 Å) /Au (500 Å) layers were deposited as an ohmic contact onto the AlGaN wafer by means of electron beam deposition. Subsequent to this, a Ni (50 Å) /Au (50 Å) Schottky contact was deposited using a resistive evaporation system. These metals were deposited without annealing the ohmic contacts. The Schottky contact mask produced Schottky diodes with a diameter of 0.6 mm. *I-V* measurements were performed using an HP 4140B pA Meter/DC Voltage Source. *C-V* measurements were done using an HP 4192 A LF Impedance Analyser. The theory used for determining the *I-V* and *C-V* characteristics is well known [8, 9]. For photo measurements, a Digikrom DK 240 1/4 meter monochromator and a 30 W deuterium lamp were used. The light intensity was calibrated with a Si-based detector. Due to the nature of our sample, the measurements were performed by means of front illumination. There are a few parameters which are important to the optical characterization of photodiodes. Two of these have been measured for our study namely the quantum efficiency and the responsivity. The sample was isochronously annealed in a furnace at different ambient temperatures for 5 minutes at 200, 300, 400, and 500 °C in argon gas. After each annealing step, opto-electronic characterization was done at room temperature (about 300 K). In order to perform transmittance measurements, a Ni (50 Å) /Au (50 Å) metal combination was deposited on a quartz substrate. This sample was annealed under the same conditions as the AlGaN sample. Transmission measurements were done using a Perkin Elmer Lambda 25 UV/VIS Spectrometer.

3. Results and Discussion

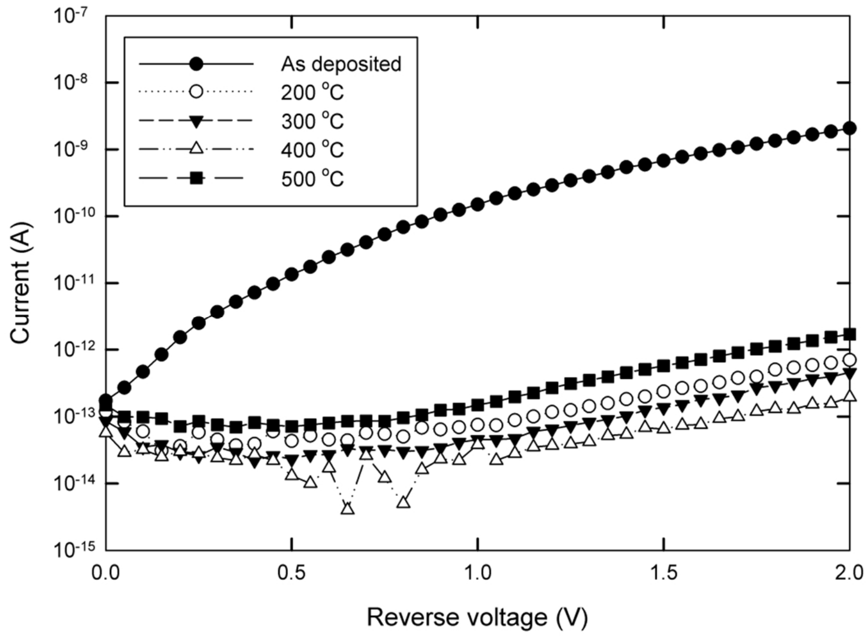

Figure 1 Reverse bias I-V characteristics of Ni/Au Schottky photodiode on AlGaN after different annealing temperatures

Figure 1 gives the reverse current of the Schottky diode after annealing at different temperatures. The reverse current initially decreases with annealing temperature. At -2 V the current decreases by 3 orders of magnitude from 2.07×10^{-9} A to 6.97×10^{-13} A (as-deposited to 200 °C annealing). The reasons for this could be that annealing the sample causes the

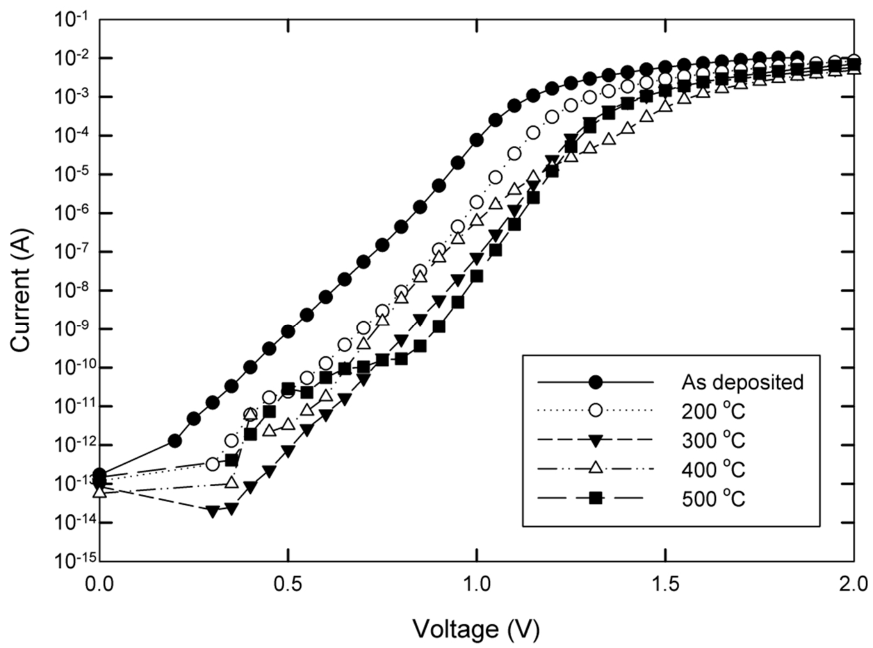

Figure 2 Forward bias I-V characteristics of Ni/Au on AlGaN after different annealing temperatures

metal to adhere more to the semiconductor as metal alloys also begin to form. It has also been suggested by Kim et al. [7] that annealing Schottky diodes causes a reduction in the interface states. These interface states can hamper electrical conductivity. The reverse current at -2 V shown in figure 1 continues to decrease slightly to 1.94×10^{-12} A after annealing at until after annealing at 500 °C, where it increases to 1.69×10^{-12} A at -2 V. This could be due to Au diffusing through the Ni to the metal-semiconductor interface [5]. It can also be seen that the reverse leakage current initially decreases with increasing reverse bias (as-deposited to 200 °C annealing). This is probably due to traps emptying. The forward bias characteristics show an improvement in terms of the barrier height with increasing annealing temperature.

Table 1 Electrical properties of Ni/Au Schottky photodiodes on AlGaN

Annealing temperature	Ideality factor	Barrier height		Reverse current
		I-V (eV)	*C-V* (eV)	at -2V (A)
As-deposited	1.85	1.04	1.47	2.07E-09
200 °C	1.64	1.17	1.59	6.97E-13
300 °C	1.64	1.22	1.82	4.54E-13
400 °C	1.46	1.25	1.87	1.94E-13
500 °C	1.27	1.46	1.89	1.69E-12

For the *I-V* characteristics it increases from 1.038 eV (as-deposited) to 1.457 eV (500 °C). That of the *C-V* measurements increases from 1.456 eV (as-deposited) to 1.895 eV (500 °C). One must mention though, that our material has at times shown evidence of non-constant doping. The ideality factor improved with annealing temperatures whereby it was reduced from a value of 1.85 to 1.27 as shown in Table 1. Figure 2 shows the forward bias *I-V* characteristics. The initial data points have been removed due to noise. This noise could be caused by the fact that we are measuring at low currents and the equipment is reaching its limit. All the samples can be explained by the thermionic emission model. As-deposited and 300 °C samples are dominated by thermionic emission and series resistance. The samples annealed at 200 °C and 500 °C include the aforementioned current transport mechanism and generation recombination although in the sample annealed at 500 °C it is more significant.

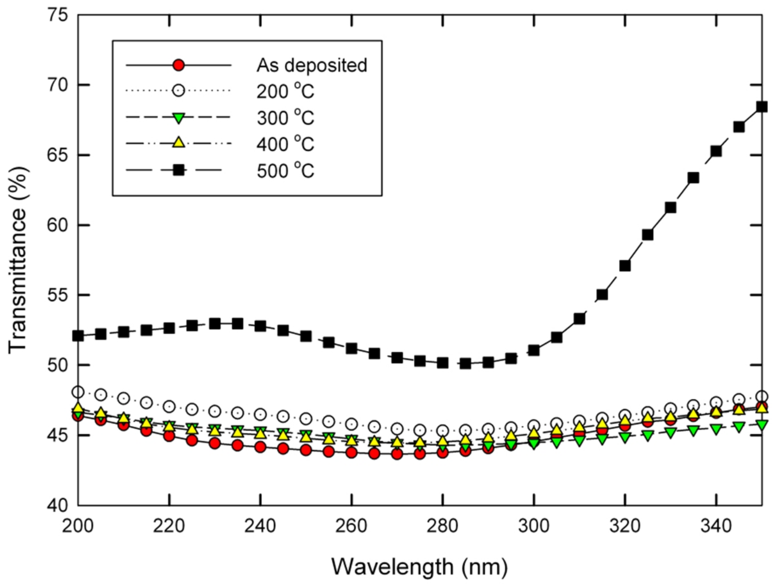

Figure 3 Transmittance spectrum of Ni/Au deposited on a quartz substrate

The 400 °C annealed sample has all the aforementioned mechanisms and includes a high injection region. For the optical measurement, the transmittance spectrum of Ni/Au as shown in figure 3 indicates that the transmittance does not change much for the as-deposited to the 400 °C annealing temperature. The transmittance ranges from 43 to 49 % within the 200 to 400 nm wavelength range. It is only at 500 °C annealing that the transmittance increases significantly. The transmittance measured after annealing at this temperature ranges from 50 to 74 % within the same wavelength range indicating that the Ni/Au becomes more transparent to UV light. The responsivity of the photodiode is shown in figure 4 for different annealing temperatures. It decreases from as-deposited to 200 °C and then increases with each annealing step. The responsivity shows its highest value at 500 °C annealing temperature. This also corresponds to the transmittance shown in figure 3. At 500 °C

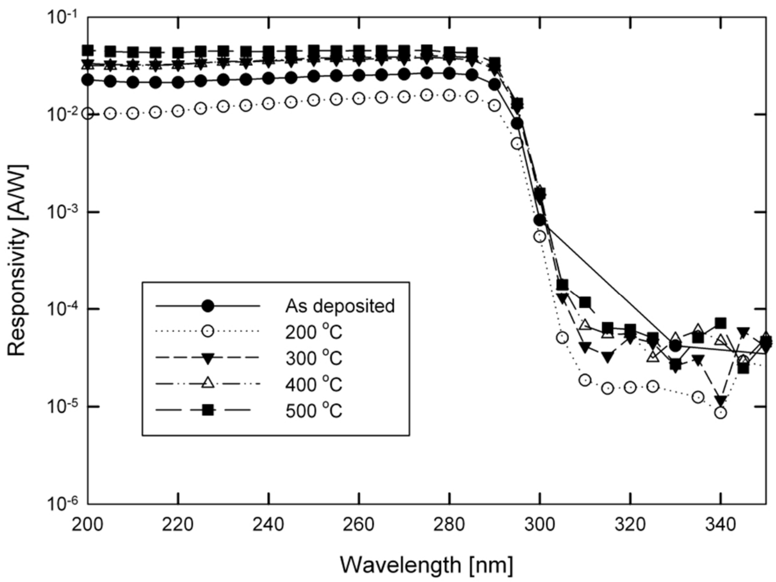

Figure 4 Spectral responsivity of Ni/Au Schottky photodiode on AlGaN at different temperatures

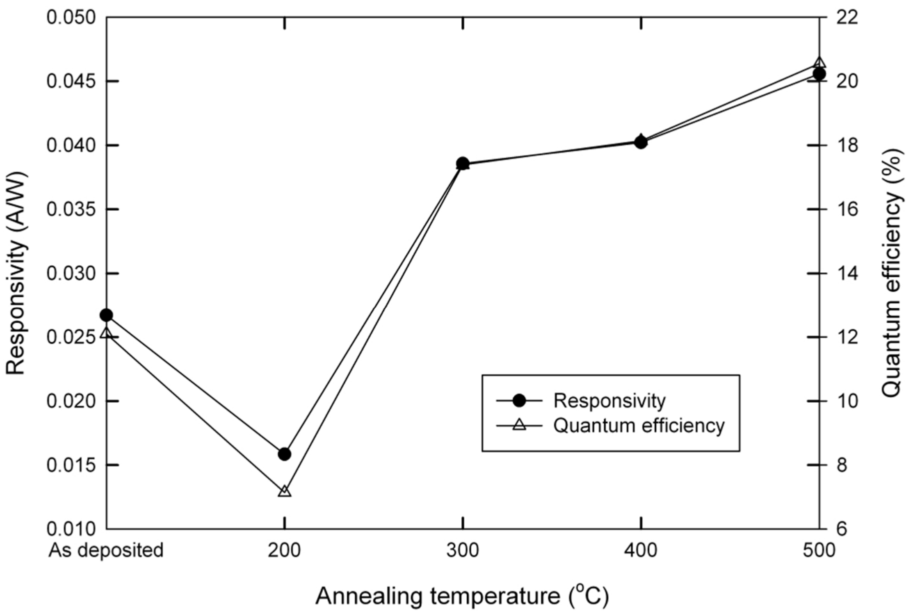

Figure 5 Responsivity and quantum efficiency as a function of annealing temperature of a Ni/Au on AlGaN Schottky photodiode

annealing temperature the Ni/Au contact exhibits its highest transmittance. The range of the responsivity of the photodiode is from 200 nm to about 300 nm, where a sharp cut-off wavelength occurs at 292 nm. Theoretically the cut-off wavelength can be determined from the ideal diode equation when the bandgap is known. In our case, the bandgap of $Al_{0.35}Ga_{0.65}N$ is found by interpolation between AlN and GaN. It has been calculated by

Omnes et al. [10] using photothermal deflection spectroscopy (PDS). The value for this has been measured as 4.22 eV, which corresponds to a cut-off wavelength of around 294 nm. This has been confirmed by Monroy et al. [11]. The peak responsivity at zero bias voltage for the different annealing temperatures occurs at a wavelength of 275 nm. Figure 5 shows the values extracted for the responsivity and quantum efficiency at different temperatures at the 275 nm wavelength. The trend of the responsivity and the quantum efficiency are similar. The maximum responsivity and quantum efficiency have been measured as 0.046 A/W and 20.5 % respectively.

4. Conclusion

Ni/Au Schottky photodiodes based on $Al_{0.35}Ga_{0.65}N$ have been successfully fabricated and characterized. The annealing temperature has been optimised and the lowest reverse current was found to be after annealing at 400 °C. The photodiode was found to be responsive in a specific wavelength range (200 to 300 nm). The peak responsivity was measured as 0.046 A/W and quantum efficiency 20 % at 275 nm wavelength. The transmittance spectrum shows that Ni/Au deposited on quartz has a much higher transmittance at 500 °C.

References

[1] Munoz E, Monroy E, Pau JL, Calle F, Omnes F, and Gibart P, J. Phys.: Condens. Matter **13** (2001) 7115.

[2] Park KY, Kwon BJ, Son JH, and Cho YH, Phys. Stat. Sol. (c) **3** no. 6 (2006) 2299.

[3] Monroy E, Omnes F, and Calle F, Semicond. Sci. Technol. **18** (2003) R33.

[4] Razeghi M, Proc. of the IEEE, **90** no. 6 (2002) 1006.

[5] Miaru N, Nanjo T, Suita M, Oishi T, Abe Y, Ozeki, Ishikawa H, Egawa T, and Jimbo T, Solid-State Electron. **48** (2004) 689.

[6] Chang PC, Chen CH, Chang SJ, Su YK, Yu CL, Chen PC, and Wang CH, Semicond. Sci. Technol. **19** (2004) 1354.

[7] Kim H, Schutte ML, Lee J, Lu W, and Mabon JC, J. Electron. Mater. **36** no. 9 (2007) 1149.

[8] Schroeder DK, *Semiconductor Material and Device Characterization*, (John Wiley and Sons, New York), 1998.

[9] Sze, SM, *Physics of Semiconductor Devices*, 2nd ed. (John Wiley and Sons, New York), 1981.

[10] Omnes F, Marenco N, Beaumont B, de Mierry Ph, Monroy E, Calle F, and Munoz E, J. Appl Phys. **86** no. 9 (1999) 5286.

[11] Monroy E, Calle F, Pau JL, Sanchez J, Munoz E, Omnes F, Beaumont B, and Gibart P, J. Appl. Phys. **88** no. 4 (2000) 2081.