

TRANSMISSION-LINE PULSE TESTING SOFTWARE DESIGN

By
Molly Pace

Senior Thesis in Electrical Engineering
University of Illinois at Urbana-Champaign
Advisor: Professor Elyse Rosenbaum

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Abstract

Transmission-line pulse testing (TLP) and very fast transmission-line pulse testing (VF-TLP) are used to study the high current behaviors of integrated circuits and semiconductor devices, to characterize device response to electrostatic-discharge (ESD) events, and to provide the quasi-static IV curve for the devices. However, commercial TLP and VF-TLP testers are extremely expensive and have limited configurability. Smaller ESD labs need alternatives to expensive equipment. Through this work, I have automated TLP and VF-TLP testing through existing instruments in the lab, making these tests available to research labs on a smaller budget. An oscilloscope, a pulse generator, a parameter analyzer, and a probing station have been integrated using C# programming language to automate both tests. All devices communicate via GPIB and are controlled through a graphical user interface (GUI). This document explains how to set up the GUI and interact with the equipment to create a very reliable tester.

Subject Keywords: transmission-line test; very fast transmission-line test; Tester; GPIB; ESD; C#

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Contents

- 1. Introduction 1
- 2. Literature Review 3
- 3. TLP and VF-TLP 5
 - 3.1 TLP and VF-TLP Hardware Design 5
 - 3.2 VF-TLP Setup 6
 - 3.3 Voltage Sweep 10
 - 3.4 TLP Setup 11
 - 3.5 Oscilloscope Trigger Algorithm 14
 - 3.6 Volts/Division algorithm 15
- 4. Conclusion 17
 - 4.1 Summary 17
 - 4.2 Future Work 17
- References 18

1. Introduction

An electrostatic-discharge (ESD) event can happen at any time in an integrated circuit. ESD is generally caused by a charged object coming into contact with a metal instrument or from human touch. Important components of integrated circuits are the structures that protect the core functionality or I/O pins of the device. In order to understand ESD failures, testers are used to characterize when and how the device fails.

A transmission-line pulse (TLP) tester and very fast transmission-line pulse (VF-TLP) tester are widely used to study characteristics in semiconductors. A pulse is sent to the device from a charge cable and the voltage and current across the device under test (DUT) are studied. These tests send square wave current pulses to a DUT. The amount of current through the DUT can be approximated but is measured for accuracy in our system. The DUT voltage is measured as a by-product of the current pulse. It is not easy to predict the voltage value because it has many transient characteristics. The quasi-static regions of the current and voltage waveforms are used to construct the IV curve for the device. The short square pulses used in VF-TLP and TLP are popular because they provide a simplified representation of an ESD waveform which is normally a complicated voltage waveform.

TLP tests need to be automated because they are repetitive, involve many pieces of equipment, and require measurements and calculations on every waveform. This is done through GPIB communication between the instruments, controlled by a Visual Studio C# program. A graphical user interface (GUI) is designed so the user can specify the pre-charge

voltages, the sampling window on the resulting waveforms, and leakage measurements for any test.

2. Literature Review

Transmission-line pulse testing was introduced to meet the need to identify where and how integrated circuits fail. Existing emulators for such failures involve complicated waveforms and could not be easily validated. The method proposed by T. J. Maloney and N. Khurana is used today to emulate high-current, short-time pulses that cause failures [1].

There was still a gap in semiconductor testing with TLP alone. Traditionally, TLP uses approximately 100 ns pulses, but some ESD events are much shorter in duration. The charged device model (CDM) requires amps of current in ones of nanoseconds [2]. H. Gieser and M. Haunschild proposed very fast transmission-line pulse (VF-TLP) testing to fill the gap. Using VF-TLP, the shorter ESD pulses can be emulated [3]. Their hardware design is used for the VF-TLP software described in the next chapter.

Kelvin probing is also used in this setup to reduce the effect of contact resistance within the measurements. Sensing needles contact the same pad as the force needles to directly measure device under test (DUT) voltage and current separately. The main discharge current generates relatively large IR drops across the contact resistance of the force side probes. Kelvin probing means measuring current and voltage separately. The DUT voltage is measured accurately because a very small current flows through the two Kelvin probes, so the IR drops are insignificant [4]. The Kelvin probes include a series resistance to limit the current that moves through the oscilloscope, giving more accurate measurement of DUT on-resistance.

Adaptive ranging is used in TLP to increase the resolution of each waveform on the oscilloscope [5]. If the oscilloscope screen is set to display a large amplitude pulse, then a small

amplitude measurement will utilize only a small portion of the screen and thus be rounded due to quantization error. We can remove this loss by zooming into the quasi-static part of each pulse. For quasi-static IV curves, we do not need to see the rising edge, only the flat top portion of the waveform. The adaptive ranging algorithm explains how to choose the volts/div of a waveform to correctly zoom into the correct portion of each.

3. TLP and VF-TLP

3.1 TLP and VF-TLP Hardware Design

TLP testers can be made using a high voltage power supply, a low-pass rise-time filter, an oscilloscope, device probing station, and charge cables. The setup used is shown in figure 1. The HV power supply charges the coaxial charge cable, which determines the width of the pulse for TLP or VF-TLP. When the switch is closed, a pulse is sent to the DUT, where voltage and/or current can be measured and sent to the oscilloscope. A large resistor is placed in series with the power supply so it does not provide current to the DUT. The low-pass rise-time filter sets the rise-time of the pulse coming from the charge cable. A reverse biased diode and 50 Ω resistor may be placed on the end of the coaxial cable to absorb the reflected pulse caused by a low-impedance DUT [6].

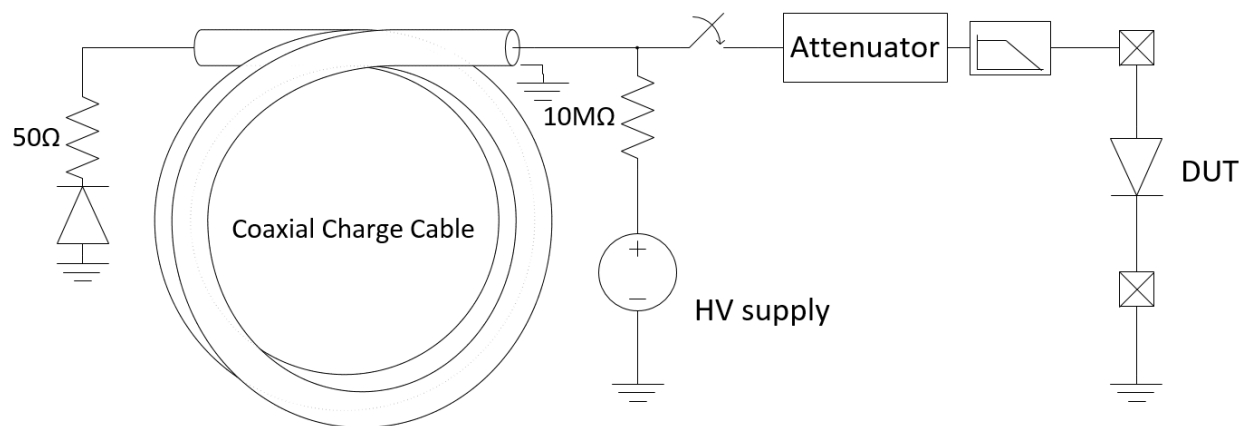


Figure 1. TLP setup showing the reverse biased diode, charge cable, power supply, filter, and DUT connections

All of the instruments can be programmed through GPIB interface from a computer. GPIB is a digital 8-bit parallel communication interface with data transfer rates up to 1 Mbyte/s. This IEEE 488 standard allows for one system controller, a computer in our case, and up to

fifteen additional instruments to be used [7]. Using this setup, I can control the voltage pulse amplitude, oscilloscope, and a device analyzer to measure leakage current. The programming guide for each instrument instructs the user how to initialize and set up each instrument as needed.

Every instrument is constructed as a class in C#. These use the GPIB driver which reads and writes to the instruments according to GPIB communication procedures. They include all the initialization procedures needed and any other functions required to control the instrument. For example, the oscilloscope can be programmed to control trigger level, volts per division, and retrieving the data once the DUT has been stressed. I will begin with an explanation of the setup of VF-TLP and voltage sweep followed by an explanation of TLP. The voltage sweeps for both are very similar but each test has a unique setup.

3.2 VF-TLP Setup

When running a VF-TLP test, I plot the incident and reflected pulse, the inverted incident and reflected pulse, the DUT voltage, and the final DUT current. The incident and reflected pulse are sent to the oscilloscope from a pick-off tee that provides a scaled replica of the pulse. The current through the DUT is determined by Eq. 1 because the measurement setup does not include a current probe. The user is able to pan and zoom the top three graphs together because the final current graph is drawn from an equation that involves all three graphs. Since the pulse is generally less than 10 ns, the cables that deliver the pulse cause too large a delay and will not give accurate measurements. The incident and reflected voltage pulse and the DUT voltage data are read from the oscilloscope into an array. I plot these two arrays along with the

inverted incident and reflected voltage. A picture of the setup GUI for VF-TLP before any panning or zooming of the graphs is shown in figure 2. Figure 3 shows the GUI after the user has zoomed in to pick the sampling window. In Eq. 1, $V_{inc,inv}(t + t_o)$ is the inverted waveform of $V_{inc}(t)$. The inverted reflected pulse is shifted by t_o to align the rising edge of the inverted reflected pulse with the rising edge of the incident pulse on the first graph. The delay of τ in V_{dut} is the offset introduced by the propagation delay from the pick-off tee to the DUT. Z_0 is the characteristic impedance (50Ω) from the coaxial charge cable and Z_{kelvin} is the series resistance included in the Kelvin probes that is specified in the GUI and can be changed by the user but is 2450Ω in our example.

$$I_{dut}(t) = \frac{V_{inc}(t) + V_{inc,inv}(t + t_o)}{Z_0} - \frac{V_{dut}(\tau)}{Z_{kelvin} + Z_0} \quad \text{Eq. 1}$$

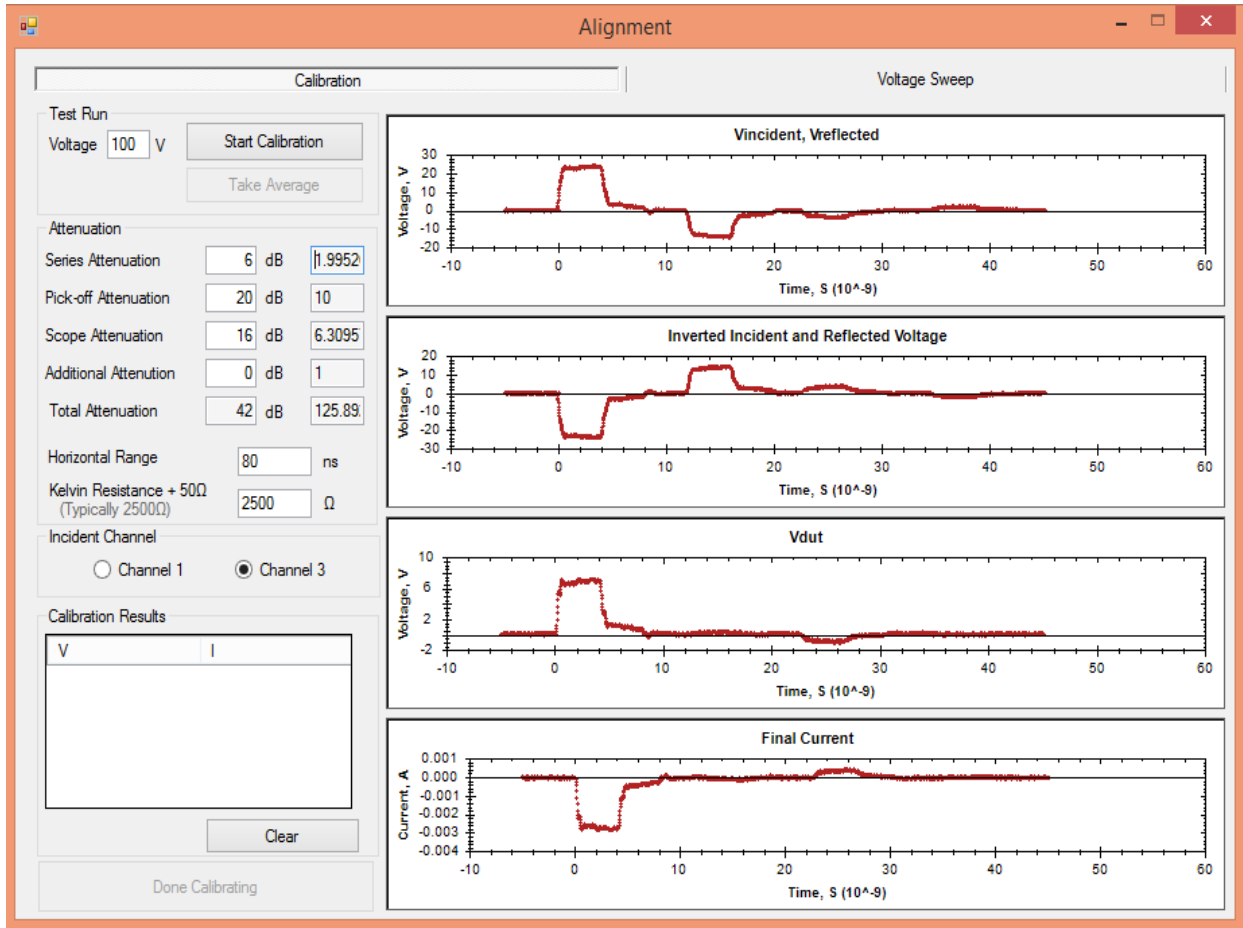


Figure 2. Setup page for VF-TLP. $V_{incident}$, Inverted Incident, and V_{dut} graphs are all taken from the oscilloscope. This is before the graphs are aligned for the correct final current calculation.

After the graphs are aligned to the user's specification, the user clicks twice on the final current graph to select the sampling window to take the data from each pulse for an IV curve.

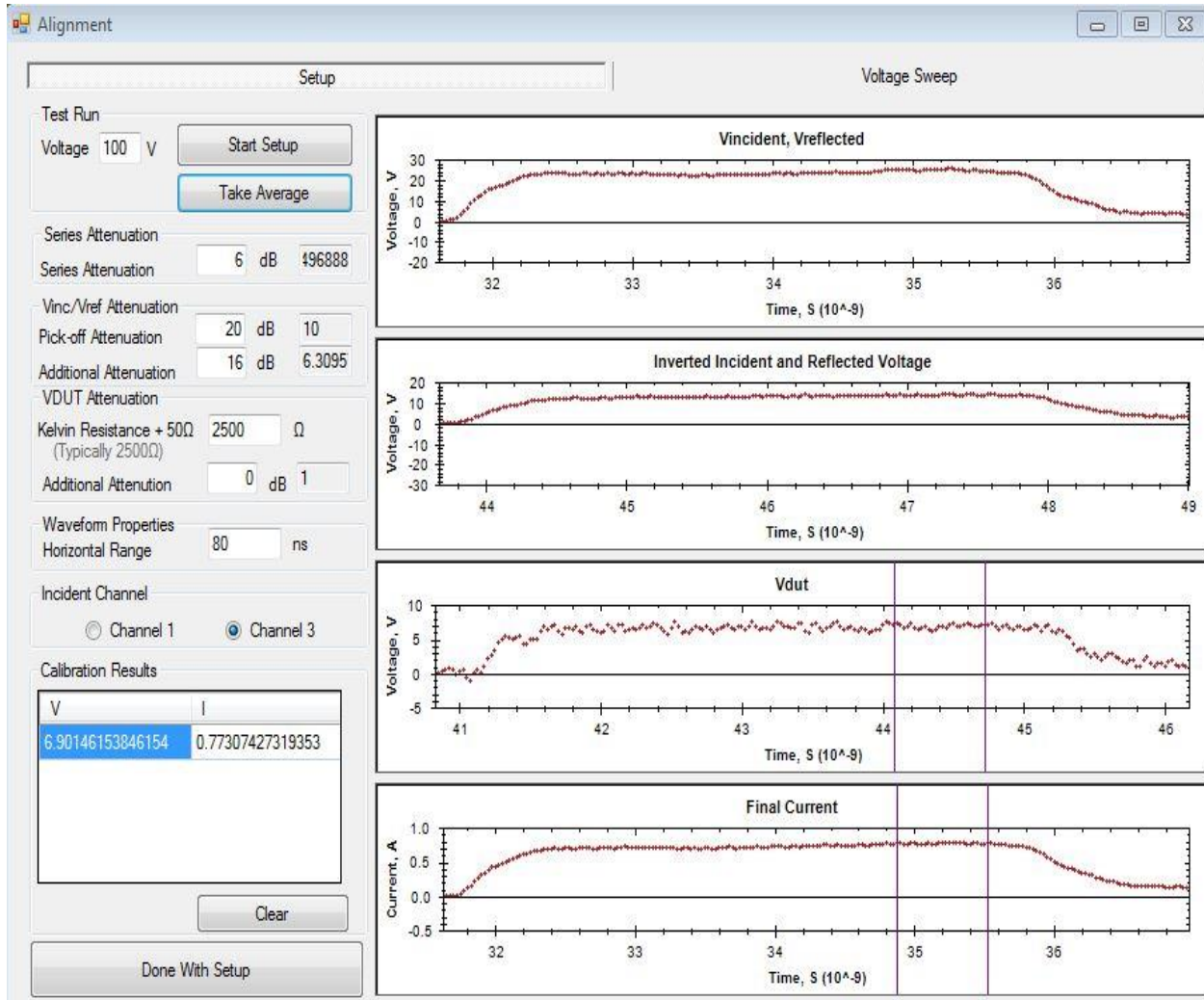


Figure 3. VF-TLP GUI after the user has zoomed and panned the top three graphs for correct alignment. The sampling window for the DUT current and voltage are shown in between the two purple vertical lines.

The attenuation coefficients on the left of the GUI represent those used in the test setup and are used in the code to correctly plot the data. In the hardware setup, there are multiple attenuators built in or inserted so as not to harm the equipment or device. These values can be replaced at any time and changed on the GUI and the graphs will be updated to reflect the changes. The series attenuation comes from the attenuation inserted at the splitter. The Kelvin resistance + 50 Ω comes from the resistance of the probe needles and the cable. The

horizontal range is set so the user can select the horizontal range of the incident voltage on the oscilloscope. The incident channel radio dials enable changing which channel of the oscilloscope to use for the incident pulse.

Next, the user clicks on the I_{final} graph to select the sampling range. The lines are replicated on V_{dut} to show the sampling window for both the current and voltage. Finally, the user clicks “Take Average” and the average values within the sampling window are displayed in the Calibration Results table. This saves the offset of the middle two graphs with respect to the first graph. This is needed because only a small part of the graph is used for the current equation. The user can now click “Done with Setup” to go to the voltage sweep tab. The user must go through these steps at least once before being able to continue on to a voltage sweep.

3.3 Voltage Sweep

The voltage sweep tab is used to construct the IV curve. The sweep control box lists the pre-charge voltages and is controlled by the start, stop, and step boxes to the right. Sweep Info is edited by the user to save information in the Excel file created to save the IV curve. The results table shows the number values that are being plotted in the IV Curve window. Below the IV curve are the Final Current and V_{dut} graphs. These update with every pulse so the user can see the pulse and the sampling window to ensure no odd pulses have occurred that might invalidate the IV plot. Figure 4 shows an example VF-TLP IV plot of a $10\ \Omega$ resistor. The voltage supply is swept from 1 to 10 Volts in increments of one, followed by 10 to 50 in increments of five, and from 50 to 100 in increments of ten. All of these data points are saved in a file along with the pulses from the setup page for each new voltage stress. A VF-TLP voltage sweep saves

each incident voltage pulse, DUT voltage pulse, and final current. A TLP voltage sweep saves each DUT voltage, DUT current, an optional V_{dut} low reference voltage, and an optional extra waveform from the other oscilloscope channel.

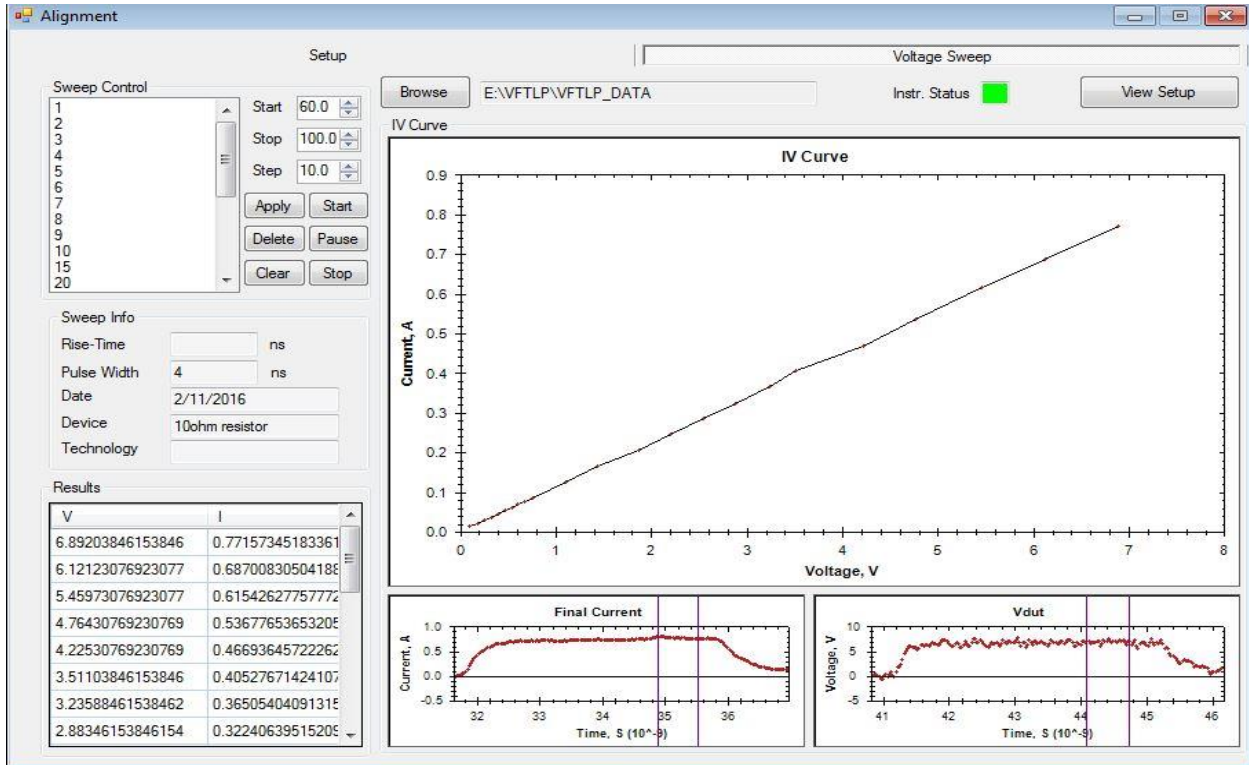


Figure 4. Voltage sweep example of a 10 Ω resistor. The Final Current and V_{dut} graph are updated with each pulse so the user can see each pulse.

3.4 TLP Setup

The TLP layout of the setup page is similar to VF-TLP but the graphs plotted are different. The DUT voltage and current are measured directly when using TLP because the pulses are around 100 ns long. The short delay in current measuring does not affect these results. The current probe type can be changed by the user. Different probes have attenuation

values and need to be taken into account when plotting the current. The GUI allows the user to pick a sampling range as with VF-TLP. The user can also drag the graphs to line them up and click on the current graph to place the bars for the sampling range as shown in figure 5. The user then clicks “Take Average” and can proceed with the measurement if they are satisfied with the average values. The “To Save” waveform can be specified in the Channel Selection box. This will save the data from the oscilloscope into an Excel file with each pulse. The “ V_{dut} Low” can be used when measuring the device with respect to a voltage other than ground.

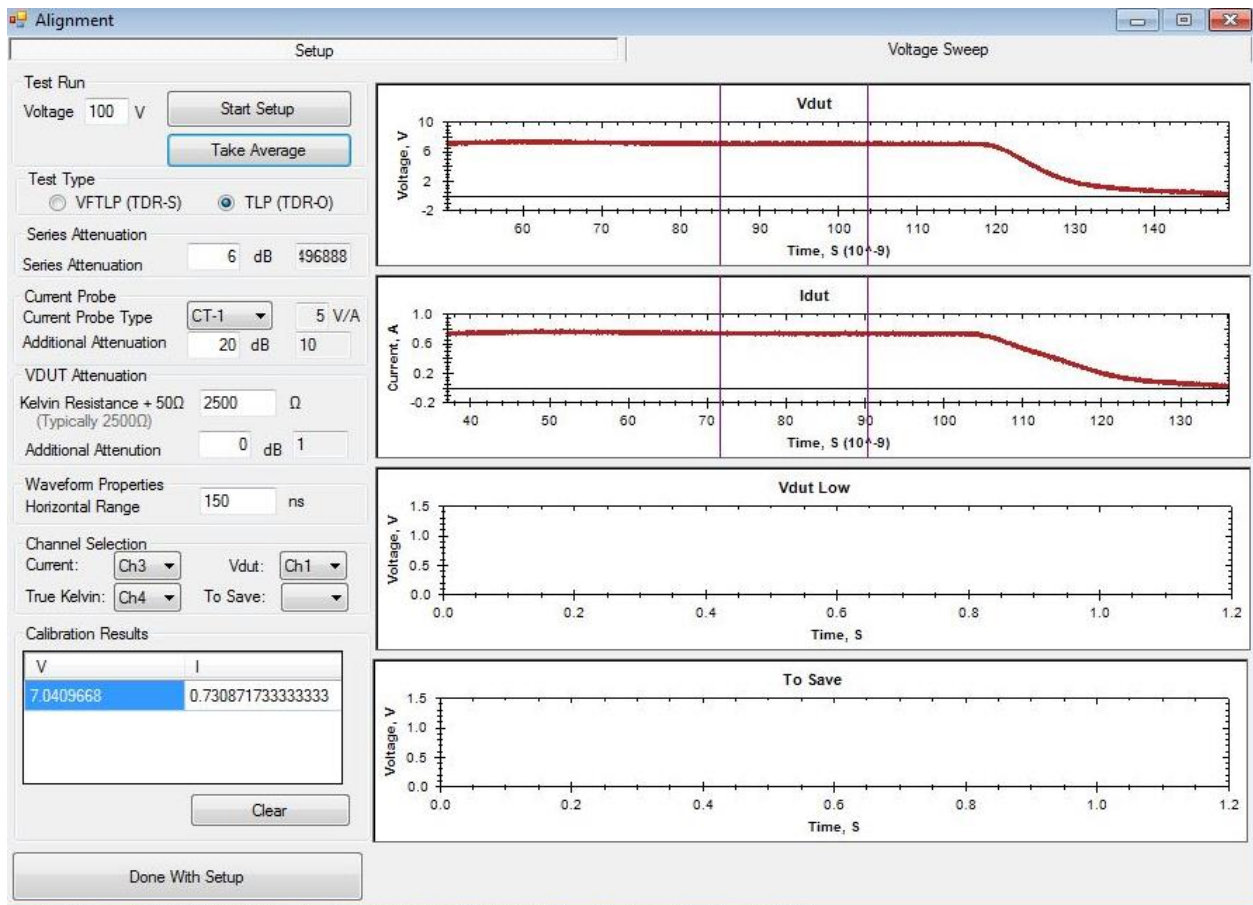


Figure 5. TLP setup GUI showing a zoomed in version of a pulse. The sampling range is specified on I_{dut} and replicated on V_{dut} automatically.

The voltage sweep tab for TLP is the same as VF-TLP. Figure 6 shows a sweep of a 10 Ω resistor along with the leakage current taken. This is an option that can be checked so the parameter analyzer will measure leakage current at each voltage pulse. Max leakage steps and max leakage cut-offs can be set by the user. The max leakage step is the difference between two consecutive leakage values and the max leakage cut-off is the largest acceptable value for a leakage measurement. If any measurement exceeds these values, a warning sign will appear with the option to abort the test.

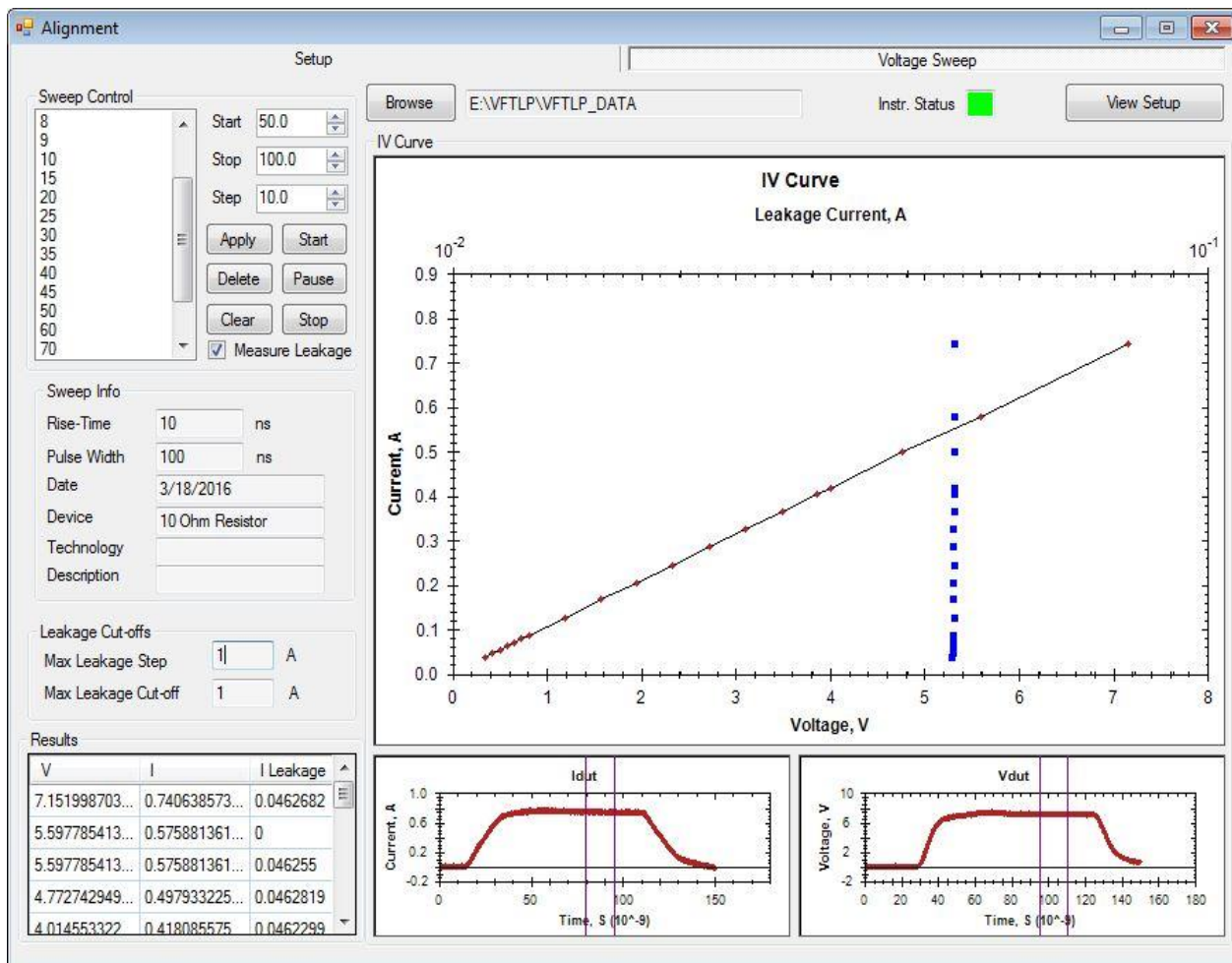


Figure 6. TLP IV curve of a 10 Ω resistor. The red connected dots are the IV curve and the blue dots are the leakage value for each current measured.

3.5 Oscilloscope Trigger Algorithm

The trigger level on an oscilloscope is used to capture a waveform once it reaches a certain threshold. The equation for determining the trigger level on the oscilloscope is determined differently for VF-TLP and TLP. VF-TLP is shown in Eq. 2 and TLP is shown in Eq. 3.

$$\text{Trigger level VF - TLP} = V_{pre} * \frac{1}{2} * \frac{1}{series_atten * pickoff_atten * scope_atten} * 0.6 \quad \text{Eq. 2}$$

$$\text{Trigger level TLP} = V_{pre} * \frac{1}{series_atten * kelvin_scalar * additional_atten} * 0.3 \quad \text{Eq. 3}$$

V_{pre} is the initial charge on the high voltage power supply. The factor of $\frac{1}{2}$ comes from the voltage divider of the 50 Ω source and a load impedance of 50 Ω . The scales in the denominator come from the attenuations that are built into the hardware. Series_atten is the attenuation at the splitter, scope_atten is the attenuation at the scope, kelvin_scalar is $\frac{2500}{50}$ where 2500 is from the probe and 50 is from the load, and additional_atten is an optional extra attenuation. Once the signal is at the oscilloscope, we multiply by 0.6 or 0.3 to take only a percentage of the peak value.

For example, if the system has a 20 dB additional attenuation, the program converts the dB value into a scalar value that is used in the above equations. The conversion is shown in Eq.

4.

$$\text{Additional_atten} = 10^{\frac{dB \text{ value}}{20}} \quad \text{Eq. 4}$$

The scalar value of 10 is used in the program and is shown in the read only box next to the dB box on the GUI.

The oscilloscope has a query function to check if the oscilloscope has triggered. If it did not, the program decreases the trigger level by 70% and tries again. To prevent triggering on noise, it does not go below 5 mV.

3.6 Volts/Division algorithm

The volts/division on the oscilloscope has to first be guessed and then checked for clipping on the oscilloscope. For VF-TLP, the incident volts/div is known to be

$$\frac{V}{div} \text{ for } V_{inc} = \frac{V_{pre}}{2} * \frac{1}{series_atten * pickoff_atten * scope_atten} * \frac{2}{\#Div} * 1.5 \quad \text{Eq. 5}$$

For V_{dut} in TLP and VF-TLP, the initial guess is shown in Eq. 5. Volts/div for I_{dut} is shown in Eq. 6.

$$\frac{V}{div} \text{ for } V_{dut} = V_{pre} * \frac{1}{serie_atten * kelvin_atten * additional_atten} * \frac{1}{\#Div} * 1.5 \quad \text{Eq. 6}$$

$$\frac{V}{div} \text{ for } I_{dut} = \frac{V_{pre}}{50} * current_gain * \frac{1}{series_atten * scope_atten} * \frac{1}{\#Div} * 1.5 \quad \text{Eq. 7}$$

The V_{dut} equation is used for VF-TLP and TLP. The factor of $\frac{1}{\#Div}$ is due to the oscilloscope being divided into ten segments. The multiplication of 1.5 provides some room in the calculation because it is an estimate. The I_{dut} equation is similar except V_{pre} is divided by 50 from the impedance of the load and the $current_gain$ is a scalar that is chosen on the setup page

depending on what current probe is in use. In this work, a Tektronix CT-1 current probe is used which amplifies the signal by a factor of five.

Once these divisions are set and the results are measured, a check is done to see if the waveform fits on the oscilloscope screen. A query of the oscilloscope for the minimum and maximum value returns the status bit. This signals whether there has been clipping high or low. If it clips high, the volts/div increases by 50%. If it clips low, the waveform is moved up. Initially, the reference for the waveform is moved down to the second-to-lowest division on the oscilloscope. This allows the waveform to use the entire screen. Also, a check is in place to determine if the top of the waveform is above the middle division. If the device experienced a snapback event, the volts/div may be much larger than needed and the waveform may be very small on the screen.

The next step in the oscilloscope volts/div setup is to implement adaptive ranging. This zooms in on the top portion of the pulse so the resolution is much better when taking an IV curve. For example, if one measurement is right on the edge of clipping but has not yet clipped, it will have better resolution and can measure small variations in the signal. However, the next measurement may be only slightly larger than before but will take up less of the oscilloscope screen due to the increase in volts/division. This increases quantization error which needs to be much smaller than the signal magnitude.

4. Conclusion

4.1 Summary

TLP and VF-TLP are commonly used in ESD labs to study failures of many devices and structures in integrated circuits. The automation of these tests is important to take precise and reliable measurements. What would have taken a day of tedious measurements and changing oscilloscope values can now be done much more efficiently and accurately. The final cost is a fraction of that of a commercial tester and produces comparable results.

4.2 Future Work

A calibration page for the software should be implemented to give better results. Small changes in resistivity in current probes can cause inaccurate measurements along with the oscilloscope resistance not being exactly 50 Ω . A calibration page can be used to determine the difference from correct values and multiply the waveforms by a scalar value to give the true measurement. This tester will be used for many years by graduate and undergraduate students to produce data for research papers and symposiums. Future users will find enhancements to the program to increase accuracy and utility across many different applications.

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