Ultra Thin Barrier Layers for mmW Frequencies in III-N HEMT Technologies

J. Gillespie, A. Crespo, K. Chabak, M. Kossler, V. Trimble, M. Trejo, G. D. Via,
B. Winningham
Sensors Directorate, Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433

B. Poling, D. Walker Jr.
Wyle Labs
Dayton, OH 45431

Keywords: HEMT, InAlN, wide bandgap, Ka-band

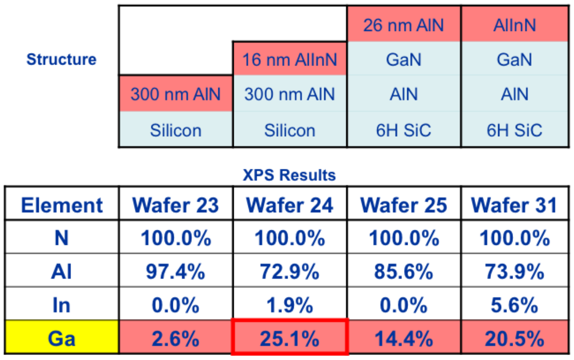
ABSTRACT

In this discussion, we present the status of InAlN/GaN HEMT device development at AFRL. Because of the frequency limitations of traditional AlGaN/GaN devices, novel III-N Schottky barriers are being considered for higher frequency applications. GaN-based epitaxy foundries have developed and supplied InAlN/GaN material on SiC substrates to AFRL. This material is designed for the purpose of scaling devices for mmW power applications up to W-band and beyond. Material was delivered with barrier layers <10nm. Record Ka-band device results of 5.8W/mm at 43.6% were achieved. In addition, on-wafer material and device measurements will be shown to demonstrate exceptional uniformity across a 3-inch wafer.

INTRODUCTION

High power solid-state device technology for RF applications is being developed for many military applications. In particular, AlGaN/GaN HEMTS are being developed for X-band through Ka-band applications. However, there is a need to expand this technology for higher frequencies while maintaining acceptable power levels. Jessen [1] has developed a model that predicts the barrier layer thickness (t_{bar}) required for a given gate length and frequency. This model shows that in order to maintain an f_t-L_g product above 14 GHz-µm, the L_g/t_{bar} ratio must be greater than 15. However, for AlGaN/GaN technology, Ibbetson[2] has shown that for $t_{bar} < 15$nm the 2DEG density starts to degrade. This would require devices to have >225nm gates to reduce short channel effects. In order to fabricate devices for frequencies above 100GHz, gate lengths should be < 0.15µm. The t_{bar} required for effective gate control at 100 GHz should be < 10nm.

Kuzmik [3] has studied different barrier and channel materials, which could extend III-N device technology beyond 100GHz or increase the power performance demonstrated by standard AlGaN/GaN HEMT. This improved performance is realized by growing these novel layers thinner while maintaining a higher sheet charge than that of traditional AlGaN barriers. In fact, AlN should demonstrate a sheet charge of $5.8\mathrm{x}10^{13}\mathrm{cm}^{-2}$ at a thickness of 4nm. Another potential structure being considered is InAlN. This material can be grown lattice-matched to GaN using 17% Indium. When lattice matched, the strain will be essentially reduced to a minimum while having a spontaneous polarization charge greater than the combined piezoelectric and spontaneous charge of standard AlGaN/GaN. At the 2007 CS ManTech conference Trejo [4] surveyed the InAlN/GaN growth and device capability. This work described how Ga was incorporating in the InAlN films even when no Ga was used in the growth process. Figure 1 describes the results of an experiment for determining the source of Ga contamination in MOCVD growths of InAlN layers. These results demonstrated the need to develop growth processes for the reduction of Ga incorporation in the InAlN films.



Structure				
			26 nm AlN	AlInN
		16 nm AlInN	GaN	GaN
	300 nm AlN	300 nm AlN	AlN	AlN
	Silicon	Silicon	6H SiC	6H SiC

XPS Results

Element	Wafer 23	Wafer 24	Wafer 25	Wafer 31
N	100.0%	100.0%	100.0%	100.0%
Al	97.4%	72.9%	85.6%	73.9%
In	0.0%	1.9%	0.0%	5.6%
Ga	2.6%	25.1%	14.4%	20.5%

FIGURE 1 Elemental analysis for different growth layers

His summary concluded that in order to realize the advantages InAlN films have for mmW applications, improvements in interface roughness, material defects, and stoichiometry were required.

EXPERIMENT

As a result of the work described by Trejo, AFRL continued working with material developers to mature III-N novel barriers in order to demonstrate the advantages, nearly double the power in X through Ka-band frequency range or equal power performance at mmW frequencies. This effort required AFRL to partner with organizations that had the capability to grow indium based III-N material. By partnering with growth foundries, AFRL was able to leverage fast device process and analysis with organizations able to perform multiple growth experiments. With the work done by Kuzmik to show the theoretical expectations of this material coupled with the practical demonstration of earlier growths and analysis of devices, AFRL was able to determine reasonable metrics for a successful InAlN/GaN demonstration. The goals for this work were to demonstrate Ga free (< 0.5%) lattice-matched InAlN barrier layer with mobility > 1200cm^2/V-s and sheet charge >2x10^{13}cm^{-2}. Device goals were to demonstrate f_t > 120GHz for a barrier layer < 12nm with I_{max} > 2A/mm.

InAlN/GaN growths were made on 3-inch 6H SiC substrates. There were two growth foundries involved, one MBE and one MOCVD. All wafer growths were delivered to AFRL for material analysis and wafer fabrication. Samples were sent out for SIMS analysis to determine the elemental concentrations and impurities. Once the barrier thickness and stoichiometry were determined the, samples were processed using AFRL's standard device layout and quick lot process. This was a 2-finger 150µm wide device with a gate length of 160nm. RF small signal measurements were made before and after passivation. In addition to device characterization, on-wafer Hall measurements were made to determine the mobility and sheet charge.

RESULTS

Early growth runs showed unacceptable levels of Ga incorporation for both MBE and MOCVD growths. Subsequent growths utilized proprietary techniques to reduce this contamination and improve interface roughness. Both MBE and MOCVD material demonstrated Ga free InAlN. The MBE material demonstrated on-wafer mobility as high as 1000cm^2/V-s with sheet charge 2.2x10^{13}cm^{-2}. This material, however, was very non-uniform across a 3-inch wafer. More work is required to optimize growth conditions. The MOCVD material also demonstrated Ga free InAlN barriers on GaN. Table 1 shows material and device results along with wafer uniformity. This material exhibited >1100cm^2/V-s mobility and 2-DEG charge of 2.4x10^{13}cm^{-2} with acceptable uniformity. Table 1 lists measurements for material processed at AFRL. This sample yielded 160nm devices Figure 2 shows record performance of 5.8W/mm with PAE = 43.6% at Ka-band.

	Gmp (mS/mm)	Idss (mA/mm)	Imax (mA/mm)	Vth (V)	Rsh_TLM [ohm/sq]	Mobility cm2/V-s	Conc. 1/cm3
Average	382	1350	1527	-4	214	1180	2.4E+13
Stdv	5.8%	4.0%	3.0%	-5.3%	6.5%	4.3%	2.3%

TABLE 1 MOCVD InAlN material and device results for a 2-finger 0.16x150µm^2 device

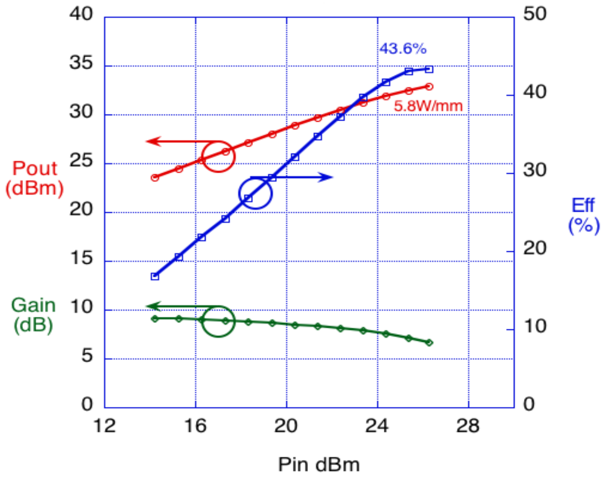


FIGURE 2 Ka-band load pull results. 5.8W/mm 43.6% PAE at V_{ds}=20 volts with gain of 6.6dB [5]

In another process run AFRL was able to demonstrated 122nm gate devices with a measured extrinsic f_t of 107GHz [6]. In addition to AFRL device results, MIT fabricated devices from this material that demonstrated record results for peak transconductance (675mS/mm) [7] and maximum drain current (2.36A/mm)[8].

CONCLUSION

The status of lattice-matched InAlN/GaN material has been discussed. The latest material has demonstrated less than 10nm thick Ga free InAlN with mobility and 2 DEG charge of 1100cm^2/V-s and 2.4x10^{13}cm^{-2} respectively. Device results were presented that demonstrate record Ka-band power (5.8W/mm) and measured extrinsic frequency response (107GHz).

ACKNOWLEDGEMENTS

The authors would like to thank Joe Breedlove, Paul Cassity and Stephen Tetlak for assisting with metal deposition, material etching and cross section analysis.

REFERENCES

[1] G.H. Jessen, R.C. Fitch, J.K. Gillespie, G. Via, A. Crespo, D. Langley, D.J. Denninghoff, M. Trejo, E.R. Heller, "Short-Channel Effect Limitations on High Frequency Operation of AlGaN/GaN HEMTs for T-Gate Devices," IEEE Transactions on Electron Devices, vol.54, no.10, pp.2589-2597, Oct. 2007

[2] J. P. Ibbetson,a) P. T. Fini, K. D. Ness, S. P. DenBaars, J. S. Speck, and U. K. Mishrab), "Polarization effects, surface states, and the source of electronsin AlGaNÕGaN heterostructure field effect transistors," Applied Physics Letters, Vol 77, No 2 10 Jul 2000

[3] J. Kuzmik, "Power Electronics on InAlN/(In)GaN: Prospect for a Record Performance," IEEE Electron Device Letters, vol.22, no.11, pp.510-512, Nov 2001

[4] M. Trejo, G. H. Jessen, A. Crespo, J.K. Gillespie, D. Langley, D. Denninghoff, and G. D. Via, J. Carlin, D. Tomich, J. Grant, and H. Smith, "Materials Characterization and Device Performance Survey of InAlN/GaN HEMT Layers from Commercial Sources," The 2008 International Conference on Compound Semiconductor Manufacturing Technology

[5] A. Crespo, M. M. Bellot, K. D. Chabak, J. K. Gillespie, G. H. Jessen, V. Miller, M. Trejo, G. D. Via, D. E. Walker Jr., B. W. Winningham, H. E. Smith, T. A. Cooper, X. Gao, S. Guo, "High-Power Ka-band Performance of AlInN/GaN HEMT With 9.8-nm-Thin Barrier," IEEE Electron Device Letters, Jan 2010

[6] A. Crespo, M. M. Bellot, K. D. Chabak, J. K. Gillespie, G. H. Jessen, M, Kossler, V. Miller, M. Trejo, G. D. Via, D. E. Walker Jr., B. W. Winningham, H. E. Smith, T. A. Cooper, X. Gao, S. Guo, "High Frequency Performance of Ga free AlInN/GaN HEMT," The 36th International Sysmposium on Compund Semiconductors 2009

[7] Jinwook W. Chung, Omair I. Saadat, Jose M. Tirado, Xiang Gao, Shiping Guo, and Tomás Palacios, "Gate-Recessed InAlN/GaN HEMTs on SiC Substrate With Al2O3 Passivation," IEEE Electron Device Letters, Vol. 30, No. 9, Sept 2009

[8] H. Wang, J. W. Chung, X. Gao, S. Guo, and T. Palacios, "Al2O3 Passivated Thin Barrier InAlN/GaN HEMTs on SiC Substrate with Record Current Density and Transconductance," International Symposium on Compound Semiconductors (ISCS), Santa Barbara, CA, Aug 30 – Sept 2, 2009.

ACRONYMS

2DEG: Two-Dimension Electron Gas
MOCVD: Metal-Organic Chemical Deposition
MBE: Molecular Bean Epitaxy
InAlN: Indium Aluminum Nitride
GaN: Gallium Nitride
AlN: Aluminum Nitride
HEMT: High Electron Mobility Transistor