Evaluation of the Surface State Using Charge Pumping Methods

Application Note 4156-9

Agilent 4155C/4156C Semiconductor Parameter Analyzer

Introduction

As device features get smaller, hot carrier induced degradation of MOSFET devices is likely to occur. To make more reliable ULSI devices, it is critical to understand this degradation mechanism. One way is the charge pumping method, which is a measurement technique that can evaluate the surface-states at the Si-SiO2 interface of MOSFET devices. This application note gives an example of evaluating the interface-states by using the Agilent 4155C/4156C to perform pumping method.

Three Methods of Charge Pumping

Charge pumping is one of the measurement methods that extracts Si-SiO2 interface-state density and captures cross section of MOSFET devices.

Figure 1 shows the measurement circuit diagram of charge pumping. The gate of MOSFET is connected to a pulse generator, and a reverse bias (Vr) is applied to the source and drain, while the substrate current is measured. This current is caused by the repetitive recombination at the interface traps of minority carriers with majority carriers, when the gate pulses the channel between inversion and accumulation.

There are three different charge pumping methods that are commonly used today. This application note covers the following methods:

Square Pulse Method

The square pulse method applies a fixed-shaped pulse to the gate. The base of the pulse is stepped from well below gate threshold to well above. At each step, the substrate leakage current is monitored. The flat part of the resultant curve is proportional to interface-state density.

Triangular Pulse Method

The triangle pulse method applies a constant height triangle wave to the gate. The frequency is increased in steps, each time measuring the resultant substrate leakage current. The average interface-state density and capture cross section are easily measured by this method.

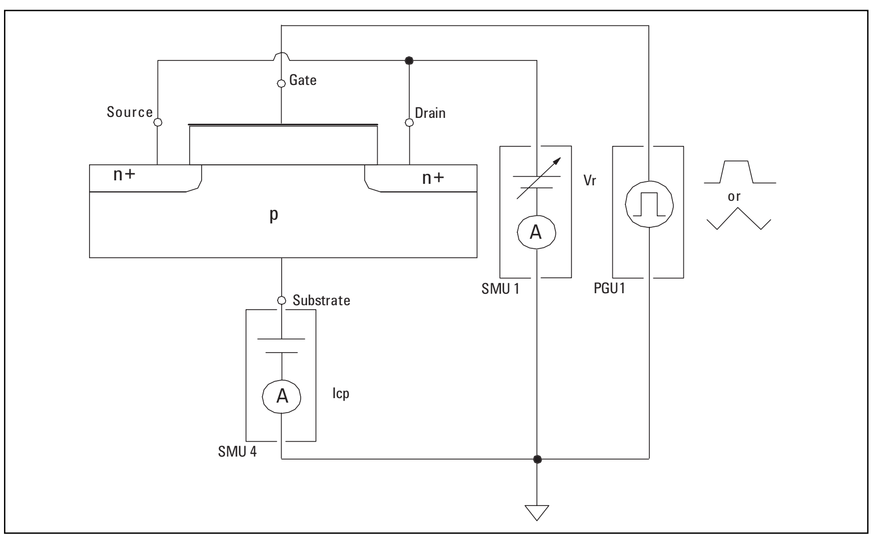

Figure 1. Measurement Circuit Diagram

Trapezoidal Pulse Method

The trapezoidal pulse method applies fixed height pulse to the gate. By varying the leading/trailing time of the pulse, you can plot interface-state density vs energy.

Problems with the Charge Pumping Method

To apply pulse bias to the gate, a pulse generator is used. The pulse voltages, frequency, width, leading time, and trailing time should be swept. While sweeping these parameters, the charge pumping currents (Icp) through the substrate are measured. The mean interface-state density and capture cross section are extracted by drawing Icp vs pulse base curve or by drawing a least-squares fit line for recombined charge calculated from Icp vs pulse frequency curve. The following are typical problems for this method:

- Interconnection between measurement instruments and pulse generator is complicated. Space for the external controller is also required.
- Programming to control the measurement instruments (especially to control the pulse voltages or timing) is complicated, and debugging takes a long time.
- Programming for graphics plot, data analysis, and calculation of the mean interface-state density and capture cross section is very complicated.

The Agilent 4155C/4156C Solution

The 4155C/4156C includes the SMUs to accurately measure the charge pumping current. As an option, you can add the Agilent 41501B, which is an expander that can contain SMUs and two pulse generator channels (PGUs). This expander solves the problem of complicated interconnection between the measurement instruments and pulse generator.

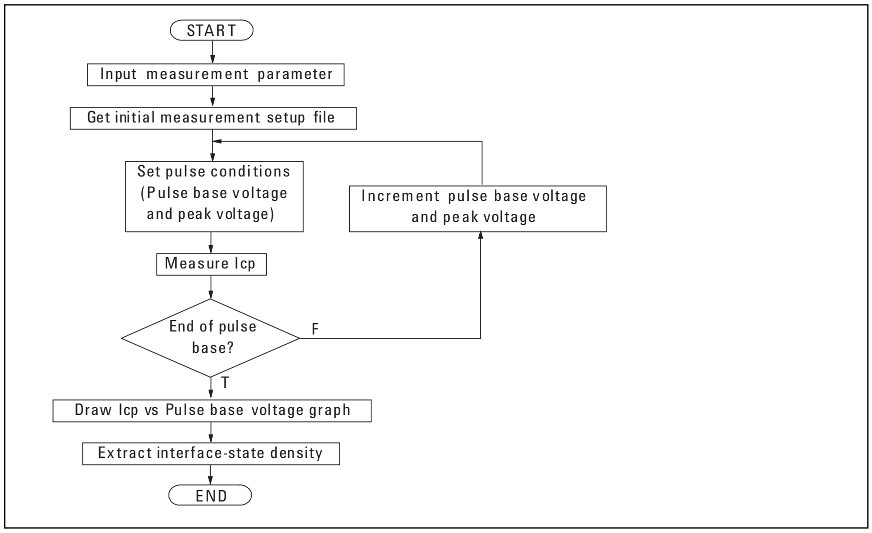

Figure 2. Flowchart of Square Pulse Method

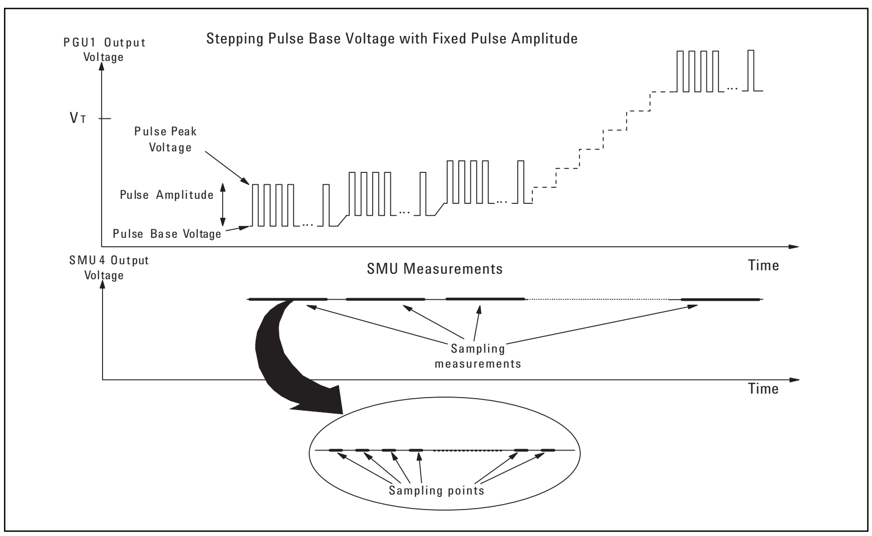

Figure 3. Timing Chart of Square Pulse Method

The PGU can be controlled as one of the modules of the 4155C/4156C. This solves the problem of complicated programming to control measurement instruments and pulse generators. Using the front panel of the 4155C/4156C, you can easily set the pulse parameters, such as pulse peak and base voltage, pulse period, pulse width, leading time, and trailing time in fill-in-the-blank manner. You can save the setup to a diskette.

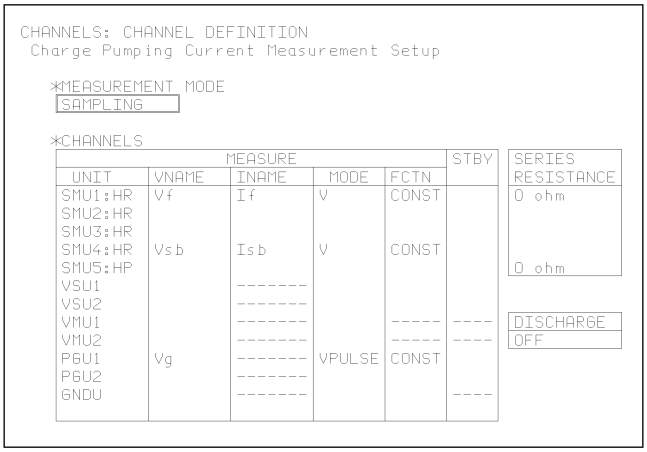

Figure 4. CHANNELS: CHANNEL DEFINITION Page

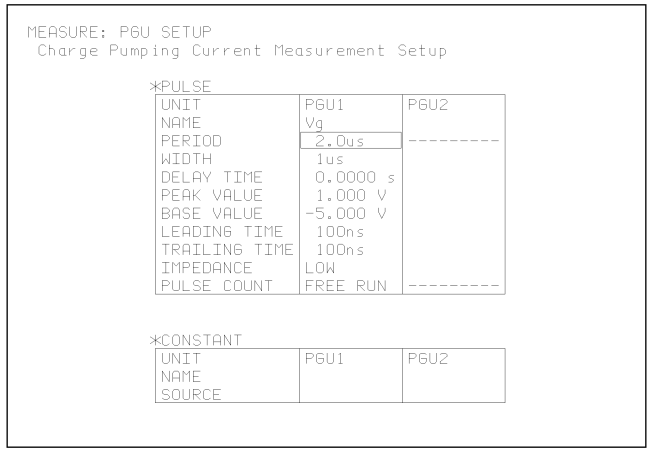

Figure 5. MEASURE: PGU SETUP Page

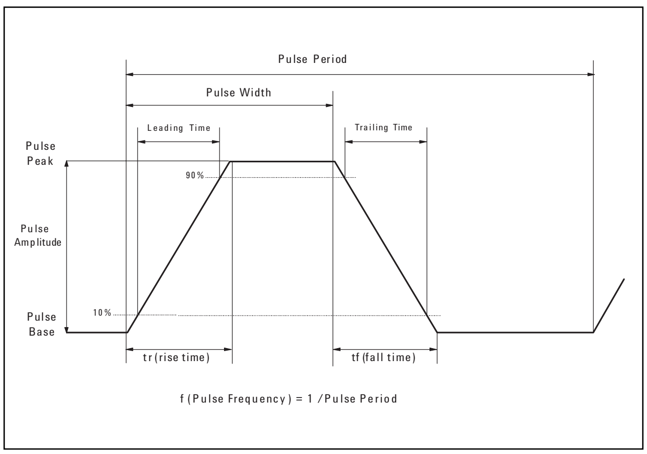

Figure 6. Definition of Square Pulse Setup Parameters

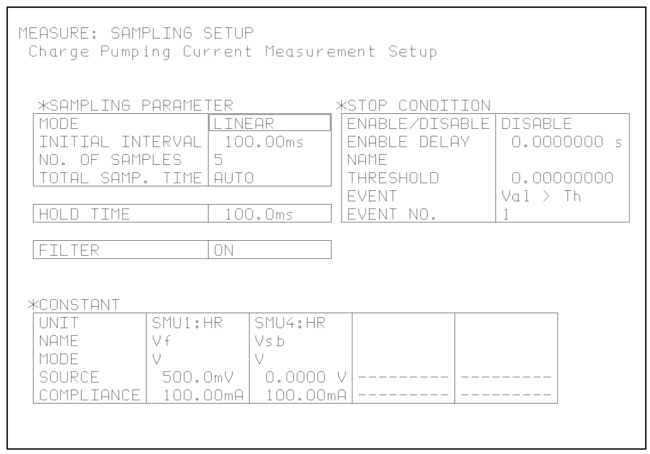

Figure 7. MEASURE: SAMPLING SETUP Page

The 4155C/4156C features a built-in IBASIC controller, which allows you to automate the entire test and control the modules of the Agilent 4155C/4156C. No external computer is required.

The IBASIC program can get the setup files from the diskette and perform the test. This simplifies programming, and also enables you to easily debug the setup. Just get the setup file and execute measurements manually. And you can check the pulse signal using an oscilloscope.

You can use the graphics page to display the data of several measurements, and to use the analysis functions, such as regression line. So, you do not need to create programs to draw graphs and analyze data.

Procedure for Measurement of Interface-state Density Using Square Pulse Method

The flowchart for the test to extract interface-state density (Nss) by using the Agilent 4155C/4156C is shown in Figure 2. The entire test is performed by the IBASIC program according to the timing chart of this test shown in Figure 3.

Figure 4 shows the CHANNELS: CHANNEL DEFINITION page on which the measurement units are defined for the circuit diagram of Figure 1.

Figure 5 shows the MEASURE: PGU SETUP page on which the pulse conditions are set. In this page, the pulse period, width, leading time, and trailing time are defined. For the definition of these parameters, refer to Figure 6.

The IBASIC program steps the pulse base voltage from well below threshold voltage to well above, as shown in Figure 3. The pulse amplitude is fixed. At each step, the substrate current is measured by sampling. The MEASURE: SAMPLING SETUP page is shown in Figure 7. The charge pumping current (Icp) for each pulse base voltage is the maximum sampling measurement result for the step.

The measurement setup should be saved to diskette file before executing the test. The setup file is loaded by the IBASIC program.

As the test result, the “Icp vs pulse base voltage” curve is drawn and Nss is extracted from the maximum Icp.

The Icp is given by equation (1).

$$\begin{aligned} Icp &= f\ Qss \\ &= f\ Ag\ q^2\ \overline{Dit}\ \Delta\psi_s \\ &= f\ Ag\ q\ Nss \qquad (1) \end{aligned}$$

Nss is expressed as equation (2).

$$Nss = Icp/f\ Ag\ q \qquad (2)$$

Where,

- Qss: recombined charge per pulse period
- f: pulse frequency
- Ag: channel area of the transistor
- q: electron charge
- $\Delta\psi_s$: total sweep of the interface potential
- $\overline{Dit}$: mean interface-state density, averaged over the energy levels swept through the Fermi level (cm-2 eV-1)

Figure 8. shows a measurement example of Nss.

Procedure for Measurement of Mean Interface-state Density and Capture Cross Section Using Triangle Pulse Method

The flowchart for the test to evaluate mean interface-state density (Dit) and capture cross section(s) is shown in Figure 9. The timing chart for this test is shown in Figure 10. The frequency of the triangular pulse is swept, and the substrate currents are measured by sampling. The charge pumping current (Icp) for each frequency is the maximum sampling measurement result for the frequency.

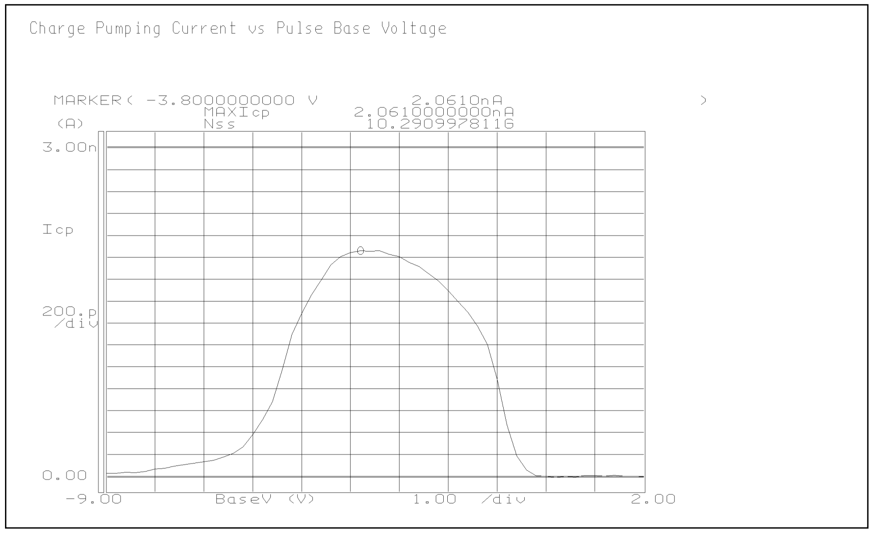

Figure 8. Square Pulse Method Nss Measurement Result

Figure 11 shows the MEASURE: PGU SETUP page on which the pulse conditions are set. The IBASIC program calculates and sets the pulse period, width, leading time, and trailing time according to the pulse frequency. The leading time and trailing time are equal so that applied pulses are triangular pulses. Figure 12 shows the definition of triangle pulse setup parameters.

For the test result, $\overline{Dit}$ and s are extracted by drawing a regression line for the “recombined charge (Qss) vs pulse frequency (f)” curve on a linear-log graph.

The recombined charge (Qss) per pulse period is calculated by equation (3).

$$Icp = f\ Qss \qquad (3)$$

When using triangular pulses, Qss can also be calculated by equation (4):

$$Qss = 2q\ \overline{Dit}\ Ag\ kT\ [\ln(\upsilon_{th}\ n_i\ \sqrt{\sigma_n\ \sigma_p}) + \ln(\frac{|V_{FB} - V_T|\ 1}{|V_{GH} - V_{GL}|\ f}\sqrt{\alpha(1-\alpha)})] \qquad (4)$$

On the “Qss vs f” curve, the pulse frequency f0 (frequency when the charge becomes zero) is the X-intercept of the regression line. Frequency f0 is used to calculate the geometric mean of the capture cross sections as shown in equation (5):

$$\sigma = \sqrt{\sigma_n\ \sigma_p} = \frac{1\ |V_{GH} - V_{GL}|\ f_0}{\upsilon_{th}\ n_i\ |V_{FB} - V_T|\ \sqrt{\alpha(1-\alpha)}} \qquad (5)$$

And the slope of the regression line is used to calculate the interface-state density $\overline{Dit}$ as shown in equation (6).

$$\text{Slope} = \frac{d\ Qss}{d \log f} = \frac{2qkT\ \overline{Dit}}{\log e}\ Ag \qquad (6)$$

Where,

σ_n: capture cross section of electrons
σ_p: capture cross section of holes
υ_{th}: thermal velocity of the carriers
V_{GH}: peak voltage value of the pulse
V_{GL}: base voltage value of the pulse
V_{FB}: flat band voltage
V_T: threshold voltage of the transistor
t_r: rise time of the pulse
t_f: fall time of the pulse
f_0: pulse frequency at which the charge becomes zero.
n_i: intrinsic carrier concentration
α: $t_r/(t_r+t_f)$

Figure 13 shows a measurement example of $\overline{Dit}$ and s. The X-axis intercept of the regression line is f_0, and slope of the regression line is used to calculate $\overline{Dit}$.

By using the graphics screen and analysis capability of Agilent 4155C/4156C, you can obtain mean interface-state density $\overline{Dit}$ and capture cross section easily with minimum programming.

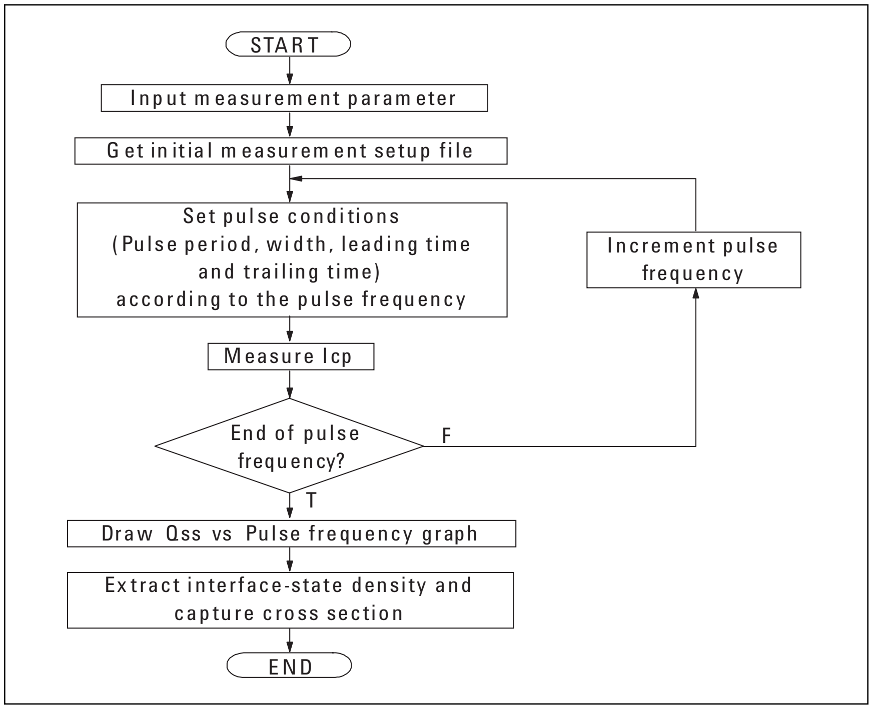

Figure 9. Flowchart of Triangle Pulse Method

Procedure for Measuring the Energy Distribution of Surface States Using Trapezoidal Pulse Method

The flowchart for the test to evaluate the energy distribution of interface-states by using the Agilent 4155C/4156C is shown in Figure 14.

This is similar to the triangle pulse method. First, Icp is measured while sweeping the pulse trailing time with constant pulse leading time. Then, Icp is measured while sweeping the pulse leading time with constant pulse

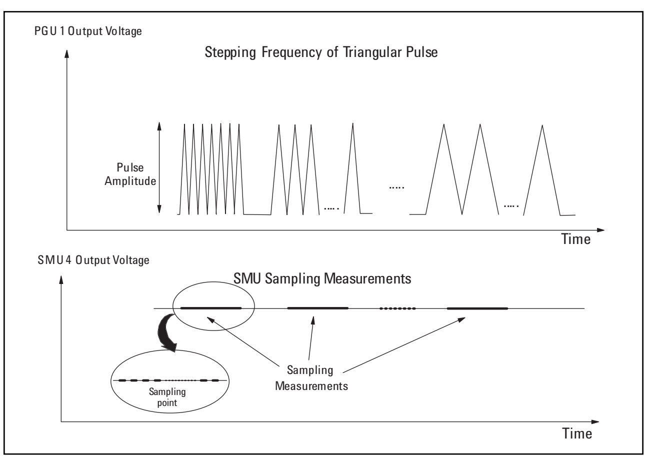

Figure 10. Timing Chart of Triangle Pulse Method

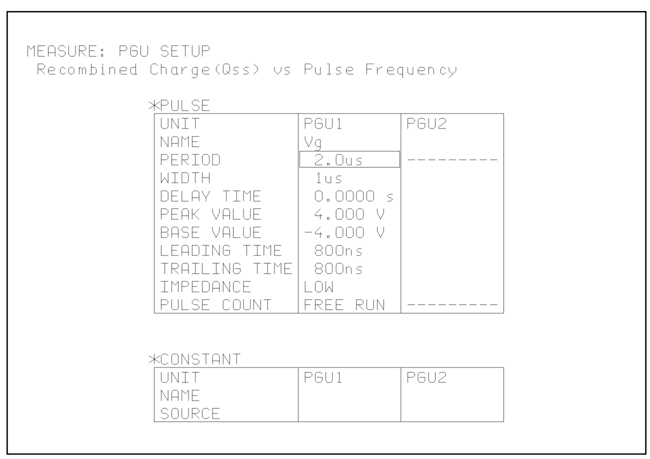

Figure 11. MEASURE: PGU SETUP Page

trailing time. Figure 15 shows the timing chart for this test. Applied pulses are trapezoidal pulses.

The energy distribution of interface-states is obtained by the follow equations (7), (8), (9), and (10):

$$\mathrm{Dit\ (E2)} = -\frac{\mathrm{tr}}{\mathrm{q\ Ag\ k\ T}\,f}\ \frac{d\,\mathrm{Icp}}{d\,\mathrm{t_f}} \qquad (7)$$

$$\mathrm{E2 = E1 - kT\ ln}\left(\upsilon_{th}\,\sigma_p\,n_i\ \frac{|V_{FB}-V_T|}{|V_{GH}-V_{GL}|}\,t_f\right) \qquad (8)$$

$$\mathrm{Dit\ (E1)} = -\frac{\mathrm{t_r}}{\mathrm{q\ Ag\ k\ T}\,f}\ \frac{d\,\mathrm{Icp}}{d\,\mathrm{t_r}} \qquad (9)$$

$$\mathrm{E1 = Ei - kT\ ln}\left(\upsilon_{th}\,\sigma_n\,n_i\ \frac{|V_{FB}-V_T|}{|V_{GH}-V_{GL}|}\,t_r\right) \qquad (10)$$

Where,

Dit: interface state density at energy E
E1 (E2): Boundaries of the energy range that is scanned
Ei: Intrinsic Fermi-level

Figure 16 shows a measurement example for energy distribution of interface-states.

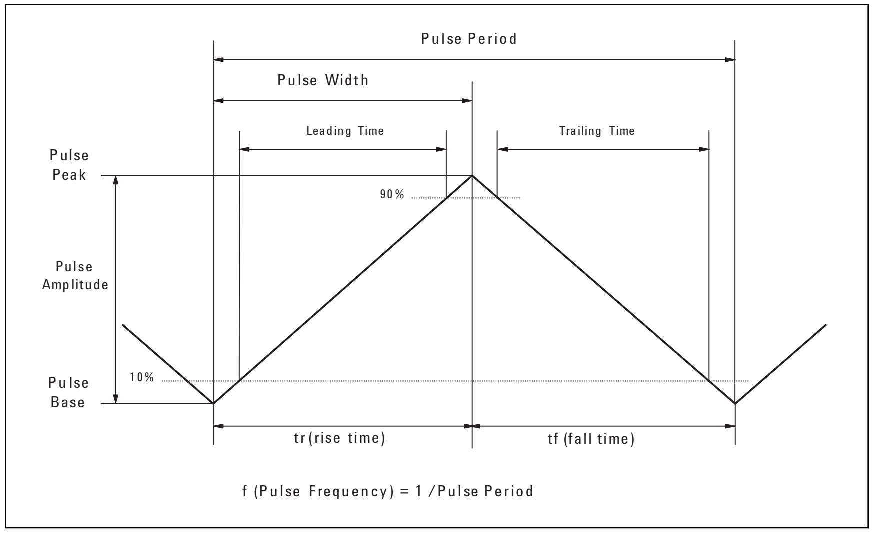

Figure 12. Definition of Triangle Pulse Setup Parameters

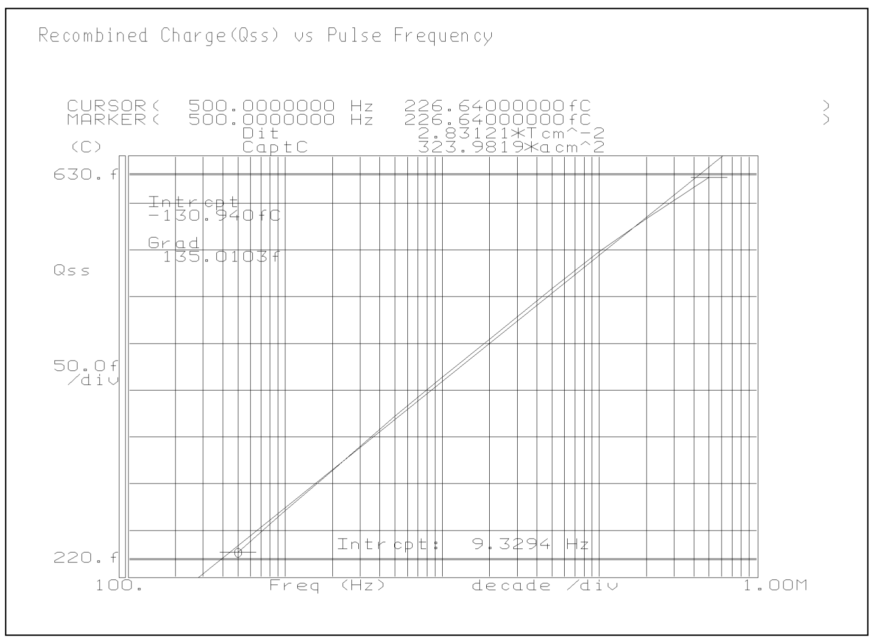

Figure 13. Measurement Result

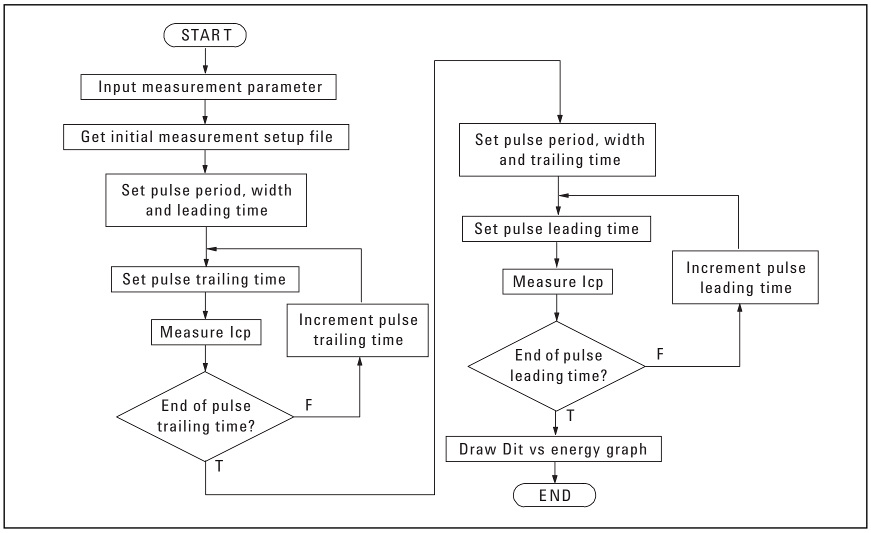

Figure 14. Flowchart of Trapezoidal Pulse Method

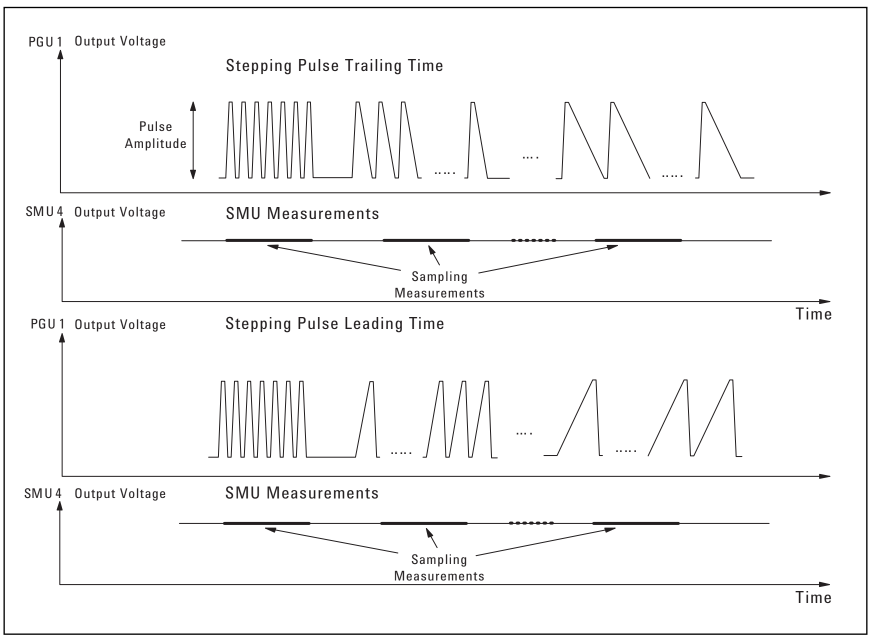

Figure 15. Timing Chart of Trapezoidal Pulse Method

Conclusion

By using the Agilent 4155C/4156C with its PGU options and Agilent 16440A, you can easily configure a small and inexpensive system to perform flash memory cell evaluation. The control of this system can easily be done by using previously saved stress and measurement setup files.

The 16440A has a special relay for opening the measurement circuit. You can perform memory cell evaluation without worrying about the life of relay.

By using the same system configuration, you can perform pulse width dependency test and pulse voltage dependency test too. The system can also be used for NAND type flash memory evaluation. The Agilent 4155C/4156C's PGU can force high enough voltage pulses for NAND type flash memory cells.

If you want much higher speed test capability or much narrower and faster pulse stresses, Agilent has a solution by using the Agilent 4062F Flash Memory Test System, which can be used for process monitoring in production lines as well.

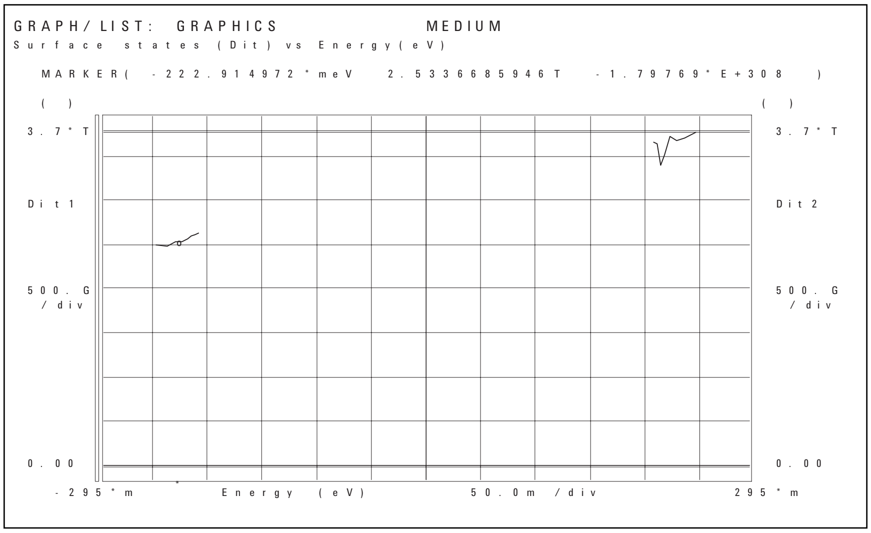

Figure 16. Trapezoidal Pulse Method Measurement Result

For more information about Agilent Technologies semiconductor test products, applications, and services, visit our website:
www.agilent.com/go/semiconductor
or you can call one of the centers listed and ask to speak with a semiconductor test sales representative.

For more information about other Agilent test and measurement products, go to
www.agilent.com

United States:
1 800 452 4844

Canada:
1 877 894 4414

Europe:
(31 20) 547 2000

Japan:
(81) 426 56 7832
Fax: (81) 426 56 7840

Latin America:
(305) 269 7500
Fax: (305) 269 7599

Australia/New Zealand:
1 800 629 485 (Australia)
Fax: (61 3) 9272 0749
0 800 738 378 (New Zealand)
Fax: (64 4) 495 8950

Asia Pacific:
(852) 2599 7889
Fax: (852) 2506 9233

Taiwan:
(886 2) 717 9524
Fax: (886) 2 718 9860

Korea:
(822) 769 0800
Fax: (822) 786 1083

Singapore:
(65) 1 800 292 8100
Fax: (65) 275 0387

Printed in U.S.A. 11/00
5964-2195E

Agilent Technologies
Innovating the HP Way