Pulsed-IV Pulsed-RF Measurements Using a Large Signal Network Analyzer

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Abstract—A new pulsed-IV pulsed-RF measurement system using a large signal network analyzer (LSNA) is proposed to address the problem of desensitization afflicting conventional pulsed-RF measurement systems. Several extraction methods using the entire spectrum measured by the system are presented to extract non-desensitized pulsed-RF S-parameters of a transistor. The comparison of the calculated S-parameters using the least-square fitting in time domain with those using only the fundamental tone reveals the significant increase in dynamic range achieved by the proposed measurement scheme.

Index Terms—Pulsed measurement, large signal network analyzer (LSNA), desensitization.

I. INTRODUCTION

Slow memory effects are low frequency dispersions originating from various physical processes in transistors such as self-heating, parasitic bipolar transistor in FETs, and traps[1]. It is essential for successful device modeling to account for these slow memory effects in the acquisition of the DC and RF device characteristics.

To account for these slow memory effects, pulsed-IV pulsed-RF measurement techniques have been developed to reproduce the conditions under which a transistor operates for large RF signals [2]. Low-frequency memory effects have indeed a slow time response and the fast pulsed-IV pulsed-RF measurements maintain a constant temperature, body BJT voltage or trap state in FETs like when there are excited by large RF signals. By bypassing slow memory effects, pulsed-IV pulsed-RF measurements enable us to obtain realistic isothermal RF characteristics of the FETs.

Most pulsed-RF measurement systems using conventional network analyzers can only acquire the center tone of the pulse spectrum and this results in a significant loss of dynamic range due to the resulting desensitization of $20\log(duty\ rate)$. Typically a 1µs duration pulse with 1% duty rate is used to avoid low-frequency memory effects [3], and the dynamic range of the network analyzer for the pulse decreases by 40dB. The reduction in dynamic range is an important problem which affects the accuracy of the pulsed measurement data obtained, especially for low duty rate pulse.

Since the power provided by the center-tone does not reflect the actual signal RF power applied during the pulse, it is desirable for more tones in the RF pulse to be included into the characterization of the DUT. Fortunately, it is possible to get a large portion of the spectrum of the pulse signal with a large signal network analyzer (LSNA). Therefore the LSNA can be expected to improve the dynamic range in the pulsed-IV pulsed-RF measurement system [4]. The goal of this paper is to introduce the new pulsed-IV pulsed-RF measurement system developed using the LSNA, and present the analysis used to recover the S-parameters from the data measured.

II. PULSED-IV PULSED-RF MEASUREMENT SYSTEM

A. System Realization

In general in pulsed-IV systems both $V_{gs}$ and $V_{ds}$ pulsed biases are applied at the gate and the drain of a transistor. In the experiment reported here, a pulse is only applied at the drain and a constant DC voltage is used at the gate. It is assumed that slow memory effects are dominated by self-heating and the contribution of traps in the gate is neglected. For this entire study, we have used the Infineon CLY 5 GaAs FET as a DUT. Fig. 1 shows the pulsed-IV pulsed-RF measurement system implemented using the LSNA. Port 1 is used for the gate, and port 2 for the drain. The constant $V_{gs}$ is applied to the gate using the LSNA internal bias tee. An external bias tee is used for the drain. A current sensor consisting of a resistor is used to measure the drain current with an oscilloscope. A FPGA digital testbed synchronized to the LSNA [5] was initially used to synthesize a band-limited pulsed-RF signal using an IQ modulator. This permitted to address the fact that the modulation bandwidth of the LSNA is presently limited to 20 MHz. However the 20 MHz bandwidth limitation is not a major concern for a 0.33μs duration pulse. The final approach adopted is to use the pulsed RF signal provided by a RF signal

![Fig. 1. Pulsed-IV pulsed-RF measurement system.](image-url)
generator (Anritsu MG3692A) as shown in Fig. 1. The pulse-modulated signal from this signal generator is very stable. Note that 104 pulses are acquired by the LSNA when using 95 Hz resolution. Fig. 2 shows a generated RF pulse with a duty rate of 0.33% and 0.33µs pulse duration.

In addition to generate a RF pulse, the RF signal generator is also triggering the $V_{ds}$ pulse generator to overlay the RF pulse upon the drain pulse signal at the proper moment. More details on the timing for the pulsed-IV pulsed-RF signals are provided in Fig. 3. The drain pulse has a duty rate of 1% and 1µs duration which is short enough to achieve the targeted isothermal condition.

### B. Measurement Bandwidth

To remove the problem of desensitization in conventional pulsed-RF system, it would be theoretically desirable to use the entire spectrum of the pulse to obtain higher measurement accuracy. In practice, however, it is not possible to acquire the complete spectrum due to the 20MHz IF bandwidth limitation of the LSNA. Nonetheless by acquiring the spectrum in a wide enough range we can enhance the measurement accuracy.

According to Parseval’s theorem, the total average power of the signal $x(t)$ is the sum of the average power in each harmonic component:

$$
\frac{1}{T} \int_0^T |x(t)|^2 \, dt = \sum_{n=-\infty}^{\infty} |C_n|^2 = 2 \sum_{n=0}^{\infty} |C_n|^2.
$$

where $C_n$ is Fourier coefficients, and usually has the form of a sinc function if $x(t)$ is a pulse signal. Thus the power included in the bandwidth range $m$ is

$$
\text{power} = \sum_{n=1}^{m} |C_n|^2 / \sum_{n=1}^{\infty} |C_n|^2 \times 100
$$

Fig. 4 shows that the main lobe of a sinc function includes about 90.3% of the total average power, providing enough power to essentially suppress the desensitization experienced in the conventional pulsed-RF system. It is also preferable to focus only on the main lobe because of the noise floor level of

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**Fig. 2.** LSNA pulse measurements at modulation frequency of 9.918KHz and resolution BW of 95.367Hz. With this setup the LSNA captures 104 pulse periods for each measurement.

**Fig. 3.** Timing for the pulsed-IV pulsed-RF system. Signals (a) and (b) indicate pulses between the input and output of the current resistor sensor for the drain (Fig.1), with a pulse width of 1µs and a duty rate of 1%. The RF signal (c) which is applied to the gate at the measurement time from 0.6µs to 0.93µs, has a 0.33% pulse duty rate.

**Fig. 4.** As the number of single-sideband (SSB) tones in a sinc function increases, the included power also goes up. With only main lobe ($m=300$), it is possible to obtain the 90.3% of total average power (duty rate: 0.33%, duration: 0.33µs).
the LSNA. In other words, with resolution bandwidth of 12KHz the noise floor level of the LSNA is typically -70dBm up to 20GHz when the IF frequency is 10MHz \[6\], and deep nulls of the sinc function are usually expected to be below the noise floor (see Fig. 2 (a)).

III. S-PARAMETER ANALYSIS

In this work the system is used to acquire the pulsed-IV pulsed-RF S-parameters of a RF transistor. For each of the 601 tones \(i\) in the pulsed RF spectrum as shown in Fig. 2 (a), an S-parameter can be defined as

\[
S_{ik}(\omega) = \frac{b_k(\omega)}{a_k(\omega)} |a_m| = 0.
\]  

Typical S-parameters resulting for all \(\omega_i\) in the center lobe are shown (green dots) in Fig. 5. Note that \(S_{11}(\omega_0)\) and \(S_{21}(\omega_0)\) which are obtained by using only the fundamental center tone \((i=0)\) will naturally be noisier due to the desensitization. In Fig. 6, it is shown that the dynamic range of the center tone decreases by about 50dB.

To estimate the pulse-RF S-parameters based on all the 601 measured tones in the spectrum, three different approaches are considered.

A. Least-square fit in frequency domain

Because the raw S-parameters \(S_{ik}(\omega_i)\) are usually noisy, an estimation of the trend of the S-parameters is needed. It is reasonable to assume that the S-parameters are basically linear functions of the frequency within the bandwidth of the main lobe. Least-square fitting in frequency domain is then used to find the best fitting straight line. The straight lines fitting the amplitude and phase of the S-parameter \(S_{ik}(\omega_i)\) are then used to predict \(S_{kl}(\omega_0)\) as shown in Fig. 7.

However, as we move away from the center tone in Fig. 7, S-parameters are getting noisier due to the sinc nature of the spectrum of \(|a_i|\). To reduce the impact of the increased noise on the edge, the least-square algorithm is applied only to a reduced bandwidth corresponding to 401 tones.

B. Envelope convolution in time domain

The signal envelope \(E[]\) of an arbitrary signal \(x(t)\) can be recovered from the amplitudes and phases in the spectrum using

\[
E[x(t)] = \sqrt{I^2(t) + Q^2(t)},
\]  

Fig. 6. 5-consecutive incident waves for a continuous wave and a pulse signal. The RF input power is 5dBm. In the case of the pulse signal (duty rate: 0.33%), the center tone at 600MHz has only -45dBm power, and indicates the 50dB desensitization.

Fig. 7. Amplitude and phase of \(S_{kl}(\omega_i)\) varying tone index. These data are fitted using the least-square algorithm to recover \(S_{kl}(\omega_0)\).
where \( I(t) \) and \( Q(t) \) are in-phase/quadrature-phase components of the signal \( x(t) \).

After getting the envelopes \( E[a_1(t)] \), \( E[b_1(t)] \) and \( E[b_2(t)] \), subsequent convolutions between these signals can be used to extract the device group-delay \( \tau \) and the amplitude of S-parameter using the following equations.

\[
\tau_{S_{ij}} = d\omega_i S_{ij} / d\omega_i 
\]

\[
|S_{ij}(\omega_0)| = |E[b_k(t)]*E[a_1(t)]*E[a_1(t)]*E[a_1(t)]| 
\]

This permit us to calculate in turns the amplitude and phase of \( S_{ij}(\omega_0) \). As a result of the larger signal amplitude, a reduced noise is expected in the S-parameters.

In addition to considering the above three analyses, additional processing steps are required for extracting S-parameters from LSNA measurements. In distinction to a conventional network analyzer, the LSNA calibration is not used for transforming the termination at port 1 and 2 into perfect match loads. It results that the small reflections from the coupler and terminations introduce reproducible oscillation features in the obtained S-parameters if port 1 and 2 are assumed to be perfectly matched. To remove these unwanted features one can alternately send an excitation at port 1 and 2. Obviously these two consecutive measurements must be performed for the same pulsing conditions. Then solving the four simultaneous equations obtained from Eq. (8) for both measurements, gives the error-corrected S-parameters.

\[
\begin{align*}
\begin{bmatrix}
    b_{1,1} \\
    b_{1,2} \\
    b_{2,1} \\
    b_{2,2}
\end{bmatrix}
&=
\begin{bmatrix}
    S_{11}a_{1,p} + S_{12}a_{2,p} \\
    S_{11}b_{1,p} + S_{12}b_{2,p} \\
    S_{21}a_{1,p} + S_{22}a_{2,p} \\
    S_{21}b_{1,p} + S_{22}b_{2,p}
\end{bmatrix}
\end{align*}
\]

where \( a \) and \( b \) are incident / reflected components that are reconstructed using the least-square fitting in time domain, and \( p \) indicates the primary port (1 or 2) excited.
IV. EXPERIMENTAL RESULTS

A. Pulsed-IV characteristics

Fig. 10 shows the measured pulsed-IV and DC IV characteristics for the GaAs FET. It is clear that due to self-heating the DC IV characteristics include the negative drain conductance at high bias. Typically the FET used has a maximum thermal resistance \( R_{th} \) of 35°K/W, and the observed maximum temperature \( T_{dev} \) is 93°C for the gate-source voltage of 0V. But, on the other hand, the pulsed-IV characteristics bypass low-frequency dispersions as a result of traps and thermal effects.

Based on the pulsed-IV characteristics, a DC quiescent point with \( V_{ds} = 3V \) and \( I_{ds} = 350mA \) is used for S-parameter measurements.

B. Comparison of S-parameters

Fig. 11 compares the S-parameters obtained using four different methods:

1) Using only the center tone in the pulses.
2) Using the main lobe in the pulses, and by
   - applying a least-square fitting in frequency domain.
   - applying a least-square fitting in time domain.
3) Using a continuous wave for a single tone signal.

These data are all averaged over 5 consecutive measurements. As expected, the S-parameters obtained using center tones show bigger distortion due to the desensitization. The S-parameters given by the other methods are smooth functions of frequency because both for the continuous wave and for the pulse wave recreated from main spectrum lobe, the measurements use 100% and 90.3% of the average CW and peak pulse power, respectively. However, note that the DC IV
characteristics in Fig. 10 are submitted to strong low-frequency dispersion due to self-heating. To approximately compensate for this self-heating effect in the continuous wave measurement of the S-parameters, the gate voltage was arbitrarily adjusted (by about 0.2 V) to obtain the same DC drain current as in the pulsed-IV measurement. Fig. 11 also shows that the least-square fitting in time domain is better than the fitting in frequency domain. In addition, note that the small loops observed in $S_{22}$ in Fig. 11(b) are reproduced in 5 subsequent pulsed RF measurements. This reproducible feature indicates that these loops most likely arise either from the bias-tee deembedding or a residual calibration error.

To get satisfactory results from center tone extraction, one may need to increase the output power of the RF signal generator to compensate for the desensitized power at the risk of introducing non-linear effects (see self-biasing shift of load-lines in Fig. 10). Fig. 12 shows the S-parameters for two different RF input powers. As the RF input power increases, the S-parameters obtained from the center tone data are notably stabilized. But even the stabilized S-parameters for the RF power of 5dBm show more distortion than those extracted by least-square fitting in time-domain from the main lobe for an RF power of -10dBm.

It is verified in Fig. 13 that the S-parameters obtained by least-square fitting in time-domain show good consistency for a wide range of RF input power. This is largely due to the fact that the family of tones in the main lobe of the sinc spectrum provide enough energy to calculate accurate S-parameters. This measurement benefits also from the fact that the LSNA makes it possible to measure very small signals with power around -70dBm.

V. CONCLUSION

A pulsed-IV pulsed-RF measurement system using an LSNA is implemented to overcome the problem of desensitization. It is confirmed that by using a large number of tones in the spectrum one can reduce the noise compared to using the center tone only, yielding a more reliable small-signal measurement of the DUT. This measurement setup could also be easily modified for the acquisition of pulsed-RF S-parameters for pulsed-gate voltage to study trap effects in GaN devices. Finally this LSNA-based pulsed-RF system makes possible the acquisition of the pulsed-RF harmonic ($n\omega_0$) response of the device under various load terminations. In that regard such non-linear applications would follow in the footsteps of the work done at IRCOM [7] except that the measurement scheme used in our approach does not require any modification of the LSNA hardware.

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