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# THE EFFECTS OF ANNEALING TREATMENT ON GaN-BASED UV PHOTODETECTORS

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## ABSTRACT

The III-V nitrides (GaN and AlGaN) are wide band gap semiconductor materials, having excellent properties for fabricating electronic as well as optoelectronic devices operating under high-temperature and high-power conditions. The III-V nitrides are ideal photodetector materials operating at a detection range of between 240-360nm, with long wavelength response cut-off, which is directly related to the band gap of the material in the active region and thus does not require external filters. Low dark current detectors are extremely important to produce a photodetector with high detectivity, where the limitation to a photodetector's detectivity is due to the photodetector's noise level. The achievement of low dark current is critical to producing a UV photodetector with a high signal-to-noise ratio. In this work, GaN-based metal-semiconductor-metal (MSM) ultraviolet (UV) photodetectors with nickel (Ni) Schottky contacts were fabricated and characterized. A comparative study of annealing treatment at various temperature (400°C-700°C) to the photodetectors' dark current level were carried out. Cryogenic cooling after the annealing treatment was also performed to determine the effects of this treatment to the devices' performance. Electrical characterization was performed by current-voltage (I-V) measurement to investigate the Schottky contact properties of the photodetectors.

## INTRODUCTION

The research on wide band gap semiconductors such as the III-V nitrides, AlGaN, and SiC has led to many advances in the field of optoelectronics. In recent years, the GaN and AlGaN are being actively investigated for its potential in ultraviolet (UV) photodetection such as flame sensing, missile plume detection, UV biological effects, UV astronomy, engine control, and secure space-to-space communications. The many advantages for fabricating optoelectronic devices based on the wide band gap semiconductors mentioned above are due to the outstanding thermal and chemical stability which enable them to operate at high temperatures, high powers and also in hostile environments.

One of the most important considerations in fabricating a photodetector is achieving a low dark current condition, which is critical in producing ultraviolet (UV) photodetectors with a high signal-to-noise ratio. The introduction of the effects of thermal annealing on UV photodetectors based on GaN are investigated, which are mainly due to the high thermal stability of GaN that has prompted us to bring out the best from thermal treatment to the electrical characteristics of the UV photodetectors. Thermal treatment has been proven to be useful in reducing the leakage current in Schottky diodes, as well as reducing the dark current level in a Schottky contact based metal-semiconductor-metal (MSM) photodetectors [1,2] which is the subject that we are discussing in this paper.

## EXPERIMENTAL

The GaN (grown on sapphire ($Al_2O_3$) substrate) samples used for the fabrication of the photodetectors are transparent, with a thickness of about 4.5 μm, are unintentionally doped n-type, and have a background electron concentration in the high $10^{16}cm^{-3}$ range. Our photodetectors are the metal-semiconductor-metal (MSM) photodiodes with both interdigitated contacts (electrodes) forming Schottky barriers. The fingers width is 230 μm and the finger spacing is 400 μm. The length of each electrode is about 3.3 mm, and it consists of 4 fingers at each electrode.

The metal that was used for forming both interdigitated Schottky contact electrode was thermally evaporated. For the wafer cleaning process prior to metallization of the contact metal, the GaN samples were dipped in a 1:20 $NH_4OH:H_2O$ solution for 15 seconds followed by a 10 seconds dip in a 1:50 $HF:H_2O$ solution. The last step of the cleaning process was a 10 minutes etch in boiling aqua regia ($HCl:HNO_3$ = 3:1). The fabricated photodiodes were then annealed at temperatures from 400°C-700°C in a conventional tube furnace in flowing nitrogen environment. For the samples (photodiodes) annealed at temperatures from 400°C and 500°C, the annealing duration was 15 minutes, while the 600°C samples were annealed for 5 minutes and 2 minutes for the 700°C samples. Samples were prepared in pairs for each annealing temperature. The objective was just to study the annealing effects (*A*) and also cryogenic cooling effects right after annealing treatment (*A+C*) to the photodiodes' performance following some encouraging results reported for this kind of low temperature treatment to ohmic contacts [3]. Therefore, apart from studying the effects of annealing treatment to the photodiodes, the effects of cryogenic treatment were studied where some of the samples were subsequently cooled in liquid nitrogen right after annealing treatment. After the annealing treatment, the electrical properties of the photodiodes were analyzed by means of I-V characteristics of the devices. After I-V characterization, the *A* and *A+C* treatment as described above was repeated for those samples as described above as a way to study the photodiodes' thermal stability and also the effects of further annealing (extended annealing duration) to the photodiodes' performance. In this time, the annealing durations for the 400°C and 500°C treatment was 10 minutes, followed by 3 minutes for the 600°C treatment, and 2 minutes for the 700°C treatment. The electrical properties of the photodiodes were characterized again by I-V measurements after these additional annealing treatments.

## RESULTS AND DISCUSSIONS

The Schottky contact properties of the MSM photodiodes can be closely described by the equation below [4,5]

$$I = I_0 \exp(eV/nkT)[1 - \exp(-eV/kT)] \quad (1)$$

where I is the current, $I_0$ is the saturation current, V is the bias voltage, and n is the ideality factor. The expression for the saturation current, $I_0$ is

$$I_0 = AA^*T^2 \exp(-e\Phi_b/kT) \quad (2)$$

where A is the Schottky contact area, $\Phi_b$ is the Schottky barrier height, and A* is the Richardson constant where here we use the theoretical value of *A** [6] to be 26.4 Acm$^{-2}$K$^{-2}$. Equation (1) can be rewritten as

$$\frac{I \exp(eV/kT)}{\exp(eV/kT) - 1} = I_0 \exp(eV/nkT) \quad (3)$$

At $T \leq 370$K and when $V \leq -0.5$V, equation (3) can be simplified to [7]

$$I \exp\left(\frac{eV}{kT}\right) = I_0 \exp\left(\frac{eV}{nkT}\right) \quad (4)$$

$$\ln\left[I \exp\left(\frac{eV}{kT}\right)\right] = \ln I_0 + \frac{eV}{nkT} \quad (5)$$

Here, the plot of $\ln[I \exp(eV/kT)]$ vs V will give a straight line with the slope = e/nkT and y-intercept at $\ln I_0$.

By referring to Table 1, in the initial annealing process (before further annealing), we found that high temperature annealing (600°C and 700°C) resulted in a more significant changes to the dark current characteristics compared to the lower temperature annealing treatments. High temperature annealing treatment has increased the barrier height as well as it has also reduced the dark current level, and also resulted with a stable ideality factor when compared to the as-deposited conditions. For lower temperature annealing (400°C and 500°C), the barrier height for the *A+C* treated samples increased while the *A* treated samples experienced a reduction in the barrier height. This is mainly due to the better surface morphology of the *A+C* treated samples [3]. The smoother surface morphology of the *A+C* treated samples which resulted in better electrical properties can be attributed to the subsequent and fast cooling of cryogenic treatment which minimizes the effect of compressive stress and strain induced in the metal-semiconductor contact resulting from the heating and cooling

Table 1: Summary of the dark current characteristics of the samples annealed at different temperatures.

| Temperature (°C) | Samples (MSM photodiodes) | Ideality factor, n | Barrier height, $\Phi_b$ (eV) | Current at 15V (mA) |
|---|---|---|---|---|
| 400°C | As-deposited (*A*)* | 1.007 | 0.485 | 25.0 |
| | *A* | 1.007<br>(1.007) | 0.450 (0.452) | 79.3 (77.1) |
| | As-deposited (*A*+*C*)* | 1.007 | 0.484 | 20.3 |
| | *A*+*C* | 1.010<br>(1.007) | 0.519 (0.485) | 29.3 (29.6) |
| 500°C | As-deposited (*A*)* | 1.010 | 0.521 | 26.9 |
| | *A* | 1.007<br>(1.007) | 0.468 (0.469) | 43.3 (40.4) |
| | As-deposited (*A*+*C*)* | 1.008 | 0.504 | 18.5 |
| | *A*+*C* | 1.009 (1.01) | 0.514 (0.518) | 20.1 (24.2) |
| 600°C | As-deposited (*A*+*C*)* | 1.007 | 0.479 | 36.6 |
| | *A*+*C* | 1.007<br>(1.007) | 0.488 (0.500) | 25.2 (17.7) |
| 700°C | As-deposited (*A*+*C*)* | 1.008 | 0.480 | 54.1 |
| | *A*+*C* | 1.008<br>(1.007) | 0.487 (0.555) | 29.7 (1.24) |

* Here, we cannot assume that the electrical characteristics of all our samples used to fabricate the detectors are totally identical, as can be seen by the as-deposited Schottky contact properties in Table 1. We have also found this to be true because the current conduction magnitude of the as-deposited Schottky contacts on our MSM photodiodes does varies slightly from one sample to the other as similar claims were also previously reported [8-11].

Note 1: 1) As-deposited (*A*) : As-deposited samples before annealing treatment.
2) *A* : Samples treated with annealing only.
3) As-deposited (*A*+*C*) : As-deposited samples before annealing-and-cryogenically-treated.
4) *A*+*C* : Annealed-and-cryogenically-treated samples.

Note 2 : The values in brackets are the values obtained after further annealing treatment.

process of normal annealing treatment [3]. The compressive stress and strain present during the heating process as well as the cooling down process to room temperature after annealing can be attributed to the differences of thermal expansion coefficient between the Ni ($\alpha \sim 13.4\times10^{-6}$ $K^{-1}$) [12] and GaN ($\alpha \sim 6\times10^{-6}$ $K^{-1}$) [13]. Thus, *A+C* treatment has resulted in a laterally more uniform contact surface which is essential for achieving a metal-semiconductor contact with good electrical properties. However, under high voltage stressing at 15V, all of the samples experienced an increase in dark current level except for those samples annealed at 600°C and 700°C upon comparison with their respective as-deposited samples. A 45% reduction in dark current level is observed (Figure 1) in the 700°C samples while the 600°C samples experienced a 31% reduction in dark current level (Fig. 2) at 15V.

Due to degradation of the metal contacts of the samples under *A* treatment at temperatures of 600°C and 700°C, we could not obtain any data from the I-V measurement system. However, the application of cryogenic treatment does help in preventing severe degradation of the metal contacts under high temperature annealing. We suspect the diffusion of Ni metal layer into the samples away from the GaN surface has resulted in a degraded metal-semiconductor contact for the samples under *A* treatment. Since the samples were still hot at the time they were taken out of the furnace, a great deal of diffusion of the metal layer will still take place. Thus here, the effect of cryogenic cooling right after thermal annealing in this case will minimize the diffusion of the metal layer which then led to a better metal-semiconductor contact.

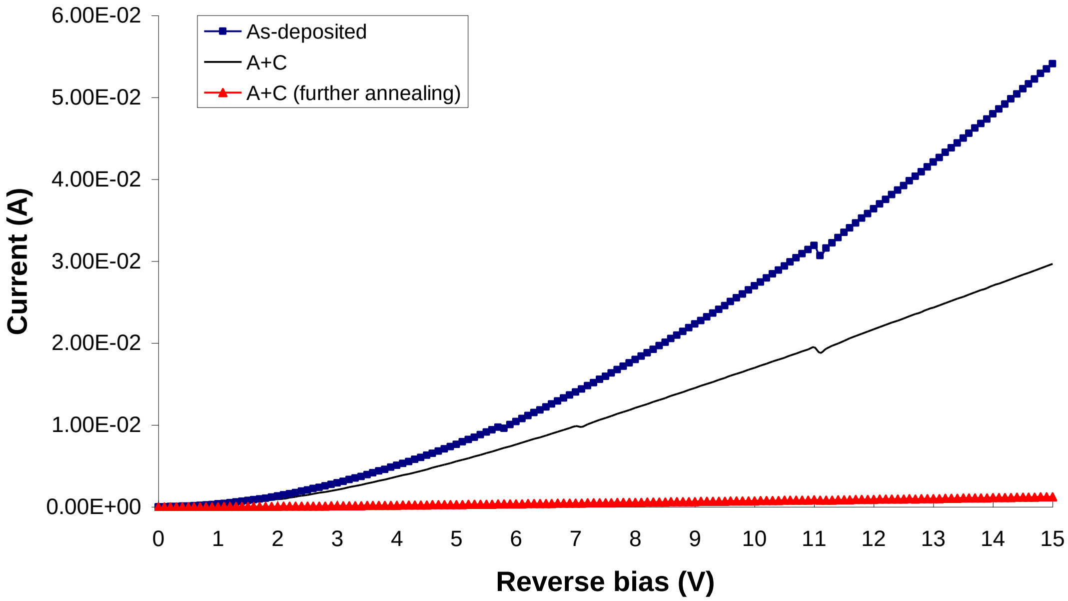

Figure 1: Current-voltage (I-V) characteristics of the samples annealed at 700°C.

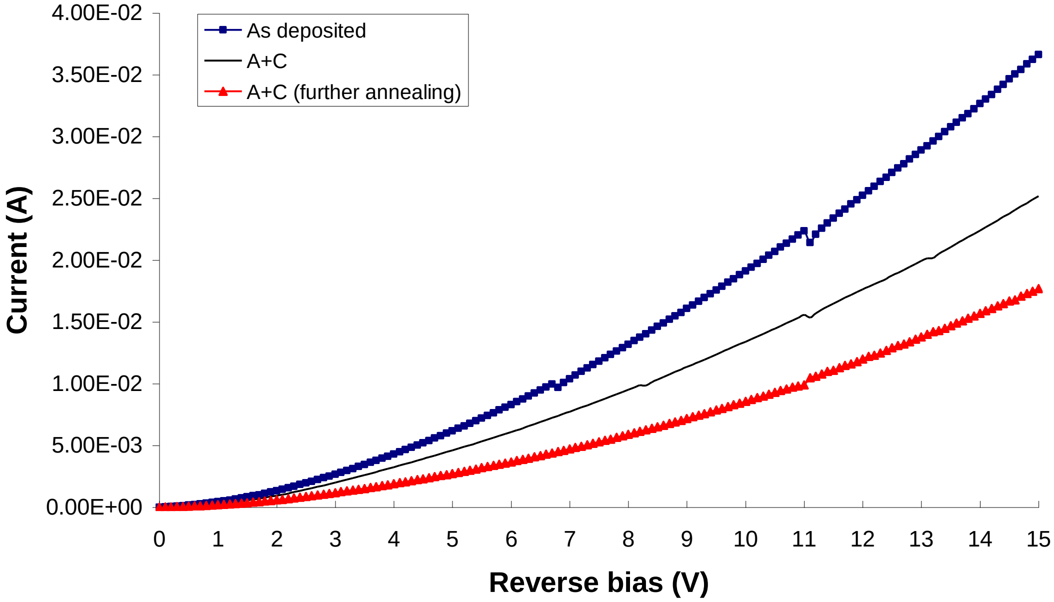

Figure 2: Current-voltage (I-V) characteristics of the samples annealed at 600°C.

In order to study the thermal stability of the photodiodes as well as the effects of further annealing to the photodiodes' performance, we have introduced further annealing treatment. Thus, upon further annealing, we can see that the trend is not stable for the lower annealing temperature (400°C and 500°C) treatment where there are increases and reductions in the ideality factors, barrier heights, and the current magnitudes at 15 V when compared to the results obtained from initial annealing treatment. On the other hand, the results obtained from the high temperature annealing treatment (600°C and 700°C) were encouraging, which resulted in a better or unchanged ideality factors which are near to unity, a better (increased) barrier height, and also a reduction in the dark current level at high voltage stressing (15V). When compared to the as-deposited condition after further annealing, a 98 % reduction of dark current level is observed (Figure 1) in the 700°C samples while the 600°C samples experienced a 52 % reduction in dark current level (Figure 2) at 15V. From the results obtained, we can see that the optimum annealing condition is at 700°C which yielded the lowest dark current level (~1.24mA) at 15V and the highest barrier height at 0.555 eV.

Thus, here we can see that high temperature annealing is more significant in producing a more stable and preferable electrical characteristics of our MSM photodiodes because the samples treated under high temperature resulted in not only an increase in the Schottky barrier height, but are also able to withstand high voltage stressing i.e. the dark current level has been reduced when compared to the as-deposited condition at 15V biasing. The changes in barrier height as well as the dark current level upon high temperature annealing treatment (600°C and 700°C) are mainly due to some macroscopic interactions between the metal contact and the semiconductor [1,14]. Other than that, the high dark current level and low barrier height of the photodiodes are mainly due to high tunneling component resulting from high background carrier concentration, defects present in the films, and also due to the fact that MSM photodiodes are being operated at reverse bias mode where the effect of applied bias can be much greater when compared to the forward bias mode of a normal Schottky diode.

## CONCLUSION

The application of thermal annealing treatment to our Ni/GaN MSM photodiodes at various annealing temperatures (400°C-700°C) was investigated. Significant improvement to the Schottky contact properties of the photodiodes can be achieved at high annealing temperature (600°C and 700°C) with the assistance of cryogenic treatment. The optimum annealing condition is at 700°C which yielded the lowest dark current level (~1.24mA) at 15V and the highest barrier height at 0.555 eV with the ideality factor of 1.007 after further annealing treatment. High temperature annealing-only treatment (*A*) leads to the degradation of the metal-semiconductor contacts of the photodiodes. In conclusion, cryogenic treatment after annealing (*A+C*) does helps in the enhancement of the electrical properties of the metal contacts of the photodiodes especially at high temperature thermal treatment.

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