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Characterizations of Metal-Oxide-Semiconductor Field-Effect Transistors of ZnGaO Grown on Sapphire Substrate

YI-SIANG SHEN[1], WEI-KAI WANG[2], AND RAY-HUA HORNG[1,3] (Fellow, IEEE)

1 Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung 402, Taiwan
2 Department of Materials Science and Engineering, Da-Yeh University, Changhua 515, Taiwan
3 Institute of Electronics, National Chiao Tung University, Hsinchu 300, Taiwan

CORRESPONDING AUTHOR: R.-H. HORNG (e-mail: rhh@nctu.edu.tw)

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ABSTRACT Zinc gallate (ZnGaO) epilayers were grown on a c-plane sapphire substrate by metalorganic chemical vapor deposition and fabricated into metal-oxide-semiconductor field-effect transistors (MOSFETs). The ZnGaO MOSFETs exhibited a complete channel pinch-off of the drain current for $V_{GS} < -4.43$ V, high off-state breakdown voltage of 378 V, high I_{ON}/I_{OFF} ratio of 10^6, and low gate leakage current.

INDEX TERMS Zinc gallate, metal-oxide-semiconductor field-effect transistors (MOSFETs), channel pinch-off.

I. INTRODUCTION

Wide-band gap oxides have attracted interests as new materials and possess unique properties for application in next-generation semiconductor power devices and deep ultra-violet (UV) detectors [1], [2]. Among these oxides, $ZnGa_2O_4$ has been paid great attention as a transparent conducting oxide in the UV region due to its high chemical stability and outstanding optical properties [3]–[5]. The material $ZnGa_2O_4$ consists of ZnO and Ga_2O_3, which crystallizes in the spinel structure and has an energy gap of about 5.2 eV [6]. In previous report, $ZnGa_2O_4$ is a phosphor and is a promising application in field emission displays operating at low accelerating voltage [7]. Up to now, most of the reports are relative to the synthesis of $ZnGa_2O_4$ nanostructures with different morphologies, such as nanowires, nanorods and nanocrystal [8]–[10]. The corresponding electronic transport and optical properties of the $ZnGa_2O_4$ nanostructure were also studied [11]. However, there are still very few works to investigate the film and epilayer properties of $ZnGa_2O_4$. In addition, as far as we know, no relevant research about MOSFET based on $ZnGa_2O_4$ epilayer has been reported yet. In this work, the material qualities of zinc gallate (ZnGaO; ZGO) were described. Moreover, MOSFETs made of ZGO epilayers grown on c-plane sapphire by MOCVD were also studied. The device performances indicated that the ZGO MOSFET has potential for application in transparent power electronic devices.

II. DEVICE STRUCTURE AND FABRICATION

ZGO MOSFETs were fabricated using 200-nm-thick single-crystal ZGO epilayers grown on c-plane (0001) sapphire substrates at 600°C by metalorganic chemical vapor deposition. Diethylzinc (DEZn) and triethylgallium (TEGa) were employed as the Zn and Ga precursors, respectively. Ar (99.999 %) and purified oxygen (99.999 %) were adopted as carrier gases and oxidizer, respectively. During the growth of GZO thin films, Ar passed through the bubblers to deliver the DEZn and TEGa vapors to the reactor. After growth, the intrinsic ZGO is a n-type epilayer confirmed by Hall measurement. In order to demonstrate the film was ternary epilayer, the x-ray diffractemery was used to measure the crystal structure. The electrical mobility, resistivity, and electron concentration of ZGO used for the MOSFET study were 2.2 cm^2/V.s, 47.5 Ω.cm, and 5.9×10^{16} cm^{-3}, respectively, and were obtained through Hall measurement at room temperature (RT). The process commenced with mesa isolation

in an inductively coupled plasma reactive ion etching system by using $BCl_3/Cl_2/Ar$. Ti/Al/Ti/Au (25/125/50/60 nm) was evaporated to form the metal contacts for the source (S) and drain (D) electrodes. Notably, the Ti metal contacting to ZGO exhibited ohmic contact behavior without any thermal annealing. The 40-nm Al_2O_3 dielectric layer was deposited through ALD at 300°C. Finally, Ni/Au (150/50 nm) gate metals were deposited on the Al_2O_3 by e-beam evaporation. The lengths of the device channel, gate, and the access region were 20 μm, $L_G = 3$ μm, and $L_{GS} = L_{GD} = 8.5$ μm, respectively. The current-voltage (*I-V*) characteristics of these samples were measured using an Agilent 1505B parameter analyzer at RT. In order to evaluate the crystal structure of the ZGO epilayer, the X-ray diffraction (XRD, PANalytical, Cu Kα radiation) was used to measure the crystalline quality. Microstructure of the ZGO film was investigated by transmission electron microscopy (TEM).

III. RESULTS AND DISCUSSION

Fig. 1 shows the XRD diffraction pattern of ZGO film grown on sapphire substrate. The XRD pattern shows strong peak at around 42° which was identified to be the Al_2O_3 (0006) plane. Moreover, the monoclinic β-Ga_2O_3 film with very small peak located at diffraction angles of 38.4° corresponding to the (-402) planes reflections was obtained. It was also found that there were additional features of diffraction intense peaks observed at 18.57°, 37.61°, and 57.82°. These peaks very closed to the 18.40°, 37.34°, and 57.40° characteristic reflections of (111), (222) and (333) crystal planes of $ZnGa_2O_4$ (JCPDS card 381240). These results indicated that the epilayer has transferred most of Ga_2O_3 into the ZGO epilayer. The measured XRD data are also shown in Table 1.

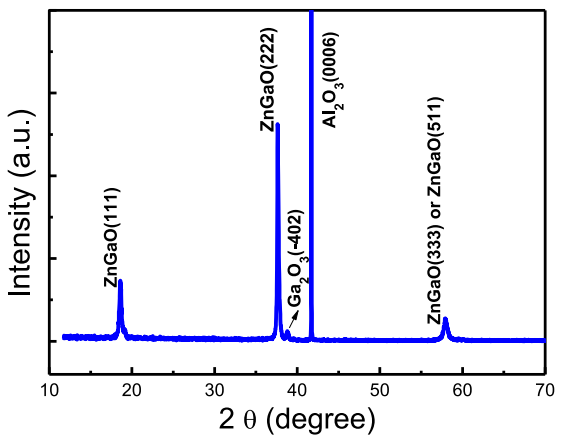

FIGURE 1. XRD pattern of ZGO film grown on c-plane sapphire substrate.

Fig. 2(a) shows the high-resolution TEM bright field image focused on the interface between ZGO film and c-plane sapphire substrate. According to our analysis, the d-spacing of 2.42 Å of ZGO film was obtained in this image, which was very close to the standard d-spacing of 2.406 Å of $ZnGa_2O_4$(222) plane. In addition, the high-resolution TEM bright field image taken at the middle region of ZGO film

TABLE 1. XRD diffraction measured results of ZGO film.

$ZnGa_2O_4$ (Cubic, fcc)	Ga_2O_3 (Monoclinic)	ZnO (Hexagonal)	ZGO (Epilayer)
18.40° (111)	18.95°(-201)		18.57° (111)
37.34° (222)	38.39°(-402)	36.25°(101)	37.61° (222)
57.40° (511)	59.19°(-603)	56.25°(101)	57.82°(333)

is displayed in Fig. 2(b). Based on our observation, the most lattice features shown in Fig. 2(b) belonged to that marked with green parallel lines. These lattices possess the d-spacing value of 4.809 Å, where the standard d-spacing of $ZnGa_2O_4$(111) plane is 4.808 Å. On the other hand, a fraction of lattice features presented in this image was also labeled with yellow parallel lines, and its d-spacing was much similar to the standard one of Ga_2O_3(-402) plane. Obviously, the TEM observations are in well agreement with the XRD result, as shown in Fig. 1. In other words, the main crystal structure formed in the ZGO film is the $ZnGa_2O_4$ phase with the (111)-family planes. Besides, a small portion of Ga_2O_3(-402) phase existed in the ZGO film also can be confirmed by TEM. Fig. 2(c) shows the selected area electron diffraction pattern of the $ZnGa_2O_4$ region shown in Fig. 2(b). The diffraction dots with a regular arrangement indicates the microstructure is single crystalline. Moreover, this single crystalline diffraction pattern reveals the $ZnGa_2O_4$ phase of ZGO film is formed along the [111] direction (with the [1-21] zone axis).

In order to demonstrate the epilayer has become the ZGO film, the energy gap of ZGO was evaluated by cathodeluminescence (CL) measurement. Fig. 3 shows CL spectrum of ZGO film at RT. The spectrum consists of two ultraviolet (UV) luminescence emission bands at the wavelength peaks position of 330 nm (3.75 eV; E_{CL1}) and 242 nm (5.12 eV), respectively. In the visible region, there exists a weak intensity at peak of 500 nm (2.48 eV; E_{CL2}). The weaker CL intensity at peak 242 nm could be due to the conduction band to the valence band transition of ZGO. Theoretically, the E_g of $ZnGa_2O_4$ is about 5.2 eV. In this work, the ZGO is not a perfect $ZnGa_2O_4$. Nevertheless, it has demonstrated again that the epilayer is the ZGO and not Zn-dopant Ga_2O_3. On the other hand, a strong UV emission band (330 nm) could be attributed to the radiative carriers transition from the donor level (E_d) to the valence band. Although the ZGO is the dominated structure, there exists a few part of β-Ga_2O_3 (demonstrated by XRD and TEM, shown in Figs. 1 and 2). Obviously, suppress of intrinsic green emission band centered at around 500 nm which is induced by donor-acceptor-pair transition in β-Ga_2O_3 through Zn-incorporation, and further contribution on the UV emission band was obtained. Based on above analysis, the E_d was estimated to be approximately about 1.37 eV by a formula $E_d = E_g - E_{CL1}$, which is consists with previous reported by Varley *et al.* [12]. An acceptor level (E_a) for the Zn_{Ga} was calculated to be 1.27 eV,

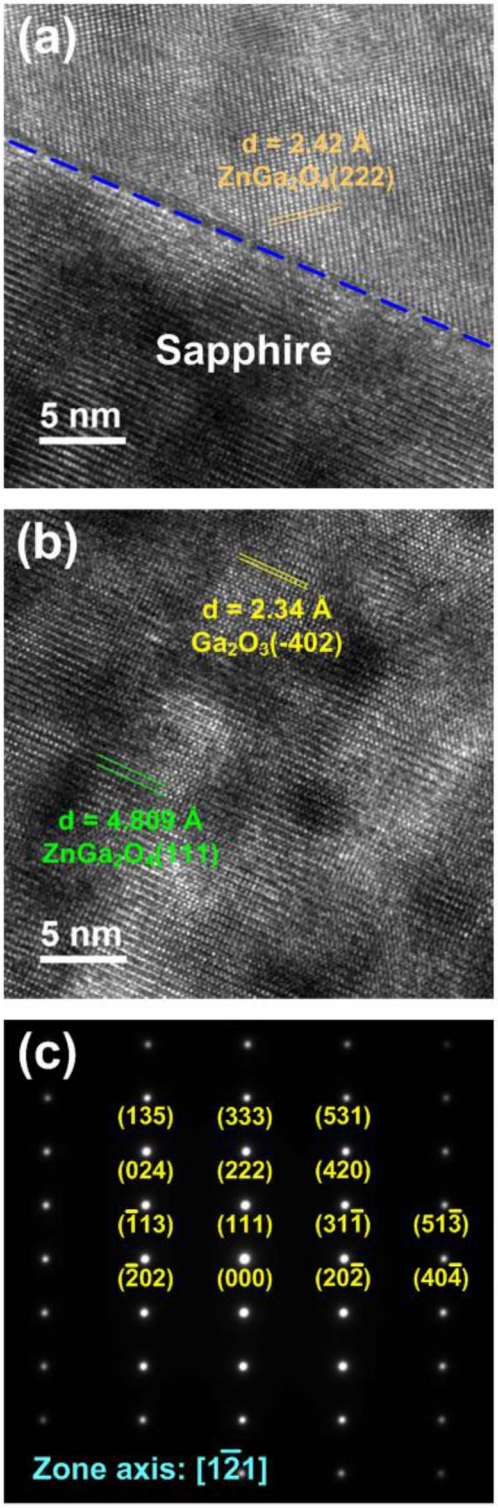

FIGURE 2. **HR-TEM images taken at (a) the interface between ZGO and sapphire and (b) the middle region of ZGO film. (c) Selected area electron diffraction pattern of $ZnGa_2O_4$ phase shown in Fig. 2(b).**

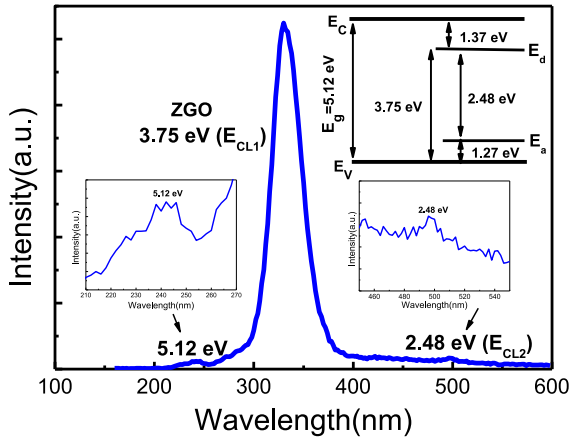

FIGURE 3. **CL spectrum of ZGO film grown on sapphire substrate measured at RT. Insets are the magnified 5.12 eV, 2.48 eV spectra and the energy levels diagram in the ZGO film.**

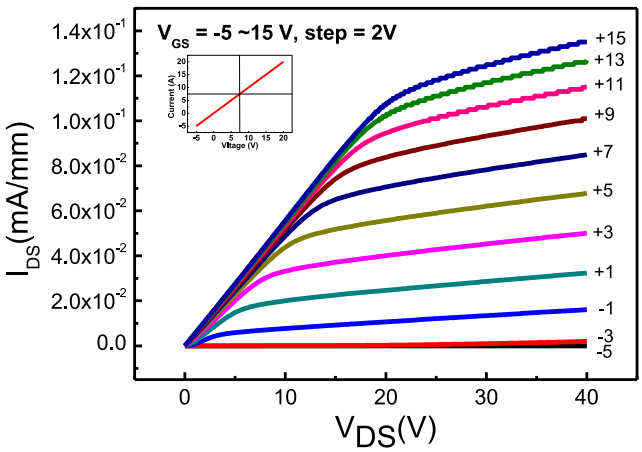

FIGURE 4. **DC I–V characteristics of ZGO MOSFET measured at RT.**

$(E_a = E_{CL1} - E_{CL2})$. Schematic diagram of the energy levels in the ZGO film is also illustration in the inset of Fig. 3.

Fig. 4 shows the DC output I-V (I_{DS}-V_{DS}) characteristics of ZGO MOSFET at gate voltage (V_{GS}) from -5 to 15 V in steps of 2 V, while the V_{DS} was swept from 0 to 40 V at RT. The device exhibited a clear pinch-off behavior and maximum I_{DS} of 0.135 mA/mm at $V_{GS} = +15$ V. In addition, the transistor shows favorable gate-modulation performance with I_d saturation, whereas the channel mobility and sub-threshold slope of ZGO MOSFET were calculated about 2.46 cm^2/V.s and 40 mV/decade, respectively. Moreover, the insert plot in Fig. 4 shows the linear I-V characteristic of Ti/Al/Ti/Au on ZGO without thermal annealing. Obtaining ohmic contacts was thus easy in this study because Ti metal layer can be ohmic contact with the ZGO. Similar reports on the ohmic contact through Ti/Al/Ti/Au multiple metals were found by Wang *et al.* [13].

Fig. 5 shows the transfer characteristics at a V_{DS} of 13 V. The threshold voltage on ZGO MOSFET was -4.43 V, which suggests that the device presented the depletion mode characteristic. Clearly, the ZGO was n-type and could enhance the conductivity through formation oxygen vacancy due to Zn atom compensation effect [14]. However, it is necessary to attract more electrons by applying

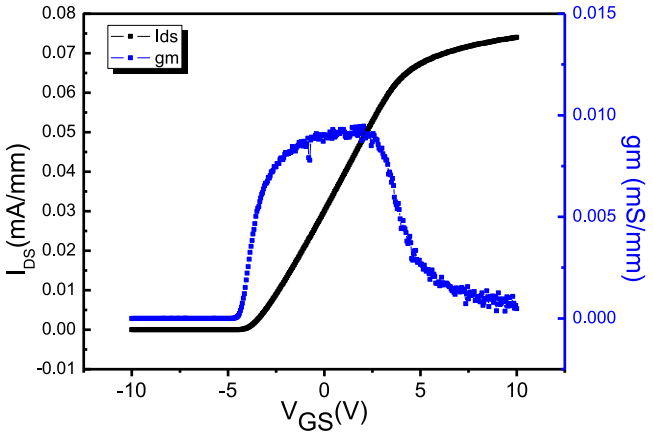

FIGURE 5. **Transfer characteristics of ZGO MOSFET at V_{DS}=13 V measured at RT.**

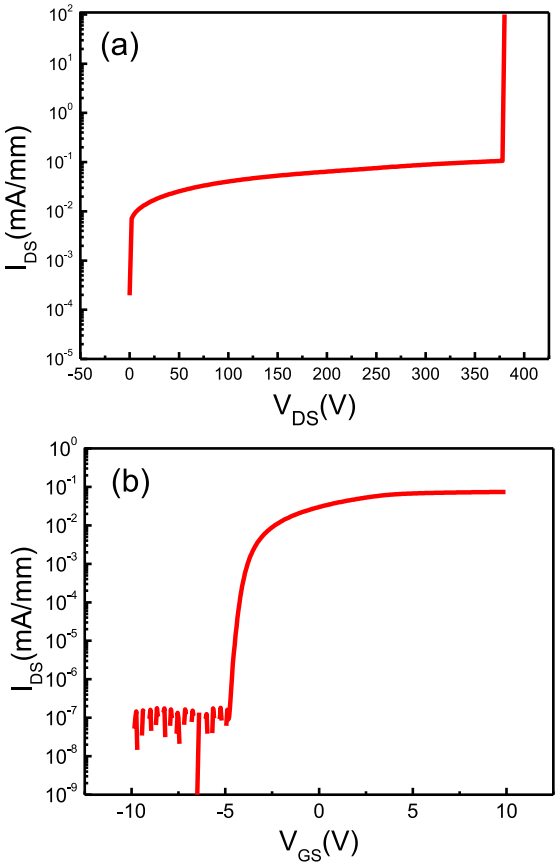

FIGURE 6. **(a) Breakdown voltage characteristic of ZGO MOSFET and (b) I_{DS}-V_{GS} curve of ZGO MOSFET measured at 13 V of V_{DS}.**

positive voltage on gate electrode to switch the transistor on. The peak intrinsic maximum transconductance (gm) was 9.46×10^{-3} mS/mm at a V_{DS} of 13 V, which could be attributed to the both of substitutional defects (from Zn-incorporated into β-Ga_2O_3) and the lattice mismatch between the sapphire substrate and ZGO film. These defects resulted in the reduction of electron density and mobility in the ZGO film. Moreover, the carriers' scattering effect, attributable to defects and impurities, reduced the mobility of the ZGO MOSFET. These results are consistent with those of Dang *et al.* [15].

The three-terminal breakdown behavior of the ZGO MOSFET device was evaluated and is shown in Fig. 6 (a). The breakdown voltage could be attributed to the leakage current through the Al_2O_3 layer or ZGO epilayer breakdown. However, a low gate leakage current was less than 1.45×10^{-5} mA/mm (data not shown) from the ZGO film device. Therefore, the breakdown voltage was as high as 378 V at V_{GS} of 0 V, indicating that ZGO MOSFET with Zn-incorporated exhibits enhanced off-state breakdown voltage. Nevertheless, the measured reverse gate leakage is low enough for device application. Fig. 6 (b) presents the I_{DS}-V_{GS} curve of ZGO MOSFET at a V_{DS} of 13 V. The low off-state leakage current (10^{-7} mA/mm) through the ZGO film was a result of the Al_2O_3 gate dielectric. At a V_{DS} of 13 V, I_{DS} on/off ratio of approximately six orders of magnitude were achieved.

IV. CONCLUSION

We have fabricated ZGO MOSFET on a c-plane sapphire substrate and obtained improved device characteristics, such as a high I_{ON}/I_{OFF} drain current ratio of six orders of magnitude, clear pinch-off behavior, and breakdown voltage of 378 V. Moreover, we have demonstrated the strong potential of the cost-effective growth of ZGO-on-sapphire for application in future transparent electronic power devices.

REFERENCES

[1] H. He *et al.*, "First-principles study of the structural, electronic, and optical properties of Ga_2O_3 in its monoclinic and hexagonal phases," *Phys. Rev. B.*, vol. 74, no. 19, Nov. 2006, Art. no. 195123.

[2] X. H. Wang *et al.*, "Electrical properties and emission mechanisms of Zn-doped β-Ga_2O_3 films," *J. Phys. Chem. Solids*, vol. 75, no. 11, pp. 1201–1204, Nov. 2014.

[3] I. J. Hsieh, K. T. Chu, C. F. Yu, and M. S. Feng, "Cathodoluminescent characteristics of $ZnGa_2O_4$ phosphor grown by radio frequency magnetron sputtering," *J. Appl. Phys.*, vol. 76, no. 6, pp. 3735–3739, Sep. 1994.

[4] L. E. Shen, R. K. Datta, and J. J. Brown, Jr., "Photoluminescence of Mn^{2+}-activated $ZnGa_2O_4$," *J. Electrochem. Soc.*, vol. 141, no. 7, pp. 1950–1954, Jul. 1994.

[5] I. K. Jeong, H. L. Park, and S. I. Moh, "Photoluminescence of $ZnGa_2O_4$ mixed with $InZnGaO_4$," *Solid State Commun.*, vol. 108, no. 11, pp. 823–826, Mar. 1994.

[6] T. Omata, N. Ueda, K. Ueda, and H. Kawazoe, "New ultraviolet-transport electroconductive oxide, $ZnGa_2O_4$ spinel," *Appl. Phys. Lett.*, vol. 64, no. 9, pp. 1077–1079, Feb. 1994.

[7] S. H. Yang, "Electrophoretic prepared $ZnGa_2O_4$ phosphor film for FED," *J. Electrochem. Soc.*, vol. 150, no. 10, pp. H250–H253, Sep. 2003.

[8] L. Zou, X. Xiang, M. Wei, F. Li, and D. G. Evans, "Single-crystalline $ZnGa_2O_4$ spinel phosphor via a single-source inorganic precursor route," *Inorg. Chem.*, vol. 47, no. 4, pp. 1361–1369, Jan. 2008.

[9] K.-W. Chang and J.-J. Wu, "Formation of well-aligned $ZnGa_2O_4$ nanowires from Ga_2O_3/ZnO core–shell nanowires via a Ga_2O_3/$ZnGa_2O_4$ epitaxial relationship," *J. Phys. Chem. B.*, vol. 109, no. 28, pp. 13572–13577, Jan. 2005.

[10] M.-Y. Lu, X. Zhou, C.-Y. Chiu, S. Crawford, and S. Gradečak, "From GaN to $ZnGa_2O_4$ through a low-temperature process: Nanotube and heterostructure arrays," *Appl. Mater. Interfaces*, vol. 6, no. 2, pp. 882–887, Jan. 2014.

[11] S. C. Yan *et al.*, "A room-temperature reactive-template route to mesoporous $ZnGa_2O_4$ with improved photocatalytic activity in reduction of CO_2^+," *Angew. Chem.*, vol. 122, no. 36, pp. 6544–6548, Aug. 2010.
[12] J. B. Varley, J. R. Weber, A. Janotti, and C. G. Van de Walle, "Oxygen vacancies and donor impurities in β-Ga_2O_3," *Appl. Phys. Lett.*, vol. 97, no. 14, Oct. 2010, Art. no. 142106.
[13] D. F. Wang *et al.*, "Low-resistance Ti/Al/Ti/Au multilayer ohmic contact to *n*-GaN," *J. Appl. Phys.*, vol. 89, no. 11, pp. 6214–6217, Jun. 2001.
[14] Y. Guo, H. Yan, Q. Song, Y. Chen, and S. Guo, "Electronic structure and magnetic interactions in Zn-doped β-Ga_2O_3 from first-principles calculations," *Comput. Mater. Sci.*, vol. 87, pp. 198–201, May 2014.
[15] G. T. Dang, T. Kawaharamura, M. Furuta, and M. W. Allen, "Mist-CVD grown Sn-doped α-Ga_2O_3 MESFETs," *IEEE Trans. Electron Devices*, vol. 62, no. 11, pp. 3640–3644, Nov. 2015.

YI-SIANG SHEN received the B.S. degree in electrical engineering from National Normal University, Kaohsiung, Taiwan, in 2014, and the M.S. degree from the Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung, Taiwan, in 2016. His major research focuses on nitride-based electric power device.

WEI-KAI WANG received the B.S. degree in manufacturing engineering from Yuan Ze University, Chungli, Taiwan, in 2000, the M.S. degree in electrical engineering from the University of Chung Hua, Hsinchu, Taiwan, in 2002, and the Ph.D. degree from the Department of Materials Engineering, University of Chung Hsing, Taiwan, in 2006. He is currently an Assistant Professor with the Department of Materials Science and Engineering, Da-Yeh University, Changhua, Taiwan. His research interests include development of GaN-based optoelectronic semiconductors and electric devices.

RAY-HUA HORNG (M'07–SM'11–F'02) received the B.S. degree in electrical engineering from National Cheng Kung University, Tainan, Taiwan, in 1987, and the Ph.D. degree in electrical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, in 1993.

She is currently a Distinguished Professor with the Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan. Her current research interests include solid-state lighting devices, solar cells, power device, HEMT, flexible electronics, optoelectronics, and nitride and oxide semiconductor MOCVD growths.