

Model created in COMSOL Multiphysics 6.4

# Memristor

## *Introduction*

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A memristor, short for “memory resistor,” is a two-terminal electronic component that controls the flow of electric current while retaining a memory of the charge that has previously passed through it. As a nonvolatile memory device, it preserves stored information even after power is removed. This distinctive feature makes memristors promising candidates for next-generation memory storage systems and emerging technologies such as neuromorphic computing, resistive random-access memory (ReRAM), and artificial synapses in neural networks.

Structurally, a memristor comprises a thin semiconductor layer — typically a metal oxide — sandwiched between two metal electrodes. When a voltage is applied, charge carriers such as oxygen vacancies migrate within the oxide layer, redistributing in a way that alters the material’s conductivity and thus its resistance. This change in resistance is what gives the memristor its memory capabilities. Once the voltage is removed, the distribution of charge carriers remains stable, allowing the device to retain its resistance state without power.

The model presented here simulates the dynamic resistive switching behavior of an oxide-based memristor.

## *Model Definition*

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This model adopts the approach outlined in [Ref. 1](#) to simulate the dynamic resistive switching behavior of an oxide-based memristor. It uses a 2D-axisymmetric geometry, which enables the simulation of a 3D system through a 2D cross-sectional representation. This approach significantly reduces computational costs while effectively capturing the 3D behavior of the device. The structure consists of two oxide layers — a highly resistive layer stacked atop a low-resistivity layer — with thicknesses of 30 nm and 5 nm, respectively. These oxide layers are sandwiched between two metal electrodes, each 30 nm thick, positioned at the top and bottom. [Figure 1](#) illustrates the configuration and geometry of the modeled memristor. The domain with a high concentration of charge carriers is identified as the conductive filament (CF), where local electrical conduction exhibits metallic behavior. The concept of CF formation and rupture has been employed to explain resistive switching behavior. The material properties, such as electric conductivity and thermal conductivity for each domain, are defined according to the approach described in [Ref. 1](#). The dynamic resistive switching behavior of the modeled memristor is governed by oxygen vacancy drift–diffusion, current continuity, and heat transfer, along with their fully coupled multiphysics interactions. The model utilizes the Joule Heating interface to

account for resistive heating, while the Transport of Charge Carriers interface captures the transport equations for oxygen vacancies as charge carriers.

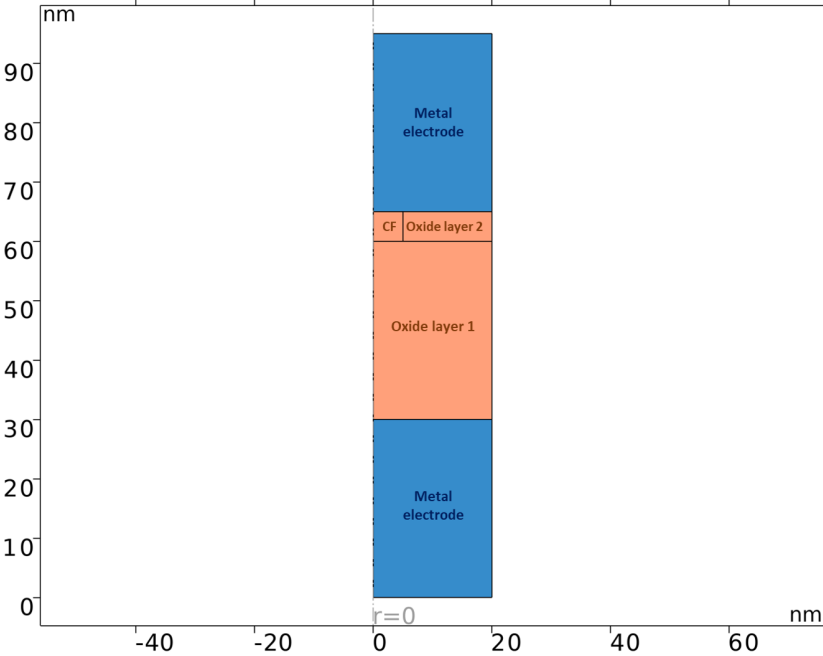


Figure 1: Configuration of the modeled memristor in a 2D-axisymmetric geometry, including metal electrodes and oxide layers.

The outermost boundaries of the two electrodes are defined with specific boundary conditions to ensure an accurate simulation of Joule heating effects. The bottom electrode is grounded for the electric potential, while a time-dependent voltage is applied to the top electrode. Additionally, a constant temperature is maintained at both the top and bottom contacts. For charge transport, a No flux boundary condition is imposed on all outer boundaries of the oxide domains, including the interfaces between the oxides and metal electrodes.

The detailed procedure of the implementation is described in the [Modeling Instructions](#) section.

*Results and Discussion*

Figure 2 presents the I-V characteristics of the modeled memristor, with the color table illustrating the evolution of time with respect to the applied voltage. At the beginning of

the simulation, the device is initialized in a high-conductivity state. When a positive time-dependent voltage is applied, the device undergoes a “reset” transition, shifting from high to low conductivity. In contrast, applying a negative time-dependent voltage induces a “set” transition, restoring the device to its high-conductivity state. These transitions demonstrate the resistive switching behavior characteristic of oxide-based memristors.

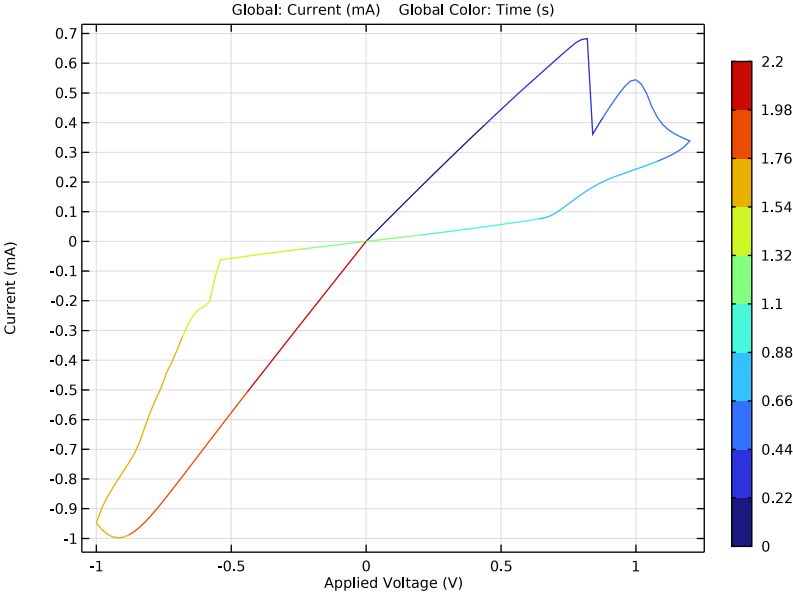
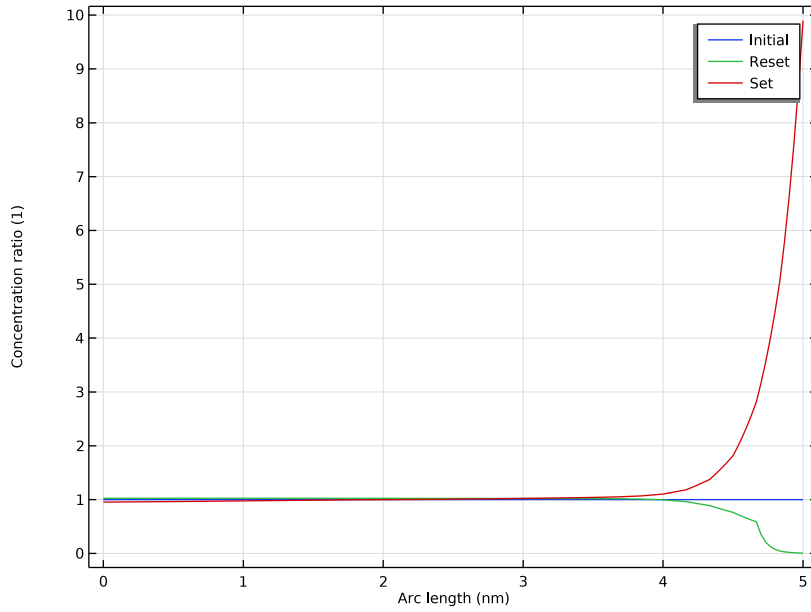
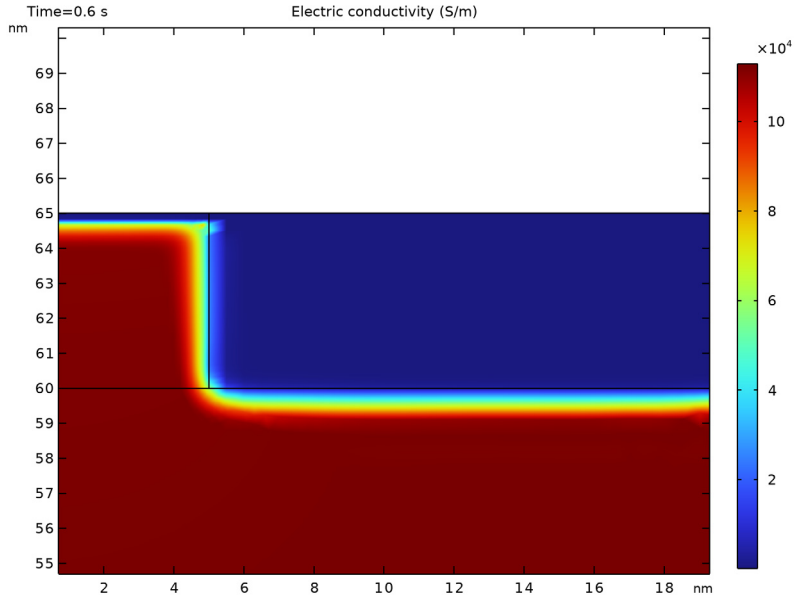


Figure 2: *I–V characteristics of the oxide-based memristor.*

An analysis of the concentration profiles provides insight into the physical mechanisms governing the set and reset processes. Figure 3 shows the concentration ratio (defined as the charge carrier concentration divided by the initial concentration,  $n/n_0$ ) along the CF at  $r = 0$ , at the initial state, reset, and set processes. During the reset process, a 1 nm depletion region forms close to the CF–metal electrode interface, resulting in a decrease in electric conductivity. In contrast, during the set process, charge accumulation occurs at the interface, restoring the high-conductivity state of the memristor. The low- and high-conductivity states, corresponding to the reset and set processes, are illustrated in Figure 4 and Figure 5, respectively.



*Figure 3: Concentration ratio of the charge carriers along the CF at  $r = 0$  at the initial state, reset, and set states.*



*Figure 4: Electric conductivity profile illustrating the region of low electric conductivity near the CF-metal electrode interface following the reset state.*

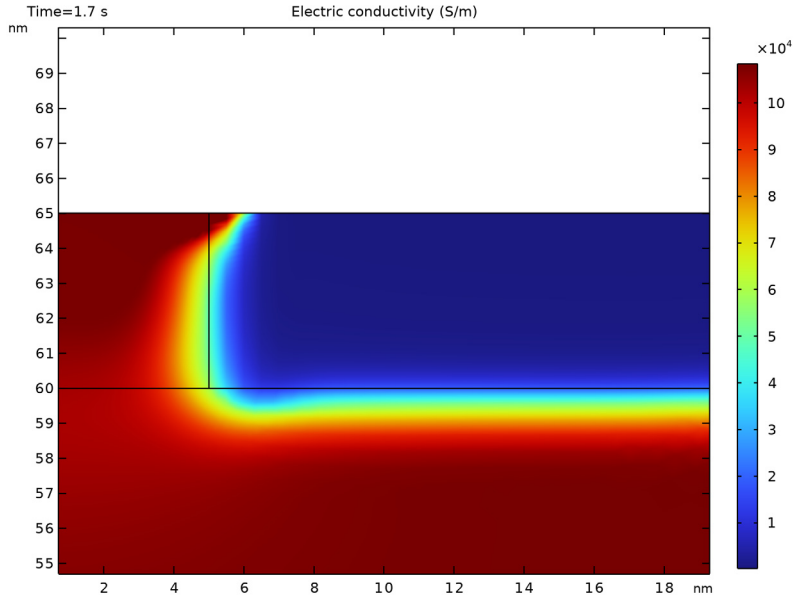


Figure 5: Electric conductivity profile illustrating the region of high electric conductivity near the CF-metal electrode interface following the set state.

### Reference


1. S. Kim and others, “Comprehensive physical model of dynamic resistive switching in an oxide memristor,” *ACS nano.*, vol. 8, no. 3, pp. 2369–2376, 2014.

**Application Library path:** Semiconductor\_Module/Device\_Building\_Blocks/memristor




### Modeling Instructions

From the **File** menu, choose **New**.

#### NEW

In the **New** window, click  **Model Wizard**.

## MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D Axisymmetric**.
- 2 In the **Select Physics** tree, select **Heat Transfer > Electromagnetic Heating > Joule Heating**.
- 3 Click **Add**.
- 4 In the **Select Physics** tree, select **Electric Discharge > Transport of Charge Carriers (tcc)**.
- 5 Click **Add**.
- 6 Click  **Study**.
- 7 In the **Select Study** tree, select **General Studies > Time Dependent**.
- 8 Click  **Done**.

## 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
d_BE	30[nm]	3E-8 m	Bottom electrode thickness
d_TE	30[nm]	3E-8 m	Top electrode thickness
d_ox1	30[nm]	3E-8 m	Oxide1 thickness
d_ox2	5[nm]	5E-9 m	Oxide2 thickness
w	20[nm]	2E-8 m	Oxide radius
r_CF	5[nm]	5E-9 m	Conductive filament radius
T0	300[K]	300 K	Reference temperature
n0	1e21 [1/cm^3]	1E27 1/m <sup>3</sup>	Initial concentration
a	0.1[nm]	1E-10 m	Hopping distance
f	1e12[Hz]	1E12 Hz	Escape-attempt frequency
Ea	0.85[eV]	1.3619E-19 J	Diffusion barrier

## DEFINITIONS

### *Interpolation 1 (int1)*

- 1 In the **Definitions** toolbar, click  **Interpolation**.
- 2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `sigma0`.

4 In the table, enter the following settings:

t	f(t)
0	10
1	940

5 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
<code>sigma0</code>	S/cm

6 In the **Argument** table, enter the following settings:

Argument	Unit
t	1

#### *Interpolation 2 (int2)*

1 In the **Definitions** toolbar, click  **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `E_AC`.

4 In the table, enter the following settings:

t	f(t)
0	0.05
0.5	-0.006
1	-0.006

5 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
<code>E_AC</code>	eV

6 In the **Argument** table, enter the following settings:

Argument	Unit
t	1

#### *Interpolation 3 (int3)*

1 In the **Definitions** toolbar, click  **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `k_th0`.

4 In the table, enter the following settings:

t	f(t)
0	0.12
1	57.5


5 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
<code>k_th0</code>	W / (m*K)

6 In the **Argument** table, enter the following settings:

Argument	Unit
<code>t</code>	1

#### *Applied Voltage*

1 In the **Definitions** toolbar, click  **Interpolation**.

2 In the **Settings** window for **Interpolation**, type Applied Voltage in the **Label** text field.

3 Locate the **Definition** section. In the **Function name** text field, type `V0`.

4 In the table, enter the following settings:

t	f(t)
0	0
0.6	1.2
1.2	0
1.7	-1
2.2	0

5 Locate the **Units** section. In the **Function** table, enter the following settings:

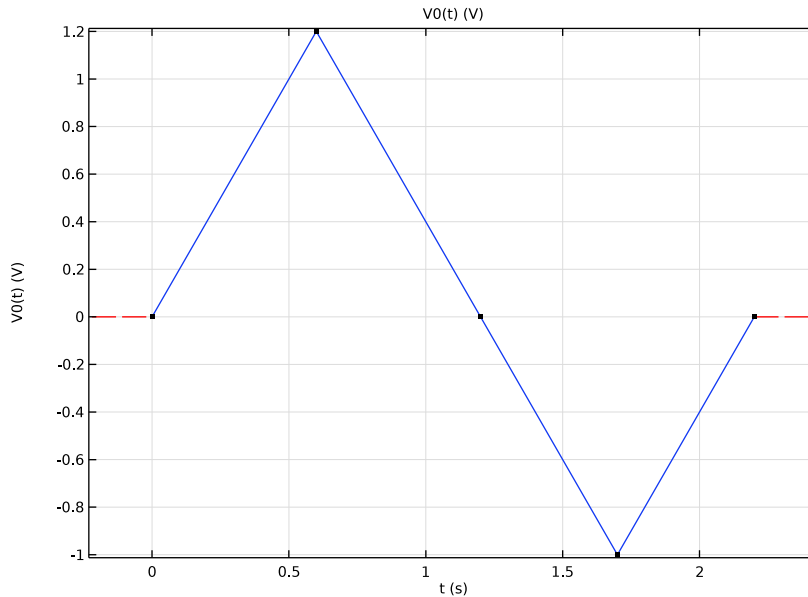
Function	Unit
<code>V0</code>	V

6 In the **Argument** table, enter the following settings:

Argument	Unit
<code>t</code>	s

7 Click  **Plot**.

A time-dependent voltage is applied at a rate of 2V/s.



*Variables 1*

- 1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.
- 2 In the **Settings** window for **Variables**, locate the **Variables** section.
- 3 In the table, enter the following settings:


Name	Expression	Unit	Description
D_n	$(0.5*a^2*f*\exp(-Ea/(k\_B\_const*T)))$	m <sup>2</sup> /s	Diffusion coefficient
S	$-Ea/(k\_B\_const*T^2)$	l/K	Soret diffusion coefficient
v_Er	$a*f*\exp(-Ea/(k\_B\_const*T))*\sinh(e\_const*a*ec.ER/(k\_B\_const*T))$	m/s	Velocity due to Electric field, r component
v_Ez	$a*f*\exp(-Ea/(k\_B\_const*T))*\sinh(e\_const*a*ec.EZ/(k\_B\_const*T))$	m/s	Velocity due to Electric field, z component

Name	Expression	Unit	Description
v_Sr	$D_n \cdot Tr \cdot S$	m/s	Velocity due to Soret effect, r component
v_Sz	$D_n \cdot Tz \cdot S$	m/s	Velocity due to Soret effect, z component
vr	$v_{Er} - v_{Sr}$	m/s	Total velocity, r component
vz	$v_{Ez} - v_{Sz}$	m/s	Total velocity, z component
k	$n/n_0$		Concentration ratio
sigma	$\sigma_0(k) \cdot \exp(-E_{AC}(k) / (k_B \cdot \text{const} \cdot T))$	S/m	Electric conductivity
k_th	$k_{th0}(k) \cdot (1 + 0.1 [1/K] \cdot (T - T_0))$	W/(m·K)	Thermal conductivity


## GEOMETRY I

- 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 **nm**.


### Rectangle 1 (r1)

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type w.
- 4 In the **Height** text field, type d\_BE.

### Rectangle 2 (r2)

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type w.
- 4 In the **Height** text field, type d\_ox1.
- 5 Locate the **Position** section. In the **z** text field, type d\_BE.

### Rectangle 3 (r3)



- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type w.

- 4 In the **Height** text field, type  $d_{ox2}$ .
- 5 Locate the **Position** section. In the **z** text field, type  $d_{BE}+d_{ox1}$ .
- 6 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (nm)
Layer 1	$r_{CF}$



- 7 Select the **Layers to the left** checkbox.
- 8 Clear the **Layers on bottom** checkbox.

#### *Rectangle 4 (r4)*

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type  $w$ .
- 4 In the **Height** text field, type  $d_{TE}$ .
- 5 Locate the **Position** section. In the **z** text field, type  $d_{BE}+d_{ox1}+d_{ox2}$ .
- 6 Click  **Build All Objects**.

## DEFINITIONS

#### *Integration 1 (intop1)*

- 1 In the **Definitions** toolbar, click  **Nonlocal Couplings** and choose **Integration**.
- 2 In the **Settings** window for **Integration**, locate the **Source Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 5 Select Boundary 9 only.

#### *Variables 1*

- 1 In the **Model Builder** window, 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
I	$-\text{intop1}(\text{ec.JZ})$	A	Current

## MATERIALS

### *Palladium*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, type Palladium in the **Label** text field.
- 3 Select Domains 1 and 4 only.
- 4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Electric conductivity	$\sigma_{iso}$ ; $\sigma_{iij} = \sigma_{iso}$ , $\sigma_{ij} = 0$	9.5E4 [S / cm]	S/m	Basic
Thermal conductivity	$k_{iso}$ ; $k_{ii} = k_{iso}$ , $k_{ij} = 0$	71.8 [W / (m*K) ]	W/(m·K)	Basic

### *TaxOy*

- 1 Right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, type TaxOy in the **Label** text field.
- 3 Select Domains 2, 3, and 5 only.
- 4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Electric conductivity	$\sigma_{iso}$ ; $\sigma_{iij} = \sigma_{iso}$ , $\sigma_{ij} = 0$	$\sigma$	S/m	Basic
Thermal conductivity	$k_{iso}$ ; $k_{ii} = k_{iso}$ , $k_{ij} = 0$	$k_{th}$	W/(m·K)	Basic

## ELECTRIC CURRENTS (EC)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electric Currents (ec)**.
- 2 In the **Settings** window for **Electric Currents**, click to expand the **Equation** section.
- 3 From the **Equation form** list, choose **Stationary**.
- 4 Click to expand the **Discretization** section. From the **Electric potential** list, choose **Linear**.


#### *Current Conservation in Solids I*

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Electric Currents (ec)** click **Current Conservation in Solids I**.
- 2 In the **Settings** window for **Current Conservation in Solids**, locate the **Constitutive Relation D-E** section.
- 3 From the  $\epsilon_r$  list, choose **User defined**.

#### *Ground I*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Ground**.
- 2 Select Boundary 2 only.

#### *Electric Potential I*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Electric Potential**.
- 2 Select Boundary 9 only.
- 3 In the **Settings** window for **Electric Potential**, locate the **Electric Potential** section.
- 4 In the  $V_0$  text field, type  $V_0(\tau)$ .

#### **HEAT TRANSFER IN SOLIDS (HT)**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Heat Transfer in Solids (ht)**.
- 2 In the **Settings** window for **Heat Transfer in Solids**, click to expand the **Equation** section.
- 3 From the **Equation form** list, choose **Stationary**.
- 4 Locate the **Physical Model** section. In the  $T_{\text{ref}}$  text field, type  $T_0$ .
- 5 Click to expand the **Discretization** section. From the **Temperature** list, choose **Linear**.


#### *Solid I*

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Heat Transfer in Solids (ht)** click **Solid I**.
- 2 In the **Settings** window for **Solid**, locate the **Thermodynamics, Solid** section.
- 3 From the  $\rho$  list, choose **User defined**. From the  $C_p$  list, choose **User defined**.

#### *Initial Values I*

- 1 In the **Model Builder** window, click **Initial Values I**.
- 2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 3 In the  $T$  text field, type  $T_0$ .

### *Temperature 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Temperature**.
- 2 Select Boundaries 2 and 9 only.
- 3 In the **Settings** window for **Temperature**, locate the **Temperature** section.
- 4 In the  $T_0$  text field, type T0.

### **TRANSPORT OF CHARGE CARRIERS (TCC)**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Transport of Charge Carriers (tcc)**.
- 2 Select Domains 2, 3, and 5 only.
- 3 In the **Settings** window for **Transport of Charge Carriers**, locate the **Transport Mechanisms** section.
- 4 Clear the **Electric field drift** checkbox.
- 5 Select the **Convection** checkbox.


### *Transport Properties 1*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** > **Transport of Charge Carriers (tcc)** click **Transport Properties 1**.
- 2 In the **Settings** window for **Transport Properties**, locate the **Convection** section.
- 3 Specify the **u** vector as


$v_r$	$r$
$v_z$	$z$

- 4 Locate the **Diffusion** section. In the  $D_n$  text field, type  $D_n$ .

### *Initial Values 2*

- 1 In the **Physics** toolbar, click  **Domains** and choose **Initial Values**.
- 2 Select Domains 2 and 3 only.
- 3 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 4 In the  $n_n$  text field, type  $n_0$ .


### *No Flux 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **No Flux**.
- 2 In the **Settings** window for **No Flux**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **All boundaries**.


## MESH I

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh I**.
- 2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.
- 3 From the **Element size** list, choose **Extremely fine**.
- 4 Right-click **Component 1 (comp1)** > **Mesh I** and choose **Edit Physics-Induced Sequence**.

### *Mapped I*

- 1 In the **Mesh** toolbar, click  **Mapped**.
- 2 In the **Settings** window for **Mapped**, locate the **Domain Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Select Domains 3 and 5 only.

### *Distribution I*

- 1 Right-click **Mapped I** and choose **Distribution**.
- 2 Select Boundaries 5, 6, 8, 10–12, and 15 only.
- 3 In the **Settings** window for **Distribution**, locate the **Distribution** section.
- 4 In the **Number of elements** text field, type 30.
- 5 Click the  **Zoom to Selection** button in the **Graphics** toolbar.

### *Mapped I*


- 1 In the **Model Builder** window, click **Mapped I**.
- 2 Drag and drop below **Size**.

### *Free Triangular I*

In the **Model Builder** window, right-click **Free Triangular I** and choose **Build All**.


## STUDY I

### *Step 1: Time Dependent*

- 1 In the **Model Builder** window, under **Study I** click **Step 1: Time Dependent**.
- 2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
- 3 In the **Output times** text field, type range (0,0.01,2.2).
- 4 In the **Study** toolbar, click  **Compute**.

## RESULTS

### *I-V*

- 1 In the **Results** toolbar, click  **ID Plot Group**.

2 In the **Settings** window for **ID Plot Group**, type I-V in the **Label** text field.

#### *Global I*

Right-click **I-V** and choose **Global**.

#### *Color Expression I*

1 In the **Model Builder** window, right-click **Global I** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type  $t$ .

4 Click to expand the **Title** section. From the **Title type** list, choose **Automatic**.

5 Locate the **Coloring and Style** section. From the **Color table type** list, choose **Discrete**.

#### *Global I*

1 In the **Model Builder** window, click **Global I**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.


3 In the table, enter the following settings:

Expression	Unit	Description
I	mA	Current


4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type  $V_0(t)$ .

6 Click to expand the **Legends** section. Clear the **Show legends** checkbox.

7 In the **I-V** toolbar, click  **Plot**.

#### *Concentration Ratio-z*

1 In the **Results** toolbar, click  **ID Plot Group**.

2 In the **Settings** window for **ID Plot Group**, type Concentration Ratio-z in the **Label** text field.

#### *Initial*

1 Right-click **Concentration Ratio-z** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, type Initial in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 From the **Time selection** list, choose **First**.

5 Select Boundary 5 only.

6 Locate the **y-Axis Data** section. In the **Expression** text field, type  $k$ .


7 Click to expand the **Title** section. From the **Title type** list, choose **None**.

- 8 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 9 Find the **Include** subsection. Select the **Label** checkbox.
- 10 Clear the **Solution** checkbox.


#### *Reset*

- 1 Right-click **Initial** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, type **Reset** in the **Label** text field.
- 3 Locate the **Data** section. From the **Time selection** list, choose **Manual**.
- 4 In the **Time indices (1-221)** text field, type **61**.

#### *Set*

- 1 Right-click **Reset** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, type **Set** in the **Label** text field.
- 3 Locate the **Data** section. In the **Time indices (1-221)** text field, type **171**.
- 4 In the **Concentration Ratio-z** toolbar, click  **Plot**.

#### *Electric Conductivity*

- 1 In the **Results** toolbar, click  **2D Plot Group**.
- 2 In the **Settings** window for **2D Plot Group**, type **Electric Conductivity** in the **Label** text field.

#### *Surface 1*

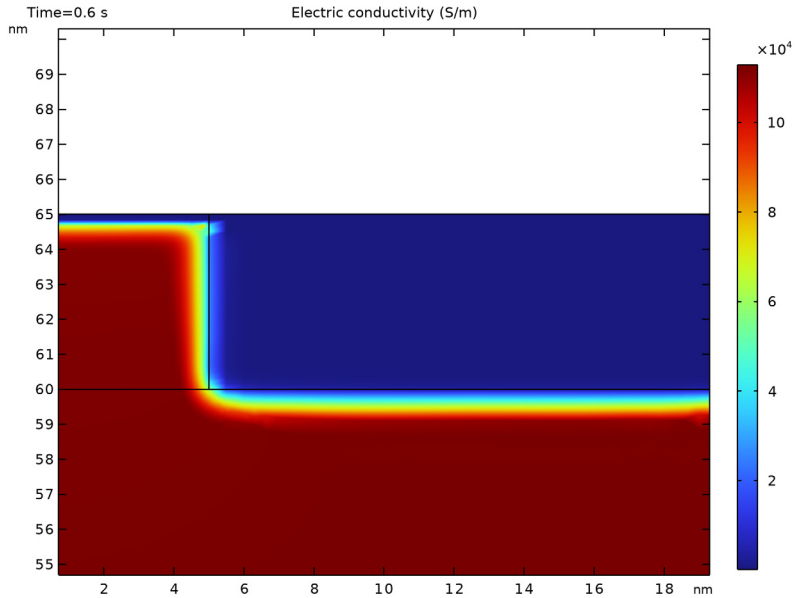
- 1 Right-click **Electric Conductivity** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type **sigma**.

#### *Electric Conductivity*

- 1 In the **Model Builder** window, click **Electric Conductivity**.
- 2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.
- 3 From the **Time (s)** list, choose **0.6**.

4 In the **Electric Conductivity** toolbar, click  **Plot**.

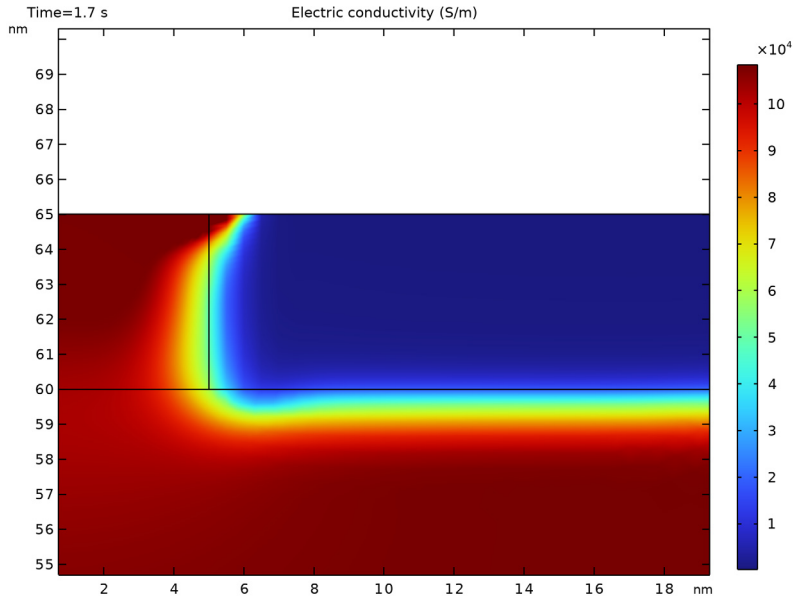
This profile illustrates the reduced electric conductivity near the CF-metal electrode interface as a result of the reset process.



5 From the **Time (s)** list, choose **1.7**.

6 In the **Electric Conductivity** toolbar, click  **Plot**.


This profile illustrates the increased electric conductivity near the CF–metal electrode interface as a result of the set process.




### *Thermal Conductivity*

- 1 Right-click **Electric Conductivity** and choose **Duplicate**.
- 2 In the **Settings** window for **2D Plot Group**, type Thermal Conductivity in the **Label** text field.

### *Surface 1*

- 1 In the **Model Builder** window, expand the **Thermal Conductivity** node, then click **Surface 1**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type  $k_{th}$ .
- 4 In the **Thermal Conductivity** toolbar, click  **Plot**.

### *Thumbnail*

- 1 In the **Results** toolbar, click  **3D Plot Group**.
- 2 In the **Settings** window for **3D Plot Group**, type Thumbnail in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

- 4 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

#### *Volume 1*

- 1 Right-click **Thumbnail** and choose **Volume**.
- 2 In the **Settings** window for **Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electric Currents > Electric > ec.normE - Electric field norm - V/m**.
- 3 Locate the **Coloring and Style** section. From the **Color table** list, choose **Prism**.




#### *Transparency 1*

- 1 Right-click **Volume 1** and choose **Transparency**.
- 2 In the **Settings** window for **Transparency**, locate the **Transparency** section.
- 3 Find the **Transparency** subsection. Set the **Transparency** value to **0.35**.

#### *Volume 2*

- 1 In the **Model Builder** window, right-click **Thumbnail** and choose **Volume**.
- 2 In the **Settings** window for **Volume**, locate the **Expression** section.
- 3 In the **Expression** text field, type **sigma**.
- 4 Locate the **Coloring and Style** section. From the **Color table** list, choose **RainbowLight**.

#### *Thumbnail*

- 1 In the **Model Builder** window, click **Thumbnail**.
- 2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
- 3 From the **Time (s)** list, choose **1.7**.
- 4 Click the  **Show Grid** button in the **Graphics** toolbar.
- 5 Click the  **Show Legends** button in the **Graphics** toolbar.
- 6 In the **Thumbnail** toolbar, click  **Plot**.