High Power / High Temperature GaN-Devices

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Abstract

GaN based FET devices represent at present the solid state power sources of highest microwave output power. Their materials structure and technology is briefly reviewed and their limitations and problems are discussed. These concern thermal management and the associated temperature limit and charge storage effects related to the materials properties and the associated power dispersion leading to a power reduction at high frequency.

Introduction

GaN based FET structures offer the potential of high speed, high power and high temperature operation beyond that of Si and GaAs. Theoretical considerations concerning FETs predict an output power density in the range of 20W/mm, with a power density above 6 W/mm being obtained at three laboratories (Cree, Nitres, HRL) and 9.8 W/mm being the present record [1]. Such high power densities may result in high channel temperatures and the thermal stability of the structure becomes important as well as the thermal management. Indicative for the thermal stability may be the materials Debye-temperature, which is approx. 750°C in the case of GaN.

In Germany work on GaN based heterostructure FETs for power applications is actively persued by two companies (Infinieon and DaimlerChrysler). To support such activities, in our group at the University of Ulm we have tried to assess the temperature stability and power handling capability of GaN-based HFETs and the presently limiting factors. Thus, this work has concentrated on the analysis of a variety of FET structures concerning their temperature behavior, thermal stability and their large signal dispersion effects. It is a common phenomenon in GaN-based HFET devices that the microwave output power is only a fraction of what is extracted from the quasi-DC characteristics and it seems that this effect is the second limit besides the thermal limit for the obtainable power density presently.

Technology

To test the devices at high temperature and power a technology based on high temperature stable contacts based on refractory metals and testing at high temperature (in vacuum) under bias stress operation was developed [2].

Since GaN belongs to the semiconductor materials with a dependence of the Schottky barrier height on the metal-semiconductor work function difference [3] metals with low work function (Ti, Al) may be used for ohmic contacts and metals with high work function (Pt, Ni, Au, Ir, Pd) may be used for the Schottky barrier gate contact. The overlay metallization is commonly Au and therefore a diffusion barrier may be needed. In our case the ohmic contact system developed consisted of Ti:W/W:Si:N/Au and that of the Schottky contacts of Pt/Au. The AlGaN/GaN heterostructures used were grown by MOCVD and MBE on sapphire at various laboratories containing high resistive GaN buffer layers with low thermal activation, which is a prerequisite for low leakage high temperature operation.

Thermal Stability

On-wafer probing in vacuum using a high temperature test station resulted in the IV-output characteristics of a doped-channel AlGaN/GaN HFET at 750 °C as shown in fig.1, indicating that a very high temperature of operation is possible with this materials system.

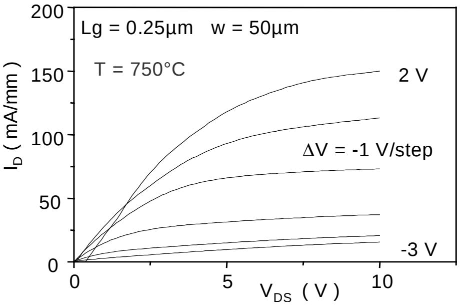

Fig.1:
Output characteristics of doped channel FET measured at 750 °C. The device was held for 20 min at this temperature. The heterostructure was grown on sapphire by MOCVD with an AlGaN barrier layer of 15% Al and an Si-doped GaN channel; after [2].

A more general investigation using doped channel AlGaN/GaN HFETs, AlGaN/GaN MODFETs and AlN/GaN doped channel MISFETs of various laboratories showed that irreversible changes in the output characterisitics (mainly a reduction in current) appear in the temperature range of 650 °C to 850 °C [4]. This is compiled in table 1.

SAMPLE	HETEROSTRUCTURE	T (I/I_0 = 0.1)
MBE	AlGaN/GaN (Al=25%) MODFET	650°C
MOCVD(a)	AlGaN/GaN (Al=15%) MODFET	650°C
MOCVD(b)	AlN/GaN (Al=100%) channel doped HFET	650°C
MBE	AlGaN/GaN (Al=26%) MODFET	700°C
MBE	AlGaN/GaN (Al=33%) MODFET	700°C
MOCVD(a)	AlGaN/GaN (Al=18%) channel doped HFET	700°C
MOCVD(b)	AlGaN/GaN (Al=15%) channel doped HFET	750°C
MOCVD(a)	AlGaN/GaN (Al=18%) channel doped HFET	800°C

Table 1:
Result of thermal stability tests applied to various types of AlGaN/GaN HFET structures. Criterion for degradation was the reduction in output current to 10% after 20 min. of operation at the indicated temperature (after increasing the temperature in steps of 50 °C starting from R.T.) and cooling to R.T. All devices were unpassivated; after [4].

Although it appears that there are differences in the temperature stability of the individual devices, which may reflect the quality of the materials structures, failure (of these unpassivated devices) is generally observed in a range centering around the thermal decomposition temperature [5] and Debye-temperature of GaN, indicating that the chemical/mechanical materials properties limit the usuable temperature range.

Thermal Management

The above discussed results may indicate that a high temperature of operation may be possible, although reliability results are not yet available. Nevertheless, at high temperature the electron mobility is degraded and leakage currents are activated. Therefore, for high power operation an effective thermal management is important. As can be seen from fig.2 a 4-finger FET structure on sapphire will reach already 500 °C at a power level of 6 W/mm. However, transfering this structure onto SiC will reduce this temperature already to below 100 °C. Using diamond as dielectric heat spreader on top of the surface (using a 100 nm Si_3N_4 interfacial layer) an operating temperature well below 100°C will be possible at an RF power loss of 15 W/mm; see fig.2.

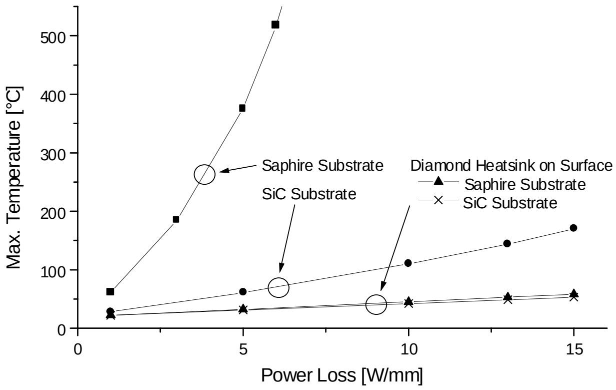

Fig.2:
Comparison of different heat spreader concepts for GaN based HFETs. The topography used in this comparison was a 4-finger structure with 150 µm wide gates separated by a 50 µm spacing; after [6].

RF Power Dispersion

A factor commonly observed is the compression in microwave output power as compared to quasi-DC, which can largely be traced back to a large signal current compression at high frequency. This is illustrated with fig.3, showing the waveform of the full output current swing at 1 kHz and 300 kHz respectively. At high frequency the channel cannot be opened completely anymore and the current is cliped.

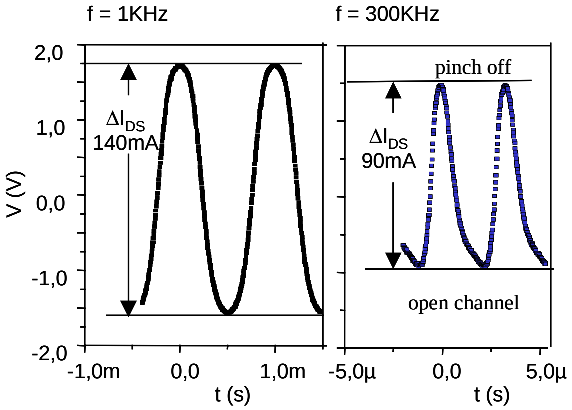

Fig.3
Illustration of current compression in GaN-based FETs by showing two output current swings at 1 kHz and 300 kHz respectively of an AlGaN/GaN MODFET (after [7]). In the experiment a steep load line of 33 Ω was used.

The effect of current compression is found in many devices using various heterostructure configurations as is shown in fig.4. Here the behavior of an AlGaN/GaN doped-channel structure (A) is shown, which has already been used in the high temperature analysis. Furthermore, two AlGaN/GaN MODFET structures are listed, where the device (B1) is grown by MBE, contains 25% Al in the barrier layer and is passivated, and whereras (B2) is grown by MOCVD, contains 30% Al in the barrier layer and is unpassivated. The device (C) is an MOCVD grown piezo-FET, where the entire heterostructure is undoped with 8% Al in the barrier layer. All structures were grown on sapphire.

The transition from the DC to the RF current swing is found to spread over a large frequency range streching roughly from 1 kHz to 10 GHz. The time scale in which this effect is observed depends on the particular sample, on the measurement temperature, illumination and bias condition. However, no correlation of the transition frequency range with the device configuration is identified. Only one transition is observed for each device. It is however not likely that there is only one specific defect dominating with one specific capture cross-section varying by several orders of magnitude and with trapping dynamics up to GHz frequencies.

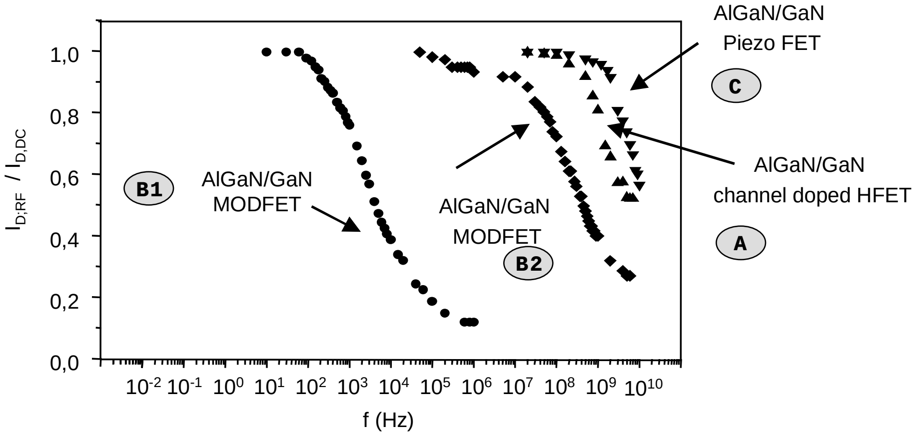

Fig.4
Compression of GaN-based HFET maximum current swing with frequency for a variety of HFET structures on sapphire. The devices tested were manufactured at various labratories. Details will be given elsewhere.

These characteristics point rather towards a charge storage/discharge mechanism through conduction in a lossy dielectric or at the surface than towards trap capture and emission dynamics. Note also that in device (B1) the amplitude of the RF signal is only 10% of that at DC. Thus approx. 90% of the electron channel sheet charge (which is in the order of 10^{13} cm^{-2}) has been been removed. Again this points towards charge pile-up in the gate/drain region acting as second gate and current limiter, see [7]. Since device (C) is an undoped structure, it seems also feasible to assume that the effect cannot be related to deep traps only but is also related to piezo charge states.

Conclusion

GaN based HFET structures represent at present the solid state micowave power sources with the highest output power. They may also allow operation at extremely high temperatures. Although some detrimental effects still need to be overcome, even now very high power densities up to 15 W/mm and beyond may be extrapolated, heat extraction not being the main limiting factor. The microwave performance has not been subject of this contribution, however here also advances in the hetrostructure materials technology have resulted in high channel mobilities above 1500 cm^2/Vs and high cut-off frequencies above 100 GHz.

Acknowledgment

The author would like to thank many contributors from many laboratories especially for providing the various samples for this evaluation. Special thanks are to Ingo Daumiller, who fabricated many of the devices discussed here and Eberhard Strobel, who designed the large signal measurement procedure in our laboratory. Financial support by the German Research Council (DFG) is greatfully acknowledged.

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