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01 Aug 2003

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### Recommended Citation

K. Wang et al., "Impact of ESD Generator Parameters on Failure Level in Fast CMOS System," *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility, 2003. EMC 2003*, Institute of Electrical and Electronics Engineers (IEEE), Aug 2003.

The definitive version is available at <https://doi.org/10.1109/ISEMC.2003.1236563>

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# Impact of ESD Generator Parameters on Failure Level in Fast CMOS System

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## Abstract

*Electrostatic Discharge (ESD) generators are used for testing the robustness of electronics towards ESD. Most generators are built in accordance with the IEC 61000-4-2 specifications. It is shown that the voltage induced in a small loop correlates with the failure level observed in an ESD failure test on the systems comprising fast CMOS devices, while rise time and current derivative of the discharge current did not correlate well. The electric parameters are compared for typical and modified ESD generators and the effect on the failure level of fast CMOS electronics is investigated. The consequences of aligning an ESD standard with the suggestions of this paper are discussed with respect to reproducibility and test severity.*

## Keywords

ESD generator, induced loop voltage, Fast CMOS system

## I. INTRODUCTION

The use of high-speed logic makes modern electronic systems highly susceptible to electrostatic discharge (ESD). To test the robustness of electronic equipment against ESD event, ESD generators are widely used to reproduce the human event. Some EUTs (Equipment Under Test), mainly high-speed digital equipment, will experience vastly different failure levels during ESD tests depending on the brand ESD generators [1..6]. The parameters that correlate to EUT failures need to be understood in order to determine which parameters need to be specified in ESD standard. An effort has been undertaken to understand the reasons for these variations. Possible reasons have been considered:

- Discharge current derivative ("smoothness of the waveform")
- Spectral density of the discharge current
- Transient fields

Other parameters such as Peak current, Rise Time, Current at 30 ns, Current at 60 ns, lumped capacitance and lumped resistance, are less relevant since these parameters do not vary sufficiently among different ESD generators to effect the failure levels.

Using identical CMOS systems setups, this paper presents data on failure level variations, as large as 1:5, due solely to changing the ESD generator. Furthermore, this paper

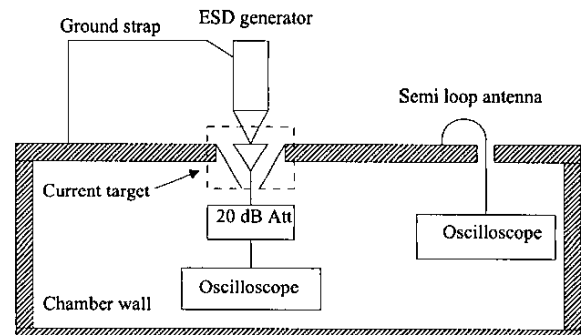
will show that the voltage induced in a small loop correlates well to the failure levels. Data will be presented that will advocate the use of specification controls for transient fields. Finally, the consequences of aligning the 61000-4-2 [7] standard with the suggestions of this paper are discussed with respect to reproducibility and test severity.

## II. The ESD failure test on a fast CMOS system

During non-destructive ESD failure testing, the results show different failure levels depending on the brand ESD generators used. In order to determine parameters that need to be standardized in the ESD generator standard, the electrical parameters which cause the EUT to fail need to be understood. First, the ESD measurement setup such as current, transient fields, human-metal ESD, and induced loop voltage measurement of our lab are presented.

### A. ESD Measurement setup

The setup to measure the ESD discharge current is shown in Figure 1 and the loop antenna to measure the induced voltage is shown in Figure 2



**Figure 1: The induced loop voltage measurement and ESD current measurement setup.**

The current target was mounted on the chamber wall. Due to insufficiencies of the Pelligrini target for measurements above 1 GHz, an improved current target was used. Its frequency response is within +/- 0.3 dB up to 1 GHz and +/- 0.8 dB up to 4 GHz.

Two Tektronix TDS7404 oscilloscopes (single channel, 4 GHz, 20 GS/sec) were used to measure the induced loop

voltage and transient fields. All the measurements were made in the chamber to minimize the unwanted interference such as coupling to the instrument and cables.

To measure the transient fields, the semi-loop antenna was replaced by a H-field and E-field sensor. The data was taken in the chamber, using a 20 G/s sampling rate oscilloscope. The frequency response of the E and H field sensors is up to 2GHz. The ARC length of human-metal ESD can also be measured. A person holding a metallic discharge electrode in hand, was charged to 5KV via a 100M $\Omega$  resistor. As the person moves the electrode toward the current target, a discharge occurred. The current was initiated by the spark breakdown of the gap between the discharge electrode and the ground plane. Current, the gap distance at the moment of the breakdown (i.e., the arc length), transient fields using broad-band field sensors and induced voltages were measured.

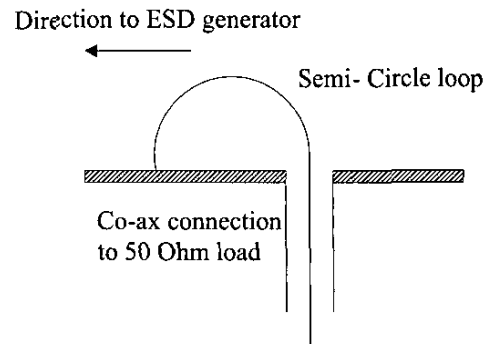
### B. Semi-circle loop antenna

It is difficult to require that a transient field measurement specification should be included in the ESD standard since it requires broadband flat frequency response transient field sensors. Most laboratories will not be able to conduct these measurements. An alternative is to measure the voltage induced in a ground plane mounted semi-loop of given size with a given termination resistance. This measurement scheme provides the following advantages:

- The voltage induced in a small loop follows the intuition of the coupling process. One can associate an equivalent loop area for each connector, trace or socket and obtain an estimate of the induced voltage from this data.
- The frequency response of the field sensors used in our lab is limited to 2 GHz, while the frequency response of a loop can be characterized from its mechanical dimensions up to higher frequencies.
- Due to the transfer function (Predominantly H-field to voltage at the load), low frequency components are suppressed, subsequently improving the dynamic range for the high frequency components. The dynamic range of a nominal 8 bit oscilloscope limits the ability to measure high frequency components, as the vertical scaling is determined by low frequency components. The quantization noise and possibly artifacts from A/D converter misalignment often mask the high frequency components. The ability to improve S/N ratio, using averaging in the time domain is limited due to pulse-to-pulse repeatability at high frequencies. Without careful attention to pulse-to-pulse repeatability and trigger point jitter, time domain averaging may act as a low pass filter.
- The ability to measure transient fields is not widely available in EMC laboratories, although the technology is available. Every lab can manufacture a small loop and the technology used to measure ESD cur-

rents can be directly used to obtain the induced voltage.

- The voltage induced in such a small loop correlates well to the failure levels (soft-errors) in fast CMOS devices, as shown in the later parts of this article.



**Figure 2: The diagram of the semi-circle loop antenna**

Figure 2 shows the semi-circle loop antenna. Semi-circle loops on the ground plane having radius of 14 mm and 5 mm were used. The wire diameter was 0.7 mm. The loops were placed at distances of 0.1 to 0.6 m from the current target center. The loops were loaded with 50 Ohms and were not shielded.

### C. ESD failure test on a fast CMOS system

Different EUTs (equipments under test) have been tested for non-destructive failures by using different brand ESD simulators. The setup was similar to the one given by [7]. Failure variations due to generator selection had almost no impact on slow CMOS-logic circuitry, while in contrast to fast CMOS-logic where a dramatic impact was seen. A system was assembled containing fast CMOS IC's manufactured using less than 1.5  $\mu$ m technology. Utilizing modified and various models of ESD simulators, this system were tested for soft-errors using the contact discharge method in the vicinity of the system. The ESD failure levels of the fast CMOS system and the rise times, peak current derivatives and the corresponding induced voltages in a small semi-loop antenna mentioned above for different brand ESD generators and modified generators are shown in Table 1. The semi-loop was placed 0.4 m away from the discharge point.

The entire induced loop voltage and current derivative are scaled to 1 kV discharge voltage. It is important to note that the ESD test results are repeatable for the same ESD generator.

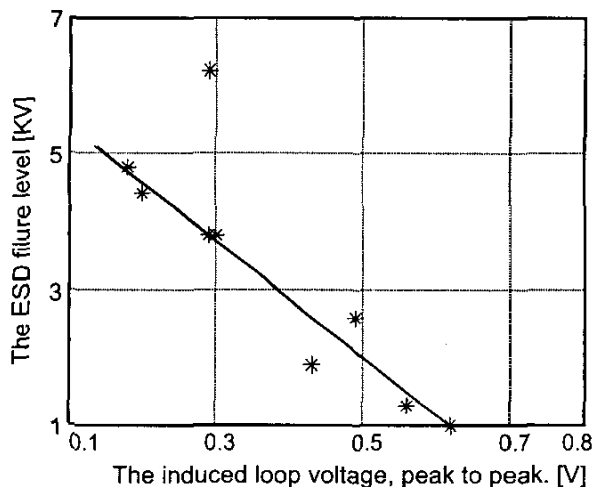
The important finding is that for the same system setup, a 1:5 variation in the ESD failure test result is introduced by differences between the ESD generators. A detailed investigation on the electrical parameters of the ESD generator has been made to determine the reasons for this difference.

**Table 1: ESD failure test result and ESD generator parameters.**

ESD generator	EUT ESD Failure level (kV)	Induced loop voltage, Peak to peak value (V)	Rise time (10% - 90% of the peak value) (ps)	Maximum Current Derivative A/(kV*ns)
ESD A	1.3	0.56	1000	5.37
ESD B	6.2	0.29	1000	5.87
ESD C	2.6	0.49	900	7.55
ESD D	1.3	0.56	860	5.25
ESD E	4.8	0.18	990	5.10
Optimized ESD C1	3.8	0.29	580	10.70
Optimized ESD C2	1.9	0.43	440	14.50
Optimized ESD C3	3.8	0.30	400	11.64
Optimized ESD C4	4.4	0.20	1030	7.32
Optimized ESD C5	1.0	0.62	200	18.30

Three conclusions can be drawn from the data in table 1 and the data of the ESD parameters measurement:

1. There is a good correlation between the ESD failure levels and the induced loop voltages. The correlation between the induced loop voltages and the ESD failure levels for different generators is shown in figure 3 which shows a good linear relationship. Higher the induce voltage at the loop antenna, the EUTs will be more effected by the ESD event.
2. The peak current derivative and the rise-times do not correlate well to the failure level. A failure level variation of 1:5 was observed for generators having rise time variations of only between 0.7-1ns, i.e., rise time and peak current derivative alone cannot explain the variations.



**Figure 3: Correlation between ESD failure level and induced voltage data. The data is from Table 1.**

3. A 1:4 variation in the induced loop voltage is introduced by differences between the ESD generators.

There is no strong relationship between the current derivative and the induced loop voltage. There is also no strong relationship between the current derivative and the ESD failure levels.

The analysis of the data shows that among of all the parameters (rise-time, current derivative of the discharge current, and induced voltage) the induced voltage at the semi loop is the best indicator of the failure level. In addition, there is a weaker correlation to the rise times and peak current derivatives. No other parameters appear to influence the failure level during the contact mode testing.

It is understandable that there is a linear correlation between the ESD failure level and the induced loop voltage since the voltage induced in the semi-loop is closely related to the transient fields, which strongly couples into the circuit of the EUT. But there are two questions need to be answered regarding the ESD test result in Table 1. The remainder of this paper will discuss these questions:

1. Why is there is a 1:4 variation in the induced loop voltage if different ESD generators are used while they are designed according to the same IEC ESD standard?
2. What can be included in the new version of the IEC ESD standard regarding the transient fields achieving ESD repeatability during diverse test environments?

### III. The parameters of ESD generators

Nearly all the ESD generators in the market are designed in accordance with the IEC 61000-4-2 specifications. Using few waveform parameters, this standard specifies the peak current, the rise-time and the falling edge but lack a transient field specification.

The objective of the ESD IEC standard is to reproduce the stress level of ESD as it might be experienced by electronic systems. There are a wide variety of possible ESD events for which the severity is dependent on the voltage and the arc length. If a human or an object is charged to the same voltage and discharged repeatedly, a large variation

of current waveforms will be observed. The variations in the current are a result of differences in arc length. The shorter the arc length is, the larger the peak current and the faster the initial current rise will be. If the ESD discharges have about 0.85mm arc length, the rise-times and peak values of these discharges are very close to the IEC specifications [7]. For that reason they have been selected as a basis for the human-metal ESD reference event and considered to be included in the new IEC standard.

The measured result shown in Table 1 of various ESD generators are built according to the IEC specifications. They show large variance in the induced loop voltage. The comparison of the induced loop voltages of the ESD generators and human-metal ESD reference event in the time domain and frequency domain are shown in figure 4 and figure 5 respectively.

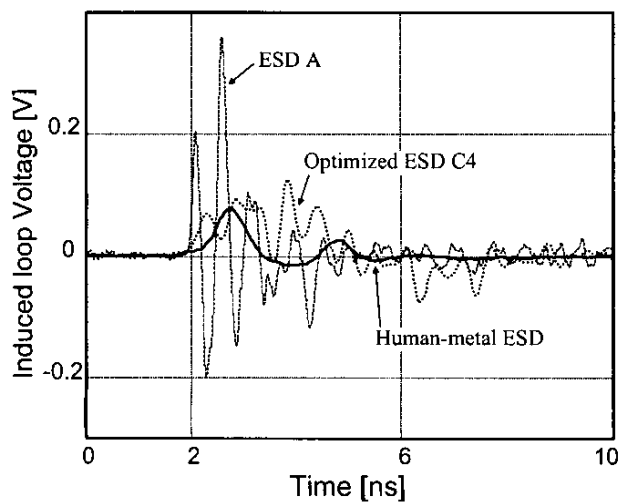


Figure 5: The comparison of the induced loop voltage between ESD generators and Human-metal ESD event.

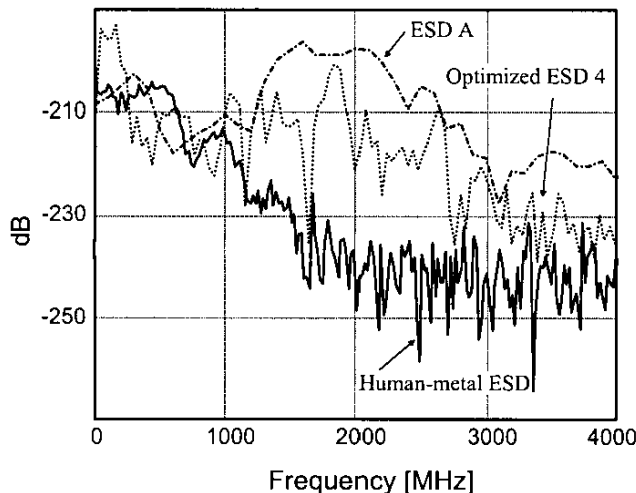


Figure 6: A comparison of the spectral density of the induced loop voltages produced by human-metal ESD with the discharges from ESD generators.

Two generators ESD A and Optimized ESD C4, were compared with the human-metal ESD event. The arc length of the Human-metal ESD in figure 4 has the arc length of 0.783mm, and 0.8 nsec rise time. In figure 4, the induced loop voltage of the ESD A is 4 times more than that of the Human-metal ESD event. In figure 5, there is about a 30 dB difference between the ESD A and Human-metal ESD event in the comparison of spectrum density of the induced voltage at 1.5 GHz frequency. There is also a big difference between ESD generators used to collect time and frequency domain data. Those differences significantly affect the ESD failure test results. To improve the ESD generator, a smooth induced loop voltage and smooth transient H field are needed.

The semi-loop antenna couples mainly the magnetic field. The current IEC standard only specifies the discharge current. If you assume initially that a smooth current waveform will yield a smooth transition of the electromagnetic fields, it would be sufficient to regulate the discharge current alone. An additional limit to the positive and negative current derivative would prevent the current from rising and falling too fast and limit the amount of ringing of the current. But the relationship between discharge current and fields are much more complex than the above assumption suggests. There are two sources of the transient fields during the ESD event, which is shown in figure 6. One source of the transient fields measured by the semi-loop is the discharge current and the other source is the current distribution of the complete ESD generator structure which we call inner current or fast changing current. The generator structure especially impacts the high frequency inner currents occurring inside the generators.

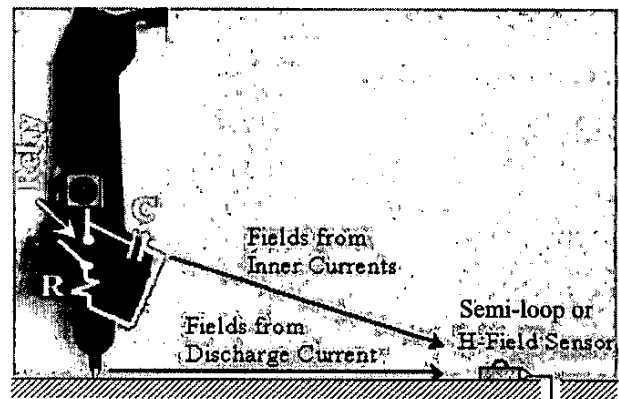


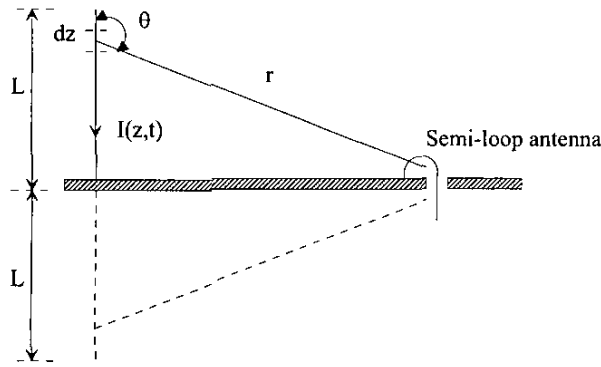
Figure 7: The source of the transient fields in the ESD.

Within a few cm, the field is governed by Ampere's law and can be estimated from the discharge current. As the distance increases from the discharge point, the magnetic field will be determined by the current distribution from the complete ESD generator structure and its ground strap, not only by the current at the discharge point as often mistakenly assumed. While the discharge current may vary smoothly and may show a rise-time of 0.7-1 ns, the other current components within the generator may rise much

faster. The sources of the magnetic field are analyzed below.

**A. The magnetic field associated with the discharge current.**

In this case, the magnetic field of ESD can be modeled by the electric dipole model. The discharge current is simulated by a current rod, which is shown in the figure 7.



**Figure 8: The H field dipole model.**

The H field strength at the semi-loop antenna can be calculated as:

$$dH_{\phi}(r,t) = \frac{dZ}{2\pi} \sin(\theta) \left[ \frac{i(t-\frac{r}{C})}{r^2} + \frac{1}{Cr} \frac{di(t-\frac{r}{C})}{dt} \right] \quad (1)$$

Where C is the speed of light.

There are two terms in equation (1).

1. The far field term which is proportional to the current derivative. It decays with distance by 1/r.
2. The near field term which is proportional to the current. It decays with distance by 1/r<sup>2</sup>.

To calculate the field, the equation (1) has to be integrated along the whole radiating current rod.

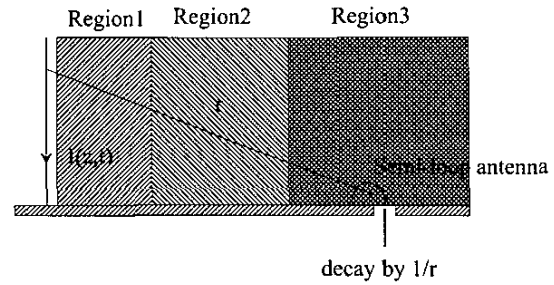
If the far field term (current derivative term) does not dominate, the magnetic field at the ground plane can be calculated at any distance using quasi static equations [6].

$$H_{\phi}(r,t) = \frac{I}{2\pi} \cdot 2 \frac{l}{\sqrt{4r^2 + 4l^2}} \quad (2)$$

In the very near field region where r << L, ESD magnetic field decays by 1/r according to equation (2).

If the far field term (current derivative term) dominates, the magnetic field at the ground plane decays by 1/r and is proportional to the current derivative.

The ESD magnetic field in the ground plane can be distinguished between three regions as shown in figure 8.



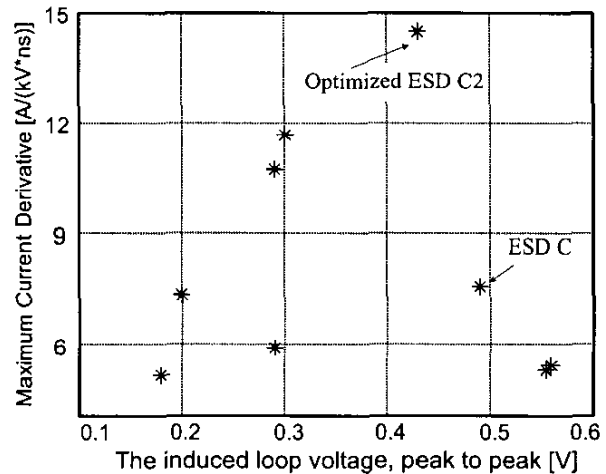
**Figure 9: Distance variation of magnetic field.**

In region 1 where the observation point is very close to the discharge point, the discharge current term dominates. The field and current waveform look alike and decay by 1/r. In region 3 where is the far field region, the current derivative term dominate and field also decays by 1/r. The field in region 2 is the combination of two terms.

**B. The magnetic field associated with the inner current.**

There are fast changing, high frequency current components inside the ESD generator structure. Most of these fast changing current components are associated with the charging and discharging process of the relay inside the generators. These current radiates the high frequency magnetic field as shown in figure 6. Compared with the Human-metal ESD, the ideal condition for ESD generators is to have the transient fields associated only with the discharge current because there is no unwanted high frequency radiation from the human body.

The research shows that the ESD magnetic field caused by the radiation of the high frequency current contribute significantly to the induced loop voltage and it is one important reason for the 1:4 variation for the induced loop voltage of different generators.

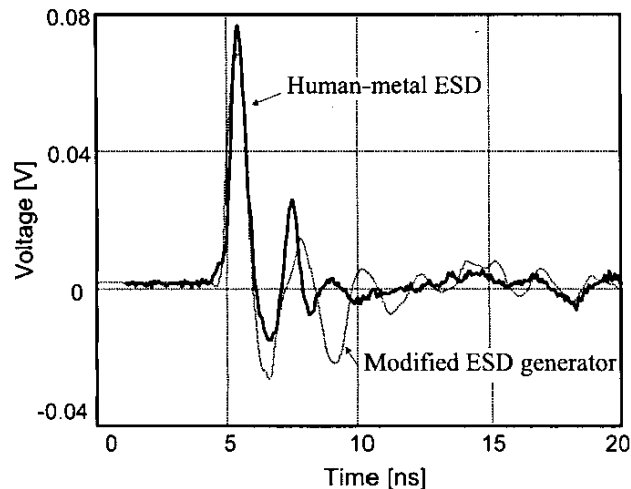


**Figure 10: The correlation between the discharge current derivative and the induced loop voltage.**

Figure 9 shows that while there is a linear correlation between the induced loop voltage and the ESD failure level,

there is no direct correlation between the discharge current derivative and the induced loop voltages. In reality, both transient fields sources (source A and source B) contribute to the loop voltage. For marketed generators the fast changing currents dominate the induced loop voltage, such that the induced loop voltage does not correlate well with the rise time. If these fast changing currents would be shielded, the rise time as well as the peak current derivative would correlate to the induced voltage. For such a case, one would expect that rise time would be predictive for the response of fast EUTs. But for now, the generators contain too much unshielded fast changing currents that overwrite the often expected correlation between discharge current rise time at the tip and the EUT response.

We modified a typical ESD generator to reduce the unwanted transient fields associated with the fast changing current. Special efforts have been made to shield the radiation from the inner current inside the generators. The induced loop voltage of this modified generator is compared with the human-metal ESD event in figure 10.



**Figure 11: The induced voltage of a modified ESD generator**

The induced loop voltage in figure 10 is reduced compared with other ESD generators and looks similar to the human-metal ESD event. The comparison in the spectrum density also shows great agreement. All the data are scaled to 1 KV.

#### Changes to the ESD standard for reducing the effect of the ESD generator model on the test results

In our opinion, the ESD standard should be revised such that ESD generator performance is as similar to the reference events as possible in all their parameters. The following changes are suggested by the authors to the new IEC ESD standard.

- Discharge current derivative. The present rise-time limit amended by a maximal current derivative would ensure a smooth current rise. An additional limit to the negative current derivative would prevent the current

from falling too fast after the initial rise and limit the amount of ringing on the current.

- ESD Transient fields. It may be difficult to require transient fields measurements in an ESD standard. An alternative is to measure the voltage induced in a ground plane mounted semi-loop of given size having a given termination resistance.

#### Conclusion

Using measurements of arc length, current and fields of human-metal ESD and more than 15 different ESD generator models and design variations and system level tests this paper shows that the transient fields of the generator are responsible for the variations in the ESD failure level test and peak-to-peak value of the voltage induced in a small loop correlates with the failure level in fast CMOS devices.

The peak-to-peak voltages and the spectral content of the induced voltages vary greatly between different brand ESD generators. This correlates well with failure level variations in fast CMOS electronic systems of up to 1:5. The data supports that a revised ESD standard will reduce the test result uncertainty if current derivative and most of all, the induced voltage are included as specifications for the design of ESD generators. As unintended radiations from the ESD generators would be reduced, the change might reduce the test severity for very fast digital systems.

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