Gallium Nitride High Electron Mobility Transistor (GaN-HEMT) Technology for High Gain and Highly Efficient Power Amplifiers

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The ubiquitous network society is evolving at an accelerated pace using various mobile communication tools, especially mobile phones. The driving force behind such a rapid development of the network is the rise in requirements of various bandwidth sensitive user applications. This leads to a demand for large capacity mobile communications, with availability anytime, anywhere and with anything. The transmission capacity of the improved third generation mobile system has been increased from 2 Mbit/s to 14 Mbit/s (in static mode) with a high-speed communication service system called HSDPA (High Speed Download Packet Access). Furthermore, various field tests have been conducted for mobile WiMAX (Worldwide interoperability for Microwave Access) with a transmission speed of 75 Mbit/s. Also, research and development of a transmission capacity, more than 100 Mbit/s in the 4th generation mobile system, is progressing aggressively with practical implementation to start from 2010. High gain and high power characteristics of a transmission power amplifier are very important for a high speed wireless based station and its characteristics strongly influence the communication quality. However, the higher output power amplifier devices lead to an increase in the base station's equipment size and also lead to an increase in the power consumption of the system. In addition, the higher power costs and environmental concerns of base stations become focused on the high efficiency of the power amplifier devices because power consumption is a dominant factor of the base station system. Power amplifier devices with high output, high gain and high efficiency, are required to meet such a challenging demand.

We have been developing the device and fabrication technologies of the Gallium Nitride High Electron Mobility Transistor (GaN-HEMT) out of interest for the high potential of the GaN material's capability. In this paper we introduce the GaN-HEMT with a source field plate (SFP) structure, including its power characteristics with a very high gain and efficiency.

GaN-HEMT characteristics

GaN-HEMTs differ in the following beneficial aspects from existing silicon (Si) devices and Gallium Arsenide (GaAs) devices, since Gallium Nitride (GaN), which is a wide bandgap semiconductor, is used as a channel for GaN-HEMT devices:

- The concentration of the Two Dimensional Electron Gas (2DEG), which is formed between the AlGaN and GaN heterostructure interfaces, is about ten times as large as that of Si (increasing the amount of drain current).
- The electron saturation velocity of GaN material is about twice as fast as that of Si (high frequency).
- The breakdown of the electric field is about ten times larger than that of Si (high breakdown voltage).

Fig. 1 shows a comparison of the devices based on the material performance and figure of merit (FM) in view of the high frequency and power devices[1]. GaN-HEMT and Silicon Carbide (SiC) devices are expected to be the next generation power devices for high material potential; on the other hand, in **Fig. 1** Si and GaAs-HEMT devices represent existing conventional devices. The Johnson's FM and Keyes' FM shows the performance of power transistors. The saturation velocity and electron mobility, as well as f_{max}, are indicators for the high frequency characteristics. Furthermore, the breakdown voltage and 1/Ron have a close relationship to the operation voltage and power efficiency, respectively. It can be seen in the diagram that GaN-HEMT has the highest potential among these devices in the high frequency and power characteristics.

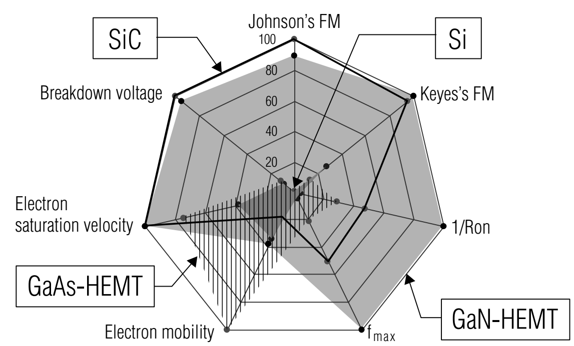

Fig. 1 Diagram with performance indices and materials of respective devices

Device structure of GaN-HEMT

A schematic cross-section of our GaN-HEMT device with a source field plate structure is shown in **Fig. 2**. The epitaxial layers, which consist of a buffer layer, GaN layer and AlGaN layer, were grown by a metal organic chemical vapor deposition (MOCVD) on 3-inch semi-insulating 4H-SiC substrates with a good thermal conductivity. The concentration of the 2DEG, about 1×10^{13} cm^{-2} formed between AlGaN and GaN interface, is very attractive and makes it capable of drain current density about ten times higher than that of Si devices. As a result high output power characteristics are quite feasible since a large drain current can be realized. However, it was difficult for GaN-HEMTs to obtain good

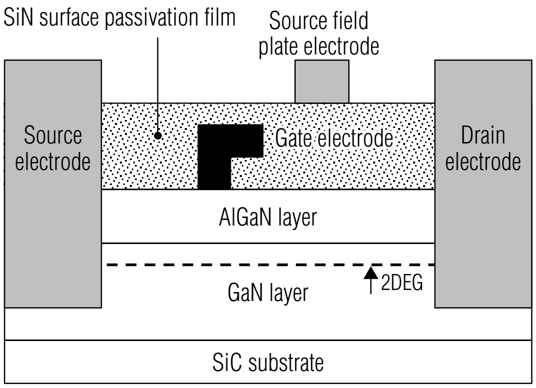

Fig. 2 Schematic cross-section of GaN-HEMT

contact characteristics between the 2DEG and ohmic electrodes through the AlGaN layer due to the barrier height of the wide bandgap semiconductor. An ohmic contact resistance is needed as low as possible to achieve a good device performance, whereas the lowest resistance of the ohmic contact characteristic impacts the device characteristics. Recess etching in the ohmic region was conducted in order to enhance the electron tunneling probability by means of reducing the distance between the 2DEG and ohmic electrodes[2), 3)]. **Fig. 3** shows the recess etching depth dependence of the ohmic contact resistance. It is possible to reduce the contact resistance as low as 1.0 Ω mm with deep etching over the hetero-junction between AlGaN and GaN. We found that direct contact between the 2DEG and ohmic electrodes could be achieved to obtain good ohmic contact characteristics.

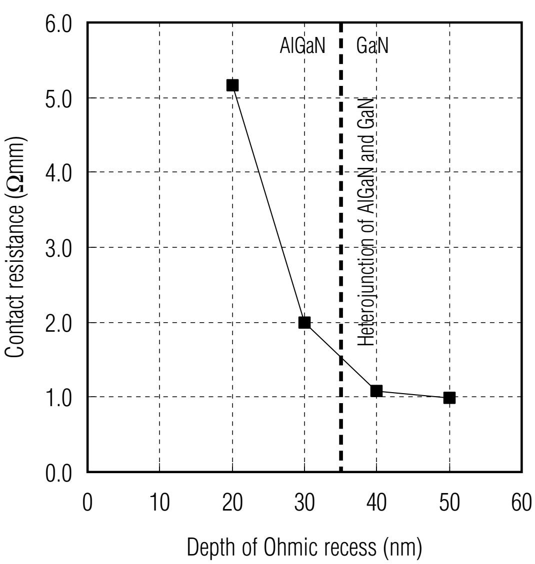

Fig. 3 Dependence of contact resistance on recess depth in ohmic region

Effect of source field plate electrode

A device structure was important to utilize the high breakdown field of GaN material. The Γ (gamma) shaped gate electrode towards the drain (GFP: gate field plate electrode) was sometimes employed to reduce the electric field at the edge region of the gate electrode. The potential distribution on the device with GFP was investigated through a device simulation method as shown in **Fig. 4, to the left**, with a drain voltage of 100 V and a gate and source voltage of 0 V. It is clear that a concentration of the electric field still existed due to the dense electrical potential distribution under the gate field plate. Since the electric field concentration causes the breakdown voltage to degrade in the device, it was important to reduce the electric field concentration in the device area, especially in the region between the gate and the drain electrode. Another field plate electrode connecting the source electrode was added to the surface passivation film between the gate and the drain electrodes, which is the so called source field plate (SFP). The electrical potential distribution of the device with SFP is shown in **Fig. 4 to the right**. It indicates that the electric field concentration was modified by the SFP electrode of 0 V as the same voltage potential of the source electrode. The electric field intensity at the GaN channel is shown in **Fig. 5**. The SFP electrode could reduce the maximum electric field strength by about 30%, from 1.3×10^6 V/cm to 0.9×10^{16} V/cm. Furthermore, we investigated the influence of the SFP position in the RF characteristics. When the SFP covers the gate electrode the gate-source capacitance (Cgs) increases and it affects the RF characteristics of FET. The position of the drain side edge of the SFP electrode was fixed and the

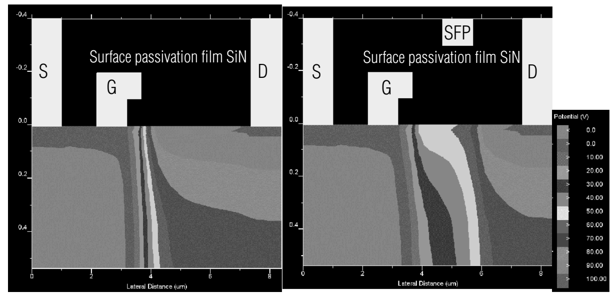

Fig. 4 Relaxation effect of electrical potential distribution using SFP electrode

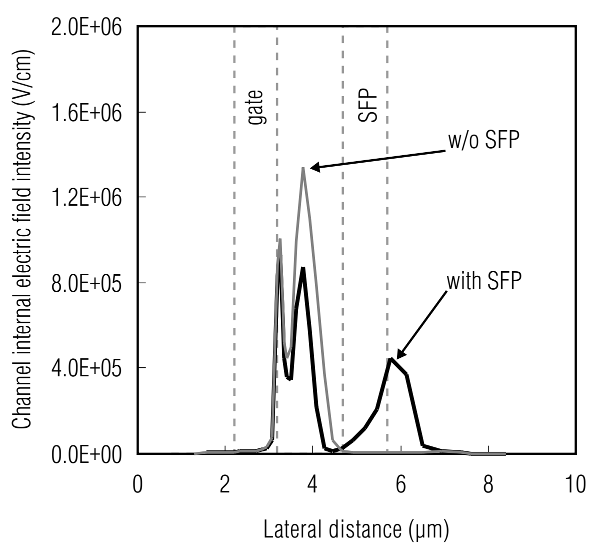

Fig. 5 Change of electric field intensity in channel using SFP electrode

length of the SFP was varied to enable an investigation of the dependence in terms of distance between the gate and the SFP electrode. The positional dependency of the SFP electrode for the cut-off frequency (fT) is shown in **Fig. 6**. It was determined that fT degradation can be avoided by placing the SFP electrode about 1 μm away from the gate electrode since the fT of the conventional FET without an SFP electrode is 10 GHz.

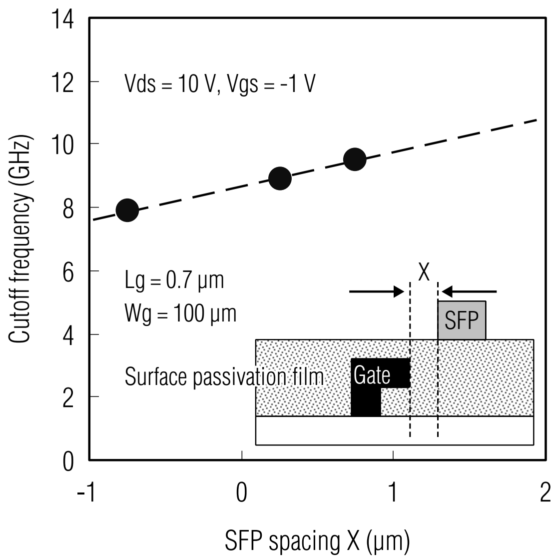

Fig. 6 SFP position influence on cut-off frequency

Shown in **Fig. 7** are the I-V characteristics of GaN-HEMT with a conventional structure (top) and our developed GaN-HEMT with the SFP electrode (center), as well as the high voltage pinch-off characteristics (bottom). The breakdown voltage in the pinch-off state (BVdsoff) was defined at 1 mA/mm of the drain current. The I-V characteristics show good pinch-off characteristics with a maximum drain current (Idsmax) of 600 mA/mm and maximum transconductance (gmmax) of 180 mS/mm. The BVdsoff is indicated as 300 V, which means significant improvements have been made by the effects of reducing the electric field strength in comparison with BVdsoff of 200 V in a conventional device without an SFP electrode. Another reality was the current collapse phenomenon, wherein the drain current that was dropping during the operation, was not emerging up to the drain voltage of 100 V in the I-V characteristics with the SFP structure. The current collapse phenomenon was triggered by the electron trapped on the surface of the semiconductor and thus a deep relationship existed with the electric field concentration. This is also an effect of the SFP electrode due to the relaxation of the electric field concentration.

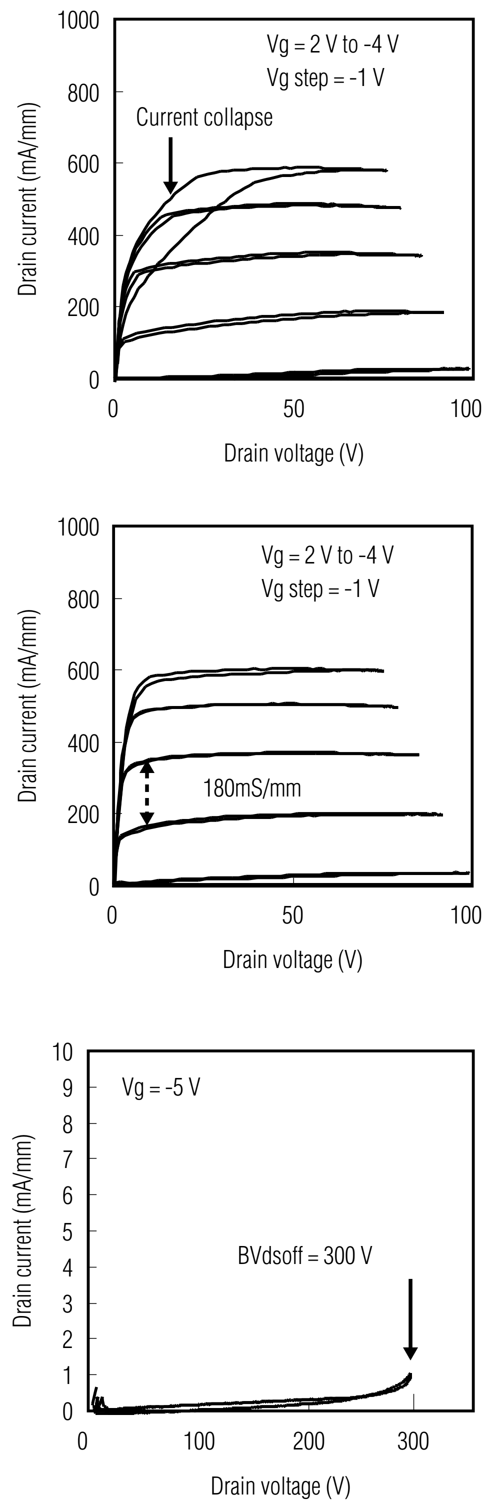

Fig. 7 DC characteristics of GaN-HEMT
Top: Conventional structure
Center: GaN-HEMT with optimized SFP structure
Bottom: High voltage Pinch-off characteristics of GaN-HEMT with optimized SFP structure

High gain and highly efficient output power characteristics

A microphotograph of a 50 W-class GaN-HEMT device with a multi-finger gate, which was applied to the developed HEMT, is shown in **Photo 1**, as well as a photograph of the ceramic package. The gate length and gate width are 0.7 μm and 13.5 mm, respectively. **Fig. 8** shows the input and output power characteristics of the GaN-HEMT of the 50 W-class. As shown in **Fig. 8**, we attained a highly linear gain of 17 dB and high drain efficiency (ηD) of 58% at the frequency of 2.14 GHz and an operating voltage of 50 V. In addition, the package of the device did not contain any input and output impedance matching circuits and the output characteristics were obtained by the external matching circuits.

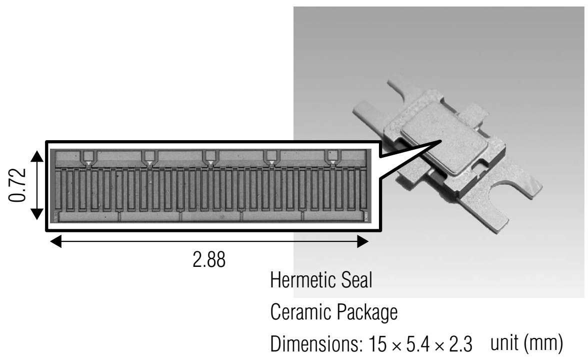

Photo 1 Microphotograph of 50 W-class GaN-HEMT with multi-finger gate and mounted ceramic package

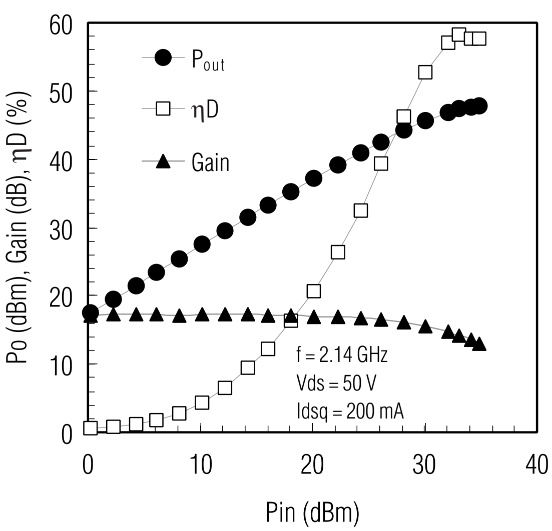

Fig. 8 Input and output power characteristics of recently developed 50 W-class GaN-HEMT

Conclusion

We developed a GaN-HEMT device with a source field plate structure as a high output power amplifier for next-generation base station applications. A low contact resistance of 1.0 Ωmm was achieved by recessed etching in the ohmic region. This made it possible for us to obtain superior device characteristics of 600 mA/mm and gmmax of 180 mS/mm. At the same time we were also able to relax the electric field strength at the channel by means of optimizing the dimension of the source field plate electrode between the gate and the drain electrodes. Furthermore, we achieved a high voltage breakdown voltage of 300 V without sacrificing the high frequency characteristics. We applied this FET with a SFP structure to the high output device with a multi-finger gate and evaluated the RF characteristics with the prototype mounted in a ceramic package. We achieved high gain and very efficient characteristics with the operation voltage of 50 V, a saturation output power of 50 W, linear gain of 17 dB and drain efficiency of 58% at frequency of 2.14 GHz.

In future we intend to proceed with our work on the practical application of the recently developed GaN-HEMT. At the same time we will proceed with the GaN-HEMT development of an extremely efficient, high gain and high output power device at a higher frequency, which are expected to be applied to the fourth-generation mobile phone system for the ubiquitous network society.

References

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