Correlation Considerations II: Real HBM to HBM Testers

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Abstract - This work expands on earlier real HBM initial front rise (0 to 15 Volts) sub-nanosecond measurements with faster equipment using both 1 Ω and a 50 Ω resistance current sensors to identify the complete range of peak current and risetime of HBM discharges. Several accurate high-speed measurements were made which show real HBM being significantly faster, and that they can have higher peak currents than the present HBM test specification.

I. Introduction

Our earliest work [1] in this area identified dV/dt effects on a widely used type of ESD protection circuit. It used a precisely defined and completely controlled risetime Transmission Line Pulse (TLP) test pulse to analyze different Human Body Model (HBM) ESD component level testing failure levels that occur when the test pulse risetime is changed. It became obvious that a high percentage of modern on-chip protection, specifically Gate Coupled NMOS (GCNMOS) circuits, have dV/dt turn-on sensitivity. An analysis of this effect led us in 2001 [2] to identify the early voltage rise of the HBM waveform to the Vt1 point as being the critical dV/dt parameter.

We identified that phenomenon as the Initial Front Rise (IFR) voltage of the threat, which is the amplitude that turns protection devices on at the Vt1 point. That understanding led us to measure the IFR from the beginning of a pulse to a level of about 15 volts for “Real HBM” discharges from humans. Although the Vt1 point varies, the 15 volt level was chosen as a representative value for many circuits. This is a new but very important parameter, because TLP clearly identified how different dV/dt rates of rise to the Vt1 point affect both the TLP and HBM failure at the same level.

In analyzing this data, we determined that the presently used HBM waveform risetime specification of 10% to 90% is not what actually exercises dV/dt sensitive protection circuits. That data and an analysis of it provides insight as to why different IFR rates, which may easily be present in different HBM testers, could cause different failure levels with dV/dt sensitive protection structures.

The work presented here describes accurate, high-speed measurements on over 500 “real world HBM” discharges from 12 humans. This is presented in the hope that users within the electronics industry will become aware of how real world threats affect protection circuits having previously passed standard HBM testing. The interaction between rate of rise and the threats to which they are exposed must be considered for sensitive devices. An analysis of these interactions will not be made here because it is beyond the scope of this paper.

II. Real HBM Measurements

Our work of 2001 [2] has been repeated with a faster digitizer in an attempt to capture both the IFR rate and risetime of real HBM discharges from humans. We used an Agilent 54846A Infinium digitizing oscilloscope with a bandwidth of 2.25 GHz and 156 ps risetime. Real HBM discharges from 12 humans were made into a 1 Ω, HBM system current sensor, BEI Model 4603, with a risetime of less than 30 picoseconds (ps). Figure 1 below shows the schematic of the 1 Ω current sensor configuration used to measure the real HBM discharges.

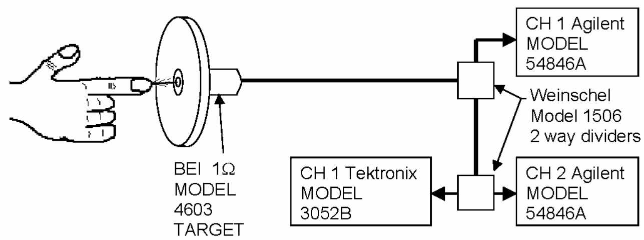

Figure 1. 1 Ω current sensor configuration

Measurements were also made using a 50 Ω current sensor with a similar risetime of less than 30 ps. Figure 2 shows the schematic of the 50 Ω current sensor configuration used to measure the real HBM discharges. This sensor had a contact diameter of 0.250 inch with a 50 Ω outer conductor. The coaxial line has a gradual, constant 50 Ω taper down to a type N connector and has no added attenuation. A pair of these tapered lines has less than 0.2 dB loss to above 10 GHz and is used to test the 1 Ω target (BEI Model 4603) used for system level HBM testing. The output of the 50 Ω tapered lines is connected to a 20 dB attenuator (BEI 142-20) and then to an additional 20 dB attenuator (BEI model 2). The resulting 100/1 attenuation (approximate) is needed to avoid overvoltage on the oscilloscope input for the range of current pulses measured.

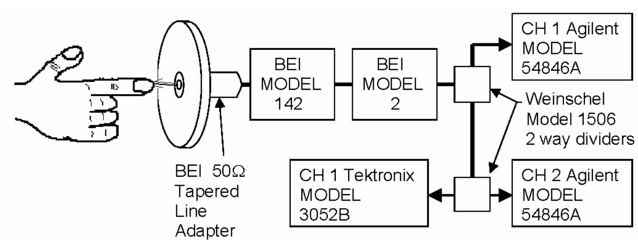

Figure 2. 50 Ω current sensor configuration

Both the 1 Ω current sensor and the 50 Ω current sensor (with attenuators) measurement systems produced nearly identical sensitivity levels of slightly less than 8 amps per volt. The channel 1 measurement produced roughly 4 amps per volt, but that IFR data is not used in this paper. The 50 Ω current sensor was included in these tests to determine what measurable differences (if any) in peak current and risetime values resulted from the 1 Ω current sensor.

The output of each fast response current sensor was split into three paths using two 2-way dividers (Weinschel Model 1506A), also with risetimes of less than 30 ps. Type N connectors were used for all direct connections, the only exception being BNC connectors on the coax due to oscilloscope BNC connections. RG-223 coax cables (approximately 18 inches in length) were used to make connections to the oscilloscopes. These cables and BNC connectors produced the major risetime additions to the oscilloscope risetime and impacted the total system risetime limit. Two channels on the HP Infinium oscilloscope were used to record waveforms at different vertical sensitivities using a sweep speed of 0.5 ns per division at 8 GS/s. This particular oscilloscope stores data points and, after capturing a waveform, allows for changes in sweep speed to optimize time base and improve risetime and peak current identification.

The third signal from the two dividers was recorded on one channel of a Tektronix TDS 3052, which has a limited risetime of 700 ps. This particular oscilloscope, operated at 10 ns per division, provided an additional measurement of peak current and risetime. Results proved similar to the Infinium oscilloscope, but were only useful for risetime and peak current measurements for discharges with risetime values slower than 2 ns.

The Infinium 54846A digitizer has a 2.25 GHz bandwidth. In the time domain, that provides a risetime of about 156 ps. With the associated dividers, attenuators, and connecting cable losses, the risetime for our measurements was limited to about 180 ps. While the measurements were being made (figure 3), we realized that several of the measured risetimes were nearly as fast as the risetime of the measurement system. This is evident in the data plotted in Figures 4 to 9, as many of the HBM discharge risetime values measured 180 ps. Since the measurement system has a 180 ps risetime, any discharge risetime near that value is obviously faster than the high-speed system was able to measure. Therefore, the fastest risetime of real HBM is not yet known, especially for discharges below 6 kV. Determining the speed of real HBM events is the next challenge. Peak current values for very fast risetime discharges will also increase somewhat with the use of a faster measurement system.

The higher sensitivity measurement channel on the faster Infinium oscilloscope was intended to be used to identify IFR rates of discharges; the unexpectedly high speed of many discharges prompted us to limit this report to the 10% to 90% risetime measurements alone. The IFR identity became less important for this paper when we realized that the greatest majority of the highest threat peak current waveforms had sub-nanosecond risetime values.

This approach does not abandon the IFR concept, because the early part of a rising voltage is the driving force behind turning on dV/dt sensitive devices. Since the highest peak current discharges have risetimes less than 0.5 ns, the time to rise to 5% or 50% of the peak voltage (IFR) is obviously much faster than the time to rise from 10% to 90% of the peak amplitude. Therefore, the IFR is important; although the extremely fast risetime of real HBM discharge measurements has now become the more important consideration for this paper and for HBM testing.

III. Data Collection

A grand total of over 300 Real HBM discharge current waveform measurements from ten different humans were made with the 1 Ω current sensor, and more than 200 discharges were made into the 50 Ω current sensor. Each voltage had over 100 discharges recorded. The human “volunteers” stood on a 10 mil Teflon film protected from abrasion by a top layer film of 7 mil Mylar. This insulation was placed on an ordinary (non-ESD type) one-eighth inch thick vinyl tile floor. A six-inch concrete layer underneath the vinyl flooring had one-half inch steel reinforcement cables on 36-inch centers, three inches under the top surface. Current sensors were located seven inches above center on a 32-inch wide by 59-inch tall sheet metal ground plane. Volunteers wore “everyday” shoes (e.g., tennis shoes of many different types). Measurements were taken at an elevation of 2530 feet and with a humidity level of approximately 10%. Figure 3 shows a photograph of the real HBM testing configuration.

Volunteers were charged to levels between 1 kV and 6 kV (within 1%) by holding one end of a 1 GΩ resistor (for safety) and touching the other end to a high voltage power supply. After charging for at least two seconds, the volunteer disconnected from the HV supply and touched the current sensor with a finger to produce a discharge event measured by the two oscilloscopes. There were no long lasting effects and many creative comments were generated. Charging humans to levels between 1 kV and 6 kV provided a wide range of real HBM discharge threats.

Figure 3. Photo of real HBM test configuration with human “volunteer” touching the current sensor

IV. Test Results

Figures 4 through 9 below show data points of real HBM discharges into both 1 Ω and 50 Ω current sensors. One plot is given for each voltage level and a best-fit average line is drawn through the risetime and peak current points. The data reveals that higher peak current values correspond to faster risetimes and lower peak current values correspond to slower risetimes. Each plot also indicates the present HBM waveform specification for standard peak current and 2 ns to 10 ns risetime measurements.

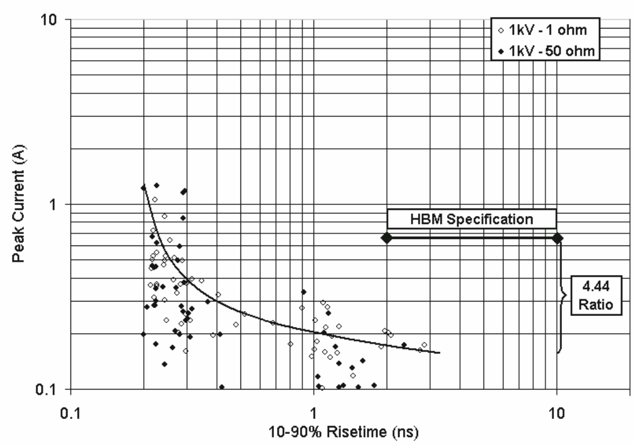

Figure 4. Real HBM measured at 1 kV

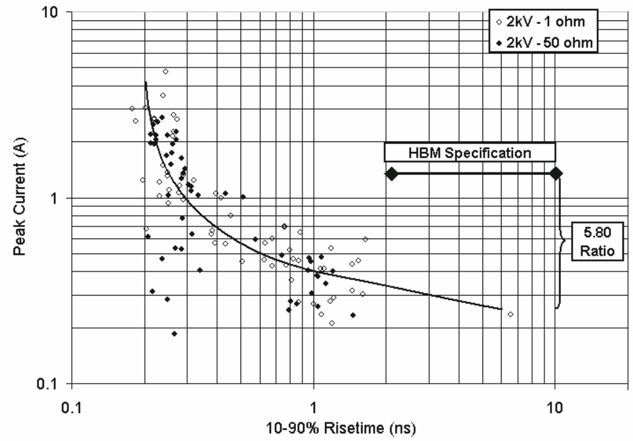

Figure 5. Real HBM measured at 2 kV

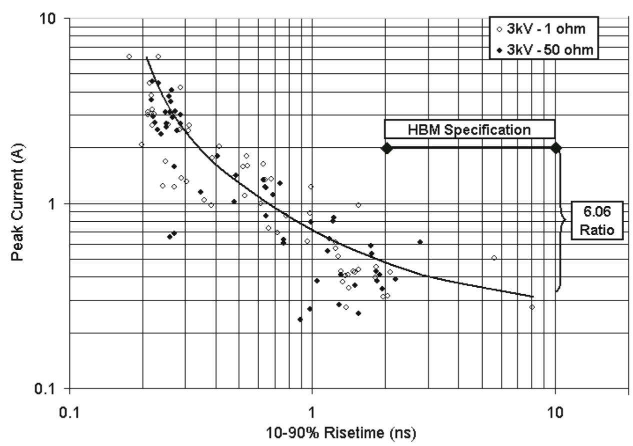

Figure 6. Real HBM measured at 3 kV

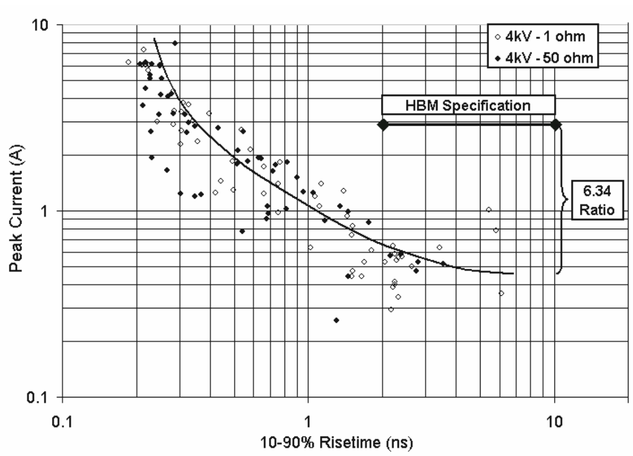

Figure 7. Real HBM measured at 4 kV

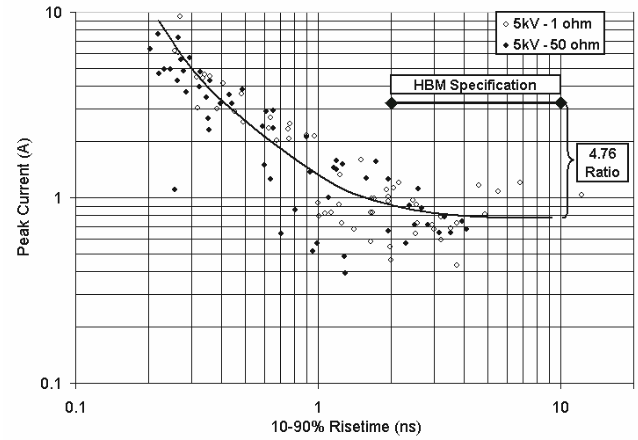

Figure 8. Real HBM measured at 5 kV

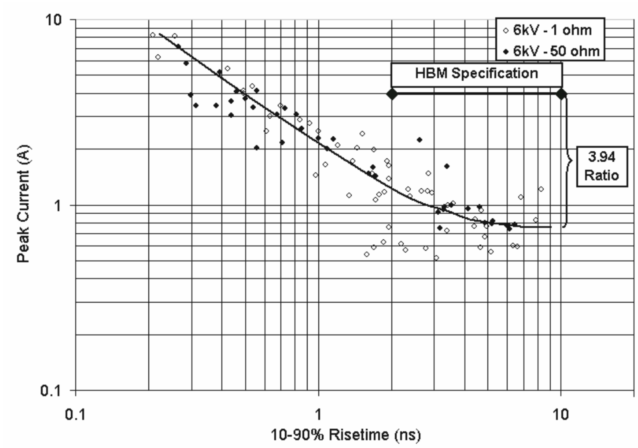

Figure 9. Real HBM measured at 6 kV

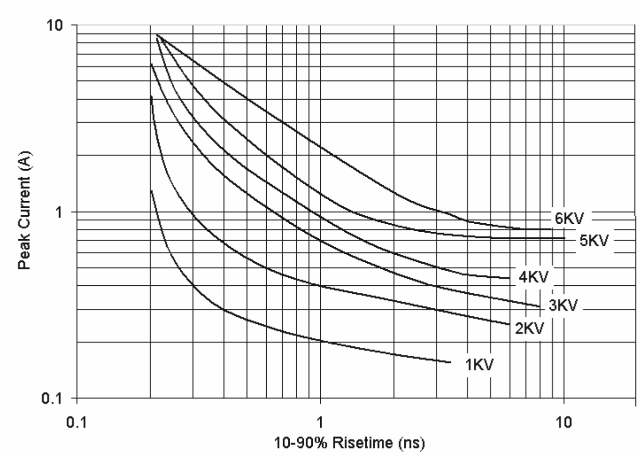

Figure 10. Peak Current to Risetime best fit averages for real HBM from 1 kV to 6 kV

Figure 10 above shows a composite plot of the six best-fit averages from Figures 4 through 9. Note that the risetime limit of roughly 200 ps is not due to the spark formation time; it is definitely limited by the measurement system risetime as discussed earlier in section II. The 6 kV best-fit curve is probably no faster than the 200 ps measurement system risetime limitation. However, each of the lower voltage risetime values has a greater curvature (due to the faster risetimes) as it approaches the 200 ps boundary. The degree of curvature for each discharge voltage is merely a guess; but if the lower voltage curves happen to be as linear as the 6 kV best-fit for risetimes less than 1 ns, the actual risetime for 1 kV could be 50 ps or faster.

IV.a. Overshoot on Fast Rising Waveforms

Our measurements found that the majority of waveforms with risetimes faster than approximately 1.5 ns exhibited an overshoot, or the impulse observed at the leading edge of the real HBM discharge waveform. The fastest waveforms had very narrow impulses that nearly doubled the peak current value of the standard HBM waveform specification we have all grown to know with intimate detail. Three of these real HBM waveforms are shown below in Figures 11, 12, and 13. While the vertical scale sensitivities used for each waveform are different, the waveforms are only intended to demonstrate that faster risetime waveforms exhibit a higher overshoot (impulse) at the early leading edge. Waveforms were captured using a TEK 3052B 500 MHz oscilloscope and are shown with a 10 ns/div time scale to better illustrate the overshoot phenomenon.

Figure 11 shows a 1 kV real HBM discharge taken with the slower TEK 500 MHz oscilloscope. Measurement results using the Infinium 2.25 GHz oscilloscope revealed a 10% to 90% risetime value of 236 ps and a peak current value of 0.478 amps with an initial impulse width of approximately 200 ps. Figure 11 shows only the slight beginning of an overshoot (impulse) due to the inability of the slower oscilloscope to record such a narrow impulse.

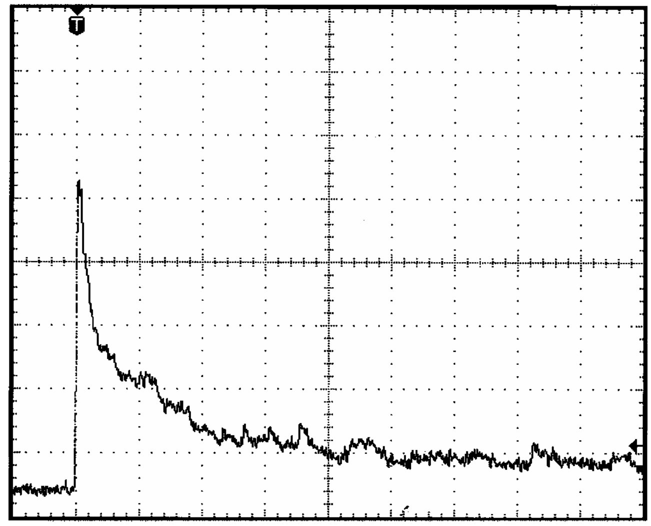

Figure 11. High peak current overshoot from a very fast risetime (236 ps) real HBM discharge at 1kV (500 MHz oscilloscope)

Figure 12 shows a 2 kV discharge that, when measured with the 2.25 GHz Infinium oscilloscope, reveals a measured risetime value of 495 ps and a peak current value of 1.403 amp.

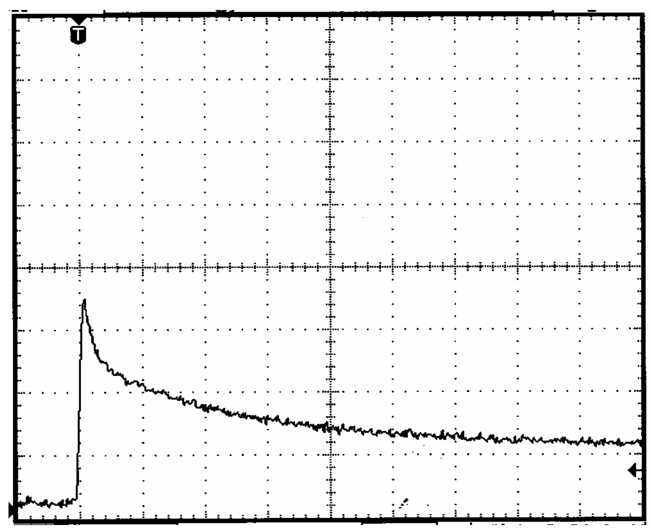

Figure 12. Moderate peak current overshoot from a fast risetime (490 ps) real HBM discharge at 2 kV (500 MHz oscilloscope)

Figure 13 shows a 6 kV discharge that, when measured with the 2.25 GHz Infinium oscilloscope, reveals a measured risetime value of 1.920 ns and a peak current value of 1.598 amp.

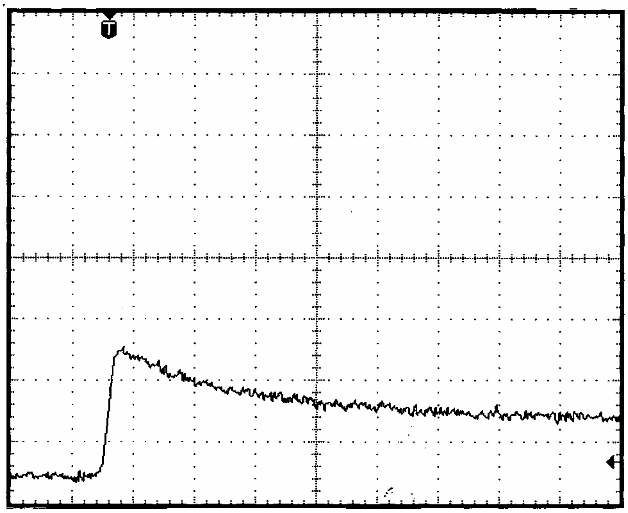

Figure 13. Minimal peak current overshoot from a slower risetime (1.920 ns) real HBM Discharge at 6 kV (500 MHz oscilloscope)

The narrow overshoot impulses measured using the slower 500 MHz oscilloscope were significantly lower than those measured using the faster 2.25 GHz oscilloscope. There is no simple relationship between amplitude measurements of narrow impulses on different oscilloscopes (and their corresponding risetime limitations) since both the impulse width and the measurement system risetime limitation directly affect the measurement. The risetime and peak current data used in this paper were acquired using the high-speed 2.25 GHz Infinium waveforms and a much faster time base. At the time these measurements were taken the importance of the peak current overshoot was not recognized. The faster time base (2.25 GHz) results may be more precise, but the trade-off is an inability to show the relationship between the overshoot impulse and the exponential decaying waveform to the degree of the slower time base (500 MHz).

V. Potential HBM and MM Early Rise Effects

Real world HBM System level ESD events between metal conductors have been shown to produce extremely fast risetimes. Previous work [3] used very wide bandwidth (40 ps risetime) test equipment, made especially for high-speed ESD discharge measurements, to clearly identify the ultimate speed of metal-to-metal ESD discharges. This data suggests that the relationship between device level HBM and system level HBM risetime values is much closer than previously reported. The fast risetime values shown in this paper and the expected faster risetime values of real MM discharges could be the cause of correlation problems encountered in both MM and HBM testing. Further investigation in this area is warranted.

If real HBM discharge waveforms have sub-nanosecond risetimes, then MM discharges between metal conductors certainly have equal or faster risetime values. Air discharges between metal conductors have revealed measured risetime values faster than 50 ps [3]. Those values were measured in 1996 with the 1 Ω fast response current sensor (target) similar to the one used in this paper for real HBM (human finger) discharge waveform measurements. The 1996 measurements used a Tektronix SCD 5000 digitizer equalized to 12 GHz with a risetime of approximately 30 ps.

Measurements of MM discharges from a selection of metal structures simulating those found in semiconductor manufacturing and assembly facilities should be made in order to determine real MM waveforms and risetime values. It has been extremely difficult to obtain permission to perform real MM discharge testing on machines in operating assembly facilities. Metal framework dummies with or without metal skins can closely simulate the electrical characteristic; discharges from these controlled structures may closely simulate real world MM and provide the needed information.

VI. Discussion

Concern for correlation issues affecting HBM testers drove the authors to take a different approach than the perennial question of correlation between TLP and HBM testers. We have used accurate measurements of real world events initiated by the analysis of TLP data for dV/dt sensitive devices. The TLP system precisely controls the sub-nanosecond portion of the test pulse and provides a clean, controlled Gaussian risetime pulse.

TLP, with its controlled risetime and rectangular pulses that clearly identified the dV/dt problem, has become the reference for analyzing HBM testers for their ability to produce threats that simulate real world conditions. This information persuaded us to make the real HBM measurements discussed in this paper with the fastest risetime equipment ever used for this purpose. Precise real HBM discharge data can now be obtained and confirmed by experimenters within the ESD industry.

VI.a. HBM and CDM Testing Speculations

Real world HBM risetimes have been measured and are found to be faster than previously identified. In addition, the high amplitude narrow overshoot impulses on the rising edge of the waveform could possibly exercise any CDM protection circuitry associated with the HBM protection scheme. These measurements have nearly identified the ultimate speed of real HBM. As shown by the best-fit curves in Figure 10, the 6 kV waveform measurements appear to be an accurate measurement of the peak current and risetime. However, the best-fit curves for discharge levels of 1 kV, 2 kV, and 3 kV strongly suggest that their true risetime values are faster than that observed using the 180 ps risetime limited measurement system. The actual risetime for the 1 kV discharge level may indeed be as fast as 50 ps. These results have also shown that the fastest risetimes corresponded to the highest peak current threats.

The present HBM waveform specification for risetime (2 ns to 10 ns) ignores the very fast risetime and peak current overshoot impulse described in this paper. However, the present CDM testing, with real air discharge sparks, does test with a very fast risetime and short impulse duration. It may be serendipitous that CDM and HBM testing in combination provide the total testing required to simulate real HBM events.

VII. Summary

VII.a. Description of The Problem

It is the conclusion of these authors that insufficient knowledge of the high speed electrical waveforms produced in atmospheric discharges and a reliance on older, slower measurements and incorrect speed of discharge initiation assumptions may have collectively limited the ability of HBM testers to accurately simulate real world ESD. If field failures from ESD events are a minor problem, then this information will not be useful. However, if the cause of some of the field failures is unknown, then this work may provide a new insight and help solve previously unidentifiable problems. The interaction between HBM testers, the protection circuit, and real HBM threat risetime values identified in this paper should be considered in order to provide the optimum protection for dV/dt sensitive circuits. ESD sensitivity can only be determined with TLP; HBM testing does not control the IFR rate, or the early rise portion of the HBM tester waveform.

Lord Kelvin said, “When you measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, … your knowledge is of a meager and unsatisfactory kind.” It follows that accurate measurements make your knowledge of any physical effect more precise. Improving the knowledge of real ESD threats allows for the manufacture/design of ESD testers that can more accurately simulate real world threats. This can also minimize the amount of over-protection needed to provide immunity to well defined threat levels.

VII.b. Measurement Equipment for Real HBM Discharges

The fact that data plots for both 1 Ω and 50 Ω current sensors are found to be similar indicates that 50 Ω current sensors can be used for all but the most precise peak amplitude measurement requirements. For the relatively few data points at high peak current levels, the highest 1 Ω current sensor measurement was roughly 25% greater than the highest values for the 50 Ω current sensor. This information will allow other investigations to repeat the pulse current risetime and peak current measurements discussed in this paper with readily available 50 Ω systems. The only additional requirement for a 50 Ω test is use of voltage capability attenuators to avoid burnout.

VII.c. Solutions to HBM Testing Repeatability Problems

We suggest three basic solutions to the problem of “tester to circuit” interaction in the IFR range.

i. Designers can use both high speed and low speed simulations to analyze and test dV/dt sensitive (GCNMOS) structures; thereby avoiding unexpected circuit failures when different HBM testers are used.

ii. HBM testers can be modified to provide specific IFR portions of the discharge waveform.

iii. New HBM testers can be designed and manufactured to provide specific IFR portions of the discharge waveform.

VII.d. Information for ESD Designers

Designers need to understand how the dV/dt HBM tester threat will affect their circuits in order to create optimum solutions that will meet all challenges. Passing an HBM test is only the first step in protection; real world ESD awaits the unwary.

VIII. Conclusions

By analyzing the data presented in this paper, we have now confirmed that the presently used HBM 10% to 90% risetime specification is not representative of the real world. The measurement data demonstrates that real HBM events have much faster risetimes than the traditionally accepted values. Although the IFR voltage at the Vt1 point turns on snapback devices, the extremely fast risetime and high peak current threat should also be considered during HBM testing.

Fast and slow speed TLP test measurements have led to a new understanding of HBM waveforms and allow for a more precise analysis of tester/device interactions. The "real HBM" waveform peak current versus risetime data measured with high-speed oscilloscopes now provides a clear understanding of the real threat. This work provides direct and specific information necessary to understand how accurate tests can be made on modern dV/dt sensitive circuits. We have also identified the improvements required so that the high speed waveform parameters generated by a new type of HBM tester can better simulate real world threats.

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