

# Agilent 4083A DC/RF Parametric Test System

A fully automatic on-wafer RF S-parameter measurement environment

Application Note 4080-2



## Introduction

The current telecommunications revolution rests upon myriad innovations in the electronics industry. In particular, advances in semiconductor fabrication technologies have had a strong impact due to continuous improvements in logic devices such as microprocessors, memories, etc. New high-speed digital technologies have also taken over many of the signal processing tasks traditionally performed by analog circuits. Moreover, not only computational but also wired and wireless communication technologies have been enhanced due to the demands of the telecommunications industry.

There are several interrelated forces driving the need for increased RF testing of semiconductor devices at the wafer level. Many devices (such as transistors) used in the telecommunications industry operate in the microwave or millimeter wave frequency ranges, and actual RF testing is the only way to guarantee their performance. In addition, as lithographies continue to shrink to 65 nm and below, transistor gate oxides can be 1.5 nm (or less) in thickness. These ultra-thin gate oxides are accompanied by extremely large leakage currents due to electron tunneling, making traditional capacitance versus voltage (CV) measurement at 100 kHz or 1 MHz impossible. The only way to overcome this leakage issue is to increase the CV measurement frequency to decrease the dissipation factor (D). Finally,

smaller lithographies are associated with increased variation not just across a wafer but even between adjacent devices. This requires the measurement of more samples in both the DC and RF regimes in order to get sufficient data to adequately characterize the process. Thus, not just DC current versus voltage (IV) and CV measurements but also RF S-parameter measurements are required to guarantee process integrity, extract device models, and characterize high-frequency behavior in modern semiconductor processes.

To meet these needs, Agilent Technologies has developed the 4083A DC/RF parametric test system. This application note highlights the features and benefits of the 4083A.



Agilent Technologies

## On-wafer RF S-parameter measurements in a fully automatic prober environment

Due to the importance of small-signal S-parameter network analysis for the reasons previously mentioned, semiconductor manufacturers have long desired the ability to make on-wafer S-parameter measurements in a fully automated production environment. While there have been some previous attempts to realize this goal with commercial products, all of them have had serious disadvantages. The Agilent 4083A DC/RF parametric test system has overcome these disadvantages and supports easy RF S-parameter measurement in a production environment. Each of the following sections describes a key advantage of this new solution.

## Well-proven Agilent PNA used for vector network measurements

The Agilent PNA series of vector network analyzers are well-accepted for on-wafer S-parameter measurement in the laboratory using manual and semi-auto wafer probers. Now this same capability is available in a fully automated production environment.

The Agilent PNA series of vector network analyzers have higher throughput and more stable and lower trace noise than previous generations of vector network analyzers (such as the Agilent 8720ES). The measurement cycle time is also four times faster, and the dynamic range is improved by about 15 dB at the test ports. Trace noise of 0.006 dB is achieved at 1 kHz of IF bandwidth.

## RF docking interface with blind-mate connectors supports automated test environments

Traditional manual and semiautomatic RF wafer probing environments required skill and training to make good RF contacts, since manipulation of xyz manipulators while viewing through a microscope was required. This was extremely tedious for the operator and required a lot of time, especially when using a manual prober that required realignment for each new die.

To solve this issue the 4083A utilizes an RF interface consisting of ten blind-mate RF connectors that accept an RF probe card. The RF probe card is designed to match the RF docking interface of 4083A as shown in Figures 1a and 1b. The blind-mate connectors eliminate the need for an operator to adjust the RF connec-

tors to a specified torque and allow proper RF connections to be made simply by docking the testhead to the prober. This solution also permits semiautomatic and fully automatic probe card changers to be used with the RF probe card, which has obvious advantages for production environments.

The Agilent 4083A supports RF probe card designs as shown in Figure 1b. This particular example shows Cascade Microtech's Pyramid Probe™ card design for RF measurement on the 4083A. Once the probe card is set on the probe card tray, an operator can easily dock it to the RF docking interface by pressing buttons shown on the operator console.

The probe tips and probing pads are recognized by the cameras in the prober, and the wafer prober can automatically move from one die to the next after receiving commands from the test system controller.



Figure 1a. The 4083A RF docking interface

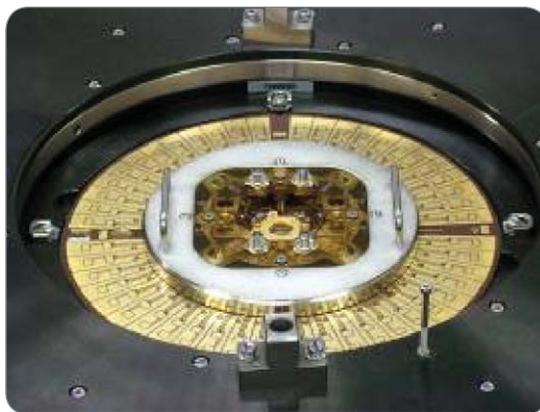


Figure 1b. Probe card with RF female connectors (supplied courtesy of Cascade Microtech, Inc.).

## Tight integration of network analyzer with testhead improves performance and serviceability

Maintaining a short distance between the network analyzer and the probe tips is essential to minimize signal loss and obtain accurate and stable S-parameter measurements. To achieve this, a manipulator extension shelf is attached to the side of testhead manipulator as shown in Figure 2. This allows the network analyzer to be mounted adjacent to the test head.

Besides improving measurement quality, this arrangement also improves serviceability since it is not necessary to remove the RF cables from the network analyzer when inverting the test head for maintenance.

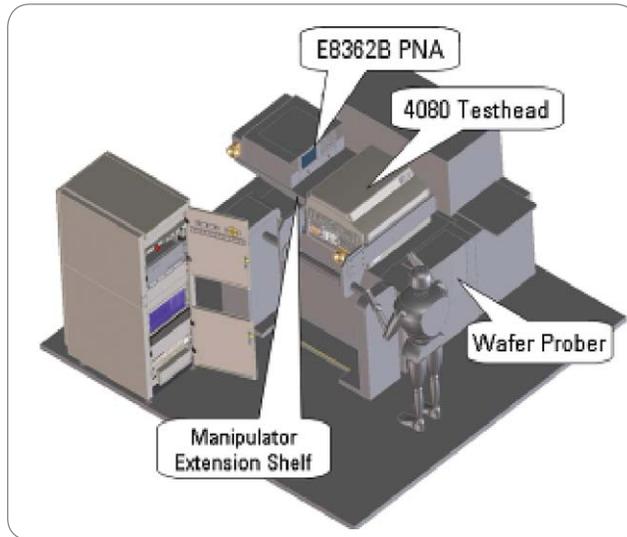


Figure 2. Illustration showing 4083A manipulator extension shelf.

## RF switching matrix option increases probe card life

Two 4x5 RF switching matrices are an available option. The RF switching matrices permit the probing of multiple RF structures in a single touchdown, which can reduce probe card wear-and-tear and result in a longer probe card life.

For example, suppose that there are five pairs of GSG-GSG probe tips arranged face-to-face as shown in Figure 3a. If the test structures (including the open and short dummy structures) are arranged as shown in Figure 3b, then a single touchdown can probe five devices. Arranging the open, short, and MOSFET structures as shown permits everything to be measured with only two touchdowns, which results in a longer probe card life.

Note that the total measurement throughput may not be improved, because S-parameter measurements take longer to make than does indexing the wafer prober. Also the RF performance may be degraded relative to a direct RF connection due to insertion losses and the longer signal paths inside the RF switching matrices.

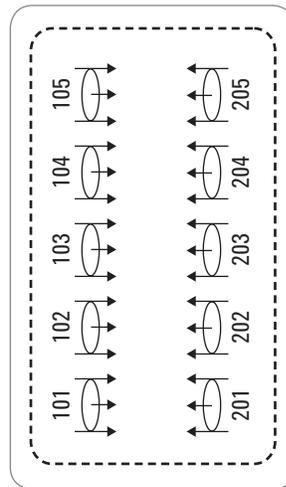


Figure 3a. Probe tip configuration.

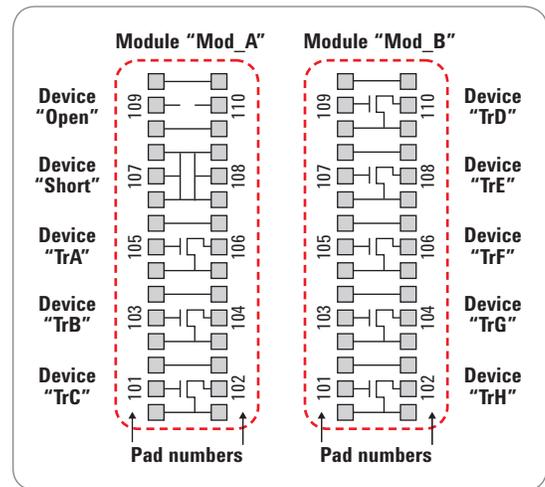


Figure 3b. Example pad layouts for performing multiple RF measurements in a single touchdown when using the 4x5 RF switching matrix option.

## RF S-parameter measurement supported in TIS commands

Just like traditional DC and CV resources, test instruction set (TIS) commands are available to control RF S-parameter resources such as the PNA and its bias sources. Users already familiar with the TIS commands of the 4062 and 4070 series testers will find the programming environment both familiar and intuitive. For example, to set the bias source for a network analyzer the 'Force\_v()' subprogram or function is used. The 'Rfs\_set\_s()' subprogram or function is used to set the stimulus in the network analyzer, and the 'Rfs\_measure\_s2()' subprogram or function triggers and retrieves the two-port S-parameter measurement results. Please refer to Figures 4a and 4b.

```
#include <tis.h>

int pn1 = 102, pn2 = 202;
double freq[201]
COMPLEX s11[201], s21[201], s12[201], s22[201];

connect_pin( RFU11, pn1 );
connect_pin( RFU12, pn2 );
sync_th(0.02);

force_v( RFU11, 0.8, 0.0, 0.01;
force_v( RFU12, 1.8, 0.0, 0.1;

rfs_set_s( pn1, LINEAR_F, 1.0e+7, 2.0e+10, 201, -20.0, 200.0 );

rfs_measure_s2( pn1, pn2, freq, s11, s21, s12, s22, DEMB_OFF );
```

Figure 4a. C/ANSI C TIS commands to perform RF S-parameter measurement

```
OPTION BASE 1
INTEGER Pn1,Pn2
REAL Freq(201)
COMPLEX s11(201),s21(201),s12(201),s22(201)
!
Pn1=105
Pn2=205
!
Connect(FNPort(6,11,Pn1)
Connect(FNPort(6,12,Pn2)
Sync_th(0.02)
!
Force_v(FNPort(6,11),0.8,0.0,0.01)
Force_v(FNPort(6,12),1.8,0.0,0.1)
!
Rfs_set_s(Pn1,1,1.0E+7,2.0E+10,201,-20.0,200.0)
!
Rfs_measure_s2(Pn1,Pn2,Freq(*),s11(*),s21(*),s12(*),s22(*),0)
```

Figure 4b. BASIC/UX TIS commands to perform RF S-parameter measurement.

## Automated calibration procedure with ISS adapter disk

Calibration can be automatically performed on fully-automatic wafer probers using an impedance standard substrate (ISS). The ISS can be placed on the groove of the adapter disk, which is set in the inspection tray of the full-automatic prober as shown in Figure 5, and it can be loaded and aligned on the wafer chuck for probing. S-parameter measurements are executed by moving to the locations of the calibration standards on the ISS, which in-turn permits the calibration coefficients to be calculated. This is a vast improvement over semiautomatic and manual wafer probing environments, where an expert is needed to perform the RF calibration procedure.



Figure 5a. Using an impedance standard substrate (ISS) on an adapter disk in an automated wafer prober.



Figure 5b. Close-up of the ISS on the adapter disk.

## Production-capable RF probe cards

High performance RF probe cards contribute to the ease-of-use of the 4083A fully automatic RF S-parameter measurement solution. Although DC probe card design is relatively easy, the design of an RF probe card requires an understanding of the distributed element characteristics of the transmission lines on the probe card, and these depend upon a variety of factors such as the insulation materials used, the shape of the conductive materials, etc. As of December 2007, two vendors, Cascade Microtech Inc. and GGB Industries, Inc., can provide RF probe cards for the 4083A system as shown in Figure 6.

Probe cards from both of these companies have RF probe tips as well as DC probe tips. The RF signal is routed via SMA-compatible RF connectors on the probe card, and these RF connectors are docked with RF blind-mate connectors on the testhead side as mentioned previously. Of course, in addition to the RF connections contact with the testhead pogo pins is also made at the same time.



Figure 6a. The Cascade Microtech, Inc. Pyramid Probe card for the 4083A RF docking interface

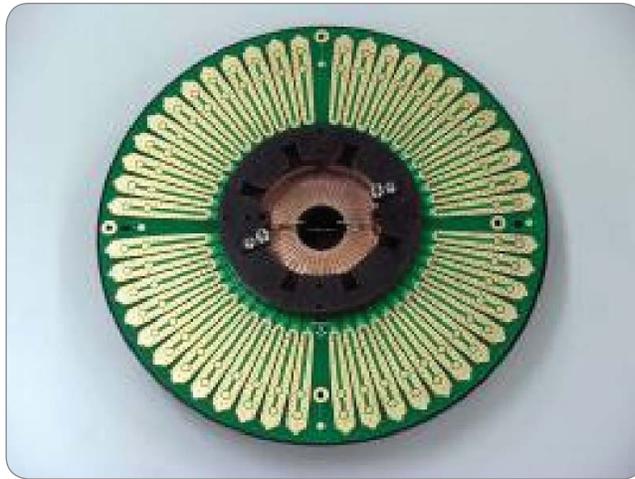


Figure 6b. The GGB Industries, Inc. Picoprobe probe card for the 4083A RF docking interface

## Easy operation of S-parameter measurements with interactive debug panel (IDP)

The 4080 system software interactive debug panel (IDP) supports not only DC and CV measurement resources, but also S-parameter measurement resource just as if a virtual network analyzer existed in the Linux environment. The stimulus settings can be entered through a series of fill-in-the-blank menus. After an S-parameter measurement is executed the measurement results can be displayed in a variety of graphical formats such as LogMag, Phase, Smith-chart, Admittance-chart, etc.

Figure 7 shows the IDP panel for entering the stimulus settings for an S-parameter measurement and the measurement results plotted on Smith charts. The available fields are sweep type (linear or logarithmic), start and stop frequencies, number of points, output power, IF bandwidth, and averaging factor. Besides setting these parameters, you also must select measurement ports and, if the RF switching matrix option is present, specify the RF port to pin connections. A simple click of the "Execute" button then starts the frequency sweep and executes the S-parameter measurement.

Once completed, a window named "RF Graph" appears to display the S-parameters in graphical format. As mentioned above, you have a wide selection of plotting options from which to choose.

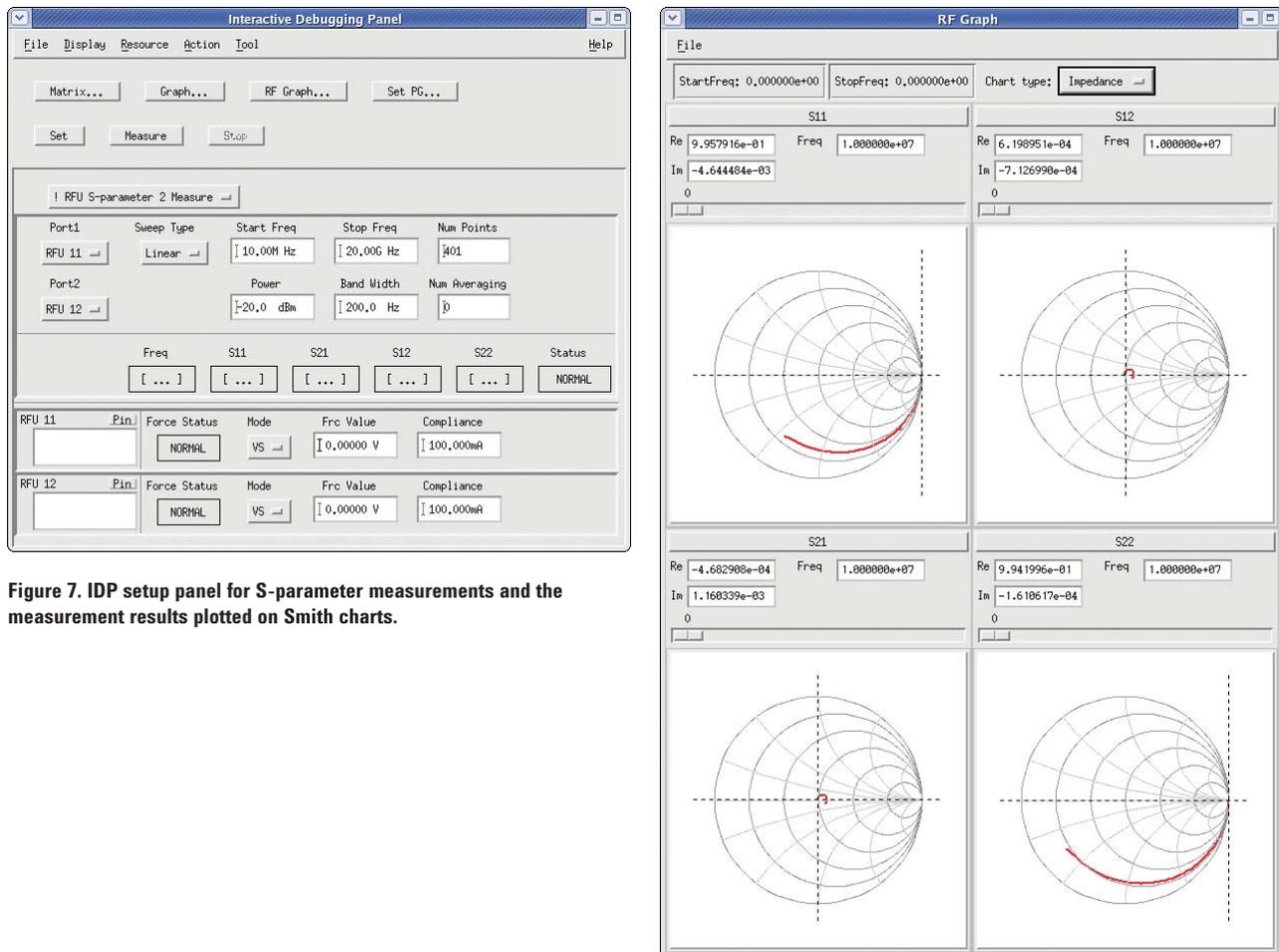


Figure 7. IDP setup panel for S-parameter measurements and the measurement results plotted on Smith charts.

## RFCV measurements

In addition to supporting 1-port and 2-port S-parameter measurements, the IDP can also automatically extract CV curves from the measured S-parameters. This can be done by selecting the “RFU CGV Sweep Measure” measurement item in the IDP menu. Figure 8 shows a sample IDP panel for defining an RFU CGV sweep measurement and a plot of the measurement results.

The stimulus settings and RF port to pin connections (optional) are the same as for a standard S-parameter measurement. However, additional measurement items allow you to specify bias voltage settings for the CV sweep and to return capacitance values calculated from the measured S-parameters. Once the RFCV measurement completes, an X-Y graph appears and displays the CV graph.

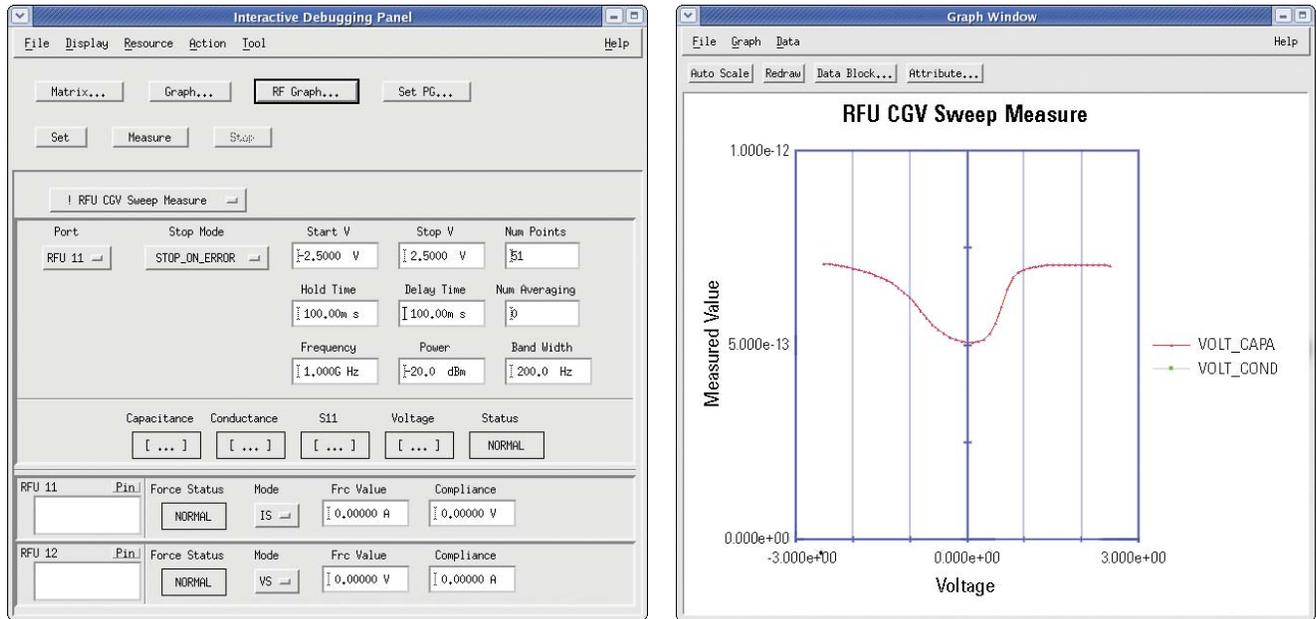


Figure 8. IDP setup panel for CG versus V measurements and the measurement results.

## Statistical RF parameter data analysis

The Agilent SPECS (Semiconductor Process Evaluation Core Software) test shell can be used with the Agilent 4083A for test plan and data management. This section will give an overview of SPECS data management capabilities and show an example of RF parameter data management.

In the SPECS environment a test consists of wafer, die, probe and test specifications. Measured data is stored in the ADT format along with the following information:

- Raw measured data (spot and swept).
- Statistical data such as average and standard deviation.
- Bin data and yield information for lot, wafer, and die.

The “Quick Query” (quick\_q) data management tool provides both data viewing and data filtering capabilities

In the selection field, you can select a target ADT-formatted file by highlighting a filename and by clicking the “Open” button as shown in Figure 9. Once a target ADT file is selected, you can perform the following operations:

- Convert data into spreadsheet compatible format
- Generate spot data statistical information
- Generate sweep data X-Y graphs
- Create wafer maps from spot data

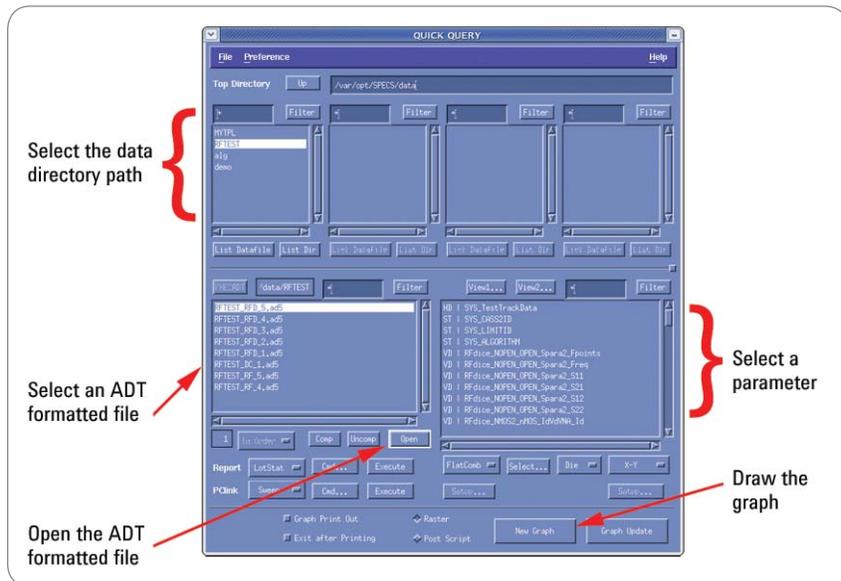


Figure 9. Using the SPECS quick query features to perform data analysis.

Figures 10a, 10b, and 10c illustrate some of the various ways in which data can be displayed using the Quick Query feature.

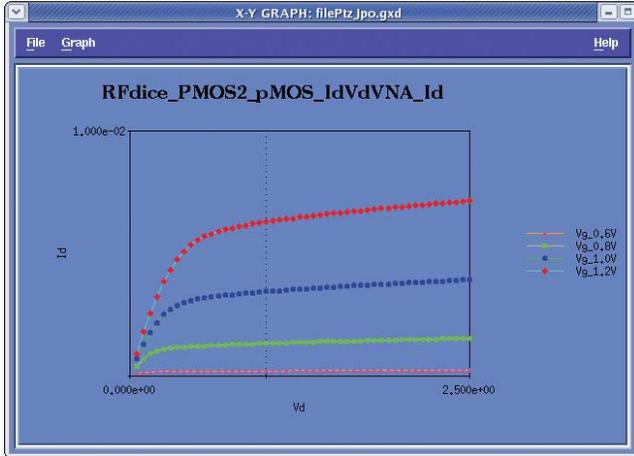


Figure 10a. Id-Vd plots made through bias tees.

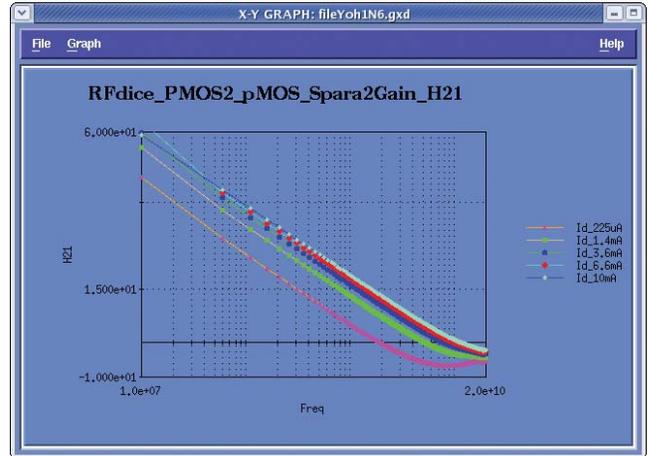


Figure 10b. H21 current gain versus frequency curves (calculated from the S-parameters).

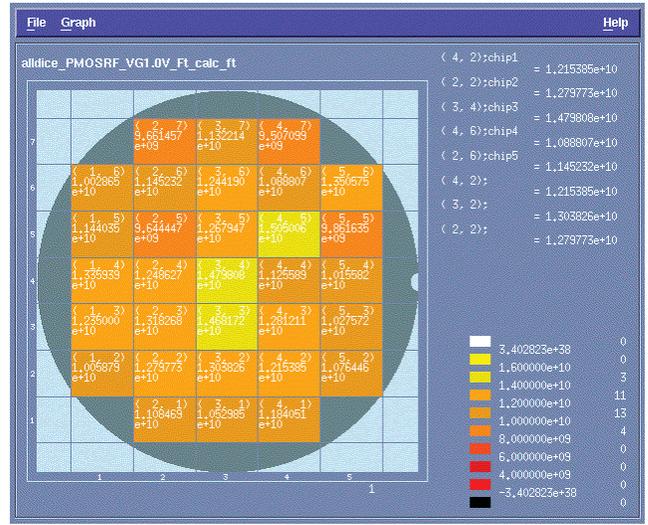
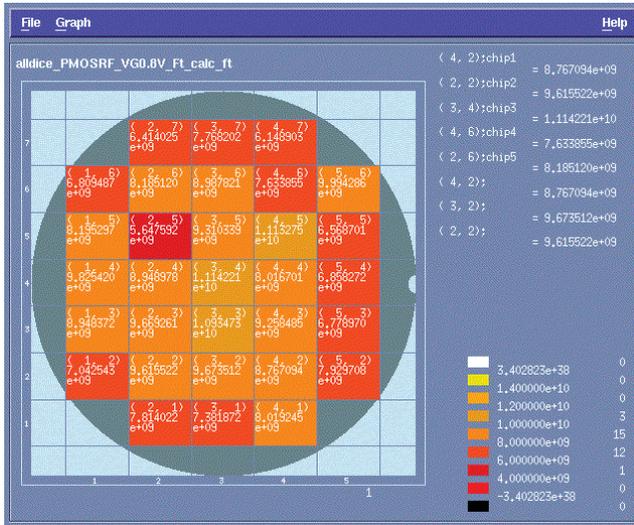


Figure 10c. Wafer map  $f_1$  plotted at two different bias conditions.

It is very easy to convert data into a format that can be imported into a spreadsheet. You only need to select “Sweep” in the PC-link area; a CSV text file is then generated in the /var/opt/SPECS/pclink directory. You can copy this CSV formatted file to your PC and import it into a spreadsheet tool such as Microsoft Excel for data processing.

For example, when you convert the ADT-formatted data to draw graphs with a spreadsheet application, highlight an ADT file, click “Open,” select “Sweep” in the “PClink” row, then click “Execute” button. A file starting with the ADT filename is created in the /var/opt/SPECS/pclink directory. This file is tab separated two-dimensional file, so you can load it into a spreadsheet application as a text file. Please refer to Figure 11.

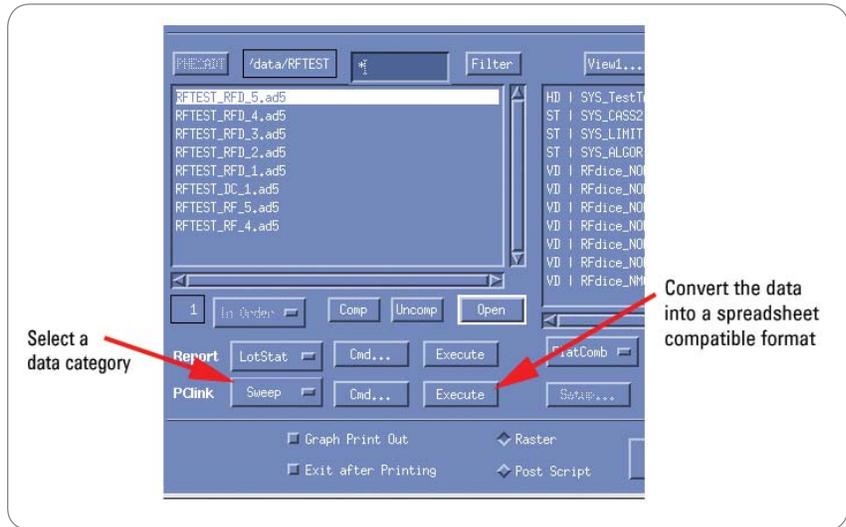


Figure 11. Converting data into a spreadsheet compatible format using Quick Query.

## Summary

This application note has reviewed some of the typical applications of RF S-parameter measurements, which are required to characterize state-of-the-art semiconductor processes and advanced device technologies. The Agilent 4083A DC/RF parametric test system meets these needs by providing not only DC IV and CV but also RF S-parameter measurement capabilities in a fully automated wafer probing parametric measurement environment. The Agilent SPECS test shell can also be used with the 4083A for test plan and data management.



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