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High-Reflectivity Al-Pt Nanostructured Ohmic Contact to p-GaN

Ho Gyoung Kim, Parijat Deb, and Timothy Sands, *Member, IEEE*

Abstract—The effect of nanoscale Pt islands on the electrical characteristics of contacts to p-type gallium nitride (GaN) has been investigated to explore the feasibility for the flip-chip configuration light-emitting diodes (LEDs) using an Al-based reflector. An as-deposited Al contact to p-GaN with a net hole concentration of $3 \times 10^{17} \text{ cm}^{-3}$ was rectifying. However, an Al contact with nanoscale Pt islands at the interface exhibited ohmic behavior. A specific contact resistivity of $2.1 \times 10^{-3} \Omega \cdot \text{cm}^2$ and a reflectance of 84% at 460 nm were measured for the Al contact with nanoscale Pt islands. Current–voltage temperature measurements revealed a Schottky barrier height reduction from 0.80 eV for the Al contact to 0.58 eV for the Al contact with nanoscale Pt islands. The barrier height reduction may be attributed to electric field enhancement and the enhanced tunneling due to the presence of the nanoscale Pt islands. This will offer an additional silver-free option for the p-type ohmic contact in flip-chip configuration LEDs. Theory suggests that the ohmic contact characteristics may be improved further with smaller Pt islands that will enhance tunneling across the interface with the GaN and in the vicinity of the Pt–Al interface.

Index Terms—Contact resistivity, flip-chip configuration, Pt islands, Schottky barrier height (SBH), tunneling.

I. INTRODUCTION

GALLIUM nitride (GaN) and related nitride semiconductors are of great technological importance for short-wavelength light-emitting devices including green, blue, and UV laser diodes and light-emitting diodes (LEDs) [1]. In the conventional LED configuration, light is emitted through the last-grown p-GaN layer. The high sheet resistance of the p-GaN layer necessitates a transparent current spreading layer with low contact resistance to p-GaN. The conflicting demands of transparency and low series resistance limit the external quantum efficiency of the device. The device performance can be substantially improved by employing a flip-chip configuration [2]–[4], in which a blanket p-GaN ohmic metallization serves as a mirror to direct light through the n-GaN layer. If

the sapphire substrate is retained, its index of refraction being intermediate between those of the GaN and the epoxy package enhances external light coupling. Alternatively, the sapphire substrate can be removed by laser liftoff (LLO) [5], and the exposed GaN surface can be modified for optimal external light coupling. In either flip-chip configuration, the relatively low sheet resistance of the n-GaN obviates the need for a transparent ohmic contact. The challenge becomes the fabrication of an ohmic contact to p-GaN that has both high reflectivity and low contact resistance. From the perspective of reflectivity, a pure silver contact would be optimal, with Al as the best alternative. Silver, however, exhibits poor adhesion to GaN as well as void formation during deposition and annealing [6]. Aluminum, with its superior resistance to agglomeration and its passivating oxide, is therefore a more suitable option for a reflecting contact. From the perspective of contact resistance, however, pure Al is not an option. The relatively low work function of Al suggests a high barrier height to holes and low barrier height to electrons. The Al/n-GaN interface is more complex, as Al reacts with GaN to form AlN, and the depletion of N from the GaN near the interface generates donors related to N vacancies [7], reducing the specific contact resistance to n-GaN. One strategy for retaining the high reflectivity of Al while achieving an ohmic contact to p-GaN is to utilize a small areal fraction of the interface for current transport through a metal with a higher work function. This heterogeneous approach should be superior to a uniform ultrathin ohmic contact metallization followed by an Al overlayer. Sohn *et al.* [8] showed improved ohmic contact characteristics of Ni/p-GaN with Au nanodots deposited using porous anodic alumina (PAA) as a nanomask. Song *et al.* [9] incorporated nanoscale Ni islands using thermal annealing in Ag/ITO/p-GaN and observed improved ohmic contact characteristics. Lee *et al.* [10], depositing Ti nanodots by an aerosol method, investigated the Schottky barrier reduction in Ti/SiC contacts. In this paper, nanoscale Pt islands embedded in Al reflecting films at the interface with the GaN are shown to reduce both the Schottky barrier height (SBH) and ohmic contact resistance to p-GaN as compared to pure Al contacts. The mechanism of current transport across the metal–semiconductor (MS) contact has been elucidated using current–voltage temperature (I – V – T) measurements in conjunction with modeling.

II. EXPERIMENTAL

Mg-doped p-type GaN film grown by organometallic vapor phase epitaxy (OMVPE) on c-plane sapphire substrates was used for this paper. The carrier concentration determined by capacitance–voltage (C – V) measurements was about

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$3 \times 10^{17} \text{ cm}^{-3}$. Four metal schemes were prepared: a 150-nm thick Pt layer, a 150-nm thick Al layer, a Pt (2 nm)/Al (150 nm) bilayer (denoted as Pt/Al), and a 150-nm thick Al contact with nanoscale Pt islands (denoted as nano-Pt/Al). Prior to metal deposition, the GaN samples were cleaned ultrasonically using acetone, methanol, rinsed in DI water, blown dry with N_2 , and then dipped into boiling aqua regia ($\text{HCl}:\text{HNO}_3 = 3:1$) for 10 min to remove the surface oxide. A 2-nm thick Pt layer was deposited by electron-beam evaporation over the p-GaN surface of the one sample followed by rapid thermal annealing at 750°C for 1 min in an N_2 ambient to agglomerate a 2-nm thick Pt layer into nanoscale Pt islands. The blanket GaN samples and GaN layer with nanoscale Pt islands were cleaned ultrasonically using acetone, methanol, rinsed in DI water, blown dry with N_2 , and then dipped into buffered oxide etchant (BOE) for 10 min to remove the native oxide layer. The circular transfer length method (CTLTM) was used to measure the specific contact resistivity. The outer dot radius was $200 \mu\text{m}$, and the spacing between the inner and outer radii was in the range of $5\text{--}45 \mu\text{m}$. Metallization patterns were defined by standard photolithography. Prior to metal deposition, all samples were dipped into BOE to remove the surface oxide.

Four p-GaN samples with a size of about $3 \times 5 \text{ mm}$ were utilized to fabricate Schottky diodes for investigating the current flow mechanism across the MS contact. One of the samples was chosen to include nanoscale Pt islands that were prepared by depositing a 2-nm thick Pt layer on one half of the sample, followed by thermal annealing at 750°C for 1 min in an N_2 ambient. For each of the four samples intended for Schottky barrier characterization, a large area ohmic contact was fabricated on the other half of the sample surface. The ohmic contact was fabricated by first cleaning the samples in acetone, methanol, and then removing the surface oxide in a BOE solution immediately prior to loading into an electron-beam evaporator. A Pt/Au (50 nm/50 nm) bilayer was deposited over approximately half of the sample to serve as the ohmic contact. Without thermal annealing, it showed an ohmic characteristic with a contact resistivity of $\sim 5 \times 10^{-4} \Omega \cdot \text{cm}^2$. The same four metal schemes used to measure the specific contact resistivity were employed for the Schottky contact using a metal shadow mask with an exposed diameter of $250 \mu\text{m}$. Current–voltage (I – V) and C – V measurements were performed with a Keithley 238 high current source and an HP 4275A LCR meter.

III. RESULTS AND DISCUSSION

Fig. 1 shows a field-emission scanning electron microscopy (FESEM) image obtained from the 2-nm thick Pt layer on the p-GaN surface after annealing at 750°C for 1 min in an N_2 ambient. The Pt thin film was agglomerated into nanoscale islands with lateral dimensions in the range of $40\text{--}100 \text{ nm}$ and a density of $2 \times 10^9 \text{ cm}^{-2}$, corresponding to about 13% areal coverage. Fig. 2 shows the I – V characteristics, measured with a gap spacing of $10 \mu\text{m}$. The uniform Al contact shows a nonohmic behavior. However, the Pt contact and the nano-Pt/Al contact show linear I – V characteristics. To minimize the contact resistance between the probe tip and the metal layer, a four-point probe configuration was used to measure the

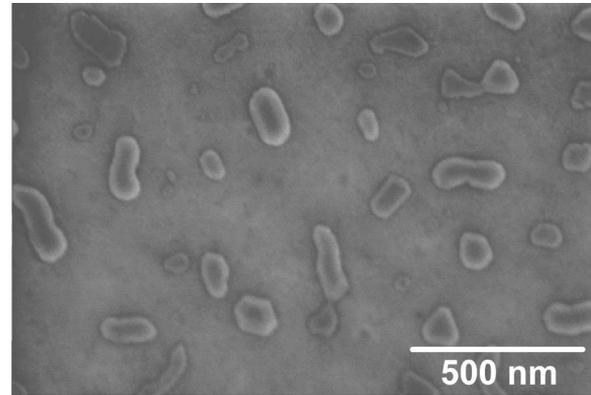


Fig. 1. FESEM image of the nanoscale Pt islands on the GaN film formed after annealing a 2-nm thick Pt layer at 750°C for 1 min in an N_2 ambient.

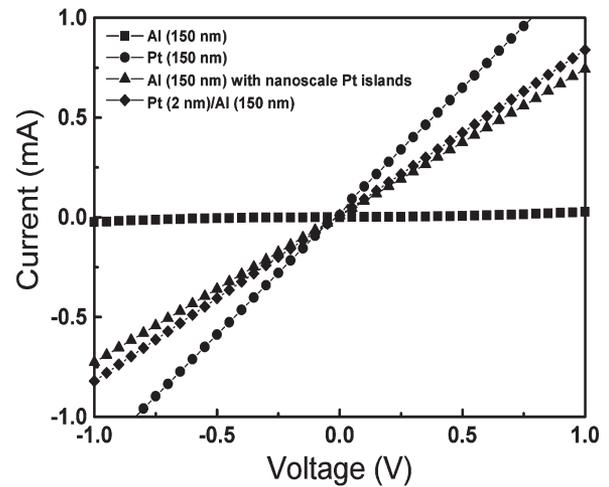


Fig. 2. I – V characteristics of an Al contact, a Pt contact, and an Al contact with nanoscale Pt islands measured with a gap spacing of $10 \mu\text{m}$.

total resistance between the inner and outer dots. The specific contact resistivity was determined to be $2.8 \times 10^{-4} \Omega \cdot \text{cm}^2$ for the Pt contact, $1.0 \times 10^{-3} \Omega \cdot \text{cm}^2$ for the Pt/Al contact, and $2.1 \times 10^{-3} \Omega \cdot \text{cm}^2$ for the nano-Pt/Al contact, respectively. The presence of nanoscale Pt islands at the Al contact interface reduced the contact resistivity significantly. The mechanism of the improved electrical properties with nanoscale Pt islands was investigated further utilizing Schottky diodes.

The forward-bias characteristics of a Schottky diode can be analyzed using the thermionic-emission (TE) model [11]:

$$I = I_0 [\exp\{q(V - IR_S)/nk_B T\} - 1] \quad (1)$$

$$I_0 = AA^{**} T^2 \exp(-q\phi_B/k_B T) \quad (2)$$

where A is the device area, A^{**} is the effective Richardson constant, ϕ_B is the barrier height, n is the ideality factor, and R_S is the series resistance. The ideality factors obtained from (1) at room temperature are 1.98, 2.78, 2.44, and 2.33 for the Al contact, the Pt contact, the Pt/Al contact, and the nano-Pt/Al contact, respectively. These high n values indicate

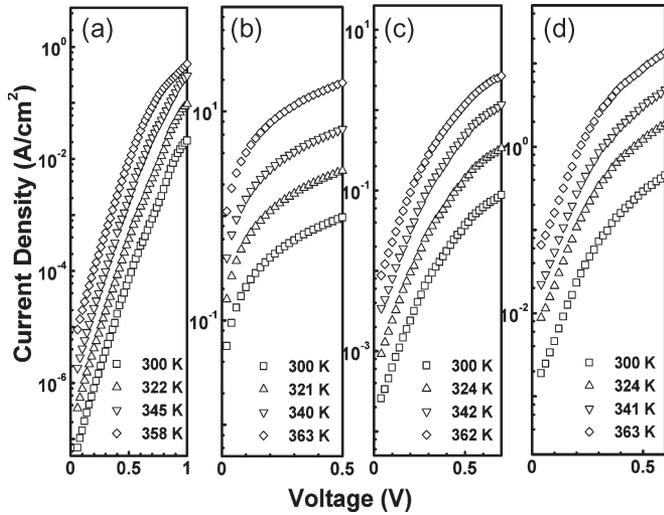


Fig. 3. Forward current J - V curves with various temperatures for (a) Al contact, (b) Pt contact, (c) nano-Pt/Al contact, and (d) Pt/Al contact.

that the current transport cannot be explained by the pure TE model. In order to investigate this behavior more quantitatively, I - V - T measurements were conducted. Fig. 3 shows the current density-voltage (J - V) characteristics at various temperatures. The thermionic model predicts a $1/k_B T$ dependence for the linear region of the $\ln J$ - V curves. In contrast, the experimental data exhibit little temperature dependence of the slope of the $\ln J$ - V characteristics in the linear region (Fig. 3). The parallel shifts of the $\ln J$ - V curves indicate electron transport with a tunneling component [12], [13]. The forward bias characteristics using a tunneling model are given by [13]

$$I \sim AA^{**} B \exp(-q\phi_B/E_{00}) \exp(qV/E_{00}) \quad (3)$$

$$E_{00} = q\hbar\sqrt{(N_a/m^*\epsilon_s)/2} \quad (4)$$

where B is the parameter related to the temperature and the Fermi level in the semiconductor, N_a is the acceptor concentration, ϵ_s is the dielectric constant of the semiconductor, and E_{00} is the characteristic energy related to the tunneling probability. According to (3), the slope of the $\ln J$ - V characteristics is independent of temperature. In addition, the slope of the $\ln J$ - V characteristics in the linear region yields the value of E_{00} . The extracted E_{00} values are 35, 50, 44, and 42 meV for the Al contact, the Pt contact, the Pt/Al contact, and the nano-Pt/Al contact, respectively.

The current-transport mechanisms at the MS contact are dependent on the tunneling parameter E_{00} , such as thermionic emission (TE) for $E_{00}/k_B T \ll 1$, thermionic field emission (TFE) for $E_{00}/k_B T \sim 1$, and field emission (FE) for $E_{00}/k_B T \gg 1$ [14]. As a result, TFE is dominant for all metal contacts. Smit *et al.* [15] showed the decrease of the Schottky barrier thickness with decreasing diode size. Consequently, the resistance of the diode was reduced due to the enhanced tunneling. Therefore, the increase in the E_{00} value in this paper from 35 meV for the Al contact to 42 meV for the nano-Pt/Al contact can be explained by the enhanced tunneling due to the presence

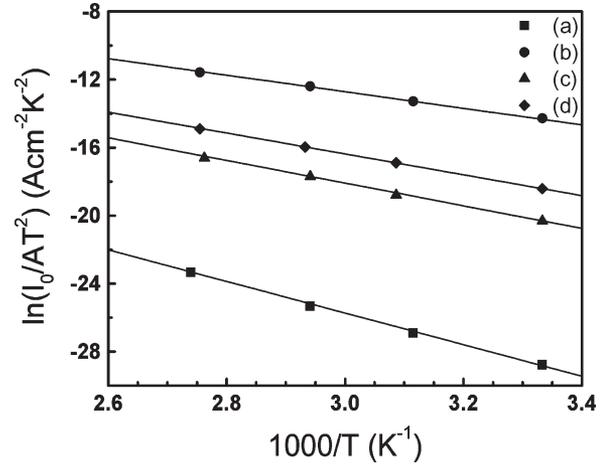


Fig. 4. Richardson plot of $\ln(I_0/AT^2)$ versus $1000/T$ for (a) Al contact, (b) Pt contact, (c) nano-Pt/Al contact, and (d) Pt/Al contact. The effective Schottky barrier height and Richardson constant were determined.

of Pt islands with nanoscale dimensions at the MS contact interface.

Narayanan *et al.* [16] demonstrated the reduction of contact resistance in silicon by metal nanocrystals embedded in another metal with a different work function. They attributed this phenomenon to the enhanced electric field in silicon close to triple interface, in which the barrier is significantly thinner than normal. As a result, the tunneling cross section is proportional to the sum of perimeters of all nanoscale Pt islands in the contact region. Smaller nanoscale islands will provide enhanced tunneling by increasing the total perimeter length at the same areal coverage. The decrease in the radius of the nanoscale islands from 100 to 10 nm yields an increase of ten times of the total perimeter length. Furthermore, enhanced tunneling for smaller nanoscale islands is expected due to the effect of geometrical curvature. Therefore, smaller Pt islands in the Al contact will improve the ohmic contact characteristics.

Fig. 4 shows the Richardson plots. The effective SBH and Richardson constant (A^{**}) can be obtained by plotting $\ln(I_0/AT^2)$ versus $1/T$ as dictated by (2). The SBH and A^{**} were determined to be 0.80 eV and $8.5 \text{ A} \cdot \text{cm}^{-2} \cdot \text{K}^{-2}$, 0.42 eV and $6.7 \text{ A} \cdot \text{cm}^{-2} \cdot \text{K}^{-2}$, 0.53 eV and $7.8 \text{ A} \cdot \text{cm}^{-2} \cdot \text{K}^{-2}$, and 0.58 eV and $6.8 \text{ A} \cdot \text{cm}^{-2} \cdot \text{K}^{-2}$, respectively, for the Al contact, the Pt contact, the Pt/Al contact, and the nano-Pt/Al contact. The theoretical value of A^{**} is determined to be $103.8 \text{ A} \cdot \text{cm}^{-2} \cdot \text{K}^{-2}$ with the effective hole mass of $m^* = 0.8 m_e$ [17]. This large discrepancy of Richardson constant between the theoretical value and obtained values in this paper indicates the presence of a barrier, through which the electrons must tunnel [18].

According to the current transport theory in the TFE regime, the specific contact resistivity ρ_c is given by [14]

$$\rho_c = \frac{\coth^{1/2}(E_{00}/k_B T) \cosh(E_{00}/k_B T)}{(qA^{**}/k_B^2)[\pi E_{00}q(\phi_B + \psi_F)]^{1/2}} \times \exp\left[\frac{q(\phi_B + \psi_F)}{E_{00} \coth(E_{00}/k_B T)} - \frac{q\psi_F}{k_B T}\right] \quad (5)$$

and in the FE regime, ρ_c is given by [14]

$$\rho_c = \frac{k_B}{qA^{**}} \exp \left[\frac{q\phi_B}{E_{00}} \right] \left\{ \frac{\pi T}{\sin(\pi C_1 k_B T)} - \frac{\exp[-C_1 q \psi_F]}{k_B C_1} \right\}^{-1} \quad (6)$$

where ψ_F is the energy difference between the Fermi level and the valence band and $C_1 = \ln[4\phi_B/\psi_F]/(2E_{00})$. Using the extracted values of ρ_c , E_{00} , and A^{**} , the SBHs were determined to be 0.50, 0.55, and 0.57 eV for the Pt contact, Pt/Al contact, and nano-Pt/Al contact, respectively, according to (6) (FE regime). The SBHs were found to be 0.63 eV for the Pt contact, 0.64 eV for both the Pt/Al contact and the nano-Pt/Al contact from the FE model is closer to the SBH of 0.42 eV from the I - V - T measurement for the Pt contact. For both the Pt/Al contact and the nano-Pt/Al contact, the SBHs obtained from the FE model are closer to the SBHs of 0.53 and 0.58 eV from the I - V - T measurement than those calculated from the TFE model. Although the TFE model was expected to be applicable from the relation of E_{00} and $k_B T$ for the Pt/Al contact and the nano-Pt/Al contact, the FE model provides a better fit to the experimental data. Thus, it can be inferred that the SBH and depletion width around the Pt islands were reduced compared to the Al contact, and this enhances the tunneling probability, resulting in an improved ohmic contact.

According to Tung's model, the potential distribution and the electric field for circular patch geometry at the MS interface can be expressed as [19]

$$V(0, 0, z) = V_{bb} \left(1 - \frac{z}{w} \right)^2 + V_a + V_p - \Delta \left(1 - \frac{z}{(z^2 + R_0^2)^{1/2}} \right) \quad (7)$$

where $V_{bb} = \phi_B^0 - V_p - V_a$ is the band bending due to the MS junction with a uniform SBH, V_p is the energy difference between the Fermi level and the valence band, z is the distance from the surface of the semiconductor, w is the depletion width, Δ is the barrier height difference between the uniform barrier height region and the patch, and R_0 is the radius of the circular patch. When the patch size is comparable to or smaller than the average depletion layer width, the conduction path in front of this patch becomes "pinched-off" by the surrounding high barrier region [19], [20]. Fig. 5(a) shows the calculated potential distribution as a function of distance from the surface. Potential pinchoff is clearly seen for small patches. However, the average size of Pt islands is larger than that of the average depletion width (~ 45 nm) in this paper. Thus, potential pinchoff is not seen as shown in Fig. 5(a). The total current through the MS interface can be regarded as the sum of the current passing the uniform barrier height region, and patches according to the parallel conduction model, which is given by [21]

$$\phi_C = -\frac{k_B T}{q} \ln \left\{ \frac{S_l}{S} \left[\exp \left(-\frac{q\phi_l}{k_B T} \right) - \exp \left(-\frac{q\phi_h}{k_B T} \right) \right] + \exp \left(-\frac{q\phi_h}{k_B T} \right) \right\} \quad (8)$$

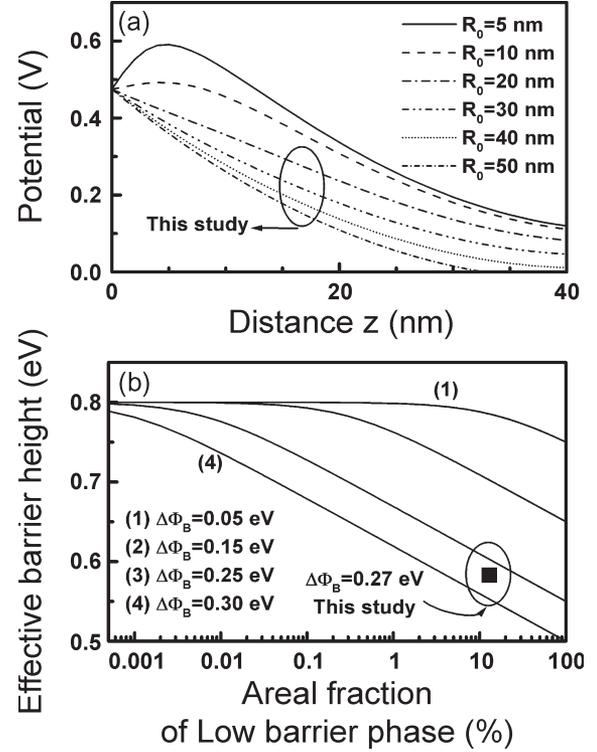


Fig. 5. (a) Calculated potential distribution as a function of distance from the surface. (b) Calculated effective barrier height versus areal fraction of low barrier phase.

where S_l is the area of low barrier phase, ϕ_h is the high barrier height, ϕ_l is the low barrier height, and ϕ_C is the effective barrier height. Fig. 5(b) shows the calculated curves of effective barrier height versus areal fraction of low barrier height phase (S_l/S). By taking the uniform barrier height as 0.80 eV (Al contact), the fraction of the total patch area as 0.13, and the effective barrier height for the nano-Pt/Al contact as 0.58 eV, a calculation yielded the barrier height difference between the uniform region and the patches as 0.27 eV. In other words, the effective barrier height of the patches (Pt islands) is 0.53 eV. This value is higher than that (0.42 eV) from I - V - T measurement for the Pt contact, but closer to that (0.50 eV) from (6).

Reflectance measurements were carried out in order to evaluate the potential of the Al-Pt ohmic contact to flip-chip LEDs. A 150-nm thick Pt layer, a 150-nm thick Al layer, a Pt (2 nm)/Al (150 nm) bilayer, a 150-nm thick Al contact with nanoscale Pt islands, and a Ni (3 nm)/Au (5 nm)/Al (150 nm) contact were deposited on the p-GaN surface of the LED samples grown on double-side polished sapphire substrates. The reflectance of the Al surface side with a 150-nm thick aluminum mirror deposited on glass was used as a reference (relative reflectivity of 100%). Fig. 6 shows the optical reflectance spectra obtained from the Al contact, the Pt contact, the Pt/Al contact, and the nano-Pt/Al contact. The relative reflectances measured through the sapphire substrate side at 460 nm were determined to be 88%, 64%, 78%, and 84% for the Al contact, the Pt contact, the Pt/Al contact, and the nano-Pt/Al contact, respectively. The relative reflectance measured with the conventional contact scheme of Ni/Au/Al contact was to be 65% at 460 nm. The relative

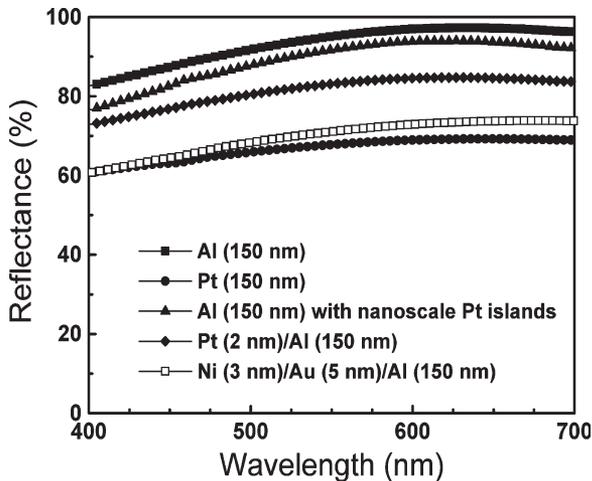


Fig. 6. Relative reflectance spectra obtained from Al contact, Pt contact, Pt/Al contact, nano-Pt/Al contact, and Ni/Au/Al contact as measured through the sapphire substrate and GaN heterostructure. A front-side Al mirror (150 nm) was used as a reference and assigned a relative reflectivity of 100% at all wavelengths.

reflectance of the nano-Pt/Al contact is about 6%–8% higher than that of the Pt/Al contact, and about 18%–22% higher than that of the Ni/Au/Al contact. The nano-Pt/Al contact has higher reflectance when compared to the previous studies of a NiO/Al contact [22] and a Ni/Au/Al contact [23]. Therefore, it can be inferred that the Al contact with nanoscale Pt islands in this paper would be a satisfactory reflective ohmic contact for LEDs.

IV. CONCLUSION

In conclusion, we have investigated the effect of nanoscale Pt islands on the contact resistivity and SBH in Al/p-GaN contact. It was shown that the Al contact with nanoscale Pt islands produced good ohmic characteristics and high reflectance. I - V - T measurements in combination with modeling showed that the electric field enhancement and the increase of the possibility of the tunneling due to the nanoscale Pt islands result in an improved ohmic contact. These results indicate that the Al contact with nanoscale Pt islands can be applied for the fabrication of flip-chip LEDs with high reflectance, thereby providing a more robust Al-based alternative to the Ag-based reflective contacts to p-GaN.

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