A UNIVERSAL MEASUREMENT SYSTEM FOR MICROWAVE POWER TRANSISTORS

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ABSTRACT

We describe a measurement system for model parameter extraction and full characterization of power transistors in frequency and time domain. It provides bias dependent linear S parameters, power transfer characteristics, intermodulation data, and RF waveforms in dependence on harmonic load tuning. The power level exceeds 30 dBm for highly mismatched devices. The system is for full on-wafer operation including all calibration steps. Examples of measurements, e.g. RF-I/V curves, are presented for low-voltage GaInP/GaAs HBTs. These experimental results are confirmed by a scaleable large-signal HBT model, which demonstrates both usefulness of the measurement system and performance of the nonlinear model.

MOTIVATION

Load-pull measurement systems provide the information required for developing new power transistors and also make available the CAD data necessary to incorporate these transistors in nonlinear circuit design. To make progress in nonlinear modeling, however, more information is desirable. In particular the verification of RF-*I/V* waveforms (i.e., the time-domain data) under different operation conditions at high power levels is the most stringent test of such a model (Rudolph et al. (1)). The described universal on-wafer measurement system for microwave diagnostics of power transistors allows routine load-pull and parameter extraction for small- and large-signal modeling.

It includes the following main features:

- Linear and nonlinear network analysis (measurements of *S* parameters from 0.3 MHz to 18 GHz; Reflection and transmission coefficients of the nonlinearly driven device from 2 GHz to 18 GHz up to 30 dBm power level).
- Multiharmonic active load-pull technique (tuning of load reflection coefficients Γ_l at 2 GHz fundamental frequency and second and third harmonic).
- Measurement of power transfer characteristics up to P_{out} = 30 dBm for highly mismatched and up to 38 dBm for matched devices.
- Source pull (source reflection coefficient Γ_s = 0…0.8).
- Passive load-pull at the fundamental frequency (measurement of two-tone intermodulation and verification of active load-pull results).
- RF waveform measurements in dependence on the harmonic tuning state.
- DC-*I/V* characteristics and Gummel plots up to 2 A output current using bias tees, which prevent device oscillations. These bias tees were specifically developed for this purpose.
- Full on-wafer compatible calibration including harmonic phase correction angles by a nonlinear transmission line (NLTL) as multiharmonic reference generator.

Data acquisition is based on a HP 71500 microwave transition analyzer (MTA) and force/sense bias supplies (Kompa and van Raay (2)). The measurement system is completely PC-controlled with software based on LabWindows/CVI.

The described set-up covers the frequency range of wireless communications. The actual operation frequency is given by some narrowband components, e.g. power amplifiers, isolators and electronic phase shifters. We present results at a fundamental frequency of 2 GHz and its second- and third-order harmonics. The example deals with GaAs hetero-bipolar power transistors (HBT) for low bias voltages at 3 V, because this is of special interest for mobile communication applications (Achouche et al. (3)).

MEASUREMENT SYSTEM

Figure 1 presents the block diagram. All units are permanently connected and appropriate switching activates the special measurement configuration. The passive load branch is connected to an additional output probe. This is due to the demand of placing the tuner in a position right next to the device in order to minimize losses. The VNA HP8753C is used for linear *S* parameter measurements down to 0.3 MHz and partly for system calibration.

For the active load-pull operation the fundamental frequency output (2 GHz) of source 1 is split in a source and three load parts. The fundamental wave a_1 is fed to port 1 via a 33-dBm power amplifier, bias-tee, and reflectometer R I. The wave incident to port 2 is adjusted in magnitude and phase with respect to a_1 by an attenuator (79 dB, step 1 dB) and a continuous electronic phase shifter. It is amplified by a 39-dBm amplifier and forms the fundamental wave a_2. The second- (4 GHz) and third-harmonic (6 GHz) signals are generated from the remaining two load parts by a frequency doubler and tripler, respectively. These waves are adjusted in magnitude and phase by control components of the same kind as the fundamental one. The power is provided by 30-dBm amplifiers. These three harmonic power waves are superimposed at port 2 to the "reflected" wave a_2. The power waves at input (a_1, b_1) and output (a_2, b_2) of the DUT are separated by the reflectometers and measured by the MTA.

Third-order intermodulation measurements are performed by adding a second tone to the 2-GHz input signal. It is provided by source 2 at 2.01 GHz and adjusted to the same power at port 1 as the first tone. The output spectrum is measured via the passive load branch by a spectrum analyzer. That means, the active load is not used for this measurement.

POWER LIMIT AND DEVICE SCALING

There are two power limitations for an on-wafer active load-pull system.

(1) The amplitude of the "reflected" wave a_2 which determines $|\Gamma_l|$ becomes very high if a small output resistance must be matched. For example a 2-W transistor for 3-V operation has a loadline of 2 Ω and requires 12 W for the "reflected" wave a_2. This approaches the limit of on-wafer power handling.

(2) The thermal limit. The heat transfer from the device to the chuck as heat sink is not well defined. It depends on wafer thickness, backside metallization and an unintentional air gap between wafer and chuck. We have measured coplanar devices up to 3 W RF power on a 0.5 mm thick GaAs wafer with no via holes and no back metallization on an uncooled chuck.

Anyway, the development of transistors above a few Watts of output power requires the capability to measure and to model scaled devices. That means, all elements of the equivalent circuit, of the large-signal model, and the power transfer properties must show a physically meaningful scaling with the size of the device. Then, even the development of power transistors that are beyond the above restrictions can be supported by the measurement system. The principal features of a scaleable nonlinear HBT model have been demonstrated recently (Rudolph et al. (4)). The model parameters are obtained with the described system. We start with common multibias *S* parameter and DC measurements. The actual size of the transistor under test does not require any adaptation of the linear part of the measurement system, except the increasing importance of *S* parameters in the Megahertz range for large devices.

This is not valid, however, for the power measurement setup because it has consequences for the source tuning. Full-scale power transistors for 2 GHz are usually highly mismatched devices. Γ_{in} and Γ_{out} are close to a short. Increasing source power drives high RF-currents into the device. On the other hand, Γ_{in} and Γ_{out} for small-sized devices are close to an open and increasing source power leads to a large voltage sweep at the input, which is not suitable for proper device operation. In this case, source match at the fundamental frequency by a tuner could be recommended.

We tested both arrangements in the described system. The improved power transfer to the device by strong transformation is at the expense of increasing losses in the tuner itself. Another problem is the value of Γ_s for the actual transformation state. If pre-measured values are used it is difficult to account for the changing Γ_{in} with power and Γ_l. Thus the actual setting must be measured. The Γ_s measurement cannot be done without the switch between R I and DUT. The switch enables the feed of a stimulus signal in opposite direction to measure the source reflection coefficient in the network analyzer mode when the power amplifier is switched off. A source of error with the tuner is also the strong re-reflection of incident and reflected wave on the input line where the waves a_1 and b_1 are measured with the reflectometer R I.

These disadvantages lead to the conclusion that the effectiveness of a tuner between source and DUT is limited. We do not use the tuner in the investigation of full-sized HBT power cells and perform the measurements with the 50-Ω source only. For small-sized devices, however, in particular FETs, it is beneficial to use source tuning with the effect of reducing the real part of the input impedance.

MEASUREMENT EXAMPLE AND MODELING

The power transfer characteristics of a 12(3×30) µm^2 GaInP/GaAs HBT is shown in figure 2(a). The distinctive feature of the presented system is its ability to measure at realistic power levels of 30 dBm and above and to tune the harmonic loads to any value of the Smith chart. The *I/V* contours in the microwave range are strongly influenced by the reactive components of the transistor and by the load reflection coefficients at the harmonic frequencies. Thus the measured waveforms of a power HBT near the 1 dB compression point as shown in figure 3 give the wave shaping which actually can be achieved. The basic effect of harmonic tuning can be seen clearly. Voltage flattening with second-harmonic short ("squaring the sine-wave"), which is typical for class F, is not the optimum for low-voltage operation (Heima et al. (5)). On the contrary, as shown here, increasing the RF-voltage maximum with second-harmonic open ("voltage peaking") leads to better P_{out} and *PAE*. This operating condition is similar to inverse class F (Inouhe et al. (6)). The flattening of the bottom part of the voltage waveform, enabling the smooth fit to the left part of the *I/V* characteristics becomes also obvious. These very peculiar waveforms can be verified by our nonlinear transistor model (1). Figure 2(b) shows the voltage spectral components in this tuning state. Figure 2(c) shows the power dependence of collector current I_c and of the base-emitter voltage V_{be}, which is necessary to drive a constant base-emitter current.

CONCLUSION

The described system is a powerful tool for nonlinear on-wafer measurements. This is very helpful when designing high-efficiency power amplifiers, e.g. for mobile communications. It is also suitable for foundry requirements with the need of tuning process parameters for new power transistors as well as to test nonlinear CAD models of those devices. One feature is the access to vectorial RF current and voltage waveforms that are the most important intrinsic parameters of transistor operation. These measurements can be performed at power levels up to 30 dBm with $|\Gamma_l| \leq 0.9$ for the fundamental wave and $|\Gamma_l| = 1$ at the second and third harmonics.

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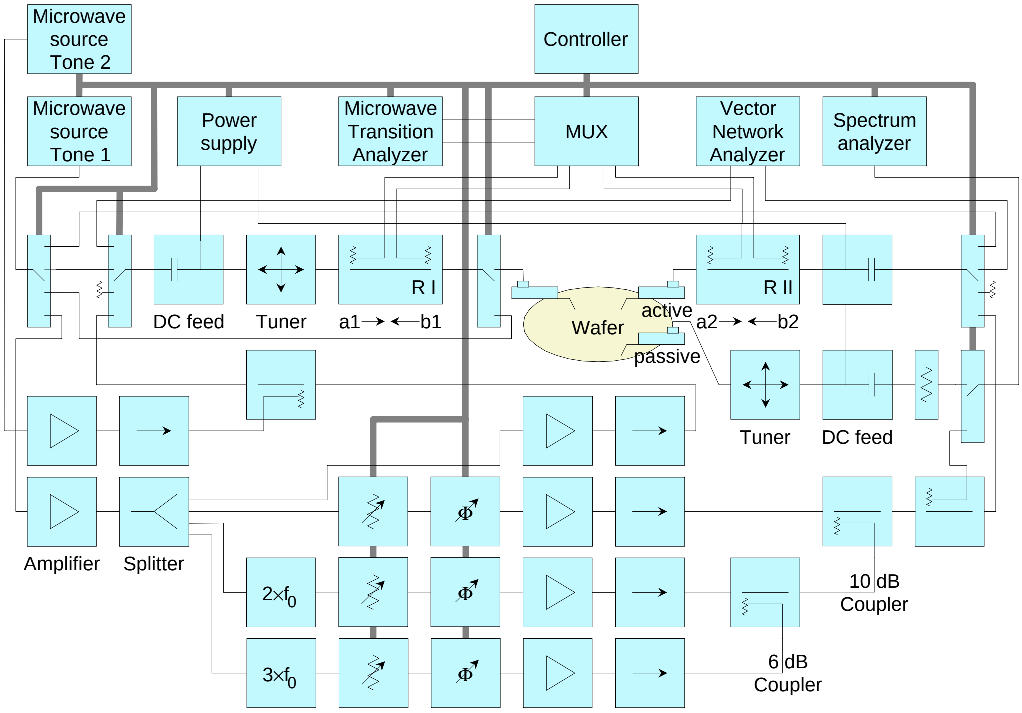

Fig. 1. Nonlinear measurement system for power transistors.

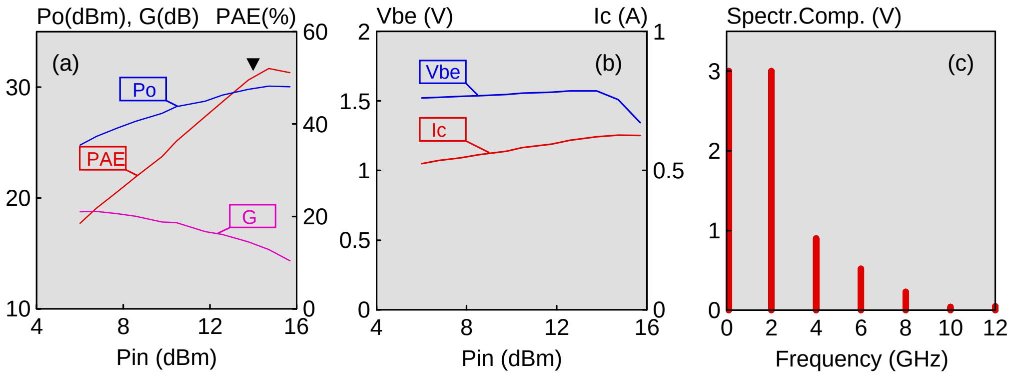

Fig. 2. Measured data of a 12(3×30) μm^2 GaInP/GaAs power HBT with harmonic tuning.
f = 2 GHz, V_{ce} = 3 V, I_b = 7 mA, $\Gamma_l(f)$ = 0.85/180°, $\Gamma_l(2\times f)$ = open, $\Gamma_l(3\times f)$ = short.
(a) Power transfer, (b) V_{be} and I_c versus P_{in}, (c) Voltage spectral components.

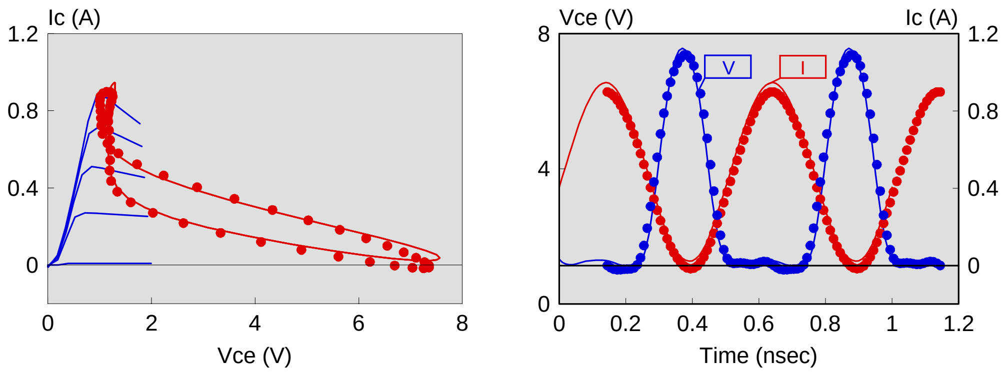

Fig. 3. RF-*I/V* waveforms near the 1 dB compression point (conditions as in Fig. 2). Symbols: measurement, solid lines: model calculation.