ARMY RESEARCH LABORATORY

FETest User's Guide Version 2.0

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13. ABSTRACT *(Maximum 200 words)*

This report details the operation of *FETest* version 2.0, a software package written at ARL, which allows for automated and manual control of a variety of electrical tests on ferroelectric capacitors used for nonvolatile memory applications. The *FETest* software, when coupled with the proper electronic test hardware, provides a core set of frequently used tests for evaluating FE thin films for nonvolatile memory applications. These tests include measuring and plotting a hysteresis loop, and performing *I-t* leakage measurements to analyze the resistivity of FE films. It can also automatically run extended fatigue and retention tests.

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1. Overview

Ferroelectric (FE) thin-film technology is a good candidate for high-speed, high-density, radiation-hardened nonvolatile memories, in large part because many FE thin films exhibit good fatigue properties ($>1 \times 10^{10}$ cycles), long retention times (>1 year), and fast write/read times (<100 ns). Many types of FE films and deposition procedures are currently under investigation in the FE community. Before any of these FE films or deposition procedures obtain a wide acceptance in the commercial or military marketplaces, the various FE thin-film candidates must be evaluated in a consistent and meaningful way. Testing software called *FETest* was written by the Radiation Effects Branch of the Army Research Laboratory to improve the efficiency of FE thin-film testing.

The *FETest* software, when coupled with the proper electronic test hardware, provides a core set of frequently used tests for evaluating FE thin films for nonvolatile memory applications. These tests include measuring the retained polarization (pulse test method) in FE thin-film capacitors under various conditions, measuring and plotting a hysteresis loop, and performing current versus time (*I*-*t*) leakage measurements to analyze the resistivity of FE films. It can also automatically run extended fatigue and retention tests. The test software graphically displays test results immediately on-screen and can also save them into standard tab-delimited text files for import into commercial graphing and spreadsheet programs. *FETest* features a user-friendly, menu-based interface and is capable of autonomous operation for lengthy test procedures.

2. Installation

2.1 Hardware Requirements

The *FETest* program requires the following electronic test equipment.

For general operation,

- IBM AT or compatible PC system with 286 or later CPU
- National Instruments GPIB-PC NI-488 interface card, software, and cables

For pulse tests,

- HP8115A, HP8112A, or HP8110A pulse generator
- HP54111D digitizing oscilloscope

For hysteresis loop measurements,

- HP8116A function generator
- HP54111D digitizing oscilloscope

For *I-t* measurements,

- Keithley 230 voltage source
- Keithley 619 electrometer

Failure to have all of the hardware listed above will result in error messages at startup, but will only affect operation of functions that require the missing hardware.

2.2 Software Installation

To install *FETest*, simply copy the following files onto your hard disk:

- **fetest.exe** It is recommended that you place **fetest.exe** into a directory that is part of the MS-DOS PATH listing (in **autoexec.bat**) so that you can run *FETest* from any directory you wish.
- **modern.fon** This fonts file must be in every directory from which you wish to run *FETest*.

Upon execution and exit, *FETest* will save a file into the current directory called fetest.ini. This file contains the settings you used in the program, and whenever *FETest* is run from the same directory in the future, it will load in these settings. Thus, it is recommended that you keep one directory per project, each with its own settings (**fetest.ini**) and font (**modern.fon**) file.

2.3 Hardware Setup

1. Connect all equipment to the GPIB-PC interface card on the computer using GPIB cables, per the instructions in the GPIB-PC manual.
2. Make certain that all devices have unique GPIB addresses (often set by dip switches in the back of each device).
3. Run the *IBConf* program supplied with GPIB-PC (type **ibconf** at the DOS prompt).
4. Follow the program instructions to connect all the devices. Name them as follows:

- HP54111D oscilloscope—"HP54111"
- HP8112A pulse generator—"HP8112A"
- HP8115A pulse generator—"HP8115A"
- HP8110A pulse generator—"HP8110A"
- HP8116A function generator—"HP8116A"
- Keithley 230 voltage source—"KITH230"
- Keithley 619 electrometer—"KITH619"

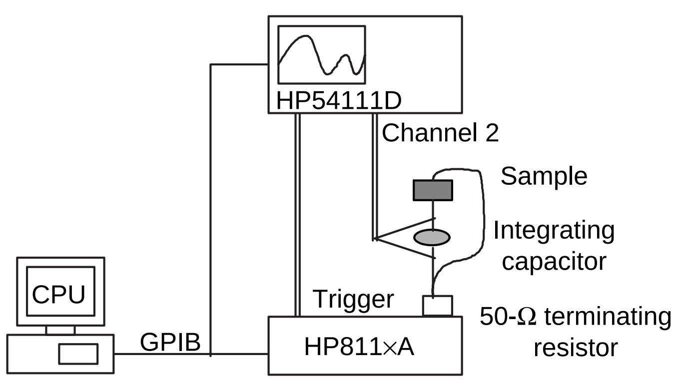
5. In the case of the Keithleys, specify the EOS character to be linefed (Hex 0A, Decimal 10). For all the instruments, make certain that the primary address matches the device's address set by the dip switches. Also, ensure that the Keithley 619's secondary address is set per the instructions in the Keithley 619 manual.
6. Save the configuration.

2.4 Test Setup

2.4.1 Pulse Tests

Refer to figure 1 when making connections.

Figure 1. Test system connection diagram for pulse tests.



1. Connect the HP811xA *TRIGGER OUTPUT* to the HP54111D *TRIG 3 INPUT*.
2. Connect the 50-Ω terminating resistor to the HP811xA *OUTPUT 1*.
3. Choose a suitable size capacitor, which will be used to integrate the current released by the FE sample into a voltage level recordable by the oscilloscope.
4. Connect FE sample in series with the capacitor.
5. Connect the free end of the capacitor to the ground of the HP811xA *OUTPUT 1*, and connect the free end of the sample to its signal wire.
6. Connect oscilloscope *CHANNEL 2* across the integrating capacitor. You may use the other channel to monitor the pulses output by the pulse generator if you wish.

2.4.2 *Hysteresis Loop*

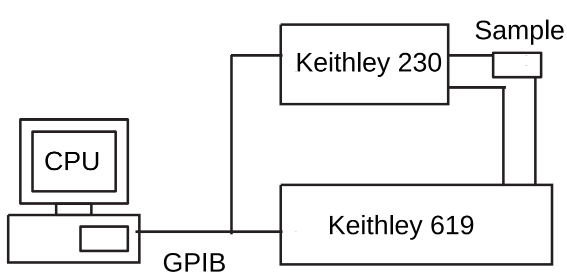
Connect in the same way as for the pulse test (see section 2.4.1), but use the HP8116 continuous function generator in place of the HP811×A pulse generator.

2.4.3 *I-t Resistivity Measurements*

Refer to figure 2 when making connections.

Connect the Keithley 619 electrometer in series with the sample between the *OUTPUT* and the *COMMON* of the Keithley 230 voltage source.

Figure 2. Test system connection diagram for *I-t* tests.



3. Test Theory

3.1 Pulse Test

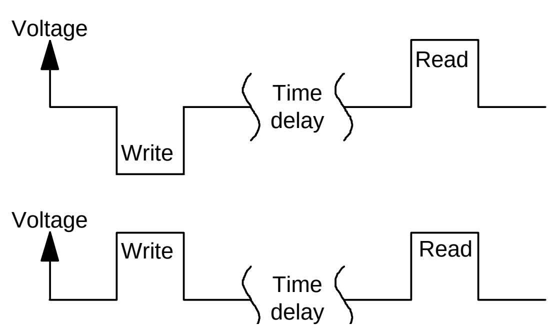
The pulse test is designed to evaluate the performance of FE samples in terms of *retained polarization*. This quantity is essentially the *memory window* of the sample, i.e., the difference between a stored 1 and a stored 0. Since a nonvolatile memory application will use discrete pulses similar to those used in the pulse test, the retained polarization measurement recorded by the pulse test is an excellent method for evaluating the FE capacitor's practicality for such an application.

The standard pulse test consists of two series of two pulses, as seen in figure 3, with the positive read pulse condition. The first pulse in each series is designated the *write* pulse. It polarizes the FE capacitor into one of two possible orientations, depending on whether the pulse is high (positive) or low (negative). After a preset time delay, a *read* pulse is sent and the digitizing oscilloscope records the resulting voltage across the integrating capacitor. This read pulse may be preset high or low, but remains the same for both series of pulses. Since a polarity reversal causes the FE capacitor to pass more current (and therefore generate a greater voltage across the integrating capacitor) than a series of similarly oriented pulses, the voltage waveforms recorded for the two series differ in amplitude (see fig. 4). In practice, this amplitude difference would allow memory circuitry to tell whether the stored bit in a FE memory cell was a logical 1 or 0 (i.e., previous write pulse was low or high; note that this is a destructive read process). The greater the amplitude difference, the greater the effective memory window. The retained polarization value reported by the pulse test is directly proportional to the size of the *memory window* and to the voltage differential. Therefore, the greater the retained polarization the pulse test reports, the more easily a sense amplifier in a nonvolatile memory could distinguish a stored 0 from a stored 1. The *FETest* software reports the data in microCoulombs per square centimeter (μC/cm^2).

3.2 Hysteresis Loop

The hysteresis loop test obtains a measure of switched charge by continuously varying the applied voltage with a sine wave. The resulting voltage across the integrating capacitor can then be plotted against the "input"

Figure 3. Series of pulses applied to sample during pulse test.



voltage in order to generate a hysteresis loop in x-y space. This measurement is the classical way to determine the remanent polarization (2*P_R) and the coercive field (E_C) for a FE sample as indicated in figure 5.

3.3 *I-t* Resistivity Measurement

The purpose of the *I-t* measurement is to record and analyze the manner in which current passing through the FE capacitor changes as a steady-state voltage is applied. These steady-state voltages are typically held for much longer periods than would be used in a typical memory application. At present this measurement records the *I-t* data for a graph (see fig. 6) and the peak current, which typically occurs immediately after voltage is applied as the FE capacitor charges, and after the average level current, which is the steady leakage current that remains after the initial peak, drops off. Both the applied voltage and the duration of the test can be varied before the test.

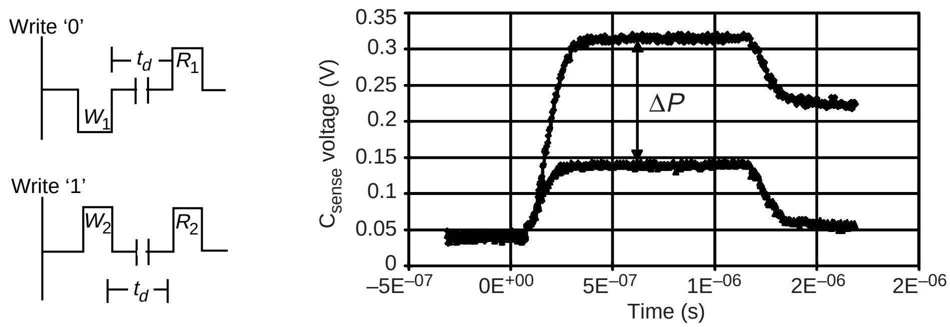


Figure 4. Schematic of retention test pulse train (positive read) and results of each series as measured across integrating capacitor. Memory window is indicated as ΔP.

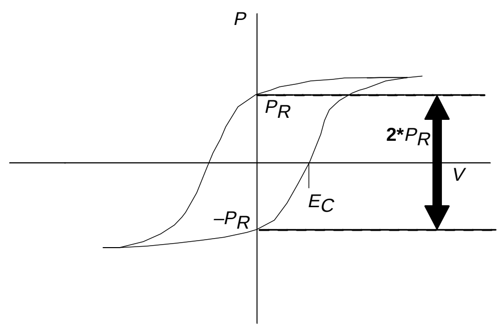


Figure 5. Hysteresis loop schematic showing polarization as function of applied voltage. Remanent polarization (2*P_R) is calculated from measurement as indicated.

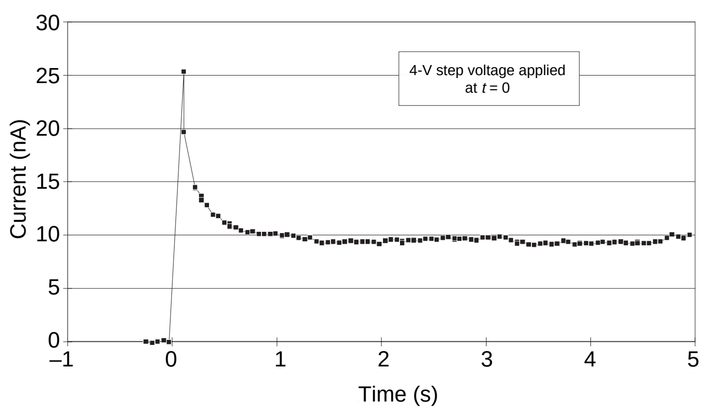


Figure 6. Sample resistivity measurement output.

4. Operation

4.1 Overview

4.1.1 Escape Key

For most menu windows in the program, you have the option to either press the *Escape* key to abort the current action or to press *Enter* to continue the action. You may also press *Escape* to abort a testing procedure; in that case, data collection will stop and further presses of *Escape* will ensure that data taken during that procedure will not be saved. If it is a repetitive procedure, only the data taken during the iteration when the Escape key was pressed will not be saved.

4.1.2 Menus

Within a menu, you may move among the choices with the cursor keys and either press *Enter* to select a choice or press *Escape* to abort the menu. Alternatively, if a menu choice is of the form "(M)enu choice," where one of the letters is surrounded by parenthesis, you may simply press that letter on the keyboard to select that menu item, without moving to the menu choice first with the cursor keys.

4.1.3 Data Entry Windows

Many windows feature data entry fields, each with a description of the data to be entered and a box where you may enter the data. Most fields have a default data value. If you wish to keep the default value, simply press *Enter*. If you wish to change the value, type in the new value and press *Enter*. Each press of *Enter* moves you toward the next input field. Pressing *Escape* will abort the data entry window.

You may navigate most data entry windows with the cursor keys. You may also use *Tab* and *Shift-Tab* to move to the next and previous input fields, respectively. Pressing *Ctrl-Enter* is a quick way to approve of all the values in the input fields—it is the same as pressing *Enter* for every input field.

4.1.4 Common Requesters/Windows

Save Data Requester.—This window allows the user the option of saving the test data. If you do not wish to save test data, simply leave the filename field blank. To save the data, enter a proper DOS path and filename, as well as a file comment, if desired. The available storage space in kilobytes is shown at the top of the window.

At this point a menu appears, giving the user the option of saving either a summary only of the recorded results or both the summary and the measured data in an *X-Y* table suitable for graphing. Saving only the results will result in smaller files but may not provide useful results if the samples are not performing as expected. This is usually only a problem for samples with unusually high leakage currents.

If you have previously entered the name of a file that already exists, you will be given the option to choose a new filename, append to the file, or write over the file. Appending to the file will simply add the test data to the end of the file. Overwriting a file will *destroy the old file and replace it with the new test information and data*. Note that all of the previous data will be irretrievably lost.

Error Window.—The red Error Window appears when the program has encountered a serious error. Within the window is a description of the error. Pressing *Escape* at this point will quit the program. Pressing *Return* may or may not allow the program to continue, depending on the seriousness of the error.

Warning Window.—The Warning Window appears normally to warn the user of some action or to report a mild alert. Pressing *Escape* will abort the action about to be taken, while pressing *Return* confirms it.

4.2 Main Menu

To run *FETest*, simply type **fetest** at the DOS prompt. If there are no problems with the hardware setup, the following menu options should appear:

Run Pulse Test	Executes one or more simple pulse tests.
Run Retention Test	Varies the write-to-read delay time in a series of pulse tests.
Run Voltage Sweep	Varies the write/read voltage in a series of pulse tests.
Run Fatigue Test	Pulses the sample rapidly and uses the pulse test to check for fatigue.
Run Write Width Test	Varies the write pulse width in a series of pulse tests.
Run Both Width Test	Varies the write/read pulse widths in a series of pulse tests.
Run Disturb Test	Adds disturb pulses into the write/read delay of a series of pulse tests.
Run Resistivity Test	Applies a voltage and acquires *I-t* data.
Capture Hysteresis Loop	Captures a hysteresis loop by oscillating the input voltage.
Send Low Pulse	Sends a single low pulse according to settings.
Send High Pulse	Sends a single high pulse according to settings.
Get Scope Data	Captures the oscilloscope waveform and allows you to save it.
Change Test Parameters	Modifies the basic pulse test settings.

Initialize Equipment	Reinitializes the equipment.
Quit to DOS	Quits the program, saving the **fetest.ini** settings file.

(Pressing *Escape* at this point will also quit the program, without saving the settings, however.)

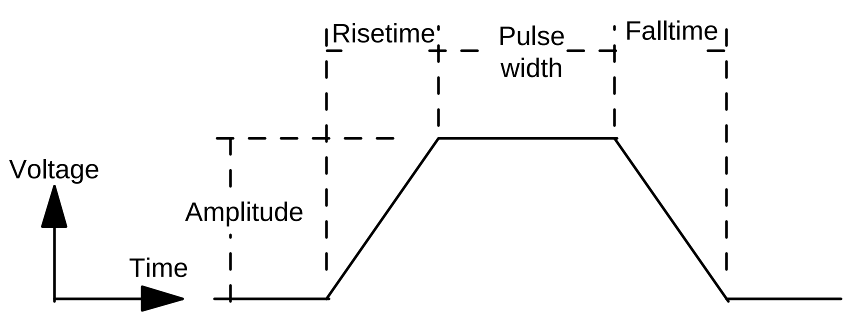
If you are starting a new testing project, you should first **Change Test Parameters.**

4.3 Change Test Parameters

The variables modifiable in this window affect the pulse test and all measurements that use that test. They are also the variables saved in the **fetest.ini file**. These values may be overridden and varied during some test sequences, but the default values (from the **fetest.ini** file) will be reset after any test. An explanation of each variable follows (also refer to fig. 7):

Number of SetPulses	You may wish to consistently "pre-orient" the sample before the pulse test is run each time. This number specifies how many pulses you wish to use to "set" the sample; default is 0.
SetPulse Voltage	The voltage used in these set pulses.
Risetime	The time from zero to maximum amplitude for all pulses. It should be set as low as possible without causing "ringing" in the circuit.
Time Delay	The time elapsed between a write pulse and a subsequent read pulse.
Measure Start	A percentage of the width of the read pulse that indicates at which point *FETest* should begin to measure the amplitude of the voltage pulse seen across the integrating capacitor. For example, a value of 20 would cause *FETest* to begin considering data after 0.20× pulsewidth has elapsed since the end of the risetime.
Measure Stop	Tells *FETest* when to stop considering data in the same manner as Measure Start. The amplitudes between Measure Start and Measure Stop are averaged into what *FETest* reports as the amplitude of the detected pulse.

Figure 7. Typical pulse and its parameters.



Integrating Capacitor	Capacitance of the integrating sense capacitor; used for polarization calculations.
Ferro Capacitor	The approximate capacitance of the FE; used only to scale the oscilloscope for optimum resolution and no clipping. You may need to experiment with this value until the scope is being properly scaled.
Ferroelectric Area	The area of the FE; used for polarization calculations.
Use PUND	Expands the retention tests to include full PUND pulse sequences. The PUND tests add extra pulses to the standard pulse sequences to measure (in addition to the stored polarization) the switchable and nonswitchable polarization components. These additional polarization components will be stored in the output datafiles.
Read Pulse Polarity	Sets the standard polarity for the pulse test read pulses, either positive or negative.
Pulse Gen. HP811n	Specifies which pulse generator should be used for the pulse testing. You should choose a pulse generator based on the availability and the nature of the test and type in 2 for the 8112A, 5 for the 8115A, or 0 for the 8110A.
Write/Read Widths	Specifies the length of the read/write pulses.
Write/Read Voltages	Specifies the amplitude of the read/write pulses.

Once you have entered these values for your current testing project, make certain that you quit the program normally at least once during your testing so that the **fetest.ini** file is saved. The next time you run the program from your project directory, all of these settings will be reloaded in as they were when you quit.

4.4 Pulse Test

Because the pulse test uses all of the values you have entered in the test parameters window, the only additional variable asked for is the number of times you would like the test to be run. Values greater than 1 may be useful if you would like to collect data for averaging. This test reports the amplitudes (in mV) of the pulses read across the integrating capacitor (channel 2) during applied read pulses for both write pulse conditions and reports the difference between these values scaled to units of $\mu C/cm^2$ (retained polarization).

4.5 Retention Test

The retention test is a series of pulse tests during which the delay time between writing to and reading from the sample is progressively increased to examine retained polarization versus delay time dependence. You are asked for the initial and final delay times; the program then executes a pulse test at the initial delay time, increments the delay time, executes a pulse test at the new delay time, and so on, until the final delay time is reached. The delay time is incremented in logarithmic (1, 2, 5, 10, 20, ...) fashion; thus, if your initial delay time is 10 s, the next will be 20 s, the next 50 s, and so on. Delay times can be varied from 1× the pulsewidth to as long as needed. The typical range is from 50 ns to 10,000 s.

4.6 Voltage Sweep

The voltage sweep is a series of pulse tests during which the read/write amplitude is increased to examine polarization-voltage dependence. You are asked for the initial and final voltage values, as well as the increment you wish to use. The program then runs a pulse test at the initial voltage, adds the increment, runs another pulse test, adds the increment, and so on, until the final voltage is reached. The voltages can be varied from 0 to 8 V.

4.7 Fatigue Test

The fatigue test is a series of pulse tests between which the FE is subjected to large numbers of rapid pulses of alternating polarity. The purpose of this test is to determine if the sample is fatigue-prone and to gain an idea of its useful life cycle in a memory application. You are asked for the initial and final numbers of fatigue cycles to apply and also for the previous existing number of fatigue cycles. The previous existing number should be an estimation of how many times the sample has been switched in its lifetime and is automatically added to all the cycle numbers reported by the program. The program then fatigues the sample for the initial number of cycles and proceeds toward the final number of cycles, taking pulse tests at logarithmic intervals.

4.8 Write Width Test

The write width test is a series of pulse tests during which the width (or time length) of the write pulse is increased to examine polarization versus write width dependence. The read pulse width is held constant. You are asked for the initial and final write widths; the program then executes a pulse test at the initial write width, increases the write width in logarithmic fashion, performs another pulse test, and so on, until the final write width is reached.

4.9 Both Width Test

This test is identical to the write width test, except that both the write and read pulse widths are varied together from the initial to final pulse widths you specify.

4.10 Disturb Test

The disturb test examines the FE thin film's susceptibility to small voltage disturbances. You are asked for the initial and final number of disturb pulses and the disturb voltage, and the program then executes a series of pulse tests, inserting disturbance pulses (of the specified amplitude and with the same width as the write pulses) between the write and read pulses on the FE capacitor, and increasing the number of disturb pulses in logarithmic fashion until the final number is reached. This test reports the retained polarization versus the number of disturb pulses applied.

4.11 Resistivity Test

The resistivity test applies a voltage across the sample for a specified duration and records the resulting current readings to generate an *I-t* graph. Initially, you are asked to enter a voltage level and, optionally, a voltage increment value. If you enter a nonzero increment, you will also be asked for the final voltage and a minimum delay time between tests. In either case, you will also be asked for the duration for which the voltage is to be applied and the number of data points you would like the program to take. The program will configure the electrometer reading rate to comply with the specified duration and number of data points. A large number of data points and a short duration will offer high time resolution, but will also produce less accurate and more noisy current readings, whereas fewer data points will result in more accurate current readings taken at longer intervals. When the instruments are configured, the program will inform you that the test is ready to run. It will then acquire additional current readings (about 5% of the total number of data points) before the voltage is applied. Once the voltage is applied, the program will collect the specified number of data points (displaying the current readings on-screen) for the specified duration before shutting off the voltage source. If you have previously entered a nonzero increment value, the program will wait at least as long as the minimum time delay value you have chosen before incrementing the voltage and running the test again, until the final voltage is reached.

4.12 Capture Hysteresis Loop

Before capturing a hysteresis loop, make sure that the HP8116A function generator is connected properly. When you select this function the oscilloscope is readied for capturing the loop. You are then asked for the applied frequency and the applied voltage. The applied voltage is simply the total negative to positive amplitude of the sine wave that the HP8116A will output, and the applied frequency is the frequency of that sine wave. Once you enter these values, the HP8116A will be configured to output the sine wave; however, its output will still be disabled. You will need to *manually* toggle the Disable button on the HP8116A to enable its output. Then, press any key on the computer keyboard when you would like to capture the hysteresis loop from the oscilloscope (typically when a stable hysteresis loop forms). Pressing another key will give you the option to save the data if you wish.

4.13 Send Low Pulse

This function sends a single low pulse, with a width and amplitude that is based on the test parameters. It can be used to manually perform tests with nonstandard pulse sequences (in conjunction with the Send High Pulse function, described below).

4.14 Send High Pulse

This function sends a single high pulse, with a width and amplitude that is based on the test parameters.

4.15 Get Scope Data

After you specify which oscilloscope channel to get, the program will get that channel data from the oscilloscope, display it on-screen, and give you the option to save to disk. This feature can be used with Send Low Pulse and Send High Pulse (above) to capture data created by nonstandard pulse sequences.

4.16 Initialize Equipment

Reinitializes and rescales the oscilloscope and pulse generator. This function is usually only needed if you have manually used the devices and would like to return them to the setup used by *FETest*.

5. Extract Program

5.1 Purpose

The purpose of the *Extract* program is to pull out only the essential data needed for creating graphs out of *FETest* ***.dat** files. The new ***.xtr** files created can then be easily imported into database applications such as *Microsoft Excel* and quickly graphed, while the original ***.dat** files can be archived and maintained as a record of the experiment because they contain much more information (including time, date, program settings, comments, etc.), all of it in text form.

5.2 Operation

The *Extract* program is an MS-DOS utility and is used from the DOS command line. To extract a data file, simply type **extract**, followed by the name of the file, and a corresponding ***.xtr** file will be created. For example, to extract the data file "ret_tst1.dat," you would type:

extract ret_tst1.dat

You may use standard DOS wildcards and may also specify a destination directory. For example, to extract all ***.dat** files that begin with "vsw" into the "mydir\extract" directory, you would type:

extract vsw*.dat mydir\extract

Then all of the vsw***.xtr** files would be created into the "mydir\extract" directory.

If you are extracting files that were created earlier than August 1994, they may be in the old format. If the normal extracting method does not work, you can tell the Extract program to use the old format by inserting "-O" or "-Oldformat" before the file name. For example to extract the old format file "oldfile.dat" you would type:

extract -Oldformat oldfile.dat

You can still use wildcards and destination directory specifications. Once you have some ***.xtr** files, you can easily import them into Excel by specifying them as text files delimited by tab in the *Excel* OpenFile menu.

6. Summary

This report has detailed the operation of *FETest* version 2.0, a software package written at ARL, which allows for automated and manual control of a variety of electrical tests on FE capacitors used for nonvolatile memory applications. The test procedures focus on three main aspects of FE capacitor testing: (1) the pulse test for measuring retained polarization, (2) the hysteresis loop for measuring the continuous remanent polarization, and (3) the *I-t* resistivity test. Each test method can be used for measuring the basic performance and degradation phenomena associated with the use of FE thin-films in nonvolatile memory applications, including fatigue, retention time, imprint, and aging.

The software was also written to be compatible with commercial graphics and spreadsheet programs using the *extract* program (written at ARL for use with *FETest*). Once the *extract* program has been run the data can be imported into the commercial plotting or spreadsheet programs to yield charts of the FE test data.

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