On Secondary ESD Event Monitoring and Full-wave Modeling Methodology

Shubhankar Marathe, Darwin Li, Ahmad Hosseinbeig, Hossein Rezaei, Pengyu Wei, Jianchi Zhou, David Pommerenke

EMC Laboratory, Missouri University of Science and Technology, 4000 Enterprise Dr., Rolla, MO, 65401, USA

tel.: 573 341 4139, fax: 573 341 4477, e-mail: skmcr4@mst.edu

Abstract–An adjustable spark gap structure is designed to generate Secondary ESD. The primary and the secondary discharge current are directly measured. The setup is modelled using CST full-wave simulation software. The goal is to predict secondary ESD induced current levels using simulation methods, to assist designers in product development in the early design stage.

I. Introduction

Secondary electrostatic discharge (ESD) events may cause damage inside electronic products [1]. Typically, a product is evaluated for its system level ESD robustness using the IEC 61000-4-2 testing [2]. The secondary ESD event occurs when a floating metal discharges to a surrounding grounded metal inside a product. The discharge occurs across a spark gap between the floating and the grounded metal. The over-voltage across the spark gap leads to the breakdown of the spark gap and the initiation of the secondary ESD current. A statistical time lag is associated with the initiation of the secondary ESD current, which is investigated in the study [3]. Methods to model the secondary ESD have been investigated in [4-5]. The modelling method requires a two-step process for determining the fields caused due to the occurrence of the secondary ESD current. It requires the re-import of the secondary ESD current into the full-wave simulation model.

A decorative floating metal setup is designed to generate secondary discharges for known spark gap distances. This measurement setup is similar to the in-situ measurement setup in [1] for monitoring the secondary ESD current measurements. The study performed in [1] makes use of the measured secondary ESD currents to improve the ESD robustness of the desired IC under test. However, the in-situ measurement setup does not monitor other waveforms such as the ESD gun discharge currents and the floating metal voltage.

The decorative metal geometry is modelled using CST full-wave software. The secondary ESD event peak current, statistical time lag and the voltage on the decorative metal are compared with the simulation model. This study introduces the full-wave modelling method to predict the currents induced during a secondary ESD event. The simulated results are compared to the measured waveforms and the accuracy of the full-wave simulation method is discussed.

II. Measurement Setup

Figure 1 shows the block diagram of the measurement setup for the decorative metal. This simplified setup is designed to generate repeatable secondary ESD events. A metal screw is mounted on the decorative metal plate. The distance between the screw tip and the current target (1.9 Ω) is called as the spark gap distance. Accurate spark gap distance of 0.8 mm is obtained using feeler gauges.

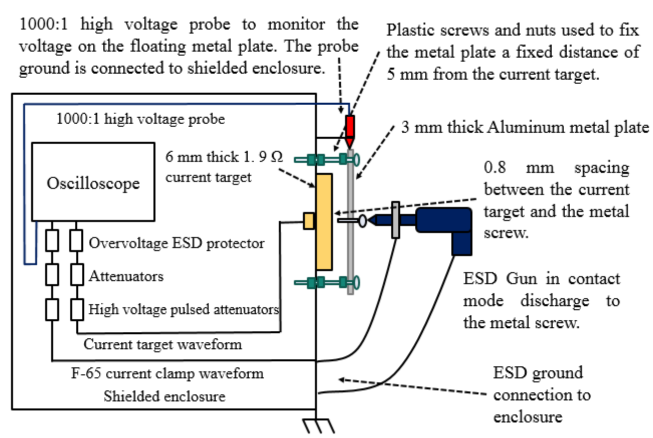


Figure 1: Decorative floating metal measurement setup.

The current target measures the secondary ESD current, when the overvoltage-spark gap breaks down. The decorative metal plate is kept approximately at a distance of 5 mm from the shielded enclosure. The simplified measurement setup is improved from one of the measurement setups in [6], and offers the capability to monitor the floating metal voltage. A 1000:1 high voltage Tektronix probe is used measure the high voltage generated on the decorative floating metal. The ESD gun is discharged in contact mode at 6 kV voltage setting on the metal screw connected to the decorative metal. Clip-on ferrites are added to the measurement cables to reduce field coupling due to the ESD gun discharges. Sand paper is used to expose the metal surface of the shielded enclosure. The high voltage probe ground is well connected to the enclosure by gasket. Tie wraps are used to increase the mechanical contact of the probe ground to the shielded enclosure.

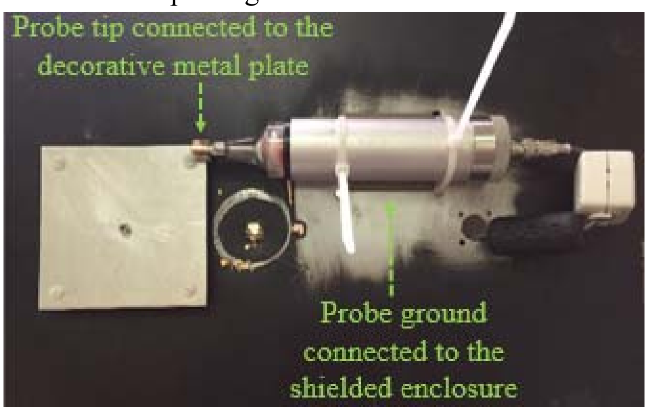


Figure 2: 1000:1 high voltage Tektronix probe is used for measuring the decorative floating metal voltage. Gasket is used at the tip of the high voltage probe and the decorative metal to ensure electrical contact between the two surfaces.

An F-65 current clamp is used to measure the primary discharge current at the tip of the ESD gun. The frequency bandwidth of the measurement setup enabled to resolve the secondary ESD current rise time down to 50 ps. To protect the oscilloscope from undesired ESD testing related damages, the high voltage pulsed attenuators [7] and overvoltage ESD clamps are used in the measurement setup.

III. Measured Waveforms

The measurement results are post-processed to correct for the attenuation introduced by the cables and the pulsed attenuators. Figure 3 shows the measured current clamp (primary discharge), the current target (secondary discharge), and the high voltage probe (floating metal voltage). The measured waveform parameters are summarized in the Table 1.

The Paschen value for the static breakdown of the spark gap distance d equal to 0.8 mm is calculated to be 3.91 kV using the formula [8], where d is in cm and U is in kV units.

$$U = 25.4 * d + 6.64\sqrt{d} \tag{1}$$

The voltage on the decorative floating metal rises when the primary discharge occurs on the floating metal. If the voltage is higher than the Paschen value, then the secondary ESD discharge will occur after a time delay. This time delay is called as the statistical time lag. The statistical time lag is the parameter is calculated by the difference in time instant (t_1) at which the floating metal is equal to the Paschen value and the time instant (t_2) at which the floating metal voltage collapses, indicating the initiation of the secondary ESD event.

The ringing measured near the falling edge of the floating metal voltage waveform is an artifact from the probing. The high voltage probe frequency bandwidth is up to 75 MHz and the frequency content present in the fast falling time of the voltage waveform is higher than that of the probe. Trade off was made by using a bandwidth limited probe in order to monitor the high voltage (1000:1 attenuation). It should be noted that the bandwidth limitation does not limit the capability of the probe to measure the statistical time lag parameter associated with the floating metal voltage measurement.

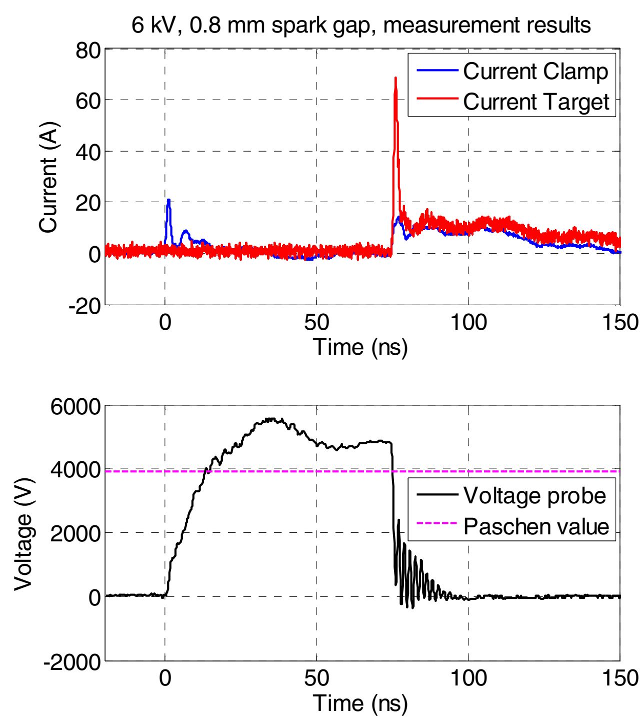


Figure 3: Primary discharge, secondary discharge and the measured floating metal voltage.

IV. Full-wave Simulation Modelling

The primary discharge current levels of the current target and the ESD gun are verified in simulation to make sure that the passive component parameters of the ESD gun match the one used in the measurement. The verification step involves the ESD Gun discharging directly to a target in contact mode and making sure that the peak discharge current and rise time match measurement. After the model is verified, the decorative floating metal plate is introduced in the model, as shown in Figure 4. The secondary ESD event will occur at the location shown by a red arrow numbered 3 in the Figure 4.

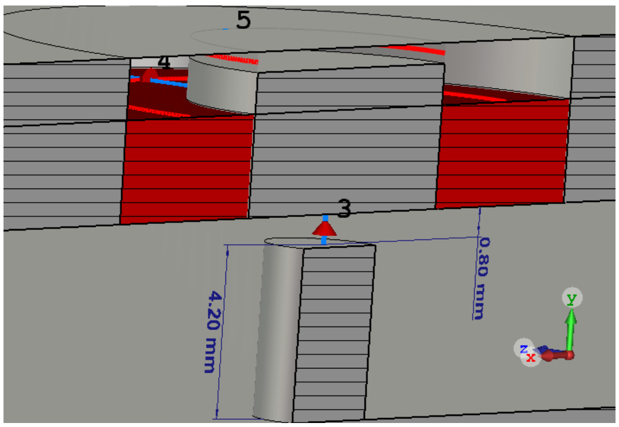
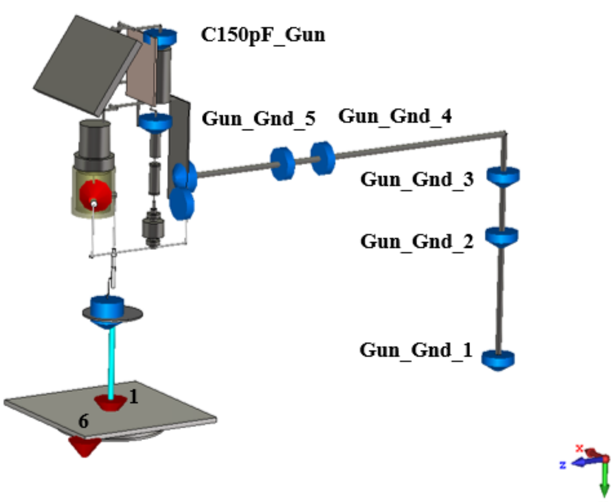
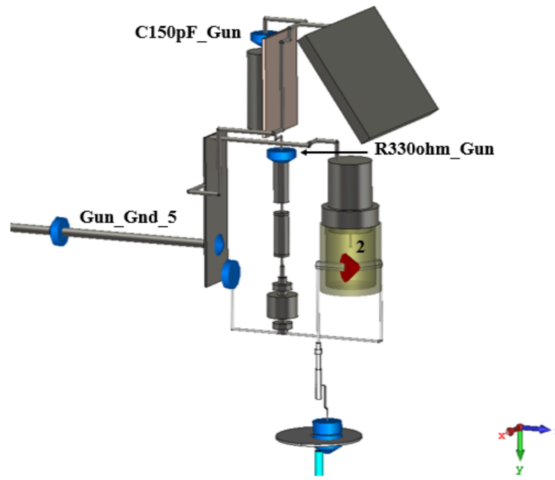


Figure 4: The metal screw to current target interface in the full-wave simulation model is shown. Secondary ESD event occurs across this spark gap interface. 3D Model's ports 3 through 5 are shown in this image.

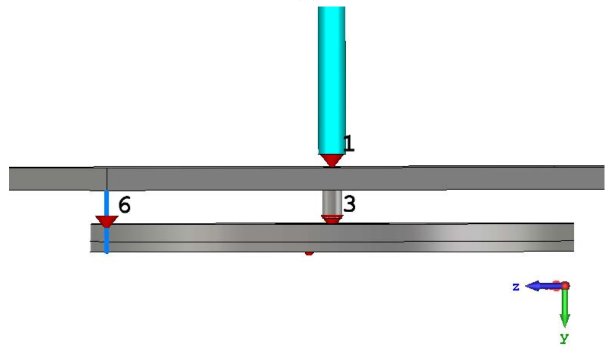
Figure 5 shows the full-wave model snapshot. The red arrow numbered 1 represents the primary discharge monitor. The red arrow numbered 6 represents the floating metal voltage monitor. It measures the voltage between the decorative floating metal and the ground.



(a)



(b)



(c)

Figure 5: (a) Overview of full-wave simulation model (b) Port 2 location in the full-wave model (c) ESD gun discharging to a plate with a current target underneath to measure the secondary ESD event in the simulation model. Ports 1, 3 and 6 location are shown in the full-wave model.

In the circuit model shown in Figure 6, the primary discharge is monitored at the yellow port number 3. The yellow port number 3 connects to the 3D block's pin 1 labeled as "Primary Discharge" in the same figure. This pin 1 represents the port 1 of the 3D model in Figure 5. The secondary discharge is monitored at P3 or P4 in the schematic shown below. The yellow color port 1 connects to the relay in the ESD gun, yellow color port 2 connects to the 50 ohm coaxial port impedance, yellow port 3 connects to the 0.1 ohm impedance, and yellow port 4 is connected to the current target parallel resistors.

In the circuit modeler of CST [9], a switch is used to control the on or off state of the Rompe-Weizel (RW) model [8]. This is shown in Figure 6. The switch is needed to model the statistical time lag. The RW model has an initial charge value which allows it to start current flow. The switch determines when the RW model will initiate the discharge current [10]. Thus, the switch allows to model the statistical time lag. Here multiple approaches are possible. If time lag data is known for the geometry the switch delay can be set appropriately, if no time lag data is known one can use the gap voltage as guidance. In most cases the discharge will be initiated once the field strength has reached 50 kV/cm. In cases in which the surface is clean and smooth it may take 200 kV/cm to initiate the breakdown. Thus, by using the gap distance one can estimate the voltage at which the field strength is high enough to create enough initial electrons that will lead to a breakdown with less than a few nanosecond delay [5].

In this case the initiation of the secondary ESD event in the simulation model is adjusted to be close to the collapse voltage value of the decorative floating metal obtained by monitoring the floating metal voltage. The decision of closing the switch and initiating the secondary ESD event in the simulation model, and, at the same time, instant the collapsing of the voltage on the floating metal is made by selecting the peak floating voltage value from the measurement. It should be noted that the voltage value must be higher than the Paschen value of 3.91 kV obtained using the formula for a spark gap distance of 0.8 mm. The Paschen value represents the over-voltage required over the spark gap (0.8 mm) to cause the initiation of the secondary ESD event. The criterion for closing the switch is based on measurement data. The accuracy of the resulting waveforms is discussed in the following section.

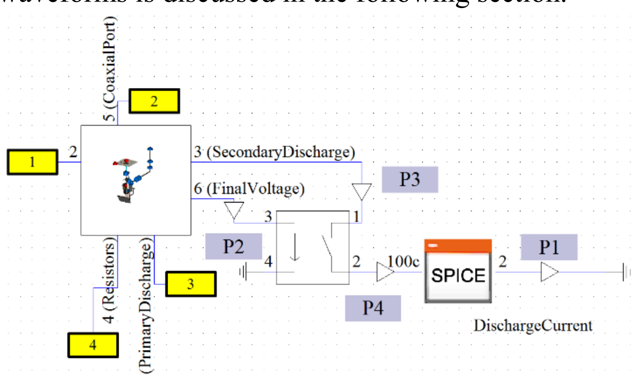


Figure 6: Switch-controlled RW model implementation in circuit modeler of the full-wave simulation software.

V. Measurement and Simulation Comparison

The measurement waveforms are shown in Figure 3 and the simulated waveforms are shown in Figure 7. The measured statistical time lag can vary and it is affected by many parameters such as the humidity, shape of the spark gap geometry, high voltage across the spark, gap etc. The definition of statistical time lag is explained in [4], [5], and is exemplified in Figure 8. There is a statistical time lag between the primary charging current and secondary discharge current. The statistical time lag is defined as the time difference when the Paschen voltage is reached and the point in time of formation of the arc. In Figure 8, this is marked by starting at the Paschen Voltage in the Voltage plot and ending when the secondary discharge current begins to rise (the Current plot and Voltage plot in Figure 8 are synchronous in time). The measured and simulated waveforms are plotted in different figures, because it is difficult to match the measured statistical time lag with the simulated value. Therefore overlaying the measured and the simulated waveforms will make it difficult to observe individual waveforms for the given figure axis scale settings.

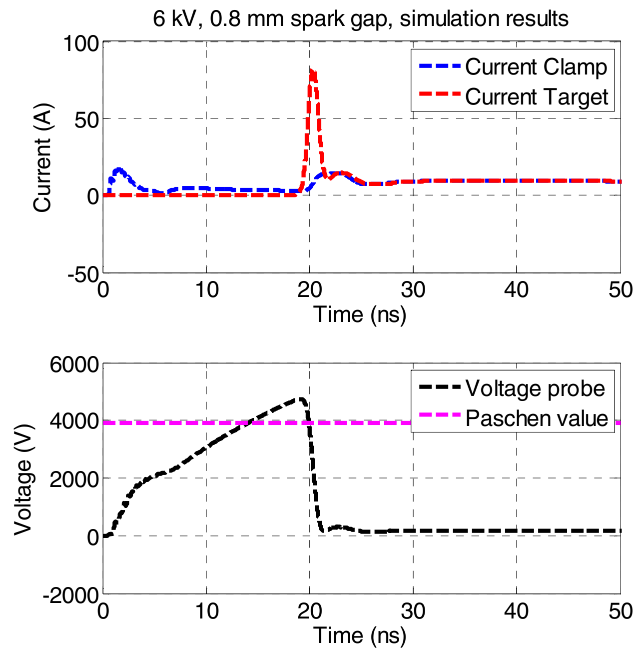


Figure 7: The simulated waveforms obtained from the full wave model.

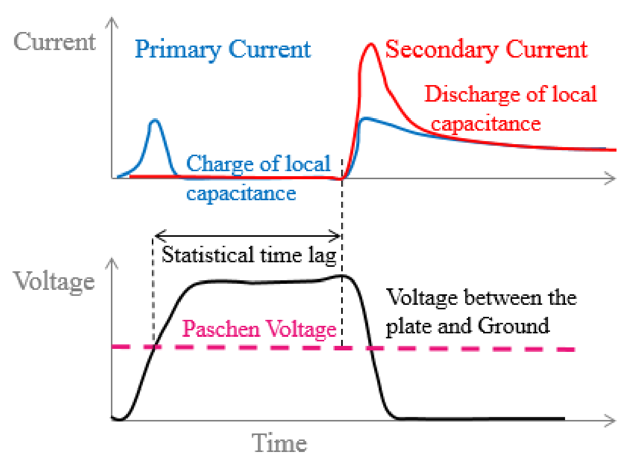


Figure 8: Abstraction of the Secondary Discharge process.

Table 1 shows the comparison results for the various parameters between the measurement and the simulation.

Table 1: Comparison of measured and simulated parameters

Parameters for 6 kV at 0.8 mm spark gap	**Measurement**	**Simulation**
Primary charging current peak	21 A	19 A
Primary charging current rise time (20% - 80%)	650 ps	550 ps
Secondary ESD peak current	69 A	82 A
Secondary ESD current rise time (20% - 80%)	550 ps	520 ps
Statistical time lag between the primary charging current and Secondary ESD	61 ns	5 ns
Paschen breakdown voltage	3.91 kV	3.91 kV
Peak metal plate voltage	5.6 kV	4.7 kV

The primary charging current is expected to be around 3.75 A/kV to be around 22.5 A for contact mode discharge into a large ground plane. The simulated primary discharge current is within 10% variation of the measured current in to the decorative metal plate.

In simulation, when the peak floating decorative metal voltage is at 4.7 kV, the peak secondary ESD current was found to be 82 A. This corresponds to around a 20% error when compared to the measurement. The peak decorative metal plate voltage is explicitly handled for simulation because by design of the switch, it will point exactly to when the secondary discharge occurs. However, this peak decorative metal plate voltage for measurement is affected by the stochastic process of air discharge and the measurement tools that cause the secondary breakdown to occur at a value lower than the peak floating decorative metal voltage. This is a very important concept because it gives credence to the RW model since it can correctly form the arc resistance with the appropriate voltage at the point of breakdown.

Discussion and Conclusion

In general, the rise time of the secondary ESD currents is faster than that of the primary charging ESD current from the ESD gun. In real products measuring the secondary discharge at the source location would be difficult to access and would require the use of external measurement equipment such as the wire loop antenna, F-65 current clamp or monitoring the floating metal voltage in the real product using a high voltage probe to detect the occurrence of the secondary ESD event [6]. In some cases, it may not be possible to access the source location of the secondary ESD event inside a real product, which will lead to bandwidth limitation of the rise time measurements performed using the external equipment. The rise time measurement is bandwidth limited due to the added inductance/capacitance in the measurement due to the equipment being away from the source location of the secondary ESD event.

The secondary discharge setup represents a product example having decorative metal placed for aesthetic purposes. The floating metal is modelled using the CST software. In this study, a controlled setup is used to measure the induced secondary ESD peak current, rise time and the statistical time lag. The current target is placed right at the source of the secondary ESD event. This measurement setup allows the user to measure the secondary discharge currents at the spark gap, which may not be always be possible in complex electronic products. The full-wave simulation methodology predicts the measured secondary ESD current within 20% accuracy.

This simulation methodology can be extended to real systems, but one needs to modify the decision control in the closing of the switch in the circuit modeler in order to initiate the secondary ESD event. To identify the worst case rise time, and the peak secondary ESD current, closing the switch at twice or three times the Paschen value. In measurements, this will be affected by the statistical process of the statistical time lag, and may be difficult to reproduce the statistical time lag, which may cause the breakdown of the spark gap geometry at twice or three times the Paschen value for a specific value of the spark gap distance (0.8 mm in this case). If the statistical time lag is long, it may give the floating metal voltage the time required to reach twice or thrice the Paschen value. If in measurement the statistical time lag parameter is small, then the collapse of the floating metal voltage will occur before it reaches the twice or thrice the Paschen value. The rise in the floating metal voltage depends on the local capacitance between the floating metal and the ground. It should be noted that the collapse of the floating metal voltage is associated with the initiation of the secondary ESD event.

In real systems, it would be difficult to measure the rise time and the peak secondary ESD current, if the source location of the event is not accessible. This makes it difficult to assess the accuracy of the parameter values obtained from the simulation model. In such cases, the values obtained can be considered as a suggestive guideline for worst case rise time and peak secondary ESD discharge current.

In modeling the geometry of the ESD gun with the DUT, the combined mesh count is often based on the complex model between the DUT and the ESD gun. As long as both are meshed properly individually, then combining the two models with the mesh of the more complex model will also be accurate. Material properties should also be as accurate as possible, though more studies need to go into what type of simplifications we can make. Understanding the most likely spark gap geometries on a product and performing early design stage simulations will help to predict the worst case secondary ESD current stress on the electronic product.

Acknowledgment

This material is based upon work supported by the National Science Foundation (NSF) under Grants IIP-1440110.

References

[1] H. Wolf, H. Gieser, “Secondary discharge – A potential risk during system level ESD testing,” in Electrical Overstress/Electrostatic Discharge Symposium (EOS/ESD), 2015 37th, vol., no., pp.1-7, 27 Sept.-2 Oct. 2015.

[2] IEC 61000-4-2, ‘Electromagnetic compatibility (EMC) – Part 4-2: Electrostatic discharge immunity test’, Ed. 2.0, 2008.

[3] F. Wan, V. Pilla, J. Li, D. Pommerenke, H. Shumiya, K. Araki, "Time Lag of Secondary ESD in Millimeter-Size Spark Gaps," IEEE Trans. Electromagn. Compat., vol. 56, no. 1, pp. 28–34, Feb. 2014.

[4] J. Xiao, D. Pommerenke, J. L. Drewniak, H. Shumiya, T. Yamada, and K. Araki, "bmodel of secondary ESD for a portable product," Electromagnetic Compatibility (EMC), 2011 IEEE International Symposium on, 14-19 Aug. 2011, pp. 56-61.

[5] J. Xiao, D. Pommerenke, J. L. Drewniak, H. Shumiya, J. Maeshima, T. Yamada, and K. Araki, “Model of secondary ESD for a portable electronic product,” IEEE Trans. Electromagn. Compat., vol. 54, no. 3, pp. 546–555, Jun. 2012.

[6] S. Marathe, H. Rezaei, D. Pommerenke, and M. Hertz, "Detection Methods for Secondary ESD Discharge During IEC 61000-4-2 Testing," in IEEE International Symposium on Electromagnetic Compatibility, 2017.-to appear

[7] High Voltage Pulse Attenuator. [Online]. Available: https://www.esdemc.com/

[8] D. Pommerenke, “ESD: Transient fields, arc simulation and rise time limit,” J. Electrostat., vol. 36, pp. 31–54, 1995.

[9] CST Microwave studio. (2017). [Online]. Available: https://www.cst.com/

[10] D. Pommerenke and M. Aidam, “To what extent do contact-mode and indirect ESD test methods reproduce reality,” in Proc. Electr. Overstress/Electrostatic Discharge Symp., 1995, Sep. 12–14, 1995, pp. 101–109.