Uncertainties in Charge Measurements of ESD Risk Assessment

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50 Words Abstract – Charge measurement techniques are often considered too complicate to the process control of electronics manufacturing. In his study, we show that expensive instrumentation is not necessarily needed for characterizing ESD source parameters in a risk assessment. Measurement can be made accurately when uncertainties are properly taken into account.

I. Introduction

An electric charge is one of the most important quantities in electrostatic control although it is often ignored in factory level measurements. Generally, charge measurement is not required by standards, and therefore, it is not applied in the qualification or compliance verification procedures of ESD control items. Electric potential (V) is widely used instead.

ESD risk assessment is generally based on the estimation of electrostatic parameters of charged objects, such as ESD sensitive devices (ESDS) and other conductive parts. Without any information about the charge or capacitance, an ESD source remains unknown, even if the potential would be measured. Therefore, it is essential to assess both the potential and charge. Voltage measurement followed by mobile charge measurement has been recognized as one of the best practices to assess ESD sources in a process assessment [1].

In this study, we have focused on the applicability of charge measurements in electrostatic control. We will show how mobile electric charge of relatively small objects can be measured without remarkable statistical uncertainties. Two different measurement techniques are discussed in this paper.

In addition, we will discuss the uncertainty factors and measurement errors of charge measurements.

II. Measurement Techniques

A. Process Essential Insulators

Generally, measurements of immobile charges do not bring additional value for the risk assessment. Sometimes the risk of electrostatic influence can be measured directly at conductive objects influenced by an electrostatic field. ANSI/ESD S20.20 [2] provides electrostatic field limits for process essential insulators as a guideline or illustration, but compliance verification is complicated in a real process assessment. If the field meter would have a specification of 2 % of the full scale of 1000 V/inch, the accuracy would then be ± 20 V/inch. The limit of the electrostatic field on a process essential insulator at one inch distance from the ESDS parts could be assessed theoretically as (125 ± 20) V/inch. However, this accuracy could be achieved only if the object was a planar conductor, large enough and not affected by surrounding objects [3]. Therefore, we are not able to assess standard limits from the process in practice.

In theory, a Gaussian surface (closed surface in three-dimensional space around the charged object) could be used for the estimation of influence, but there is no practical way to estimate surface charge densities of insulators. We can measure a net charge from the insulating object if we could collect the total electric flux. However, Faraday cup measurements are not practical due to the uncertainties related to the artificial movement of an object under test. In addition, objects cannot always be taken away from the process. The electrostatic field is maybe the most practical way to roughly assess an influence of a charged insulator. The measurement is useful only if the dimensions of an object, measurement distance, and surroundings are properly taken into account [3].

B. Conductors

A mobile charge can be measured by transferring the charge from the conductive object under investigation.

In a risk assessment, an electrostatic potential is measured directly from the object with a contact or non-contact voltmeters followed by a mobile charge measurement. The most important electrostatic parameters such as a capacitance and potential energy of the ESD source can then be calculated [4].

Generally, charge measurements are focused on ESDS parts. Direct charge measurement results in a CDM type of discharge. Therefore, an effect of this CDM stress shall be considered before making the contact. The risk can be reduced by capturing charges from the ground planes or ground pins instead of the signal lines. Series resistors at the probe can also be used for limiting the amplitude of the current pulse. Scrapping ESDS parts after measurement may be considered.

Charge measurements shall also be applied to isolated conductors that come into contact with an ESDS. Measurement in a changing environment is challenging due to the electrostatic influence of surrounding objects. The object will be grounded at the time of the measurement, but the voltage may increase again immediately after the measurement, depending on the motion and an influence of surrounding electrostatic fields.

Mobile charges cannot always be measured from the objects in a running process. If the potential is measured with a non contact voltmeter from the moving object, there may be a possibility to interrupt the process and capture charges, but only if a remarkable leakage is not observed. In this case it is important to follow the possible voltage drop before capturing the charge.

1. Integrating Capacitor

Electrometers and other charge meters generally have an accurately known integrating capacitor, that is placed in the feedback loop of the amplifier so that the voltage is proportional to the integral of the input current in accordance with the formula [5]:

$$V = \frac{1}{C}\int I dt = \frac{Q}{C} \qquad (1)$$

Charge is transferred through the current limiting resistor. The voltage is scaled and displayed as charge. Due to the relatively slow response, charge measurement takes typically several seconds.

2. Current Integration Method

A current integration method can be used for slow charge transfers, but it is useful also in ESD current measurements, with an oscilloscope and a current probe. Some oscilloscopes have a current integration function for easy access for the cumulative charge information. Charge is integrated from the current waveform with the formula:

$$Q = \int I dt \qquad (2)$$

III. Measurement Uncertainties

The evaluation of uncertainty based on the statistical analysis of observations is termed a type A. The result xi is estimated from ten independent repeated observations in accordance with Equation 3 [6]. Standard uncertainty $u(xi)$ is then calculated in accordance with Equation 4 [6]. In a normal distribution standard deviation of the mean encompasses about 68 % of the distribution. Confidence factor k =2 equals 95 % confidence level. Respectively k =3 equals 99.7 % confidence.

$$xi = \overline{X}_i = \overline{q} = \frac{1}{n}\sum_{k=1}^{n} X_{i,k} \qquad (3)$$

$$u(x_i) = s(\overline{X}_i) = \sqrt{\frac{\sum_{k=1}^{n}\left(X_{i,k} - \overline{X}_i\right)^2}{n(n-1)}} \qquad (4)$$

Another type B evaluation of uncertainty is usually based on scientific judgment using all the other relevant information available [6, 7, 8]. For example accuracy specification of instrumentation is categorized as type B.

In this study, type A and type B uncertainties are combined in accordance with Equation 5. Total uncertainty is also presented as % from the reading.

$$U_{Total} = \sqrt{U_A^2 + U_B^2} \qquad (5)$$

The other concern is stability of the measurand (a physical quantity to be measured). Any ESD source is influenced by the surrounding environment. In a quasi-static situation, electric charge is constant, but the electric potential is reversely proportional to the capacitance. Therefore, the charge measurement is not as sensitive to changing environment as the potential in a measurement situation. However, electrostatic charges of ESD sources may vary in the time domain, that makes a process assessment challenging.

Due to the electrostatic fields, a polarization of the isolating medium between the metal surfaces affects the capacitance of the source. In a laboratory, a behavior of ESD source can be studied by changing the polarity and repeating the measurement. In a process assessment, conclusions are based on the observations captured from the process at the certain time.

Contact electrification and charge accumulation are random phenomena in nature. Speed of movement, capacitive coupling, backflow current, leakage, electrochemical effects, contamination, and moisture – all parameters affect the chargeability of ESD sources. Because of the unpredictable nature of the measurand, in general, the process cannot be classified as "safe" in a short assessment period. However, an acceptable confidence can be achieved by repeating the measurements regularly.

A. Slow Charge Transfer

The most important uncertainties in integrating capacitor measurements are probably the leakage currents of the capacitor and test arrangement, input bias current and offset. In addition, unknown voltage sources and electromotive forces may also cause continuous current flow in low scale measurements. Depending on the serial resistance and the response of the meter, integration time is typically more than a million times longer than in ESD current measurements.

ESD is a high frequency phenomenon that cannot always be assessed with the slow measurement techniques. In a risk assessment it is important to recognize that the quasi-static source parameters are not necessarily the same than the source parameters of ESD. For example, a static dissipative assembly stand affects the charge transfer of ESD as illustrated in Figure 1. All the quasi-static charges will be transferred in tens of milliseconds instead of nanoseconds due to the slow capacitive response of the electrostatic dissipative medium.

The most generic measurement errors can be avoided by following the reading of the meter carefully during the measurement. Scrolling reading indicates instable measurement.

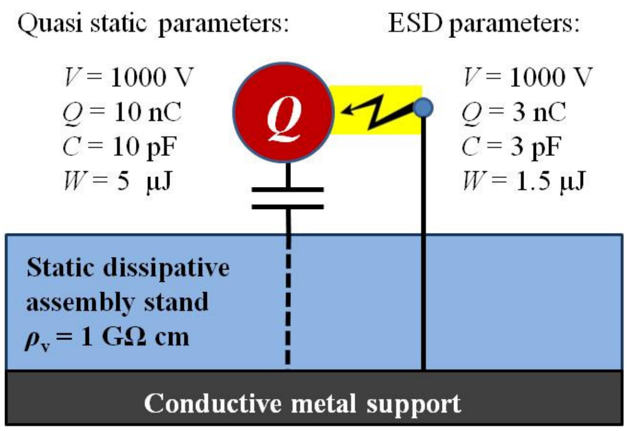

Figure 1: Quasi-static and ESD parameters of the isolated conductor on the static dissipative assembly stand

B. Fast Charge Transfer

The following uncertainties shall be taken into account in fast measurements: bandwidth of the oscilloscope and the current probe, sampling rate and capacitive coupling.

In ESD current measurements, vertical offset shall also be compensated due to the cumulative effect on integration. An example is shown in Figure 2. The current waveforms and charge transfers are shown before and after compensation. A current waveform has a positive offset causing an integration error to the charge transfer. In this example, the error is approximately one nanocoulomb in four seconds.

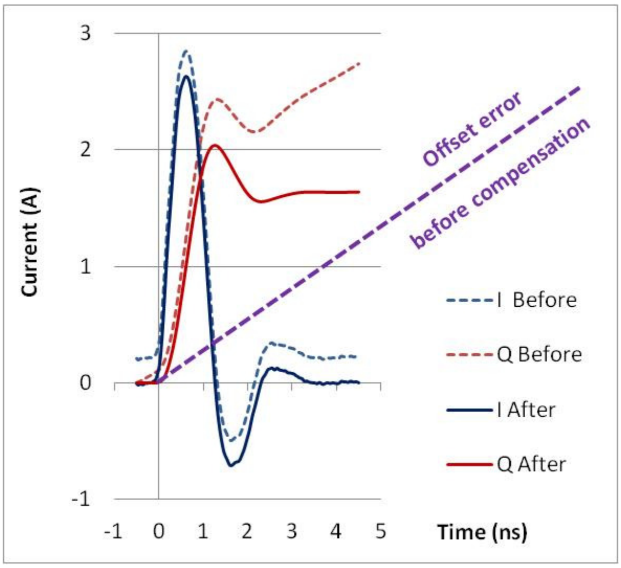

Figure 2: Offset compensation

Horizontal accuracy is typically insignificant and therefore it can be ignored in uncertainty estimation. In this study, we will show that wide bandwidth is not necessarily needed in charge measurements.

IV. Experiments

To keep this study simple, we have measured charges with the different methods from the different sizes of isolated metal objects. Four coins in Euro were selected into the comparison tests: 1 cent, 5 cent, 10 cent and 50 cent. 120 µm thin polypropylene (PP) sheet was placed between the coins and the ground plane. Coins under test are shown in Figure 3. Diameters of the coins from the left to the right are 16.25 mm, 21.25 mm, 19.75 mm, and 24.25 mm.

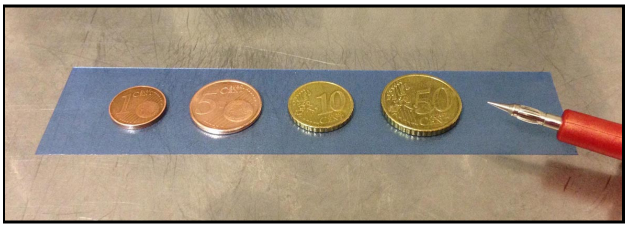

Figure 3: Electrostatic sources in comparison tests

Coins were placed on PP sheet tail or head side up. Tail and head are the two sides of the coins. Electrostatic potential (100 ± 1) V was applied to the isolated coins for each charge measurement. All the measurements were made in laboratory conditions (23 ± 2) °C, RH (12 ± 3) %.

A. Slow Charge Transfer

At first all the coins were measured with an electrometer and then the measurements were repeated with the low-cost handheld meter. Test arrangements are shown in Figures 4 and 5.

Electrostatic potential was applied to the isolated coin by touching it with the red probe. Charge was then captured from the coin with a passive probe.

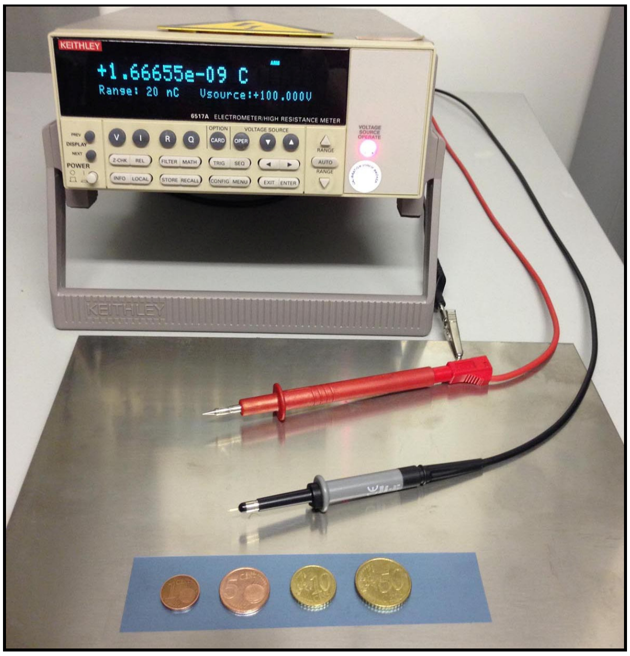

Figure 4: Charge measurement with an electrometer

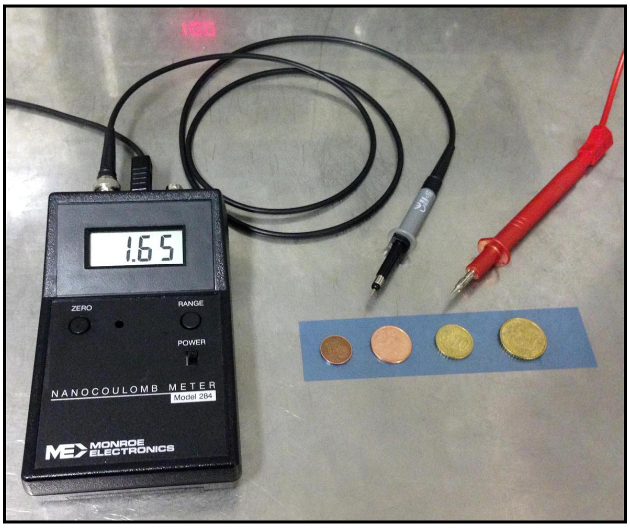

Figure 5: Charge measurement with a nanocoulomb meter

B. Fast Charge Transfer

ESD current was measured from the coins with an oscilloscope Tektronix 7404B, 4 GHz, 20 GS/s and a CT 6 current probe. A test arrangement is shown in Figure 6. Measurements were then repeated with lower bandwidth 200 MHz, 2 GS/s Tektronix TDS 2022 and CT 2 current probe. The test arrangement is shown in Figure 7.

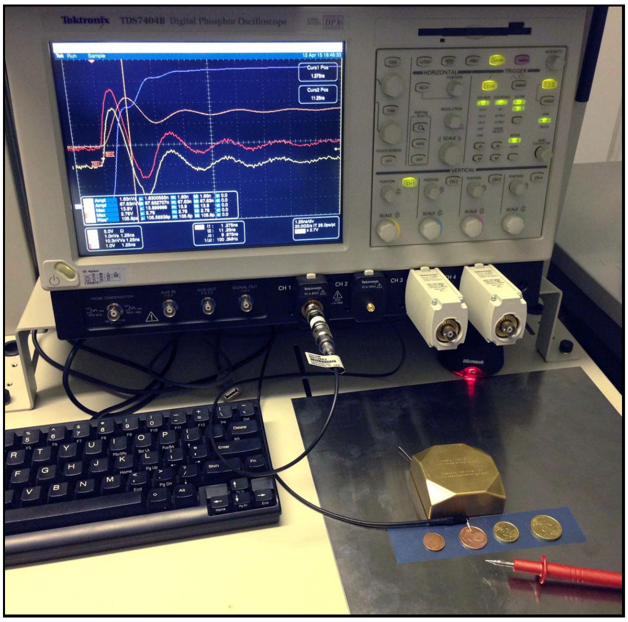

Figure 6: Charge measurement, TDS 7404B and CT6

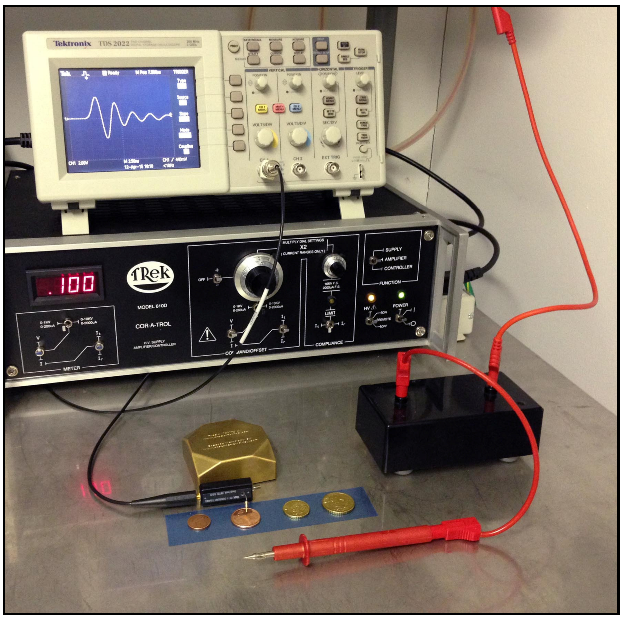

Figure 7: Charge measurement, TDS 2022 and CT2

C. Measurement Results

1. Electrometer

Averages of ten results are shown in Figure 8. A summary of the uncertainty estimation is shown in Table 1. Type B uncertainty from one year specification of the instrument is ± (0.4 % from reading + 5 counts). The average of the standard deviations was 29 pC.

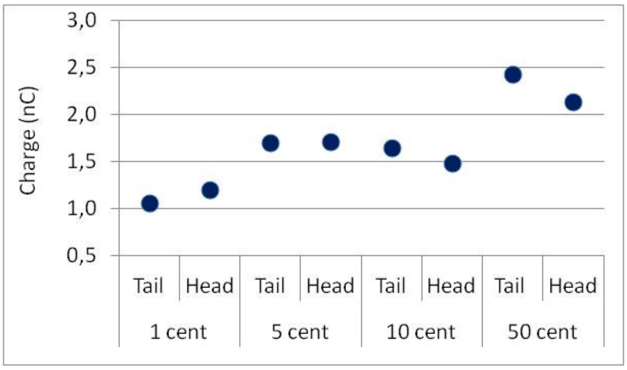

Figure 8: Electric charge of coins at 100 V, Electrometer

Table 1: Measurement uncertainties, Electrometer

ESD Source		Result (nC)	Type A (nC)	Type B (nC)	Total (nC)	Total %
1 cent	Tail	1.06	0.0046	0.0047	0.007	0.6
	Head	1.20	0.0073	0.0053	0.009	0.8
5 cent	Tail	1.69	0.0062	0.0073	0.010	0.6
	Head	1.71	0.0054	0.0073	0.009	0.5
10 cent	Tail	1.64	0.0075	0.0071	0.010	0.6
	Head	1.48	0.0105	0.0064	0.012	0.8
50 cent	Tail	2.42	0.0236	0.0102	0.026	1.1
	Head	2.13	0.0079	0.0090	0.012	0.6

2. Handheld Nanocoulomb Meter

Averages of ten results are shown in Figure 9. A summary of the uncertainty estimation is shown in Table 2. Measurement accuracy of 2 % was presented in the specifications of user's manual. If the specification means % from the reading, a resolution 0.01 nC shall be taken into account. If the specification means % from the full scale, accuracy of the meter was underestimated. We made the assumption that the specification means ± (2 % from the reading + 1 count). The average of the standard deviations was 24 pC.

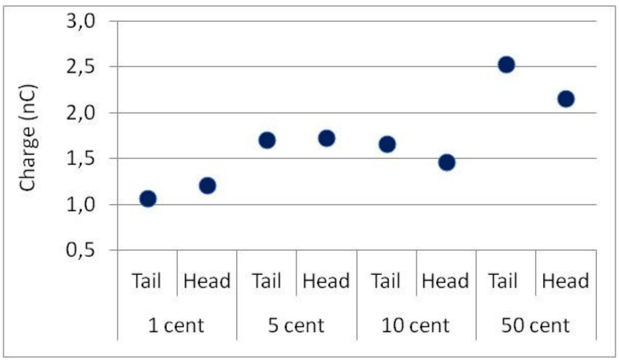

Figure 9: Electric charge of coins at 100 V, Nanocoulomb meter

Table 2: Measurement uncertainties, Nanocoulomb meter

ESD Source		Result (nC)	Type A (nC)	Type B (nC)	Total (nC)	Total %
1 cent	Tail	1.07	0.0066	0.0314	0.032	3.0
	Head	1.20	0.0078	0.0341	0.035	2.9
5 cent	Tail	1.71	0.0086	0.0441	0.045	2.6
	Head	1.72	0.0086	0.0445	0.045	2.6
10 cent	Tail	1.66	0.0073	0.0432	0.044	2.6
	Head	1.46	0.0052	0.0393	0.040	2.7
50 cent	Tail	2.53	0.0080	0.0606	0.061	2.4
	Head	2.16	0.0088	0.0531	0.054	2.5

3. Faraday Cup and Electrometer

A charged coin was picked up with the polypropylene sheet and slid into Faraday cup. The minimum, maximum and averages of ten results are shown in Figure 10.

The measurement results depend on the handling. In this experiment all the coins were handled similarly in each measurement by the same person. The average of the standard deviations was 120 pC.

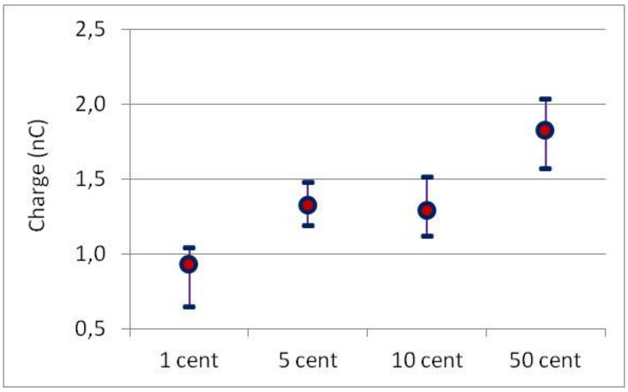

Figure 10: charge of coins at 100 V, Electrometer and Faraday cup

4. ESD, Full Bandwidth, CT 6

The average waveforms of 16 discharges are shown in Figure 11. The electric potential of the coins before the discharge was 100 V. Average charge transfers are shown in Figure 12. Underdamped waveforms were then calculated by Equations 6 and 7. The results are shown in Figure 13.

$$I_{(t)} = \left(\frac{V_0}{L\omega}\right) e^{-\left(\frac{R}{2L}t\right)} \sin(\omega t) \qquad (6)$$

where $$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (7)$$

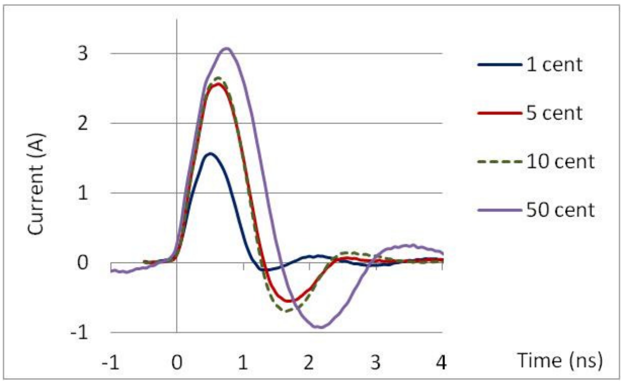

Figure 11: ESD current of coins, tail side up, CT 6

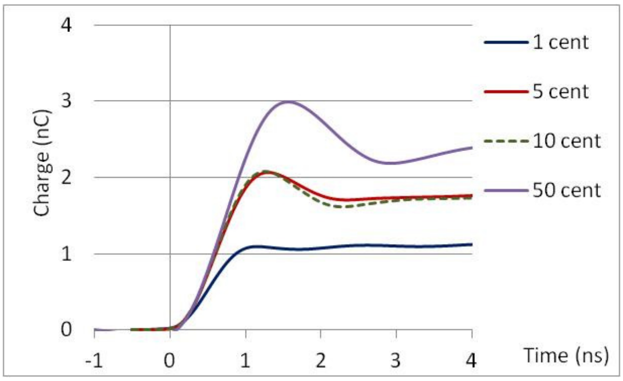

Figure 12: Charge transfer, tail side up, CT 6

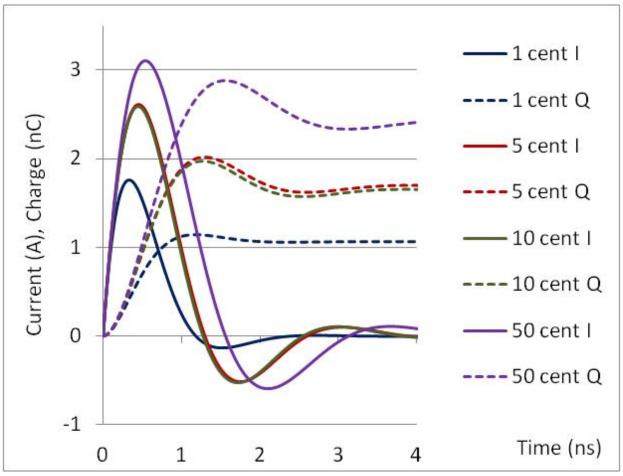

Figure 13: Example of RLC calculations

ESD source capacitances used for calculations are presented in Table 3. Inductance of a discharge wire was approximately 8 nH. If the capacitance is the only changing parameter in a test setup, the peak current is proportional to the charge. However, the resistance is not a constant. If the other parameters remain the same, the resistance is inversely proportional to the charge. The following resistances were selected to the calculations: 35 Ω for 1 cent, 20 Ω for 5 cent, 20 Ω for 10 cent, and 17 Ω for 50 cent.

5. ESD, Limited Bandwidth, 200 MHz

The average waveforms of 16 discharges are shown in Figure 14. The electric potential of the coins before the discharge was 100 V. Average charge transfers are shown in Figure 15. Peak currents are clearly decreased because of bandwidth limitation, but the pulse width is increased.

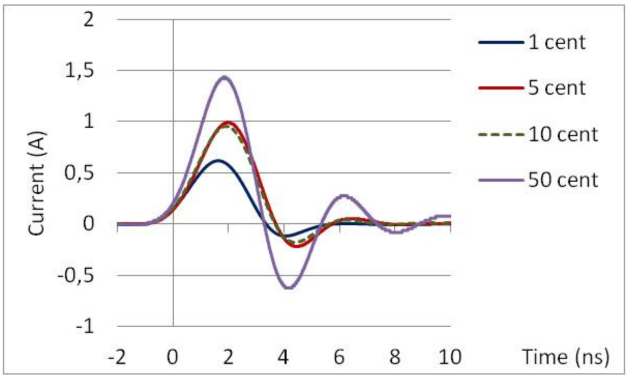

Figure 14: ESD current of coins, tail side up, CT 2

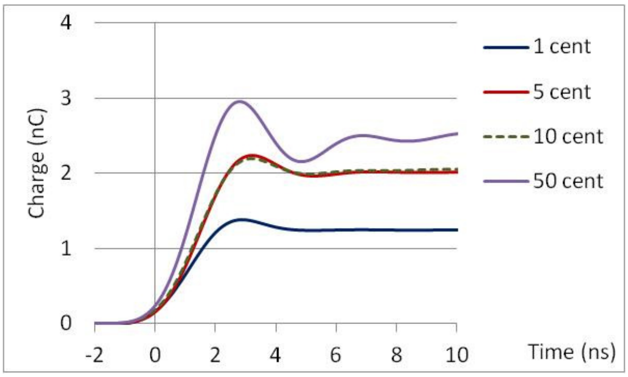

Figure 15: Charge transfer, tail side up, CT 2

6. ESD Source Parameters

Capacitances and potential energies were calculated in accordance with Equations 8 and 9. The electrostatic source parameters of the coins under test are shown in Table 3.

Table 3: ESD source parameters of the coins, Electrometer

ESD Source		Potential (V)	Charge (nC)	Capacitance (pF)	Energy (nJ)
1 Cent	Tail	100	1.06	10.6	53
	Head	100	1.20	12.0	60
5 Cent	Tail	100	1.69	16.9	85
	Head	100	1.71	17.1	86
10 Cent	Tail	100	1.64	16.4	82
	Head	100	1.48	14.8	74
50 Cent	Tail	100	2.42	24.2	121
	Head	100	2.13	21.3	106

$$C = \frac{Q}{V} \qquad (8) \qquad W = \frac{Q \cdot V}{2} = \frac{C \cdot V^2}{2} \qquad (9)$$

V. Conclusions

A peak current of ESD is one of the most relevant parameters in a risk assessment, but the measurement is time consuming and it requires expensive instrumentation. It is also challenging to measure the discharge without disturbing it.

If the ESD current measurements cannot be used, the process assessment can be based on the evaluation of electrostatic sources. The charge measurement provides additional information of the ESD source. Based on the results above, the low cost handheld meters can be used for charge measurements in a process assessment instead of the expensive and heavy instrumentation. A wide measurement bandwidth is not always needed for characterizing ESD source parameters in a risk assessment. Although the amplitude of the current waveform was decreased due to the 200 MHz bandwidth limit, the integrated charge remained about the same with 2 GHz.

It was also shown in practice that the electric charge has a remarkable effect on the potential energy and peak current of ESD in cases where the electric potential was constant 100 V. The peak current correlates with the charge and capacitance in RLC circuit. Therefore, it is essential to estimate the capacitance or a mobile charge of the ESD source in a complete risk assessment. If a contact voltmeter is used, then the mobile charge may also be measured.

An electric potential or charge alone without further information may result in erroneous conclusions.

The statistical uncertainty of integrating capacitor measurements was relatively low. This was demonstrated by presenting clearly noticeable differences in the measured charge between the heads and tails of the coins. This indicates that the methods were accurate enough for recognizing the dimensional deviations of the small objects under test, and the total uncertainty can be considered sufficient enough for the practical electrostatic control.

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