Improving the Performance of GaN Power Devices for High Breakdown Voltage and High Temperature Operation

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ABSTRACT GaN, like SiC and AlN and other wide bandgap semiconductors, has outstanding features such as being able to operate at high breakdown voltages, high frequencies and high temperatures, and it is therefore expected to find wide application in power conversion devices, etc. In this work the authors have investigated a unique Ti/AlSi/Mo electrode as the ohmic electrode of an AlGaN/GaN HFET. This has made it possible to achieve a contact line resistance less than one-third that of Ti/Al. Fabricating an AlGaN/GaN HFET with a gate width of 200 mm using this electrode, we have achieved operating currents of 20 A or more at room temperature and 10 A or more in a 500-K environment, and off breakdown voltages in excess of 450 V at 500 K. And by using high-refractive index SiN_x as the surface passivation film, it was possible to achieve a reduction in gate leakage current of about two orders of magnitude compared to SiO_2.

1. INTRODUCTION

In recent years there has been a growing need for energy development that takes account of environment policies like reduction of carbon dioxide. Specifically, the Kyoto Accords, issued on February 16, 2005 with the aim of stabilizing greenhouse gases in the atmosphere, have imposed on Japan a duty to reduce greenhouse gases by 6 % relative to 1990 levels from 2008 to 2012. This is the background against which the need for more efficient electric power and energy-saving measures has arisen. Currently power conversion devices use silicon-based switching elements, but in recent years the physical limitations of silicon are being approached, creating a desire for alternative materials.

GaN, like SiC and AlN and other wide bandgap semiconductors, has a bandgap width about three times greater than Si and an insulation breakdown voltage about an order of magnitude greater, giving it superior thermal insulation and breakdown voltage properties, thereby enabling higher frequency operation and various other superior performance indices [1)~6)].

Particular noteworthy is the fact that the on-state resistance (R_{on}) during FET operation can theoretically be reduced to more than an order of magnitude less than that of Si-based devices. This promises simpler, smaller and lighter cooling systems, and is drawing much attention as an alternative to Si as a semiconductor material for ultra-low-loss power devices.

Early development of GaN was carried out in the area of light-emitting devices—green LEDs, lasers, etc.—but its superior performance as noted above and the needs of society led to R&D work for electronic devices being conducted world-wide. Specifically, the AlGaN/GaN HFET structure permits the formation of a high-density electron layer known as a two-dimensional electron layer on an AlGaN/GaN hetero interface by adding impurities to the carrier supply layer of AlGaN. Thus this AlGaN/GaN HFET structure holds out the possibility of achieving a high-frequency output device surpassing the characteristics of existing devices.

Furukawa Electric has been involved in this development from the earliest stages, and has reported the world's first prototype inverter circuit using an AlGaN/GaN HFET. This inverter is made up of a DC converter using an AlGaN/GaN HFET and an AC inverter. Its operating output power was 50 W and maximum output power was 200 W [7)]. More recently a device with an output power in excess of 200 W has been reported [8)], and its application as a high-output power device is anticipated.

In this paper we describe the results of investigations in an AlGaN/GaN HFET, of, first of all, a Ti/AlSi/Mo structure for a unique ohmic electrode having reduced on-state resistance. We also describe how this ohmic electrode evolved into a larger device (gate width: 200 mm) and mounted in a package designed for operation in a high-temperature environment, and its characteristics at 500 K

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have been evaluated, confirming satisfactory operation at high temperatures. We also describe the results obtained from investigations focusing on the refractive index of SiN_x surface passivation films with the aim of reducing gate leakage current.

2. LOWER RESISTANCE USING AlSi-BASED OHMIC ELECTRODES

In order to improve FET performance, a reduction in on-state resistance is essential, and this requires decreased contact resistance between the ohmic electrode and the AlGaN layer. According to examples reported in the literature, methods such as implantation of Si, an n-type dopant, in the AlGaN layer have been used [9)~11)]. In our effort to reduce on-state resistance, we adopted selective area growth (SAG) of a high-density n-GaN layer immediately beneath the ohmic electrode, thereby achieving lower contact resistance [12)]. This technique, however, is subject to reduced yields due to faulty deposition of the SAG layer, and to reductions in breakdown voltage thought to be attributable to degraded crystallization and to the occurrence of damage. Taking these problems into consideration, we may conclude that it is necessary to form a low-contact-resistance ohmic electrode directly, with no special processing on the AlGaN layer.

In the literature, Ti/Al-based ohmic electrodes have been commonly used and it has been reported that, using Ti as the contact electrode on AlGaN, the forming of nitrogen holes by Al diffusion under high-temperature heat treatment contributes to reducing contact resistance [13)]. Since the melting point of Al is low, around 660°C, high-temperature heat treatment is difficult, and sufficient reduction in contact resistance cannot be obtained. There is also a problem in that high-temperature heat treatment gives rise to deterioration of the electrode surface. Accordingly we tried investigating an electrode with a multilayer structure, with a barrier metal of high melting point sandwiched between, by which means reduced contact resistance and improvements to surface conditions were achieved [14)~17)].

In this work, in trying to achieve reduced contact resistance we applied a Ti/AlSi/Mo electrode structure using AlSi instead of Al in the frequently reported TiAl, and disposing Mo, which has a higher melting point and comparatively low metallic resistivity, on the uppermost surface, and we examined the results.

All the epitaxial wafers in this report were fabricated on 2-inch sapphire (0001) substrates by successive deposition by MOCVD of a buffer layer, a GaN layer (thickness 3 μm), and $Al_xGa_{1-x}N$ layer (x = 0.22 and thickness 30 nm).

The structure of the ohmic electrode examined was Ti (25 nm) / AlSi (100 nm) / Mo (200 nm), fabricated by sputtering. After the ohmic electrode was formed, it was heat treated at 850°C for 30 sec.

The contact line resistance R_c and channel sheet resistance R_{sh} were evaluated by transfer length measurement (TLM). TLM pad gaps were 10, 20, 30, 40, 50 and 100 μm. Table 1 shows the structure of the ohmic electrodes investigated and the results of TLM evaluation. In the one with the lowest contact line resistance we were able to obtain 0.48 Ωmm, representing less than one-third compared to Ti/Al.

With respect to the surface morphology of the Ti/AlSi/Mo structure before and after heat treatment, observations were made by atomic force microscopy (AFM). Virtually no change in surface morphology was observed before and after heat treatment, and compared to an RMS value of 5.5 nm before heat treatment, the value afterwards, at 5.7 nm, was virtually the same.

Table 1 Results of investigation of Ohmic electrodes.

Barrier metal	Mo	None	Mo
Al or Al-Si	Al-Si	Al	Al
R_c (Ωmm)	0.48	1.66	NG
R_{sh} (Ω/□)	432	426	—

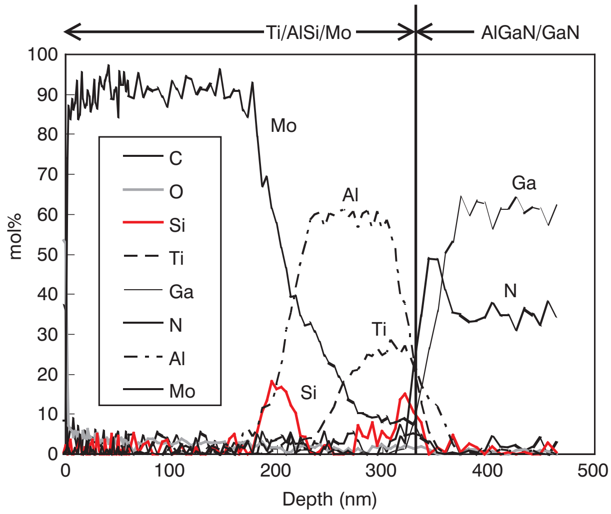

Figure 1 Analysis of Ti/AlSi/Mo ohmic electrode after heat treatment by AES.

To understand whether or not contact line resistance was improved by Ti/AlSi/Mo, we analyzed samples after annealing using Auger electron microscopy (AES). Figure 1 shows the results, and, as can be seen, we found that the Si of the AlSi was diffused as far as the interface layer between the AlGaN and the electrode. We may conclude that this contributes to the improvement in contact line resistance.

Thus we see that, by means of our unique Ti/AlSi/Mo electrode structure, we have been able to provide a highly superior ohmic electrode, with a contact line resistance significantly better than that of the commonly used Ti/Al, and in which electrode surface degradation caused by heat treatment was inhibited.

Accordingly we moved to actually fabricate an AlGaN/GaN HFET device using the Ti/AlSi/Mo ohmic electrode. Figure 2 shows a cross-sectional view of this device, which has a gate length of 2 μm, a gate-to-drain distance of 10 μm, a gate-to-source distance of 3 μm, and a gate width of 400 μm.

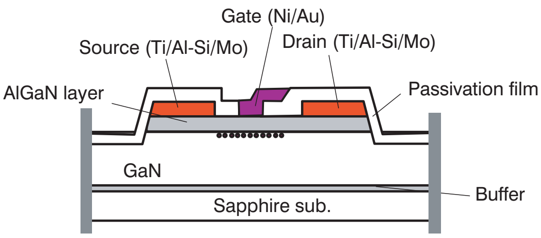

Figure 2 **Cross-section of AlGaN/GaN HFET.**

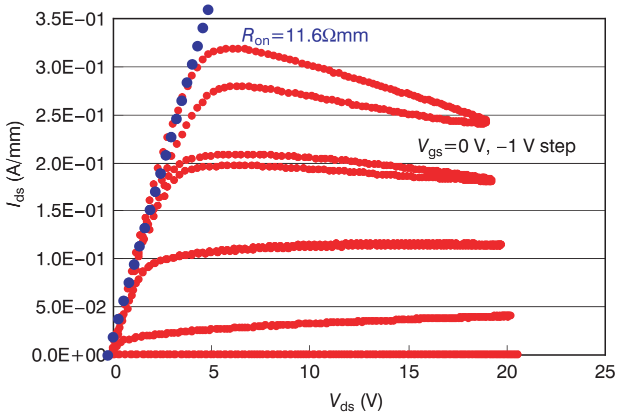

Figure 3 ***I-V*** **characteristic of AlGaN/GaN HFET with gate width of 400 μm.**

Figure 3 shows the I-V characteristic of a device with a gate width of 400 μm. With respect to on-state characteristics, we were able to obtain a current of 250 mA/mm or more at a gate voltage of 0 V. On-state resistance of 11.6 Ωmm was obtained, a satisfactory characteristic.

3. AlGaN/GaN HFET WITH 200-mm GATE WIDTH

Using the unique Ti/AlSi/Mo ohmic electrode structure discussed above, we fabricated an AlGaN/GaN HFET with a gate width increased to 200 mm. Figure 4 is a photograph of this device. Its cross-sectional structure is fundamentally as shown in Figure 2, with a gate length of 2 μm, a gate-to-drain distance of 10 μm, and a gate-to-source distance of 3 μm. It was possible to form a large-scale AlGaN/GaN HFET with a gate width of 200 mm by linking the source, gate and drain electrodes, respectively, of 1000 unit FETs each having a gate width of 200 μm.

3.1 On-State Resistance

Figure 5 shows the results of an evaluation of the on-state resistance of an AlGaN/GaN HFET with 200-mm gate width at room temperature. The on-state resistance was 55.1±1.9 mΩ, and uniformity within the surface was good. Since the effective surface area of the device was 12 mm², we obtain an on-state resistance per unit area of 6.3 mΩ·cm².

3.2 Package

We designed a package to accommodate the AlGaN/GaN HFET with the aim of supporting operation in high-temperature environments. Figure 6 shows a photograph of this package. The package material was selected for considerations of heat-diffusion. With respect to the thermal resistance of the package, a thermal analysis simulation resulted in an estimate of 0.45 K/W, showing that heat dissipation is satisfactory.

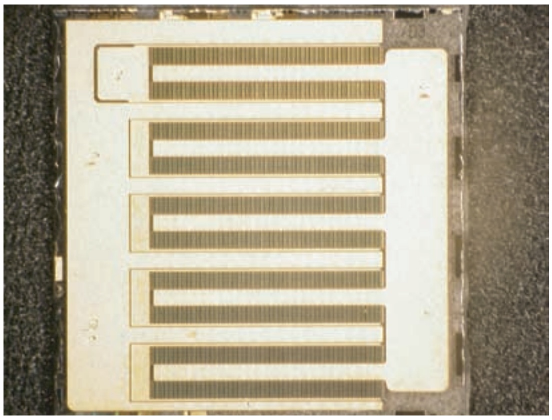

Figure 4 **Photograph of AlGaN/GaN HFET with 200-mm gate width.**

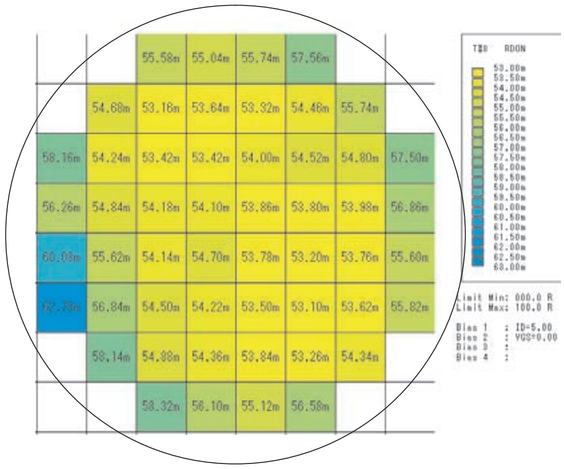

Figure 5 **Results of evaluation of on-state resistance (I_{ds} = 5 A).**

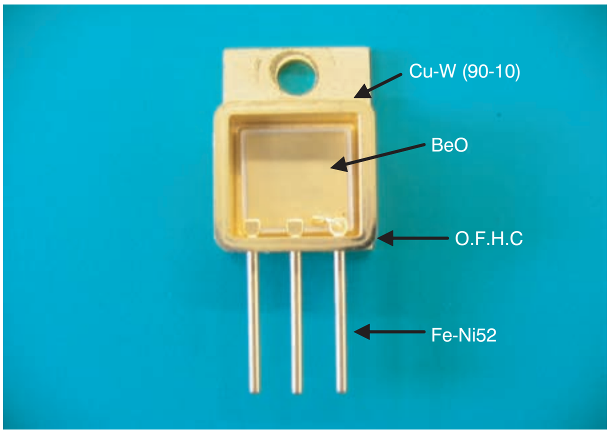

Figure 6 **Photograph of package for high-temperature operation.**

3.3 Evaluation of Characteristics of a Packaged AlGaN/GaN HFET

The characteristics of the AlGaN/GaN HFET were then evaluated when mounted in the package we designed, and Figure 7 shows the I-V characteristic. It was possible to obtain a drain current of more than 20 A at room temperature (300 K), and even at 500 K more than 10 A was obtained. As a result we conclude that the use of our unique Ti/AlSi/Mo ohmic electrode was the major factor in our success in reducing on-state resistance. Furthermore, our achievement of high-output operation, even in environments as hot as 500 K, is indicative of the superior temperature characteristics of the GaN material itself. Figure 8 shows the results obtained when off-state characteristics were measured in a high-temperature environment and the off breakdown voltage evaluated. An increase in off breakdown voltage to over 450 V was achieved.

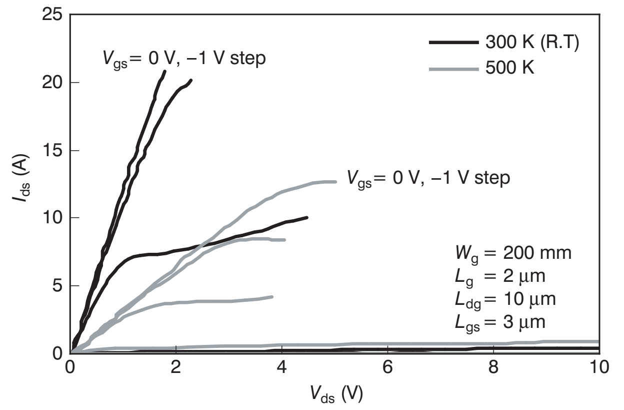

Figure 7 ***I-V* characteristic of AlGaN/GaN HFET with gate width of 200 mm.**

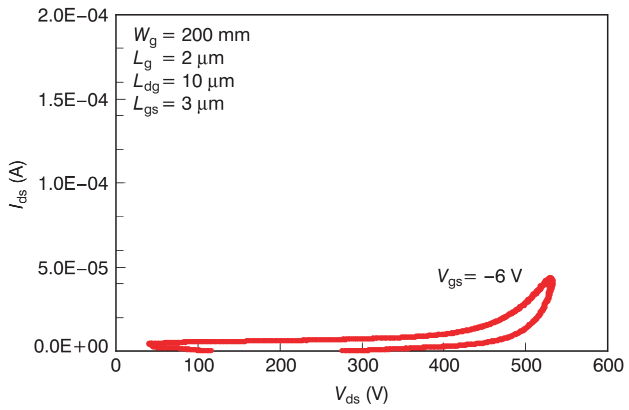

Figure 8 **Off breakdown voltage characteristic of AlGaN/GaN HFET (large scale).**

4. INVESTIGATION OF SiN_x PASSIVATION FILMS FOR DECREASING GATE LINK CURRENT

Among the problems arising in the commercialization of the AlGaN/GaN HFET, we may mention suppression of the so-called current collapse phenomenon in which the drain current is drastically decreased during high-voltage operation, and the reduction of the extremely large gate leakage current. These problems are considered to be largely caused by surface morphology [18].

Accordingly consideration was given to a recessed gate structure [19], a field plate structure [20], MIS structures [21), 22)], surface passivation films [23)~25)], and so on. There have been a particularly large number of reports of the use of SiN_x in passivation films, thereby suppressing current collapse. These may be attributed to the difference in interface level densities between a passivation film of SiN_x, SiO_2, etc. and the AlGaN (GaN), and there is a report of the use of SiN_x resulting in a reduction in interface level density of an order of magnitude or more compared to SiO_2 [25]. It was therefore concluded that the use of SiN_x as the passivation film is effective in suppressing current collapse.

On the other hand it has been reported that in GaAs FETs the piezoelectric charges, which occur because of passivation film stress and are concentrated at the gate terminal, cause degradation in characteristics [29]. Accordingly we focused our attention on SiN_x stress, and investigated the effect that film stress has on gate leakage current.

4.1 Evaluation of SiN_x Stress

First we grew a 300-nm film of SiN_x on a silicon substrate using the PCVD method to vary the refractive index, and investigated the relationship between stress and refractive index for SiN_x. We evaluated stress by measuring the amount of substrate flexure before and after deposition of the SiN_x film and calculating the stress. Figure 9 shows the results.

The stress for SiN_x was all tensile stress, and with a shift to a higher refractive index the stress decreased, becoming substantially constant at a refractive index of about 2.1. For purposes of comparison we also evaluated SiO_2 in the same way, and found that for SiO_2 the stress was 2.46 Pa, and, contrary to SiN_x, was compressive.

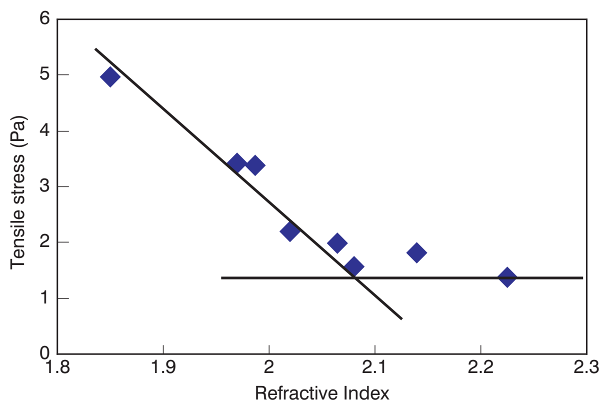

Figure 9 **Relationship between stress and refractive index for SiN_x.**

4.2 Evaluation of Properties of AlGaN/GaN HFET

The four types of passivation films that we evaluated, as shown in Table 2, were three types of SiN_x with varying refractive indices and SiO_2. The stress values shown in Table 2 are the results of this evaluation. The devices evaluated had a gate length of 2 µm, a gate-to-drain dis-

Table 2 Refractive index and stress of passivation films.

Film	Refractive index	Stress (Pa)
SiN_x (1)	1.85	−4.98
SiN_x (2)	2.02	−2.19
SiN_x (3)	2.09	−1.65
SiO_2	1.46	+2.46

* + = compressive; − = tensile

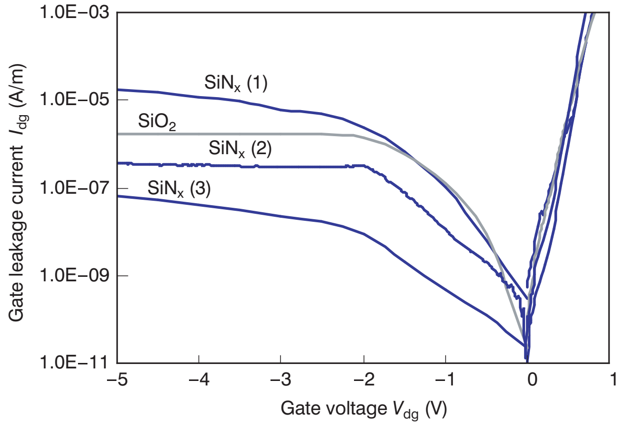

Figure 10 Source-to-drain *I-V* characteristic.

tance of 10 μm, a gate-to-source distance of 3 μm, and a gate width of 400 μm.

Figure 10 shows the gate leakage current characteristic measured between source and drain (I_{dg}). Focusing on SiN_x, it can be seen that, with a shift toward a higher refractive index (i.e., as stress decreases), gate leakage current decreases. With respect to the characteristics of SiO_2, which in absolute value of stress is positioned between SiN_x(1) and SiN_x(2), the gate leakage current is lower than that of SiN_x(1) and higher than SiN_x(2). These results suggest that gate leakage current is dependent on stress. It also suggests that the lower the stress in terms of absolute values, that is to say the higher the refractive index for SiN_x, the more gate leakage current will decrease. It was further found that by using SiN_x with a higher refractive index as the passivation film, values would be some two orders of magnitude smaller than for SiO_2.

Figure 11 shows the off breakdown voltage characteristic of the device fabricated in this work, when a gate voltage of −6 V is applied. As a result SiN_x(1), with a low refractive index, has low values for both leakage current and off breakdown voltage. It can also be seen that, as the absolute values of stress decrease further—SiO_2, SiN_x(2) and SiN_x(3)—leakage current goes down and off breakdown voltage goes up. It is thought that these results are reflective of gate leakage current. Thus we may say that using SiN_x with a low gate leakage current and high refractive index for the passivation film makes for a device with lower leakage current and higher off breakdown voltage.

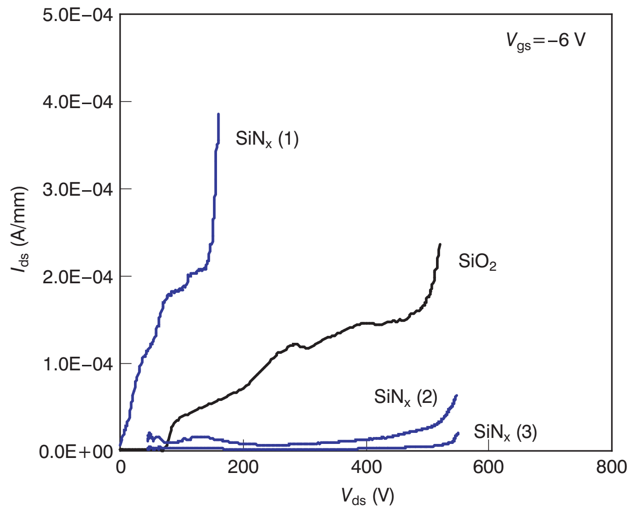

Figure 11 Off breakdown voltage characteristic.

5. CONCLUSION

We investigated increasing the performance of AlGaN/GaN HFETs, which hold promise in applications as power conversion devices. First of all, by applying an ohmic electrode using our unique Ti/AlSi/Mo structure we were able to achieve a contact line resistance of 0.48 Ωmm. This factor technology was applied to a large-scale device with a gate width of 200 mm. As a result it was possible to obtain an on-state resistance per unit area of 6.3 mΩ·cm². We conducted investigations with respect to packages for operation in high-temperature environments, mounted AlGaN/GaN HFETs, and carried out evaluations, with the result that we achieved operating currents of 20 A or more at room temperature and 10 A or more in a 500-K environment, and off breakdown voltages in excess of 450 V in a 500-K environment. Further, by using SiN_x having a high refractive index as the passivation film, we achieved a reduction in gate leakage current of approximately two orders of magnitude compared to SiO_2. The above results suggest that the AlGaN/GaN HFET holds promise as a high-efficiency power conversion device, and broader application is to be expected.

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