Correlation Considerations: Real HBM to TLP and HBM Testers

Jon Barth, John Richner

Barth Electronics, Inc., 1589 Foothill Drive, Boulder City, NV 89005 USA
tel.: (702)- 293-1576, fax: (702)-293-7024, e-mail: jonbarth@ieee.org

Abstract - This paper discusses the previously unexplored initial front rise differences between Real HBM, TLP and HBM tester waveshapes. The dV/dt of the HBM test pulse amplitude below 2% has been shown to affect the high current immunity of Snapback type ESD protection circuits, and should replace the present time specification for a high voltage HBM pulse to rise from 10% to 90% of the peak amplitude, commonly known as risetime.

I. Introduction

It is the objective of this paper to present data from our study of the behavior of HBM testers and real HBM discharges. The original HBM test circuit and specifications, which defined the waveform parameters, were designed to simulate what were considered the critical factors for HBM threats on semiconductors. The risetime was determined by measuring the time to rise between 10% and 90% of the peak amplitude of real HBM discharges. For example, the ESDA specification HBM waveform is 2 to 10 nanoseconds. [1] However, because of the lack of a better specification for dV/dt, there has been a problem with correlation between HBM testers for some time.

Accurate TLP measurements with different risetimes have clearly identified dV/dt effects in some types of ESD protection structures. The magnitude of this effect is obvious when testing dV/dt sensitive structures with both 0.2 ns and 10 ns risetime pulses. [2] Because of this demonstrated fact, we believe that the present HBM specification on risetime is incomplete, and has misdirected the effort to provide better agreement between HBM testers. Some modern ESD protection circuits have shown a great sensitivity to dV/dt, which occurs during the time that a device turns on and begins to conduct to provide protection by shunting out the applied ESD threat. This rate of rise (dV/dt) from zero to the voltage where the device begins to conduct is not considered in the present HBM specification. This fact has led us to examine the first few volts of a threat pulse, which puts a protection circuit into conduction. This is important because the response of some protection circuits, and their maximum current handling capability, is directly determined by the rate of this Initial Front Rise portion of the voltage waveform.

We are introducing a new term “Initial Front Rise” (IFR) to describe the beginning of the rise, starting at zero volts, and rising until the ESD protection circuit is turned on. This part of the waveform turns the protection on and the dV/dt at this amplitude is far more important than that part of the waveform between the 10% and 90% levels presently used to define HBM dV/dt.

Our experience with TLP testing of many different snapback devices has shown their It1 point typically to be in the range of 5 to 15 volts for digital devices. Analog or RF devices Vt1 points can range from approximately 10 to 50 volts to avoid turning the ESD protection on with higher signal voltages. When a 1 kilovolt HBM test pulse is applied to a snapback device, even the highest Vt1 snapback voltage of 50 volts is reached well before the 10% amplitude of the test pulse. The snapback voltage point is reached during the IFR of the test pulse. This part of the HBM discharge waveform is of primary interest here, because of the time for the threat pulse to reach the snapback voltage for this type of ESD protection circuit. The standard for HBM testers considers the peak voltage and the 10% to 90% risetime, but ignores the IFR time, which is below 10% of the peak voltage. Although many papers showing HBM discharges seem to indicate that the initial rise is much slower than the rest of the rise, when the sensitivity of the voltage measurement is increased, and the sweep speed is increased, the rate of the initial rise is usually found to be in the sub-nanosecond range. We suggest that this voltage range of all HBM ESD pulses should be considered.

II. HBM Tester IFR

Because the 4002 TLP system demonstrated that the voltage rate of rise (the dV/dt) across the DUT is the critical parameter in determining how the protection circuit is turned on, and because it can affect the failure current levels, we became interested in measuring this parameter on HBM testers. [2] When the Initial Front Rise parameter for two different HBM testers and for real HBM discharges was measured, both were found to be much faster than initially suspected. This fact completely changed our approach to studying this phenomenon. The waveforms from two different testers were measured with particular attention to the initial front rise to 15 volts.

II.a. IMCS 5000 Tester Measurements

Figure 1. shows two measurements of the same waveform from the IMCS 5000 split out by a 50 ohm matched three way divider as shown in Fig 2.

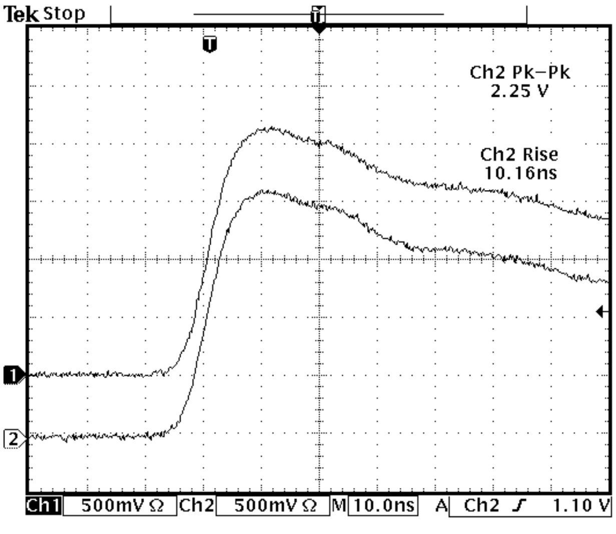

Figure 1: Two views of same 2 kV HBM tester waveform

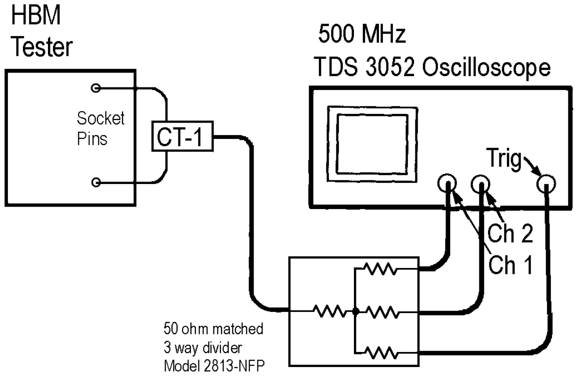

Figure 2: IMCS 5000 HBM Tester measurement setup

The setup for this tester used a three way divider (3/1 Vr) with one of the three identical signals going to the scope trigger. We could not trigger on channel 1 when set at high sensitivity because the IMCS 5000 HBM tester had a small impulse a short time before the main HBM discharge pulse. This caused the scope to trigger early on the impulse. One of the three signals was sent to the scope trigger so that we always triggered on the desired pulse. The two remaining signals were sent to channels 1 and 2 on the scope. Channel 1 was set to record the low amplitude range of the pulse at high sensitivity. Channel 2 was set at a lower sensitivity to record the total risetime and obtain the peak current value. This confirmed that we recorded the correct HBM discharge pulse.

This HBM tester radiated a ringing waveform at about 800 MHz, which coupled directly into the unshielded scope during the time of interest and added objectionable noise to the high sensitivity record. We eliminated this noise by placing the scope 25 feet from the tester and carrying the test pulse from the CT1 to the divider and scope with low loss coax.

Figure 3. shows the same two waveforms with channel 1 sensitivity increased from 500 mV/div to 100 mV/div. The channel 1 waveform begins to show some of the initial rise information. Going from Figure 3 to Figure 4, the sensitivity of channel 1 is increased by a factor of five, to 20 mV/div, the sweep speed is increased to 2 ns/div. and the IFR begins to be more clearly seen.

Moving from Figure 4. to Figure 5. increases the sensitivity by a factor of four to 5 mV/div, the sweep speed is increased to 1ns/div., and the IFR can be clearly seen.

The rate of the 15 volt IFR is measured at 0.32 ns in Figure 5.

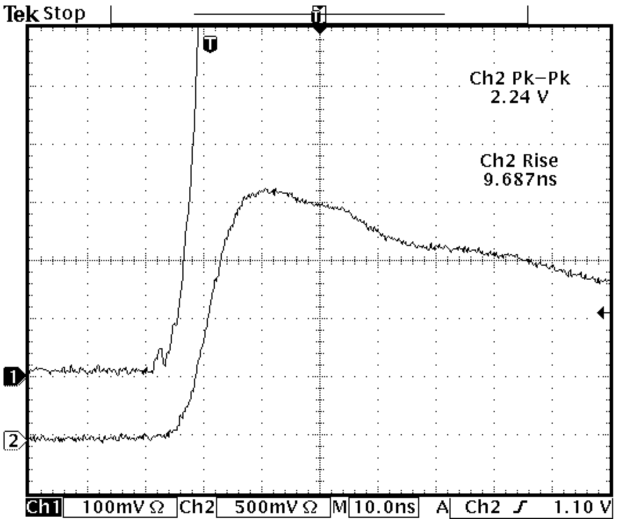

Figure 3: IFR & Peak of 2 kV pulse from IMCS 5000

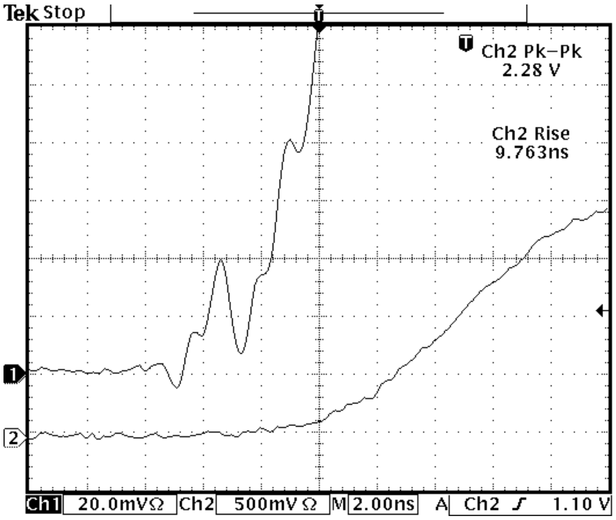

Figure 4: Expanded IFR & Peak of 2 kV pulse from IMCS 5000

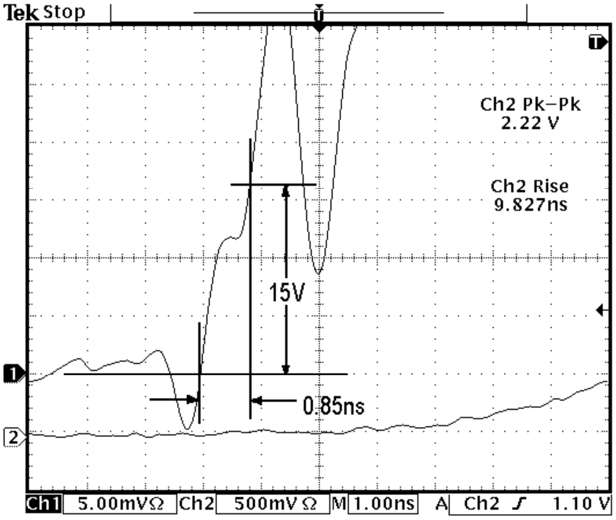

Figure 5: Expanded IFR & Peak of 2 kV pulse from IMCS 5000

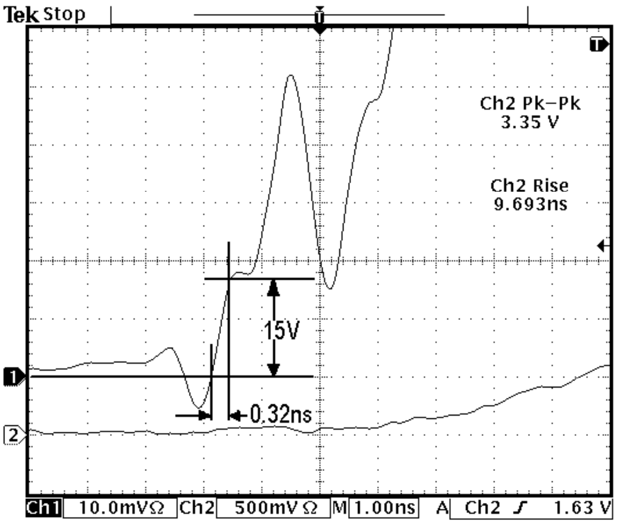

Figure 6: Expanded IFR& Peak of 3 kV pulse from IMCS 5000

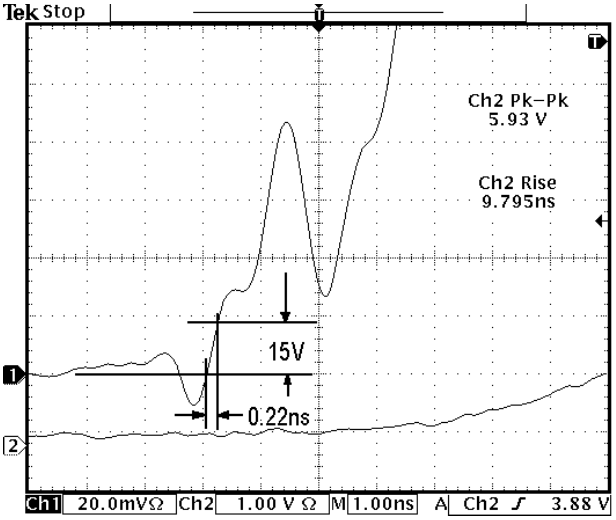

Figure 7: Expanded IFR & Peak of 5kV pulse from IMCS 5000

II.b. Verifier V3 Tester Measurements

The Verifier V3 tester was measured with two different scopes. The test setup is shown in Fig. 8 below. The first tests were made by passing the discharge current through a short circuit with a CT1 current sensor. The CT1 was fed into a 10 times voltage ratio attenuator which then fed into one channel of a DSA 602 scope. This scope has a 600 MHz bandwidth and the 10-x voltage ratio attenuator has at least a 5 GHz bandwidth. When these are used in conjunction with the 1 GHz bandwidth CT1, the combined system measurement risetime is about 0.68 ns.

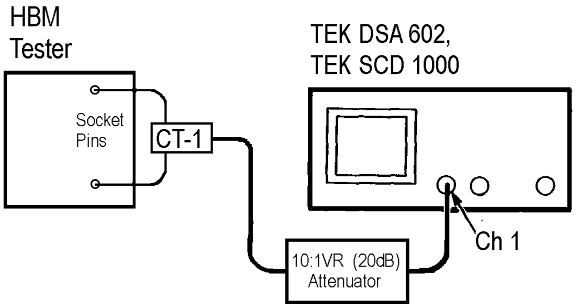

Figure 8: Verifier V3 HBM tester measurement setup

The Verifier V3 waveforms Measured with Tek DSA 602A scope are shown below in Figures 9, 10, and 11.

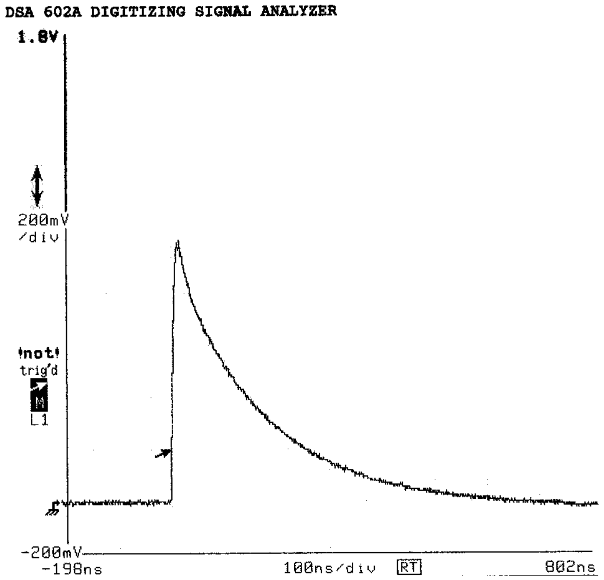

Figure 9: Full pulse from V3 HBM tester at 3 kV

With DSA 602A scope

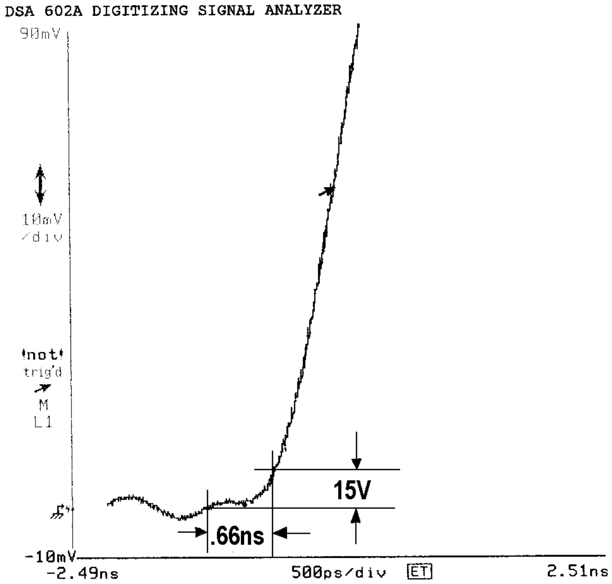

Figure 10: IFR pulse from V3 HBM tester at 3 kV with DSA 602A scope

The IFR to 15 volts was measured at 0.66 ns in figure 10, with the test pulse at 3 kV, and was measured at 0.29 ns in Figure 11 with the test pulse at 1 kV.

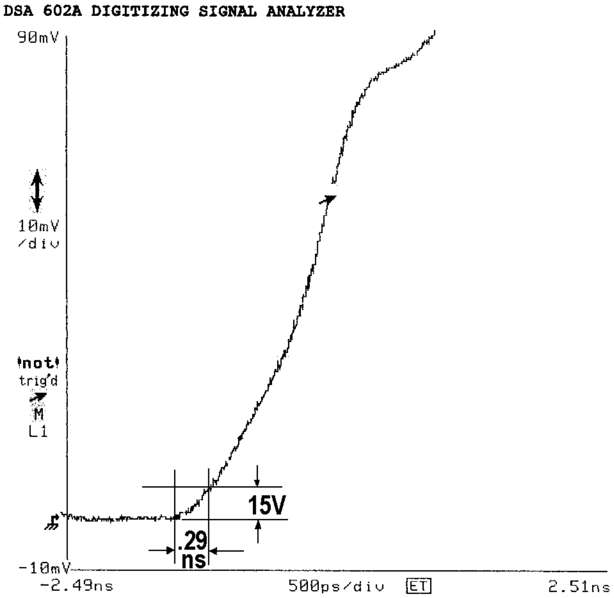

Figure 11: IFR of V3 HBM tester at 1 kV

Additional measurements of the V3 tester waveform were made on a SCD 1000 digitizer, are shown in Figures 12, and 13. This measurement system, at 0.50 ns, has the fastest risetime used for these measurements.

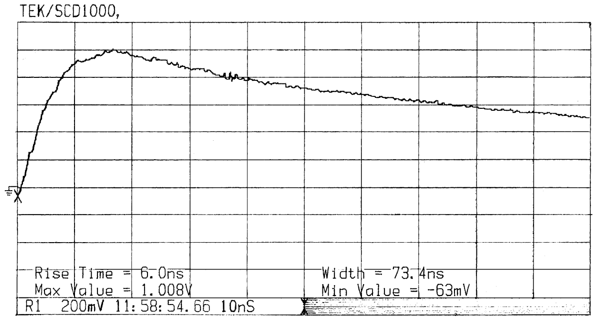

Fig 12: SCD 1000 full amplitude measurement of V3 at 3 kV

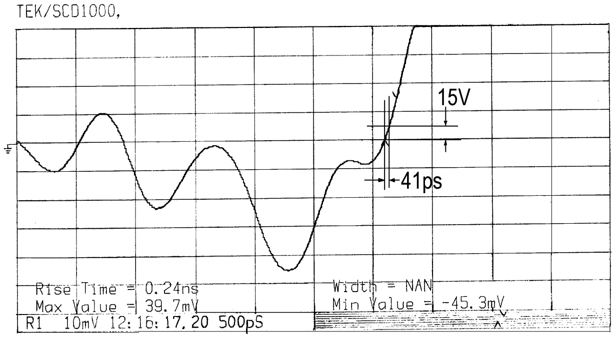

Fig 13: SCD 1000 IFR measurement of V3 at 3 kV

Note that the rise time calculated from some of these measurements exceed the inherent risetime capabilities of the test equipment. This is because the measurements were made over less than the 10% to 90% amplitude while the waveform was in rapid transition. This leads to the speculation that some of these dV/dt rates are probably faster than we measured

III. Real HBM IFR

When data from two HBM testers demonstrated sub-nanosecond time to rise to 15 volts, we decided to make measurements of real HBM discharges. Real HBM discharge waveforms have been measured and published many times. Some of the earlier waveforms are shown in reference and appear to have a slow rise at the beginning. [3,4,] This turned out to be an erroneous assumption.

We made over 100 digital recordings of HBM waveforms using six different size people. The volunteers stood on a 0.125 inch polyethylene plastic sheet to be insulated from ground. We used a thick plastic insulator because we were only interested in the initial part of the discharge which is not affected by reduced human body capacitance from a thick plastic insulator.

The volunteers held a 1 Giga ohm resistor in one hand to momentarily connect to an adjustable HV supply and charge themselves. They removed the charging resistor from the HV supply and quickly discharged themselves to the wide bandwidth, one ohm Model 4603 current transducer. [5,6] The voltage signal from the discharge current was put into a two to one divider to split the signal equally to two channels of the Tektronix TDS 3052 oscilloscope/digitizer. The model 2812-NFP two way resistive divider has a voltage division ratio of two to one, with a 10 GHz bandwidth.

The HBM waveform measurements setup is shown in Figure 14.

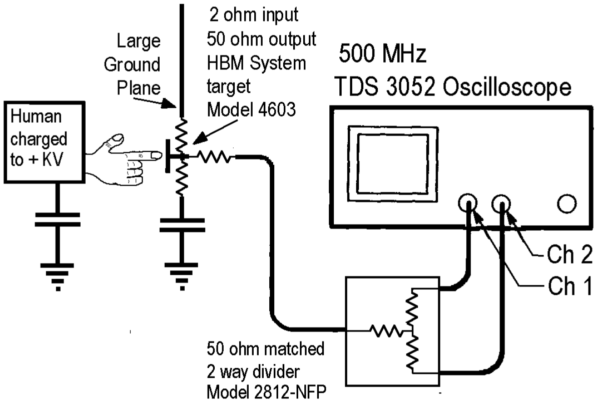

Fig 14: Real HBM waveform measurement setup

The signal into channel 2 displayed the full amplitude to the peak current of the rising edge of the discharge. Channel 1 was set at a much higher sensitivity where an expanded, measurement of the IFR of each discharge waveform could be made. Some of the measured waveforms are shown below in Figures 15 to 21.

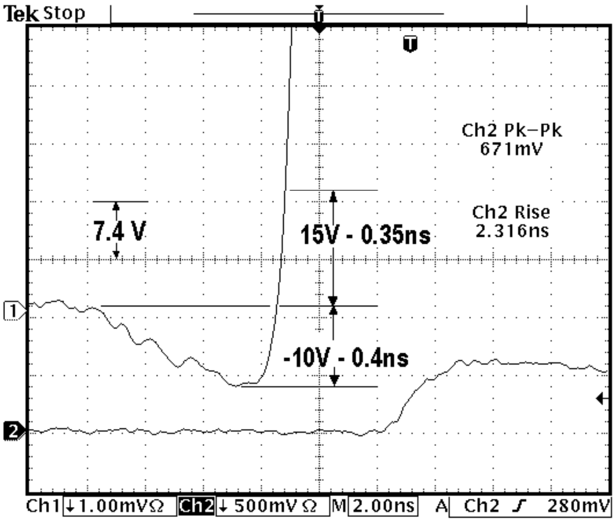

Fig 15: Tek 3052 measurement of real HBM at 5kV

Note that the Model 4603, 1 ohm target has a very wide bandwidth and because it is resistive, it has no distortion at any amplitude of the waveform. Measured waveforms show a relatively fast rate of rise from zero to 15 volts, which then increases at even faster rates of rise for some time. Our rates of rise measurements were limited by the 0.70 ns risetime of the scope we used. The real rates of rise are certainly faster than the sub-nanosecond responses that were measured.

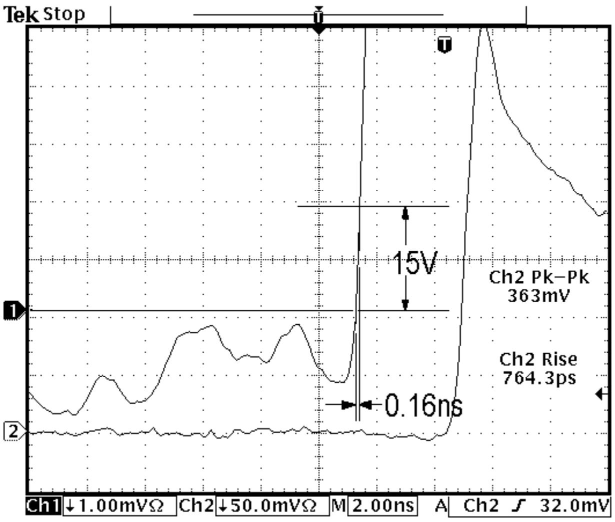

Figure 16: Tek 3052 scope 3 kV real HBM

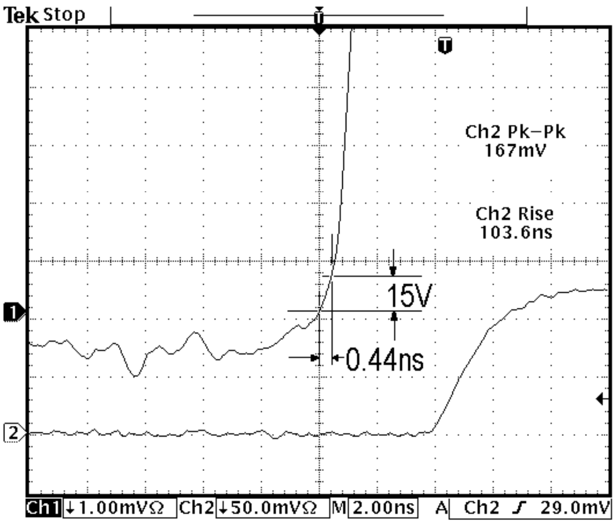

Figure17: Tek 3052 scope 4 kV real HBM

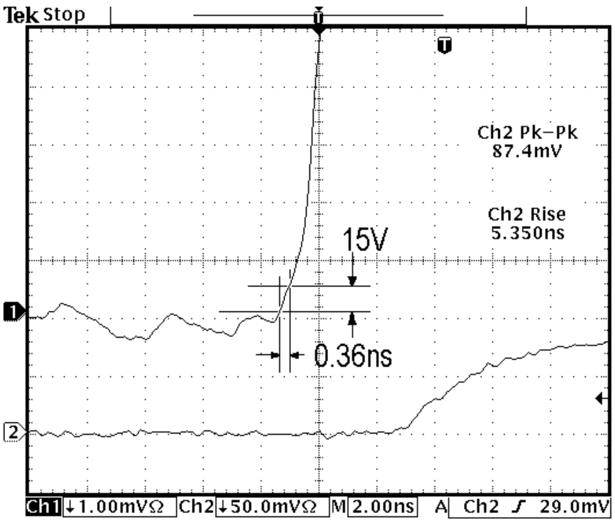

Figure 18: Tek 3052 scope 3 kV real HBM

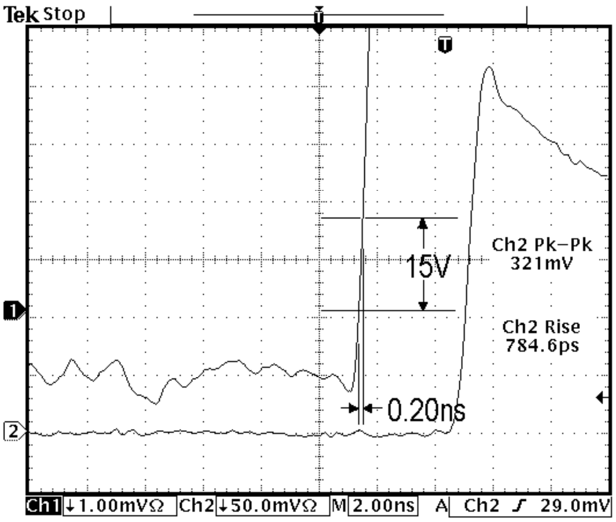

Figure 19: Tek 3052 scope 3 kV real HBM

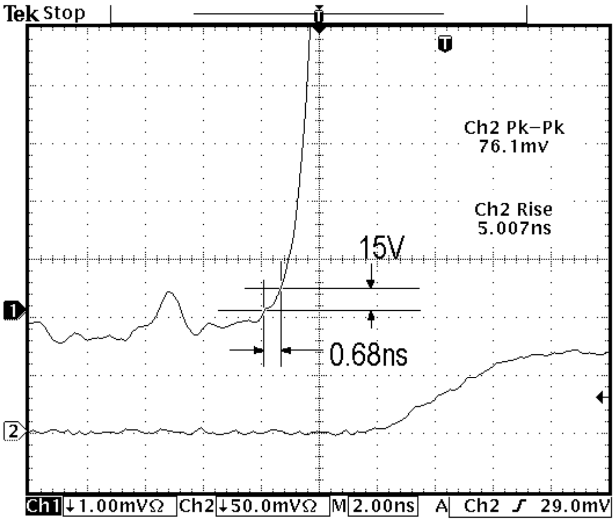

Figure 20: Tek 3052 scope 3 kV real HBM

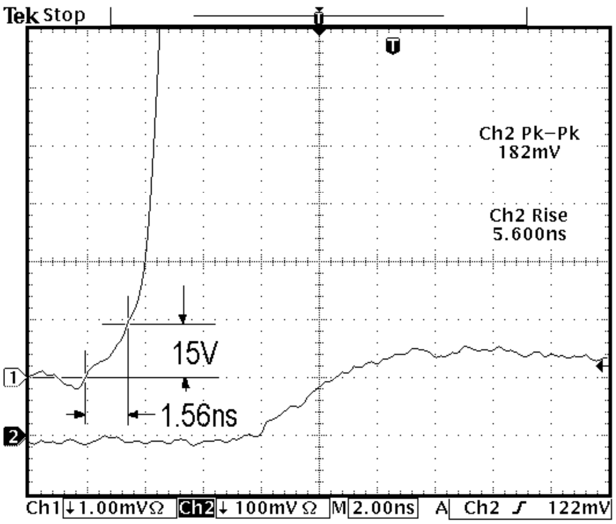

Figure 21: Tek 3052 scope 3 kV real HBM

The Channel 1 record started at zero volts (baseline) and was set at high sensitivity to capture the IFR of the pulses. See the circuit diagram shown in figure 14. Channel 2 was set to capture the entire amplitude of the HBM discharge to measure the peak current. The peak current value was used to calculate where to measureme the equivalent of the 15 volt level.

This calculation assumes that the resistance of the spark as it formed is constant. We know this is not true; but it is an approximation to compare the IFR of a real HBM pulse to that from an HBM tester. The time between zero volts and the 15 volt level was identified and is shown in each HBM plot. The times to reach the IFR level of 15 volts range from 0.16 to 1.56 nanoseconds.

For the sake of discussion, let us define the resistance of an ESD spark discharge by considering only the peak current of that discharge. Is it safe to say, at that time, the resistance of the spark is E/I? We have done this for many years in building HBM testers to meet a well considered standard circuit, with resistance capacitance and voltage. If we assume a value for the resistance of the spark at the peak, what is the resistance of a spark near the beginning of the spark? It certainly has a higher resistance because ions and electrons are just beginning to form.

If a high resistance spark measured with a low resistance current transducer were able to be measured momentarily with a much higher resistance transducer, would not the voltage across the transducer be much higher during that moment? After all, it is voltage that turns ESD protection circuits on. We would need to measure the rate of the voltage IFR across an actual device that draws very little current until it snaps back and starts conducting, to know what the real IFR rate of voltage rise could be.

Some of the IFR waveforms from real HBM discharges have a negative transition before they rise above zero volts. HBM discharges at 4 kV and above show a pronounced tendency for this negative transition which lasts for a few nanoseconds.

These measurements were made at an elevation of 2495 feet at 5 % to 10 % humidity, with the barometer at 29.80 to 30.00 inches of mercury. Additional measurements using more people at an elevation closer to sea level and at somewhat higher humidity would be of value to complete a data base of the rate of IFR for more HBM discharges.

IV. TLP Risetime Discussion

The TLP 50 system uses a Gaussian shaped test pulse, because this pulse maintains a similar rate during the IFR as the test pulse amplitude is increased. A TLP 50system uses voltages, which are much lower than that from a 1500 ohm HBM system to create the same current through a device. [2]

Current through a device is determined by the source voltage and source impedance. TLP 50 pulses for the IFR can be specified in risetime because it has a controlled low voltage rise. HBM test pulses cannot be specified in risetime for the IFR because the IFR point is reached far before this pulse reaches 10% amplitude. The TLP Gaussian waveform is the only method to provide a reasonably constant rate of rise to a DUT over the full range of pulse currents, as the test pulse amplitude increases.

V. Summary

This testing has shown that both HBM tester waveforms and real HBM discharges exhibit sub-nanosecond IFR rates and can be quite similar. Because the Initial Front Rise turns protection circuits on, this parameter is far more important than HBM risetime. The data presented here identifies the threat from the IFR low voltage part of tester waveforms. By changing the dV/dt specification from HBM risetime levels, to the IFR amplitude, more effective specifications for HBM testers can be developed. This explains different test results when using different HBM testers, and can improve correlation if this new specification is used. From our measurements of real HBM it will also provide closer simulation to real world threats.

Ringing in the Initial Rise can start below the baseline and rise to 15 volts in 0.2 ns or less may cause ESD protection circuits, which are dV/dt sensitive to respond in unexpected ways. If an HBM tester has significant ringing before or during the IFR it can turn the protection circuit on and off with each transition. Once a circuit turns on and limits further increases to itself, any effects of the initial front rise are ended.

The negative current shown in the real HBM discharge tests presented here may be associated with negative voltage swings across the DUT immediately before the positive pulse.

Our discussions concerning dV/dt rates and ESD protection circuits are obviously only concerned with circuits that have a sensitivity to this test pulse parameter. Our first interest was in measuring the IFR rate for HBM testers. A 1996 paper my Musshoff et. al. [7] showed correlation between failure amplitudes and the rate of rise of an HBM pulse during the 5% to 40% risetime. Although that work did not measure the initial front rise from zero to the voltage where protection circuits are turned on, they did show a remarkable correlation between the 5% to 40% risetime and higher failure levels with faster rising TLP pulses. They concluded by suggesting, "a definition of the initial slope should be considered for HBM and MM standardization". From an analysis of these HBM measurements, we believe that the initial slope should be measured at IFR, the lowest voltages where devices actually turn on.

VI. Conclusions

From the measurements made here we believe that the initial rise portion of test pulses has far more control over correlation between HBM, HBM, and TLP, than the presently used risetime specification.

The fact that TLP systems, and in particular the TLP 50 system, show correlation with 1500 ohm HBM testers, clearly proves the point that any dV/dt threat to the devices under discussion is completely controlled by the rate of the Initial Front Rise (IFR). The IFR voltage turns the protection circuit on. The voltage between 10% and 90% of an HBM test pulses has no direct effect for turn on of protection circuits.

TLP 50 testing uses low voltage pulses to produce the same current through the device as HBM, but it never reaches the kilovolt range. In fact, a 3 kV HBM pulse is clamped, and never reaches the kilovolt range, at the ESD protection circuit. The rate of the IFR for any threat or test pulse is present and effective only until the protection device turns on. Once that occurs, the rate of voltage rise across it is controlled by its I-V characteristics.

A new requirement for HBM test waveform specification has become apparent. From the data presented here the IFR of HBM testers should be considered by the HBM Standards Working Groups. The existing 10% to 90% risetime HBM specification can remain, but IFR has been shown to be the critical factor in exercising ESD protection circuits. TLP50 testing with controlled 10 ns risetime pulses have demonstrated that the protection in some dV/dt sensitive circuits do not turn on as designed, and fail at lower currents than when tested with faster rise pulses. [2]

We leave the analysis of which types of circuits are susceptible to this dV/dt effect to those experienced in semiconductor protection design and analysis.

For HBM testing to provide the greatest threat, in most cases the IFR rate needs to be specified to be much slower than those measured on testers described here.

The test board capacitance may affect the IFR of an HBM test pulse, and also needs to be considered. The work by Russ et. al. [8] on complex interactions between devices and testers provides valuable information on this capacitance as well as analysis of the transmission lines on the test board.

We have investigated and made the IFR of testers and real HBM available to the ESD community for their consideration.

The present dV/dt specification for HBM, needs to be changed to the dV/dt for the initial front rise to 15 volts, or to the snapback voltage (Vt1) for devices sensitive to rates of rise. Because actual measurements of IFR rates of real HBM are sub-nanosecond; HBM testers specifications to simulate this same IFR rate should be considered.

Acknowledgments

The authors would like to thank Mark Kelly for his valuable work in making many measurements of waveforms from a modern HBM tester over the very wide range needed for this investigation.

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