논문 2004-41SD-11-5

AlGaN/InGaN/GaN HEMTs의 RF Dispersion과 선형성에 관한 연구

(RF Dispersion and Linearity Characteristics of AlGaN/InGaN/GaN HEMTs)

이 종 욱*

(Jong-Wook Lee)

요 약

본 논문에서는 molecular beam epitaxy (MBE)로 성장한 AlGaN/InGaN/GaN high electron-mobility transistors (HEMTs)의 선형성과 RF dispersion 특성을 조사하였다. 전극 길이가 0.5 ㎛인 AlGaN/InGaN HEMT는 최대 전류 밀도가 730 mA/mm, 최대 전달정수가 156 mS/mm인 비교적 우수한 DC 특성과 함께, 기존의 AlGaN/GaN HEMT와는 달리 높은 게이트 전압에도 완만한 전류 전달 특성을 보여 선형성이 우수함을 나타내었다. 또한 여러 다른 온도에서 측정한 펄스 전류 특성에서 소자 표면에 존재하는 트랩에 의한 전류 와해 (current collapse) 현상이 발생되지 않음을 확인하였다. 이 연구 결과는 InGaN를 채널층으로 하는 GaN HEMT의 경우 선형성이 우수하고, 고전압 RF 동작조건에서 출력저하가 발생하지 않는 고출력 소자를 제작할 수 있음을 보여준다.

Abstract

This paper reports the RF dispersion and linearity characteristics of unpassivated AlGaN/InGaN/GaN high electron-mobility transistors (HEMTs) grown by molecular beam epitaxy (MBE). The devices with a 0.5 ㎛ gate-length exhibited relatively good DC characteristics with a maximum drain current of 730 mA/mm and a peak g_m of 156 mS/mm. Highly linear characteristic was observed by relatively flat DC transconductance (g_m) and good inter-modulation distortion characteristics, which indicates tight channel carrier confinement of the InGaN channel. Little current collapse in pulse $I-V$ and load-pull measurements was observed at elevated temperatures and a relatively high power density of 1.8 W/mm was obtained at 2 GHz. These results indicate that current collapse related with surface states will not be a power limiting factor for the AlGaN/InGaN HEMTs.

Keywords : InGaN, molecular beam epitaxy (MBE), GaN, HEMTs, Heterostructure

I. Introduction

The wide bandgap AlGaN/GaN material system has relatively low intrinsic carrier generation, high breakdown fields (> 3 MV/cm), very high sheet carrier density (1×10^{13} /cm^2) and high saturation velocity (1.2×10^7 cm/sec)[1]. In the form of AlGaN/GaN HEMT, these properties translate to high current drive capability and high breakdown voltage. High power operation is further facilitated by the use of high thermal conductivity (3.3 W/cm-K) semi-insulating SiC substrates. The excellent material properties of AlGaN/GaN material system indeed delivered a new level of microwave power and frequency operation. A breakdown voltage as high as 570 V in an AlGaN/GaN HEMT with a source-drain spacing of 13 ㎛ and a gate length of 0.5 ㎛ using

---

* 정회원, 경희대학교 전자정보대학 전파통신공학과
(School of Electronics and Information, Kyung Hee University)

※ 이 연구는 2004년도 경희대학교 지원에 의한 결과임(KHU-20040447)

접수일자: 2004년4월26일, 수정완료일: 2004년11월7일

an overlapping gate structure was reported[2]. AlGaN/GaN HEMTs with current density of 2.1 A/mm have also been reported[3]. In terms of power, wide bandgap AlGaN/GaN HEMTs on semi-insulating SiC substrates have demonstrated practical operation for high power-added efficiency (PAE) and high power at K-band[4].

To further improve the microwave power performance, InGaN channel can be used in the context of past research directed to InGaAs material system[5]. InGaN layers have been used in the active region of blue-green light emitting diodes(LEDs) and laser diodes for their higher efficiency than GaN layers[6]. The theoretical study through the use of physical parameters of InAlN and InGaN predicted that InAlN/InGaN material system could achieve very high power performance due to its higher polarization-induced two-dimensional electron gas (2DEG) than AlGaN/GaN structure. Enhanced sheet carrier concentration with potentially higher mobility of InGaN channel can provide higher current drive capability than conventional GaN channel. For example, the total polarization charge is 0.03 C/m^2 at GaN/$In_{0.2}Ga_{0.8}N$ interfaces, compared to 0.013 C/m^2 at $Al_{0.15}Ga_{0.85}N$/GaN ones[7]. Another advantage of using InGaN channel is its effectiveness in suppressing DC-RF dispersion related to surface trap states[8]. The RF dispersion or current collapse is considered a power limiting factor of GaN HEMTs. Also, it is related to reliability issue required for widespread commercial usage.

Previously, a continuous wave (CW) power density of 4.2 W/mm at 2 GHz was achieved in an AlGaN/InGaN HEMT on SiC substrates with a gate length of 1 μm[9]. Compared to InGaN on SiC, the power density of InGaN grown on sapphire substrates is relatively low, which is 0.4 W/mm due to self-heating and, especially, current collapse observed in the device[10].

In this paper, we examined the linearity and RF dispersion characteristics of AlGaN/InGaN/GaN HEMTs grown by MBE. Previously reported InGaN channel HEMTs were grown by metal-organic chemical vapor deposition (MOCVD)[8-10]. Using molecular beam epitaxy (MBE), more uniform and reproducible high quality AlGaN/InGaN/GaN epilayer structure will be possible. Furthermore, linearity and RF dispersion characteristics of InGaN channel devices were not fully investigated, especially at high temperatures. Investigation of linearity and RF dispersion characteristics of the devices is meaningful because of different channel confinement characteristics of InGaN channel from conventional GaN channel. Assessing device performance at high temperatures is important because microwave applications of GaN-based HEMTs can involve higher temperatures than conventional devices based on GaAs and Si.

The device results that will be presented showed promising linearity characteristics and little current collapse in large-signal measurements, indicating the potential of InGaN channel HEMTs grown by MBE.

Ⅱ. Epitaxial Layer Structure and Device Processing

The layer used in this study was grown by MBE on sapphire substrate. The epitaxial layer structure contains an AlN nucleation layer, 2 μm of undoped GaN, 5 nm of InGaN (10 % In mole fraction), 18 nm of AlGaN (25 % Al mole fraction), and 2 nm undoped GaN capping layer. Hall measurements showed a sheet carrier concentration of 1.3 × 10^{13} /cm^2 and an electron mobility of 710 cm^2/V-sec at room temperature. The relatively low mobility may be attributed to roughness at the AlGaN/InGaN interface.

Device fabrication started with mesa isolation using Cl_2/Ar plasma in an inductively-coupled-plasma reactive ion etch (ICP-RIE) system. Ohmic contacts were formed by rapid thermal annealing of evaporated Ti/Al/Mo/Au. Ni/Au mushroom-shaped gates with a gate length of 0.5 μm was fabricated using electron beam lithography and a lift-off process. The devices had a gate width of 100 μm (2 × 50 μm) and a source-drain spacing of 3 μm.

III. Linearity Characteristics of InGaN HEMTs

On-wafer DC data were obtained using an HP4142 modular DC source and Agilent ICCAP software[11]. On-wafer S-parameters from 1 to 40 GHz were measured using an HP8510B network analyzer in conjunction with a temperature controlled CPW probe station to determine the RF characteristics of the device.

Figure 1 shows the DC transfer characteristics of a typical device at V_{DS0} = 8 V under different temperatures. The maximum drain current was 800 mA/mm at -50 °C (730 mA/mm at room temperature), and decreased to 657 mA/mm and 580 mA/mm at 100 °C and 200 °C, respectively. The corresponding peak transconductance, g_m, was 165 mS/mm, 132 mS/mm, and 116 mS/mm, respectively. The g_m was 156 mS/mm at room temperature. Compared to typical AlGaN/GaN HEMTs fabricated using the similar process[4], the device showed less g_m roll-over characteristics at high gate voltage. Futhermore, the transconductance maintained relatively flat characteristics over the temperature range measured. The results demonstrate good carrier confinement in the InGaN channel at even elevated temperatures up to 200 °C. The small signal RF measurement resulted in a device unity gain cut-off frequency (f_T) of 17.3 GHz, and a maximum frequency of oscillation (f_{MAX}) of 28.7 GHz at a drain bias of 10 V under room temperature.

Large-signal measurement of device linearity characteristic was performed using two-tone inter-modulation distortion measurement on a 0.5 μm × 100 μm AlGaN/InGaN HEMT. The output was tuned for maximum power at 2 GHz when biased at V_{DS0} = 20 V and V_{GS0} = -2.0 V. Figure 2 shows the measured two-tone inter-modulation characteristics of the device. The measured output third-order intercept point (OIP_3) is 23 dBm and the corresponding input third-order intercept point (IIP_3) is 15 dBm using the 3:1 slope of the third-order inter-modulation product (IM_3). Higher IIP_3 compared to GaAs-based devices with similar gate width is attributed to high drain bias voltage achievable for GaN-based devices[12]. The two-tone 1-dB output power ($P_{1dB,2tone}$) obtained at P_{in} = 8 dBm, is 12.3 dBm, resulting in OIP_3 - $P_{1dB,2tone}$ = 10.7 dB. If we compare measured OIP_3 with single-tone 1-dB output power (P_{1dB}), a difference of 12.7 dB is obtained as $P_{1dB,2tone}$ levels is approximately 2 dB lower than the P_{1dB} levels under single-tone excitation[13]. As an analytic power series

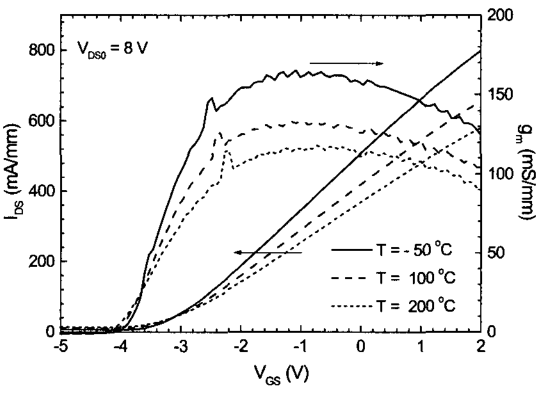


그림 1. 온도에 따른 0.5 μm 전극 길이를 가지는 AlGaN/InGaN HEMT의 전류 전달 특성. 바이어스 조건은 V_{DS0} = 8 V

Fig. 1. DC transfer characteristics of a 0.5 μm gate-length AlGaN/InGaN HEMT as a function of ambient temperature: -50 °C (solid line), 100 °C (long-dash line), 200 °C (short-dash line). The device was biased at V_{DS0} = 8 V.

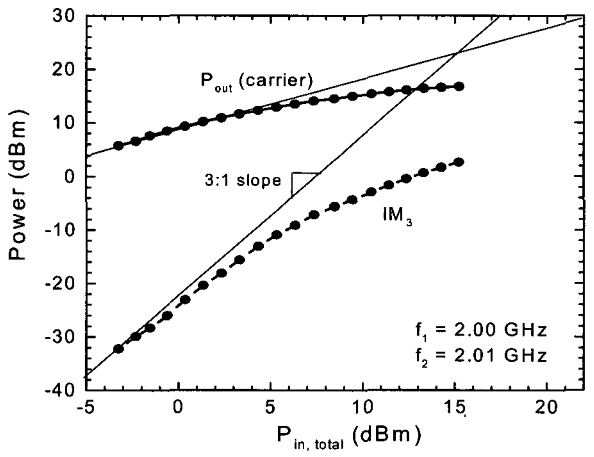


그림 2. 2 GHz에서 측정한 0.5 μm 전극 길이를 가지는 AlGaN/InGaN HEMT의 상호 변조 왜곡 특성. 바이어스 조건은 V_{DS0} = 20 V, V_{GS0} =-2 V

Fig. 2. Measured two-tone inter-modulation (f_1 = 2.00 GHz, f_2 = 2.01 GHz) response of the 0.5 μm gate-length AlGaN/InGaN HEMT versus total input power. The device was biased at V_{DS0} = 20 V and V_{GS0} =-2 V.

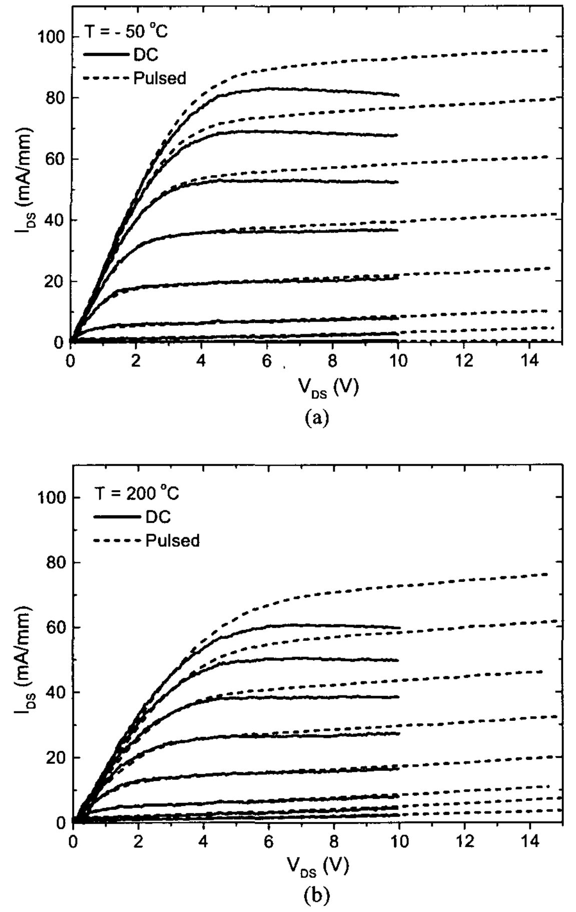


그림 3. 게이트 전극 길이가 0.5 μm인 AlGaN/InGaN HEMT의 (a) -50 ℃ (b) 200 ℃ 에서의 DC 와 펄스 전류 특성. 바이어스 조건은 V_{DS0} = 20 V, V_{GS0} = -5 V

Fig. 3. Measured pulsed (dashed-line) and DC (solid-line) I-V of the 0.5 μm gate-length AlGaN/InGaN HEMT at (a) -50 ℃ (b) 200 ℃. Pulsed I-V was measured at bias voltages, V_{DS0} = 20 V, V_{GS0} = -5 V. V_{GS} = -5 V, step 1.0 V.

analysis using up to third order polynomial for device transfer function predicts 9.6 dB difference[13], these results indicate good linearity of the device.

Ⅳ. RF Dispersion Characteristics of InGaN HEMTs

DC current measurements up to 800 ℃ examined stability characteristics of GaN-based device operating at high temperature[14]. However, little work has been published on the investigation of temperature-dependent dynamic characteristics of GaN-based HEMTs, such as pulsed I-V and microwave power performance. Operation under elevated temperature results in decreased current and transconductance, due to a decrease in the 2DEG mobility and velocity. To examine RF dispersion characteristics of the InGaN HEMTs over wide range of temperature, pulsed I-V data were measured using a ACCENT DIVA dynamic I-V analyzer[15]. The system employs dual pulsing where both the gate and drain terminals of the device are pulsed with signals superimposed on DC bias levels V_{GS0} and V_{DS0} with a 1 kHz repetition rate and a duty cycle of 0.2 %. A compason of the DC and pulsed drain current for the AlGaNInGaN HEMTs at quiescent bias voltages, V_{DS0} = 20 V and V_{GS0} = -5 V, is shown in Fig. 3. The measurements were performed at different tempe-ratures (-50 ℃ and 200 ℃) to examine the effectiveness of using InGaN channel for high temperature, harsh environment applications.

The decrease in drain current, and increase in pinch-off and knee voltages at elevated temperature can be observed, all of which are due to the increasing temperature, but there was no difference between DC and pulsed I-V in the region where self-heating is negligible over the temperature range we measured. This observation is in contrast to typical pulsed I-V characteristics of unpassivated AlGaN GaN HEMTs, in which surface traps severely limit the pulsed drain current[16].

In AlGaN/GaN heterostructure, the polarization effect of strained AlGaN layer provides channel carriers. Therefore, the use of AlGaN as barrier layer is prone to surface charging effects due to its inherent piezoelectric polarization[1]. In case of GaN/InGaN heterostructure, the piezoelectric polarization fields develop across the compressively strained InGaN channel. The induced charge dipoles are situated at the InGaN channel interfaces, and the effect of surface charging states on device characteristics should be relatively small. Thus, the device results obtained show that the current collapse is absent in the InGaN channel heterostructure.

Large signal continuous wave (CW) power measurements were performed using a Focus Micro

-waves automatic load pull system. The output was tuned with V_{DS0} = 25 V for output power at maximum efficiency input drive power while the input was tuned for small-signal gain at room temperature. Figure 4 shows temperature-dependent large signal performance of the 0.5 μm gate-length AlGaN/InGaN HEMT at 2 GHz. The device had a saturated output power density of 1.8 W/mm with an associated power gain of 6.8 dB at 25 °C. The DC current, I_{DS}, gradually increased with input power for all the temperature range measured, indicating that current collapse related to surface effects is not a major problem in these unpassivated AlGaN/InGaN HEMTs. In addition to charged surface states[8], insufficient confinement of the channel charges is considered as one of possible cause of RF current collapse because current collapse indicated by compressed DC current occur with high RF input drive, high current injection condition[17]. As the flat g_m characteristic shows, the AlGaN/InGaN heterostructure has good carrier confinement, which translates to current collapse free in large-signal characteristics.

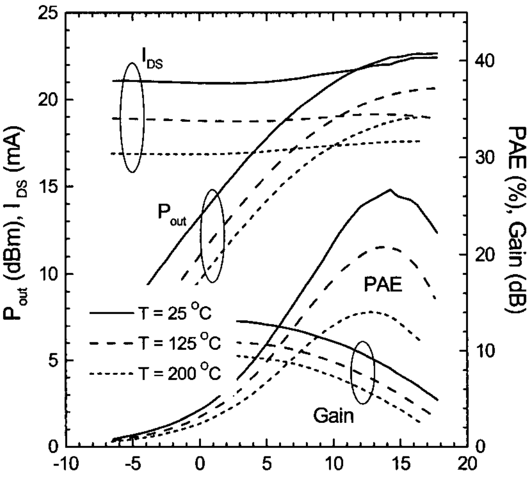


그림 4. 2 GHz에서 측정한 0.5 μm 전극 길이를 가지는 AlGaN/InGaN HEMT의 대신호 특성. 바이어스 조건은 V_{DS0} = 25 V, V_{GS0} = -1.7 V

Fig. 4. Large signal characteristics of the 0.5 μm gate-length AlGaN/InGaN HEMT at 2 GHz as a function of temperature: 25 °C (solid line), 125 °C (long-dash line), 200 °C (short-dash line). The device was biased at V_{GS0} = 25 V and V_{GS0} = -1.7 V.

V. Conclusions

This paper reported on the device characteristics of unpassivated 0.5 μm gate-length AlGaN/InGaN/GaN HEMTs grown by MBE on sapphire substrate. The devices exhibited relatively flat transconductance characteristic with a peak value of 156 mS/mm, and an f_T of 17.3 GHz, and an f_{MAX} of 28.7 GHz. Pulse *I-V* and load-pull measurements over different temperatures showed little current collapse in the device, indicating the effectiveness of InGaN channel for RF current collapse suppression. These results indicate that surface states related current collapse will not limit output power of the InGaN channel HEMTs. With the commercialization of InGaN-based blue and green light emitting diodes by mature growth techniques, InGaN can be a promising alternative channel material to GaN due to the great potential for superior carrier transport properties.

References

[1] L. F. Eastman, V. Tilak, J. Smart, B. M. Green, E. M. Chumbes, R. Dimitrov, H. Kim, O. S. Ambacher, N. Weimann, T. Prunty, M. Murphy, W. J. Scha, and J. R. Shealy, "Undoped AlGaN/GaN HEMTs for microwave power amplification," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 479 - 485, Mar. 2001.

[2] N. Q. Zhang, S. Keller, G. Parish, S. Heikmann, S. P. DenBaars, and U. K. Mishra, "High breakdown GaN HEMT with overlapping gate structure," *IEEE Electron Device Lett.*, vol. 21, pp. 421 - 423, Sept. 2000.

[3] A. Chini, R. Coe, G. Meneghesso, E. Zanoni, D. Buttari, S. Keikman, S. Keller, and U. K. Mishra, "2.1 A/mm current density AlGaN/GaN HEMT," *Electron. Lett.*, vol. 39, no. 7, pp. 625 - 626, 2003.

[4] R. S. Schwindt, V. Kumar, A. Kuliev, G. Simin, J. W. Yang, M. A. Khan, M. E. Muir, and I. Adesida, "Millimeter-wave high-power 0.25-μm gate-length AlGaN/GaN HEMTs on SiC substrates," *IEEE Microwave Wireless Compon. Lett.*, vol. 13, no. 3, pp. 93 - 95, Mar. 2003.

[5] J. Kuzmik, "Power electronics on InAlN/(In)GaN:

Prospect for a record performance," *IEEE Electron Device Lett.*, vol. 22, no. 11, pp. 510 - 512, Nov. 2001.

[6] S. J. Pearton, J. C. Zolper, R. J. Shul, and F. Ren, "GaN: processing, defects, and devices," *J. Appl. Phys.*, vol. 86, pp. 1 - 78, 1999.

[7] A. D. Carlo, F. D. Sala, P. Lugli, V. Fiorentini, and F. Bernardini, "Doping screening of polarization fields in nitride heterostructures," *Appl. Phys. Lett.*, vol. 76, no. 26, pp. 3950 - 3952, June 2000.

[8] E. Kohn, I. Daumiller, M. Kunze, M. Neuburger, M. Seyboth, T. J. Jenkins, J. S. Sewell, J. V. Norstand, Y. Smorchkova, and U. K. Mishra, "Transient characteristics of GaN-based heterostructure field-effect transistors," *IEEE Trans. Microwave Theory Tech*, vol. 51, no. 2, pp. 634 - 642, Feb. 2003.

[9] G. Simin, X. Hu, A. Tarakji, J. Zhang, A. Koudymov, S. Saygi, J. Yang, A. Khan, M. S. Shur, and R. Gaska, "AlGaN/InGaN/GaN double heterostructure field-effect transistor," *Jpn. J. Appl. Phys.*, vol. 40, no. 11A, pp. L1142 - L1144, Nov. 2001.

[10] Y.-M. Hsin, H.-T. Hsu, C.-C. Chuo, and J.-I. Chyi, "Device characteristics of the GaN/InGaN-doped channel HFETs," *IEEE Electron Device Lett.,* vol. 22, no. 11, pp. 501 - 503, Nov. 2001.

[11] Agilent Technologies, *IC-CAP modeling software*, 2000.

[12] N. Vellas, C. Gaquiere, Y. Guhel, M. Werquin, F. Bue, R. Aubry, S. Delage, F. Semond, and J. C. De Jaeger, "High linearity performances of GaN HEMT devices on silicon substrate at 4 GHz," *IEEE Electron Device Lett.*, vol. 23, no. 8, pp. 461-463, Aug. 2002.

[13] S. C. Cripps, *RF power amplifiers for wireless communications*, Artech House, 1999.

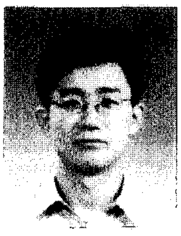
[14] I. Daumiller, C. Kirchner, M. Kamp, K. J. Ebeling, and E. Kohn, "Evaluation of the temperature stability of AlGaN/GaN heterostructure FET's," *IEEE Electron Device Lett.*, vol. 20, no. 9, pp. 448 - 450, Sep. 1999.

[15] Accent Optical Technologies, Inc, *DIVA User Manual*, 2001.

[16] G. Verzellesi, R. Pierobon, F. Rampazzo, G. Meneghesso, A. Chini, U. K. Mishra, C. Canali, and E. Zanoni, "Experimental/numerical investigation on current collapse in AlGaN/GaN HEMTs," in *IEDM Tech. Dig.*, 2002, pp. 689 - 692.

[17] R. J. Trew, "AlGaN/GaN HFET amplifier performance and limitations," in *IEEE MTT-S Int. Microwave Symp. Digest*, 2002, vol. 3, pp. 1811 - 1814.

저 자 소 개



이 종 욱(정회원)
1997년 서울대학원 전기공학과 공학석사
2003년 Purdue University at West Lafayette 공학박사
2003년～2004년 University of Illinoisat Urbana-Champaign (Postdoc research associate)
2004년 3월～현재 경희대학교 전자정보대학 전임강사
<주관심분야: RF/마이크로파 소자 및 회로설계>