Measurement of Spark Length for Air Discharges of Electrostatic Discharge Generators

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Abstract—Electrostatic discharges (ESDs) due to the collision of charged metals cause serious malfunctions in high-tech information devices. In particular, the fast collision provides severe ESD events, while the mechanism has not fully been elucidated, though the approach speed is known to affect a spark length. In this study, to investigate this mechanism experimentally, we developed a setup for electronically measuring a spark length in air discharges of ESD generators (ESD guns), and measured spark lengths at charge voltages from +1 kV to +8 kV with two constant approach speeds of 20 mm/s and 100 mm/s. Measurement of the spark length was conducted using a commercially available velocity meter based on the laser Doppler effects, which was validated by comparing the calculated values from three different types of empirical formulae based on the Paschen’s law. As a result, we found that regardless of the approach speed, the measured spark lengths at charge voltages above +4 kV agree well with those calculated from one type of the empirical formula, while the spark lengths at voltages less than +4 kV for the fast approach are in agreement with other type of the formula. It should be noted that the approach speed did not almost affect spark lengths and the fast approach at charge voltages below +3 kV would rather cause slightly longer spark length than the slow approach.

Keywords—electrostatic discharge (ESD); air discharge; approach speed; spark length; measurement

I. Introduction

With the high speed and low voltage operation of integrated circuits, the electromagnetic (EM) immunity of electronic devices against EM disturbances has been degrading. On the other hand, electrostatic discharge (ESD) events from charged humans produce transient EM fields with broadband frequency spectra. Therefore ESD events from charged human are known to cause a more serious failure in high-tech information equipment [1-5], while its mechanism remains unknown.

From this background, an ESD-immunity test is being prescribed in the IEC 61000-4-2 standard [6], which is normally conducted by contact discharges of an ESD generators(called hereafter ESD gun). However, real ESD events consist of air discharges not contact discharges. Nevertheless, the IEC standard recommends the contact discharge mode, since current waveforms from air discharges have instability and poor reproducibility, which comes from unexplained peculiar phenomena in a generation mechanism of air discharges. One of the above-mentioned peculiar phenomena is that an approach speed of the ESD gun affects a spark length [7-10]. In our previous study [10], an experiment was conducted using a hand-held tip electrode of the ESD gun charged from +200 V to +8000 V, and the corresponding spark lengths were estimated from a spark-resistance formula. In that experiment, the hand-held electrode approached a ground plane. Results showed that spark lengths for the fast approach were a little shorter than those for the slow approach at charge voltages above +500 V, especially 0.6 to 0.7 times shorter at +6 kV to +8 kV.

In this study, we developed a setup for electronically measuring the spark length in air discharges of ESD guns, and measured spark lengths at charge voltages from +1 kV to +8 kV with two constant approach speeds of 20 mm/s and 100 mm/s to reveal a relationship between the spark length and approach speed.

II. Measurement Method of Spark Length

Figure 1 (a) shows an experimental setup for measuring a spark length in air discharges of an ESD gun. An ESD-gun (NoiseKen ESS-B3011, GT30R) was fixed as shown in Fig.1(a), and was charged at voltages from +1 kV to +8 kV. As an approach electrode, a stainless steel circular plate with a diameter of 50 mm was used for a ground plane connected to the earth, and was approached the ESD gun by a linear actuator. Since the IEC specified radius of curvature of the electrode’s tip for an ESD gun is 4 mm and our previously measured results [8-10] on spark length were from several tens of micrometer to few millimeter, the size of a circular ground plane with a radius of 25 mm can be considered sufficiently large for spark discharges to occur. The approach speeds were taken as 100 mm/s and 20 mm/s for fast and slow approaches, respectively, which were measured with a commercially available velocity meter based on the laser Doppler effects. The spark length can be obtained by measuring the time taken from the discharge to the collision. The elapsed time was set 2
We measured spark lengths ten times for each of charge voltages under a room temperature of 23 - 25°C and relative humidity of 70 - 80 % in the following way. When an ESD occurs, it emits the resultant radiated transient electric field, which was detected by a mono pole antenna connected to a digital oscilloscope (band width: 40 MHz). Channel 1 of the oscilloscope was triggered by the rising part of the voltage waveform induced in the antenna. On the other hand, collision time was identified from an abruptly changed output-voltage waveform of the Laser Doppler velocimeter (Canon LV-20Z, S-100Z, P-20Z), which was displayed on channel 2 of the oscilloscope.

Prior to the above mentioned experiment, spark lengths between the fixed plate and ESD gun at charge voltages from +1 kV to +8 kV were measured. This setup is shown in Fig. 1(b). Spark lengths were obtained as follows. First of all, the stainless steel circular plate slowly approached the ESD gun until a spark happens, which can be detected with the buzzer that an ESD detector (SANKI ES-300V) sounds. We then measured with a caliper the distance from the discharge position to the electrode of the ESD gun as a spark length. Measurement of the spark lengths was conducted ten times for each of charge voltages.

Figure 2 shows the approach speeds of 100 mm/s and 20 mm/s during 2 second period, which were measured with a laser Doppler velocimeter. In this figure, solid and grey lines indicate the approach speeds, which have average speeds \(20.3 \pm 3.5 \text{ mm/s}\) and \(98.2 \pm 4.8 \text{ mm/s}\), respectively, during 2 second period. Fig. 2 demonstrates that the speed of the stainless steel circular plate was roughly constant from the beginning of the approach to the collision and the approach speed abruptly dropped at collision time.

Figure 3 shows measurement of the elapsed time \(\tau\) from discharge to collision time. Left and right sides of the vertical axis shows the approach speed \(v(t)\) of the stainless circular plate and the output voltage of the velocimeter, respectively. Solid and gray lines show the approach speed and output voltage of the antenna, respectively. From these
measurement results, an elapsed time $\tau$ from the discharge to the collision was obtained, and finally the spark length $\delta$ was calculated as $\delta = v(\tau) \times \tau$.

To validate the above measurement method of a spark length, we used three types of empirical formulae for a uniform electric field at the atmospheric pressure and a room temperature of around 20 centigrade degrees, which were derived from the Paschen's law. The formulae applied for parallel plate electrodes are expressed in [11] and [12] as

$$\delta [\mu m] = \frac{V_s [kV] - 0.376}{0.1179 \times 760} \times 10^4 \quad (1)$$

and

$$\delta [\mu m] = \frac{1}{4} \left[ \sqrt{0.329^2 + \frac{4V_s [kV]}{23.85}} - 0.329 \right] \times 10^4 \quad (2)$$

, respectively. Here $V_s$ is a spark voltage in kilo-volt between the electrodes. Another type of the formula [12] used for sphere ball electrodes is given by

$$\delta [\mu m] = \frac{V_s [kV]}{27.9 + \frac{27.9 \times 0.53}{\sqrt{r [cm]}}} \times 10^4 \quad (3)$$

where $r$ is a radius of the sphere ball electrode.

III. Results and Discussion

Figure 4 shows the measured spark lengths $\delta [\mu m]$ at charge voltages $V_c [kV]$ from 1 kV to 8 kV. Thin and thick solid lines show the calculated spark length from (1) and (2), respectively. Dotted solid line shows the calculated spark length from (3). For the calculations of the formulae, we considered $V_C$ as $V_s$. In the figure, $\bullet$ indicates the results for the fixed electrodes with a polished surface, which agree well with the calculated values from (2) at charge voltages above $+2$ kV and (1) at a charge voltage of $+1$ kV. On the other hand, $\times$ shows the results for the fixed electrodes with a rough surface measured at charge voltages below $+4$ kV, which also agree with the results for the polished surface electrode except for the result at a charge voltage of $+1$ kV. These results indicate that at low voltage discharges, roughness of the electrode surface remarkably affects a uniformity of the electric field. For reference, $\circ$ shows the spark lengths obtained by Kawamata et al [13] for a needle electrode with a curvature of 0.5 mm and flat-plate electrode with a diameter of 20 mm and a polished surface, which were measured with a micrometer when the needle approached slowly the electrode until a spark happened. Their results agree well with the calculated values from (1). This implies that the formula (1) could be applicable to the electrodes having polished surfaces at charge voltages below 1 kV. Then $\square$ and $\bigcirc$ indicate the results when the circular plate approached the ESD gun with approach speeds of 100 mm/s (fast approach) and 20 mm/s (slow approach), respectively, which agreed well with the results for the fixed electrode and the calculated values from (2) at charge voltages above $+4$ kV regardless of the approach speeds. It should be noted that at charge voltages below $+3$ kV the fast approach causes a slightly longer spark length than the slow approach. With

![Fig. 4. Measured spark length at charge voltages from 1kV to 8kV.](image)

<table>
<thead>
<tr>
<th>Charge voltages [V]</th>
<th>Results of this study* (Ave. ± S. D.)</th>
<th>Reference [10]** (Ave. ± S. D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast: 100 mm/s</td>
<td>Slow: 20 mm/s</td>
</tr>
<tr>
<td>+200</td>
<td>12 ± 3</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>+400</td>
<td>17 ± 2</td>
<td>14 ± 2</td>
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<tr>
<td>+600</td>
<td>38 ± 5</td>
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<td>1192 ± 44</td>
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<tr>
<td>+7000</td>
<td>1623 ± 77</td>
<td>1492 ± 72</td>
</tr>
<tr>
<td>+8000</td>
<td>1999 ± 93</td>
<td>1872 ± 86</td>
</tr>
</tbody>
</table>

* Approach electrode : ground plane
** Approach electrode : high voltage electrode

Unit: [µm]

Approach speed: collision speed (measured)
Approach speed: average speed (not measured)
respect to this finding, however, our previous study showed that when the hand-held tip electrode of the ESD gun at charge voltages above + 800 V approached, estimated spark lengths from a spark-resistance formula were shorter for a fast approach than those for a slow approach, especially 0.6 to 0.7 times shorter at + 6 kV to + 8kV [10], despite the fact that the approach speeds were not measured.

Table 1 summarizes the findings obtained for the spark length. Namely, our previous study shows that the approach speed of the ESD gun affects the spark length at high charge voltages, while Fig. 4 shows that the approach of the ground plane does not affect the spark length at charge voltages above + 4 kV, and also that at charge voltages below + 3 kV, the spark length for the fast approach is longer than the case for the slow approach. At present, however, its reason remains unknown.

In our experimental setup, under the assumption that the approach of a ground plane in lieu of an ESD gun gives the same effects on spark discharges as the approach of the ESD gun, we moved a circular ground plane to a fixed ESD gun due to the ease of the experiment. As a result, speed-dependence of the measured spark length was different from that in our previous papers [8-10]. At this stage, therefore, we cannot say whether or not there is the speed-dependence of spark length in our experimental condition since quantitative verification for the measurement accuracy of spark length has not been done. The above-mentioned assumption and the measurement accuracy of spark length should be verified as our future task.

IV. Conclusions

To experimentally investigate an air discharge mechanism, we developed a setup for electronically measuring a spark gap length, and measured the spark length at charge voltages from +1kV to +8 kV with 20 mm/s (slow approach) and 100 mm/s (fast approach) approach speeds. As a result, we found that the measured spark lengths agree well with the ones calculated from the empirical formula (2) and also the results for the fixed electrode. It should be noted that the approach speed did not affect the spark length at charge voltages above +4 kV. We also found that the fast approach caused spark lengths slightly longer compared to the slow approach at charge voltages below +3 kV.

Our future task is to grasp a relation between the fast approach speeds above 100 mm/s and the spark lengths.

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References