GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTORS

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ABSTRACT

A summary of the performance of AlGaN/GaN heterostructure field effect transistors on sapphire and SiC substrates are presented. High total power have been demonstrated by these devices at microwave frequencies. The prospects of utilizing the devices for high power integrated amplifiers are excellent although the issue of thermal management will need to be addressed especially for devices and circuits on sapphire.

INTRODUCTION

Over the last decade, GaN-based material system has received wide attention primarily because of their potential applications to optical devices. The bandgaps of GaN, InN, and AlN are 3.39, 1.89, and 6.2 eV at room temperature. These make them and their ternary alloys (e.g. $Al_xGa_{1-x}N$) useful for optical emitters and photodetectors at short wavelengths. Light emitting diodes of various wavelengths with sufficient luminosities to be used as traffic signals and in full color displays have been demonstrated [1]. Also laser diodes have demonstrated continuous wave operation at blue wavelength for over 10,000 hrs. This reliability is such that applications to compact disk players is essentially imminent. Various forms of photodetectors including metal-semiconductor-metal, vertical Schottky diodes, and PIN have been demonstrated for visible- and solar-blind applications [2]. These tremendous advances have been due to the progress made in the growth of GaN-based materials.

Another application of GaN-based materials is in the area of electronic devices such as heterostructure field effect transistors (HFETs) and heterojunction bipolar transistors (HBTs). The wide bandgap in conjunction with the excellent transport properties of electrons in GaN and related compounds make them suitable for high speed, high power and high temperature applications. The inefficient ionization of p-type dopants and the low hole mobility in GaN has been an obstacle to the development of HBTs to date. However, AlGaN/GaN HFETs grown on sapphire and SiC are being investigated intensively [3-19]. In this paper, we review the extent of the progress made so far in HFET development and report on the state-of-the-art results.

MATERIALS AND PROCESSING

High quality AlGaN/GaN heterostructures for field effect transistors have been grown primarily using metal-organic chemical vapor deposition (MOCVD) techniques. In this approach, trimethylgallium and trimethylaluminum are reacted with ammonia at substrate temperatures in the range of 1000 °C under atmospheric or low pressure environment. A typical HFET structure is illustrated in Figure 1, and consists, from the substrate up, of a thin AlN buffer layer, an insulating GaN buffer, a GaN channel which can be doped or undoped, a thin undoped AlGaN spacer layer, and an AlGaN doping layer. There are variations in this structure relating to thicknesses, AlGaN composition, doping concentration, and type of substrate. Sapphire has been the substrate of choice due to its low cost but it has a poor thermal conductivity of 0.5 W/cm-K. SiC has a high thermal conductivity of 4.9 W/cm-K which makes it desirable for high power and high temperature applications but it is very expensive. Another

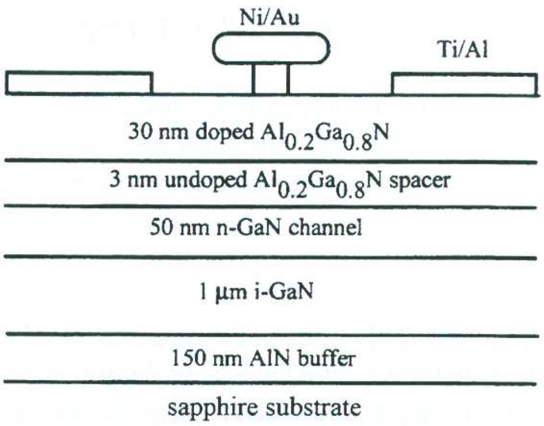

Figure 1 A typical HFET layer design.

significant problem is the high density of defects in the GaN epitaxial layers due to the non-lattice matching with these substrates. These facts notwithstanding, intensive efforts are currently being made to study HFETs grown on sapphire and SiC of various types and conductivities.

Some important processing steps in HFET fabrication are isolation, ohmic formation, and Schottky gate formation. The unique chemical properties of the nitrides make their processing very different from conventional compound semiconductors, so research in these areas have also been very important. Etching or ion implantation are utilized for isolation. Reactive ion etching in Cl_2-based plasmas is the most prevalent method of achieving mesa isolation for AlGaN/GaN HFETs since the nitrides cannot be wet-etched in common acids and bases [20]. Excellent isolation has also been achieved with ion implantation using He ions [21]. Multi-energy implants may be required depending on the layer structure. Annealed Ti/Al has become the standard basis for n-type ohmic contacts. To prevent oxidation of the Al which can inhibit probing, a Ti/Al/Ni/Au ohmic metallization has been proposed [22]. Annealing of the contacts is carried out in the temperature range of 900 - 950 °C for ~30 s. For Schottky contacts, Ni/Au and Pt/Au are the most commonly used metallization schemes. This is due to the relatively high barrier heights of Ni and Pt on n-GaN which are 0.95 and 1.01 eV, respectively [23]. Figure 2 shows an SEM sideview of a T-shaped 0.25 μm gate-length device.

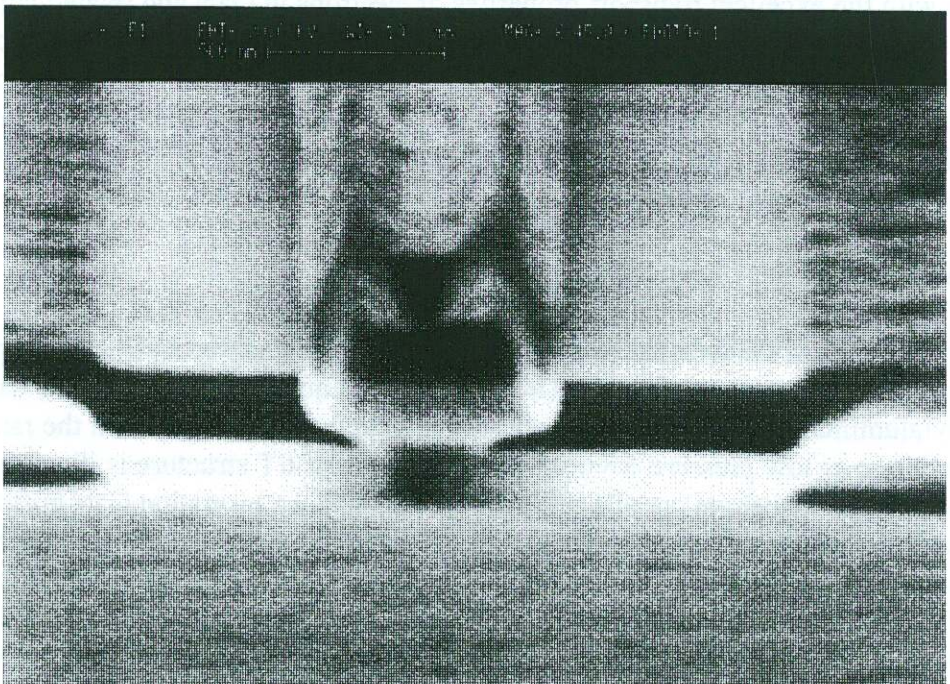

Figure 2 SEM sideview of 0.25 μm gate-length device.

HFETs

As mentioned above, a typical doped-channel HFET structure is shown in Fig. 1. Two dimensional electron gas (2-DEG) is present at the hetero-interface between the AlGaN and GaN. The electron gas is characterized by the sheet charge density or carrier concentration and mobility. The doping in the channel is used to enhance the channel electron concentration over structures with undoped channels. Piezoelectric effect is exhibited at AlGaN/GaN hetero-interface due to the strain present in the heterostructure. The piezoelectric effect also play a role in enhancing the electron concentration in the channel. Typical properties of the 2-DEG are sheet concentrations and mobilities of 1×10^{13} cm^{-2} and 1,000 cm^2/V.s., respectively. It is believed that the higher than usual (as compared to modulation-doped heterostructures in other compound semiconductors) electron concentration is due to the piezo-electric effect [24].

Table I shows a summary of representative results for HFETs in AlGaN/GaN layers on sapphire. Figures 3 (a) and (b) show the dc current-voltage characteristics of a 0.25 μm gate-length HFET on sapphire. In Fig.3 (a), an I_{dmax} of 700 mA/mm is obtained at a V_{ds} of 7 V. Beyond a V_{ds} of 10 V, it is observed that I_d decreases for high gate bias. This is due to channel heating with no commesurate heat removal due to the low thermal conductivity of the sapphire substrate. Excellent pinch-off characteristics is observed in Fig. 3 (b) along with a maximum g_{mext} of over 200 mS/mm. An I_{dmax} of over 1.0 A/mm has been obtained by for an HFET of the same gate-length demonstrating the high current density

Author	μ_n (300 K) cm^2/V-s	n_s (300 K) cm^{-2}	L_g (μm)	I_{dmax} (mA/mm)	G_{mext} (mS/mm)	f_t (GHz)	f_{max} (GHz)	RF power (W/mm)	@ freq. (GHz)
Khan et al.[3]	563	1.15×10^{13}	4	40	28	--	--	--	--
Wu et al.[4, 5]	1500	7.9×10^{12}	1	310	140	6	15	1.1	2
Khan et al.[6]	--	--	0.15	600	120	29.8	97.3	0.27	10
Nguyen et al.[7]	--	--	0.25	420	120	27	80	--	--
Chen et al. [8, 9]	1044	1.4×10^{13}	0.25	1020	142	37.5	80.4	1.73	8.4
Burm et al.[10]	--	--	0.12	475	80	46.9	103	--	--
Aktas et al.[11]	350	1.6×10^{13}	2	850	105	6	11	1.5	4
Wu et al. [12]	--	--	0.25	1130	240	52	82	3.05	18

Table I Summary of representative results on AlGaN/GaN HFETs grown on sapphire.

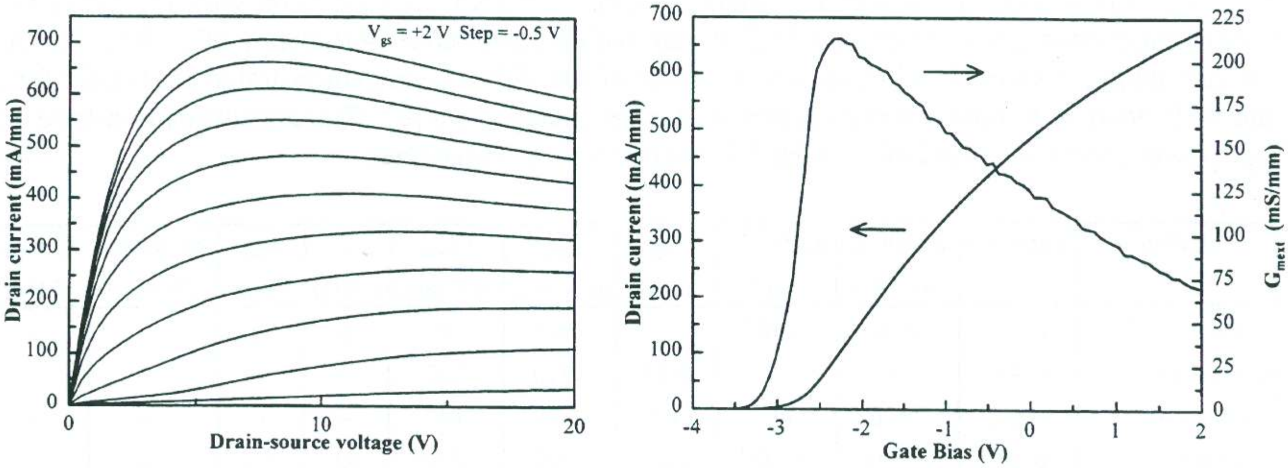

Figure 3 (a) Drain current vs. drain bias for a 0.25 μm gate HFET on sapphire.

Figure 3(b) Transfer characteristics for a 0.25 μm gate HFET on sapphire. (V_{ds} = 10 V) capability of these devices. The excellent sub-threshold characteristics of the 0.25 μm device in Fig. 3 is shown in Fig. 4 where the sub-threshold swing is ~ 80 mV/decade. The microwave performance of the device is shown in Fig 5 with a unity current-gain cutoff frequency, f_T, of 41 GHz and a maximum frequency of oscillation, f_{max}, of 95 GHz. It is seen from Table I that this performance represent the state-of-the-art for a 0.25 μm device. In Table I also, the results for microwave power have been enumerated where measured. Power density over 3.0 W/mm has been reported but the total power have usually been low due to the low thermal conductivity of sapphire. To overcome this disadvantage, Wu et al. [19] have utilized the flip-chip bonding technique as a means of thermal management. This approach has resulted in a 1 μm gate-length, 2 mm-wide AlGaN/GaN HFETs yielding a total power of 3W at 4 GHz with a power-added-efficiency of 30%.

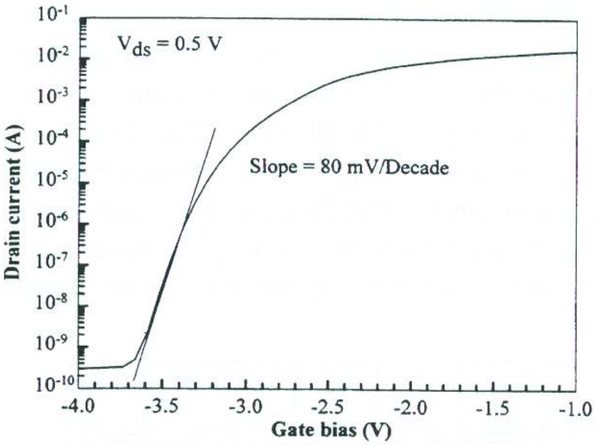

Figure 4 Sub-threshold voltage characteristics of a 0.25 μm gate-length device.

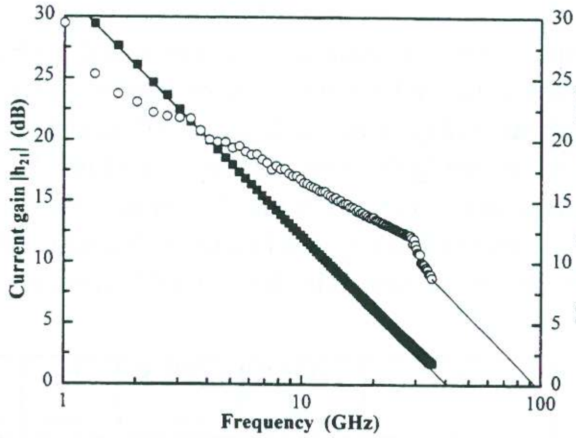

Figure 5 Current-gain and max. avail. power gain vs. freq...

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the maintenance of near constant f_T and f_{max} across a broad sweep of V_{ds} and I_{ds}. This is particularl true on SiC substrates where thermal effects are minimal. Figure 6 shows the variation of f_T and f_{ma} with V_{ds}. This is useful for power amplifiers. To date, AlGaN/GaN HFETs on semi-insulating Si have demonstrated a power density of 5.3 W/mm with a power-added-efficiency of 35.9 % for 0.4 μm gate-length devices. In addition, a total power of 4.0 W has been demonstrated at 10 GHz for mm-wide devices without any extra efforts at thermal management [8]. These results demonstrate th high power potential of AlGaN/GaN HFETs even at higher frequencies.

Author	Substrate	μ_n (300 K) cm^2/V-s	n_s (300 K) cm^{-2}	L_g (μm)	I_{dmax} (mA/mm)	G_{mext} (mS/mm)	f_t (GHz)	f_{max} (GHz)	RF power (W/mm)	@ freq (GHz)
Binari et al.[14]	n-SiC	1200	$6x10^{12}$	1	200	70	6	11	--	--
Chen et al. [15]	n-SiC	--	--	0.25	1710	222	--	--	--	--
Gaska et al.[16]	n-SiC	1400	$1.5x10^{13}$	1.5	950	142	--	--	--	--
Ping et al.[17]	p-SiC	1500	$1x10^{13}$	0.25	1430	229	53	58	--	--
Sullivan et al.[18]	i-SiC	--	--	0.7	1100	270	15	42	1.8	10
Sheppard et al.[19]	i-SiC	--	--	0.45	680	200	28	114	5.28	10

Table II Summary of results of AlGaN/GaN HFETs grown on SiC substrates.

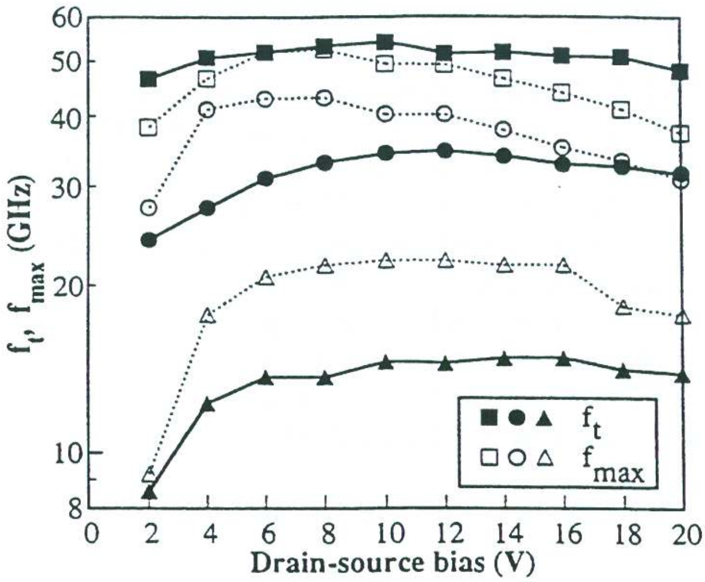

Figure 6 Cut-off frequency and maximum frequency of oscillation vs. drain -source bias for 0.25 μm (■,□), 0.5 μm (●,○), and 1 μm (▲,△) gate-length HFETs grown on p-type SiC. (V_{ds} = 10 V, I_d = 0.5 A/mm)

SUMMARY

The dc, rf, and power characteristics of AlGaN/GaN HFETs on various substrates have been reported. Current techniques of growth and processing for these devices were presented. Further improvements in these techniques will result in significant enhancements in device performance. In addition, improvements in the quality of semi-insulating SiC and a reduction in its cost will be important for the continued development of AlGaN/GaN HFETs. The prospects of the utilizing these devices for high power applications at microwave frequencies are excellent.

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