Performance comparison of Pt/Au and Ni/Au Schottky contacts on Al_xGa_{1-x} N/GaN heterostructures at high temperatures*

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In contrast with Au/Ni/$Al_{0.25}Ga_{0.75}$N/GaN Schottky contacts, this paper systematically investigates the effect of thermal annealing of Au/Pt/$Al_{0.25}Ga_{0.75}$N/GaN structures on electrical properties of the two-dimensional electron gas in $Al_{0.25}Ga_{0.75}$N/GaN heterostructures by means of temperature-dependent Hall and temperature-dependent current–voltage measurements. The two-dimensional electron gas density of the samples with Pt cap layer increases after annealing in N_2 ambience at 600 °C while the annealing treatment has little effect on the two-dimensional electron gas mobility in comparison with the samples with Ni cap layer. The experimental results indicate that the Au/Pt/$Al_{0.25}Ga_{0.75}$N/GaN Schottky contacts reduce the reverse leakage current density at high annealing temperatures of 400–600 °C. As a conclusion, the better thermal stability of the Au/Pt/$Al_{0.25}Ga_{0.75}$N/GaN Schottky contacts than the Au/Ni/$Al_{0.25}Ga_{0.75}$N/GaN Schottky contacts at high temperatures can be attributed to the inertness of the interface between Pt and Al_xGa_{1-x}N.

Keywords: gate leakage current, high temperature, Frenkel–Poole emission

PACC: 7360L, 7340N, 7330, 7320H

1. Introduction

The thermal stability of Schottky contacts on Al_xGa_{1-x}N/GaN heterostructures has significant effects on the device performance of GaN-based high electron mobility transistors (HEMTs) at high temperatures.[1,2] Self- or external-heating in high power or harsh environment applications, respectively, requires metal contacts which do not suffer from degradation at working temperatures. The effect of high temperature annealing on morphology and electrical properties of Schottky contacts on nitrides have been reported in Refs. [1], [3]–[5]. However, most of these works are focused on post-annealing characterizations at room temperature (RT), little research at the time of annealing has been conducted so far. The electrical performances of a device after annealing are not identical to those at the time of annealing. In this work, we present electrical properties of Ni/Au and Pt/Au Schottky contacts on Al_xGa_{1-x}N/GaN heterostructures after and during annealing by Hall and current–voltage (I–V) measurements. Qualitative explanations are suggested about the annealing effects.

The Ni Schottky gate metal is widely used in GaN-based HEMTs by virtue of its high work function and good adhesive ability.[1,3] However, Ni diffusion during annealing can induce the acceptor-like deep level which results in the significant degradation of the transport properties of the two-dimensional electron gas (2DEG) in Al_xGa_{1-x}N/GaN heterostructures.[6] The product of the 2DEG density and mobility has a direct impact on the output power density of HEMTs, so it is of considerable importance to find a promising candidate for Schottky contacts on Al_xGa_{1-x}N/GaN heterostructures at high temperatures.

In this paper, in contrast with Au/Ni/$Al_{0.25}Ga_{0.75}$N/GaN Schottky contacts, the effect of thermal annealing of Au/Pt/$Al_{0.25}Ga_{0.75}$N/GaN structures on electrical properties of the 2DEG in $Al_{0.25}Ga_{0.75}$N/GaN heterostructures has been systematically investigated by means of temperature-

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dependent Hall and temperature-dependent I–V measurements.

2. Experiments

The $Al_{0.25}Ga_{0.75}N$/GaN heterostructures have been grown on the (0001) surface of sapphire substrate by using metal–organic chemical vapour deposition (MOCVD). A nucleation GaN buffer layer has been grown at 530 °C, followed by a 2.2-μm-thick unintentionally doped GaN (i-GaN) layer deposited at 1070 °C. The temperature was then increased to 1090 °C to grow the AlN interlayer (about 1 nm) and the 25-nm-thick unintentionally doped $Al_{0.25}Ga_{0.75}N$ barrier. The typical mobility and density of the 2DEG in the heterostructures at RT are 1560 cm^2/Vs and 1.165×10^{13} cm^{-2}, respectively.

After the MOCVD growth, Hall samples with van der Pauw configuration and Schottky diode structures have been fabricated on the wafer. First, Ti/Al/Ni/Au (20/130/50/400 nm) Ohmic contacts were deposited in sequence, followed by rapid thermal annealing in N_2 ambience at 850 °C for 30 s (as-prepared). For Hall samples, a 10-nm-thick Ni or Pt cap layer was then deposited on the surface of $Al_{0.25}Ga_{0.75}N$ barrier by means of e-beam evapouration, respectively (Ni-treated or Pt-treated). Subsequently, the thermal treatments, listed in Table 1, were performed on the Hall samples (Ni-annealed or Pt-annealed). Finally, Ni/Au (50/100 nm) and Pt/Au (50/100 nm) Schottky metal were deposited on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures by means of e-beam evapouration, respectively.

Table 1. Hall measurement results of samples with Ni or Pt cap layer for each processing step.

step	process	2DEG mobility/(cm^2/Vs)		2DEG density/(10^{13} cm^{-2})	
		Ni-related	Pt-related	Ni-related	Pt-related
1	samples without Ni or Pt cap layer for Hall measurements	1530	1560	1.304	1.165
2	e-beam evaporation of 10-nm-thick Ni or Pt film on above samples	1180	1490	1.226	1.144
3	annealed in N_2 ambient at 600 °C for 5 min	1000	1490	1.114	1.201
4	annealed in N_2 ambient at 600 °C for another 5 min	948	1480	1.118	1.221
5	annealed in N_2 ambient at 600 °C for another 10 min		1480		1.233

Temperature-dependent Hall measurements have been performed in vacuum on an Accent HL5500 Hall measurement system with an HL5550 liquid N_2 stage from 90 K to 450 K with 20 K interval and an HL5590 hot stage from 25 °C to 600 °C with 50 °C interval. The temperature-dependent I–V characteristics of the Schottky contacts on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures were performed in vacuum by using an Agilent 4155C semiconductor parameter analyser and an Accent HL5590 hot stage from 25 °C to 600 °C with 50 °C interval.

3. Results and discussion

Table 1 shows the changes of the 2DEG mobility and density of the samples with Ni[6] or Pt cap layer in $Al_{0.25}Ga_{0.75}N$/GaN heterostructures at various steps. The 2DEG mobility at RT decreases from 1530 cm^2/Vs to 1180 cm^2/Vs after the deposition of Ni cap layer. In the meanwhile, the 2DEG density at room temperature is reduced by 7.8×10^{11} cm^{-2}. It is likely that the Fermi level of Ni/$Al_xGa_{1-x}N$/GaN structures will be driven down by Ni deposition and the 2DEG density in $Al_xGa_{1-x}N$/GaN heterostructures decreases.[7,8] Meanwhile, more deep levels in $Al_{0.25}Ga_{0.75}N$ barrier will be ionized due to the decrease of the Fermi level, which enhances the Coulomb scattering on the 2DEG and leads to the degradation of the 2DEG in the heterostructures.[6] For the similar reason, the 2DEG mobility and density decrease to 1490 cm^2/Vs and 1.144×10^{13} cm^{-2}, respectively, after the deposition of Pt cap layer. Both the 2DEG mobility and density of the Ni-treated sample further decrease to 1000 cm^2/Vs and 1.114×10^{13} cm^{-2}, respectively, after annealing in N_2 ambience at 600 °C for 5 min. The 2DEG mobility and density decrease further after annealing in N_2 ambience at 600 °C for another 5 min in the Ni-treated sample, while the annealing treatment has little effect on the 2DEG mobility of the Pt-treated sample, as shown in Table 1. The reason for the degradations of the 2DEG mobility and density of the Ni-annealed samples was that the acceptor-like deep levels have been introduced into the heterostructures during the annealing.[6] The 2DEG density of the Pt-treated sample increases after annealing in N_2 ambience at 600 °C. Although GaN

does not dissociate in vacuum until above 800 °C, formation of nitrogen is accelerated by the reaction of Pt and GaN to form Ga_2Pt and N_2.[9,10] Therefore, we believe that Pt impurity in the annealing will react with adjacent Ga atoms to form Ga-containing compounds, such as Ga_2Pt, and N_2. The effective removal of nitrogen from the $Al_xGa_{1-x}N$ surface appears to be responsible for the forming of N-vacancy (V_N) or/and V_N-related complex, which induce the increase of the 2DEG density.

The temperature dependence of the 2DEG mobility (a) and density (b) of the samples with Ni and Pt cap layer was investigated, as shown in Fig. 1. The 2DEG mobility in as-prepared sample increases dramatically with decreasing temperature from 900 K to 90 K, while in the Ni-annealed one, it increases slightly with decreasing temperature in the same temperature range. The 10-nm-thick Pt cap layer and the related annealing process have little effect on the 2DEG mobility of the Pt-related samples. The 2DEG density is much lower in the Ni-annealed sample than that in the as-prepared one and increases slightly with increasing temperature, while the 2DEG density of the Pt-related samples increases dramatically with increasing temperature, especially at high temperatures. Such behaviour in Ni-annealed sample indicates that the acceptor-like deep levels have been probably introduced into the heterostructures during the Ni-related annealing process.

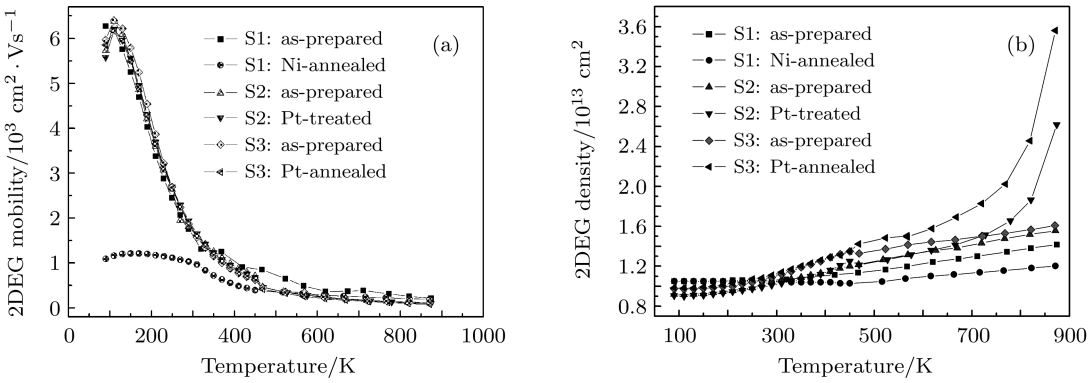


Fig. 1. The temperature dependence of the 2DEG mobility (a) and density (b) of the samples with Ni and Pt cap layer, respectively.

In Fig. 2, we present the current density–voltage (J–V) characteristics of the Ni/Au (a) and Pt/Au (b) Schottky contacts on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures annealed at various temperatures from 400 °C to 600 °C for 10 min to 30 min, respectively. The as-prepared Ni/Au and Pt/Au Schottky contacts on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures behaved in a good rectifying manner. The decrease of reverse leakage current density for low temperature annealing (400 °C) in Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky contacts is due to intimate contact between metal and semiconductor which leads to the increase of Schottky barrier heights.[11] A further increase in the annealing temperature does deteriorate the J–V characteristics of the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes. Upon annealing at 500 °C for 20 min, the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes degraded and most of the diodes did not survive additional annealing at 500 °C for longer times. The Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky contacts after annealing at 500 °C for 30 min behave nearly the same with respect to the forward and reverse J–V characteristics as the Ohmic characteristics. Such degradation is attributable primarily to the onset of interface reactions of Ni and $Al_xGa_{1-x}N$ barrier. The increase in the reverse leakage current of Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes is probably due to the indiffusion of Ni along the threading dislocations into $Al_xGa_{1-x}N$ barrier during the annealing.[12] The Ni impurities will react with adjacent Ga atoms to form Ga-containing compounds which may induce Ga vacancies in $Al_xGa_{1-x}N$ barrier, and this leads to an increase of leakage current.[13] In contrast, very unlike behaviour is observed in the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes after annealing at various high temperatures. It is interesting to note that no clear evidence of degradation is observed for 400 °C, 500 °C and 600 °C annealed diodes under prolonged thermal treatment. One additional point worths mentioning

is that when the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diode is subjected to long-term exposure, for example, 1 h, at 600 °C, the reverse leakage current keeps nearly unchanged and exhibits nearly voltage-independent characteristics. These findings seem to imply that the metal–semiconductor interface in the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes is highly metallurgically stable and nearly free of any interface reactions and component interdiffusion. The possible reason was that once the Ga_2Pt has formed, the interface becomes quite thermodynamically stable.[10,14] It not only successfully stops the outdiffusion of Ga and N from the substrate, but also essentially prevents the penetration of Pt into $Al_xGa_{1-x}N$ barrier. Thus, the formation of a highly stable thin layer between Pt and the $Al_xGa_{1-x}N$ barrier may be the reason for the good thermal stability of the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes.

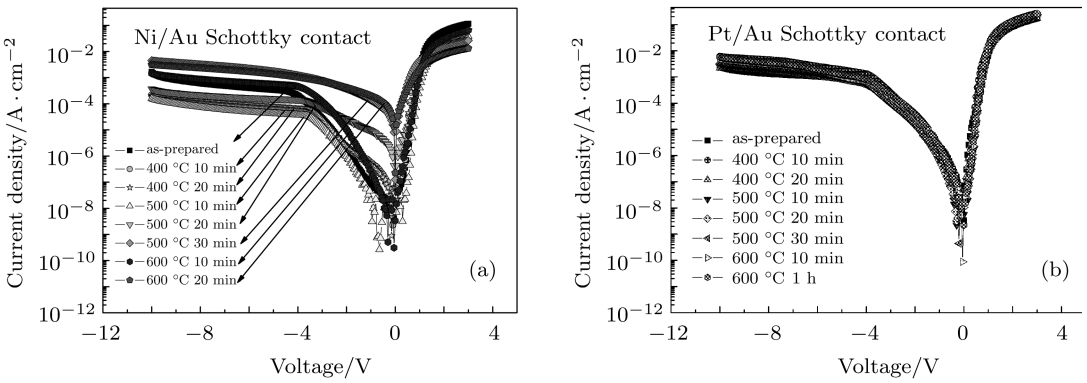


Fig. 2. The current density–voltage (J–V) characteristics of the Ni/Au (a) and Pt/Au (b) Schottky contacts on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures annealed at various temperatures from 400 °C to 600 °C for 10 min to 30 min, respectively.

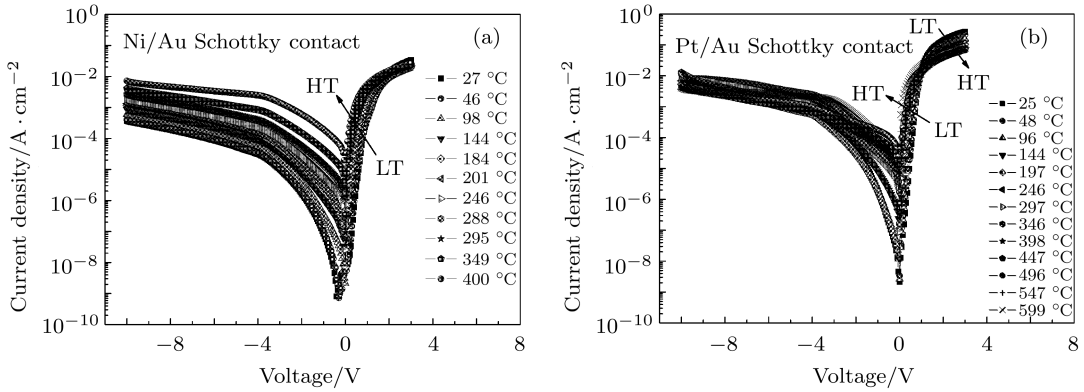


Fig. 3. The current density–voltage–temperature (J–V–T) characteristics of the Ni/Au (a) and Pt/Au (b) Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures, respectively. Direction of the arrowheads is from low temperature (LT) to high temperature (HT).

The current density–voltage–temperature (J–V–T) characteristics of the Ni/Au (a) and Pt/Au (b) Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures have been measured, respectively, as shown in Fig. 3. The thermal cycles consisted in successive upward ramps of 10 °C/min from room temperature to 600 °C holding a duration of 5 min for the measuring temperatures. The diodes were also measured during the cooling process (downward ramps of 10 °C/min). During the cooling, the currents invert the trend and approximately recover their value of the annealing process (not shown here). Here, the J–V–T characteristics of the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes were not measured exceeding 400° because most of the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes did not survive additional annealing at 500° for longer times. The J–V–T characteristics of the Pt/Au and Ni/Au Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures present a similar behaviour for forward bias but dissimilar shape when reversely biased. Temperature-dependent Hall measurements indicate that the sheet resistivity of

the heterostructures increases with increasing temperature. The increase of the sheet resistivity causes an increase of the series resistance, this effect leads to downward I–V curve at voltages larger than 1 V for the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes (2 V for the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes).

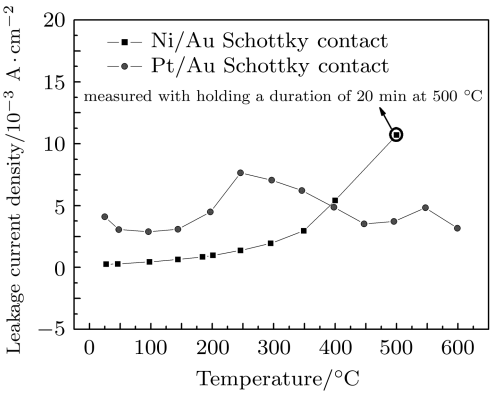


Fig. 4. The evolution of the reverse leakage current density of the Ni/Au and Pt/Au Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures as a function of the temperature measured at –9 V. The dot with a circle was measured with holding a duration of 20 min at 500 °C.

Figure 4 shows the evolution of the reverse leakage current density characteristics of the Ni/Au and Pt/Au Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures as a function of the temperature measured at –9 V. The Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes reduce the leakage current at annealing temperatures above 400 ℃ in comparison with the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes. Nevertheless, Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes produce larger leakage currents in the as-prepared diodes. However, unlike the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes, the reverse leakage current of the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes remains stable during the whole cycle (up to 600 °C) and exhibits nearly voltage-independent characteristics.

Frenkel–Poole emission refers to electric-field-enhanced thermal emission from a trapped state into a continuum of electronic states. The reverse leakage current density associated with Frenkel–Poole emission is given by[15]

$$J = CE_{\rm b}\exp\Big[-\frac{q(\phi_{\rm t}-\sqrt{qE_{\rm b}/\pi\varepsilon_0\varepsilon_{\rm s}})}{kT}\Big], \qquad (1)$$

where $E_{\rm b}$ is the electric field in the semiconductor barrier and is calculated assuming that it is constant within the $Al_xGa_{1-x}N$ barrier, $\Phi_{\rm t}$ is the barrier height for electron emission from the trapped state, $\varepsilon_{\rm s}$ is the relative dielectric permittivity, ε_0 is the permittivity of free space, T is the temperature, and k is Boltzmann's constant. The current transport by Frenkel–Poole emission, $\ln(J/E_{\rm b})$, should be a linear function of $\sqrt{E_{\rm b}}$,

$$\log(J/E_b) = \frac{q}{kT}\sqrt{\frac{qE_b}{\pi\varepsilon_0\varepsilon_s}} - \frac{q\phi_t}{kT} + \log C \equiv R(T)\sqrt{E_b} + S(T), \qquad (2a)$$

$$R(T) = \frac{q}{kT}\sqrt{\frac{q}{\pi\varepsilon_0\varepsilon_s}}, \qquad (2b)$$

$$S(T) = -\frac{q\phi_t}{kT} + \log C. \qquad (2c)$$

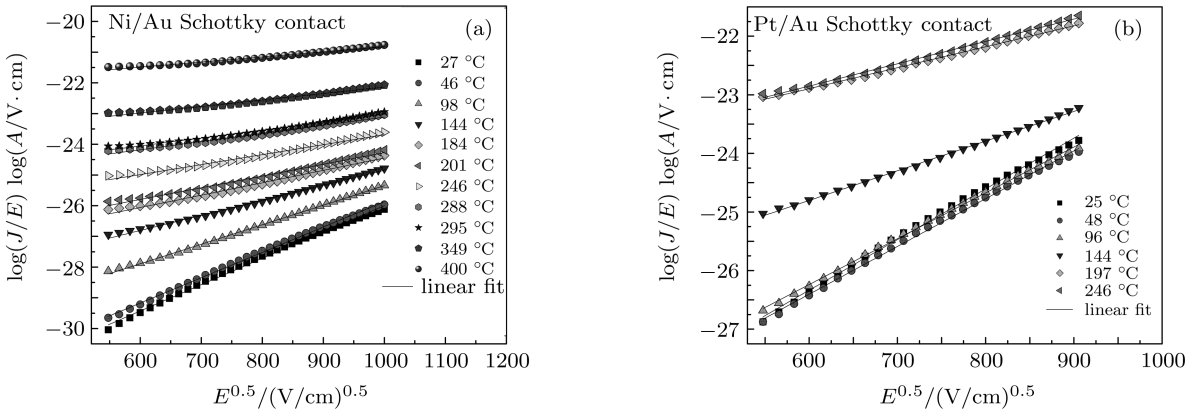


Fig. 5. Measured reverse leakage current density divided by electric field vs. square root of electric field for the Ni/Au (a) and Pt/Au (b) Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures, respectively.

As seen in Figs. 5(a) and 5(b), the leakage current densities in both the Ni/Au and Pt/Au Schottky diodes on the $Al_{0.25}Ga_{0.75}N$/GaN heterostructures are well described by the Frenkel–Poole emission. We obtain

$\Phi_t = 0.42$ eV in the temperature range of 25 °C–250 °C for the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes and $\Phi_t = 0.54$ eV in the temperature range of 25 °C–400 °C for the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes. The negative temperature dependence of leakage current in the temperature range higher than 250 °C for the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes is due to the impact ionization.[16]

4. Conclusions

In summary, in contrast with Au/Ni/$Al_{0.25}Ga_{0.75}$ N/GaN Schottky contacts, the effect of thermal annealing of Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN structures on electrical properties of the 2DEG in $Al_{0.25}Ga_{0.75}N$/GaN heterostructures has been systematically investigated by means of temperature-dependent Hall and temperature-dependent I–V measurements. In comparison with the degradation of the 2DEG mobility and density in the Ni-treated samples, the 2DEG density of the Pt-treated samples increases after annealing in N_2 ambience at 600 °C, while the annealing treatment has little effect on the 2DEG mobility of the Pt-treated samples. The Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes reduce the leakage current at annealing temperatures above 400 °C in comparison with the Au/Ni/$Al_{0.25}Ga_{0.75}N$/GaN Schottky diodes. As a conclusion, the Au/Pt/$Al_{0.25}Ga_{0.75}N$/GaN Schottky contacts are ideal candidates as thermally stable contacts for high temperatures due to the inertness of the interface between Pt and $Al_xGa_{1-x}N$.

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