AlGaN/GaN on SiC HFETs for Microwave Power Amplifiers

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Summary (for GAAS99)

This paper will describe the development of AlGaN/GaN Heterojunction Field Effect Transistors (HFETs) on SiC for high frequency and high power applications. GaN offers many advantages including high temperature, high breakdown voltage, and high thermal conductivity for high power microwave applications. Previously, work has been mostly focused on HFET or HEMT devices on sapphire substrate. High current and high power potentials have been discussed. High frequency performance (F_{max} of about 97 GHz)[1-2], and high current density (1.43 A/mm) [3-4] have been separately shown. The progress mainly came from the improved material quality and the advances in fabrication technology including the reduction in contact resistance [5-7]. However, owing to the thermal dissipation issue involved with sapphire substrates, the potential for high power microwave devices has not been realized. This paper will discuss the development of microwave GaN HFET and power amplifier effort on SiC. The use of SiC substrate with its high thermal conductivity offers realizable power applications. Again, significant progress has been made recently for HFET on SiC due to the improved material quality and the advances in fabrication technology including the reduction of contact resistance. Specifically, $Al_{0.2}Ga_{0.8}N$/GaN HFET with an output power of 2.3 W at 10GHz on semi-insulating SiC substrate has been demonstrated [2,8-10]. Likewise, with a higher Al content, e.g., $Al_{0.3}Ga_{0.7}N$/GaN, a higher current capacity with improved ohmic contacts has been attained [9]. We will discuss the progress of materials, technology, device design, and power and noise performance.

For high power and low noise applications, the contact resistance particularly due to the large bandgap of GaN is of particular importance. In order to achieve high power, high saturation current density (and high breakdown) is a key issue. We have studied the relationship of the saturation current density and the $N_s\mu$ product with various contact resistivities (from < 0.6 Ω-mm to 12 Ω-mm). Fig. 1 shows that the saturation current density of GaN HFETs is related to the 2-dimensional-electron gas conductivity (or the $N_s\mu$ product). The improvement of the $N_s\mu$ product comes from the use of higher Al contents to increase the piezoelectric induced charge in addition to doping in the barrier (and the channel) [11]. The increase in the Al content can result in an increase in the ohmic contact resistance and thus offset the advantage of the use of a higher Al content and limits the current density. From this plot, it is reasonable to predict that GaN based HFET (or HEMT) with good ohmic contact may yield a drain current density of more than 2 A/mm.

To improve the contact resistance, we have investigated several contact metal systems: Ti/Al, Ti/Al/Ni, Ti/Al/Pt, Ti/Al/Ni/Au and Ti/Al/Pt/Au, and different pre-cleaning methods before metal deposition as well as various annealing temperatures and times. Transmission lines and arrays of dots with a diameter of 100 μm were used to evaluate the contact. Among the metal systems, Ti/Al/Pt/Au (200Å/800Å/400Å/1500Å) with a 900°C, 35 sec RTA in N_2 gave the best result yielding a contact resistivity as low as 0.039 Ω-mm or a specific contact resistance of 5.38×10^{-8} Ω-cm^2. To the best of our knowledge, this value is the lowest obtained thus far for the

HFET contact resistance in the AlGaN/GaN system [6-8]. Similar results were obtained from the Ti/Al/Ni/Au system. Other aspects of device technology have also been developed including the use of the use of ion implantation for isolation and an e-beam gate, with Pd/Au as the gate metal having a typical length of 0.25 μm.

Typical DC characteristics for a HFET with a gate length of 0.25 μm and width of 80 μm is shown in Fig. 2. The steep and linear characteristics at low drain voltages indicate excellent ohmic contact. The peak current density achieved at $V_{gs} = 0.5$ V is 1.2A/mm and a peak g_m of 240 mS/mm occurs at $V_g = -4$ V. The breakdown voltage between the gate and drain is greater than 70 V. Figure 3 shows the small signal s-parameter measurements for the device at $V_{ds}=10$ V and $V_{gs} = -2$ V. The extrapolated cutoff frequency is 60 GHz. The maximum frequency of operation exceeds 100 GHz. A high f_T may also be obtained with good ohmic contacts even for other relatively low mobility materials.

For large devices, the total current has been increased to more than 2 A with a current density greater than 1.2 A/mm. The demonstrated power level has been increased to > 3W at 9.6 GHz and to higher power levels at somewhat lower frequencies. The potential power performance can be estimated from the large signal characteristics. From the measured breakdown voltage (and maximum operation voltage) as well as the current capacity, we can estimate the maximum available RF power for class A amplifier to be 12 W.

The noise behavior of amplifiers is an important parameter. For HFETs, the low frequency noise will affect the phase noise in the microwave spectrum. We examined the low frequency noise of doped and undoped channel devices. As mentioned previously, one of the special features of GaN FETs is that the two dimensional electron gas can be induced through the piezoelectric effect in addition to the use of doping in the barrier and the channel. Typical low frequency noise for both a doped and an undoped channel HFET is illustrated in Fig. 4. The barrier Al contents are 0.14 and 0.33, and the carrier sheet densities are 1.1×10^{13} cm^{-2} and 1.2×10^{13} cm^{-2} with the mobility of 1400 cm^{2}V^{-1}s^{-1} and 616 cm^{2}V^{-1}s^{-1}, respectively for the samples with doped and undoped channels. The piezoelectric effect induced sheet charge from a higher Al content makes up the doping charge to make the sheet density almost equal. Other device parameters are $L_g = 1.0$ μm, and gate width W=50 μm, $g_m = 160$ mS/mm and 182 mS/mm.

In order to assess the overall noise of the device quantitatively, the Hooge parameter α_H was extracted using the regular equation, $\alpha_H = \frac{S_V}{V^2} Nf$, where f is the frequency, N is the total number of carriers under the gate calculated from the drain-source current at which the noise was measured, and S_v is the input referred noise spectral density. At $V_{gs} = -2$ V, the Hooge parameters in the linear region are $\alpha_H^{doped} = 8.3\times10^{-3}$ and $\alpha_H^{undoped} = 7.8\times10^{-3}$. It is evident that doping in the channel degrades the noise performance. In the saturation region, the difference is less pronounced, although the channel doping still degrades the noise figures: $\alpha_H^{doped} = 7.8\times10^{-3}$ and $\alpha_H^{undoped} = 1.3\times10^{-3}$ for $V_{gs}=-4$ V and $V_{DS}= 5$ V, respectively. The noise source for the doped channel appears to come from generation and recombination. Indeed, low temperature data show a pronounced peak at 3-4 kHz for the doped channel device, suggestive of carrier fluctuation via trapping. Our results of extracted Hooge parameters indicate that the low frequency noise figure for GaN based FET can be potentially better that the counterpart of GaAs based FETs.

In summary, GaN based HFETs show improved power and noise performance through material improvement and technological advances. Further progress will make possible high power and high temperature power amplifiers for microwave applications.

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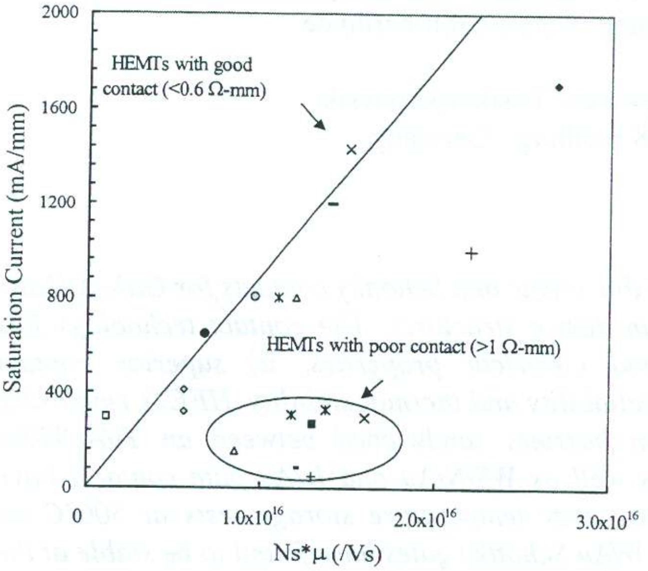

Figure 1. Experimental data showing saturation current limited by poor Ohmic contact. By improving the contact resistance, the saturation current density for GaN based HFETs may exceed 2.0 A/mm. Good Ohmic contact was achieved reproducibly on different HFET wafers. The best results correspond to a contact resistance of 5.38×10^{-8} Ω-cm^2.

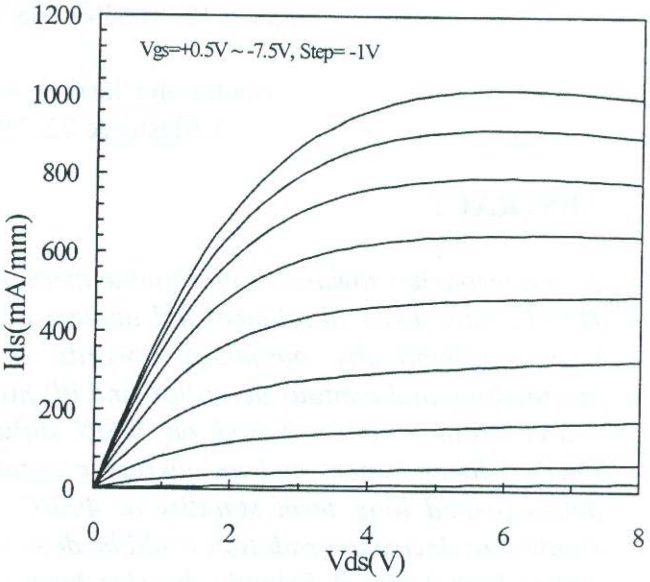

Figure 2. DC characteristics for a GaN HEMT showing the maximum I_{ds} in excess of 1 A/mm at Vgs=0.5 V.

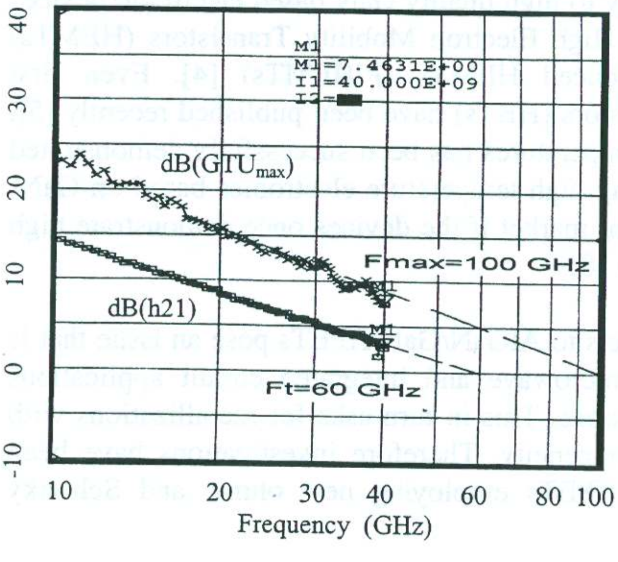

Figure 3. RF performance showing 60 GHz f_T and 100 GHz f_{max} for a 0.25 μm gate HFET device.

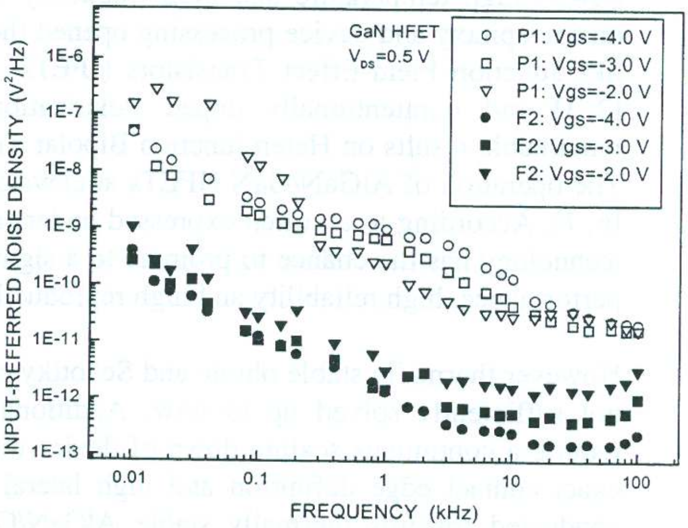

Figure 4. Input referred noise spectra for the doped channel and undoped channel GaN HFETs in the linear region (V_{DS}=0.5V). Note a significant difference in the input referred spectral density between two types of devices for all the gate biases.