Status and Perspective of GaN-based Technology in Japan

M. Kuzuhara and H. Tokuda
Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan
Email: kuzuhara@fuee.u-fukui.ac.jp Phone: +81-776-27-9714

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Abstract

Present status and perspective of GaN-based technology in Japan have been presented. An AlGaN/GaN HEMT is expanding its application field from L to W bands and it will replace the Si and GaAs based power amplifiers used in mobile phone base stations, terrestrial/satellite microwave communication systems, and collision avoidance car radar systems. A GaN-based rectifier diode will be used in AC/DC converters and also rectenna circuits due to its high breakdown voltage and low on resistance. Recently developed several process technologies are also described.

1. Introduction

GaN-based devices such as AlGaN/GaN HEMTs and diodes are attractive as high frequency power and power switching devices. Continuous efforts have been made to make the operation frequency, output power, and power efficiency higher. In this paper, present status and perspective of GaN-based technology in Japan are presented.

2. High frequency power devices

Since an AlGaN/GaN heterostructure has high breakdown field, high sheet electron density and relatively high mobility, it is applicable to high power and high frequency operations. One of the drawbacks in AlGaN/GaN heterostructures has been a large gate leakage current, however this has been notably improved by inserting a thin insulating layer to the gate (MIS-HEMT). Figure 1 shows the output power in GaN-based HEMT amplifiers recently developed in Japan as a function of frequency. An output power of 200 W was reported at S band [1]. For higher frequencies, output powers of 343 W [2], 101 W [2], 120 W [3], 20.6 W [4], and 0.35 W [5] are obtained at C, X, Ku, Ka, and W bands, respectively. These values are high enough to replace Si LDMOS devices and GaAs HEMTs used in mobile phone base stations, terrestrial microwave communication, satellite communication systems and collision avoidance car radar applications.

Normally-off type (enhancement-mode) devices are highly desired for safe operations and low power consumptions in power switching applications. Wide variety of device structures have been proposed such as recessed gate, MIS-gate, p-GaN gate, and GIT (Gate-Injection-Transistor) [6]-[10]. A positive threshold voltage of 0.7 to 3.0 V has been achieved as enhancement-mode GaN HEMTs.

GaN-based devices are attracting considerable attention for high temperature operations because of the wide band-gap nature of GaN and AlGaN. However, significant decreases in drain current and current gain cut-off frequency (ft) have been observed at high temperatures in AlGaN/GaN HEMTs. The temperature dependence of the performance becomes much less by using AlGaN instead of GaN as a channel material. Fig. 2 shows the temperature dependence of drain current (Fig. 2(a)) and ft (Fig. 2(b)) [11], [12]. In GaN-channel HEMT, the drain current decreased by as high as 80% at 300 $^{\mathrm{o}}$C from RT, while it was only 15% in AlGaN-channel HEMTs. The results indicate that an AlGaN-channel HEMT is more stable for high temperature operations, although low resistive ohmic contact technology has to be developed (discussed in Section 4).

3. Diode characteristics

Diodes are the key devices in AC-DC inverters, DC-DC converters and also Rectenna (Rectifying antenna) circuits for wireless power transmission. Low on-resistance, low capacitance and high breakdown voltage are required to improve the conversion efficiency. For inductive motor driving circuits, an efficiency of 98.2% has been reported by using a p-GaN barrier control layer [13]. The use of a free-standing GaN substrate for a vertical type diode resulted in a breakdown voltage as high as 1100 V [14]. The improvements in breakdown voltage have been reported to be due to the reduced dislocation density.

Regarding diodes for rectenna circuits, control of turn-on voltage was proposed by using a metal stack of Zr/Al/Mo/Au for Schottky contacts. A low on-resistance and capacitance (Co) of 4.2 Ω and 1.0 pF, respectively with a breakdown voltage of 24 V have been reported by Tokuda et al. [15]. Similarly, those values of 8.2 Ω, 0.36 pF, and 90 V have been reported by Ao et al. [16]. These values are expected to show over 80% conversion efficiency at 5.8 GHz in the rectenna circuits. The advantage of using GaN as compared to Si or GaAs is the high breakdown voltage, which enables handling higher microwave power, giving rise to a higher output DC voltage.

4. Process technologies

In order to improve performance in GaN-based devices, several interesting processes have been developed recently in Japan.

Reducing temperature increase inside the device under high power operation is an issue of great importance not only for improved performance but also in terms of reliability. Hirama et al. investigated the effect of diamond substrate for AlGaN/GaN HEMT [17]. The thermal resistance has reduced to 4.1 Kmm/W, which was about a half of SiC substrate (7.4 Kmm/W).

Increasing the breakdown voltage has been the continuous challenge for GaN-based devices. Field plate is one of the most commonly used technologies to achieve high breakdown voltages. Pioneering work on the design of graded field-plate structure has been done by Sakai et al. [18] using computer simulation, where they have shown the effectiveness of graded field plates for increasing breakdown voltages, however it was not realized because of its difficulty in the fabrication process. Recently, graded field plate has been successfully fabricated by utilizing etching rate difference between SiO_2 and PSG (Phospho-Silicate-Glass) [19]. The fabricated graded field plate has proved high breakdown voltage capability together with low current collapse. Other challenges for increasing breakdown voltages include “Blocking Voltage Boosting (BVB)” technology, which was reported by Umeda et al. [20]. They succeeded in increasing the breakdown voltage from 760 V to 1340 V by BVB technology.

Lowering the ohmic contact resistance is the key for increasing drain current and transconductance of HEMTs. Ion implantation into source and drain regions is a candidate to obtain low resistivity. Deguchi et al. showed 25% increase in drain current by inserting the AlN spacer layer and using Si ion implantation [21]. Another way to reduce the ohmic contact resistance is to select the ohmic metal. Ti/Al/Ni/Au or Ti/Al/Mo/Au is the most commonly used metal stack for making ohmic contacts to AlGaN/GaN. However, these metals did not give the best results for AlGaN-channel HEMTs. Yafune et al. showed that low ohmic resistances have been obtained by using a novel Zr/Al/Mo/Au metal stack [22]. Fig. 3 shows the results. As shown in the figure, relatively low ohmic contact resistivity has been obtained even for an AlGaN channel with an Al composition of 51%.

5. Summary

Present status on the development of GaN-based HEMTs and diodes in Japan has been described. The improvements in microwave output power are eminent for GaN-based HEMTs, where over 300 W and 0.3 W are achieved at C and W bands, respectively. It is expected that GaN-based power HEMTs will replace LDMOS used in the mobile phone base stations, and GaAs-HEMTs in collision avoidance car radar systems. GaN-based diodes with high breakdown voltage are also promising for applications in power switching circuits and rectenna circuits. The high conversion efficiency will significantly contribute energy saving, thus reducing the emission of carbon oxide. In order to further improve the device performance, efforts for developing new process technologies have to be continued. Some of the process technologies recently developed in Japan have been overviewed.

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References

[1] F. Yamaki, K. Inoue, N. Ui, A. Kawano, and S. Sano, IEEE MTT-S Symposium Digest, 2011, WE3D-4.

[2] H. Shigematsu, Y. Inoue, A. Akasegawa, M. Yamada, S. Masuda, Y. Kamada, A. Yamada, M. Kanamura, T. Ohki, K. Makiyama, N. Okamoto, K. Imanishi, T. Kikkawa, K. Joshin, and N. Hara, IEEE MTT-S Symposium Digest, 2009, p. 1265.

[3] K. Takagi, S. Takatsuka, Y. Kashiwabara, S. Teramoto, K. Matsushita, H. Sakurai, K. Onodera, H. Kawasaki, Y. Takada, and K. Tsuda, IEEE MTT-S Symposium Digest, 2009, p. 457.

[4] K. Matsushita, H. Sakurai, S. Nakanishi, K. Masuda, K. Takagi, Y. Takada, M. Hirose, and K. Tsuda, Abstracts of 9th Topical Workshop on Heterostructure Microelectronics 2011, Gifu, p. 11.

[5] S. Masuda, T. Ohki, K. Makiyama, M. Kanamura, N. Okamoto, H. Shigematsu, K. Imanishi, T. Kikkawa, K. Joshin, and N. Hara, Proc. of the 39th European Microwave Conference, 2009, p.1796.

[6] K. Ota, K. Endo, Y. Okamoto, Y. Ando, H. Miyamoto, and H. Shimawaki, IEEE IEDM 2009, p.153.

[7] M. Kanamura, T. Ohki, T. Kikkawa, K. Imanishi, T. Imada, A. Yamada, and N. Hara, IEEE Electron Device Lett., vol. 31, p. 189 (2010).

[8] T. Sugiyama, H. Amano, D. Iida, M. Iwaya, S. Kamiyama, and I. Akasaki, Japan. J. of Appl. Phys., vol. 50, 01AD03 (2011).

[9] Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka, and D. Ueda, IEEE Trans. Electron Devices, vol. 54, p.3393 (2007).

[10] T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, IEEE 26th Applied Power Electronics Conference and Exposition, 2011, p. 481.

[11] H. Tokuda, M. Hatano, N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto, and M. Kuzuhara, Appl. Phys. Express, vol. 3, p. 121003 (2010).

[12] M. Hatano, J. Yamazaki, N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto, and M. Kuzuhara, Abstracts of 9th Topical Workshop on Heterostructure Microelectronics 2011, Gifu, p. 13.

[13] D. Shibata, K. Kaibara, T. Murata, Y. Yamada, T. Morita, Y. Anda, M. Ishida, H. Ishida, T. Ueda, T. Tanaka, and D. Ueda, IEEE IEDM 2011, p.587.

[14] Y. Saitoh, K. Sumiyoshi, M. Okada, T. Horii, T. Miyazaki, H. Shiomi, M. Ueno, K. Katayama, M. Kiyama, and T. Nakamura, Appl. Phys. Express, vol. 3, p. 081001 (2010).

[15] H. Tokuda, F. Watanabe, A. Syahiman, M. Kuzuhara, and T. Fujiwara, Proc. of IEEE IMWS-IWPT 2011, Kyoto p.37.

[16] J. P. Ao, K. Takahashi, N. Shinohara, N. Niwa, T. Fujiwara, and Y. Ohno, IEEE Compound Semiconductor Integrated Circuit Symposium 2010, p. 1.

[17] K. Hirama, Y. Taniyasu, and M. Kasu, Appl. Phys. Lett., vol. 98 p. 162112 (2011).

[18] R. Sakai, T. Okai, K. Shiojima, and M. Kuzuhara, IEEE International Meeting for Future of Electron Devices, Kansai, Dig., pp.71-72, (2008).

[19] T. Deguchi, M. Yamashita, H. Tomita, A. Kamada, M. Arai, K. Yamasaki, and T. Egawa, Abstracts of 9th Topical Workshop on Heterostructure Microelectronics 2011, Gifu, p. 67.

[20] H. Umeda, A. Suzuki, Y. Anda, M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, IEEE IEDM 2010, p.480.

[21] T. Nanjo, T. Motoya, A. Imai, Y. Suzuki, K. Shiozawa, M. Suita, T. Oishi, Y. Abe, E. Yagyu, K. Yoshihara, and Y. Tokuda, Japan. J. of Appl. Phys., vol. 50, 064101 (2011).

[22] N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto, and M. Kuzuhara, Japan. J. of Appl. Phys., vol. 50, 100201 (2011).

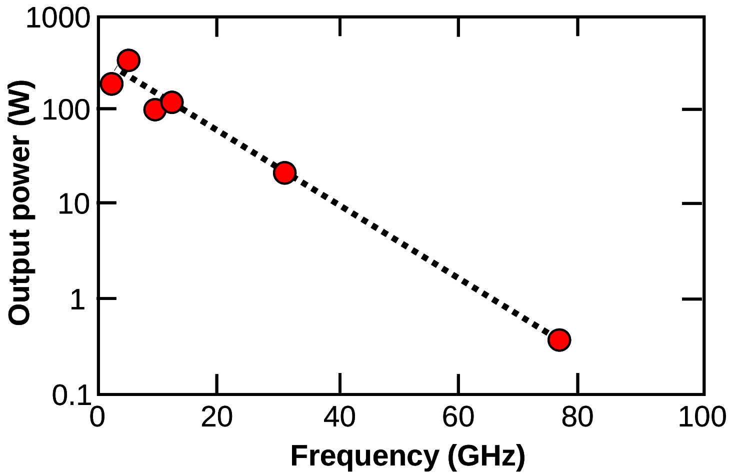
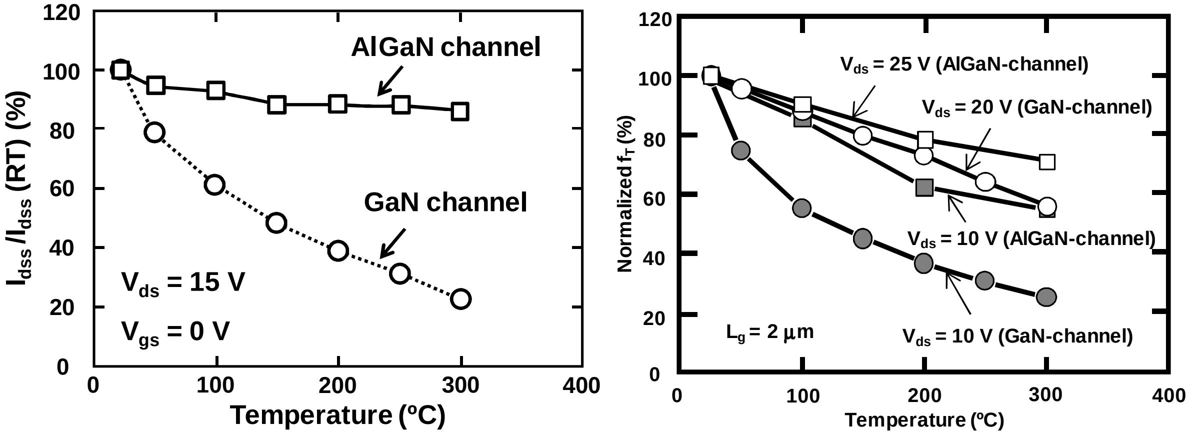


Fig. 1 Output power vs. frequency of GaN-based HEMTs developed in Japan [1]-[5].



(a) (b)

Fig. 2 Temperature dependences of (a) Idss, and (b) ft in GaN and AlGaN channel HEMTs [11], [12].

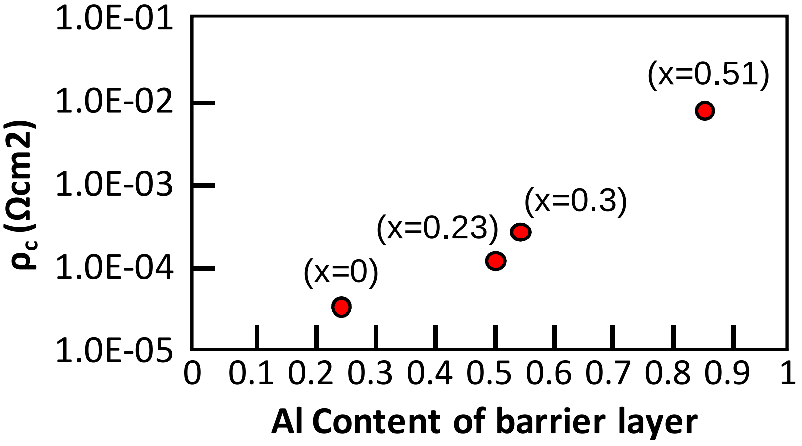


Fig. 3 Specific contact resistivity of Zr/Al/Mo/Au metal stack as a function of Al content in AlGaN barrier layer [22]. Al content of AlGaN channel layer is shown in parentheses.