AlGaN/GaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS

I. Adesida, A. T. Ping, and J. Redwing*
Department of Electrical and Computer Engineering and Microelectronics Laboratory, University of Illinois, Urbana-Champaign, IL 61801
adesida@capone.ccsm.uiuc.edu
*ATMI/Epitronics Corporation, Phoenix, AZ 85027
JRedwing@atmi.com

ABSTRACT

A brief overview of materials. Processing, technologies, and performance of AlGaN/GaN heterostructure field-effect transistors (HFETs) are presented. Sate-of-the-art results on the dc, microwave, power, and noise characteristics of these devices on sapphire and SiC substrates are discussed. It is evident that AlGaN/GaN HFETs will be used for high power applications at microwave frequencies in the future. It is also possible that these devices will find applications for low noise amplifiers.

INTRODUCTION

Optical applications of GaN and related compounds for light emitting diodes (LEDs), laser diodes (LDs), and photodetectors (PDs) have received overwhelming attention over the last several years. This is in part due to the urgency of their commercial applications in various areas. The wide bandgaps of GaN, InN, AlN and their various alloys make them ideal for optical devices operating at short wavelengths ranging from the visible to ultraviolet. Indeed, LEDs of various colors from green to blue to amber have been made using InGaN/GaN quantum wells on sapphire and SiC substrates. Many companies in the United States and Japan are now producing and shipping LEDs in commercial quantities [1]. Applications of LEDs include full color displays and backlighting for various appliances. A major frontier for GaN-based LEDs is in producing white light for solid state lighting applications. The realization of continuous-wave (CW) laser diodes is more demanding on the qualities of materials and processing technologies. This fact has been a driving factor in the advancement of growth techniques for GaN materials. To date, CW laser diodes (from Nichia, Inc.) operating at blue wavelength have demonstrated lifetimes in excess of 15,000 hours! Only Nichia has moved towards the commercialization of LDs to date. Photodetectors operating at short wavelengths are desirable for solar-blind applications. Various forms of PDs have been demonstrated. These include photoconductors, metal-semiconductor-metal and PIN photodiodes.

The applications delineated above along with excellent electron transport seem to make GaN and its related materials almost universal semiconductors! Due to their transport properties and wide bandgaps, these materials are also suitable for realizing high power, high speed, and high temperatures devices. Heterostructure field-effect transistors (HFETs) heterojunction bipolar transistors (HBTs), and static induction transistors (SITs) are some of the electronic devices that can be made with GaN materials. Indeed, HFETs and HBTs have been demonstrated with HFETs receiving the most attention to date. In this paper, we review the fabrication and performance issues for AlGaN/GaN HFETs for various applications.

HETEROSTRUCTURE FIELD EFFECT TRANSISTORS

GaN-based materials for HFETs are usually grown on sapphire and SiC substrates. The lattice-mismatch between the thin films and the substrates result in a large amount of defects. These defects are threading dislocations that are formed along the growth axis. Both metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) methods have been used to grow AlGaN/GaN heterostructures. The former method has been investigated far more intensively for growing high quality AlGaN/GaN heterostructures due to the high growth temperature needed. A typical HFET layer consists, from the substrate up, of a 50 to 150 nm-thick GaN or AlN low temperature buffer layer, 1 to 3 μm-thick undoped GaN buffer layer, 3 to 5 nm-thick undoped $Al_xGa_{1-x}N$ spacer layer, and a 20 to 30 nm-thick undoped $Al_xGa_{1-x}N$ Schottky barrier layer. Typically, the concentration, x, is 0.2 but values ranging from 0.1 to 0.5 have been investigated. A two-dimensional electron gas (2-DEG) is formed at the $Al_xGa_{1-x}N/GaN$ interface due to the large conduction energy band offset and the large piezoelectricity at the interface. The piezoelectric effect at the interface is due to the strain present in the heterostructure. Both factors enhance the 2-DEG properties with typical values for sheet concentrations and mobilities being 1×10^{13} cm^{-2} and 1000 $cm^2/V.s$, respectively. Doped $Al_xGa_{1-x}N$ can be incorporated in the Schottky barrier layer in order to increase sheet concentrations. High quality AlGaN/GaN heterostructures grown by MOCVD on SiC have demonstrated sheet concentrations in excess of 1×10^{13} cm^{-2} and mobilities as high as 2050 $cm^2/V.s$ and 9000 $cm^2/V.s$ at 300 K and 77 K, respectively [2]. Heterostructures grown by MBE have demonstrated sheet concentrations and mobilities as high as 1.4×10^{13} cm^{-2} and 1860 $cm^2/V.s$ at room temperature, respectively [3]. The MBE layer was grown MOCVD-grown GaN templates. A substantial reduction in the dislocation density that can range in value from 10^8 cm^{-2} to 10^{10} cm^{-2} for either of the two growth methods will result in even higher quality materials. In addition, a reduction in AlGaN/GaN interface roughness will improve mobility values. The lateral epitaxial overgrowth (LEO) technique has been utilized successfully to reduce defect densities in GaN-based materials. The materials obtained have demonstrated p-n junctions with low leakage currents and LDs with long lifetimes [4]. Therefore, the potential for obtaining higher quality HFET materials is very high.

The processing of GaN-based materials is sufficiently different from that of conventional III-Vs that fabrication issues for devices in GaN materials have received significant attention. GaN and related materials are chemically inert to the extent that ordinary bases and acids do not attack them; therefore, dry etch methods are most commonly used for isolation in the fabrication of HFETs. Chemically assisted ion beam etching and various forms of reactive ion etching techniques are available for this process step [5]. Recent advances in photochemical etching in KOH solutions [5] should make wet etching for device fabrication possible. Annealed Ti/Al, Ti/Al/Ni/Au, Ti/AlTi/Au are the primary ohmic metallization schemes presently used for HFET devices. Ohmic contact resistances as low as 0.3 Ω-mm have been obtained on HFETs [6]. Gate metallization usually consists of Ni/Au and Pt/Au. Issues of device passivation are yet to be addressed comprehensively.

There have been a host of reports on the performance of AlGaN/GaN HFETs on sapphire and silicon carbide substrates [6-12]. Figures 1 (a) and (b) shows the normalized dc current-voltage and transfer characteristics of an HFET with 0.25 μm gate-length. The I-V characteristics are for 1 V step in gate-source voltage. The peak drain current of 720 mA/mm occurs at a drain voltage of 5 V. Beyond this point at higher V_{ds}, the drain current decreases due to channel heating. Heating in the channel results in the reduction of mobility in GaN which translates to a decrease in drain current. The excessive rise in channel temperature is due to the fact that the sapphire substrate has a poor thermal conductivity. A peak external transconductance, g_{mext}, value of ~ 190 mS/mm along with excellent pinch-off characteristics are observed in Fig. 1 (b). Although, higher performance devices with currents densities in excess of 1 A/mm and 200 mS/mm have been obtained, the channel heat places a severe limitation on these devices especially as drain voltage increases. Figures 2 (a) and (b) show the dc characteristics of AlGaN/GaN HFETs on insulating SiC. We observe that the dc I-V characteristics are of higher linearity and flatness for devices on i-SiC. This substrate has a thermal conductivity which is an order of magnitude higher than that of sapphire. This aids in the removal of heat from the device channel. A peak drain current in excess of 1.2 A/mm is maintained for the range of V_{ds} (up to 20 V) used in this experiment. The peak g_{mext} is also high at 215 mS/mm. The microwave performance of the device on sapphire was measured to be a unity current-gain cutoff frequency, f_T, of 41 GHz and a maximum oscillating frequency, f_{max}, of 95 GHz. Also, f_T and f_{max} of the device on i-SiC are 40 GHz and 115 GHz, respectively. Figures 3 and 4 show the microwave performances of devices of various gate-lengths on sapphire and i-SiC. The effective electron velocity (v_{eff}) under the gate was estimated from the dependence of f_T on gate-length using a simplified charge-control model. Using $f_T = V_{eff} / 2\pi L_g$ and the slopes of f_T vs L_g curves in Figs. 3 and 4, we estimate v_{eff} to be ~ 6 to 8 x 10^6 cm/s. In pushing the devices to smaller gate-lengths, AlGaN/GaN HFETs on sapphire with gate-lengths of 0.15 μm have been fabricated. An f_T of ~ 70 GHz and an f_{max} of 140 GHz were obtained for these devices as shown in Fig. 5. These results represent the state-of-the-art.

From the dc I-V characteristics, it is obvious that GaN-based HFETs should be capable of delivering high power. Microwave power performances of GaN HFETs at frequencies ranging from 2 GHz to 18 GHz have been reported [6-12]. On sapphire, without any thermal management, Wu et al. [7] demonstrated a power density of 3.3 W/mm at 18 GHz. This is at least thrice what can be obtained from GaAs pHEMTs. With thermal management using flip-chip bonding, Wu et al. [11] have developed large-periphery (6 mm-wide) GaN-HFETs on sapphire with output power of up to 7.6 W at 4 GHz. They have also demonstrated 3 to 9 GHz wide bandwidth amplifiers with 3.2 output power. For devices on SiC, a record RF power density of 6.9 W/mm with a power added efficiency (PAE) of 51 % have been achieved at 10 GHz for a drain bias of 30 V [6, 12]. For a device with 3 mm gate width, a record maximum output power of 9.1 W has been demonstrated at 7.4 GHz [12]. These results demonstrate the potential of AlGaN/GaN HFETs for delivering very high microwave power. Presently, the microwave power derived from these devices is lower than what dc performance dictates. Problems relating to traps in the channel and the AlGaN layers are held responsible for this shortcoming [13]. Therefore, it is expected that the performance of GaN HFETs would improve with better materials, better processing, and improved techniques of dissipating channel heat.

Preliminary measurements on the temperature variation of f_T and f_{max} have been carried out for the devices fabricated on sapphire. Figure 6 shows the variation of f_T and f_{max} with temperature from –55 °C to 200 °C for 0.25 μm gate-length device on sapphire. For the measurements, V_{ds} was fixed at 10 V while I_{ds} was 100 mA/mm. It is observed that f_T does not change significantly while f_{max} decreased from 115 GHz at –55 °C to 80 GHz at 200 °C. Figure 7 shows the dependence of f_T and f_{max} on V_{ds} for the same devices at 25 °C and 200 °C, respectively. The results show that once the devices reach saturation, no significant changes occur in the microwave performance. Detailed modeling efforts at understanding these basic variations with temperature are necessary.

Although, GaN-based HFETs are looked upon primarily as high power devices, it may be useful to investigate the noise performance of these devices for possible applications to low noise amplifiers. It is also possible from detailed noise analysis to further elucidate the properties of the devices and the quality of the materials. Preliminary measurements of noise properties of the devices on sapphire are shown in Figs. 8 and 9. Figure 8 shows the minimum noise figure, F_{min}, and associated gain for a 0.25 μm gate-length device biased at V_{ds} = 10 V and V_{gs} = – 4V. Figure 9 shows the dependence of F_{min} and associated gain on drain current at V_{ds} = 10 V. F_{min} values below 2 dB are observed for a respectable range of device parameters. These initial results are indeed encouraging.

SUMMARY

An overview of the performance of AlGaN/GaN HFETs on various substrates were presented. dc, microwave, and power characteristics of submicrometer-gate HFETs were discussed. The dependence of bandwidths on temperature was also presented. Noise performance of AlGaN/GaN HFETs is reported for the first time. The state-of-the-art results presented here show that AlGaN/GaN HFETs will increasingly be utilized for high power applications at microwave frequencies. It may also be that these devices will be useful for low noise amplifiers.

ACKNOWLEDGMENTS

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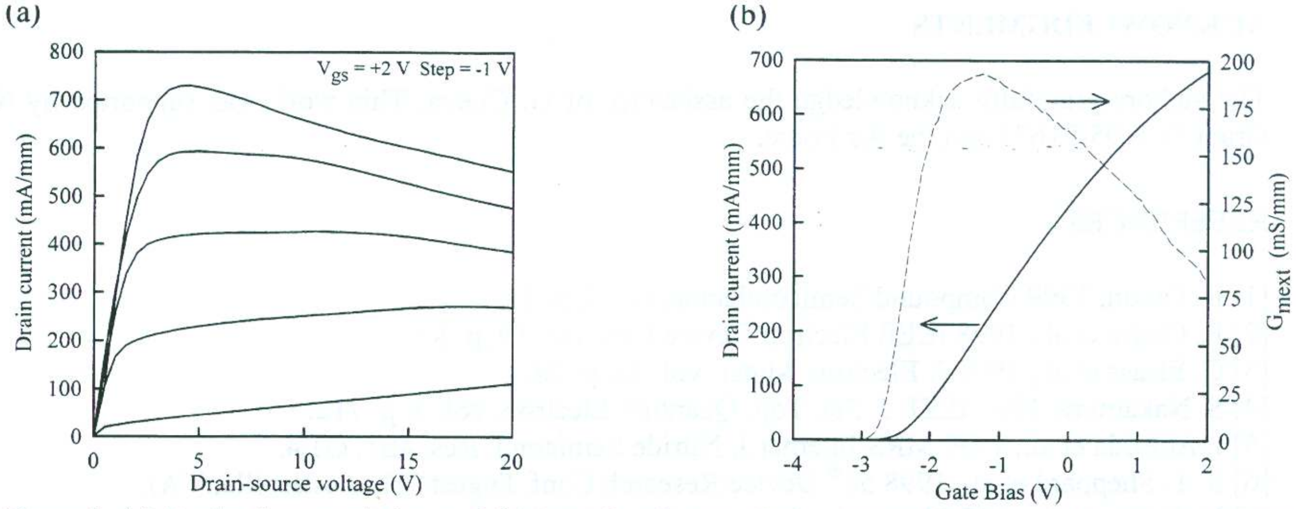

Figure1. (a) Drain characteristics and (b) transfer characteristics (V_{ds} = 8 V) for 0.25 μm gate HFET on sapphire.

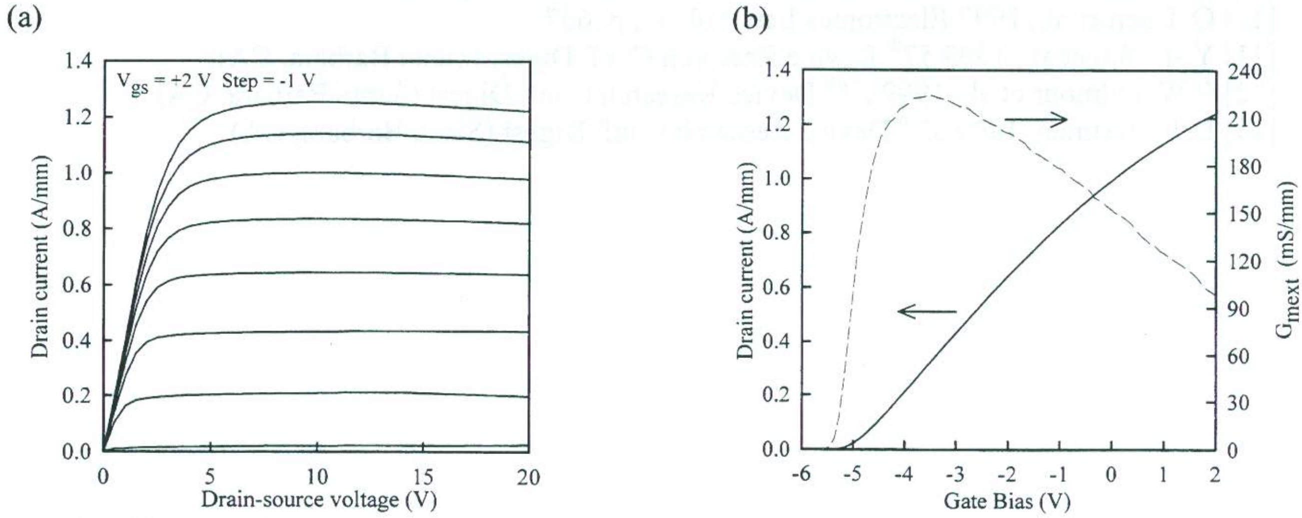

Figure2. (a) Drain characteristics and (b) transfer characteristics (V_{ds} = 10 V) for 0.25 μm gate HFET on SiC.

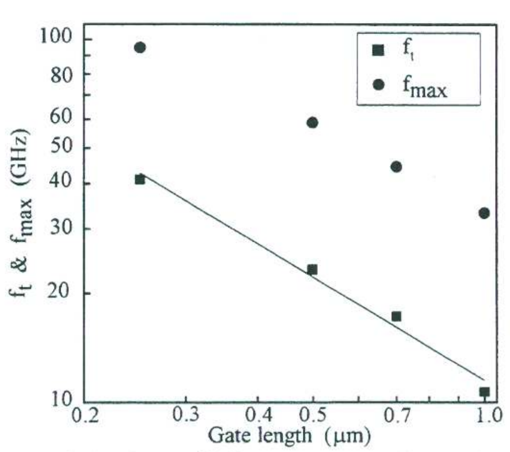

Figure 3. Cut-off frequency and maximum frequency of oscillation vs gatelength for HFETs on sapphire.

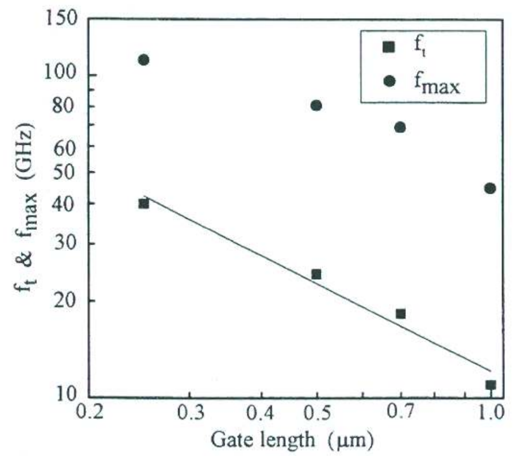

Figure 4. Cut-off frequency and maximum frequency of oscillation vs gatelength for HFETs on i-SiC.

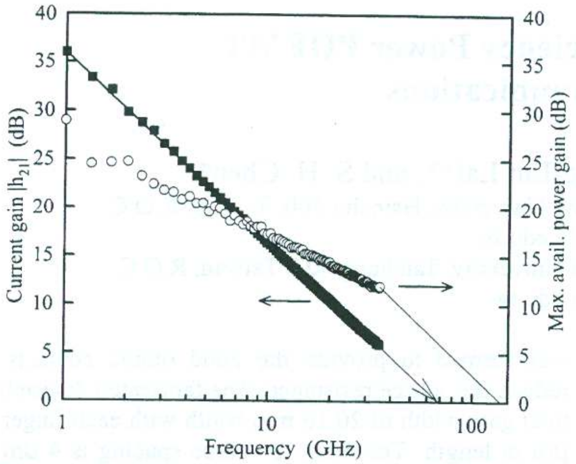

Figure 5. Microwave characteristics for a 0.15 μm gatelength HFET on sapphire.

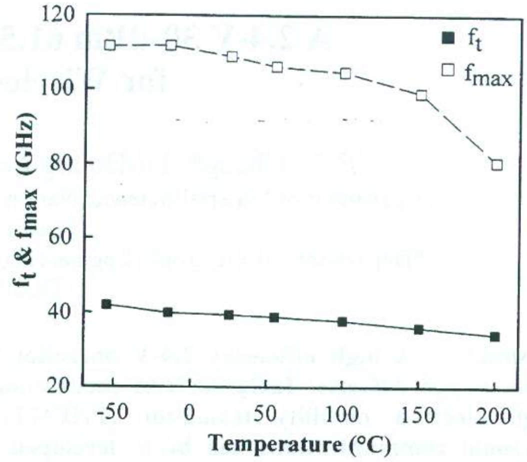

Figure 6. Bandwidth dependence on temperature for 0.25 μm gate HFET on sapphire (V_{ds} = 10 V, I_d = 100 mA/mm).

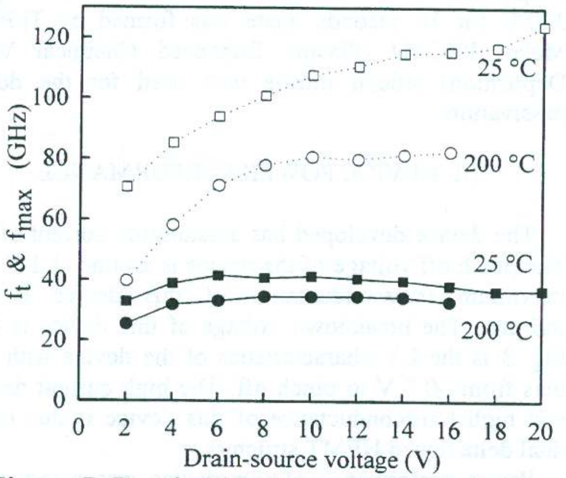

Figure 7. Bandwidth dependence on drain-source bias for 0.25 μm gate HFET on sapphire at 25 °C and 200 °C.

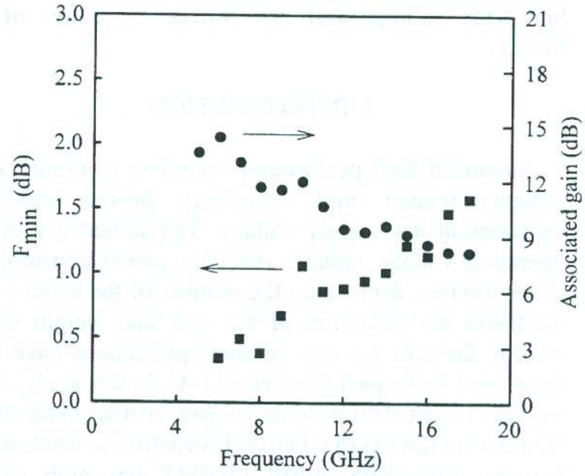

Figure 8. Noise characteristics for 0.25 μm gate HFET on sapphire.

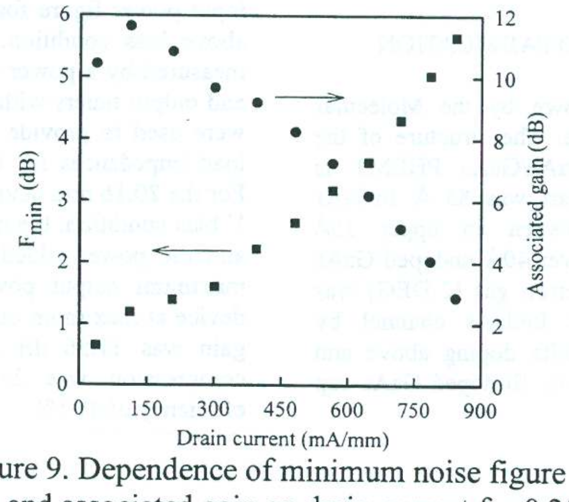

Figure 9. Dependence of minimum noise figure and associated gain on drain current for 0.25 μm gate HFET on sapphire.