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Optimization of Ni/Au Schottky Contacts on $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructure for RF Applications

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ABSTRACT

Schottky contacts to $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures with high barrier height, low reverse leakgae current and smooth surface morphology play a vital role in the development of high power, high frequency GaN High Electron Mobility Transistors (HEMTs). In this paper, we have fabricated and characterized Schottky contacts of Ni/Au on MOCVD grown $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostrucutre on semi-insulating 6H-SiC substrate. Ni/Au lift off deposition process has been used for Schottky contact fabrication. To study Schottky contact behavior on $Al_{0.3}Ga_{0.7}N$/AlN/GaN structure, gate contact metallization scheme and rapid thermal processing has been optimized. The current–voltage (I-V) and capacitance-voltage (C-V) characteristics of Ni/Au Schottky contact on $Al_{0.3}Ga_{0.7}N$/AlN/GaN structure have been investigated at room temperature. The electrical parameters such as ideality factor, Schottky barrier height (SBH) and saturation current have been evaluated from I-V data. 2DEG carrier density and threshold voltage parameters have been extracted using C-V data. A significant reduction of seven to eight orders of magnitude in reverse leakage current has been observed in $Al_{0.3}Ga_{0.7}N$ Schottky diode.

Key words: GaN HEMT, Schottky Contacts, Barrier Height, Surface Control Process, Annealing

INTRODUCTION

There is an immense potential in III-V nitrides for Nanoelectronics and optoelectronic applications. These materials are excellent candidates for high-power, high-temperature, and high-frequency electronic devices because of favorable properties like large bandgap, high breakdown voltage, high carrier mobility and high saturation velocity [1-3]. It has been reported that AlGaN/GaN based HEMTs have the capability of handling higher current densities than other III-V HEMTs because of higher two-dimensional electron gas (2DEG) density accumulated at AlGaN/GaN interface [2]. However 2DEG density and mobility is significantly affected by various scattering processes which has been calculated and experimentally compared which further leads to degradation in device performance [4,5]. The AlGaN/GaN based heterostructure with AlN as spacer layer has exhibited promising DC and RF performance for HEMT due to reduction in alloy disorder scattering [6-10]. Especially for power devices, considerable development has been done for GaN HEMTs, and GaN power amplifier MMICs [1,2]. It has also been reported, AlGaN/AlN/GaN HEMTs are promising candidates for low noise applications owing to their low noise, high linearity and robustness [3]. There is an additional requirement of RF limiting circuit in GaAs based LNAs, which degrades the noise performance and the dynamic range of the system [4], that can be

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eliminated by using GaN HEMTs in LNA MMICs. It is crucial for device performance to make reliable, high quality, efficient, thermally stable metal contacts to nitride semiconductor for these exciting applications [1,2]. A high-quality Schottky contact is needed in order to improve the performance and reliability of GaN HEMT technology. SBH is one of the important parameters to characterize Schottky contact for device performance. A large barrier height leads to higher breakdown voltage and small leakage currents which results in the improved noise and power performance of HEMTs. A significant amount of work has been published for fabricating Schottky contacts with variety of metals on $Al_xGa_{1-x}N$ [3-7]. Nonetheless, it has been reported that Schottky contacts formed on III-V materials suffer from anomalously large high leakage currents under reverse biasing [7-9]. Degradation in gate-control characteristics as well as significant power consumption has been reported due to large gate leakage currents. Reduction of four to five orders of magnitude in reverse leakage current in Ni/Au based Schottky contacts is also well reported on AlGaN/GaN based HEMTs.

Furthermore, in the present study, we are proposing a process for Schottky contact fabrication on $Al_{0.3}Ga_{0.7}N$/AlN/GaN based heterostructure using Ni/Au metal scheme with reduction of seven to eight orders of magnitude in reverse leakage current. Schottky contacts have been fabricated and characterized on $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostrucutre grown by Metal Organic Chemical Vapor Deposition (MOVCVD) on semi-insulating 6H-SiC substrate. Two elemental metals (Ni and Au) with different metal work functions (5.15eV and 5.2eV) have been selected for fabricating thermally stable Schottky contacts for high temperature operation devices. I-V and C-V characteristics of Ni/Au Schottky contact have been investigated at room temperature. The electrical parameters such as ideality factor, barrier height and saturation current have been evaluated from I-V data. 2DEG carrier density and threshold voltage parameters have been extracted using C-V data.

EXPERIMENTS

In the present work, Metal Organic Chemical Vapor Deposition (MOCVD) grown AlGaN/AlN/GaN based heterostructure on 6H-SiC substrate was used for fabricating the samples. The heterostructure consists of 60nm AlN nucleation layer, 2µm thick undoped GaN layer, 1nm AlN spacer layer, 20nm undoped $Al_{0.3}Ga_{0.7}N$ layer and 3nm Si_3N_4 passivation layer as shown in Figure 1. For this study circular transmission line method (CTLM) pattern has been fabricated as Schottky contact test structure as depicted in Figure 2.

Process flow for Schottky contact fabrication is mentioned in flowchart in Figure-3. All three samples were cleaned by degreasing in acetone and isopropyl alcohol to remove organic contamination. Photolithography for Ohmic pads was defined and followed by oxygen plasma descum for one minute to remove photo resist residues from exposed area. After descum process, followed by Si_3N_4 and $Al_{0.3}Ga_{0.7}N$ recess etching, Ohmic contact fabrication was done using optimized Ti/Al/Ni/Au metallization scheme followed by rapid thermal annealing. Photolithography for Schottky pads was defined, followed by one minute oxygen plasma descum. The topmost layer of 3nm Si_3N_4 was etched using ICP-RIE with SF6 plasma. After etching sample was dipped in HCl:DI (1:2) for one minute to minimize impact of oxidation on surface. Ni/Au (30/300 nm) metal stack was deposited by electron beam evaporation and patterned by the lift-off process. Au layer of metal stack which is the topmost layer was deposited as an outer layer to prevent the oxidation of metal stack during high temperature annealing process while Ni was deposited as a high work function metal to make efficient Schottky contact with $Al_{0.3}Ga_{0.7}N$ layer. After liftoff, sample was annealed at 450 °C for 120s under N_2 atmosphere. I-V and C-V characteristics of sample were measured at room temperature using Keithley's Semiconductor Device Analyzer, 4200A.

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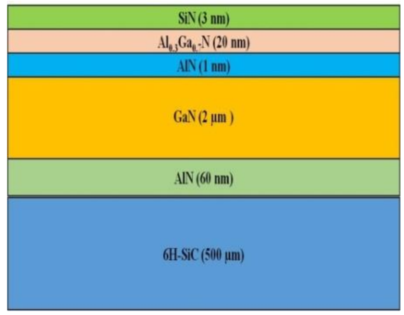

Figure 1: AlGaN/AlN/GaN Based Heterostructure

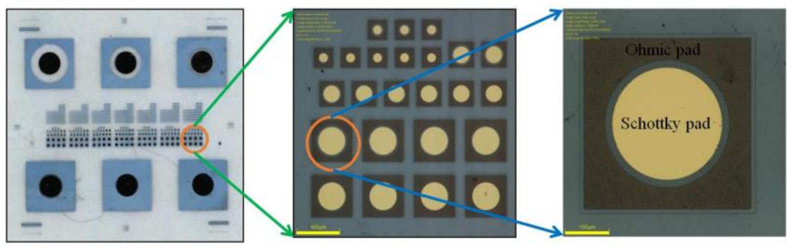

Figure 2: Optical Image of Schottky Test Patterns

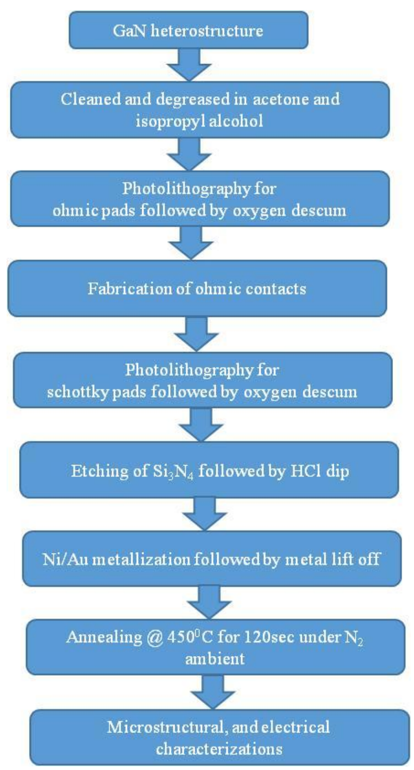

Figure 3: Flowchart Showing Process Flow for Schottky Contact Fabrication

RESULTS and DISCUSSION

In this study, Schottky contact fabrication process was optimized on $Al_{0.3}Ga_{0.7}N$/AlN/GaN based

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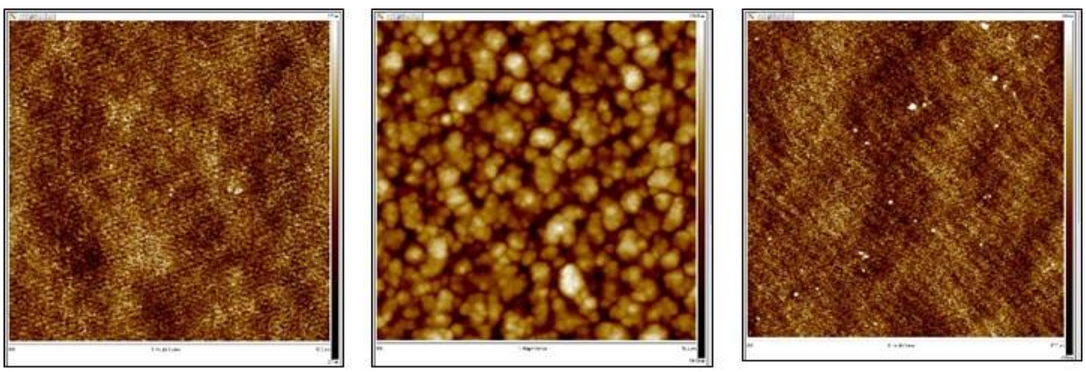
heterostructure for GaN HEMTs. As already been reported by researchers that oxygen plays crucial role in AlGaN Schottky diodes, the removal of oxygen is thus highly desirable. In view of this ,an attempt has been made to develop a surface control process using HCl:DI (1:2) dip of the sample. Moreover, in order to further reduce reverse leakage current, annealing process was also optimized to get high SBH. Details of surface morphological and electrical characterizations of fabricated sample are interpreted below:

Structural and Microstructural Characterization

Surface morphological characterization at bare heterostructure, Ohmic contact surface and Schottky contact surface was done using Atomic Force Microscope (AFM). AFM images are shown in Figure-4 and morphological characterization parameters are briefed in Table 1. AFM scan area is 10µm x 10µm and measured surface roughness is of order 0.77, 41.4 & 1.03 nm on bare heterostructure, Ohmic contact surface and Schottky contact surfaces respectively.

It shows, Schottky contact surface roughness is relatively good and suitable for formation of sharp metal/semiconductor interface. It further suggests formation of Al-Ni intermetallics which can improve the contact's surface morphology with little increment in barrier height.



(a) (b) (c)

Figure 4: (a) AFM image of bare heterostructure, (b) Ohmic contact and c) Schottky contact

Table 1: Summary of AFM characterization of fabricated sample

Parameters	Bare Heterostructure	Ohmic contact	Schottky contact
Scan Area (μm^2)	**10x10**	**10x10**	**10x10**
Roughness Rq (nm)	**0.77**	**41.4**	**1.03**

Electrical Characterization

Figure 5 shows the measured current-voltage charateristics of Ni/Au based Schottky Diode. Impact of

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higher metal work function of Ni can be related to lower inverse currents, as depicted in Figure 5.

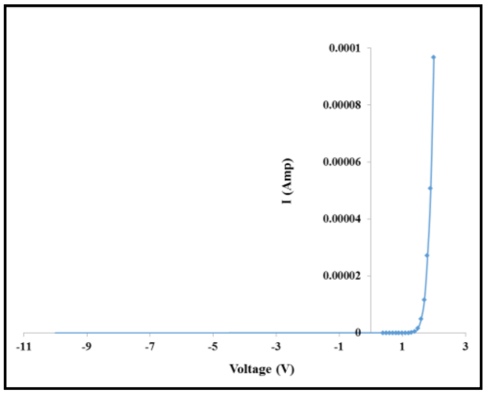

Figure 5: I-V characteristics of Schottky diode

The thermionic current voltage (I–V) expression of a Schottky barrier diode are generally described by:

$$I = Is(\exp\frac{qV}{nkT} - 1) \qquad (1)$$

$$Is = AA^{*}T^{2}\exp\left(\frac{-q\varphi_{b}}{kT}\right) \qquad (2)$$

where Is is the saturation current density, A is the contact area, A* is the effective Richardson constant, φ_b is the Schottky barrier height, n is the ideality factor, k is the Boltzmann constant, and T is the absolute temperature. From eqs. (1) and (2), following equations can be derived:

$$\ln I \approx \ln Is + \frac{qV}{nkT} \qquad (3)$$

$$\varphi_{b} = \frac{kT}{q}\ln\frac{AA^{*}T^{2}}{Is} \qquad (4)$$

According to equation (3), linear fit to the semi-log plot of the I–V curve at V = 0 yields lnIs, as shown in Figure-6.

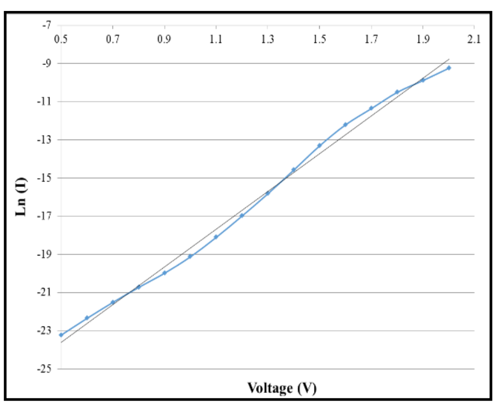

Figure 6: Plot of lnI as a function of V derived from the forward-biased I–V Schottky characteristics

Considering above equations, ideality factor, SBH, saturation current density has been evaluated before

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and after annealing. Summary of these extracted parameters is mentioned in below Table 2.

Table 2: Summary of extracted parameters from I-V data

Parameters	Before Annealing	After Annealing
Saturation Current (Amp)	-1.62×10^{-10}	-3.47×10^{-10}
Barrier Height (eV)	0.64	0.72
Ideality Factor	2.3	1.8

From Table 2, as observed from I-V data, before annealing, extracted parameters (ideality factor, SBH, saturation current density) show satisfactory formation of Schottky contacts. However, there is an improvement in quality of Schottky contacts after annealing. Fabrication of Schottky contact involves etching of Si_3N_4 passivation layer using ICP-RIE. As reported, plasma, inevitably induce damage to the AlGaN surface. These damages may exist as defects or dislocations, vacancy complexes, recombination centers, formation of dangling bonds on the surface, implanted etch ions and can lead to degrade device performance [11]. It is proposed, these defects act as surface states on AlGaN layer and leads to significant Schottky barrier tunneling of charge carriers and increase the electric field at the AlGaN layer beneath the gate electrode which results in narrowing and reduction of the effective SBH, as shown in Table 2. It is suggested that improvement in quality of Schottky contacts after annealing, reflects partial recovery of the defects. In $Al_{0.3}Ga_{0.7}N$/AlN/GaN based heterostructure for GaN HEMTs, it is studied that in Schottky contact fabrication, annealing, post gate metal deposition can remove or mitigate etching-induced damages and suppress the leakage current related to damages.

Figure 7 shows the comparison of the reverse biased Schottky diode characteristics of before (blue curve) and after annealing (red curve). Before annealing also, reduction of seven to eight orders of magnitude in reverse leakage current has been observed due to a surface control process. Moreover, further reduction is observed after annealing due to recovery of defects.

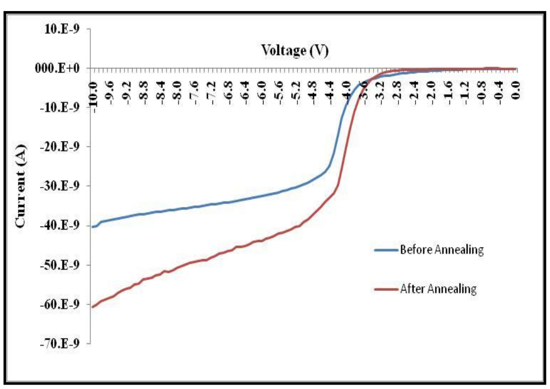

Figure 7: Reverse biased Schottky diode characteristics

In order to get better insight of fabricated Schottky diodes, C-V measurement has been carried out before and after annealing at 1MHz as shown in Figure 8. The capacitance of the depletion-layer of a

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Schottky contact is given by following equation:

$$(A/C)^2 = 2(\Psi_{bi} - V - kT/q) / q\varepsilon_s N \qquad (5)$$

where Ψ_{bi} is built-in potential, $\varepsilon_s$is the permittivity of AlGaN layer, N is the 2DEG density, q is electroncharge, k is Boltzmann constant and T is absolute temperature.

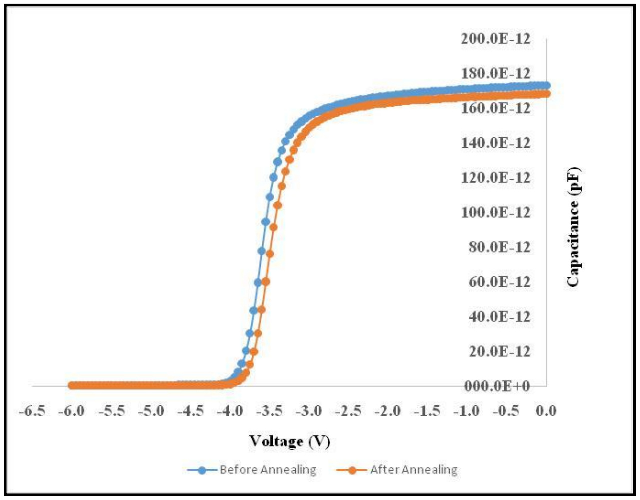

Figure 8: C-V characteristics before and after annealing

Using C-V data, 2DEG density and threshold voltage before and after annealing are extracted and summarized in below Table 3.

Table 3: Summary of extracted parameters from C-V data

Parameters	Before Annealing	After Annealing
2DEG density(cm^{-2})	1.35×10^{13}	1.30×10^{13}
Threshold voltage (V)	- 4.2	- 3.7

As depicted from Figure 8, after annealing, there is slight reduction in the 2DEG carrier density and threshold voltage is shifted towards positive direction of the X-axis. This reduction clearly indicates more depletion of channel under the gate contact after annealing due to increase in SBH. The positive shift in the threshold voltage in C-V is of great importance, as HEMT devices are depletion mode devices and this positive shift makes annealed Schottky contacts more energy efficient as a lower negative voltage is required to turn off the device.

CONCLUSION

In this study, Ni/Au gated contacts on $Al_{0.3}Ga_{0.7}N/AlN/GaN$ heterostructure have been optimized, and

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characterized. Surface control process has been attempted to reduce reverse leakage current. Moreover, annealing process for Schottky contact fabrication has also been optimized to improve Schottky contact characteristics. I-V and C-V data suggests that plasma-induced damages due to etching were partially recovered after annealing and leads to suppress gate leakage current of $Al_{0.3}Ga_{0.7}N$/AlN/GaN based HEMTs. Decrease in gate leakage results in decreasing the ideality factor and increasing SBH. In summary, surface control process and thermal annealing of Schottky contacts are found to be effective methods to improve Ni/Au based Schottky contact performance for $Al_{0.3}Ga_{0.7}N$/AlN/GaN based HEMTs.

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