Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 160-161

G-2-1 (Invited)

Parasitic effects and reliability issues on GaN based HEMTs

Gaudenzio Meneghesso[1], Christian Dua[2], Marco Peroni[3], Michael Uren[4], and Enrico Zanoni[1]

[1] Department of Information Engineering, University of Padova, Via Gradenigo 6B, 3513 Padova, ITALY
Phone: +39-049-827-7653, Fax: +39-049-827-7699 E-mail: gauss@dei.unipd.it
[2] Alcatel-Thales III-V Lab, Microel. Group, GIE, c/o Alcatel CIT Route de Nozay, 91461 Marcoussis Cédex, FRANCE,
[3] Selex SI, GaAs Foundry Unit, Engineering Department Via Tiburtina, Km 12,400, 00131 Roma ITALY
[4] QinetiQ Ltd, St. Andrews Road, Malvern, Worcestershire, WR14 3PS, UK

1. Introduction

AlGaN/GaN high-electron mobility transistors (HEMTs) are excellent candidates for high-power and high frequency applications due to the superior properties of the GaN-based material [1]. In fact GaN-based material is characterized by: high breakdown field, high electron mobility, high peak saturation velocity and high thermal conductivity. These properties allow the GaN-based devices to operate at voltages and temperature ranges beyond the more conventional compound semiconductor materials (GaAs and InP). Furthermore very high frequencies operation (beyond 100 GHz) has been proved for these devices [2].

Nowadays GaN HEMTs devices with record performances were realized: power densities as high as 20 to 40 W/mm [3], [4] and absolute powers up to 500W [5]. A number of demonstrations of GaN-based Doherty amplifiers were achieved, e.g. [6,7] for the increasing of efficiency in linear operation. Class-E amplifiers based on GaN HFETs with PAE levels beyond 80% and 10 W of output power at 2 GHz have been reported [8]. Switch-mode class-F amplifiers based on GaN HFETs are also very promising [9].

However, in spite of all these promising performances AlGaN/GaN HEMT devices technology suffer from various limiting factors that can be grouped as: i) parasitic and ii) reliability issues. Examples of *parasitic* effects are surface and bulk traps which can strongly limit the drain current level under pulsed and RF operations, dislocations or defects at the gate junction which can induce high reverse leakage current and soft breakdown, and kink effects which can result in husteresis in current-voltage characteristics. From the *reliability* point of view instead, it must be considered that high power densities and high PAE values require large values of drain bias, large peak currents, and large input/output RF-signal amplitudes. The high bias conditions used to get the maximum performance from these devices induce extremely high electric field in the device channel that can generate severe device degradation. In this paper we will present an overview of the main parasitic and reliability issues that nowadays affects the GaN-based devices.

2. Parasitic effects

Current slump.

The effect that most severely limits the RF power performance in AlGaN/GaN HEMTs is the so-called RF current collapse or RF power slump, which originates from charge trapping at the device surface and/or in the buffer [10]. Good passivation process in general is capable of minimizing this parasitic phenomenon. One alternative technological solution that has been proposed consists of using GaN/AlGaN/GaN epitaxial structures with a thin (typically 3–5 nm) n-type-doped GaN cap layer. The latter has been suggested to act as a "surface charge control" layer that reduces the effect of surface polarization charge [11]. The use of the GaN cap in combination with SiN surface passivation has actually allowed record output power performance as well as long-term stable RF operation [12]. We also investigated the use of a GaN cap layer [13]. 2D numerical device simulations have provided an explanation for the influence of the GaN cap layer on current collapse and on the gate-leakage current. Another solution to alleviate current collapse has been suggested by A. Koudymov and coworkers [14]. They demonstrated that the conductivity of the dielectric material under the field plate plays a crucial role in the current collapse removal.

Gate leakage current and breakdown voltage reduction

Actual AlGaN–GaN HEMTs present, in general, very large Schottky-gate leakage current compared to the ideal Schottky gate reverse current [15]. It has been demonstrated that the gate leakage current increases with the defect charge due to thinning of the Schottky barrier, and that the breakdown voltage is reduced due to the electric field concentration at the gate electrode edge [16]. To suppress the breakdown voltage lowering, the authors in [16] found that the surface charge density must be less than $5 \cdot 10^{11} cm^{-2}$. The field plate structure is however effective for suppressing the breakdown voltage reduction due to the defect charge, as FP enhances the relaxation of the electric field. Finally W.S. Tan and coworkers have highlighted that in a conventional HFET, the gate leakage current consists of three separate components: surface, bulk and mesa edge contributions [17]. With a specific test structure they have been able to demonstrate that passivation suppresses current flow across the ungated surface, fully consistent with the model for current slump.

Kink effect

Another parasitic effect recently observed in GaN HEMT is the kink effect (in the output characteristics). Kink is possibly due to negative charge build-up under the gate, taking place at low V_{DS} values followed by negative charge detrapping or compensation, occurring for high V_{DS} values. Dynamic measurements as well as photo-stimulated measurements strongly suggest carrier trapping and detrapping as possible explanation.

3. Reliability issues

Bias-point related degradation

Kim and coworkers [18] presented the effects of SiN passivation and hot electron stress on short-term reliability and gate lag phenomena of undoped AlGaN–GaN HFETs. They demonstrated that while SiN passivation improved the device reliability and power performance, hot electron stress exacerbated the current collapse which was alleviated by SiN passivation. Gate lag measurements on the stressed devices with SiN passivation revealed pronounced effects of charge trapping induced by high-electric field stress. We have carried out several long-term (up to 3000 hours) stress test in quarter micron T-gate GaN-HEMT biased in different conditions: ON STATE (characterized by relatively low V_{DS} values, 20-25V 6W/mm constant dissipated power), in OFF-STATE conditions (characterized by relatively high V_{DS} values 30-40V, V_{GS}=V_{TH}-1V), and in SEMI-ON-STATE (characterized by an intermediate condition, V_{DS} 30-40V, V_{GS}=V_{TH}+1V), in order to emulate the device condition on the load-line during the RF-operation. In general we have observed that the most critical situation is the SEMI-ON stress, where the presence of a large concentration of hot electrons causes the strongest degradation. We have carried out also an extensive short-term reliability evaluation of GaN HEMT biased at high-electric-field stress condition in ON- and OFF-state (for 150 h), see [13]. Degradation modes common to both stress conditions are I_D and g_m drop, gate-lag amplification, and gate-leakage current decrease. Moreover, g_m degradation is maximum at high V_{GS} or in correspondence with the g_m peak for ON-state and OFF-state stress, respectively following a degradation located mainly at the gate edge (for the off state stress) or at the drain edge (for the on-state stress). It must be underline however that Field Plate engineering [21] is a powerful way to reduce high electric fields within the device active area hence alleviating any reliability issues related to the high electric fields and hot electrons.

2D device simulations

2D device simulations [19] have also been applied to investigate the observed degradations. Simulations indicate that the degradation should be ascribed to the simultaneous generation of acceptor traps at the gate-drain surface and trap accumulation within the GaN buffer region. Only the simultaneous generation of surface and buffer traps can account for all of the observed degradation modes. However J. Mateos and coworkers [20] by using Monte Carlo simulation provided Recently an alternative explanation to the observed hot carrier degradation in 250nm gate AlGaN/GaN HEMT. They demonstrated that hot electrons can cause a localized degradation at the drain side of the gate edge (where the maximum electric field is present. The localized degradation is modeled by reducing the value of the polarization charge with respect to the unstressed device in such a region. The results of the simulations show that if strain relaxation is extended into the gate-drain region, not only the access resistance is increased, but also the threshold potential is shifted and the transconductance is reduced. These effects are in agreement with those observed experimentally in [13].

New Degradation mechanisms proposed.

Joh and del Alamo from MIT [22] have carried out systematic experiments on the electrical reliability of state-of-the-art GaN HEMTs. They have found that degradation is mostly driven by electric field and that there is a critical electric field below which negligible degradation is observed. Degradation is consistent with a model of defect formation in the AlGaN barrier as a result of the high electric field. They postulate that lattice defects are introduced by excessive stress.

4. Conclusions

In this paper we reviewed the most critical parasitic effects encountered in AlGaN/GaN HEMT technology and their associated issues on performance and reliability. The related failure mechanisms were also described.

References

[1] D. Pavlidis, *IEEE Elec Dev Meeting*, 2004.

[2] R. Quay, *Space Agency – MOD Round Table Workshop on GaN Microwave Component Technologies*, Noordwijk, The Netherlands, April 2-3, 2007.

[3] A. Koudymov et al., *IEEE El. Dev. Lett.*, v. 28, pp. 5-8, 2007

[4] Y.-F. Wu et al., in *Proc. 64th DRC*, , 2006, pp. 151–152.

[5] A. Maekawa et al., *IEEE MTT-S* Dig., 2006, pp. 722–725.

[6] K.J. Cho et al., *IEEE MTT-S Dig*., 2006, pp.1895—1899.

[7] P. Colantonio et al. , *To be presented at EuMW 2007.*

[8] W.L. Pribble et al., *Proc. IEEE Radio Wireless Symp*., 2006.

[9] D. Schmelzer et al., *Proc. IEEE CSICS 2006*, pp. 96–99.

[10] S. C. Binari et al*., Proc. IEEE*, v. 9, pp. 1048–1058, 2002.

[11] T. Kikkawa et al. *IEDM Tech. Dig., 2001*, pp. 585–588.

[12] T. Kikkawa et al., *in Proc. IEEE MTT-S Int. Microw. Symp. Dig.*, 2004, pp. 1347–1350.

[13] G. Meneghesso et al., *IEEE Transactions on Electron Devices*, vol. 53, no. 12, pp. 2932-2941, 2006

[14] A. Koudymov, et al., *IEEE El. Dev. Lett.* v. 26, p. 704, 2005

[15] H. Hasegawa et. al., *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 21, pp. 1844–1855, 2003.

[16] W. Saito et. al., *IEEE Transactions on Electron Devices*, vol. 52, no. 2, pp. 159-164, 2005

[17] W. S. Tan et al., *IEEE El. Dev. Lett.*, v. 27, pp. 1-3, 2006.

[18] H. Kim et al., *IEEE El. Dev. Lett.*, v. 24, pp. 421-423, 2003

[19] M. Faqir et al, *ROCS 2006, Reliability Of Compound Semiconductors Workshop*, San Antonio (TX) November 12, 2006.

[20] J. Mateos, et. al., *Proc. Of 31th Workshop on Compound Semiconductor Devices and Integrated Circuits, WOCSDICE 2007*, pp. 233-236, Venezia, Italy May 20-23, 2007

[21] S.Karmalkar et al. *IEEE Transactions on Electron Devices*, v.52, pp. 2534-2540, 2005.

[22] Jungwoo Joh and Jesús A. del Alamo, *IEEE International Electron Device Meeting*, pp. San Francisco, Dec. 10-13 2006.