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AND9006/D

Using Transmission Line Pulse Measurements to Understand Protection Product Characteristics

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APPLICATION NOTE

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INTRODUCTION

Transmission Line Pulse (TLP) is a measurement technique used in the Electrostatic Discharge (ESD) arena to characterize performance attributes of devices under stresses that have a short pulse width and fast rise time similar to those of ESD events. TLP is applicable for both system level ESD, as defined by IEC 61000−4−2, and integrated circuit level HBM, as defined by ANSI/ESDA/JEDEC JS−001−2010. One of TLP's prime uses is to obtain Current versus Voltage (I−V) data in which each data point is obtained from a pulse that reflects the characteristics of ESD waveforms: nanosecond rise times and 100 ns pulse width. The 100 ns pulse length and current levels up to 40 A used in TLP closely match the pulse lengths and currents that occur in ESD events. Figure 1 compares IEC 61000−4−2 and Human Body Model (HBM) current waveforms at 8 kV to TLP pulses at 8 A and 16 A. It is clear that similarities in time scale and current level makes TLP an ideal tool for characterizing the ESD properties of electronic components. This Application Note will describe the basic TLP measurements system, explain how I−V curves are obtained using the TLP system and then show some examples of how a TLP system can be used to characterize ESD protection products such as ON Semiconductors line of TVS devices.

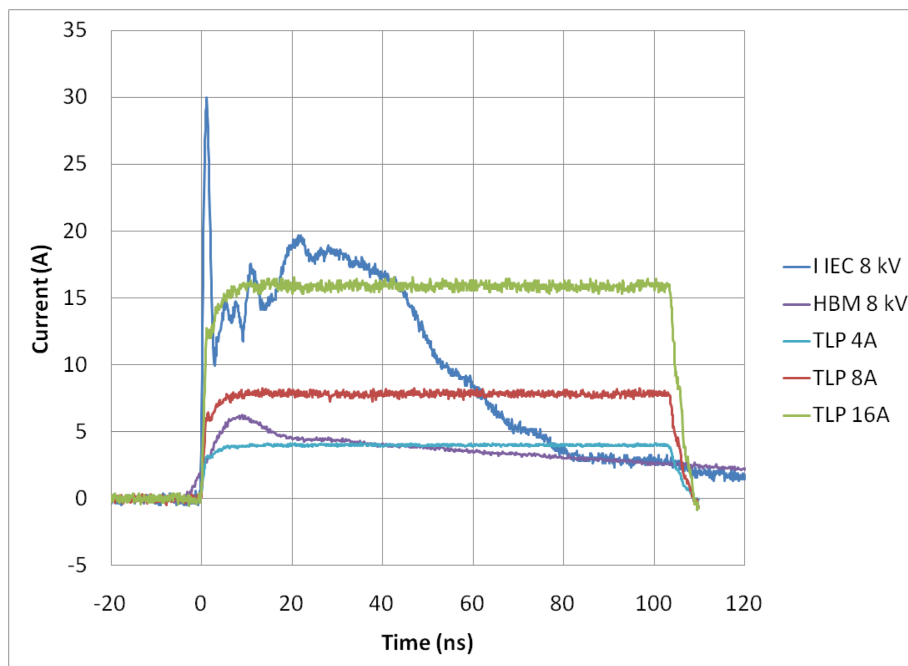

Figure 1. Comparison of the Current Waveforms of IEC 61000−4−2 and HBM Waveforms with TLP Pulses at 4, 8 and 16 A

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This application note is focused on standard or 100 ns TLP. TLP systems with deep sub nanosecond rise times and pulse lengths less than 10 ns are referred to as Very Fast Transmission Line Pulse (VF−TLP). VF−TLP systems are primarily used to explore charged device model (CDM) behavior in integrated circuits. CDM events have peak currents of several amperes and pulse widths which can be less than 1 ns. While VF−TLP systems can be useful in exploring the turn on speed of protection products they cannot deliver the energy which is required to explore the behavior under system level ESD as represented by the IEC 61000−4−2 waveform.

BASIC TLP SYSTEM

A basic time domain reflection (TDR) TLP system is shown in Figure 2. (Coaxial cables are a special case of a transmission line and the terms transmission line and coaxial cable will be used interchangeably in this document.) An approximately 10 m long 50 Ω coaxial cable, which can be charged to a high voltage, serves as the pulse source. A charged 50 Ω coaxial cable will create a rectangular pulse when discharged into a load. The length of the pulse depends on the length of the coaxial cable. The charged cable is connected to the device under test (DUT) via a switch, an attenuator and a short 50 Ω coaxial cable. Voltage and current probes on the output end of the attenuator are connected to a high speed oscilloscope so that the current and voltage of the pulses can be measured.

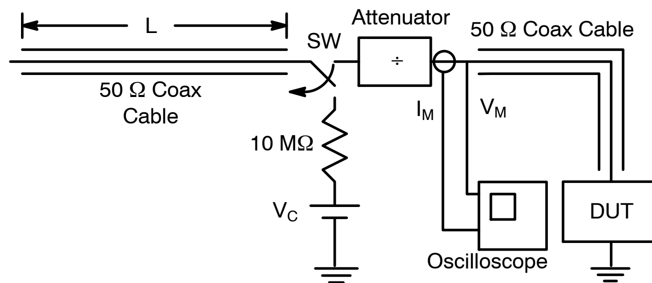


Figure 2. Basic TLP System

A TLP measurement follows a specific sequence. The transmission line is charged to a voltage and the switch SW in Figure 2 is closed. This creates the TLP pulse. The pulse passes through the attenuator, travels down the coax cable to the DUT, reflects off the DUT and travels back toward the attenuator and into the pulse source transmission line. The impedance matched attenuator is included so that reflected signals do not continue to stress the DUT after the initial 100 ns. (A pulse reflected off the DUT needs to pass through the attenuator twice before it reaches the DUT so that the magnitude of multiply reflected pulses are small enough to be ignored.) The incident and reflected signals are captured by the oscilloscope. The properties of the DUT can be determined from measured properties of the incident and reflected pulses.

When a signal on a transmission line reaches a termination the reflected signal depends on the impedance of the termination as in the following equations, in which R_{DUT} is the resistance of the DUT and Z is the characteristic impedance of the transmission line.

$$V_{ref} = V_{inc} = \frac{R_{DUT} - Z}{R_{DUT} + Z}$$

$$I_{ref} = -I_{inc} \frac{R_{DUT} - Z}{R_{DUT} + Z}$$

If R_{DUT} is 50 Ω there is no reflection. If the termination is open the reflected voltage is equal to the incident voltage while the reflected current is equal in magnitude but of opposite sign, since the charge is traveling in the opposite direction. For a short the reflected voltage is equal in magnitude to the incident voltage but is changed in sign. For a short the reflected current has the same magnitude and sign as the incident current. What is physically happening is that the reflected charge is traveling in the opposite direction from the incident pulse but because it was a short the charge is flowing back through the shield.

What the DUT experiences is the sum of the incident and reflected pulses. For 100 ns TLP the time delay between the voltage and current probes and the DUT is much less than 100 ns, which means the incident and reflected pulses overlap at the point of the voltage and current probes. During the period of overlap between the incident and reflected pulses the oscilloscope is directly measuring what the DUT experiences. This is illustrated in Figure 3a, for an R_{DUT} with a resistance less than 50 Ω. For voltage we first see the incident pulse only, but after twice the transit time between the voltage probe and the DUT the reflected pulse arrives and adds to the incident pulse. Since R_{DUT} is less than 50 Ω the reflected pulse is negative and the measured voltage is less than the incident pulse value. After the incident pulse has passed the voltage probe only the reflected pulse is measured and we see a negative going transient. The situation for current in Figure 3a is similar with an initial measurement of only the incident pulse, a period in which the incident and reflected pulses overlap, followed by the reflected pulse only. The major difference is that for current

the reflected pulse for R_{DUT} less than 50 Ω is positive, resulting in the measured current in the overlap region being larger than during the incident pulse only period.

To obtain a current/voltage pair from the pulse measurements a measurement window is defined during the time period on the oscilloscope when the incident and reflected pulses overlap, usually toward the end of this overlap period. The voltage and current during the measurement window are plotted as a point on the I−V curve, as shown in Figure 3c. To obtain a full I−V curve the process is repeated at a variety of charging voltages for the pulse source transmission line, usually starting at low charging voltages and progressing to higher voltages.

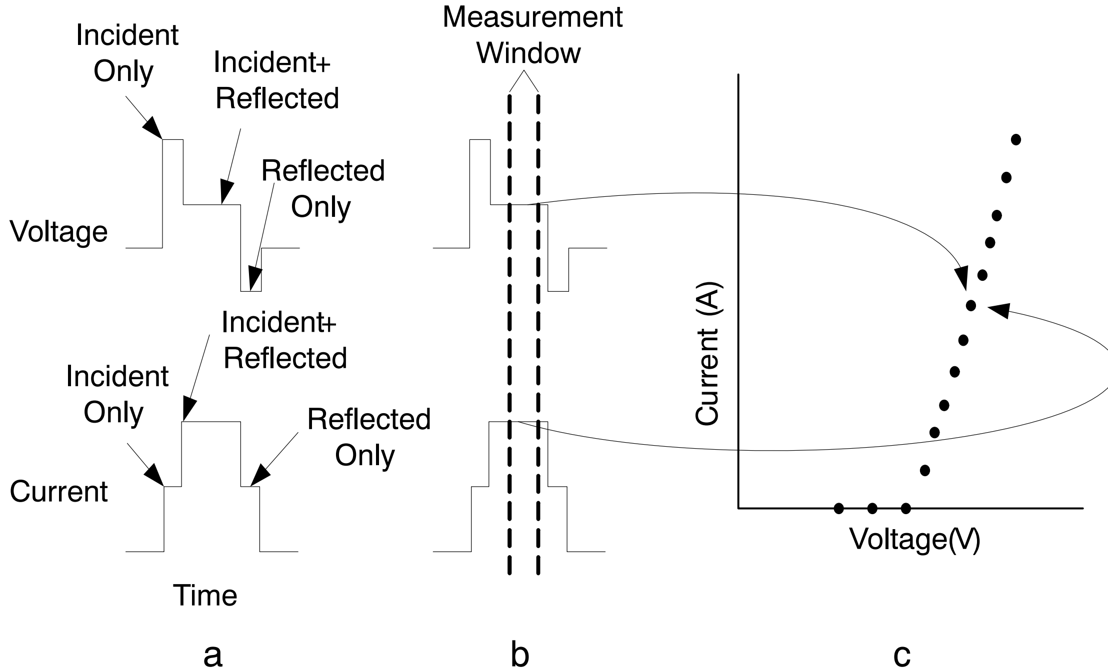


Figure 3. Explanation of How I−V Points are Determined from the TLP Incident and Reflected Pulses. The Schematic Pulse Shapes in a and b are Characteristic of a DUT with a Resistance < 50 Ω

INFORMATION FROM TLP

This section will show three examples of the use TLP to characterize ESD protection devices.

Transient Voltage Suppressor (TVS) Device in Reverse Bias

Figure 4 shows sample TLP data for a TVS diode in the reverse bias direction. In this case the TLP measurements indicate that over the measured range the TVS's properties are linear and can be represented by a linear least squares fit, as shown in Figure 4. The fit yields a dynamic resistance of 1.35 Ω and a voltage intercept of 6.49 V. (The dynamic resistance is the inverse of the slope of a current versus voltage curve over a limited range of current and voltage.) Note that the voltage intercept is not the low current breakdown voltage. The breakdown voltage of diodes is usually measured in the μA or mA range, where the current is often still increasing exponentially with voltage. TLP measurements explore the high current range, which is precisely why the resistance and voltage intercept measured with TLP more accurately reflect the protection properties of a TVS device than measurements at longer time scales.

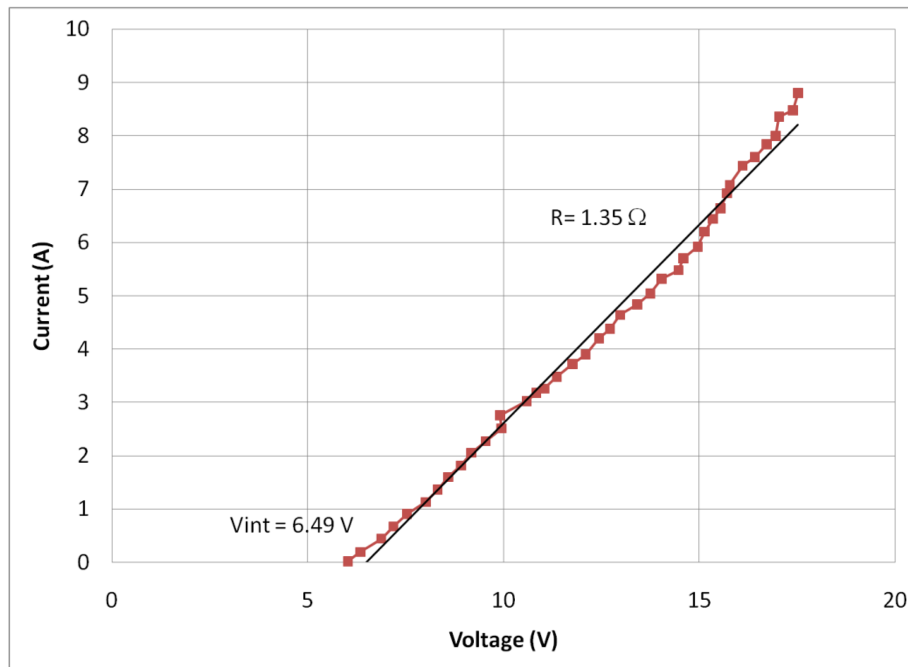


Figure 4. Sample TLP Curve of a TVS Diode

Transient Voltage Suppressor Device (TVS) in Forward Bias

Figure 5 is a TLP measurement example of a different TVS device in forward bias. At lower currents, up to about 10 A, the TVS devices shows linear behavior with a resistance of 0.86 Ω and a voltage intercept of −1.32 V. The voltage intercept for TLP measurements of a forward bias diode is well above the usual forward bias voltage of 0.6 or 0.7 V. Similar to the reverse bias breakdown voltage shown in Figure 4, the forward bias turn on voltage (often termed V_F) is usually measured at low currents where the current depends on voltage exponentially. TLP measurements explore a much higher current range and the voltage intercept from TLP is a characteristic of this higher current range.

Above 10 A of current in Figure 5 the I−V curve begins to drop below the linear relation and become curved. This occurs because at these currents the TVS device begins to heat during the pulse, even thourgh the pulse is ~100 ns long, and the resistance of the device increases. At currents above 24 A the voltage begins to decrease with increasing current. In this region the TVS device has heated to the point of melting and the device is permanently damaged.

The TLP data from this forward biased TVS device provides rich data for predicting its protective abilities. At currents below 10 A the voltage drop across the device can be easily predicted with a simple linear model. Above 10 A for a 100 ns pulse the TLP measurements show a decrease in effectiveness of the TVS to perform clamping due to self heating. Note that for shorter pulses the linear regime would extend into higher current levels.

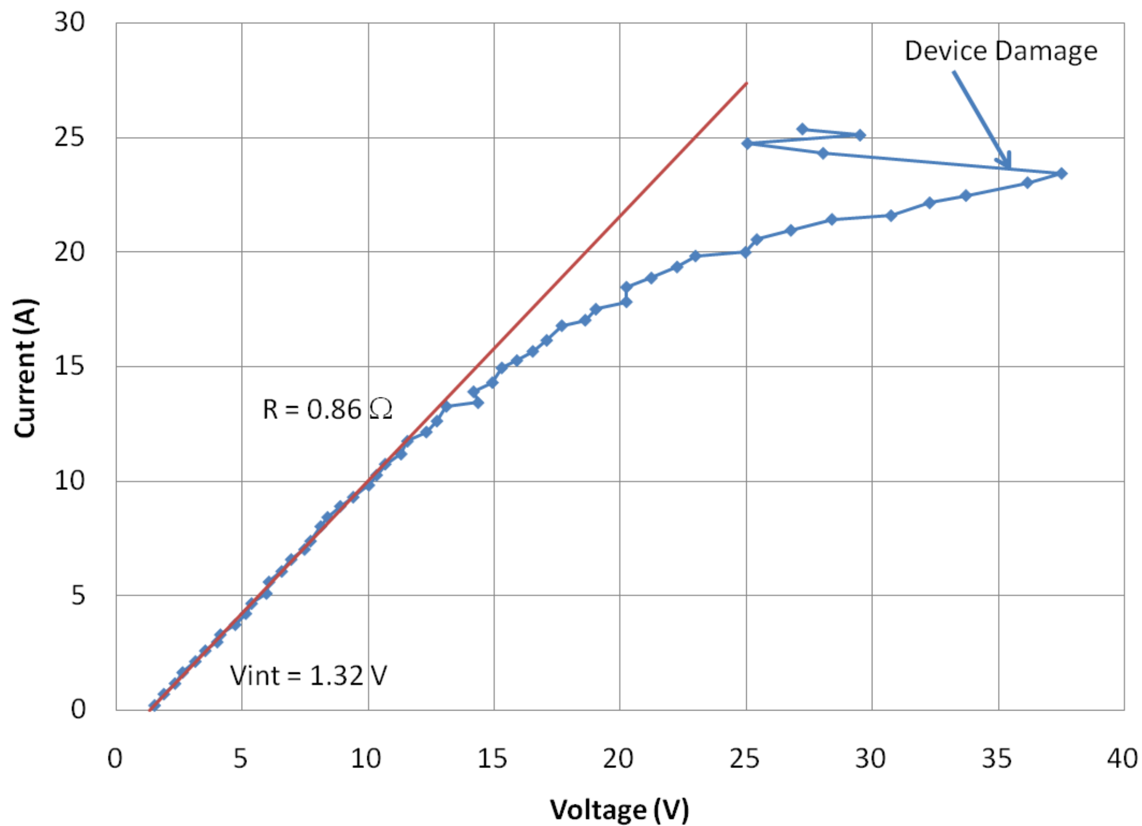


Figure 5. TLP Curve of a Forward Biased TVS Device. The Data Has Been Plotted with Negative Voltage and Current for Ease of Viewing

Low C TVS Device in Reverse Bias

TLP measurements can reveal interesting details about device behavior. Consider the TLP I−V curve of a particular low capacitance TVS deice in the reverse bias direction in Figure 6. At very low TLP stress, below breakdown, no current flows. There is a single data point at about 9 V, followed by a drop in voltage before the current increases in a decidedly non−linear fashion. The current then increases with subsequent higher TLP stress up to about 26 A. At 26 A there is a an inflection point in the data where the device is damaged.

Figure 7 shows a detail of the low current regime of this device captured with finer steps in the TLP charging voltage. (The data in Figure 7 were actually taken before the data in Figure 6 so that the low−current measurements were not made on a damaged device.) The detail shows avalanche breakdown starting at around 8 V with a resistance of 2.63 Ω up to 9.2 V. At about 9.2 V and 0.4 A the avalanche current is sufficient to trigger a bipolar junction device built into this device to turn on or “snapback”. The low current part of the snapback regime can have very low dynamic resistance, 0.33 Ω as shown in Figure 7 with a voltage intercept of 8.09 V. This dynamic resistance is not a good redictor of the device’s protection properties above 2.5 A. A better prediction of the protection properties of the device is shown in the fit of the full snapback range from 0.5 A to 26 A as shown in Figure 8. This wider range linear fit has a dynamic resistance of 0.47 Ω with a voltage intercept of 0.647 V. This example shows that when making performance predictions based on TLP data it is important that the TLP data be extracted in a current regime that matches the application.

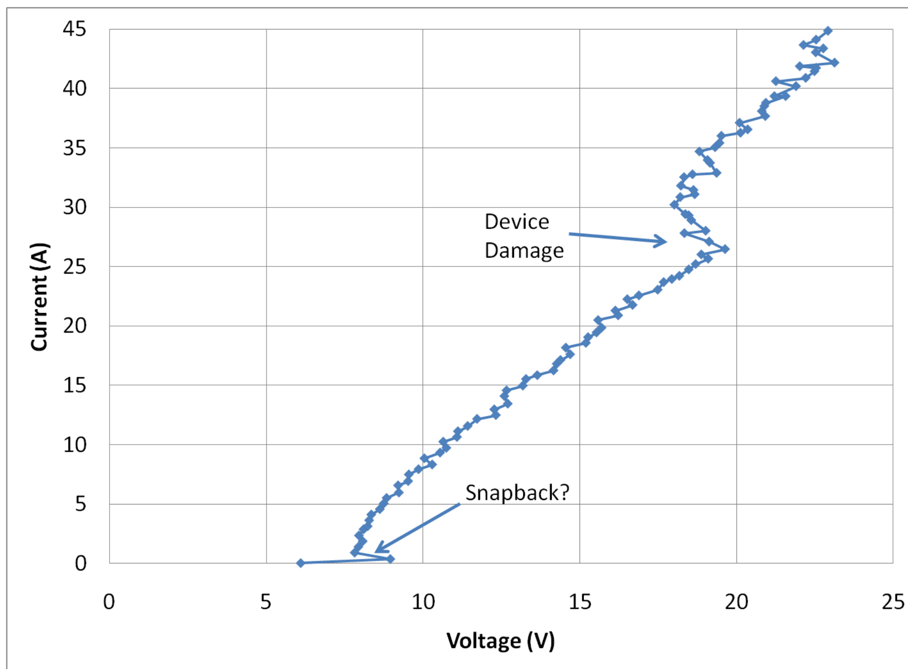


Figure 6. Example of TLP Measurement of a Low Capacitance TVS Device in the Reverse Bias Mode

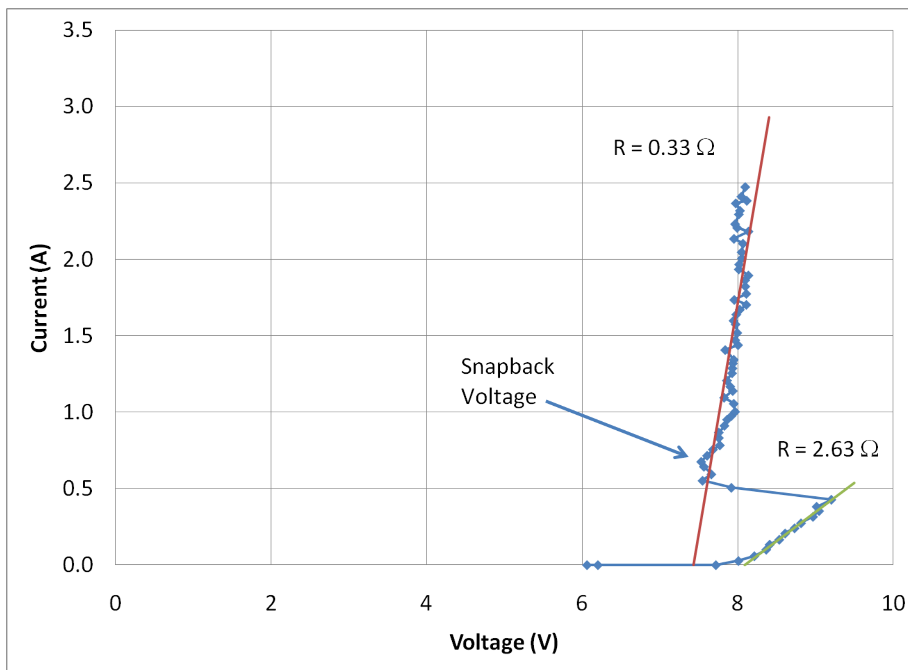


Figure 7. Detail of Low Current Region of Reverse Bias of Low Capacitance TVS

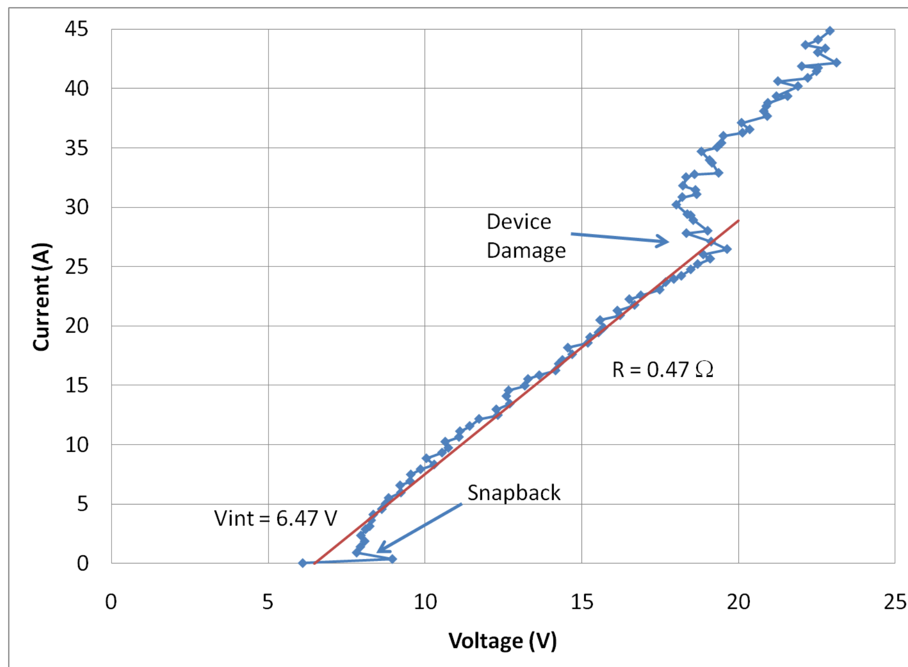
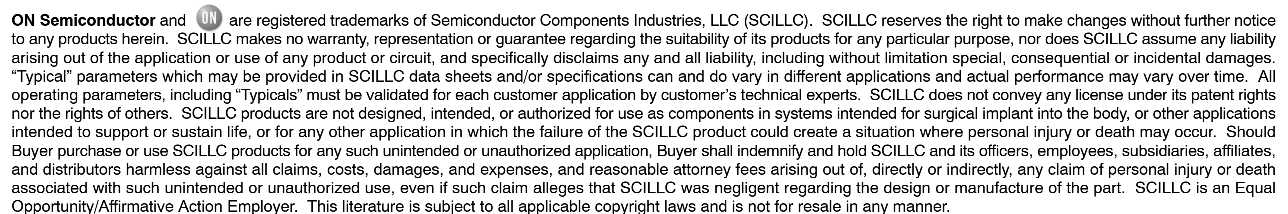


Figure 8. Example of TLP Measurement of a Low Capacitance TVS Device in the Reverse Bias Mode with a Linear Fit to the Snapback Region

SUMMARY

This application note describes how a TLP system can be used to produce I−V curves in which each data point is from a pulse whose duration and current amplitude are in the same range as system level ESD events. These I−V curves, and parameters derived from them such as dynamic resistance and voltage intercept, can be used to compare the properties of different TVS devices and can be used to predict a TVS devices performance in a circuit.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