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***For Electrostatic Discharge
Sensitivity Testing***

***Transmission Line Pulse (TLP) –
Transient Response Evaluation***

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FOREWORD

The transmission line pulse (TLP) technique is a method for pulse testing a semiconductor device to evaluate its voltage-current response, which is commonly used as an ESD characterization tool. The basic requirements of TLP methodology are defined in the standard test method ANSI/ESD STM5.5.1, which is focused on the quasi-static behavior of the device under test (DUT). All the relevant quasi-static device parameters obtained from TLP characterization following ANSI/ESD STM5.5.1 are obtained by averaging in a pre-defined measurement window. However, many semiconductor devices show peculiar physical effects when stressed by the fast-rising edge of the TLP voltage/current waveform, which in some cases may induce premature and unexpected failures during ESD testing.

These effects are not completely addressed by the TLP characterization test method in ANSI/ESD STM5.5.1. Therefore, to have a complete picture of device behavior in the ESD regime, an extension of the analysis into the initial transient phase is also necessary.

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ESD Association Technical Report for Electrostatic Discharge Sensitivity Testing – Transmission Line Pulse (TLP) – Transient Response Evaluation**1.0 PURPOSE**

The purpose of this technical report is to address two key points:

- 1) Measurement issues: under what conditions it is possible to perform a valid measurement of transient response and know that the results are real characteristics of the device being tested and not set-up artifacts.
- 2) Report a collection of already available and published characterization examples, useful to assess better the relevance of this type of measurement and the expected impact on ESD performances (especially during CDM stress).

The starting point of this report is the TLP system and its related requirements, as described in ANSI/ESD STM5.5.1. The most important modifications needed to address the initial transient response will be presented here.

2.0 PROBLEM DEFINITION AND MAIN CHALLENGES**2.1 Goal: What do We Want to Measure?**

The transient response of circuit elements is important for the effectiveness of ESD protection design not only at the device level for HBM and CDM protection but also in system-level ESD protection. A circuit element with low dynamic impedance and a low clamping voltage measured in a time range between 50 ns and 100 ns may be ineffective as an ESD protection device if the low impedance state takes a long time to turn on, or there is a large voltage overshoot required to enter the low impedance state. It is, therefore, extremely helpful to know the transient responses of all circuit elements in an ESD protection design, both the circuit elements providing protection as well as the circuit elements being protected. It can also be useful to examine the transient response of the full protection design to determine if the protection elements and the circuit elements requiring protection work well together and as expected. The list of potential circuit elements and circuits suitable for study with transient TLP is quite long. Transient response TLP may have applications outside of the field of ESD. The following list includes some of the most obvious candidates for study, but it is by no means complete:

- Diodes, especially those used as steering diodes in protection design
- MOS transistors
- SCR (npnp) structures
- Transient Voltage Suppressors (TVS) used as protection elements on printed circuit boards
- Gate oxides
- Full I/O buffers

2.2 Differences with Respect to ANSI/ESD STM5.5.1

The current EOS/ESD Association, Inc. standard test method for TLP and VF-TLP, ANSI/ESD STM5.5.1 [1], gives guidance for obtaining valid current versus voltage measurement using TLP methods. That document defines TLP methods (pulse duration in the order of 100 ns), VF-TLP methods (pulse duration shorter than or equal to 10 ns), and long pulse TLP methods (pulse duration more than 200 ns). In principle, this document applies to all, but in practice, most transient analysis will be done with VF-TLP systems. The standard test method targets device behavior characterization, assuming that the DUT is in a quasi-static state during the measurement windows for current and voltage. The waveforms used to obtain the quasi-static information may also be used to derive information on the transient behavior of the DUT. The current TLP document, ANSI/ESD STM5.5.1, discusses bandwidth requirements for quasi-static measurements but does not give guidance on how to obtain time-dependent information from TLP data. This technical report

discusses different aspects that need to be considered when using TLP systems to obtain a transient characterization of devices. Stricter hardware requirements may be demanded to avoid limiting the capabilities of existing equipment for transient characterization purposes.

2.2.1 Transient Versus Quasi-Static

Figure 1 shows examples of voltage waveforms from VF-TLP stresses with three different rise times. It shows that the voltage is nearly constant and independent of the rise time at the end of the pulse. This is the so-called quasi-static region, which is used for regular TLP characterization. In contrast, at the beginning of the pulse, the voltage changes significantly over time and depends on the selected rise time. The observed time dependence may be due to the DUT but also is impacted by the electrical influence of the measurement equipment. In general, for accurate measurements in the transient response region, the high-speed response of the measurement equipment should be optimized for the best characterization of the true time-dependent response of the device. The measurement equipment impact and best practice techniques for gathering data in the transient response region at the beginning of the pulse is the topic of this technical report.

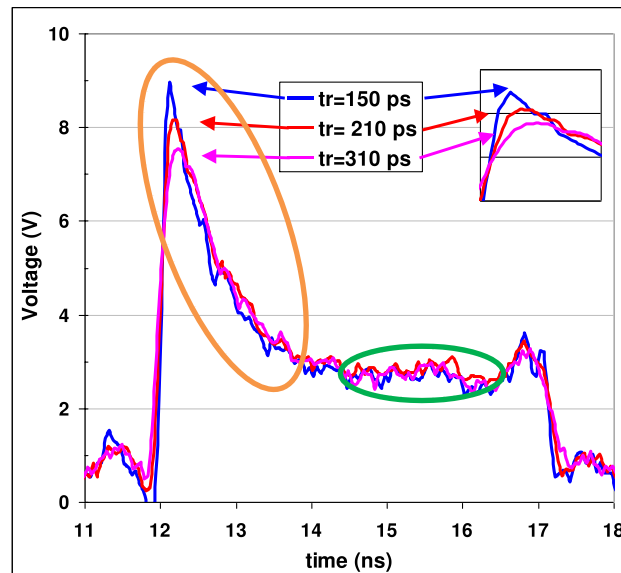


Figure 1: Voltage Waveforms Showing Transient (Orange Highlight) and Quasi-Static (Green Highlight) Behavior

2.2.2 De-Embedding Versus Calibration and Correction

An important aspect of being able to obtain good quantitative data is to minimize the impact of the measurement equipment on the results. ANSI/ESD STM5.5.1 [1] and the TLP user and application guide, ESD TR5.5-04 [2], discuss in detail that proper calibration and correction is needed to get good quasi-static results. Both are data processing calculations applied to the raw measured data. Calibration, using known reference components, ensures that the absolute value of the data is correct. Correction removes the effects of parasitic resistance in series with and parasitic conductance in parallel to the DUT. Together this ensures that the resulting I-V curve reflects the actual voltages on and currents through the DUT.

While this is also required for transient characterization, the standard procedures may not be adequate. Since all regular calibration and correction is done using quasi-static data, inductive and capacitive effects are not considered. Therefore, additional data processing may be needed to obtain the true DUT transient response. Such methods will be called de-embedding in this report.

to distinguish from calibration and correction. Several potentially relevant aspects will be covered in the next sections.

In general, the approach is to minimize the effects of cables, probes, etc. such that there is a limited impact. For the best accuracy, the raw data needs to be post-processed to separate the DUT behavior from the system characteristics. Some systems include the option to add de-embedding of the raw data, after calibration and correction, based on measured transfer characteristics of probes and cables. An example is shown in Figure 2 illustrates that the apparent overshoot and ringing are largely due to the probe characteristics.

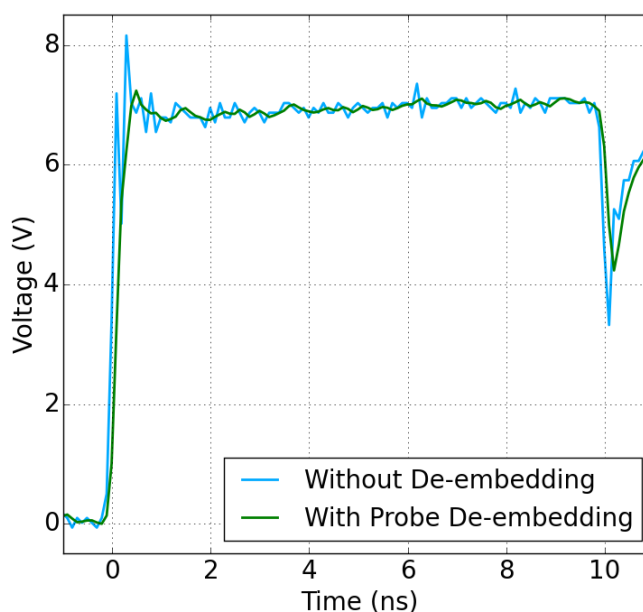


Figure 2: Example of the Waveform Post-Processing Using a De-Embedding Procedure

2.3 Pre-Requisites

As mentioned earlier, bandwidth requirements for quasi-static TLP are discussed in ANSI/ESD STM5.5.1. Since these bandwidths are aimed at quasi-static applications, typically, the bandwidths are insufficient for adequate transient analysis. ANSI/ESD STM5.5.1 also discusses oscilloscope bandwidth requirements for verification of fast TLP pulses with short rise times (see Table 1 of ANSI/ESD STM5.5.1). These requirements would also be sufficient for an equivalent transient response. For other system components, higher bandwidths are typically chosen to avoid limiting the overall system bandwidth. This may pose restrictions for DUT holders, voltage probes, etc. Examples will be given in subsequent sections, including a description of some of the issues which must be addressed when extracting time-dependent information from TLP measurements.

2.3.1 Measurement Bandwidth

In ANSI/ESD STM5.5.1, the bandwidth of measurement components is specified in a way not to be a limiting factor in the properties of resulting quasi-static current versus voltage plots. The minimum required bandwidths are therefore much smaller than needed for measuring average TLP rise times and DUT response times. Bandwidth requirements are much more critical when measuring transients. The properties of the full measurement chain need to be understood. Cables and attenuators can limit bandwidth if not chosen carefully. It is often a good practice to select cables and attenuators with bandwidths sufficiently higher than the limiting elements in the measurement chain. This is often not an option with the most central element in the measurement chain, the oscilloscope. For economic reasons, the oscilloscope bandwidth is often like, or even

smaller than, what is needed to correctly measure the fastest TLP rising edge available in a VF-TLP system. It is important to understand these limitations when looking at transient effects. Oscilloscope bandwidth can also depend on the gain or attenuation settings during measurement. The oscilloscope sample rate can limit measurements. For example, some 4-GHz oscilloscopes have a 20 GS/s sampling rate if only a single channel is used, but the sampling rate is limited to 10 GS/s if two channels are used. Slow sampling rates can result in missing the peak voltage in a sharp spike. The scope sensitivity should be set such that sufficient details are visible, noise is minimized, and the full transient is visible. The range setting should be adapted to the actual signal received. It may be necessary to add a clamping device to protect the oscilloscope input for (accidental) large signals.

The bandwidths of voltage and current sensors must be understood. This is especially true for current probes since probes with greater than 1-GHz bandwidth are rare.

2.3.2 Test Fixtures

In calibration and correction for standard TLP measurements, the only test fixture properties addressed are resistances, both shunt resistance in parallel with the DUT and resistance in series with the DUT. When addressing time dependency, both test fixture inductance and capacitance can affect measurements. As discussed below, inductance is usually a larger issue, but both need to be considered.

It is often stated that one mm of circuit board trace is approximately 1 nH of inductance. A 0.5-mm diameter wire that is 10 mm long has an inductance of approximately 7.3 nH. It is, therefore, not hard to have one or more nH of inductance in series with the DUT. For a 1-ampere pulse with a 1-ns rise time, 1 nH of inductance will produce a 1-volt spike. Since TLP currents are often many amperes and rise times are only a fraction of a nanosecond, inductive voltage spikes can be significant. It is important to know that such voltage spikes can result from the test fixture and may not be a property of the DUT. Separation of test fixture inductance from DUT inductance or overshoot is critical.

In most cases, the capacitance of a test fixture is not an issue, but it must be kept in mind. For instance, a 1-pF parasitic capacitance will have a characteristic rise time of 50 ps with a 50-ohm TLP system. This is sufficiently fast to be ignored in most situations. If, however, a time-domain reflection and transmission (TDRT) configuration is used, with its 100-ohm impedance, the 100-ps rise time is like the 100-ps rise times available with many VF-TLP systems.

This document will guide the user in identifying test fixture parasitics and procedures for removing the parasitics from measurement data.

2.3.3 Device Under Test Properties

Once test fixture parasitics are accounted for, it is important to understand the characteristics of the transient behavior that is a property of a DUT. This is especially true for voltage overshoot at the beginning of a TLP pulse. Is the overshoot due to the inductance of the DUT combined with a rapidly changing current, or is it a delayed turn-on of semiconductor circuit elements? Misidentification of the nature of the overshoot could result in considerable effort spent on trying to improve the behavior (for example, by changing the doping levels in the semiconductor), but the problem is a long trace length in a test structure or the bond wire in a package.

This document will give guidance on how to separate voltage overshoot due to inductance from delayed turn-on of semiconductor components.

2.3.4 Test Fixture Evaluation

This section will describe some simple procedures for evaluating the properties of a test fixture but will also help to evaluate a full TLP system for transient measurements. In this discussion, it is assumed that the TLP system being used can store waveforms that have been adjusted for system calibration.

The TLP system used in the following measurements is a time-domain reflection system with a 50-ohm Kelvin-like voltage measurement at the DUT. The system impedance of this system is 25 ohms (50-ohm impedance of the pulse source in parallel with 50 ohms of the voltage measurement). Voltage measurements are all direct measurements, but current measurements are from a subtraction of the incident and reflected pulses measured with a 2.2-kilohm voltage pick-off tee. All examples are for a nominal 200-volt pulse, which would measure 100 volts or less into 50 ohms.

The measurements in the remainder of Section 2.0 (except for Figure 4) were made with a 5-ns long pulse with a 0.1-ns rise time. The oscilloscope had a 4-GHz bandwidth with a sample rate of 20 GS/s if using a single channel, but only 10 GS/s if two channels are used, as in the presented measurements. A 4-GHz bandwidth is considered sufficient to measure rise times to just below 0.1 ns, using the equation $t_r = 0.45/BW$ (BW is equal to the bandwidth of the oscilloscope in Hertz). The 10 GS/s sample rate is not, however, sufficient to see the details of the rise time and could miss overshoots with a duration of less than 0.1 ns. The alternative Kelvin implementation discussed in Section 3.2.2 could have been used to obtain better time resolution since only one oscilloscope channel is required.

The first step is to understand the properties of the TLP pulse source. Most transient TLP measurements are done using VF-TLP. At pulse lengths of 5 ns and below, pulse shapes typically rise rapidly to 80% of their final value, followed by a more gradual rise to their final value. On some systems, there can be considerable slope even out to 5 ns. At the end of the pulse, the amplitude drops quickly at first but will often have a tail that extends well past the end of the pulse. The best way to understand the pulse source properties is to feed the TLP pulse output directly into a high-speed oscilloscope with 50-ohm input impedance, using as short a cable as is practical. This will avoid any potential impact on the pulse shape induced by the initial non-ideal behavior of the switch. Such a coaxial cable is already included between the switch and the output connector in most TLP systems.

Moreover, proper attenuators should be used to protect the oscilloscope. The oscilloscope can be the VF-TLP system's oscilloscope or a standalone oscilloscope with as high or higher bandwidth as the TLP system's oscilloscope. Capture several waveforms at different voltages and rise times at which final measurements will be made. These waveforms provide the standard upon which other measurements can be compared. A sample waveform directly into the system's oscilloscope is shown in Figure 3 for a 200-volt pulse.

Note: The pulse does not settle to a constant value until after about 2 ns.

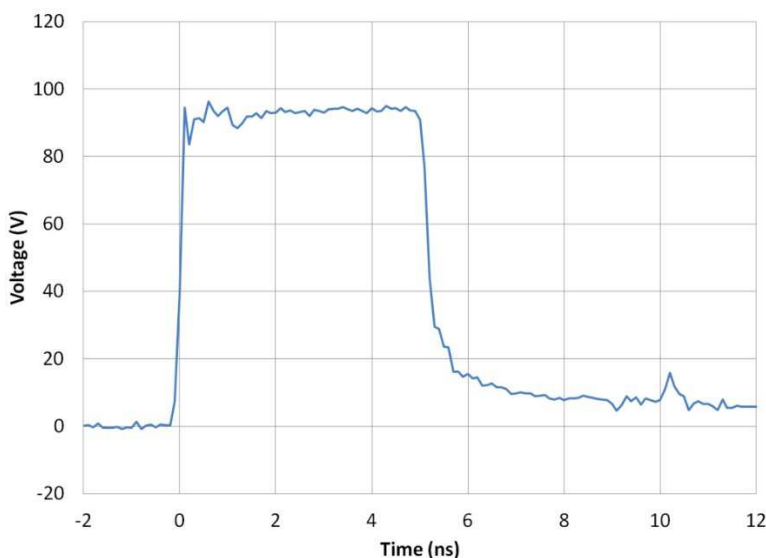


Figure 3: Sample Waveform Directly into 4-GHz Oscilloscope with 1-M Cable (Average of Ten Pulses)

After capturing the sample waveforms, set up the TLP system as it will be used during transient measurements and calibrate the system using open, Zener, resistor, and short calibration samples following the procedures in ANSI/ESD STM5.5.1 or using the manufacturer's instructions. If Kelvin measurements are being done, short calibration usually can be skipped. The calibration standards should mimic as much as possible the final DUT configuration. It is a good practice after calibration to measure TLP I-V curves of the calibration samples to ensure that the calibration was successful.

After calibration, capture several current and voltage waveforms into an open, at the same TLP voltages and rise times as used when pulsing directly into the oscilloscope. The current waveforms should be close to zero. Sharp spikes at the beginning and end of the current pulse can be an indication of an improper time delay between the incident and reflected signals when combining the incident and reflected current pulses to determine the DUT current. A double exponential current, rapid rise followed by exponential decay, could be an indication of capacitance in the test fixture. Any currents observed in this measurement represent non-ideal elements of the TLP system, which must be fixed or taken into consideration when evaluating data on unknown samples. An example of a current waveform measured on an open circuit, including these spurious effects, is reported in Figure 4.

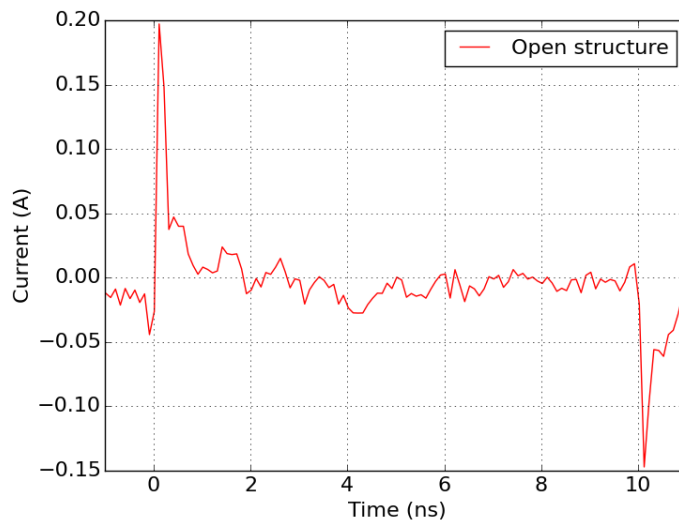


Figure 4: Example of Current Waveform Measured on an Open Circuit with Spurious Spikes Due to Non-Ideal Elements of TLP System

Comparing the voltage waveform for an open with the direct measurement of the TLP pulse waveform into the oscilloscope can give an excellent qualitative understanding of how additional cables, test fixtures, and measurement probes degrade the TLP pulse, especially within the first one or two ns. Scale the direct to oscilloscope waveform to match the magnitude in the measurement window used for system calibration. For many systems using a high impedance voltage probe, the scaling will be approximately two, because the direct to oscilloscope reading will be a 50-ohm measurement, effectively cutting the signal in half. A sample is shown in Figure 5. In the example, no scaling correction was needed since both pulses were at 200 volts, and the voltage was measured with a 50-ohm voltage sense. A small time shift, 0.1 ns, was used to account for different oscilloscope trigger conditions. The differences between the two waveforms indicate imperfections in the test fixture and measurement chain. These can include capacitance in the test fixture, differences in attenuation over frequency in the cables, deviations in the sensitivity of the voltage probe. If the voltage measurement does not use Kelvin sensing, errors in the time delay used to combine the incident and reflected pulses will result in distortion of the waveform, especially during the rising and falling edges. In the example in Figure 5, the only noticeable difference between the open measurement and the pulse directly to the oscilloscope is a small decrease in

amplitude over the first two ns. This difference may be primarily due to increased cable length that is needed to go from the pulse source to the test fixture and then to the oscilloscope, rather than from the pulse source directly to the oscilloscope.

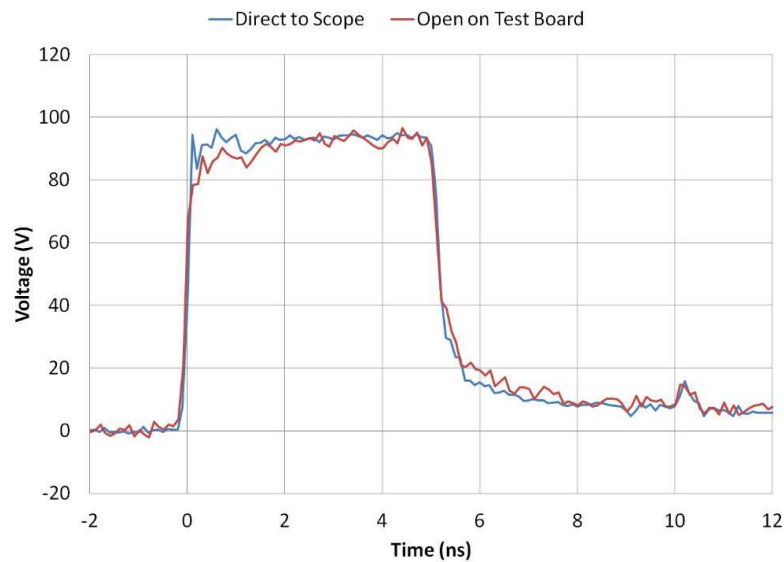


Figure 5: Comparison of Voltage Waveform into an Open with Waveform Directly into Oscilloscope

Next, measure the voltage and current waveforms into a short. Ideally, the voltage across the short should be zero. Voltage spikes at the beginning and end of the pulse can be due to two things. If the system does not use Kelvin voltage measurements, an error in the time delay between the incident and reflected pulses will create voltage spikes. It is likely, however, that there will be inductive voltage spikes at the beginning and end of the pulse, as shown in Figure 6 for the same 200-volt pulse into a short. After a discussion of the measured current through the short, how to estimate the amount of inductance of the short will be discussed.

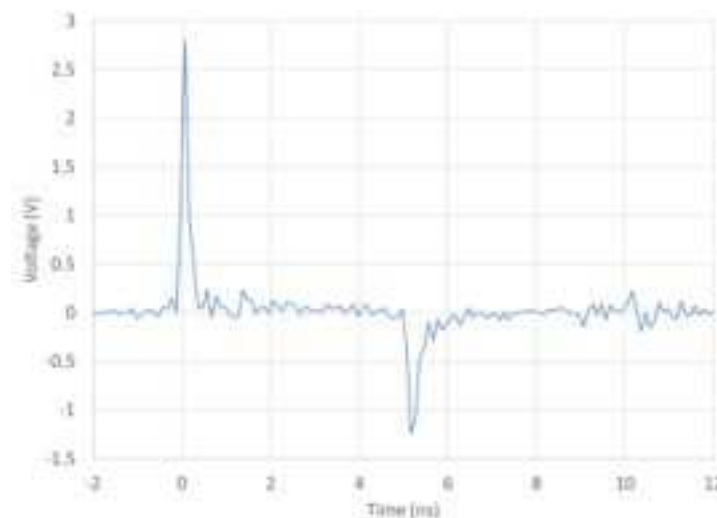


Figure 6: Voltage Measurement Across a Short

As done for voltage into an open, compare the current waveform into the short with the waveform directly into the oscilloscope at the same TLP voltage by scaling the direct to oscilloscope waveform to match the current amplitude in the time window used for calibration. The scaling factor for the voltage should be close to the TLP system's source impedance. For the data in Figure 7, the scaling factor was 25.3 ohms, very close to the system nominal impedance of 25 ohms if two 50-ohm systems are connected, with the DUT in-between, the TLP source and the 50-ohm Kelvin contact side used. If a 2.2-kilohm voltage pick-off tee is used near to the DUT, the equivalent impedance remains 50 ohms from the TLP source through the 50-ohm coaxial cable. Deviation of the current waveform from the direct-to-oscilloscope waveform will indicate non-ideal elements in the measurement path. In this case, the deviation of the current measurement from the ideal direct-to-oscilloscope measurement is like the comparison of voltage into an open compared to direct to the oscilloscope.

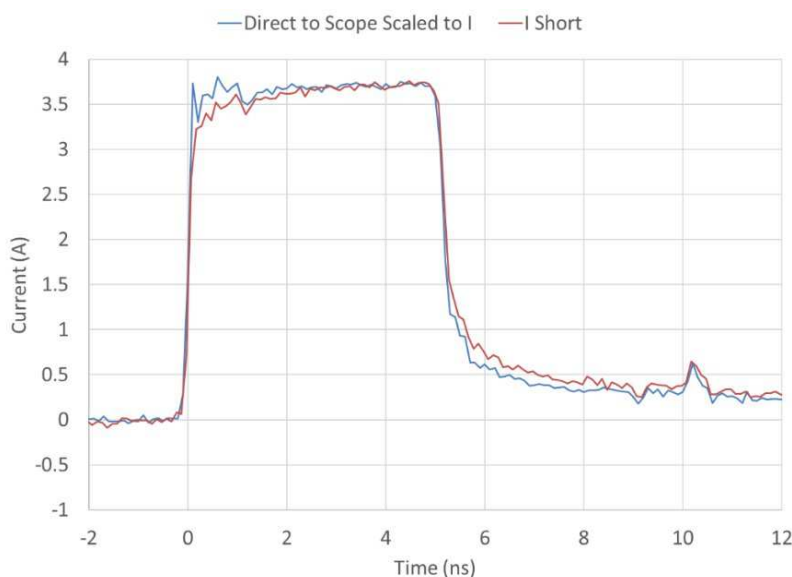


Figure 7: Comparison of Current Pulse Measured Through a Short to a Scaled Version of the Pulse Direct to the Oscilloscope

If the current waveform looks good, and if the measurement chain's bandwidth is fast enough to capture the slope in the current waveform, it is possible to estimate the amount of inductance in the short. Using the basic equation for the voltage across an inductor:

$$v = -L \frac{di}{dt}$$

Using the measured current waveform to calculate di/dt , assumed values of the inductance could be used to determine if the calculated inductive voltage waveform can be made to match the measured voltage waveform. The calculated voltage waveform should match on both the leading and trailing edges of the pulse. An example of calculated voltage spikes is shown in Figure 8 using the current data in Figure 7, combined with the voltage data in Figure 6. An inductance value of 0.15 nH was used. Since the fall time of TLP pulses is typically slower than the rise time, inductive voltage spikes on the trailing edge are usually smaller than the inductive voltage spikes on the leading edge. This is the case for the example shown in Figures 6 and 8.

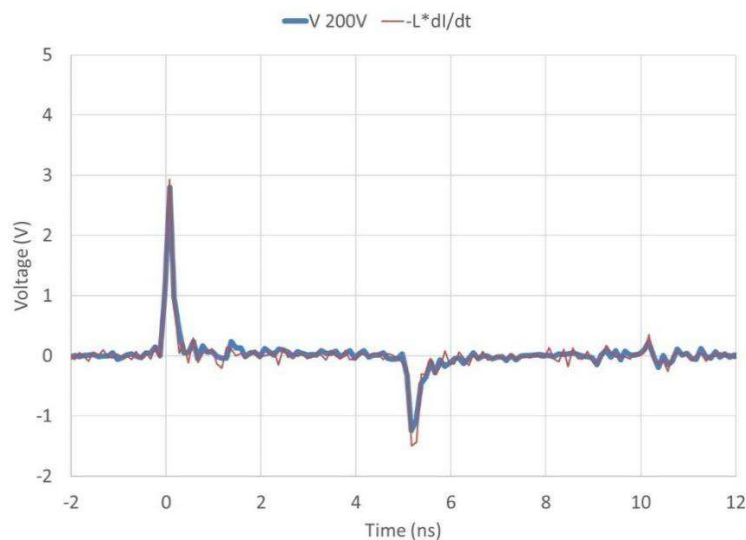


Figure 8: Comparison of Measured Voltage Across a Short and Voltage Calculated From $-L \cdot di/dt$ of Current Through the Short Assuming an Inductance of 0.15 nH

2.3.5 Transient Verification Samples

Transient VF-TLP measurements are often made at the extremes of measurement equipment capabilities, such as oscilloscope and sensor speed and the high-frequency response of test fixtures or probes. It is therefore desirable to have samples with known transient properties to verify that measured transients are indeed properties of the device being tested and not artifacts of the test system. There are two samples with known properties for this purpose, capacitors, and inductors. Capacitors in the several to tens of pF and inductors in the several nH range are available in small surface-mount form factors such as 0402 (1.0 mm x 0.5 mm) with excellent high-frequency performance.

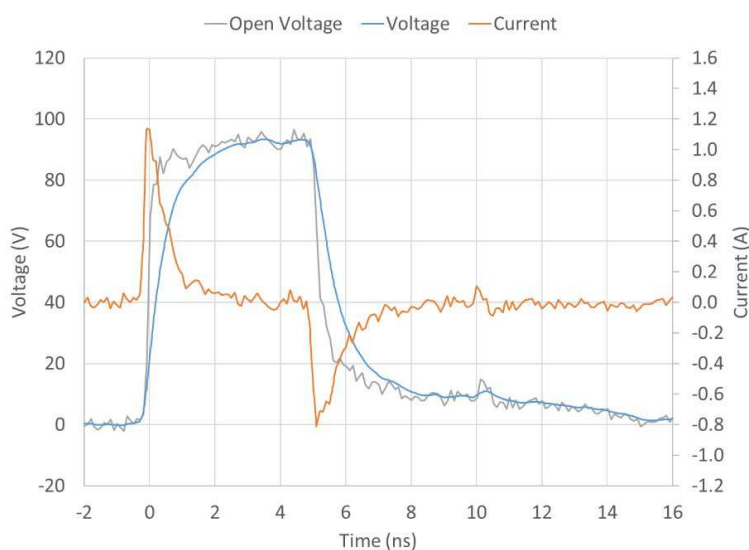


Figure 9: Circuit Simulation of the Current and Voltage for a 20-pF Capacitor When Stressed with the Open Voltage from Figure 5