Electrostatic Discharge Characteristics of Conductive Polymers

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Abstract - ESD control items are generally characterized by direct current measurements at certain voltage levels. Discharge resistance may, however, have a remarkable voltage and frequency dependency. We have assessed conductive polymers by comparing the resistivities of the solid planar objects with the resistances of electrostatic discharges. Conductive polymers may have applicable characteristics of current attenuation for ESD control items.

I. Introduction

The requirements of ESD control items vary in electronics and automotive industry. The standard procedure of tailoring is not widely exploited. Instead, there has been a tendency to improve control by tightening the limits of acceptance [1]. Without justification, unnecessary requirements may cause overkill.

Qualification of ESD control items is generally based on the direct current (DC) resistance measurements [2, 3]. An open circuit test voltage of the resistance measurement is 10 V below 1 MΩ or 100 V when 1 MΩ is exceeded [4, 5].

The DC resistance of the measurement circuit or the resistivity of the material describes whether the material under tests dissipates its own charge but does not necessarily correlate with the resistance that a charged device or board sees when it gets in contact with a different material. The most important differences are the voltage and frequency dependency and contact resistance. The geometry of an electrode used for qualification is different than a contact point between the ESD sensitive device and a control item.

In this study, we compared the DC resistivities of conductive polymers with the resistances that charged devices and charged boards see when discharging to the same conductive polymer samples.

The most important objective was to provide technical information for assessing the requirements of ESD control items such as assembly stands, jigs and tools, tote boxes and packaging materials such as trays, carrier tapes and reels of ESD sensitive devices. Test methods, results and conclusions are shown in next chapters.

II. Test Methods

Measurements were made in laboratory conditions after 48 h preconditioning of the samples at (23 ± 2) °C, (12 ± 3) % RH.

A. DC Resistance and Resistivity

Surface resistances were measured with different concentric ring electrodes (CREs) in accordance with IEC 61340-2-3 [4]. Measurements were repeated with the surface bar electrode (SRB) to reduce the contact resistance [5]. The weight of the SRB electrode was 2900 g. The width of the bars was 3 mm and the length was 50.8 mm (2 inches). The distance between the bars was 25.4 mm (1 inch). A contact surface was made of conductive rubber (3 mm, shore A 60, $\rho V < 100\ \Omega m$) or a copper. Dimensions were taken into account and the results are expressed as resistivity.

A resistance through the material was measured with a 2.3 kg (5 lbs) electrode. A diameter of the electrodes was 63 mm. Different conductive rubbers were compared to determine the lowest possible contact resistance of top and bottom electrodes with the sample. CRE could not be used due to the unreliable contact between the electrode and the samples.

In addition, DC resistances through the material were measured with the ESD contact probe with a rounded head (Figure 1).

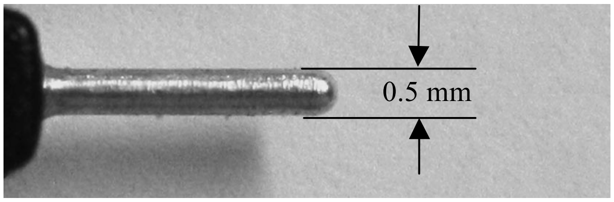

Figure 1: ESD contact probe with a rounded head

Results were recorded after 15 s electrification. Open circuit test voltage was 10 V below 1 MΩ or 100 V when 1 MΩ was exceeded. All the measurements were repeated ten times. The minimum and maximum readings with a geometric mean are shown as a result.

B. Electrostatic Discharge Attenuation

The samples were characterized with a test method shown in Figure 2. ESD source is an RLC circuit that models a charged board or charged device ESD event in series with a grounded polymer sample under test. The method was originally introduced by Jaakko Paasi in 2007 [6].

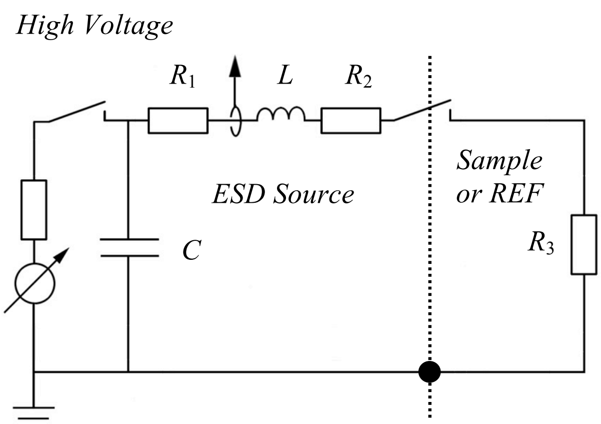

Figure 2: Simplified equivalent circuit

An example of the test setup with the device as an ESD source is shown in Figure 3.

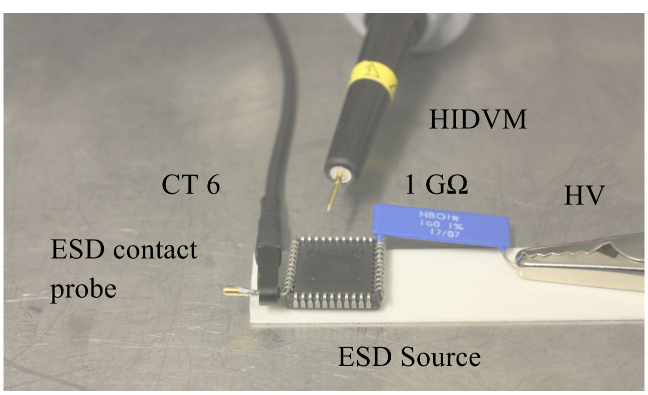

Figure 3: Device as an ESD source

In comparison tests the source capacitor C was made of two parallel steel plates and a dielectric layer between them. The capacitor was adjusted by changing the sizes of the plates and thickness of the dielectric layer.

The capacitor was charged by a high voltage generator. An electrostatic potential was measured with a high-impedance contacting digital voltmeter (HIDVM). An electrostatic discharge was obtained by bringing the grounded polymer sample shown in Figure 4 into contact with the ESD contact probe shown in Figures 1 and 3.

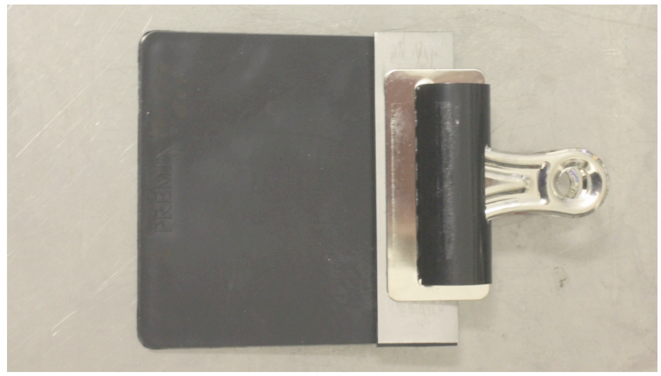

Figure 4: Sample with the ground electrode

The discharge waveform was measured by current transformers CT1, CT2, or CT6 and an oscilloscope of 4 GHz bandwidth and 20 GS/s.

All the measurements were repeated at least 16 times. Averages of the 16 current waveforms are presented as results. Other materials than metals often result in damped waveforms and relatively long charge decay. CT2 has a bandwidth of 200 MHz but it has the better response for slow transients [7]. A handheld oscilloscope with a bandwidth of 200 MHz and a CT2 are also practical tools for onsite measurements, although the results might be a bit different in magnitude.

The ESD resistance is a series resistance of R_1, R_2, and R_3, where R_1 is a resistor of 33 Ω in series with a spark resistance R_2 and R_3 is a resistance of the sample. R_1 represents the resistance where the energy is dissipated in the device under stress.

An inductance L was adjusted to approximately 80 nH with the 80 mm long discharge wire. The high inductance results in ringing but it also slows down the rate of change making the reliable measurement possible with the lower bandwidth.

The sample was grounded with a metal electrode or with a conductive rubber, depending on the sample. A contact material resulting in the lowest ESD resistance was selected for the measurement. A contact surface of the grounding electrode was 10 mm × 85 mm.

The discharge power of the ESD source was calculated with the discharge current and the series resistance of the device and the spark according to Ohm's law:

$$P_{\text{ESD source}} = I^2(R_1 + R_2) \tag{1}$$

The energy dissipation of the ESD source was integrated from the discharge current. With the shorted metal reference (*REF* in Figure 2) the energy dissipation equals with the potential energy of the ESD source:

$$W = \int_{t_0}^{t} I^2(R_1 + R_2)\,dt = \frac{C \times V^2}{2} \tag{2}$$

Current waveforms of the shorted references were compared to the calculated waveforms:

$$I_{(t)} = \left(\frac{V_0}{L\omega}\right) e^{-\left(\frac{R}{2L}t\right)} \sin(\omega t) \tag{3}$$

where $$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{4}$$

The resistance changes during the discharge due to the voltage and frequency dependency making the assessment complicated. In this study, the total ESD resistance, $R_{\text{Total}} = R_1 + R_2 + R_3$, was calculated from the complete energy dissipation using the measured discharge current and the initial voltage on the capacitor:

$$R_{\text{Total}} = \frac{W}{\int_{t_0}^{t} I^2\,dt} \tag{5}$$

The resistance based on energy dissipation was considered as an applicable simplification of the average resistance of the electrostatic discharge. A ratio between the peak currents of a shorted reference and the sample was then compared on a logarithmic scale:

$$I_{\text{Atten}} = 20\log\left(\frac{I}{I_{ref}}\right) \tag{6}$$

An energy dissipation ratio of the ESD source is then calculated in accordance with Equation 7. Here, the energy dissipation inside the device or board is compared to the total energy dissipation. Low energy attenuation means that more energy is dissipated in the device. High attenuation indicates that the energy is dissipated in the contact material.

$$W_{\text{Atten}} = 10\log\left(\frac{\int R_{Total}\cdot I^2 \cdot dt}{\int (R_1 + R_2)\cdot I_{ref}^2 \cdot dt}\right) \tag{7}$$

III. Test Results

Conductive polymers of five different samples were evaluated with three source capacitances: 2.6 pF, 11 pF, and 43 pF. The lower capacitances represent a charged device and the highest models a charged board. In addition, measurements were made with a real device having 3.4 pF source capacitance.

A. DC Resistance and Resistivity

Fixed concentric ring electrodes resulted in contact errors with the hard surfaces due to the mechanical tolerances or slightly concave or convex surfaces of the samples [5]. Therefore, the surface resistivity was measured with a spring-loaded inner electrode instead of the standard electrodes. The weight of the CRE was 3200 g.

Concentric ring electrodes are generally used for assessing insulating materials with relatively high open circuit voltages [8]. Conductive and dissipative ESD control items are measured with lower test voltages [4]. A contact resistance of the hard surface depends highly on the voltage, especially in a low humidity [5].

The samples were measured with four different CRE and two SRB electrodes. The electrode resulting in the lowest value represents the lowest contact resistance and the lowest systematic error. That electrode was selected in the final measurement of the sample.

As shown in Figure 5, the CRE caused systematically higher values than SRB. The surface resistivity is expressed as ohm in accordance with the international system of units. Geometries of the electrodes are taken into account. As a conclusion the ring electrodes with the low test voltages were inadequate for characterizing the resistivity of conductive polymer compounds under test.

ESD contact probe resulted in high values when the resistance was measured through the sample. The results are shown in Figure 6.

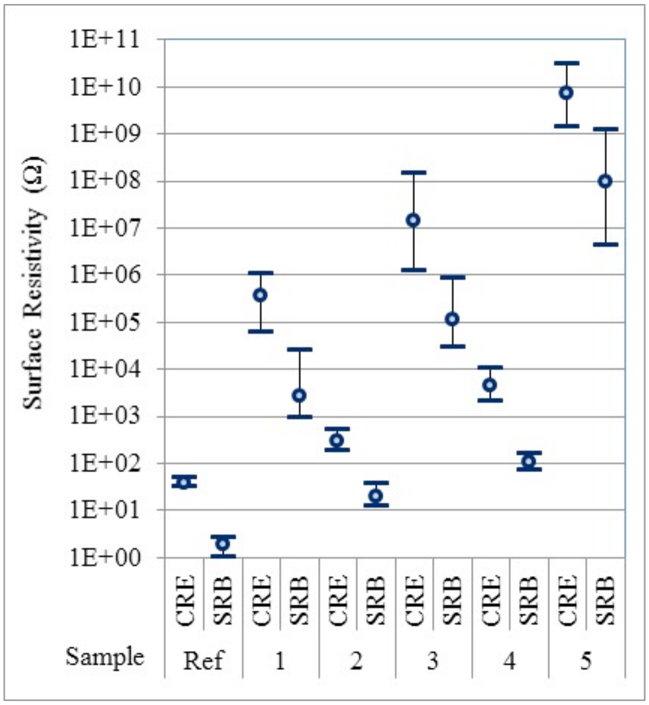

Figure 5: Surface Resistivities

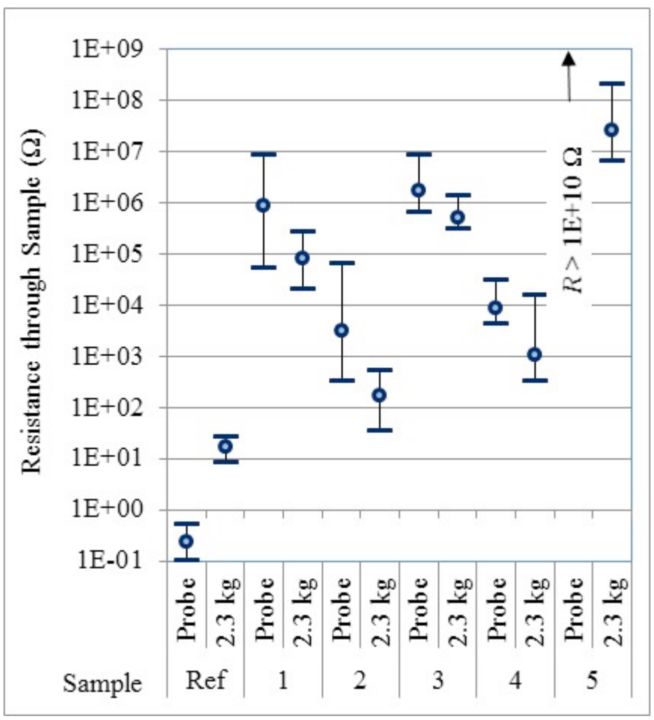

Figure 6: Resistance through the material

B. ESD References

1. Source Capacitance of 2.6 pF

ESD reference waveforms of 2.6 pF source are shown in Figures 7, 8, 9 and 10. Parameters of the 2.6 pF reference were: $V = 1000$ V, $C = 2.6$ pF, $R = 67$ Ω, 80 nH, 1.3 µJ.

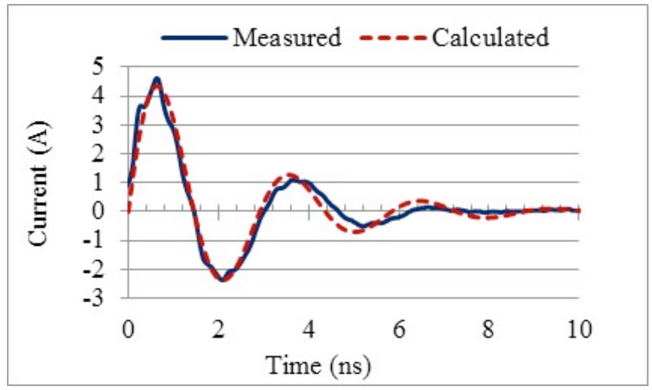

Figure 7: Current of ESD, 2.6 pF reference, 1000 V ESD

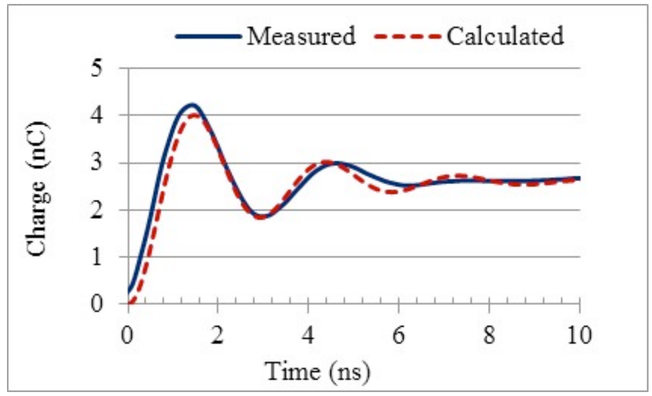

Figure 8: Charge of ESD, 2.6 pF reference, 1000 V

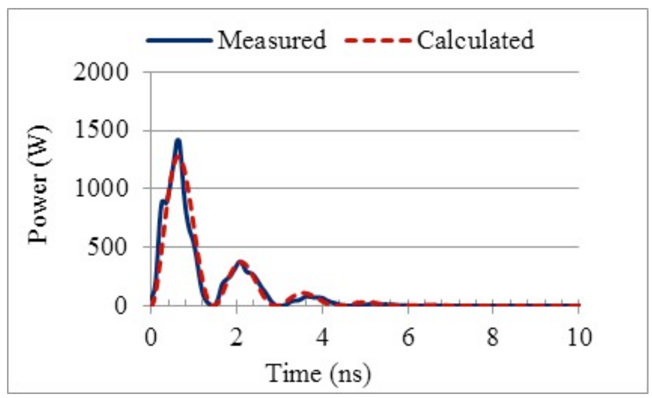

Figure 9: Power of ESD, 2.6 pF reference, 1000 V

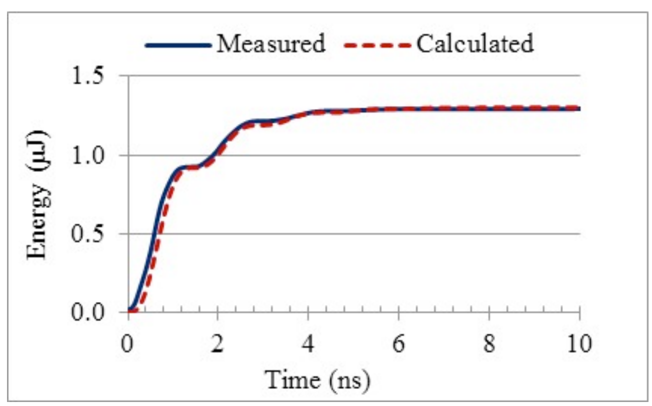

Figure 10: Energy of ESD, 2.6 pF reference 1000 V

2. Source Capacitance of 11 pF

ESD reference waveforms of 11 pF source are shown in Figures 11, 12, 13 and 14. Parameters of the 11 pF reference were: V = 1000 V, C = 11 pF, R = 50 Ω, 100 nH, 5.5 µJ.

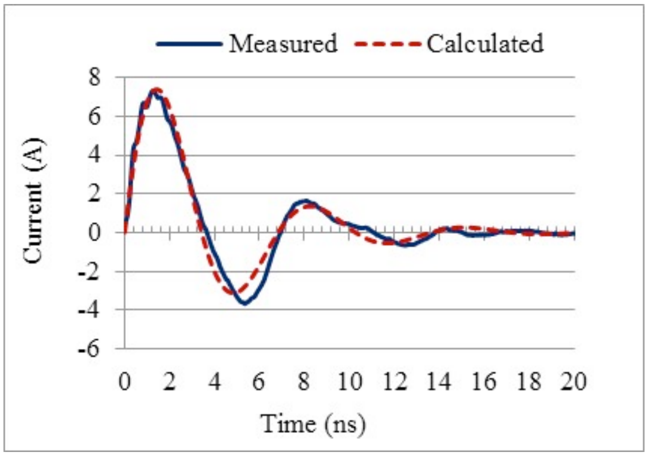

Figure 11: Current of ESD, 11 pF reference, 1000 V

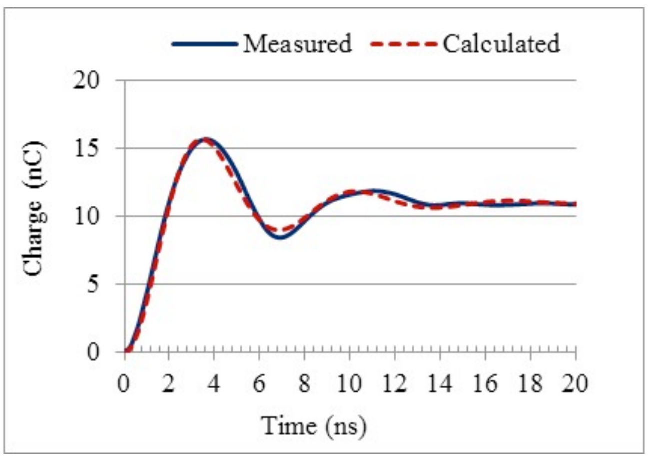

Figure 12: Charge of ESD, 11 pF reference, 1000 V

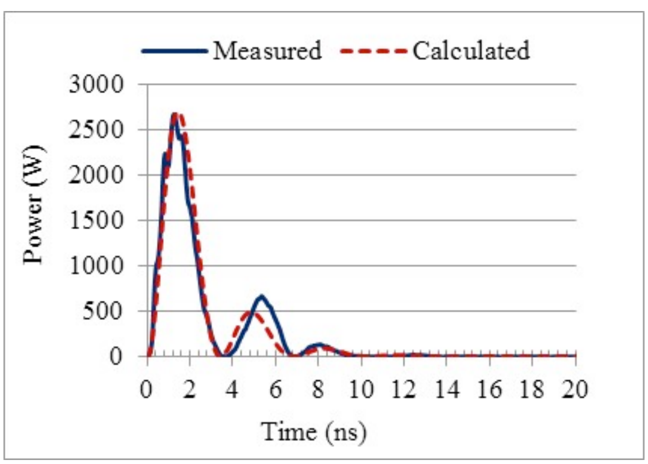

Figure 13: Power of ESD, 11 pF reference, 1000 V

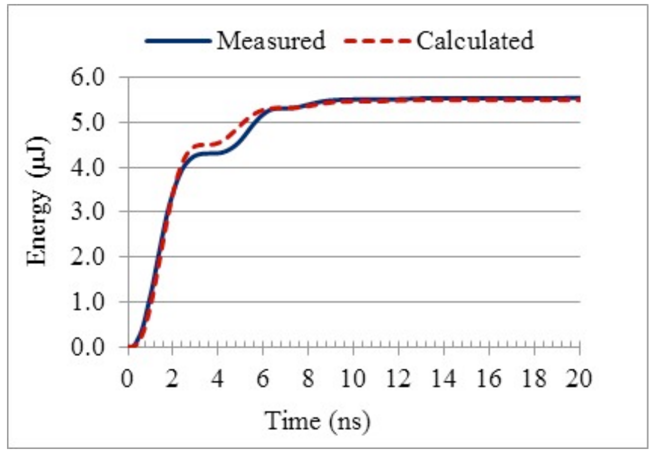

Figure 14: Energy of ESD, 11 pF reference, 1000 V

3. Source Capacitance of 43 pF

ESD reference waveforms of 43 pF source are shown in Figures 15, 16, 17 and 18. Parameters of the 43 pF reference were: V = 1000 V, C = 43 pF, R = 40 Ω, 75 nH, 22 µJ.

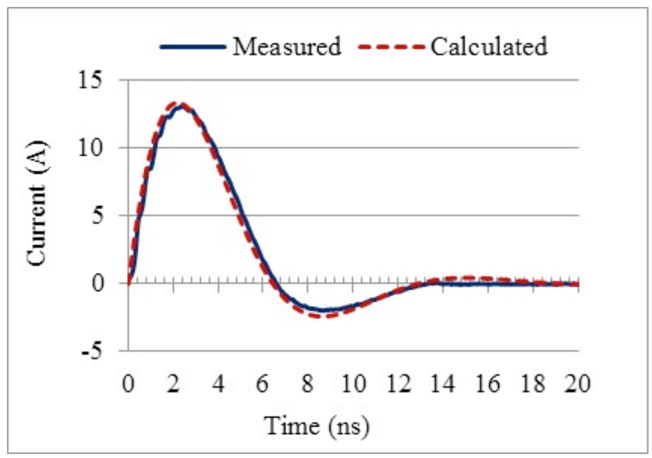

Figure 15: Current of ESD, 43 pF reference, 1000 V

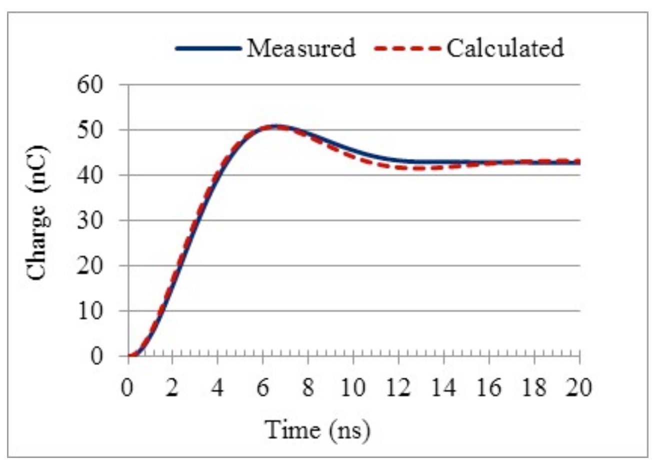

Figure 16: Charge of ESD, 43 pF reference, 1000 V

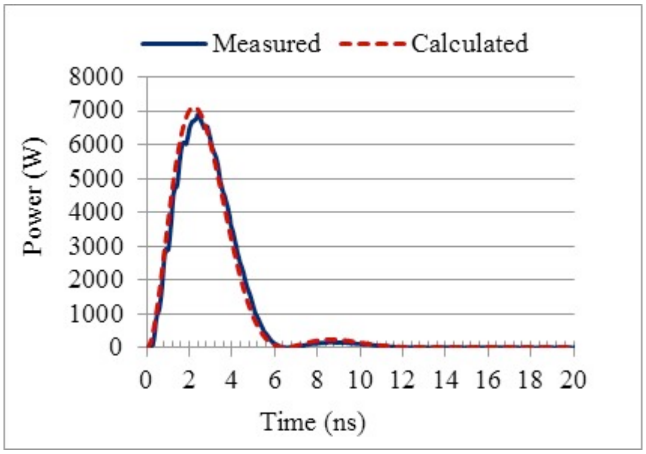

Figure 17: Power of ESD, 43 pF reference, 1000 V

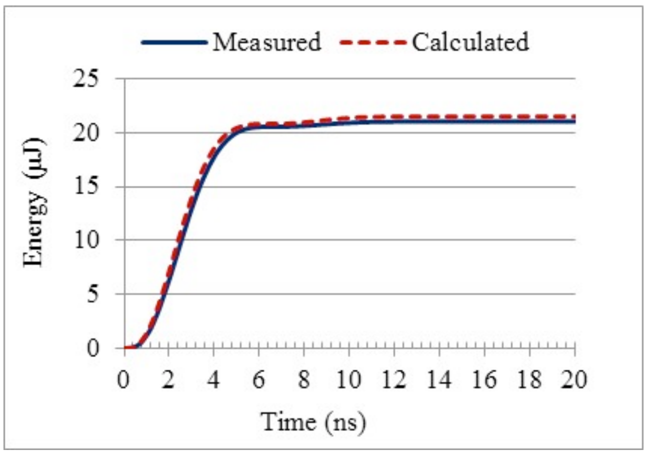

Figure 18: Energy of ESD, 43 pF reference, 1000 V

4. Device as a Source of ESD

As an example, ESD reference waveforms of the device as ESD source are shown in Figures 19, 20, 21 and 22. Parameters of the reference were: V = 1000 V, C = 3.4 pF, R = 48 Ω, 9 nH, 1.7 µJ.

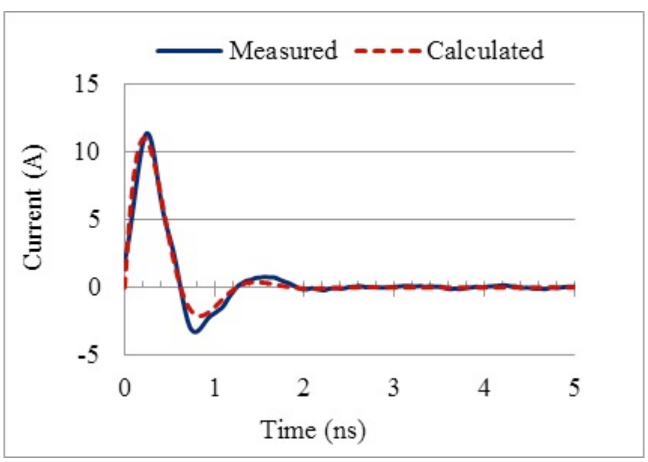

Figure 19: Current of charged device event, 3.4 pF, 1000 V

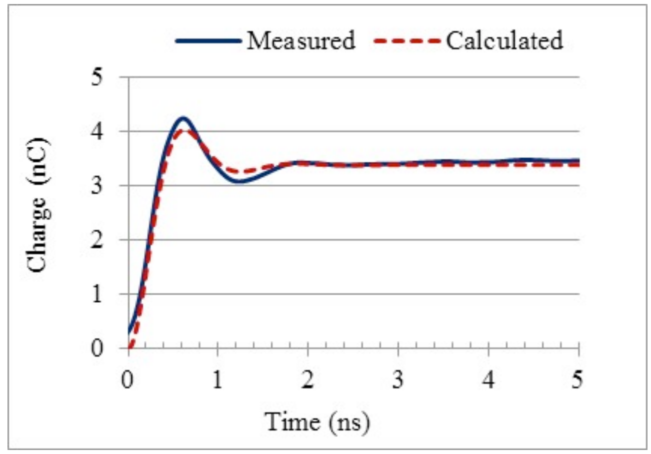

Figure 20: Charge of charged device event, 3.4 pF, 1000 V

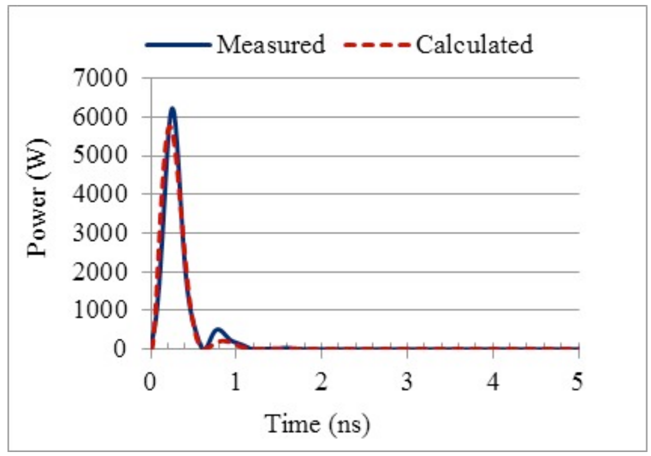

Figure 21: Power of charged device event, 3.4 pF, 1000 V

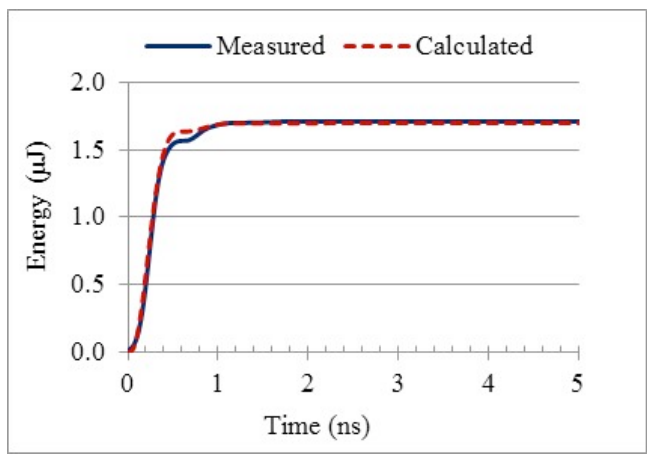

Figure 22: Energy of charged device event, 3.4 pF, 1000 V

The ESD source with the device had relatively low inductance that typically exists in the device testing. These measurements were made with CT 6 and 4 GHz oscilloscope. The measurement curves of all ESD sources complied with the calculated waveforms.

C. ESD Attenuation

ESD attenuation of the samples was evaluated by capturing ESD current waveforms with the different ESD sources having initial potential of 1000 V on the source capacitor.

1. Current Waveforms

As an example, average current waveforms of the sample 2 with the different ESD sources are shown in Figures 23, 24, 25, and 26.

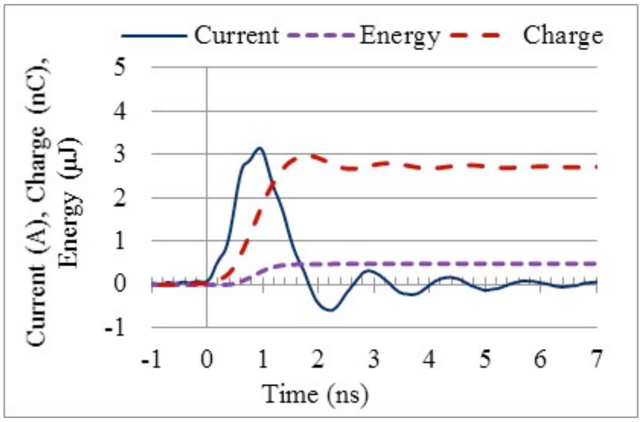

Figure 23: ESD of Sample 2 with 2.6 pF reference

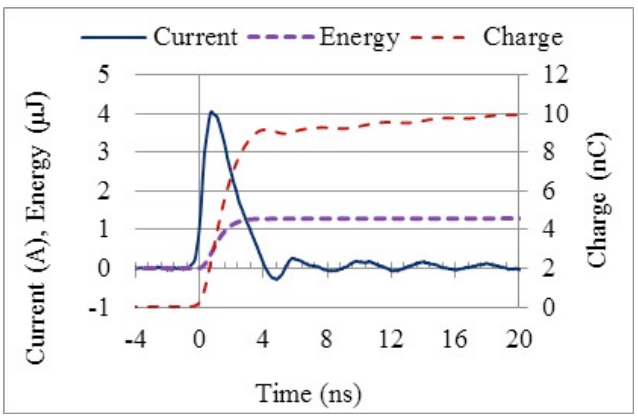

Figure 24: ESD of Sample 2 with 11 pF reference

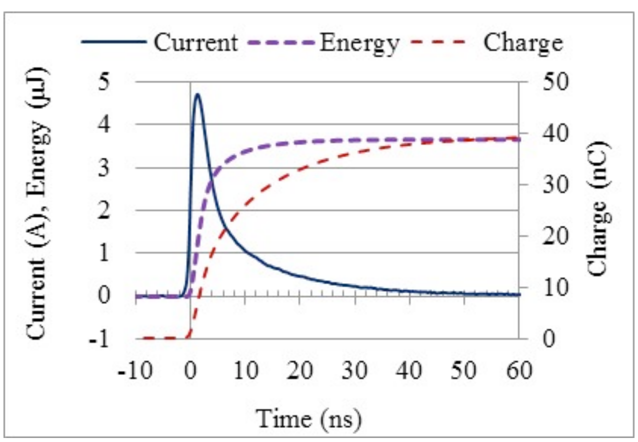

Figure 25: ESD of Sample 2 with 43 pF reference

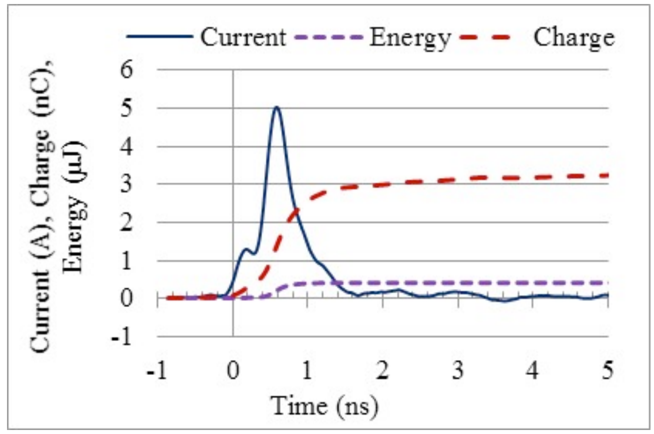

Figure 26: ESD of Sample 2 with the device, 3.4 pF

The current was underdamped or critically damped with the lower source capacitances and overdamped with 43 pF. The different ESD sources had relatively slight effect on the peak current.

2. Summary of Results

Results with different ESD sources are shown in Tables 1, 2, 3, and 4. Summary of current and energy attenuation is shown in Figures 27 and 28.

Table 1: ESD parameters with 2.6 pF reference

Sample	Peak Current (A)	ESD Energy (nJ)	Current Attenuation (dB)	Energy Attenuation (dB)
Ref	4.6	1300	N/A	N/A
1	0.4	26	-21	-17
2	3.1	490	-3	-4
3	0.13	4	-31	-25
4	1.4	132	-10	-10
5	0.1	0.3	-33	-36

Table 2: ESD parameters with 11 pF reference

Sample	Peak Current (A)	ESD Energy (nJ)	Current Attenuation (dB)	Energy Attenuation (dB)
Ref	7	5500	N/A	N/A
1	0.6	104	-21	-17
2	4	1300	-5	-6
3	0.2	32	-31	-22
4	2	452	-11	-11
5	0.1	1	-37	-37

Table 3: ESD parameters with 43 pF reference

Sample	Peak Current (A)	ESD Energy (nJ)	Current Attenuation (dB)	Energy Attenuation (dB)
Ref	13	22000	N/A	N/A
1	0.26	165	-34	-21
2	4.7	3700	-9	-8
3	0.2	64	-36	-25
4	2.2	1600	-15	-11
5	0.1	4	-42	-37

Table 4: ESD parameters with the device as a reference. 3.4 pF

Sample	Peak Current (A)	ESD Energy (nJ)	Current Attenuation (dB)	Energy Attenuation (dB)
Ref	11	1700	N/A	N/A
1	0.56	31	-26	-17
2	5.0	400	-7	-6
3	0.15	4	-37	-26
4	1.7	125	-16	-11
5	0.12	0.5	-39	-35

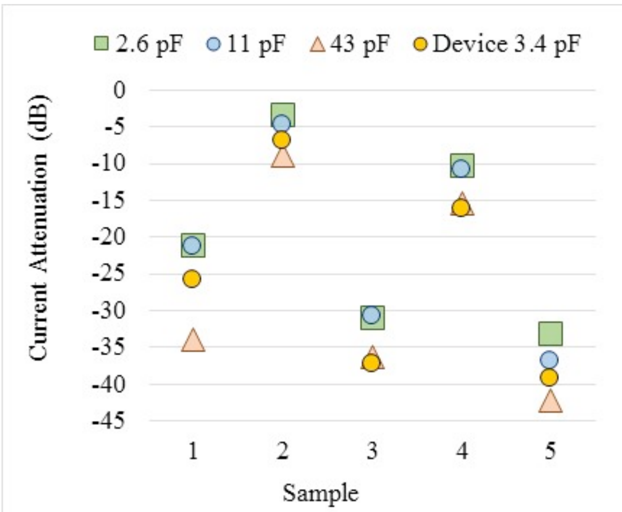

Figure 27: Summary of current attenuation

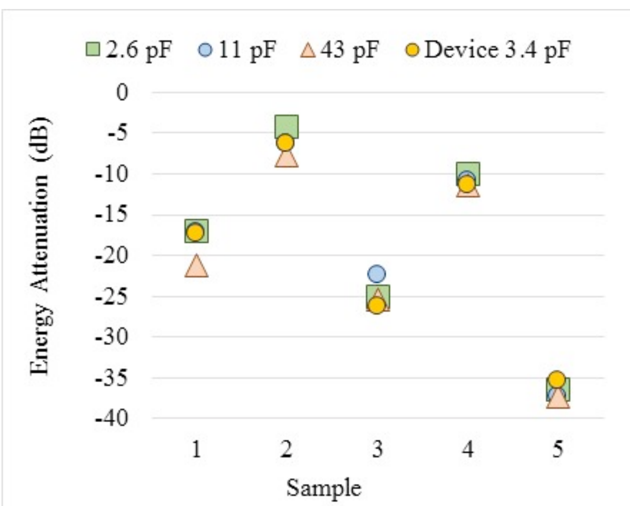

Figure 28: Summary of Energy attenuation

The final result depends on the source parameters but also on the target and grounding path. Remarkable differences in current and energy attenuation with the different ESD sources could not be seen.

ESD current and energy attenuations of the fast transients correspond to the slower transients. Current attenuations of the samples were slightly higher with 3.4 pF capacitance and 9 nH inductance compared with the slower transients of 2.6 pF and 80 nH.

D. ESD Resistance

ESD resistances were calculated with Equation 5. Source capacitance had only slight effect on resistances as shown in Figure 29. The picture represents the resistances calculated from the highest captured peak currents of the samples.

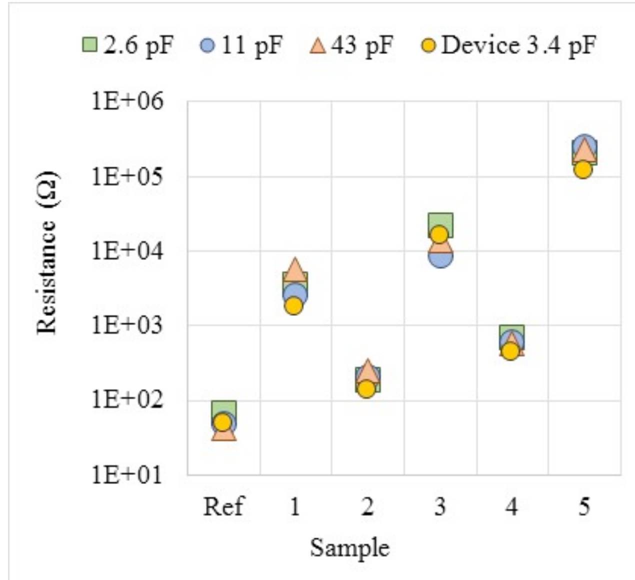

Figure 29: ESD resistances with different source capacitances

The summary of the DC resistances and ESD resistances measured with 43 pF source at 1000 V is shown in Table 5. The ESD resistance did not clearly correlate with the surface resistivity or resistance through the material. The magnitude of resistance depends on the source voltage as shown in the next chapters.

Table 5: Summary of resistivities and ESD Resistance

Sample	Resistivity (Ω)		Resistance (Ω)		
	CRE	SRB	Pin	2.3 kg	ESD
Ref	4E+01	2E+00	2E-01	2E+01	4E+01
1	4E+05	3E+03	9E+05	8E+04	7E+03
2	3E+02	2E+01	3E+03	2E+02	3E+02
3	1E+07	1E+05	2E+06	5E+05	1E+04
4	5E+03	1E+02	9E+03	1E+03	6E+02
5	7E+09	1E+08	2E+10	3E+07	2E+05

E. Effect of ESD Voltage

1. Current and Energy

As an example, the effect of ESD source voltage of the sample 2 is shown in Figures 30, 31, and 32. Energy dissipation in ESD source and the peak current had remarkable source voltage dependency.

The peak current of the discharge did not really depend on the size of the ESD source with high voltages.

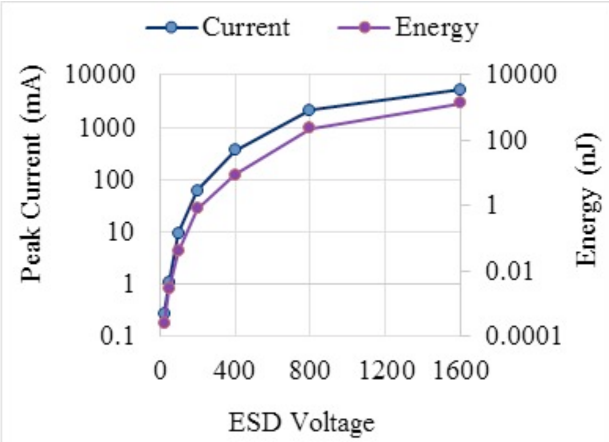

Figure 30: Voltage dependency of current and energy, Sample 2, 2.6 pF Reference

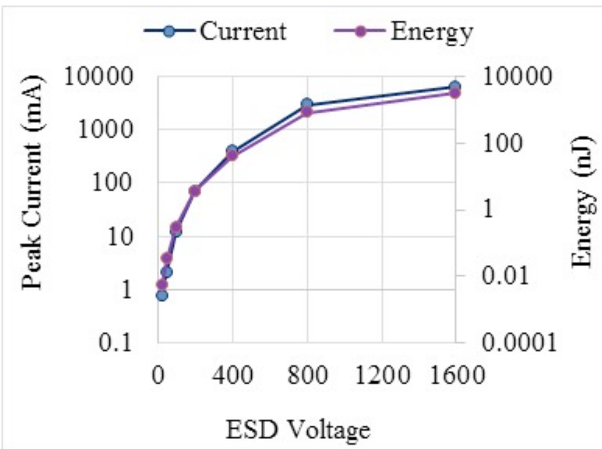

Figure 31: Voltage dependency of current and energy, Sample 2, 11 pF Reference

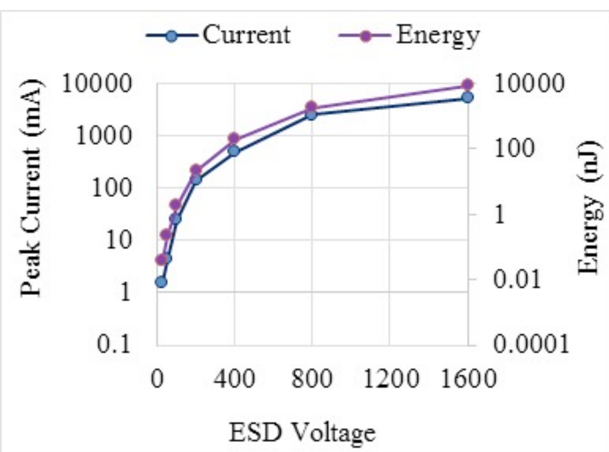

Figure 32: Voltage dependency of current and energy, Sample 2, 43 pF Reference

2. Resistance

The ESD resistance depends highly on the voltage as shown in Figure 33. The sample 2 had only 100 Ω resistance with 1600 V at 43 pF source. The same sample had approximately 500 kΩ with 100 V.

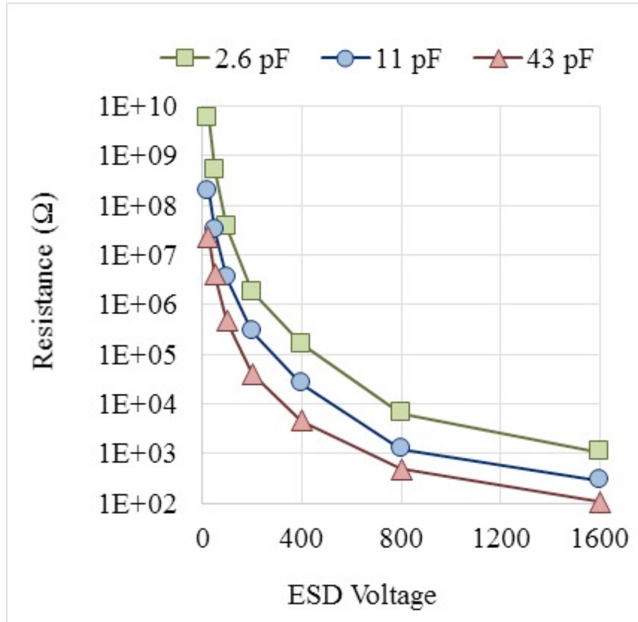

Figure 33: ESD voltage dependency of resistance, Sample 2

IV. Conclusions

The resistances of conductive polymer compounds had a remarkable effect on ESD voltage. The ESD resistance was quadratically and inversely proportional to the voltage as sown in Figure 33.

Secondly, the DC resistance did not clearly correlate with the ESD resistance. The results of DC measurements were significantly lower than the ESD resistance with low stress levels. For example, the sample having a surface resistivity of 20 Ω and resistance through the sample below 1 kΩ, had an equivalent resistance of 35 MΩ in a charged device event at 100 V stress level. In practice, an ESD control item made of conductive polymer compounds with very low DC resistances, even below 100 Ω, can provide adequate protection against high frequency ESD events. In contrast with metals, conductive compounds can be considered safe from CDM risk point of view in ESD protected areas where electrostatic potentials are controlled. Typical applications are for example carrier tapes of devices, trays, foams, bins, boxes and assembly stands.

Thirdly, the source capacitance representing the size of the charged component or a charged board had a marginal effect on attenuation of the peak current and energy. The low bandwidth of 200 MHz resulted in a slightly higher current attenuation with 2.6 pF capacitance and 80 nH inductance compared to 2 GHz measurements with 3.4 pF and 9 nH. The slow response of the measurement system may provide a minor safety margin in considerations of a charged device model (CDM) risk.

According to the results above, the risk of charged device or charge board ESD event with conductive compounds may be overestimated Unintentionally, the current standards [2, 3, 9, 10] guide to prevent the use of conductive polymer compounds when CDM is a concern. The recommendations of the lower limits of resistances may result in overkill of costs.

The standard qualification methods, based on DC resistance, are used for assessing a general tendency of charge dissipation of the ESD control items. As a guideline, DC resistance shall not be used for the estimation of ESD current when CDM or charged board event is a concern. Useless regulation and unnecessary tightening of the limits can be avoided by adequate testing. Standard recommendations shall be reviewed.

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