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Effect of rapid thermal annealing on barrier height and 1/*f* noise of Ni/GaN Schottky barrier diodes

Ashutosh Kumar,[1,2,a)] M. Latzel,[3,4] S. Christiansen,[3,5] V. Kumar,[1,2] and R. Singh[1,2,b)]
[1]*Department of Physics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India*
[2]*Nanoscale Research Facility, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India*
[3]*Max Planck Institute for the Science of Light, Günther-Scharowsky-Straße 1, 91058 Erlangen, Germany*
[4]*Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Institute of Optics, Information and Photonics, Staudtstr. 7/B2, 91058 Erlangen, Germany*
[5]*Helmholtz Center for Materials and Energy, Institute–Nanoarchitectures for energy conversion, Hahn-Meitner-Platz 1, D-14109 Berlin, Germany*

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Current-voltage (as a function of temperature), capacitance-voltage, and 1/*f* noise characteristics of Ni/GaN Schottky barrier diodes (SBDs) as function of rapid thermal annealing (RTA) are studied. It is found that RTA treatments of SBDs at 450 °C for 60 s resulted in a significant improvement of ideality factor and Schottky barrier height: the ideality factor decreased from 1.79 to 1.12 and the barrier height increased from 0.94 to 1.13 eV. The spectral power density of current fluctuations in the diode subjected to RTA at 450 °C is found to be two orders of magnitude lower as compared to the as-deposited diode. Improved diode characteristics and decreased 1/*f* noise in RTA treated (450 °C/60 s) diode are attributed to reduced level of barrier inhomogeneities at the metal-semiconductor interface and explained within the framework of the spatial inhomogeneity model. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4929829]

Gallium nitride (GaN) is a wide band gap (3.4 eV) compound semiconductor having potential applications in high frequency electronic and optoelectronic devices. High electron mobility transistors and metal semiconductor (MS) field effect transistors are widely used where Schottky contact serves as a gate while Ohmic contacts serve as source and drain.[1–6] It is desirable to have as high Schottky barrier height (SBH) as possible, good thermal stability, low leakage current, and low level of 1/*f* noise. 1/*f* noise studies coupled with other characterization techniques have been extensively performed to understand conduction mechanism in various materials and devices.[7–12] In Schottky diode, where current transport mechanism is fairly well understood,[13] origin of 1/*f* noise is still an open question due to controversies behind physical mechanism responsible for 1/*f* noise: mobility fluctuations or number fluctuations.[14–18] Number fluctuations model explained 1/*f* behaviour using distribution of time constant for capture and emission process at MS interface, which seems more realistic in case of real diodes where barrier inhomogeneities at MS interface affect current transport as well as noise properties.[19,20] There are several reports on 1/*f* noise in GaN based devices. Balandin *et al.*[8,12] reported low level of 1/*f* noise (Hooge parameter $\sim 10^{-4}$) in GaN/AlGaN heterostructure field-effect transistors and attributed origin of noise mainly to channel, not the series resistance. In these devices, level of 1/*f* noise is found to be lower with un-doped channels in comparison to doped channels.[21,22] Therefore, 1/*f* noise studies in GaN based devices are very important for competitiveness of GaN technology as substantial information about electronic transport can be extracted out. Also, reduction of 1/*f* noise is important as it can extend up to microwave frequencies limiting performance of Schottky barrier diodes (SBDs) as mixer in intermediate frequency range or it can couple with phase noise in case of oscillators.[18]

GaN based SBDs with barrier heights around 1.0 eV using different metals, like Pt, Pd, Ni, etc., have been already demonstrated.[23–27] As thermal stability of metal contacts is important for device operations at high temperatures and in harsh environments, several authors studied the effect of high temperature furnace annealing on Schottky barrier parameters in GaN based devices.[28–31] In most of these reports, furnace annealing is done for a relatively longer period (5–60 min) where Schottky barriers are found to degrade with increase in annealing temperature. For example, a reduction in SBH in Ni/GaN is observed upon annealing due to reaction of Ni with GaN forming various phases like Ga_4Ni_3, Ga_4Ni_2, etc.[30] Due to difference in heating and cooling rate in rapid thermal annealing (RTA), behavior of devices after RTA treatment is expected to be different in comparison to conventional furnace annealing. Existing literature on RTA treatment of GaN based Schottky diode is limited.[32–34] In the present work, temperature dependent current-voltage (I-V-T), capacitance-voltage (C-V), and 1/*f* noise measurements are performed to analyse the effect of RTA on diode characteristics.

Samples of 1 cm^2 size having 7.5 μm thick GaN layer grown over 300 μm sapphire by metal organic chemical vapour deposition are used for the present study. The layers are unintentionally doped having carrier concentration of 5×10^{16} cm^{-3} as determined by Hall measurements (Ecopia HMS-5000). Prior to Ohmic metallization, samples are ultrasonically cleaned using standard procedure.[25] Ohmic contact pads composed of Ti/Al/Ti/Au with thickness of 30/120/30/200 nm are deposited using radio frequency magnetron sputtering while protecting the central area of the sample by a

a)Electronic mail: ashutosh.kumar@physics.iitd.ac.in
b)Electronic mail: rsingh@physics.iitd.ac.in

metal mask. RTA of the Ohmic contacts is performed in N_2 ambient at 750 °C for 30 s to improve the Ohmic contact quality. Next, Ni/Au circular spots through a metal mask with a diameter of 1 mm and a thickness of 40/100 nm are deposited using e-beam evaporation at a base pressure of 2×10^{-6} mbar. Five identical devices are prepared as mentioned above. Keeping one device as reference, RTA of four devices are performed at different temperatures (300 °C, 450 °C, 600 °C, and 750 °C) for 60 s each at heating rate of 80 °C/min in N_2 ambient. I-V and C-V characteristics of diodes are recorded using an Agilent precision mainframe (model E5270B) and Keithley semiconductor characterization system (SCS-4200), respectively. Temperature dependent I-V characteristics from 80 to 320 K are performed by loading devices in a liquid He cryostat where temperature is stabilized within 0.1 K using a Lakeshore temperature controller (model 332). For 1/*f* noise measurements,[25] a battery generated current of 1 μA is applied across the diodes stabilized at 300 K. The voltage developed across the diode is ac coupled with the pre-amplifier (Stanford Research Systems, model 560), which blocks the non-fluctuating signal and allows only fluctuating signal to pass through it. The fluctuating signal is fed to a fast Fourier transform dynamic signal analyser (Stanford Research Systems, model 785) that displayed the spectral power density of voltage fluctuations (S_V) as a function of frequency in real time. To get noise spectra purely from the SBDs, the spectrum is recorded first at I = 0A (this includes background noise as well as noise generated by various electronic instruments like pre-amplifier, signal analyser, current source, etc.) and then at a forward current of 1 μA. By subtracting the former from the latter, a noise signal for SBDs is obtained. An average of 20 noise spectra is taken for each diode.

Current-voltage (I-V) characteristics of as-deposited and RTA treated (300 °C, 450 °C, 600 °C, and 750 °C for 60 s each) SBDs at 300 K are shown in Fig. 1(a). Forward biased logI-V curves are linear at lower voltages but deviate significantly from linearity, resulting in downward curvature at higher voltages. This is due to the effect of series resistance (R_S) which includes bulk semiconductor resistance and contact resistance.[13] According to thermionic emission theory, current flowing in a Schottky diode is given as[13]

$$I = I_S\left[e^{\frac{q(V-IR_S)}{\eta kT}} - 1\right], \quad \text{where} \tag{1}$$

$$I_S = AA^*T^2 e^{\left(\frac{-q\phi_{b0}}{kT}\right)}. \tag{2}$$

Here, I_S is the reverse saturation current, η the ideality factor, ϕ_{b0} the SBH, T the absolute temperature, k the Boltzmann constant, A* the Richardson constant, and A is the contact area. Values of η and I_S are calculated from slope and intercept of linear region of log I-V plot, respectively, where effect of R_S is negligible while ϕ_{b0} is calculated from I_S using Eq. (2). η and ϕ_{b0} for as-deposited and RTA treated SBDs are plotted as a function of RTA temperature in Fig. 1(b). The schematic of the device is shown in Fig. 1(c). Other barrier parameters like I_S, rectification ratio at ±1 V along with η and ϕ_{b0} are presented in Table I. The diodes are thermally stable up to RTA temperature of 750 °C, as no significant degradation in I-V characteristics is observed. It is found that η decreases while ϕ_{b0} increases with increase in RTA temperature up to 450 °C. At higher RTA temperatures (beyond 450 °C), η is almost constant while ϕ_{b0} decreases slightly possibly due to diffusion of Ni into GaN, which can increase the thermionic field emission causing a decrease in barrier height.[30] Our experimental findings are also supported by studies of Ménard *et al.*[33] where RTA of Ni Schottky diode at 450 °C for 3 min resulted in the formation of Ni-gallide phases at interface which resulted in improved barrier height. However, barrier height reported by them for annealed devices (0.64 eV) is quite low as compared to present work. Reddy *et al.*[32] also demonstrated improvement in Pd/Ru Schottky diode characteristics on RTA at 300 °C due to formation of Pd-gallide phases at interface. In present work, improvement in device characteristics due to formation of Ni-gallide phases at RTA of 450 °C/60 s is also possible; however, we are not focussing on structural characterization. Here emphasizes is on electrical characterization and finding level of inhomogeneities in diodes with and without RTA treatment and further relating the level of barrier inhomogeneities to 1/*f* noise. It is well known that barrier inhomogeneities at MS interface in SBDs fabricated on GaN

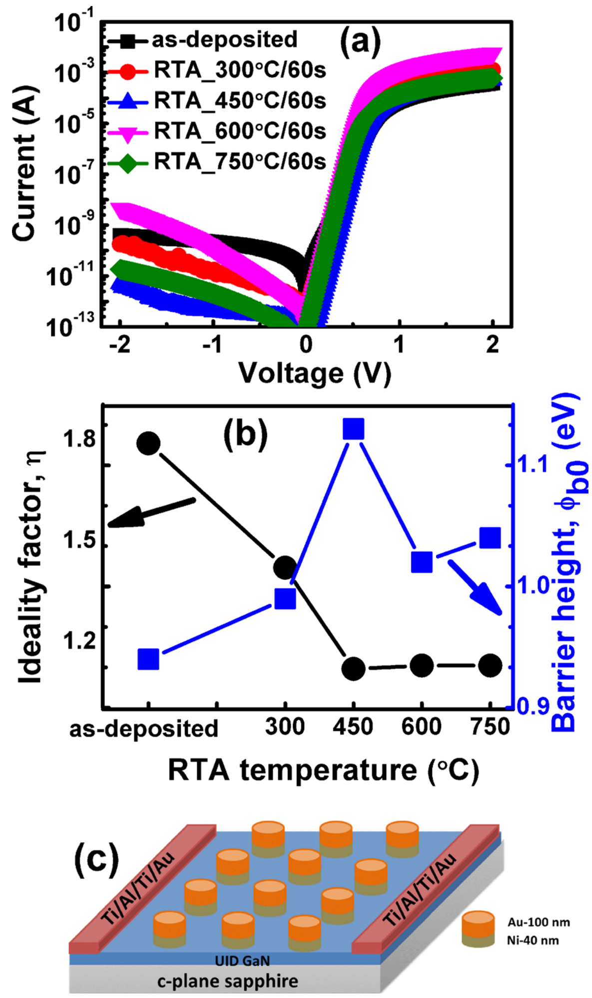

FIG. 1. (a) Current-voltage (I-V) characteristics of the as-deposited and RTA treated (300 °C, 450 °C, 600 °C, and 750 °C) Ni/GaN SBDs at 300 K. Embedded figure shows device schematic. The variation of η and ϕ_{b0} with RTA temperature for as-deposited and RTA treated diodes is shown in (b) while schematic of the characterized device is presented in (c).

TABLE I. Values of ideality factor, zero bias barrier height, reverse saturation current, and rectification (at ±1 V) for as-deposited and rapid thermally annealed SBDs.

RTA Temperature (°C)	Ideality factor (η)	Schottky barrier height, ϕ_{b0}(eV)	Reverse saturation current, I_S(A)	Rectification at ±1 V
0 (as-deposited)	1.79	0.94	4.0×10^{-12}	$\sim 4 \times 10^5$
300	1.42	0.99	5.2×10^{-13}	$\sim 1 \times 10^7$
450	1.12	1.13	3.1×10^{-15}	$\sim 3 \times 10^8$
600	1.13	1.02	1.7×10^{-13}	$\sim 9 \times 10^6$
750	1.13	1.04	7.9×10^{-14}	$\sim 7 \times 10^7$

directly affect the device characteristics.[25,27,35,36] Higher level of barrier inhomogeneities results in increase in η and decrease in ϕ_{b0}. Therefore, improved η and ϕ_{b0} after RTA treatment may be due to reduced level of barrier inhomogeneities. As diodes treated at 450 °C for 60 s showed the best barrier characteristics, so we focussed our study on as-deposited and RTA treated (450 °C/60s) diodes, which are named as D0 and D450/60 s, respectively, henceforth.

It is well known that I-V-T measurements give valuable information about conduction mechanisms in various systems.[25,35–38] Therefore, I-V-T measurements are performed for D0 and D450/60 s in the temperature range of 80–320 K, as shown in Figs. 2(a) and 2(b), respectively. The values of η and ϕ_{b0} are found to increase and decrease, respectively, with the decrease in temperature, as shown in Fig. 2(c). For D0, ϕ_{b0} varies from 0.34 to 0.98 eV, while for D450/60 s, it varies from 0.32 to 1.18 eV with the increase in temperature. Temperature dependence of η and ϕ_{b0} can be explained by departure from thermionic emission at lower temperatures and existence of barrier inhomogeneities at MS interface.[25,35,36] As a consequence of barrier inhomogeneities, barrier height is not constant but follows a Gaussian distribution given as[19,25,35,36]

$$P(\phi_{bl}) = \frac{1}{\sigma_S\sqrt{2\pi}}\exp\left[-\frac{\left(\overline{\phi_{b0}} - \phi_{bl}\right)^2}{2\sigma_S^2}\right], \quad (3)$$

where $1/(\sigma_S\sqrt{2\pi})$ is normalization constant, $\overline{\phi_{b0}}$ and ϕ_{bl} are zero bias mean and local barrier heights, respectively. The standard deviation of Gaussian distribution, σ_S, represents the level of inhomogeneities at the interface. $\overline{\phi_{b0}}$, zero bias mean barrier height, is measured from C-V characteristics while weighted average of local barrier heights represented as ϕ_{b0}, is measured from I-V characteristics. As shown in Fig. 2(c) that ϕ_{b0} for D450/60s increases at higher rate with measurement temperature as compared to D0. As movement of carriers across MS interface is a temperature activated process and ϕ_{b0} is weighted average of local barriers heights, comparison of increase in ϕ_{b0} with temperature indicates narrowing of barrier height distribution, i.e., less inhomogeneity in D450/60s as compared to D0. $\overline{\phi_{b0}}$ and ϕ_{b0} are related as[19,20,25]

$$\phi_{b0} = \overline{\phi_{b0}} - \frac{\sigma_S^2}{2kT}. \quad (4)$$

The values of $\overline{\phi_{b0}}$ as calculated from $1/C^2$-V characteristics (shown in Fig. 3) are found to be 1.16 and 1.20 eV for D0 and D450/60 s, respectively, while values of ϕ_{b0} are calculated using I-V characteristics as mentioned earlier and listed in Table I. Following Eq. (4), σ_S is calculated to be 107 meV for D0 and 60 meV for D450/60 s. Therefore, lower σ_S in D450/60 s resulted in improved η and ϕ_{b0}.

To further understand the electronic transport at MS interface, spectral power density of voltage fluctuations (S_V) is measured as a function of frequency (*f*) at 300 K in a range of 1–100 Hz for both D0 and D450/60 s. Spectral

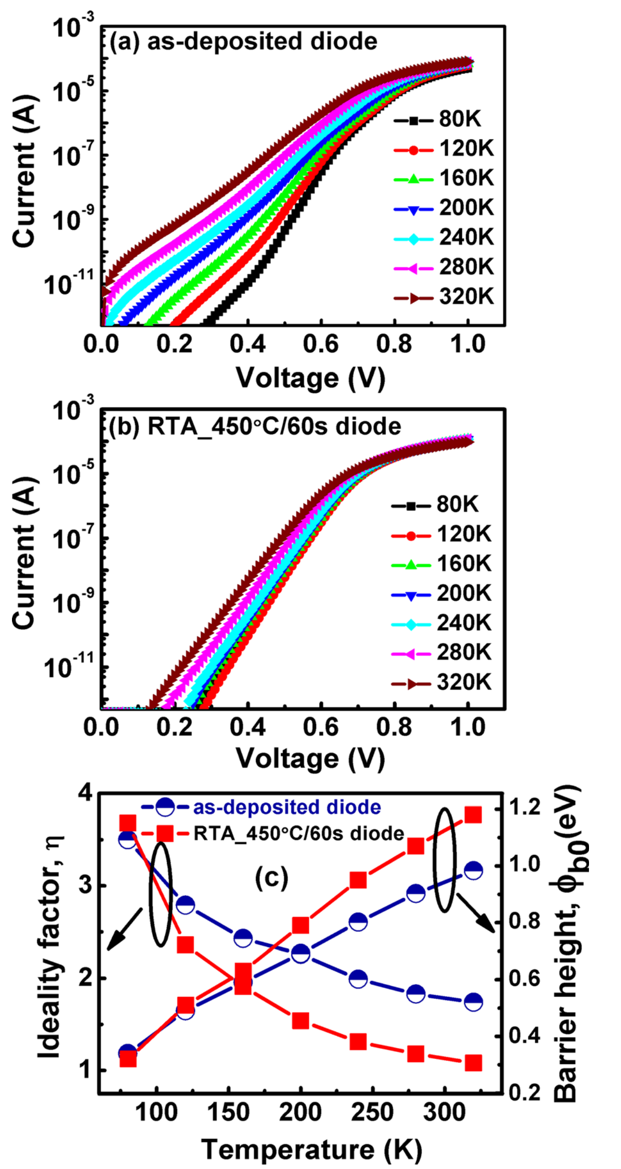

FIG. 2. Forward biased I-V characteristics in temperature range 80 K to 320 K for (a) as-deposited diode (D0) and (b) diode treated at 450 °C for 60 s (D450/60 s). (c) Variation η and ϕ_{b0} with temperature for D0 and D450/60 s.

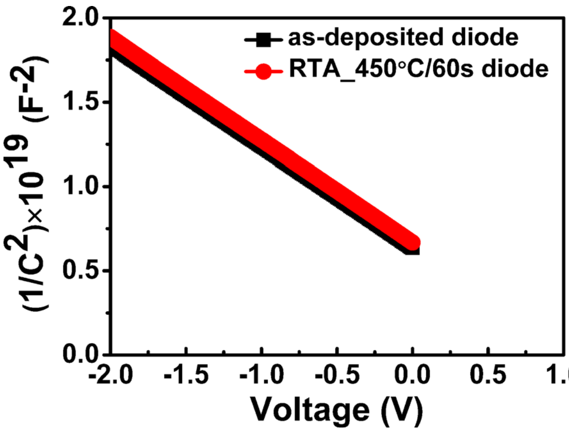

FIG. 3. $1/C^2$-V characteristics at 300 K for as-deposited diode (D0) and diode treated at 450 °C for 60 s (D450/60 s).

power density of current fluctuations (S_I) is obtained from S_V using[25,39]

$$S_I = \frac{S_V}{\left(\frac{dV}{dI} - R_S\right)^2} = \frac{S_V}{\left[\frac{\eta kT}{q(I + I_S)}\right]^2}, \quad (5)$$

where symbols have usual meanings. The S_I varied as $f^{-\gamma}$ with γ close to unity for both the SBDs as shown in Fig. 4. The 1/*f* noise in D450/60s is found to be two orders lower in magnitude in comparison to D0.

Our observations for noise behaviour could be well interpreted with the barrier inhomogeneity model, which includes density of interface states (N_{SS}) as well as level of barrier inhomogeneities to explain noise behaviour.[40] It is well known that interface states distributed over energy inside forbidden gap play a key role in electronic transport across MS interface. On the application of bias, Fermi level moves up or down depending upon interface trap levels, resulting in charge modulation in interface states, which can affect the diode parameters as well as noise behaviour. A part of applied voltage drops across these states, resulting in lesser voltage available for carriers undergoing thermionic emission, which causes an increase in η.[13] Therefore, lower value of η in D450/60s in comparison to D0 indicates

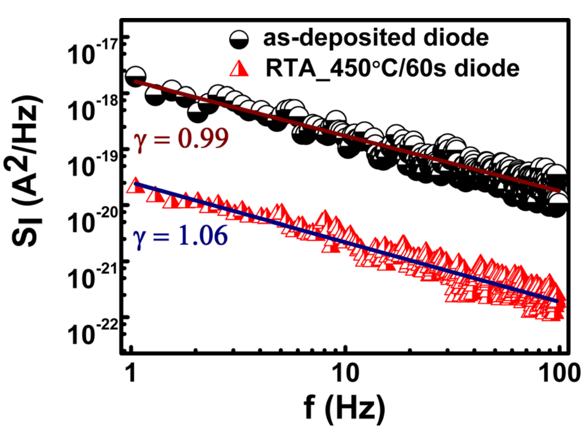

FIG. 4. Spectral power density of current fluctuations, S_I as a function of frequency (*f*) for as-deposited diode (D0) and diode treated at 450 °C for 60 s (D450/60 s) at 1 μA at 300 K. Solid lines represent least square fit.

reduced N_{SS}. The barrier height depends on interface states occupancy which is fluctuating due to random exchange of carriers with respective bands and interface states. This results in fluctuations in time constant for random capture and emission of electrons at interface states and hence, affects level of noise. A linear relationship between noise spectral density and N_{SS} is proposed by various authors.[40–42] Therefore, reduced N_{SS} in D450/60s in comparison to D0 resulted in decreased level of 1/*f* noise. Further, considering an electrically homogenous barrier, as explained by Madenach and Werner,[40] if one assumes all interface states to be mono-energetic or to be continuously distributed over a wide energy range, noise spectra follow a Lorentzian behaviour ($S_I =$ constant at the lower frequency side with respect to the peak position and $S_I \sim \frac{1}{f^2}$ at the higher frequency side).[7] In the case of electrically inhomogeneous barrier where barrier height follows a distribution, noise spectra deviates from Lorentzian towards 1/*f* behaviour.[40] Also, our previous study on Ni/GaN SBDs revealed that existence of barrier inhomogeneities at MS interface, which resulted in 1/*f* noise spectra instead of Lorentzian spectra.[25] The strength of barrier inhomogeneities (σ_S) is directly linked to number of barriers participating in conduction and therefore to the level of 1/*f* noise. Higher the σ_S, higher are the number of barriers participating in conduction. Due to this, higher range of time constants contributes to conduction, which results in higher noise. As σ_S is lower in the D450/60 s as compared to D0, this narrows the distribution of time constants contributing to noise and hence noise power density is reduced.

In summary, effects of RTA on barriers parameters and noise properties of Ni/GaN SBDs are investigated where diode treated at 450 °C for 60 s showed the most significant improvement in ideality factor, barrier height, rectification ratio, and level of 1/*f* noise. Diodes are found to be thermally stable up to 750 °C, as no significant degradation in diode parameters is observed. Temperature dependent I-V measurements revealed inhomogeneous nature of MS interface in both as-deposited and RTA treated (450 °C/60s) SBDs. Level of barrier inhomogeneities at MS interface is significantly reduced in diode treated at 450 °C for 60s. 1/*f* noise in RTA treated (450 °C/60 s) diode is found to be two orders lower as compared to as-deposited diode which is attributed to reduced level of barrier inhomogeneities and interface states. A decreased level of barrier inhomogeneities after RTA treatment narrows the Gaussian distribution of barrier heights and thus reduces number of barriers affecting conduction, which in turn reduces 1/*f* noise.

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