Title	Modeling of high-speed, large-signal transistor switching transients from s-parameter measurements
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Citation	1981 International Electron Devices Meeting, 27: 608-611
Issue Date	1981
Type	Conference Paper
Text version	publisher
URL	http://hdl.handle.net/10119/4973
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Description	1981 International Electron Devices Meeting (IEDM 81)

MODELING OF HIGH-SPEED, LARGE-SIGNAL TRANSISTOR SWITCHING TRANSIENTS FROM S-PARAMETER MEASUREMENTS

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ABSTRACT

A new technique has been developed to derive the large-signal transient response of semiconductor devices from small-signal frequency response data. The large-signal switching response can be calculated for an arbitrary input signal voltage and risetime. This new technique utilizes the Fourier transformation to combine arrays of small-signal data to compute the response waveform.

The input waveform is decomposed into a superposition of small pulses. The response to each pulse is obtained by Fourier transformation techniques, using s-parameter data at appropriate bias points. The sum of these responses approximates the overall transient response. Simulations were performed for a GaAs MESFET for step inputs with the risetimes of 8 nsec and 150 psec. Good agreement was obtained between simulated waveforms and measured output waveforms in risetime, magnitude and waveform shape.

This algorithm is general and will work for other measured small-signal transfer parameters as a function of frequency and bias.

INTRODUCTION

Two methods dominate the measurement of semiconductor device high-speed characteristics. Frequency domain measurements such as s-parameters display complex, small-signal information. Time domain measurements capture large-signal switching risetimes, magnitudes and waveforms. The s-parameter measurements are generally employed for bipolar transistor and GaAs FET measurements in contrast to time domain techniques which are utilized in FET switching and ring oscillator measurements. For passive linear circuit elements the two measurement techniques yield the same information. This information can be converted from time domain to frequency domain and back through the Fourier transformation and inverse transformation.

On the other hand the reconciliation of active device information in the time and frequency domain poses a difficult and unsolved problem. A novel technique is presented which models active semiconductor device large-signal switching characteristics in the time domain using s-parameter data.

The major difficulty in reconciling the small-signal and switching transient characterization techniques for active devices is the fact that the s-parameter transfer response is bias dependent. As a device switches, it crosses a continuum of separate bias conditions with corresponding s-parameter frequency data. In order to produce a tractable analytical solution based on s-parameter data, the quasi-static mode must be assumed. This assumption is shown to be valid for the GaAs MESFETs studied.

The approximation technique which has been developed derives the large-signal transient response of semiconductor devices from s-parameters using multiple Fourier transformations. The algorithm employed is designed to be efficient and readily implementable on a fast desktop calculator or minicomputer.

S-PARAMETER MEASUREMENTS OF SEMICONDUCTOR DEVICES

At very high frequencies s-parameters may be the only practical characterization method available. Moreover, s-parameter data can be readily transformed into y, h and z-parameters. In the technique discussed here, the output response of a device to an input pulse of arbitrary risetime and magnitude is modeled using s_{21}. Fig. 1 illustrates the flow diagram and physical configuration for the measurement of s_{21} of a FET.

In the flow diagram, a_n is the complex incident signal voltage at port n, and b_n is the complex reflected signal voltage at port n :

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} = \frac{\Delta V_D}{\Delta V_G}$$

s_{21} is the output at port 2 divided by the input at port 1 when there is no incident signal at port 2. For the FET this is equivalent to the drain output signal divided by the gate input signal. Both incident and reflected signals depend on the system impedance, which means s_{21} is dependent on the system impedance. In this work, measurements were performed with the common system impedance of 50 Ω for both input and output.

DETAILS OF MODELING TECHNIQUE

In this section, the detailed modeling technique is described which simulates time domain waveforms in the

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non-linear region of transistors using s-parameter small-signal data. The input pulse waveform is approximated as shown in Fig. 2, that is, the input waveform is decomposed into n small pulses — each with a different delay time. To express the mathematical procedure, let $f'(t)$ be a simplified pulse function : $f'(t) = u(t) - u(t - t_f)$, a pulse with width t_f. Using the time-delayed forms of $f'(t)$, the large pulse waveform in Fig. 2 can be expressed as

$$f(t) = \sum_{i=1}^{n} \frac{A}{n} f'\left(t - \frac{i-1}{n} t_r\right)$$

where t_r is the total risetime and n is the number of discretized steps. The i-th delayed pulse $f'^{(i)} = f'\left(t - \frac{i-1}{n} t_r\right)$ is Fourier transformed into frequency domain to yield $F'^{(i)}(\omega)$, which is given by

$$F'^{(i)}(\omega) = F'(\omega) \exp\left(-j\omega \frac{i-1}{n} t_r\right)$$

where

$$F'(\omega) = \frac{1 - \exp(-j\omega t_f)}{j\omega} = t_f \mathrm{sinc}\left(\frac{\omega t_f}{2}\right) \exp\left(\frac{-j\omega t_f}{2}\right)$$

This $F'^{(i)}(\omega)$ is multiplied by $s_{21}^{(i)}(\omega)$, which is the measured s_{21} data at the corresponding bias level, giving the output function $G'^{(i)}(\omega) = F'^{(i)}(\omega) s_{21}^{(i)}(\omega)$. To make the meaning of this multiplication clear, $F'^{(1)}(\omega) = F'(\omega)$ and $s_{21}^{(1)}(\omega) = s_{21}(\omega)$ are schematically shown in Fig. 3. After the multiplication in the frequency domain, the output signal responding to this small delayed pulse $f'^{(i)}$ is calculated by the inverse Fourier transformation of $G'^{(i)}(\omega)$.

In order to calculate the response to a large pulse $f(t)$ in Fig. 2, which is no longer considered to be small-signal and in the linear region, the approximation algorithm illustrated in Fig. 4 is employed. The Fourier transformation $\frac{A}{n} F'^{(i)}(\omega)$ of each delayed small-signal pulse becomes a component in a vector $\overline{F}(\omega)$. A second vector $\overline{S_{21}}(\omega)$ is created using $s_{21}^{(i)}(\omega)$ as each component. A vector dot product is then taken to form $G(\omega) = \overline{F}(\omega) \bullet \overline{S_{21}}(\omega)$, which is a linear superposition in the frequency domain to obtain the output function of the non-linear system. This calculation assumes that the intrinsic pulse response of FET is fast enough to be considered as only bias dependent and not otherwise dependent on time over the region of simulation, — thus the FET must be operated in the quasi-static mode.

In order to facilitate the calculation, $G(\omega)$ is split into two parts; a rising step and a delayed falling step, both modified by s_{21} data. Both steps have the same mathematical formula $G_0(\omega)$ except for the t_f-delay factor. The output waveform $g(t)$ can be expressed as $g(t) = g_0(t) - g_0(t - t_f)$ where $g_0(t)$ is the inverse Fourier transformation of $G_0(\omega)$.

MEASUREMENTS FOR HIGH-SPEED DEVICES

Characteristics of GaAs MESFETs are measured using s_{21} obtained with the Stanford TECAP (1,2,3) automated measurement facility. The TECAP s-parameter software was modified to achieve enhancement of calibration and measurement accuracy and to adapt it to GaAs MESFET biasing capabilities.

The s-parameters are measured using a Hewlett-Packard (HP) 8505A network analyzer and a HP 8503A s-parameter test station. Bias voltages to the FET gate and drain are supplied by HP 6131C digital voltage sources. Time domain measurements are performed on a newly developed sub-nanosecond time domain measurement system. A pulse generator or tunnel diode pulser supplies a pulse to the gate of a GaAs MESFET and to one channel of a Tektronix Digital Processing Oscilloscope (DPO). A DC offset can be added to the gate waveform through a bias network. The resultant drain switching waveform is separated into its AC and DC components by another bias network and the AC signal enters the other DPO channel. A voltage source is added to the DC input of the second bias network to provide a drain bias. The DPO contains a waveform digitizer and semiconductor memory which enables it to record and store four different waveforms. The system has the capability to measure risetimes as short as 25 psec and to perform time domain reflectometry (4,5).

The HP 9845B desktop calculator provides measurement control through the IEEE-488 bus, as well as data storage and software for calibration. The calculator is also utilized as the computer for the modeling technique calculation.

IMPLEMENTATION OF APPROXIMATION TECHNIQUE

A matrix of s_{21} data must be measured across a range of useful device bias which is compatible with the frequency range of the network analyzer. The DC bias applied to the GaAs MESFET gate is varied from 0 to -2.5 volts ($\approx$ pinch-off voltage) in 0.25 volt steps. This range of DC biases traces a 50 Ω load-line across the family of gate voltage curves on an I_D vs V_{DS} graph. At each 0.25 voltage level, the s_{21}-parameters are measured at 25 frequency points across the 0.5 MHz to 1.3 GHz range of the network analyzer. With this frequency range, the fastest input risetime which may be simulated is 0.27 nsec. For the simulation of the response to faster input, s_{21} data above 1.3 GHz was extrapolated from measured data.

As is described in the previous section and in Fig. 4, a step approximation of the input waveform is made and segmented into as many pulses as considered to be enough to both express the input waveform as well as be consistent with the small-signal assumption in each segmented region. The Fourier transformation of each step is taken yielding a frequency band at each bias level. Frequency domain information of the input signal pulses forms a vector $\overline{F}(\omega) = (F_1(\omega), ...F_n(\omega))$ and the s_{21} data obtained at appropriate bias points creates a second vector $\overline{S_{21}}(\omega) = (s_{21}^{(1)}(\omega), ...s_{21}^{(n)}(\omega))$. The dot product of these two vectors results in the output function $G(\omega)$ in the frequency domain — the inverse Fourier transformation yields the output waveform $g(t)$.

The excellent agreement between the simulation based on s-parameter data and the measured switching response is displayed in Fig. 5. Here the calculated waveform is smooth while the measured waveform contains a small AC noise. The input waveform for this simulation is 8 nsec in risetime and −2.5 volts in magnitude. The simulated waveform displays a 4 nsec risetime and 3.4 volt swing while the measured waveform displays a 5 nsec risetime and 3.5 volt change in magnitude. The waveform shapes are approximately the same. A major cause of error in this match is the approximation of the input waveform by an ideal ramp function—the actual input waveform increases more gradually at the start and end of the transition, resulting in a slower risetime.

The waveform in Fig. 6 presents a switching response of a GaAs MESFET for the input of 150 psec in risetime and 0.21 volts in magnitude. This output waveform was simulated from only one input bias level of s_{21} data. The simulated waveform has a 170 psec risetime and a 0.5 V magnitude as opposed to the measured waveform with a 100 psec risetime, about 100 psec delay time and a 0.45 V magnitude. The agreement between the modeled waveform and measured waveform is acceptable. A major cause of error with this simulation is the extrapolation of s_{21} data to frequencies higher than 1.3 GHz. Thus the s_{21} data does not exhibit correct components at the highest frequency in simulation of the time domain waveforms.

DISCUSSION AND SUMMARY

The approximate modeling technique developed in this paper demonstrates good agreement between simulated and measured waveforms. The quasi-static approximation is applicable for GaAs MESFETs because these devices have intrinsic pulse response times on the order of ten of picoseconds (6,7). The modeling technique yields a reasonable result for FET switching behavior.

Many causes of error existed in this modeling exercise. The division of the input waveform into pulse steps and neglecting of the gradual changes of slope in a realizable switching waveform contributed to deviation in the simulation. The inability to measure s_{21} data above 1.3 GHz and the use of extrapolated data in this regime causes inaccuracy in the result for fast switching events. Limitations with time domain measurement equipment, especially the bias network bandwidth, gives incorrect measurements for pulses longer than 20 nsec.

On the other hand, despite many limitations for the highest frequency applications, the technique is extremely general. The measurements and modeling methods are applicable to FETs in general. S-parameters were employed because the highest frequencies available had to be measured in order to model GaAs. Other linear small-signal parameters that measure input to output gain can readily be substituted. Care must be taken to insure that the small-signal parameters are measured using the same impedances as the desired FET switching conditions to be simulated.

ACKNOWLEDGEMENTS

The authors would like to thank the various people and companies that contributed to this research with their support and funds. Ebrahim Khalily, Terry Walker and Robert Lefferts made significant contributions in providing assistance in the measurement facets of this work. The authors also wish to thank K.Kamei for the preparation of GaAs FETs. Hewlett-Packard and Tektronix are to be thanked for invaluable logistical and technical support of this research through industrial grants. Contract support in part from the Army Research Office contract DAAG29-80-K-0013 is gratefully acknowledged.

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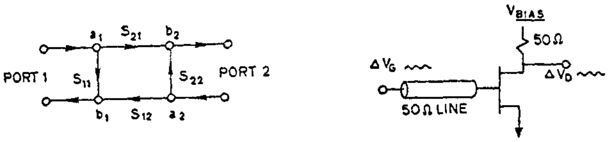
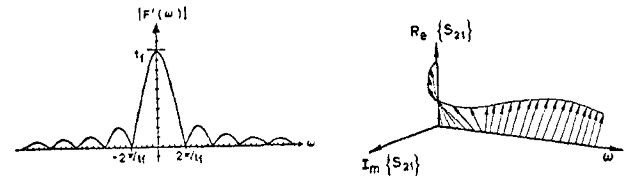


Fig. 1. S-parameter flow diagram and conceptual representation of FET s-parameter measurement.



a) $F'(\omega) = t_f\mathrm{sinc}(\frac{\omega t_f}{2})\exp\left(-j\frac{\omega t_f}{2}\right)$ b) Complex s_{21} data

Fig. 3. Conceptual representation of simplified pulse function and s-parameter data to be multiplied in the frequency domain to obtain an output function.

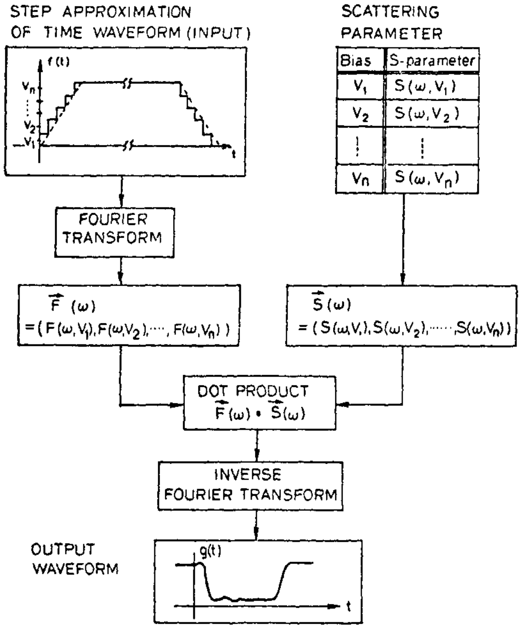
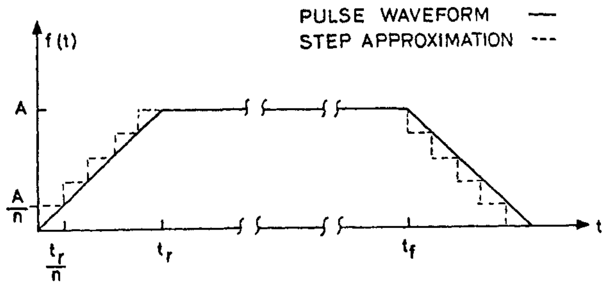


Fig. 4. Simulation procedure. An input switching pulse is segmented into voltage steps and Fourier transformed. The results are multiplied by s-parameters at appropriate voltages and summed. An inverse Fourier transformation yields the switching waveform.



$$f(t) = \frac{A}{n}\sum_{i=1}^{n}\left\{u\left(t-\frac{i-1}{n}t_r\right) - u\left(t-\frac{i-1}{n}t_r - t_f\right)\right\}$$

where

$$u(t) = \begin{cases} 1 & ; \quad t>0 \\ 0 & ; \quad t<0 \\ 1/2 & ; \quad t=0 \end{cases}$$

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\exp(-j\omega t)dt$$

Fig. 2. Approximation of input pulse waveform.

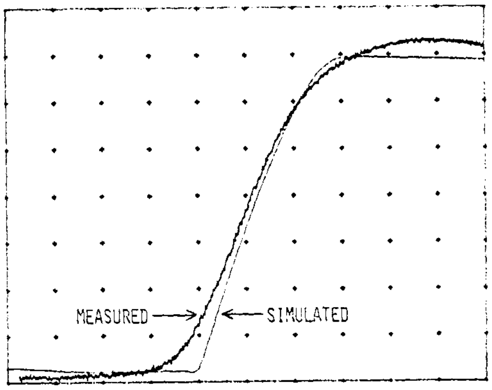


Fig. 5. Comparison of simulated and measured results of GaAs transistor switching for the input of 8 nsec risetime. (VERT: 0.5 V/div., HORIZ: 2 nsec/div.)

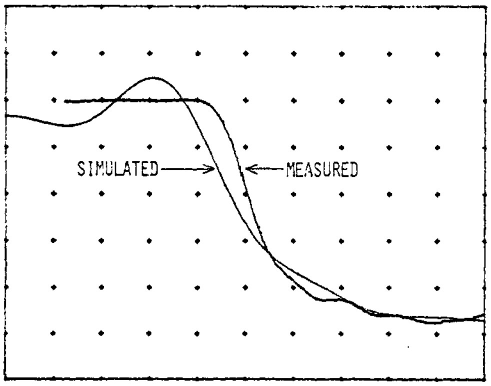


Fig. 6. Comparison of simulated and measured results of GaAs transistor switching for the input of 150 psec risetime. (VERT: 0.1 V/div., HORIZ: 100 psec/div.)