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# Contact Properties of SWNT TCEs via the Microwave Treatment

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## Abstract

**For the first time, a microwave treatment (MWT) effect of single-wall carbon nanotube (SWNT) based transparent conductive electrodes (TCEs) on a p-AlGaN for ultraviolet light-emitting devices is presented. As a result, the reduced specific contact resistance of the MWT-SWNT TCEs on the p-AlGaN was observed. In addition, compared to the pristine TCE sample, the optical transmittance of the MWT-SWNT TCEs at a wavelength of 365 nm improved from 83.9% to 85.5%.**

## 1. Introduction

Single-walled carbon nanotubes (SWNTs) have generated great expectation for applications of next-generation transparent conductive electrodes (TCEs) [1] for various types of optoelectronic devices such as flexible displays, electronic paper, solar cells, light-emitting devices (e.g. light-emitting diodes, LEDs), and organic LEDs due to the many unique and special electrical properties of the nano-carbon materials used [2]. Nevertheless, in the case of GaN based LEDs, direct application to TCEs for LEDs still requires solutions to the issue of high contact resistance between SWNTs and p-(Al)GaN layers [3], although scientists have been studying the contact properties on p-(Al)GaN to improve the situation. For example, in previous work of LED devices operated in near ultraviolet (UV) light wave bands (>365 nm), a specific contact resistance (ρc) of about 10-4 Ω · cm2 on p-GaN and a transparency of 83% at 375 nm was reported by employing Ni-embedded SWNT TCEs. K. Lee et al. also reported enhanced ρc on p-GaN by employing SWNT TCEs, which is lower than in the case of a conventional metal electrode using an Au/Ni. However, studies to improve electrical conductivity and transmittance are still required to combine additional metals such as Ni, Rh, Au, Pd, and Pt with SWNTs because it would be almost impossible to form direct ohmic contacts to p-GaN layers when using any of them alone, especially to p-AlGaN with bare SWNTs. Note that light absorption can happen in metal-combined SWNT TCEs since most metals have a narrow-bandgap and an additional process is required to combine metal and SWNTs. For UV LEDs that operate at a wavelength of <365 nm it is more difficult to form an ohmic contact with an AlGaN layer because of a larger work-function difference between SWNTs and p-AlGaN, resulting in a Schottky contact barrier. In addition, in terms of light absorption, it is necessary to employ bare SWNTs for high transmittance in the UV regions, due to higher light absorption of metal combined SWNTs than bare SWNTs.

In this work, we report a simple and reliable method to achieve a good adhesion and a stable contact by microwave absorption, which considerably lowers the contact resistance of SWNTs on a p-AlGaN layer. As a result, a $\rho_c$ of SWNT TCEs on p-AlGaN using the MWT method could be lowered. In addition, we tried to investigate an inference of improved contact and transparent properties by analyzing interfacial characteristics between the p-AlGaN layer and the SWNT TCEs using Raman spectroscopy, secondary ion mass spectrometry (SIMS), and X-ray photoelectron spectroscopy (XPS).

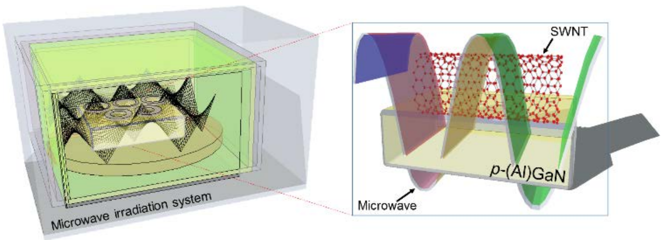


Fig. 1 Schematic illustrations of the MWT applied to SWNT TCEs for ohmic contact to the p-AlGaN. The magnified image on the right-hand side shows that microwave can be irradiated to SWNTs on the p-AlGaN using the microwave irradiation system.

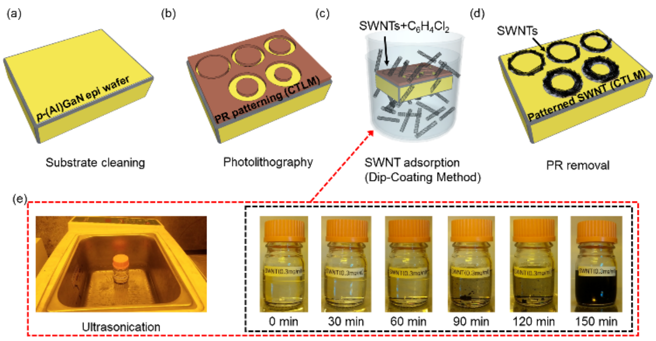


Fig. 2 Schematic illustrations for the adsorption process of the SWNT films on the p-AlGaN epi wafer via the sol-gel dip-coating method. (a) Substrate cleaning to remove the organic residues and the surface oxide from the substrates. (b) The formation of CTLM pattern of photoresist masks on the p-AlGaN substrate by photolithography process. (c) Deposition of SWNT on the p-AlGaN substrate by the dip-coating method. (d) Removal of photoresist using acetone (during this step the SWNT film with arrays of CTLM patterns is created). (e) Dispersion of SWNT using typical sonication system and the dispersion rate for SWNTs in solution over time using this system.

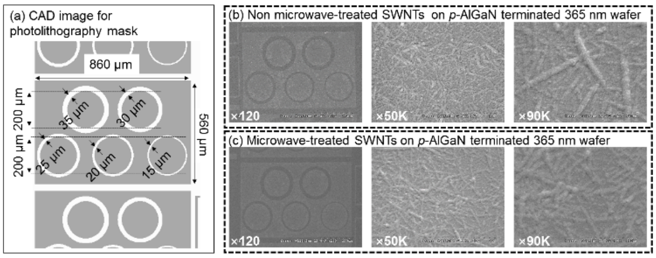

Fig. 3 (a) Fabricated CTLM structure to measure ohmic contact properties on p-AlGaN using Chrome (Cr) photomask designed using computer-aided design program. (b) Pristine SWNT and (c) MWT-SWNT films with arrays of CTLM patterns on p-AlGaN epi wafers.

## 2. Fabrication

Using the MWT method shown in Fig. 1 and the adsorption process of SWNT films shown in Fig. 2 [37-41], we fabricated SWNT films with arrays of circular transmission line model (CTLM) patterns on a p-AlGaN layer to verify the validity of the proposed MWT method. We compared properties of the two kinds of SWNT films on the p-AlGaN epi wafers before and after microwave radiation, which was conducted at 2.45 GHz frequency at a power of 600 W (for 1 minute at room temperature in air). Fig. 3(a) shows an image for a chrome photomask designed using a computer-aided design program to fabricate a SWNT based CTLM pattern. Detailed dimensions for the designed CTLM pattern are presented in Fig. 3(a); in brief, the contact dimension of the inner circle used is 200 μm, and the contact dimensions of the outer circle used are 215, 220, 225, 230, and 230 μm, respectively. We practically deposited SWNT films on the p-AlGaN epi wafers, as shown in Figs. 3(b) and (c). The SEM images of the pristine SWNT films on the p-AlGaN epi wafers were observed in Fig. 1(b) and these SEM images were compared with the MWT-SWNT films on the p-AlGaN epi wafers after MWT as shown in Fig. 1(c). It seems that the SWNT films are more strongly attached to the p-AlGaN epi wafer under the MWT process.

## 2. Results and discussion

First, in I-V result, the MWT samples clearly show an improved spacing length dependence thanks to the reinforced cohesion of the SWNT films and their enhanced contact property, while the current level gradually rises according to the number of times the cell was dipped; it was found that the MWT-SWNT cell dipped 3 times showed the most improved linearity.

To confirm the MWT effect on the current spreading property of the SWNT films, we tried to measure the $R_{sh}$. In this experiment, a tendency for resistivity increasing when samples were dipped just once or twice was seen, while resistivity decreased for the sample dipped three times, which is well consistent with the I–V curve characteristics and calculated ρc values.

When applying this to a TCE for optical devices, the transparency of the SWNT film is considered one of the main challenges. Our results show a higher optical transmittance across the whole tested range for the MWT samples compared to the pristine samples, owing to an improved crystallinity of SWNT networks by gaining thermal activation energy via the MWT process.

More details on the resistive switching characteristics of the ReRAM cells proposed in this work will be presented at the conference.

## 3. Conclusions

In summary, we proposed a new method for improved ohmic contact of a SWNT-TCE to a p-AlGaN using MWT, which successfully demonstrated its validity at a unit level by applying the SWNT-TCE to a p-AlGaN wafer. As a result, the specific contact resistance of $9.7 \times 10^{-2}\ \Omega \cdot cm^2$ for the MWT-TCEs was lower than that of $13.2 \times 10^{-2}\ \Omega \cdot cm^2$ for a pristine SWNT-TCE. From the results of Raman spectroscopy, XPS spectra, and SIMS analyses, we concluded that a reduction of a SBH caused by the creation of Ga vacancies in the p-AlGaN layer and a modification of structural and molecular properties in the SWNT film during the MWT process is responsible for the improved contact properties. In addition, through the MWT process, the optical transmittance can be increased by about 2% at a wavelength of 365 nm. These results indicate that the MWT process makes it possible to form a direct ohmic contact (or improve linearity) to the p-AlGaN.


## Acknowledgements

K. Kim, M. Yun and H.-D. Kim contributed equally to this work.


## References


[1] Avouris P, Freitag M, and Perebeinos V. Nat Photonics, 2 (2008) 341.

[2] Engel M, Small JP, Steiner M, Freitag M, Green AA, Hersam MC, and Avouris P. ACS Nano, 2 (2008) 2445.

[3] Hirayama H, Maeda N, Fujikawa S, Toyoda S, and Kamata N. Jpn J Appl Phys, 53 (2014) 100209.