

60 W Output Power C-Band High-Efficiency Broadband GaN-HEMT

Authors: Yoshitsugu Yamamoto* and Koji Yamanaka**

The AlGaIn/GaN high electron mobility transistor (HEMT) has superior characteristics of high-voltage, high-power density, and high-frequency operation, and is expected to be used for next-generation high-power devices. To date, traveling wave tube amplifiers (TWTAs) have been widely used as high-power devices for C-band or higher frequency applications, but are now expected to be replaced by GaN-HEMT thanks to its improved performance. We have recently demonstrated superior characteristics of GaN-HEMT with an output power of over 60 W and power added efficiency of over 50% with relative bandwidth of 10%, confirming that GaN-HEMT is a promising high-power device at C-band and higher frequency.

1. Introduction

High-frequency devices are now desired to have, in addition to high power and high performance, improved characteristics for practical applications such as small size, low power consumption, high reliability and low cost. Recently, silicon laterally diffused metal-oxide semiconductors (Si-LDMOSs) are widely used as high-output-power devices for mobile phone base stations and other applications, establishing their presence in the L/S band field. Meanwhile, for C-band or higher frequency applications, gallium arsenide (GaAs) based field effect transistors (FETs) and TWTAs are widely used as high-power devices. However, the former has an upper limit of output power density because of its low breakdown voltage, making it difficult to fabricate high-power or broadband devices; and the latter has problems such as large equipment size and short life time. Therefore, new devices that solve these problems need to be developed, such as GaN-HEMT. Because of its material properties, GaN-HEMT is capable of high-voltage and high-power-density operation, and thus small, highly efficient and wide-band devices are easily achievable. Consequently, if TWTA-comparable efficiency is to be achieved in addition to the good inherent reliability of solid-state devices, GaN-HEMT would even replace TWTA.

2. Challenges for High-frequency Applications

Currently, TWTAs are widely used as C-band or higher frequency and over 100-W class high-power de-

vices, and achieve operating efficiencies exceeding 70%. To verify the advantage of GaN-HEMT for high-frequency operation, TWTA-comparable performance needs to be demonstrated. Although a C-band GaN-HEMT with an output power of over 100 W has already been reported⁽¹⁾, the device had a low efficiency and needs to be improved. In addition, when the device is used for a high-power communications amplifier, it is also important to have a wide operation bandwidth and provide a stable high performance. With these backgrounds, we have worked on improving the characteristics of GaN-HEMT devices and have developed a broadband internal matching circuit, and demonstrated its high efficiency at C-band with a relative bandwidth of about 10%.

3. Improvement of Transistor Structure

To enhance transistor performance, it is important to improve the drain efficiency and operational gain. We have already successfully prevented the current collapse phenomenon by forming a surface passivation film using catalytic chemical vapor deposition (Cat-CVD)⁽²⁾, improved the pulse I-V characteristics, and reduced the on-resistance by reducing the ohmic contact resistance by means of Si ion implantation⁽³⁾. With these efforts, the drain efficiency of the transistor has been improved, but parasitic effects become dominant at higher frequency. Consequently, to improve the performance, we have developed a transistor having via holes to reduce source inductance. Considering heat management, the newly developed transistor is fabricated on a highly heat conductive SiC substrate. However, SiC is a very hard material and difficult to process, and thus via holes can not be easily formed through thick SiC substrate. To overcome this problem, we have developed new technologies to reduce the thickness of the SiC substrate with high precision and to perform high-speed etching of via holes.

Figure 1 shows an image of a via hole (80 μm di-

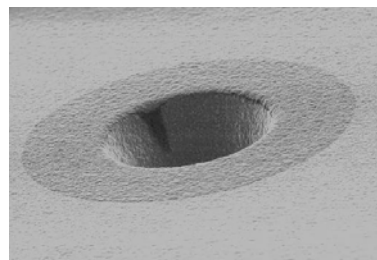


Fig. 1 SEM image of via hole

ameter) observed by a scanning electron microscope (SEM). Before we fabricated the transistor with via holes, we confirmed that good shape via holes as shown in the photograph could be stably formed without residue.

Then, we formed via holes on an actual transistor and confirmed the improvement in the gain. Figure 2 shows the device characteristics with and without via holes. The evaluated device has a gate width of 0.6 mm, and operates at a C-band frequency with a drain voltage of 50 V and a drain current of 30 mA/mm. Even without via holes, the transistor operates at high efficiency with a drain efficiency of 73%, which is calculated from the power added efficiency (PAE) and the gain at the saturated output power level. By forming via holes, the parasitic inductance is reduced, and both operational gain and maximum PAE are respectively improved by about 2 dB and 4% at the saturated output power level. These effects are likely to be even greater above C-band frequencies, and to be extremely useful for further high frequency applications in the future.

4. Development of Broadband High-Efficiency Matching Circuit

With regard to the improvement of transistor efficiency, we verified that the drain efficiency of the transistor itself was improved, and that the efficiency was boosted by improving the gain due to the reduced parasitic effect by forming via holes. However, for use as a high-power amplifier, the efficiency needs to be improved further by optimizing the internal matching circuit. In particular, if higher harmonics are generated and output from the transistor, they will reduce the efficiency. The loss in the matching circuit itself also needs to be minimized. Consequently, we have worked on improving the efficiency by effectively reflecting higher harmonics other than the fundamental wave by means of a higher harmonic reflection circuit⁽⁴⁾⁽⁵⁾. Figure 3 shows a schematic diagram of the output matching circuit that achieves high efficiency over a wide bandwidth. A second harmonic reflection circuit is directly connected to the transistor and reflects higher harmonics generated in the transistor. The reflection circuit uses parallel-connected short and

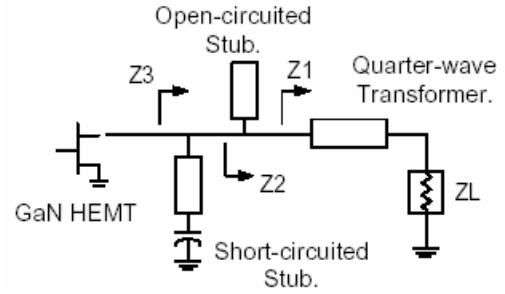


Fig. 3 Broadband high-efficiency output matching circuit

open-circuited stubs for effective reflection within the circuit. With this configuration, second harmonic waves generated in the transistor are reflected back to the transistor with very little attenuation. In addition, by appropriately setting the design parameters of the short- and open-circuited stubs, the phase condition for second harmonic reflection is satisfied over a wide bandwidth. Figure 4 shows the evaluation results of the frequency dependencies of the output power, drain efficiency, and power added efficiency of an internal matching type amplifier using the above-described transistor and matching circuit. The horizontal axis indicates the frequency ratio with respect to the center measurement frequency in C-band, F_0 . For this prototype evaluation, a transistor without via holes having a gate width of 16 mm was used, and the drain voltage was 40 V during the measurement.

These results confirm that the circuit shown in Fig. 3 effectively functions as a broadband high-efficiency output matching circuit, achieving a drain efficiency of over 53% and an output power of over 60 W across a relative bandwidth of 10% at C-band.

These results are characteristics of the transistor without via holes, so we then fabricated a device using a transistor with via holes. For this prototype, the internal matching circuit was redesigned to be optimized for the transistor with via holes. Figure 5 shows the evaluation results of the frequency dependencies of the output power and power added efficiency of a broadband high-efficiency amplifier using a transistor with via holes. The horizontal axis indicates the normalized frequency with respect to the center frequency in C-band. During

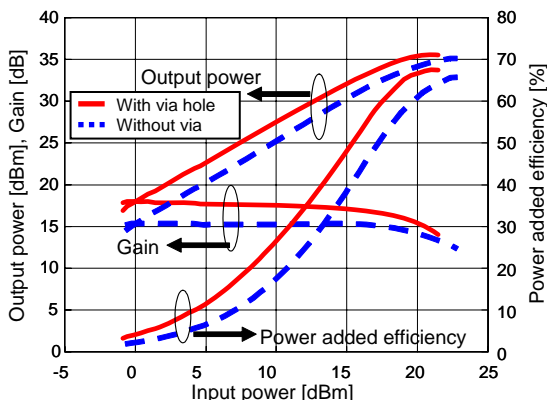


Fig. 2 Comparison of device characteristics with and without via holes

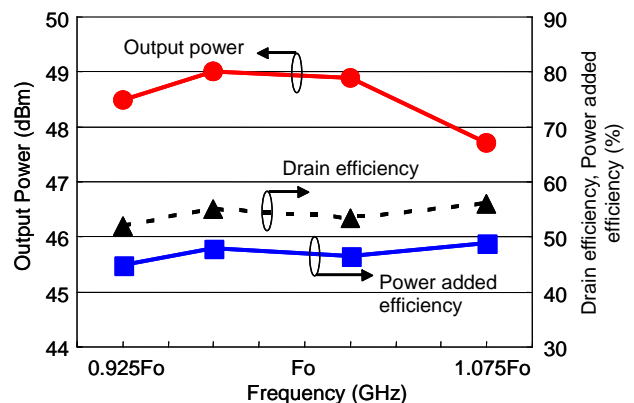


Fig. 4 Frequency characteristics of broadband high-efficiency amplifier

these measurements the drain voltage was 40 V. This chart confirms that the prototype has an output power of over 60 W and a power added efficiency of over 50% across a relative bandwidth of 10% at C-band.

Figure 6 compares these results with the reported values of C-band high-efficiency high power amplifiers (HPAs)^{(6) - (12)}. The horizontal axis shows the output power and the vertical axis the drain efficiency. Our newly developed broadband HPAs exhibit high efficiency over a wide bandwidth at C-band and have achieved the highest drain efficiency among broadband devices. These results indicate that GaN-HEMT devices offer excellent potential even at frequencies higher than C-band.

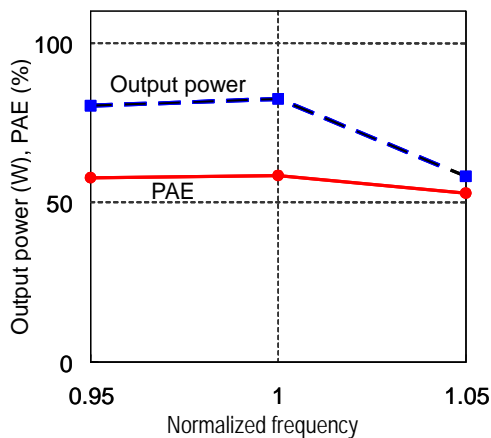


Fig. 5 Frequency characteristics of broadband high-efficiency amplifier using a transistor with via holes

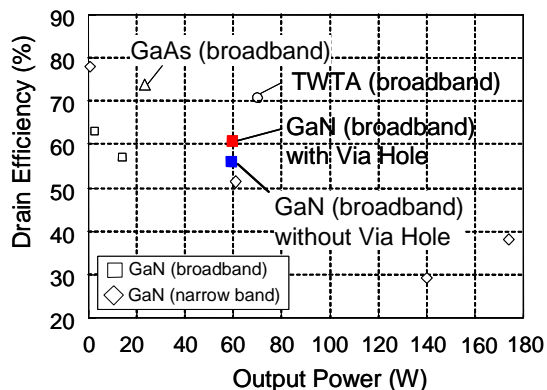


Fig. 6 Performance comparison of C-band high-efficiency amplifiers

5. Conclusion

We have developed C-band high-power broadband amplifiers using AlGaIn/GaN HEMT. We developed via hole forming technology to reduce the parasitic inductance of the transistor, and successfully demonstrated an improved operational gain. We combined this improved transistor with our newly developed broadband high-efficiency matching circuit to realize a high-frequency, broadband power amplifier device, which has the world's highest power added efficiency of over

50% with an output power of over 60 W across a relative bandwidth of 10% at C-band. These results indicate that GaN-HEMT devices are promising for operation at frequencies higher than C-band, with power and efficiency comparable with those of TWTA devices.

References

- (1) Yamanaka, K., et al.: "S and C-Band Over 100 W GaN HEMT 1 Chip High Power Amplifiers with Cell Division Configuration," 2005 European Gallium Arsenide and Other Semiconductor Application Symposium, pp. 241-244 (2005)
- (2) Kamo, Y., et al.: "A C-Band AlGaIn/GaN HEMT with Cat-CVD SiN Passivation Developed for an Over 100W Operation," Mitsubishi Technical Report, 80, No. 5, 35-38 (2006)
- (3) Oishi, T., et al.: "High Performance GaN Transistors with Ion Implantation Doping," Mitsubishi Technical Report, 79, No. 8, 39-42 (2005)
- (4) Yamanaka, K., et al.: "C-band GaN HEMT Power Amplifier with 220 W Output Power," 2007 IEEE MTT-S Int. Microwave Symp. Dig. TH1A-2 (2007)
- (5) Iyomasa, K., et al.: "GaN HEMT 60 W Output Power Amplifier with Over 50% Efficiency at C-Band 15% Relative Bandwidth Using Combined Short and Open Circuited Stubs," 2007 IEEE MTT-S Int. Microwave Symp. Dig. TH1A-3 (2007)
- (6) Ui, N., et al.: "A 100 W Class-E GaN HEMT with 75% Drain Efficiency at 2 GHz," Proc. 36th European Microwave Conf., Manchester (2006)
- (7) Colantonio, P., et al.: "A C-band High-efficiency Second-harmonic-tuned Hybrid Power Amplifier in GaN Technology," IEEE Trans. MTT-S., Vol. 54, No. 6, pp. 2713-2722 (2006)
- (8) Otsuka, H., et al.: "Over 65% Efficiency 300 MHz Bandwidth C-band Internally-matched GaAs FET Designed with a Large-signal FET Model," 2004 IEEE MTT-S Int. Microwave Symp. Dig., pp. 521-524 (2004)
- (9) Menninger, W. L., et al.: "70% Efficient Ku-Band and C-Band TWTs for Satellite Downlinks," IEEE Trans. Electron Devices, pp. 673-678 (2005)
- (10) Wu, Y.-F., et al.: "14-W GaN-based Microwave Power Amplifiers," 2000 IEEE MTT-S Int. Microwave Symp. Dig., pp. 963-965 (2000)
- (11) Chini, A., et al.: "Power and Linearity Characteristics of Field-plate Processed-gate AlGaIn-GaN HEMTs," IEEE Electron Device Letters, pp. 229-231 (2004)
- (12) Okamoto, Y., et al.: "C-band Single-chip GaN-FET Power Amplifiers with 60-W Output Power," 2005 IEEE MTT-S Int. Microwave Symp., pp. 491-494 (2005)