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Carrier Transport of Silver Nanowire Contact to *p*-GaN and its Influence on Leakage Current of LEDs

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Abstract. The authors investigated the silver nanowires (AgNWs) contact formed on *p*-GaN. Transmission line model applied to the AgNWs contact to *p*-GaN produced near ohmic contact with a specific contact resistance (ρ_{sc}) of 10^{-1}~10^{-4} $\Omega\cdot cm^2$. Noticeably, the contact resistance had a strong bias-voltage (or current-density) dependence associated with a local joule heating effect. Current-voltage-temperature (*I-V-T*) measurement revealed a strong temperature dependence with respect to ρ_{sc}, indicating that the temperature played a key role of an enhanced carrier transport. The local joule heating at AgNW/GaN interface, however, resulted in a generation of leakage current of light-emitting diodes (LEDs) caused by degradation of AgNW contact.

1. Introduction
Recently, silver nanowires (AgNWs) have been extensively investigated in the field of organic semiconductor optoelectronic devices because of their intriguing properties including high optical transmittance, low sheet resistance, flexibility, and low cost process [1-7]. Very recently, our group [8] first demonstrated group III-nitride LEDs fabricated with AgNW transparent conductive electrodes (TCEs). This was feasible because AgNWs could form a reasonable ohmic contact to *p*-GaN. Consequently, the LEDs fabricated with AgNWs produced 56% brighter light output power than the reference LEDs. This suggests that the AgNWs are quite promising for use as next-generation transparent conductive electrodes [9, 10]. However, for obtaining better performance, it is still necessary to address the contact properties of AgNWs on *p*-GaN, whereas in-depth studies on this subject are very rare.

In this connection, we investigated contact properties of AgNWs contact formed on *p*-GaN. For this purpose, a transmission line model (TLM) method was used [11, 12]. Since the direct electrical probing of AgNWs contact is impossible owing to its thin and weak network structures, the specifically designed TLM structure was used as shown in Fig. 1. The current-voltage (*I-V*) curves of contact were analyzed using universal TLM method, giving bias-voltage-dependent or current density-dependent ρ_{sc} values. The carrier transport at contact was further analyzed by using current-voltage-temperature (*I-V-T*) measurement. To investigate the reliability issues of LEDs fabricated with AgNW contacts, *I-V* curves were also investigated.

2. Experimental procedure
The AgNW films were formed using conventional spin-coating process (for 40 s at 800 rpm). The AgNW films were observed by scanning electron microscopy (SEM), revealing that their overall thickness was approximately 70 nm, as shown in figure 1. For the contact study, a TLM patterns

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having 150 μm × 200 μm contact pads and gap spacing of 10, 20, 40, 60 μm were used. Specifically, 20 nm-thick SiO_2 films were deposited on the top *p*-GaN layer of a commercially available LED wafer by an *e*-beam evaporator, and then selectively wet etched (using buffered oxide etchants) to exposed *p*-GaN layer surface for AgNWs contact. Then, a 10 nm-thick Pt pad was selectively deposited on the SiO_2 layer, followed by selective coating of the AgNWs onto the both exposed *p*-GaN layer and Pt pads. A conventional photolithographic lift-off technique was used for selective deposited Pt pads and AgNWs contact. The electrical properties of contacts were measured using a parameter analyzer (HP4156A), in which the chuck temperature varied from 250 to 350 K. The optical transmittance and the sheet resistance of the AgNW was measured using a UV/VIS spectrometer (V-670EX) and a four-point probe system (CMT-SR1000N).

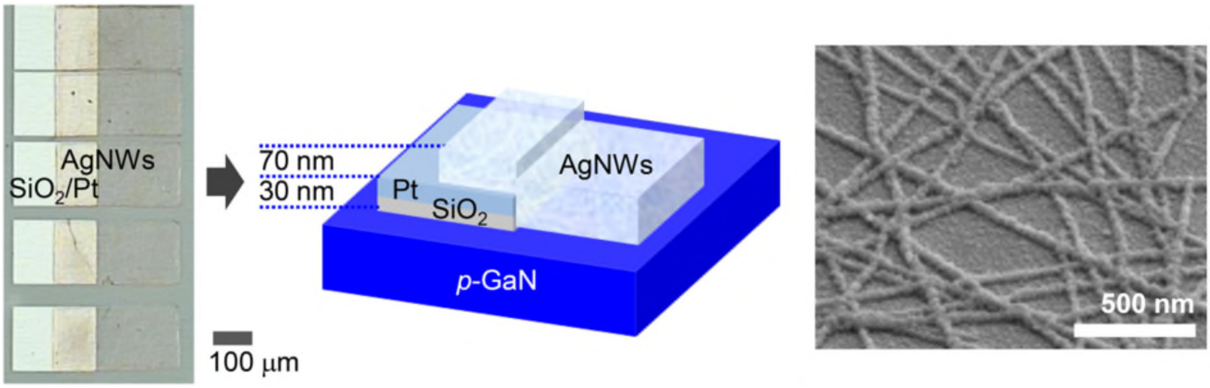

Figure 1. Optical microscopic and schematic cross-section views of AgNW TLM pad and SEM image of AgNW films.

The LEDs were also fabricated using AgNWs and conventional method to evaluate the leakage currents. For example, the rectangular mesa (200 μm × 500 μm) was defined by dry etching to a thickness of ~1.0 μm to expose the *n*-layer using an inductively-coupled plasma reactive ion etching system, on which a Ti/Al/Ni/Au (30/70/30/70 nm) layer was deposited as an *n*-electrode by an *e*-beam evaporator. Rapid thermal annealing was performed at 550°C for 1 min in ambient N_2 to form an *n*-type ohmic contact. To form AgNW TCEs on the *p*-layer, a Ti/Au (20 nm/10 nm) probing pad was formed on the mesa, followed by selective AgNW coating on the exposed *p*-layer and Ti/Au probing pads by means of a lift-off technique. The spin-coating process was performed in the last process step to minimize the possible contamination of AgNWs by additional photolithographic processing. To implement our study, commercially available LEDs wafers were used; these were grown on *c*-plane sapphire substrates by a metalorganic chemical vapour deposition. The structure of the LEDs comprised 2.0 μm of undoped GaN, 3.5 μm of *n*-GaN, 5-period GaN/InGaN multiple quantum well (MQW) active regions with 450 nm-emission, a 0.024 μm *p*-AlGaN electron blocking layer, and a 0.14 μm *p*-GaN layer. The fabricated LEDs were evaluated using a parameter analyser and optical spectrometer (Ocean Optics-USB2000+). The detailed fabrication and characterization procedures can be found elsewhere [8].

3. Results and discussion

In the SEM images of AgNW films coated on a sapphire substrate, a typical squashed arrangement with an average diameter of ~30 nm and average length of a few ten micrometers was observed as shown in figure 1. Therefore, the AgNWs are likely to have very small contact area. Consistently, the AgNW contact to *p*-GaN showed a relatively poor *I-V* curves, i.e., nonlinear and not steep, as shown in figure 2. To obtain ρ_{sc} values, a universe TLM method proposed by Piotrzkowski*et al.* [13] was used since the classical TLM method could not be used in case of having nonlinear *I-V* curve.

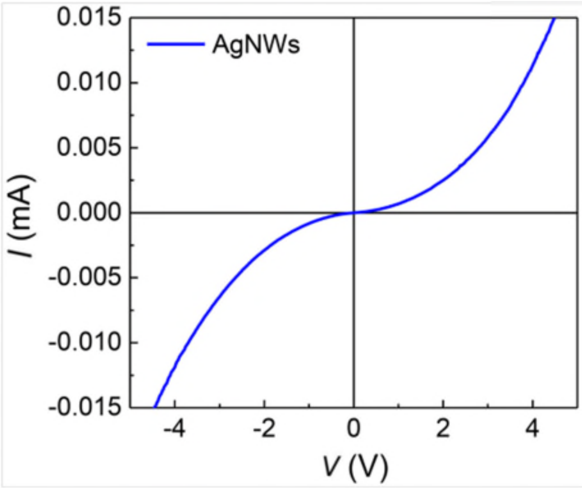

Figure 2. *I-V* curve of AgNW TLM pad, as measured from adjacent contact pad with the spacing of 10 μm.

Figure 3(a) and 3(b) shows the bias voltage and current density (J) dependent ρ_{sc} values. It is quite evident that the ρ_{sc} values drop significantly with increasing V or J. For example, the ρ_{sc} values were 2.0×10^{-3} Ω·cm^2 at V = 3.5 V and 1.5×10^{-4} at V = 5.0 V. This indicates that the higher bias induces more current flow by reducing ρ_{sc} values. Under higher bias condition, this might be attributed to the local joule heating effect, leading to a ρ_{sc} reduction. Furthermore, this is self-reinforcing process since the reduced ρ_{sc} value cause more current to flow and generate heat.

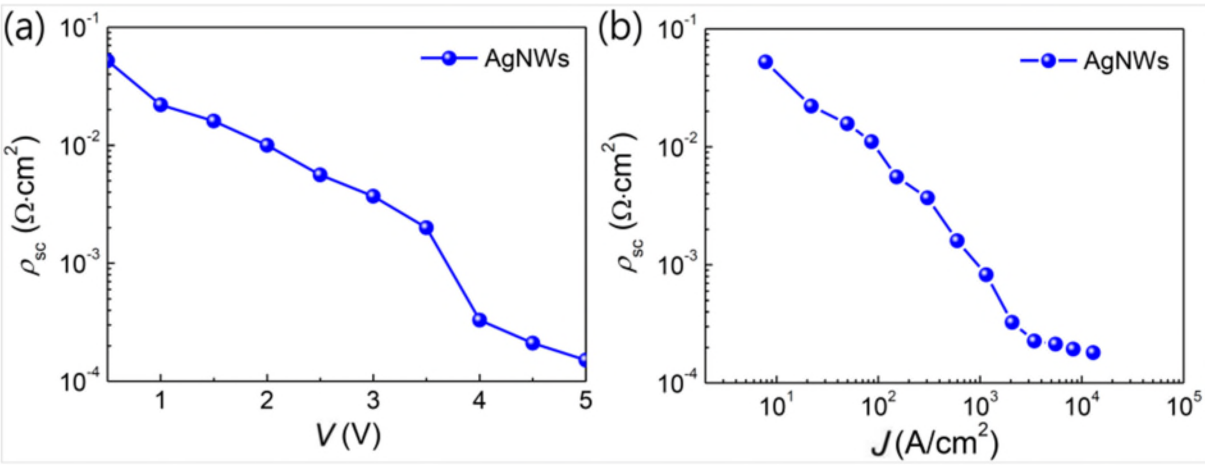

Figure 3. ρ_{sc} of AgNW electrodes versus (a) bias voltage and (b) current density.

To investigate the carrier transport mechanism, the temperature dependent ρ_{sc} values were plotted as shown in figure 4. It is shown that all bias dependent ρ_{sc} values decrease monotonously with increasing temperature. This indicates that predominant factor determining ρ_{sc} values is the temperature.

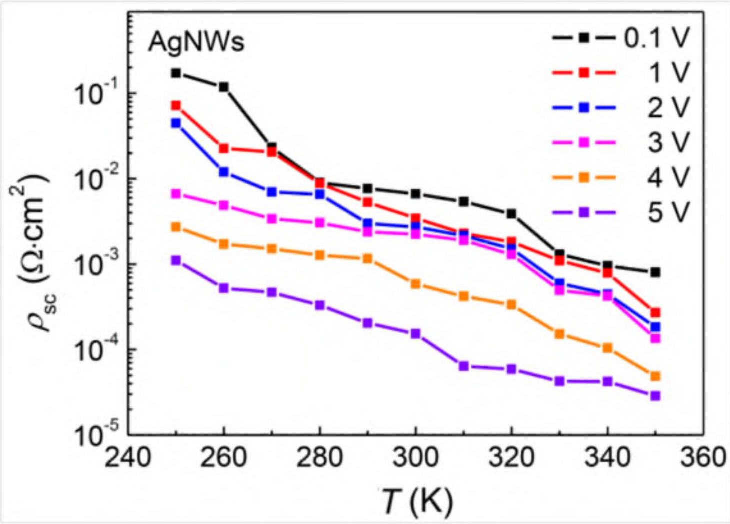

Figure 4. ρ_{sc}-T curves of AgNW electrodes of various bias voltages.

Figure 5 shows the *I-V* curves of the LEDs fabricated with AgNW and Ni/Au electrodes. The insets show the schematic of AgNW (left) and reference (right) LEDs, respectively. It should be noted that the LED fabricated with AgNW had much higher forward and reverse leakage currents than the reference LED. This is attributed to the degradation of *p-n* junction, presumably due to a significant current flow underneath small-area AgNW contact.

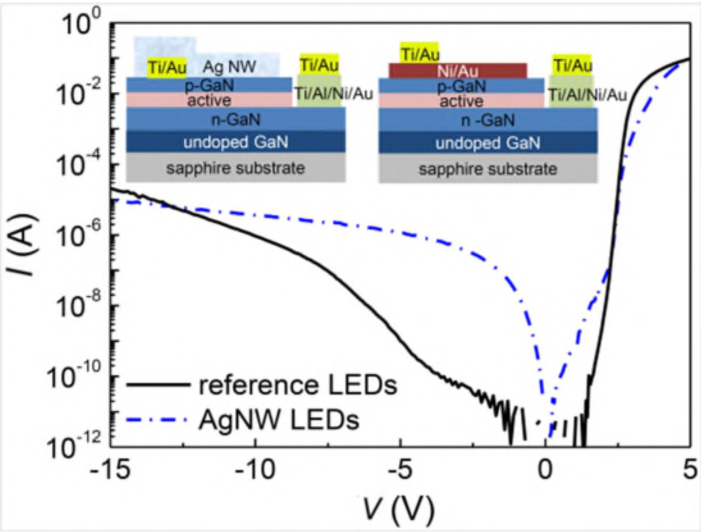

Figure 5. *I-V* curves of AgNW LEDs and reference LEDs. The inset of Fig. 5 shows the schematic diagram of AgNW and reference LEDs.

Despite these observed forward and reverse leakage currents, the LEDs fabricated with AgNW showed 1.6 times higher EL intensity than the reference LEDs as shown in figure 6. This is due to the combined effects of the enhanced light extraction associated with increased optical transmittance, i.e., the optical transmittance at 450 nm was 96.5 and 81.1 % for the AgNW and Ni/Au, respectively, and the improved current spreading associated with decreased sheet resistance, i.e., the sheet resistance was 11.7 and 11.3 Ω/sq for the AgNW and Ni/Au, respectively [8]. Indeed, this suggests that, once a novel TCE structure is designed to suppress the evolution of leakage current or to guarantee the reliability of LEDs, the AgNW will practically replace current TCE such as Ni/Au or ITO. This is presently under investigation.

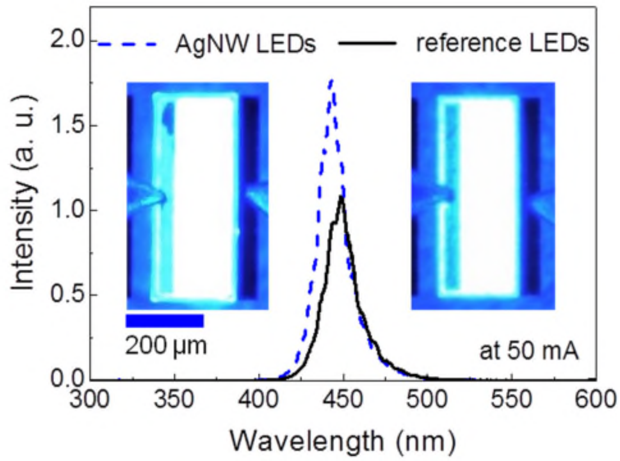

Figure 6. The room-temperature EL spectra of AgNW LEDs and reference LEDs. The inset shows the EL images taken at 3 mA.

4. Conclusions

The electrical characteristics of AgNWs contact formed on *p*-GaN was analyzed. The contact resistance dropped significantly with increasing bias-voltage or injected current. This could be due to a local joule heating effect associated with a significantly reduced contact cross-section. *I-V-T* measurement further revealed that the key parameter of ohmic contact was temperature. However, a local joule heating resulted in junction degradation and hence an evolution of leakage currents, suggesting that novel AgNW structure should be developed for practical application.

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Acknowledgments

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