Direct Monitoring of RF Overstress in High-Power Transistors and Amplifiers

A. Stopel, A. Khramtsov, S. Solodky, A. Fainbrun, and Yoram Shapira, *Senior Member, IEEE*

***Abstract*—Light emission from power transistors at a compression level in the range of 2–3 dB has been imaged using a microscope-mounted camera. Results show that the emitted light intensity distribution across the transistor is highly nonuniform and depends on the load impedance, direct current, and RF conditions. The light intensity correlates with a negative gate current, which is a result of the RF-induced impact ionization in the transistors. The nonuniformity in the light intensity is attributed to the RF-induced voltage overstress in the transistors. The observed light emission may be used as a direct and contactless monitor of the RF-induced overstress in transistors and power amplifiers.**

***Index Terms*—Breakdown, high-power amplifier (HPA), impact ionization, light emission, parasitic oscillations, power transistor.**

I. Introduction

THE PERFORMANCE of high-power amplifiers (HPAs) is continually being improved in terms of power density, efficiency, and gain without any reduction in reliability requirements [1], [2]. Efforts in this direction have become a major driving force of device evolution, with a focus on device structure and material composition. Usually, power transistors comprise a number of transistor unit cells (fingers) that are connected in parallel. The number and width of the fingers are mostly dictated by the application and frequency range, while the internal device structure is strongly dependent on the device technology. The individual device fingers are connected in parallel by interdigital electrodes, such that a large number of loops are formed between the transistor fingers. The loops may lead to a nonuniform distribution of resultant voltage V_{RF} across a loop, which is strongly affected by internal reflections in the device. In some cases, nonuniformity in V_{RF} occurs due to parasitic oscillations that are excited under actual operational conditions [3].

In this letter, we show the use of a photon-emission-based methodology for monitoring the distribution of electrical stress in power transistors and HPAs [4]–[6]. The emitted light distribution reflects the impact ionization processes across the device. It is a strong function of the operational conditions, particularly, of output impedance Z_{output}. The technique may be applied to any solid-state HPA technology, without losing the universality of the approach. In this letter, the technique is demonstrated and evaluated for mature pseudomorphic high-electron mobility transistor (PHEMT) device technology.

Manuscript received February 13, 2007; revised March 5, 2007. The review of this letter was arranged by Editor P. Yu.

The authors are with the School of Electrical Engineering, Tel Aviv University, Tel Aviv 69978, Israel (e-mail: stopel-a@013.net).

Digital Object Identifier 10.1109/LED.2007.895437

II. Sample Description and Experimental Setup

All measurements have been performed on 20 commercially available dies of power PHEMT 0.25-μm transistors with different device structures and layout parameters, and with a total gate periphery ranging from 1 to 1.5 mm (from 10×0.100 to 10×0.150 mm). All the devices underwent screening procedures, using dc and RF measurements. In addition, the electrically active defects were monitored by photoemission inspection under dc conditions that are close to the OFF-state breakdown. Uniform photoemission is used as a "defect-free" criterion. Consequent power measurements were performed on defect-free transistors under dc and small-signal parameters, according to device specifications. Using electromechanical tuners, on-wafer load-pull measurements were used to determine the output impedance for maximum power Z_{opt} at 10 GHz for a wide variety of dc operational ranges ($V_{\mathrm{ds}} = 5\ \mathrm{V} \div 9\ \mathrm{V}$, and $V_{\mathrm{gs}} = -0.9$ V, with the typical V_{br} being higher than 18 V). In addition, the $P_{\mathrm{in}} - P_{\mathrm{out}}$ characteristics of PHEMTs were measured for a number of input/output impedances around Z_{opt}. The load tuners were selected to provide the best matching at maximum power, corresponding to a gain compression in the range of $\sim$2–3 dB under actual operation conditions. For each transistor under test, output power, efficiency, gain, and gate/drain currents, as well as photon emission data, were collected. A Sony Xc555P camera and an Optem Zoom70 XL microscope provided the photon images under RF load and dc conditions. Photoemission images were processed using MATLAB. Numerical simulation and analysis were carried out using the Agilent Advanced Design System and JMP, respectively.

III. Theory

The power performance strongly depends on Z_{output}, which has to be optimized at a value that is denoted by Z_{opt}. This value is defined by load-pull measurements. The limiting mechanism of the power performance is the transistor breakdown. Breakdown source–drain voltage V_{br} is marked by a sharp increase in the gate–drain current [7], [8]. V_{br} is defined using direct measurement, where negative gate current I_g reaches a magnitude of 1 mA/mm (assuming that I_g is uniformly distributed across the transistor unit cell). The gate current increases due to minority carrier generation by the impact ionization process. This process entails free carrier generation in a region of the transistor, where the resultant electric field is above a critical value (i.e., F_{critical}). Recombination of the free carriers may lead to light emission from the device during impact ionization [9], [10]. Light emission has been observed for

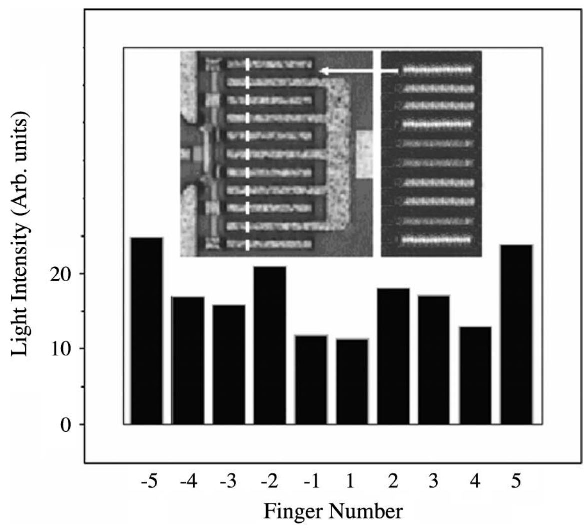

Fig. 1. Light intensity as a function of finger position for 2–3-dB compression at $Z_{\mathrm{opt}} = 19 + j13\ \Omega$. Inset: Image of the emitted light on the transistor layout. The dashed line marks the cross section.

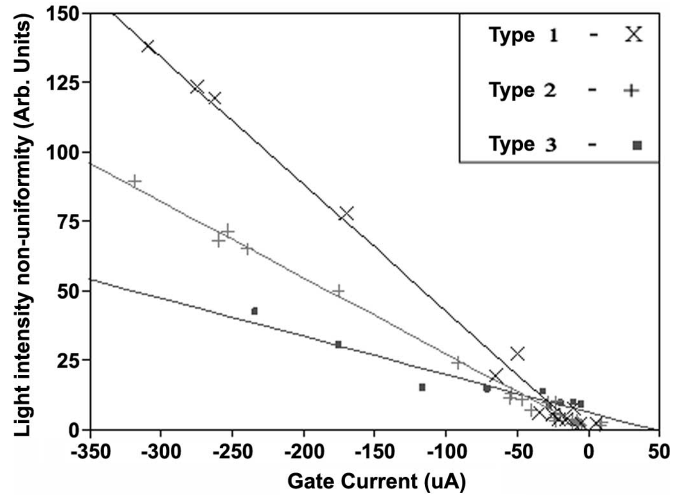

Fig. 2. Light-intensity nonuniformity $\Delta I_{\mathrm{light}}$ as a function of I_g for 2–3-dB compression.

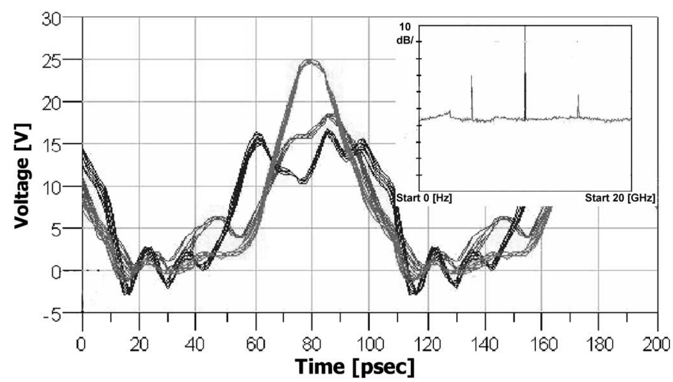

Fig. 3. Simulated time dependence of the RF voltage per transistor finger. Inset: Measured oscillation spectra under RF compression.

various device technologies [9]–[13]. Thus, the nonuniformly emitted light may be used as a fingerprint of the nonuniform voltage stress across an entire transistor, i.e., nonuniformity in the emitted light intensity reflects nonuniform impact ionization.

IV. Result and Discussion

The total emitted light intensity, which is integrated across the entire transistor, is a well-known function of the negative I_g and clearly indicates impact ionization in a device [8], [9]. This correlation reveals that the emitted light is a result of radiative recombination, following impact ionization. Our measurements fully confirm these findings. However, for some devices (for some values of Z_{output}), an increase in the negative I_g is accompanied by an increase in the light intensity locally rather than uniformly, i.e., the intensity becomes a clear function of the finger position in the device. The inset in Fig. 1 shows that the variation in the light distribution across a transistor may reach 100%.

The devices have been tested under various bias and Z_{output} conditions. Fig. 2 shows a correlation between the nonuniformity in light intensity ($\Delta I_{\mathrm{light}} = I_{\mathrm{MAX}} - I_{\mathrm{MIN}}$ across the entire transistor) and the negative gate current for three groups of devices with significantly different layout parameters. $\Delta I_{\mathrm{light}}$ and I_g are strong functions of the output impedance, drain voltage, and power compression level. These dependences lead simultaneously to intensity redistribution and variation in I_g in a wide range across the transistor. Therefore, a reasonable assumption is that the $\Delta I_{\mathrm{light}}$ distribution is related to the impact ionization rate and reflects its nonuniformity. Under actual operational conditions, the electric field is a complicated result of both dc and RF voltage (V_{RF}) drops. Moreover, the emission intensity decreases and becomes uniform when the RF signal is reduced. Thus, $\Delta I_{\mathrm{light}}$ correlates with the resultant voltage. The interdigital topology leads to multiple internal reflections of the RF signal and to pronounced nonuniformity in the V_{RF} distribution across the device. Numerical simulations, which are based on the nonlinear device model, have been applied to describe load-pull measurements for typical interdigital device geometry under relevant operational conditions. The simulations confirm that, under compression, V_{RF} is highly nonuniform and may reach several volts across the device, as shown in Fig. 3. In the region (fingers) of high V_{RF}, it may lead to severe impact ionization and pronounced light emission, while the average emitted intensity across the device is low. In addition, a number of closed loops may lead to the excitation of parasitic oscillations under actual operational conditions of RF compression [3], [14], [15]. These are quite typical for power transistors [3], [14] under RF stress, and are directly observable in our measurements [Fig. 3 (inset)]. Thus, $\Delta I_{\mathrm{light}}$ reflects the nonuniformity in the V_{RF} distribution across the device and is accompanied by strong oscillations. Changing the load impedance leads to significant light intensity redistribution across the unit cell. For some impedance values, the light intensity in different fingers may change by more than an order of magnitude. These impedances may become a high-reliability risk, while the total I_g may still be far from the maximum specified value $I_{g,\max}$). Under such conditions, the transistor cannot be characterized by the magnitude of I_g. Additional knowledge is required on the I_g distribution across the device.

Light emission imaging seems to be an effective monitor since the light intensity reflects the V_{RF}-induced stress in a transistor. The method may easily be adapted for characterizing HPAs at the chip level as well as HPAs integrated in transmit/receive modules.

During transistor characterization and modeling, imaging of emitted light as a function of Z_{output} makes it possible to get insight into the distribution of RF-induced stress across a device. This knowledge is crucial for the definition of the optimal impedance, which yields not only the desired power performance but also the uniform stress in the transistor. Proper design and choice of transistor geometry can determine impedance regions with a desirable compromise between power density and efficiency and to avoid the risks of impact ionization.

V. Conclusion

The results show that nonuniformity in light emission from power transistors strongly correlates with I_g at a compression level in the range of 2–3 dB. Under these conditions, the emitted light distribution is significantly nonuniform and reflects the V_{RF}-induced impact ionization distribution across a transistor. Imaging the emitted light may be effectively used as a contactless V_{RF} overstress monitor at the transistor and chip levels.

References

[1] A. Villanueva, J. del Alamo, T. Hisaka, and K. Hayashi, "Electrical reliability of RF power GaAs PHEMTs," in *IEDM Tech. Dig.*, Dec. 2003, pp. 719–722.

[2] T. Hisaka, Y. Nogami, A. Hasuike, H. Sasaki, N. Yoshida, K. Hayashi, T. Sonoda, A. Villanueva, and J. A. del Alamo, "Degradation mechanisms of PHEMTs under large signal operation," in *Proc. IEEE GaAs IC Symp.*, Nov. 2003, pp. 67–70.

[3] D. Teeter and A. Platzker, "Transistor amplifier having reduced parasitic oscillations," International Application Published Under the Patent Cooperation Treaty (PCT), WO 77923, Jun. 9, 2000.

[4] C. Tedesco, E. Zanoni, C. Canali, S. Bigliardi, M. Manfredi, D. C. Streit, and W. T. Anderson, "Impact ionization and light emission in high-power pseudomorphic AlGaAs/InGaAs HEMTs," *IEEE Trans. Electron Devices*, vol. 40, no. 7, pp. 1211–1214, Jul. 1993.

[5] H. P. Zappe and D. J. As, "Carrier transport in HEMT's analyzed by high-field electroluminescence," *IEEE Electron Device Lett.*, vol. 12, no. 11, pp. 590–592, Nov. 1991.

[6] R. Gaddi, G. Meneghesso, M. Pavesi, M. Peroni, C. Canali, and E. Zanoni, "Electroluminescence analysis of HFET's breakdown," *IEEE Electron Device Lett.*, vol. 20, no. 7, pp. 372–374, Jul. 1999.

[7] M. Somerville, J. A. del Alamo, and P. Saunier, "Off-state breakdown in power pHEMTs: The impact of the source," *IEEE Trans. Electron Devices*, vol. 45, no. 9, pp. 1883–1889, Sep. 1998.

[8] M. Somerville, R. Blanchard, J. A. del Alamo, K. G. Duh, and P. C. Chao, "A new gate current extraction technique for measurement of on-state breakdown voltage in HEMTs," *IEEE Electron Device Lett.*, vol. 19, no. 11, pp. 405–407, Nov. 1998.

[9] E. Zanoni, M. Manfredi, S. Bigliardi, A. Paccagnella, P. Pisoni, C. Tedesco, and C. Canali, "Impact ionization and light emission in AlGaAs/GaAs HEMT's," *IEEE Trans. Electron Devices*, vol. 39, no. 8, pp. 1849–1857, Aug. 1992.

[10] P. Cova, F. Fantini, and M. Manfredi, "Correlation between hot-electron light emission and currents in pseudomorphic HEMTs," in *Proc. 21st Int. Conf. Microelectron.*, 1997, pp. 237–240.

[11] N. Shigekawa, T. Enoki, T. Furuta, and H. Ito, "Electroluminescence measurement of InAlAs/InGaAs HEMTs lattice-matched to InP substrates," in *Proc. 8th Int. Conf. Indium Phosphide and Related Mater.*, Apr. 1996, pp. 681–684.

[12] N. Cavassilas, F. Aniel, A. Nojeh, R. Adde, M. Zaknoune, S. Bollaert, Y. Cordier, D. Theron, and A. Cappy, "Electroluminescence of metamorphic $In_xAl_{1-x}As/In_xGa_{1-x}As$ HEMTs on GaAs substrate," presented at the Gallium Arsenide Applications Symp., Paris, France, 2000.

[13] N. Armani, V. Grillo, G. Salviati, M. Manfredi, M. Pavesi, A. Chini, G. Meneghesso, and E. Zanoni, "Characterization of GaN-based metal-semiconductor field-effect transistors by comparing electroluminescence, photoionization, and cathodoluminescence spectroscopies," *J. Appl. Phys.*, vol. 92, no. 5, pp. 2401–2405, Sep. 2002.

[14] S. Goto and Y. Sasaki, "High-frequency power amplifier," U.S. Patent 20 040 222 854, Nov. 11, 2004.

[15] D. Teeter, A. Platzker, and R. Bourque, "A compact network for eliminating parametric oscillations in high power MMIC amplifiers," in *Proc. IEEE MTT-S Dig.*, 1999, pp. 967–970.