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Highly Reflective Ag/La Bilayer Ohmic Contacts to p-Type GaN

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A new Ag/La bilayer metal contact scheme has been developed for producing high reflectance and low contact resistivity ohmic contacts to p-GaN. An excellent reflectance of over 91% at 460 nm wavelength and low specific contact resistivity of 1.6 $\times 10^{-4}$ Ω cm^2 were obtained from Ag/La (150/20 nm) contact annealed at 450°C for 1 min. The La overlayer was oxidized to form La_2O_3 when exposed to air, which effectively suppresses exposure of the Ag layer to oxygen atmosphere during annealing, leading to a good ohmic contact with smooth surface morphology and high reflectance. Additionally, Ag/La contacts show excellent thermal stability after a long thermal annealing at 300°C in air ambient.
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Due to the better current spreading and efficient thermal dissipation, GaN-based vertical-structure light-emitting diode (VLED) has been considered as a promising choice for high-power applications.[1-3] In the VLEDs, a high reflectance and low resistance p-GaN ohmic contact is essential to increase the light extraction and improve device performance. Silver (Ag) is a well-known highly reflective metal across the visible spectrum and could form ohmic contacts to p-GaN by annealing in air ambient. However, agglomeration of Ag films occurred during annealing leads to degradation in electrical and optical properties.[4,5] Therefore, pure Ag films are not suitable to be used as p-GaN contacts for high-power VLEDs.

Regarding the physical origin of Ag agglomeration, two different mechanisms have been suggested, including surface diffusion to reduce the total free energy and bulk diffusion of Ag atoms by oxygen–vacancy interaction.[6,7] Different Ag-alloys, such as Ag–Al, Ag–Cu, and Ag–Mg alloys, have been investigated as p-GaN contacts and proved to be able to suppress agglomeration, and thus result in better thermal stability due to the reduction in the oxygen–vacancy interaction.[8-11] The thermal stability of the Ag-based contacts could also be enhanced by depositing an overlayer on top of a Ag film.[5,12] In this paper, we present a new Ag/La bilayer metallization scheme for p-GaN ohmic contacts. By employing Ag/La ohmic contacts, light reflectance, thermal stability, and surface morphology of the contacts are improved significantly. The effects of the La overlayer on electrical and optical properties of Ag contacts will be discussed.

Experimental

The 1 μm-thick Mg-doped GaN films used in this study were grown on c-plane sapphire substrates using metallorganic chemical vapor deposition (MOCVD). The carrier concentration determined by Hall measurements is about 3×10^{17} cm^{-3}. Prior to lithographic patterning process, the as-grown GaN samples were ultrasonically degreased using acetone and methanol, and then rinsed in deionized water. The circular transfer length method (CTLM) patterns were defined by standard photolithography for specific contact resistance measurements. The CTLM pattern has a constant outer radius of 200 μm and the gap spacing between the inner and outer pads is varied from 5 to 45 μm. Before placing into the deposition chamber for metallization, all samples were dipped into a buffer oxide etch (BOE) solution for 20 min in order to remove the surface oxide layer. Ag/La (150/20 nm) bilayer contact patterns were deposited in sequence on the p-type GaN by electron-beam evaporation followed by the lift-off process. For comparison, a Ag (150 nm) film was also deposited on the p-type GaN as a reference. The CTLM contacts were then annealed at temperatures ranging from 200 to 550°C for 1 min in air ambient using a rapid thermal annealing system. Current–voltage (*I-V*) characteristics of the contacts were examined using a semiconductor parameter analyzer (HP 4145). A UV/Vis/NIR spectrometer (JASCO V-670) was used to measure the reflectance of the Ag and Ag/La metal contact schemes deposited on quartz glass.

Results and Discussion

Figure 1a shows the specific contact resistance (frequently referred to as the specific contact resistivity) of Ag and Ag/La contacts before and after annealing as a function of the annealing temperature. Both as-deposited metal contacts show nonohmic behavior. The specific contact resistances were measured for the Ag and Ag/La contacts which reveal ohmic behavior after annealing at temperature ranges of 200–400°C and 350–550°C, respectively. For the Ag contact, the lowest specific contact resistance of 6 $\times 10^{-4}$ Ω cm^2 was obtained after annealing at 300°C, where the specific contact resistance of the Ag/La contact is higher than that of the Ag contact. However, the Ag/La contact shows the lowest specific contact resistance of 1.6×10^{-4} Ω cm^2 after annealing at 450°C. The specific contact resistance of Ag and Ag/La contacts dramatically increases at annealing temperatures higher than 350 and 500°C, respectively, which implies degradation of the contacts. Figure 1b shows the reflectance of both contacts at the wavelength of 460 nm at an annealing temperature range of 200–550°C. Both as-deposited Ag and Ag/La contacts reveal the same reflectance. The reflectance of the Ag contact degrades to 48.5% with annealing at 450°C, while the reflectance of the Ag/La contact is just slightly degraded over all annealing temperatures and showed high reflectance over 91% after annealing at 450°C. The reflectance at 460 nm was chosen for the evaluation of light reflectance because the emission wavelength of GaN LEDs for lighting applications is around that region of the spectrum. Figure 2 shows the reflectance as a function of wavelength for as-deposited and annealed Ag/La contacts. The reflectance of Ag/La contacts annealed at 450°C could maintain above 91% across the visible spectrum.

The surface morphologies of Ag and Ag/La contacts after annealing at 400°C by scanning electron microscopy (SEM) are shown in Fig. 3. The annealed Ag contact shows a very irregular and isolated island morphology, which could be explained on the basis of the high surface diffusion of Ag atoms in the oxygen-contained ambient.[13] The phenomenon of hole growth on Ag films is enhanced in the presence of oxygen and the island formation takes place by the holes joining together, leading to agglomeration. In the Ag contact, severe Ag agglomeration would strongly reduce the contact area and, thus, results in a poor specific contact resistance and a low light reflectance in reflective contacts at the high temperature region,

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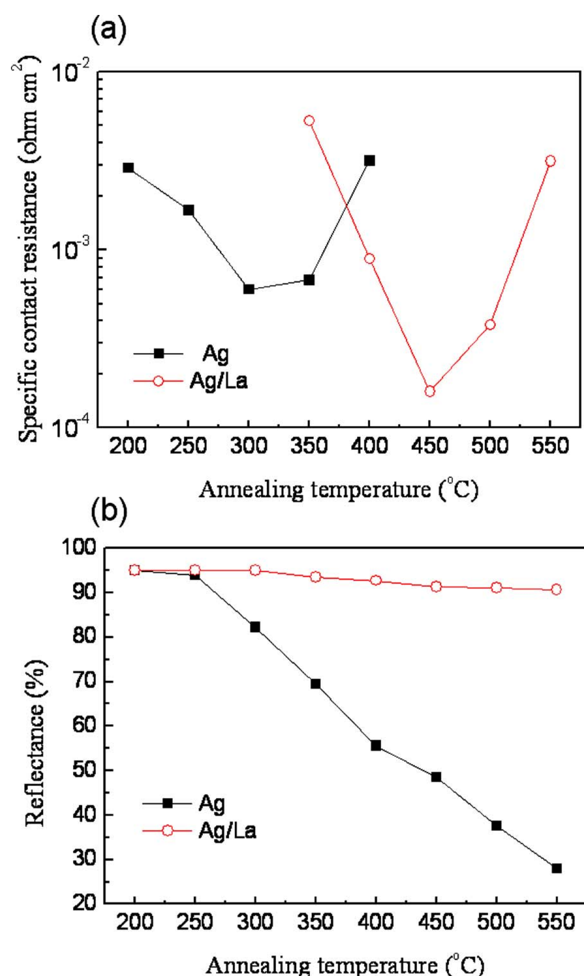

Figure 1. (Color online) (a) Specific contact resistance of Ag (150 nm) and Ag/La (150/20 nm) contacts as a function of annealing temperature in air ambient. (b) Light reflectance at 460 nm wavelength obtained from Ag and Ag/La contacts as a function of annealing temperature in air ambient.

as indicated in Fig. 1. Meanwhile, the Ag/La contact still exhibits smooth surface morphology and high reflectance even after annealing at 450°C.

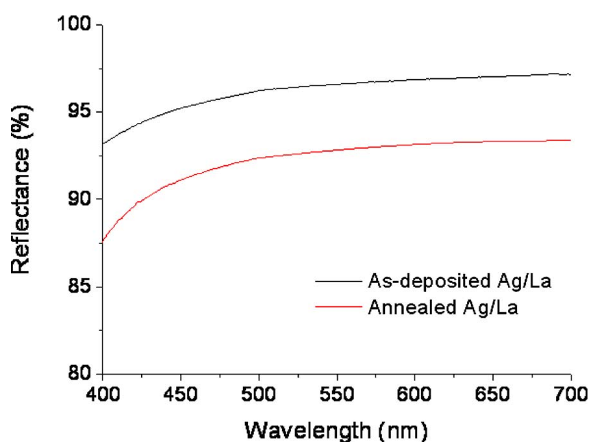

Figure 2. (Color online) Light reflectance spectra of as-deposited Ag/La and annealed Ag/La contact. Annealing was carried out at 450°C for 1 min in air.

Based on the experimental results, the improvements in the specific contact resistance and reflectance of annealed Ag/La contacts are explained. In order to investigate the interfacial reactions, X-ray photoelectron spectroscopy (XPS) analysis was carried out on both contacts. While the Ag layer is exposed directly to air during annealing in the Ag contact, the La layer, instead of Ag, is exposed in the Ag/La contact. Figure 4 shows the La3d and O1s XPS spectra of the La film at the Ag/La interface in as-deposited and annealed Ag/La contacts for studying the chemical states of lanthanum. Due to the spin–orbit interaction, La3d states split into two lines, $3d_{5/2}$ and $3d_{3/2}$, and each line has a double peak structure with a main peak and a satellite peak. For the as-deposited La film, as depicted in Fig. 4, the $La3d_{5/2}$ and $La3d_{3/2}$ features are resolved into two doublets centered at 836.0 and at 852.8 eV with a spin orbit splitting of 16.8 eV, which is similar to that found in La_2O_3 and suggests that the whole La layer could be oxidized to form a disordered La_2O_3 film by exposure to air at room temperature.[14] The O1s photoelectron spectra depicted in Fig. 4 also confirm the formation of a La_2O_3 overlayer. For the as-deposited sample, the peak at 530.5 eV in the O1s spectrum corresponds to O^{2-} of the metal oxide.[15] After annealing at 450°C, the peak positions and shapes of La3d and O1s show no change, which implies no detectable formation of Ag–La solid solutions and intermetallic compounds. This indicates that La_2O_3 still remains as an overlayer after annealing, consistent with the result of the XPS depth profiles, as indicated in Fig. 5. Because no oxygen XPS signal was observed inside the Ag contact (shown in Fig. 5), the Ag layer was not oxidized. For the annealed Ag/La contact, the surface morphology is quite smooth without the formation of holes, as shown in Fig. 3b. Since Ag agglomeration could be enhanced by annealing in the oxygen-contained ambient,[13] we suggest that the overlaid La_2O_3 layer acts as a passivation layer to reduce incorporation of oxygen into the Ag layer, and thus improve the reflectance in the annealed Ag/La contact. As shown in Fig. 5, Ag indiffusion and Ga outdiffusion were observed at the interface between p-GaN and Ag in both contacts after the annealing process. The interdiffusion during annealing leads to the formation of Ag–Ga solid solution, which produces acceptorlike Ga vacancies beneath the contact, resulting in an increase in carrier concentration at the surface region and so the reduction of the Schottky barrier height.[16] Ga outdiffusion could be enhanced by annealing in the oxygen-contained ambient due to the high reactivity of Ga with oxygen.[17] For the Ag contact, therefore, the transition from Schottky to ohmic contact behavior occurs at annealing temperature as low as 200°C. Without excessive oxygen incorporation to enhance Ga outdiffusion, formation of Ag–Ga solid solution could still be promoted at a higher annealing temperature, and then results in ohmic behavior.[18] Thus, compared with the Ag contact, the ohmic behavior was achieved for the Ag/La contact at a higher annealing temperature of 350°C and improved to reach a minimum specific contact resistance at 450°C. The improvement in the specific contact resistance for the Ag/La contact is speculated due to more Ag–Ga solid solution formed without reduction of the contact area (no Ag agglomeration) at a higher annealing temperature.

In order to evaluate the thermal stability of both contacts, we investigated the change of specific contact resistance and light reflectance as a function of annealing time at 300°C. The specific contact resistance of each sample is normalized with the minimum contact resistivity (ρ_0) obtained after annealing at 300 and 450°C for 1 min, respectively. Figure 6 shows the plot of normalized contact resistivity (ρ_t/ρ_0) versus annealing time. For the Ag contact, the value of ρ_t/ρ_0 drastically increased by a factor greater than 100 after annealing for 50 min. However, the value of ρ_t/ρ_0 is almost unchanged for the Ag/La contact after annealing for 120 min, which indicates that the La_2O_3 overlayer could suppress the degradation of the Ag/La contact and result in better thermal stability.

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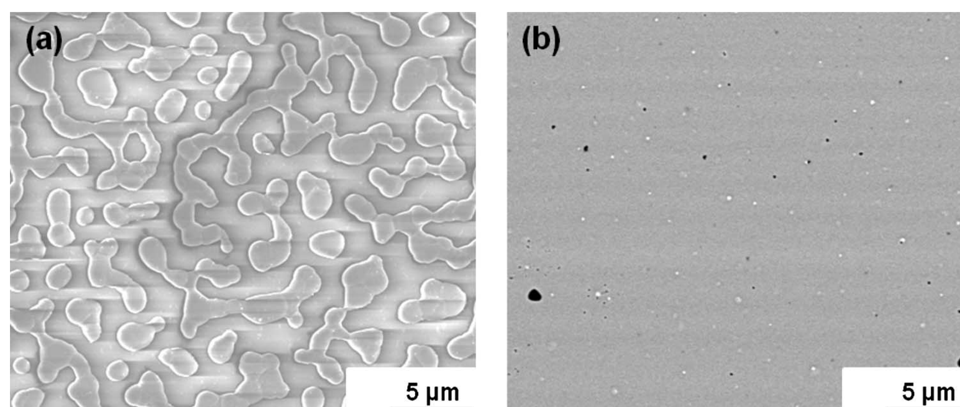

Figure 3. SEM images of (a) Ag and (b) Ag/La contacts to p-GaN annealed at 450°C in air ambient for 1 min.

Conclusion

In summary, a promising highly reflective and low resistance Ag/La ohmic contact for p-GaN has been demonstrated. The Ag/La contact shows a low specific contact resistance of 1.6×10^{-4} Ω cm^2 and high relative reflectance of over 91% at a wavelength of 460 nm after annealing at 450°C in air. The excellent thermal stability in the Ag/La contacts is attributed to the formation of the overlaid La_2O_3 layer on top of the Ag film during annealing, which serves as a passivation layer to prohibit the Ag agglomera-

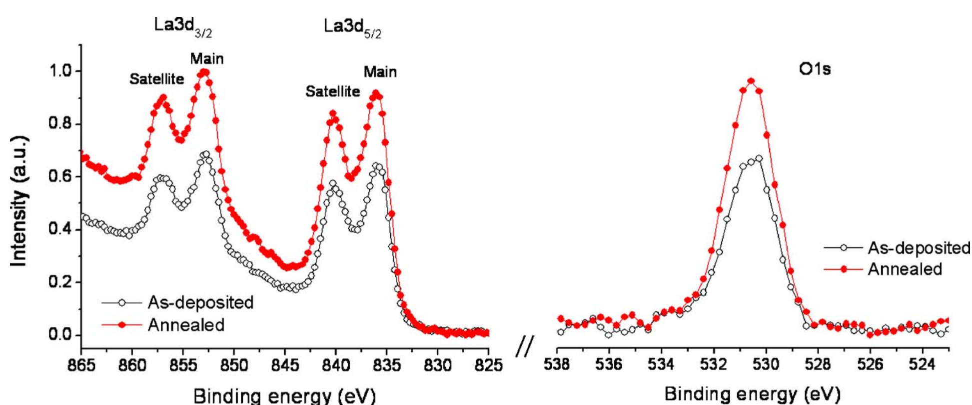

Figure 4. (Color online) XPS O1s and La3d spectra taken at the Ag/La interface of the Ag/La bilayer contact before and after annealing at 450°C for 1 min in air ambient.

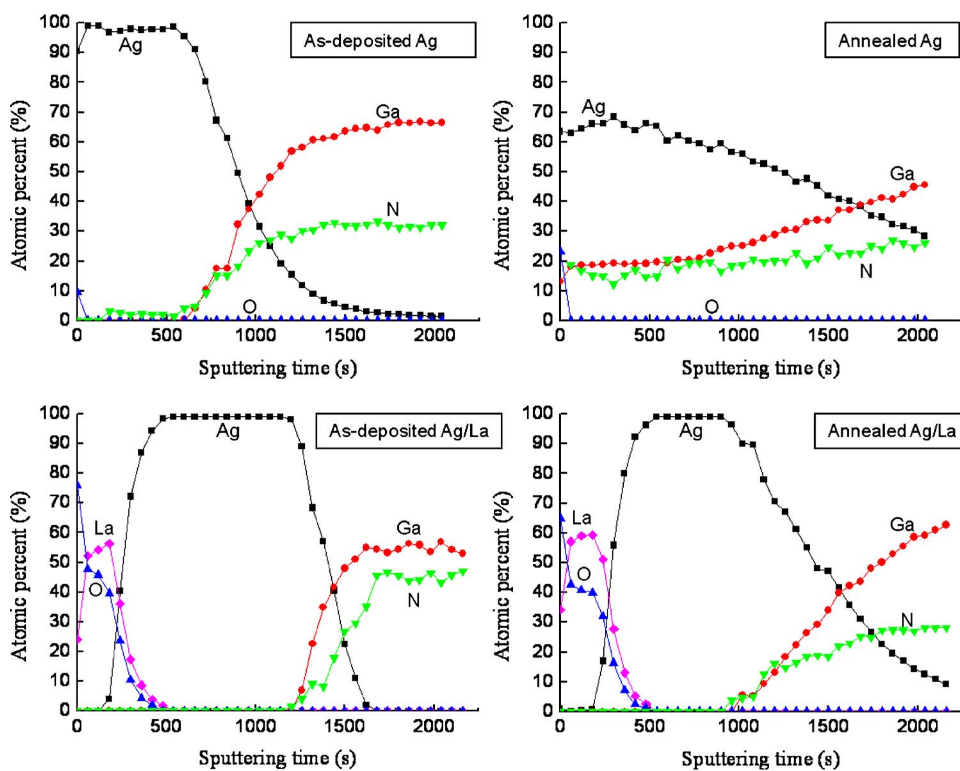

Figure 5. (Color online) XPS atomic depth profiles of Ag and Ag/La contacts before and after annealing. Ag contact was annealed at 300°C and Ag/La contact was annealed at 450°C. Both contacts were annealed under air atmosphere for 1 min.

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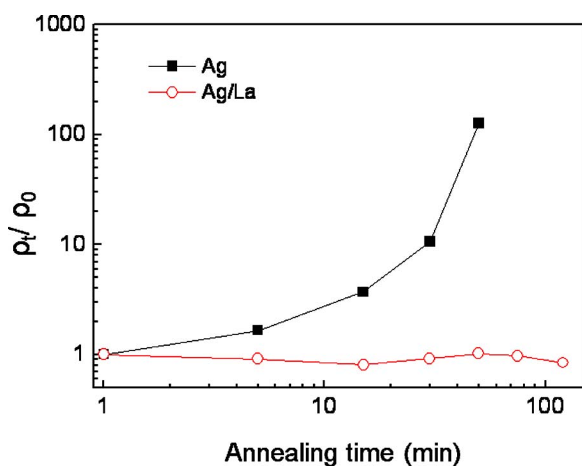

Figure 6. (Color online) Comparison of ρ_t/ρ_0 ratios for Ag and Ag/La contacts as a function of annealing time at 300°C in air ambient.

tion. The results indicate that the Ag/La bilayer contact has high potential for applications of p-GaN contact in VLEDs.

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