Characteristics of Small Gap Discharge Event and their EMI Effects

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Abstract— This paper is to report that we have found the induced voltage on antenna by the transient EM field radiated from the small gap discharge is not always proportional to the applied voltage but higher when the gap width is smaller with even lower discharged voltage.

Keywords—small gap discharg; electromagnetic interference (EMI); electrostatic discharge (ESD); transient electromagnetic fields; antenna received waveforms

I. INTRODUCTION

What we are worring about the advanced electronics system are when a person approachs a system or passes by and away from a system in dry winter, an electromagnetic interfertence (EMI) problem occurs even though any direct electrostatic discharge (ESD) between the human and the failed system .

The root cause of these failures (troubles) are the circuits functional errors. Though very tight ESD immunity test [1] is done, these failures cannot be reproduced. This is why the root cause of the failure is not thought "an ESD" and it takes a long time to fix it. This is because the traditional ESD test assumes the discharge between the charged objects and the electronics equipment as a premise.

We call these events as "induced ESD" [2] where a floating metal is charged by the field induction and discharged through a small gap with the adjacent metal object. The important point is, if any digital signal cable, bus line or circuit board exists close to the gap (several mm to cm), the transient EM field generated by this discharge couples to it and high level impulsive or burst noise is injected and as a result, CPU upset or other logic failure is induced. These failure problems because of the induced ESD had been sometimes found already in 1980s within the large computer systems, but were not much extended at that time. Today, by the downsizing of the electronics equipments and systems with more plastic cases, and by the lower voltage as well as higher speed integrated circuits these induced ESD problems tend to appear more often [3].

This paper reports the experimental results for the characteristics of the transient EM field radiated from the small gap discharge between 10um and 200um and the related electromagnetic interference (EMI) effects.

II. EXPERİEMNTS AND THE RESULTS

A. *Method of the Experiments*

Following experiment was conducted to simulate the discharging state through the small gap in case a small floating metal objet could be charged by a fluacuating static E field exposure.

Discharging set-up

To accomplish stable measurement of the discharging events between small gap with distance down to a few tens of micrometers, we made a discharging apparatus as illustrated by Fig.1 using a 10 micron resolution dial-gauge (micrometer).

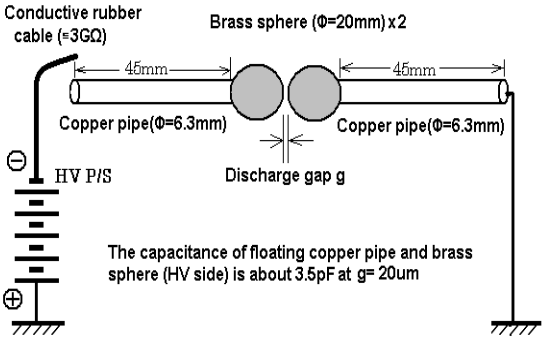

Fig.1. Discharging electrodes and charging method

Electrode structure

The brass sphere with 20mm diameter is soldered to the 6.3mm outer diameter and 45mm length copper pipe, and 2 sets of these were made. The surface of the brass spheres were polished using #4000 abraisives as a mirror.

The floating electrode, where the high voltage is applied (left electrode in the Fig. 1), was held by a 20mm square acryl pillar with 160mm length for the isolation. The isolation resistance of this acryl is the order of 10^{14} Ω and does not cause the charge leakage problem during such short period as several tens of seconds order.

The grounding electrode side (right electrode in the Fig. 1) is attached to the high-resolution position control mechanism (micro-manipulator) where the separation gap distance, g, is measured by the dial gage of the micrometer. This electrode is grounded through the 20cm length flat stranded copper wire. However, the most HF current flows through the dial gage mechanism to the base grounded plate.

The method to apply high voltage

The output of the maximum + or –10kV variable DC supply is connected through the 600mm conductive rubber cable (R≈3GΩ) to the floating electrode to charge it up by shortly*1 contacting it. The purpose to use this conductive rubber cable is a) to avoid the electric shock, b) to provide enough charging time constant and c) to suppress unnecessary EM radiation.

*1: As the capacitance of the floating electrode is about 3pF, the charging time constant (τ=CR) is roughly 10ms and the voltage of this electrode will arrive at Vo (output voltage of the HV P/S in Fig. 1) after 50ms (about 5τ).

B. *Measurements of the Transient Electromagnetic Fields*

The radiated EM field (E and H) from the discharge were detected by the 2 types of antenna as described below located close to the discharging electrodes. The reason why the near field was selected is to examine the coupling states between the elecrtonics cuicuits such as cables and the transient EM field caused by the induced ESD events within an electronics equipment.

Transient E field measurement

Antenna: 10mm short monopole antenna;
Antenna configuration:
Length of the center conductor; 10mm with base plate (diameter =10mm) and with SMA connector
Resonant Frequency (f_r): about 7.5GHz
Frequency response: 0.5GHz-6.5GHz
The distance from the discharging electrodes d= 60mm
The height from the base (ground plane) h= 60mm

Transient H field measurement

Antenna: loop antenna, diameter = 45mm
Loop construction: Shielded single loop unbalanced output (50Ω), Self inductance (L) : 110nH
Resonance frequency (f_r) : 680MHz (at C = 0.5pF)
Frequency Response: 250kHz to 600MHz*2
Antenna position: d=85mm, h=60mm

*2: This is because calibration was done using a TEM cell with max driving frequency of 600MHz.

C. *Results of the experiments*

Recieved waveform by the 10mm short monopole antenna

The received waveform by the 10mm short monopole antenna was measured by a 50 ohms input of the 6GHz bandwidth oscilloscope (Tektronix TDS6604B, 6GHz, 20GS/s), where the radiation source was the discharge between 20mm diameter brass spheres with gap width, g, from 10um to 100um (narrow gap state). Negative polarity high voltage was applied at all experiments.

The position of the short nomopole antenna was horizontally apart 60mm (=d) from the center of the charged electrode (left copper pipe) and 60mm (=h) above the ground plate.

At this position, a positive transient E-field was observed because the discharge forced the negative static E-field to return to zero potential. Fig. 2 is the induced waveform with g = 20um (discharge voltage at -440V) that indicates severe damped oscillation. At g = 50um, the damped oscillation with less ringing waveform than Fig.2 was found. On the other hand, gap width exceeds some 60um (discharge voltage at -960V), the waveform became unstable damping oscillation waveform with large variation and much slower period damping oscillation were occasionally observed.

Fig. 3 shows the waveform with g = 100um (at -960V) that was completely different dampimg oscillation from the waveform at g = 20um and 60um.

The peak induced voltage of this antenna (Vop) during this experiment conditions were not always proportional to the charged voltages. The peak induced voltages were maximum at gap width g around 40um to 50um and above these gap widths, the peak voltage showed the tendency of decrease. Fig. 4 illustrates this situation.

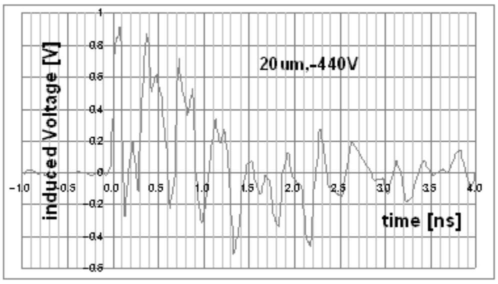

Fig. 2. Antenna induced voltage at g = 20um , V_{BD} = minus(-)440V.

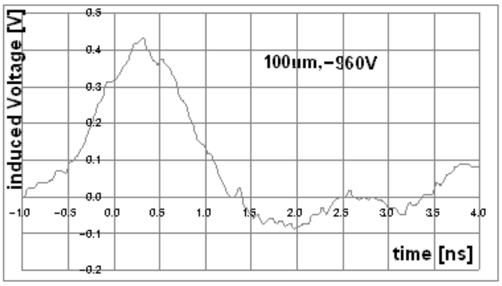

Fig. 3. Antenna induced voltage at g = 100um , V_{BD} = -960V.

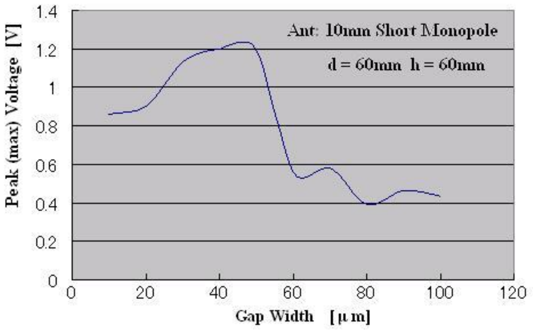

Fig. 4. Antenna induced peak voltage as a function of gap width g.

Recieved waveform by the loop antenna

We measured the recieved waveform of the loop antenna (diameter = 45mm) from the discharge at 6.3mm diameter brass shperes with gap width g between 10um and 360um.

The loop antenna was located flat at the horizontal distance, d = 85mm (from the gap to the center of the antenna loop) with the vertical height, h = 60mm, above the ground plate.

During these experiments, the induced voltage of the short monopole antenna (d = 60mm, h = 60mm) also recorded. Because negative high voltage is applied, short nomopole antenna (close to the charged - left - copper pipe electrode) recieved a positive polarity E-field and loop antenna recieved a negative polarity H-field.

Fig. 5 shows the 2 waveforms at 2 types of antenna radiated from the gap width of 20um (-450V) where channel 1 (Ch1: 200mV/div) is the waveform picked up by the short monopole antenna and channel 2 (Ch2: 2V/div) by the loop antenna. The time scale of this figure is 500ps/div but the skew of these channels due to the connection cable length difference is not adjusted. The induced voltage of this loop antenna is as high as 6V peak to peak (Vpp) at the initial portion of the waveform. Fig. 6 is the waveform data given from the wider gap, g = 360um (-2000V) than Fig. 5, where both the loop antenna and the short monopole antenna detected wider width damping oscillation. From these waveform data, it was found that very different waveforms are generated by the less than about 60um gap width discharge and a few hundreds of um's gap width discharge.

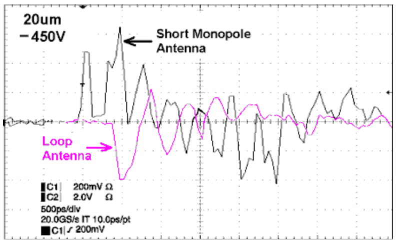

Fig. 5. Antenna induced voltage at g = 20um, V_{BD} = -450V, 500ps/div
Ch1 : 10mm Short monopole antenna. 200mV/div
Ch2 : Loop antenna (diameter =45mm). 2V/div

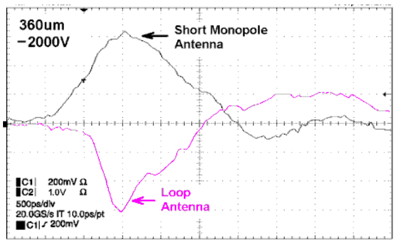

Fig. 6. Antenna induced voltage at g = 360um, V_{BD} = -2000V, 500ps/div
Ch1 : 10mm Short monopole antenna. 200mV/div
Ch2 : Loop antenna (diameter = 45mm). **1V/div**

III. DISCUSSION

The relation between the gap width (discharge voltage) and the static E-Field

Fig. 7 ilustrates the relation of gap width and the static E-field between the gap given by this experiments when 20mm spheres were used as the electrodes. As it is clear from this Fig.7, the E-field, just before the discharge is stronger if the voltage is lower. For example, E=3.6x10^7 V/m at g=10um but E=7.3x10^6 V/m at g=200um. The E-field at 10um gap was about 5 times higher than the E-filed at 200um gap. As described by the following equation (1), an electron (q_0) gets the force F from this E-filed and is accelerated to the positive electrode.

$$F = q_0 E \ [N] \qquad (1)$$

This largely impacts the electron behavior during the discharge. In other words, narrower gap (lower voltage) accerelates electron more than wider gap (higher voltage) as well as narrower gap shorten the flight time of the electron resulting the faster current rise time t_r. But, as g (gap width) increases, E decreases, the force to an electron decreases, then current rise time becomes slow. At the narrow gap (low voltage) state, because discharging current rapidely changes (OFF – ON – OFF) and not only the current derivative di/dt but also voltage derivative dV/dt increases and contribute to transfer EMI energy.

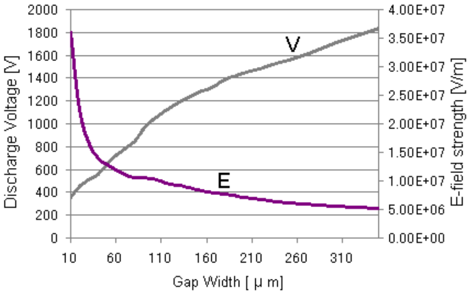

Fig. 7.The relation between gap width g, and static E field between the gap when the shperes with Φ=20mm was used as the discharging electrodes.

Relation between the static E-field and the discharging current rise time

Because the field strength E is higher if gap width g is narrower (see Fig. 7), the force, F, to an electron q_0 increases by the equation (2). Especially, at gap width less than a few tens of um and with extremely high E field (10^7V/m to 10^8V/m), the motion speed of the electron to one direction becomes very fast, accordingly electron mean free path[*3] (λ_e) increases so that the same electron kinetics as those in the vacuum tube (about 10^{-5} Torr) model could be applied [4].

[*3] : In case no E-field exists, the electron mean free path (λ_e) in the gas is proportional to the absolute temperature T and inversely proportional to the gas pressure P ($\lambda_e \propto T/P$).
For example, in the air, 0 degree C (273 degree K) and 1 atm, λ_e is equal to 0.38um.

The average flight velocity v of the electron q_0 in the gap (with gap distance g) is given by the equation (2). The flight time t is assumed to be the discharging current rise time t_r, it could be defined by the equation (3).

$$v = \frac{1}{2}\sqrt{\frac{2q_0 E g}{m_e}} \qquad (2)$$

$$t_r = \frac{g}{v} = \frac{2g}{\sqrt{\frac{2q_0 E g}{m_e}}} \qquad (3)$$

where,
t_r : Discharging current rise time [s]
g : Gap width [m]
v : Average flight velocity between the gap [m/s]
q_0 : Charge of an electron =1.602×10^{-19} [C]
m_e: Static mass of an electron =9.109×10^{-31} [kg]

The relation between the gap width and discharging current rise time is calculated and plotted using this equation, and Fig. 8 is derived.

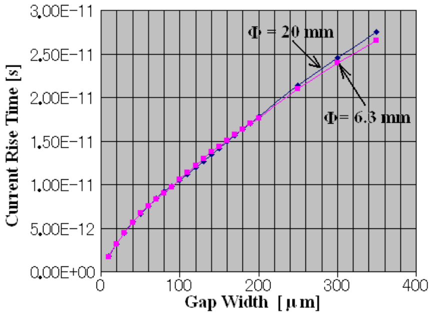

Fig. 8. Rise time of discharge current as a function of gap width.

As it is clear by the Fig. 8, independent of the electrode diameter, the calculated rise time of the discharging current is less than 5ps at gap width about 30um or less showing that the small gap state causes ultra fast current variation once discharged.

ESD noise on the short nomopole antenna

The fact that an only 10mm length straight line conductor induces less than 500ps pulse width and over 1V amplitude noise, causes big problems to the real world high speed electronics circuits as the point of EMI. This is because the PC boards or the circuits in the chassis include a lot of open end lines (between unconnected connector pin and IC pin) or lines that are terminated with high-Z, for example input of the CMOS IC [5]. Once the ESD noise are coupled to these lines, the derivative components (di/dt, dV/dt) repeatedly coupled (as Mdi/dt, CdV/dt) causing functional failures to the high speed logic circuits such as CPU.

If the gap width g extends from low voltage (narrow gap) discharge to high voltage (wide gap) discharge, it was found that the induced voltage at the antenna, tend to reduce (Fig. 4). At the same time the pulse width increases and the di/dt, dV/dt etc. decrease. As a whole, the EMI effects at high voltage discharge are reduced compared to the small gap state lower voltage discharge.

ESD noise on the loop antenna

The recieved voltage V_{loop} of the loop antenna (loop area : S) that was located near the discharge source at distance r = 85mm was considerably large, 4V at the initial peak voltage (V_{op}). This value is equvalent to the instantaneous power ($P=V_{op}^2/R$) of 320mW (about 25dBm) consumption at R= 50 ohms resistance.

The transient magnetic fields (H or the magnetic flux density B) generated by this discharging current are emanated to the whole near space surrounding the electrodes and if any PC board or small loop-shape conductor (with area A) exists close to the narrow gap ESD, this will be a crucial cause of the EMI. This is because the narrow gap discharge events generate very fast current transient di/dt (for example 10A/100ps) and accordingly, time variation dH/dt of the H-field generated by the discharge current, will be also very high. And, few thousands mm^2 loop area will easily induce from a few hundreds millivolts to a few volts ESD noise.

IV. CONCLUSION

We discussed the basic characteristics of the narrow gap discharge ("induced ESD"), the EMI effects based on the experiments data and following conclusions are derived.

Under this experiment condition, both experimental data measured by the short monopole antenna and the loop antenna showed that the detected voltage on these antennas increased when the discharge gap is increased up to some gap width (40 to 70um) and when the gap width is further increased, the detected voltage on these antennas started to decrease.

At the relatively low voltage discharge with the gap width less than a few tens of microns, ultra fast discharge occurred and this lead to EMI effects much harder than the higher voltage ESD.

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