Performance improvement of an ESD suppressor by studying its characteristics

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Abstract. The finite-difference time-domain (FDTD) method was used to study the characteristics of an ESD suppressor. The obtained capacitance of the ESD suppressor filled with air was validated by measurement data and another numerical result obtained by time-domain moment method (TDMM). Under the same conditions, no large differences are found among the obtained capacitances for the ESD suppressor filled with air, neon, argon, and helium. But the ESD suppressor filled with air has a much higher trigger and clamping voltages than the ESD suppressor filled with neon, argon, or helium. Capacitance is found to decrease with the increase of the spark gap distance or the operating frequency. But the capacitance increases with increasing relative dielectric constant of the substrate or the overcoat. It is observed that ESD currents with a transient waveform reach a maximum value and decays sharply as the time increases under the condition of the spark gap distance of 5 μm. Outside the spark gap, the maximum electric field is below the breakdown strength, but the magnitude of the electric field radiated from ESD events is still very large when the distance from the ESD suppressor is less than 2 mm.

1. Introduction
Modern electronic products are becoming smaller, lighter, and simpler while having a higher speed data rate. For these products operating in radio-frequency (RF) and microwave bands, an ESD event can easily damage high sensitivity electronic components which make extensive use of digital technology and fast-speed memory integrated circuit (IC) chips with very high density of multilevel interconnects. Therefore, circuit designers must take ESD problems into account in their quest for a functional and reliable product. For protecting sensitive electronic circuits operating at RF and microwave frequencies, the ESD suppressors are connected in parallel with the signal lines. When an ESD event occurs, the ESD suppressors clamp the ESD voltage to a level where the sensitive electronic circuits can survive and shunt the ESD current away from the data line and the protected sensitive electronic circuits into the chassis ground [1]. The ESD suppressors are designed to have extremely low capacitance which can provide clamping functions for transient suppression and electromagnetic interference (EMI) filtering against unwanted high-frequency signals that couple into the protected sensitive electronic circuits.

In this research work, the FDTD method is used to calculate an ESD suppressor’s characteristics under different conditions. Originally, the ESD suppressor is filled with air in the space between two

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discharge electrodes. Alternatively, the space between two discharge electrodes is filled with argon, helium, or neon in order to investigate the performance improvement of the ESD suppressor. In FDTD simulations, a double exponential electric field pulse [2, 3] is proposed to model the ESD excitation. The capacitances, ESD currents, maximum electric fields, trigger voltages, and clamping voltages of the ESD suppressor are presented in this report.

2. The FDTD method
In 1966 Yee [4] first proposed the basic FDTD method for electromagnetic analysis. Due to its powerful and versatile features, in recent years the FDTD method has become a very popular technique for solving many electromagnetic problems. In the FDTD solution procedure, the coupled Maxwell’s equations in differential form are solved for various points of the scatter as well as its surrounding in a time-stepping manner until convergent solutions are obtained. Following Yee’s notation and using centered difference approximation on both the time and space first-order partial differentiations, six finite-difference equations for six unique field components within a unit cell are obtained. In these six finite-difference equations, electric fields are assigned to half-integer (n+1/2) time steps and magnetic fields are assigned to integer (n) time steps for the temporal discretization of fields. To ensure numerical stability, the time step δt is set to δ/2C0, where δ and C0 are the cell size and the speed of light, respectively. The center difference approximation ensures that the spatial and temporal discretizations have second-order accuracy, where errors are proportional to the square of the cell size and time increment [4]. Several absorbing boundary conditions (ABC) have been proposed in the FDTD method such as second-order Mur [5], and Liao [6], and perfectly matched layer (PML) [7]. In our formulation, the second-order Mur approximation of absorbing boundary conditions [5] is used for the near-field irradiation problems. We use them because they do not require much memory and have a reasonable accuracy. The details of the FDTD method may be found in many publications and will therefore not be repeated here.

3. Characteristic study on an ESD suppressor
In FDTD simulations, an ESD voltage $V_0(t)$ with a double exponential voltage pulse [2, 3] similar to a standard ESD pulse current waveform, specified in International Standard IEC 801-2, is used to model the ESD excitation in the gap between the two discharge electrodes expressed by

$$V_0(t) = V_{esd}(e^{at} - e^{bt})$$

for $t \geq 0$  

(1)

The double exponential voltage pulse is modelled with the sum of a fast wave and a slow wave, where constants $a$, and $b$ are given below

For the fast wave:

$$a = 4.55 \times 10^8, \quad b = 5.00 \times 10^8 \quad \text{for} \quad 6.81 \text{ ns} > t \geq 0$$

(2)

For the slow wave:

$$a = 4.55 \times 10^7, \quad b = 5.00 \times 10^7 \quad \text{for} \quad t \geq 6.81 \text{ ns}$$

(3)

The maximum voltage occurs at time $t_m = \ln(b/a)/(b-a)$, where constants $a$ and $b$ are equal to $4.55 \times 10^8$ and $5.00 \times 10^8$, respectively. From the calculation, it is found that the maximum voltage occurs at the time $t_m = 2.09$ ns. The waveform has a 1.20 ns rise time (the pulse increases from 10% to 90% of its peak value). The ratio of the voltage at 30 ns to the maximum voltage at 2.09 ns is 0.53 and the ratio of the voltage at 60 ns to the voltage at 30 ns is 0.48. It should be noted that the ESD pulse waveform is usually poorly reproducible in practice. Taking the trigger voltage as the maximum voltage, $V_{esd}$ can be calculated for the ESD suppressor filled with air, argon, helium, and neon under the conditions of various spark gap distances. For FDTD simulations, the ESD voltage $V_0(t)$ is transferred into an electric field over the spark gap between the two discharge electrodes by $E(t) = V_0(t)/d$, where $d$ is the distance of the spark gap between the two discharge electrodes. Applying the excited electric fields in FDTD simulations, electric fields at any location inside and outside the ESD
suppressor can be calculated. From boundary conditions, electric fields obtained near the two copper electrodes can be used to calculate the surface charge density \( \rho_s \) on their surfaces expressed by

\[
\nabla \cdot D = \rho_s = \varepsilon_r \varepsilon_0 E_2n - \varepsilon_0 E_{1n}.
\]

where \( E_{1n} \) and \( E_{2n} \) are the normal components of electric fields in and outside the discharge electrodes, \( D \) is the electric flux density, \( \varepsilon_r \) and \( \varepsilon_0 \) are the relative dielectric constant of materials and the dielectric constant of air, respectively. The total charge on any one surface of the two discharge electrodes is determined by integrating the surface charge density over the surface expressed by

\[
Q(t) = \int_s \rho_s(t) ds'
\]

where \( s' \) denotes the surface of the two discharge electrodes. Once the total charges are obtained, the capacitance can also be calculated by

\[
C = \frac{Q(t)}{V_0(t)}
\]

It should be noted that the capacitance depends only on the geometric structure, material used in the ESD suppressor, and the operating frequency; it does not depend on the applied voltage or current.

The ESD current is calculated by the following equation:

\[
I(t) = \frac{\partial Q(t)}{\partial t} = \frac{Q(t) - Q(t - \Delta t)}{\Delta t},
\]

where \( \Delta t \) is the time increment and \( Q(t) \) is the total charge at time \( t \) in one of the two electrodes.

The ESD suppressor is composed of two copper discharge electrodes (suppressor element), an Al\(_2\)O\(_3\) substrate, a protective epoxy resin coating (overcoat), two zinc backside electrodes, two nickel connect electrodes, and a solder layer as shown in figure 1. The copper discharge electrodes have a thumbnail structure on the opposite sides of the spark gap and a thickness of 50 \( \mu \)m.

![Figure 1. Illustration of the structure of the ESD suppressor.](image)

Originally, the ESD is filled with air in the space between two discharge electrodes. Alternatively, the space between two discharge electrodes is filled with argon, helium, and neon in order to investigate the variation in capacitance, trigger voltage, clamping voltage, and the maximum electric field of the ESD suppressor. The FDTD model including the ESD suppressor, computational region, and the space between the absorbing boundary and the scattering objective for FDTD simulations is constructed with 10434000 cubic cells, where the cell size is taken to be \( \delta = 5 \) \( \mu \)m.

Under the conditions of the ESD suppressor filled with air, a spark gap distance of 5 \( \mu \)m, the ESD suppressor with Al\(_2\)O\(_3\) substrate and epoxy resin overcoat, and operating frequency of 1 GHz, the capacitance of 0.0242 pF calculated by the FDTD method as shown in figure 2 is in good agreement with the measurement data of 0.025 pF provided by TA-I Technology Co. [8] and the numerical result of 0.0264 pF obtained by the time-domain moment method (TDMM) [1]. Simulation results of
capacitance for the ESD suppressor filled with helium, neon, and argon under the same conditions are also shown in figure 2. The relative dielectric constants only have a small variation among air, helium, neon, and argon. As expected, the obtained capacitance for the ESD suppressor filled with air has a little higher value than that obtained for the ESD suppressor filled with helium, neon, or argon. It is also found that the capacitance increases with the increase of the relative dielectric constants of the substrate and the overcoat. It is also found that the capacitance decreases as the operating frequency increases from 1 to 6 GHz and the spark gap distance increases from 5 to 50 μm.

![Figure 2. Simulation results of capacitance for the ESD suppressor filled with air, helium, neon, and argon.](image)

All ESD suppressors have a limited life-time span. In order to extend the suppressor’s life-time span, the trigger and clamping voltages should be designed as low as possible. Based on breakdown strengths and spark gap distances, the trigger and clamping voltages of the ESD suppressor filled with air, argon, helium, and neon for various spark gap distances are calculated and shown in figures 3 and 4.

![Figure 3. Trigger voltage versus spark gap distance](image)

![Figure 4. Clamping voltage versus spark gap distance.](image)

Time responses of ESD currents for the ESD suppressor filled with air, helium, neon, and argon under the condition of a spark gap distance of 5 μm are obtained. It is found that ESD currents with a
transient waveform reach a maximum value in a variety of 3.2-5.6 mA at 0.9 ns and decays sharply as the time increases. The duration of the transient phenomenon is very insignificant as compared with the operation time of an electronic system. Yet it is very important because the transient ESD current may cause a serious failure in high sensitive information circuits if the ESD current is not removed from the protected high sensitive information circuits. Maximum ESD currents versus spark gap distance for the ESD filled with air, helium, neon, and argon are also obtained. It is found that the maximum ESD current decreases as the spark gap distance increases.

In order to investigate the electric field near the ESD suppressor, electric field distributions on the horizontal plane which consist of the center of the spark gap are calculated. It is found that the maximum electric fields decay from $4.338 \times 10^7$ to $1.436 \times 10^7$, from $1.266 \times 10^7$ to $8.136 \times 10^3$, from $9.169 \times 10^6$ to $6.171 \times 10^3$, and from $7.637 \times 10^6$ to $2.736 \times 10^3$ V m$^{-1}$ for the ESD suppressor filled with air, neon, argon, and helium as the distance from the spark gap increases from 0.0 to 2.125 mm, respectively. Outside the spark gap, the maximum electric field is below the breakdown strength, but the magnitude of the electric field resulting from ESD events is still very large as the distance from the ESD suppressor is less than 2 mm. This observation hints that the high sensitivity electronic circuits should be kept away from the ESD suppressor, because high sensitivity electronic circuits connected to external ports are susceptible to a damaging ESD pulse from the operating environment and from peripheral interference.

4. Conclusions

The obtained capacitance of the ESD suppressor filled with air under the condition of a spark gap distance of 5 m was validated by measurement data provided by TA-I Technology Co. and the numerical result obtained by the TDMM. After checking the validity of the FDTD method, the FDTD method was used to further studies on the capacitance, ESD current, and electric field for the ESD suppressor filled with air, neon, argon, and helium under different conditions. Only a tiny variation of obtained capacitances for the ESD suppressor filled with air, neon, argon, and helium under the same conditions was found. But it should be noted that the ESD suppressor filled with air has a much higher trigger and clamping voltage than the ESD suppressor filled with neon, argon, or helium. From obtained capacitances, it is shown that the substrate or the overcoat with a higher dielectric material used for an ESD suppressor will produce higher capacitances. Higher capacitances have slower response time features so that data waveform distortions and signals without integrity may occur. It is observed that the capacitance decreases as the operating frequency increases from 1 to 6 GHz. It is observed that ESD currents with a transient waveform reach a maximum value in a variety of 3.2-5.6 mA at 0.9 ns and decays sharply as the time increases. The maximum electric fields near the ESD suppressor were also calculated. The maximum electric fields of $4.338 \times 10^7$, $1.266 \times 10^7$, $9.169 \times 10^6$, and $7.637 \times 10^6$ V m$^{-1}$ are obtained for the ESD suppressor filled with air, neon, argon, and helium under the condition of a spark gap of 5 m, respectively. Outside the spark gap, the maximum electric field is below the breakdown strength, but the magnitude of the electric field resulting from ESD events is still very large as the distance from the ESD suppressor is less than 2 mm.

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