Created in COMSOL Multiphysics 6.3

Electrostatic Discharge

Introduction

Electrostatic discharge (ESD) occurs when there is a sudden flow of electricity between two objects with different electrical potentials. This often happens when a charged object, like a human hand, comes into contact with a conductive material, such as metal. The process begins with the accumulation of static charge on the human body, typically due to frictional contact with various materials—like walking across a carpet or rubbing against certain fabrics. The human body can store this static electricity, leading to a significant voltage build-up.

As the charged hand approaches the metal object, the electric field between the two intensifies. Once the hand is close enough, the electric field becomes strong enough to ionize the air molecules between them, creating a conductive path. This allows the accumulated charge to rapidly discharge from the hand to the metal, resulting in a brief, high-current pulse—an ESD event. This discharge equalizes the potential difference between the hand and the metal, often producing a visible spark and potentially damaging sensitive electronic components.

To simulate this complex phenomenon, the model connects the Electrical Discharge interface with the Electrical Circuit interface. The Electrical Discharge interface is used to simulate the ionization and discharge process between the hand and the metal. Meanwhile, the Electrical Circuit interface represents the human body, modeling how it stores and releases the static charge. Together, these interfaces allow for a detailed simulation of how ESD current is generated and how it interacts with electrical circuits.

Model Definition

FIELD–CIRCUIT MODEL

The human body is represented by a typical RLC circuit as shown in Figure 1. In this model, it is assumed that human body is charged to 8 kV and has a resistance, inductance, and capacitance of 1500 Ω, 5 nH, and 100 pF, respectively. The Electrical Circuit interface is employed to model this circuit. The node names (0, 1, 2, 3) is also labeled in Figure 1. To integrate the circuit with the physical discharge model, the External U vs. I feature is used to establish the connection between the circuit and the discharge simulation.

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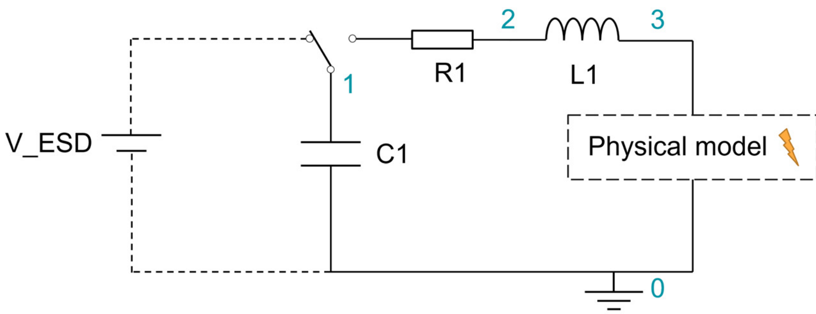


Figure 1: The Field–Circuit Model.

CHARGE TRANSPORT MODEL

The spark discharge between human finger and metal is modeled using the built-in charge transport model in the Electric Discharge interface.

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (\mathbf{w}_i n_i - D_i \nabla n_i) = R_i$$

where

$$i = \mathrm{e, p, n}$$

$$z_{\mathrm{e,\,p,\,n}} = \text{-}1, +1, \text{-}1$$

$$\mathbf{w}_i = z_i \mu_i \mathbf{E}$$

$$R_\mathrm{e} = \alpha|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \eta|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p}$$

$$R_\mathrm{p} = \alpha|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n}$$

$$R_\mathrm{n} = \eta|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n}$$

where

- e, p, n denote electrons, positive ions, and negative ions
- n_i is the number density of the charge carrier (SI unit: $1/\mathrm{m}^3$)
- $\mathbf{E}$ is the electric field (SI unit: V/m)
- z_i denotes the carrier charge (SI unit: 1)
- μ_i denotes the carrier mobility (SI unit: $\mathrm{m}^2/(\mathrm{V{\cdot}s})$)
- $\mathbf{w}_i$ is the drift velocity in the electric field (SI unit: m/s)
- D_i is the diffusion coefficient (SI unit: m^2/s)
- R_i is the reaction rate (SI unit: $1/(\mathrm{m}^3{\cdot}\mathrm{s})$)

- α is the ionization coefficient (SI unit: 1/m)
- η is the attachment coefficient (SI unit: 1/m)
- β_{ep} is the electron–ion recombination coefficient (SI unit: m^3/s)
- β_{pn} is the ion–ion recombination coefficient (SI unit: m^3/s)

The above transport equations are fully coupled with Poisson's equation through the electric field and the space charge:

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \mathbf{E}) = \rho$$

$$\rho = e \sum_i z_i n_i$$

where e is the electric charge.

Results and Discussion

Figure 2 plots the z-component of the electric field for several instants during the ESD simulation. Figure 3 shows the ESD current. The two pulses are easily identified: the first pulse is introduced by the spark/streamer discharge between a human finger and the metal and the second one corresponds to the charge transfer and relaxation due to the human body.

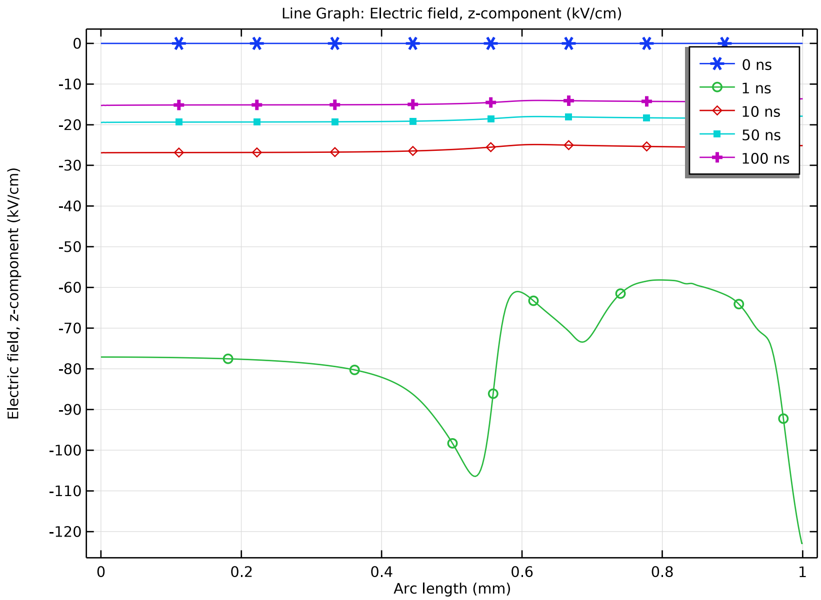


Figure 2: Electric field distribution in the discharge gap.

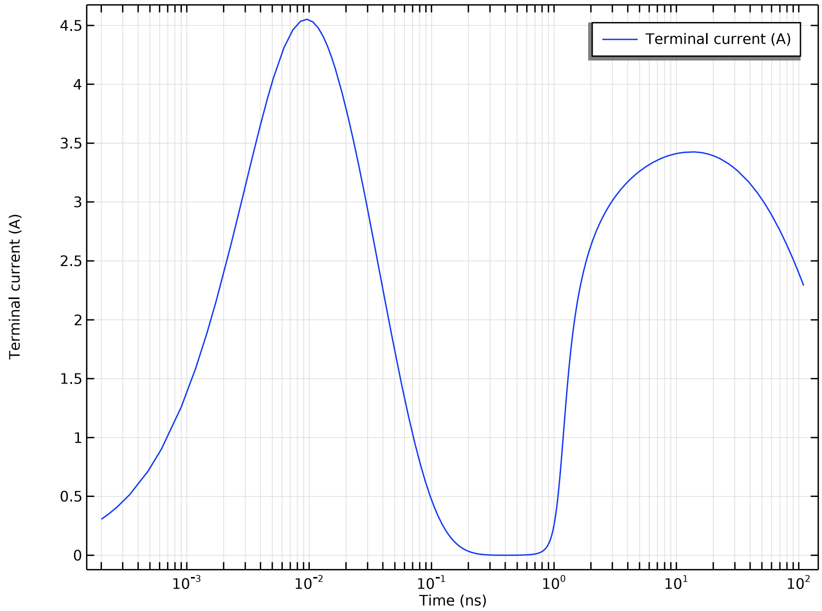


Figure 3: Simulated ESD current.

Application Library path: `Electric_Discharge_Module/Electrostatic_Discharges/esd`

Modeling Instructions

ROOT

Open the double_headed_streamer model.

APPLICATION LIBRARIES

1 From the **File** menu, choose **Application Libraries**.

2 In the **Application Libraries** window, select **Electric Discharge Module** > **Streamer Discharges** > **double_headed_streamer** in the tree.

3 Click **Open**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
V_ESD	8[kV]	8000 V	
C1	100[pF]	1E-10 F	
R1	1500[Ω]	1500 Ω	
L1	5[nH]	5E-9 H	

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

2 Go to the **Add Physics** window.

3 In the tree, select **AC/DC** > **Electrical Circuit (cir)**.

4 Click the **Add to Component 1** button in the window toolbar.

5 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

ELECTRICAL CIRCUIT (CIR)

Capacitor 1 (C1)

1 In the **Electrical Circuit** toolbar, click **Capacitor**.

2 In the **Settings** window for **Capacitor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
n	0

4 Locate the **Device Parameters** section. In the C text field, type `C1`.

5 In the U_{C0} text field, type `V_ESD`.

Resistor 1 (R1)

1 In the **Electrical Circuit** toolbar, click **Resistor**.

2 In the **Settings** window for **Resistor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	1
n	2

4 Locate the **Device Parameters** section. In the R text field, type `R1`.

Inductor 1 (L1)

1 In the **Electrical Circuit** toolbar, click **Inductor**.

2 In the **Settings** window for **Inductor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	2
n	3

4 Locate the **Device Parameters** section. In the L text field, type `L1`.

External U vs. I 1 (UvsI1)

1 In the **Electrical Circuit** toolbar, click **External U vs. I**.

2 In the **Settings** window for **External U vs. I**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	3
n	0

ELECTRIC DISCHARGE (EDIS)

In the **Model Builder** window, expand the **Component 1 (comp1)** > **Electric Discharge (edis)** node.

Electrode 2

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Electric Discharge (edis)** > **Gas 1** node, then click **Electrode 2**.

2 In the **Settings** window for **Electrode**, locate the **Terminal** section.

3 From the **Terminal type** list, choose **Circuit**.

ELECTRICAL CIRCUIT (CIR)

External U vs. I 1 (UvsI1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Electrical Circuit (cir)** click **External U vs. I 1 (UvsI1)**.

2 In the **Settings** window for **External U vs. I**, locate the **External Device** section.

3 From the *I* list, choose **Terminal current (edis/gas1/ece2)**.

STUDY 1

In the **Model Builder** window, expand the **Study 1** node.

DEFINITIONS

Global Variable Probe 1 (var1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

2 Right-click **Definitions** and choose **Probes** > **Global Variable Probe**.

3 In the **Settings** window for **Global Variable Probe**, type `ic` in the **Variable name** text field.

4 Locate the **Expression** section. In the **Expression** text field, type `edis.I0_1`.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

4 In the **Geometry** toolbar, click **Build All**.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** click **Variables 1**.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
N0	(1e8+1e12*exp(-((z/(1[mm])-0.5)/0.027)^2-(r/(1[mm])/0.021)^2))[cm^-3]	1/m³	Initial number density

MESH 1

In the **Model Builder** window, expand the **Component 1 (comp1) > Mesh 1** node.

Distribution 2

1. In the **Model Builder** window, expand the **Component 1 (comp1) > Mesh 1 > Mapped 1** node, then click **Distribution 2**.
2. In the **Settings** window for **Distribution**, locate the **Distribution** section.
3. In the **Number of elements** text field, type `400`.

RESULTS

Electron Density

In the **Model Builder** window, under **Results** right-click **Electron Density** and choose **Delete**.

STUDY 1 (OLD STUDY)

1. In the **Model Builder** window, click **Study 1**.
2. In the **Settings** window for **Study**, type `Study 1 (Old Study)` in the **Label** text field.

ADD STUDY

1. In the **Study** toolbar, click **Add Study** to open the **Add Study** window.
2. Go to the **Add Study** window.
3. Find the **Studies** subsection. In the **Select Study** tree, select **General Studies > Time Dependent**.
4. Click the **Add Study** button in the window toolbar.
5. In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Time Dependent

1. In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
2. From the **Time unit** list, choose **ns**.
3. In the **Output times** text field, type `range(0,0.5,2.5) range(5,5,50) 100`.
4. In the **Model Builder** window, click **Study 2**.
5. In the **Settings** window for **Study**, locate the **Study Settings** section.
6. Clear the **Generate default plots** checkbox.
7. In the **Study** toolbar, click **Compute**.

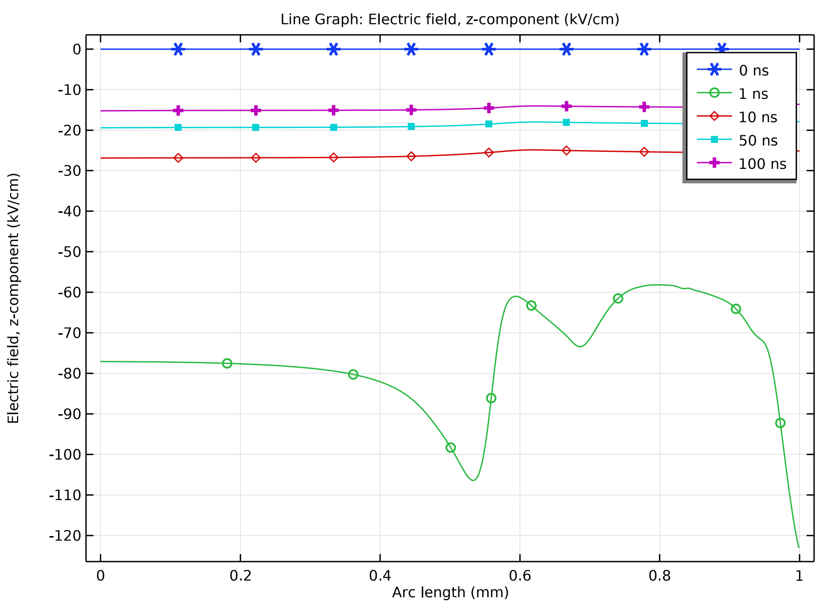
RESULTS

Electric Field

1. In the **Model Builder** window, under **Results** click **Electric Field**.
2. In the **Settings** window for **1D Plot Group**, locate the **Data** section.
3. From the **Dataset** list, choose **Study 2/Solution 3 (sol3)**.
4. In the **Electric Field** toolbar, click **Plot**.
5. From the **Time selection** list, choose **From list**.
6. In the **Times (ns)** list, choose **0**, **1**, **10**, **50**, and **100**.

Line Graph 1

1. In the **Model Builder** window, expand the **Electric Field** node, then click **Line Graph 1**.
2. In the **Settings** window for **Line Graph**, click to expand the **Legends** section.
3. Select the **Show legends** checkbox.
4. Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.
5. From the **Positioning** list, choose **Interpolated**.
6. In the **Electric Field** toolbar, click **Plot**.
7. Click the **Zoom Extents** button in the **Graphics** toolbar.



ESD Current

1 In the **Model Builder** window, under **Results** click **Probe Plot Group 2**.

2 In the **Settings** window for **1D Plot Group**, type `ESD Current` in the **Label** text field.

3 Locate the **Axis** section. Select the **x-axis log scale** checkbox.

4 In the **ESD Current** toolbar, click **Plot**.