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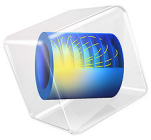

Si Solar Cell 1D

This tutorial uses a simple 1D model of a silicon solar cell to illustrate the basic steps to set up and perform a semiconductor simulation with the COMSOL Semiconductor Module.

Introduction

The solar cell model consists of a 1D silicon p–n junction with carrier generation and Shockley–Read–Hall recombination.

The p–n junction is formed by p-doping the front surface of an n-type Si wafer. The uniform bulk n-doping is assumed to be $1{\cdot}10^{16}$ cm^{-3}. The front surface p-doping is assumed to have a peak concentration of $1{\cdot}10^{19}$ cm^{-3}, and a Gaussian drop off with a junction depth of 0.25 μm.

The carrier generation mechanism from the photovoltaic effect is not modeled in detail. Instead, for simplicity, a user-defined spatially dependent variable is created for the generation rate, using an integral expression involving the solar irradiance and silicon absorption spectra. In addition, the Shockley–Read–Hall model is employed to capture the main recombination effect.

Under normal operating conditions, photo-generated carriers are swept to each side of the depletion region of the p–n junction. A small forward bias voltage is applied to extract the electrical power, given by the product of the photocurrent and the applied voltage.

Model Definition

This model simulates the behavior of the solar cell under forward bias with a voltage between 0 and 0.61 V. The modeled domain has a thickness of 150 μm. The built-in Si material data is assumed.

An **Analytic Doping Model** feature is used for the uniform bulk doping and a **Geometric Doping Model** is used for the front surface doping (the surface is specified in the **Boundary Selection for Doping Profile** subnode).

The Shockley–Read–Hall recombination model is implemented in a **Trap-Assisted Recombination** feature, and the photo-generation is done in a **User-Defined Generation** feature. The electrical connections to the front and back surfaces are done with two **Metal Contact** features.

The integral expression for the photo-generation rate is

$$G(z) = \int_0^\infty \alpha(\lambda)\phi(\lambda)\exp(-\alpha(\lambda)z)d\lambda \quad (1)$$

where z is the depth into the device from the surface, λ is the wavelength, $\alpha(\lambda)$ is the absorption coefficient defined by

$$\alpha(\lambda) = \frac{4\pi\kappa(\lambda)}{\lambda} \quad (2)$$

where $\kappa(\lambda)$ is the imaginary part of the refractive index (data given by Ref. 1), and $\phi(\lambda)$ is the photon generation rate defined by

$$\phi(\lambda) = \frac{\lambda}{hc}F(\lambda) \quad (3)$$

where $F(\lambda)$ is the spectral irradiance (here approximated by the AM 1.5 spectrum given by Ref. 2)

The mesh is adjusted from the default in order to resolve the steep gradients near the surface of the relatively thick device. The voltage sweep is done using a Stationary study with **Auxiliary sweep** enabled, using the solution from a **Semiconductor Equilibrium** study step as the initial condition.

Results and Discussion

Figure 1 shows the donor and acceptor concentrations for the depths of first 10 μm beneath the front surface. It is always a good idea to check the doping profile for unintentional setup errors.

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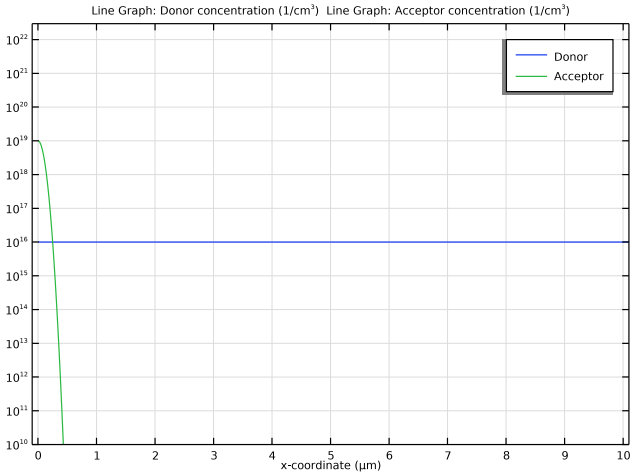

Figure 1: Donor and acceptor concentrations for the depths of first 10 µm beneath the front surface.

Figure 2 shows the Shockley–Read–Hall recombination rate and the user-defined photo-generation rate throughout the thickness of the cell.

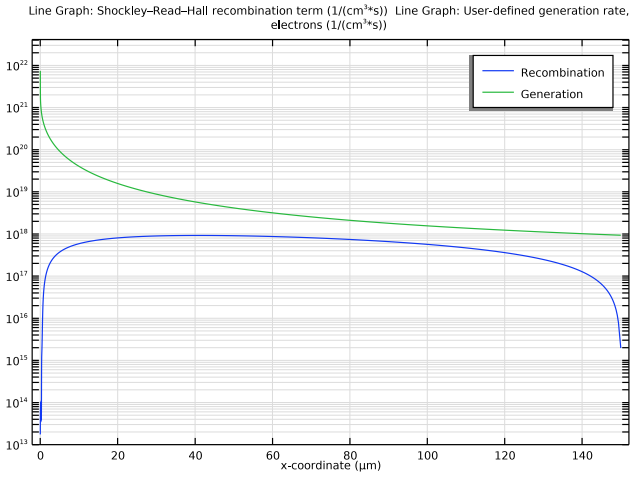

Figure 2: Shockley–Read–Hall recombination rate and user-defined photo-generation rate throughout the thickness of the cell.

Figure 3 and Figure 4 show the I–V and P–V curves. These graphs allow us to read off essential operating parameters such as the open circuit voltage (~0.61 V), the short circuit current (~33 mA), and the max power (~16.7 mW).

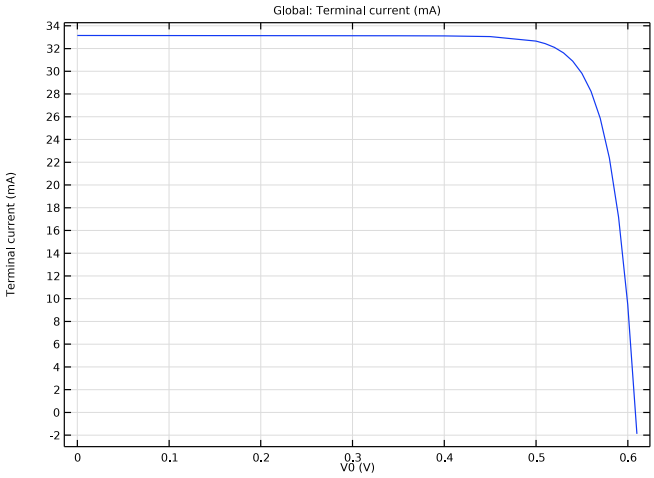

Figure 3: I–V curve of the solar cell.

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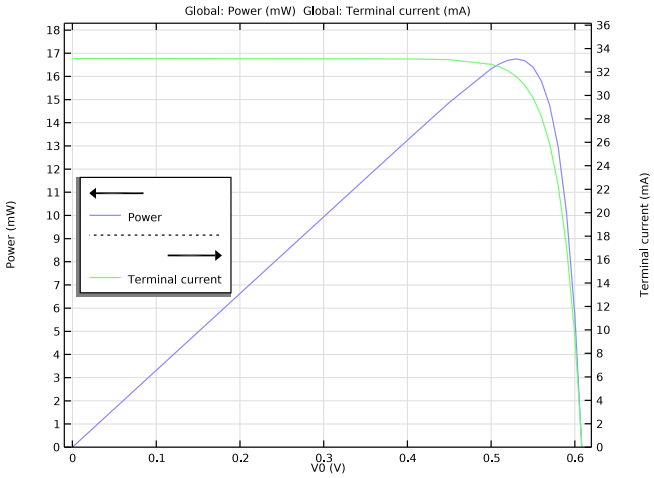


Figure 4: P–V curve of the cell.

References

1. https://refractiveindex.info/?shelf=main&book=Si&page=Green-2008.

2. https://www.nrel.gov/grid/solar-resource/spectra.html.

Application Library path: `Semiconductor_Module/Photonic_Devices_and_Sensors/si_solar_cell_1d`

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 **1D**.

2 In the **Select Physics** tree, select **Semiconductor>Semiconductor (semi)**.

3 Click **Add**.

4 Click **Study**.

We will start with the **Semiconductor Equilibrium** study type, which often helps us find a good initial condition for subsequent study steps.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> Semiconductor Equilibrium**.

6 Click **Done**.

Start by creating a global parameter for the applied voltage. Global parameters are independent of space and time in a model.

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
V0	0[V]	0 V	applied voltage

Create a simple geometry, using um as the length unit for convenience.

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 **µm**.

Interval 1 (i1)

1 Right-click **Component 1 (comp1)>Geometry 1** and choose **Interval**.

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

3 In the table, enter the following settings:

Coordinates (µm)
0
150

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

Define functions and variables for the spectra and generation rate of the charge carriers. First, for the solar spectrum, we use a rough approximation of the Reference AM 1.5 Spectra, the original data of which is available from Ref. 2. The unit of this function is irradiance per wavelength, or power per area per wavelength (`W/m^2/nm`).

GLOBAL DEFINITIONS

Interpolation 1: solar spectrum

1 In the **Home** toolbar, click **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, type `Interpolation 1: solar spectrum` in the **Label** text field.

3 Locate the **Definition** section. From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `si_solar_cell_1d_AM15_approx.txt`.

6 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
F	1

7 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
Column 1	nm

8 In the **Function** table, enter the following settings:

Function	Unit
F	W/m^2/nm

9 Locate the **Definition** section. Click **Import**.

For the silicon absorption spectrum, import a file that has two output columns, one for the refractive index `n` and the other for the extinction coefficient `k`. The original data is available from Ref. 1.

Interpolation 2: Si absorption spectrum

1 In the **Home** toolbar, click **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, type `Interpolation 2: Si absorption spectrum` in the **Label** text field.

3 Locate the **Definition** section. From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `si_solar_cell_1d_n_k_data.txt`.

6 In the **Number of arguments** text field, type `1`.

7 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
nref	1
kref	2

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

Function	Unit
nref	1
kref	1

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

Argument	Unit
Column 1	um

10 Locate the **Definition** section. Click **Import**.

DEFINITIONS

Finally add a variable for the photo-generation rate. Variables can in general depend on space and time. Here we will use the stationary study to solve for the steady state, so the generation rate is spatially dependent and time independent. The solar and silicon spectra are used in the integral over the range of wavelengths where both the irradiance on Earth and the absorption in silicon are significant.

Variables 1: Photogeneration

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Variables 1: Photogeneration` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **All domains**.

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

Name	Expression	Unit	Description
G_ph	`4*pi/(h_const*c_const)*integrate(kref(lm)*F(lm)*exp(-4*pi*kref(lm)*x/lm),lm,250[nm],1300[nm])`	1/(m³·s)	

Add the built-in silicon material.

ADD MATERIAL

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

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

3 In the tree, select **Semiconductors>Si - Silicon**.

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

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

Set up domain and boundary conditions for the physics.

SEMICONDUCTOR (SEMI)

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

2 In the **Settings** window for **Semiconductor**, locate the **Cross-Section Area** section.

3 In the A text field, type `1[cm^2]`.

4 Locate the **Model Properties** section. From the **Carrier statistics** list, choose **Fermi–Dirac**.

Add a uniform bulk doping.

Analytic Doping Model 1

1 In the **Physics** toolbar, click **Domains** and choose **Analytic Doping Model**.

2 In the **Settings** window for **Analytic Doping Model**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Locate the **Impurity** section. From the **Impurity type** list, choose **Donor doping (n-type)**.

Then add a Gaussian doping decaying away from the surface of the device to form the p-n junction. The **Geometric Doping Model** is convenient for setting up this kind of doping profiles. Remember to make a selection of the boundary for the subnode **Boundary Selection for Doping Profile**.

Geometric Doping Model 1

1 In the **Physics** toolbar, click **Domains** and choose **Geometric Doping Model**.

2 In the **Settings** window for **Geometric Doping Model**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Locate the **Impurity** section. In the N_{A0} text field, type `1e19[1/cm^3]`.

5 Locate the **Profile** section. In the d_j text field, type `0.25[um]`.

6 From the N_b list, choose **Donor concentration (semi/adm1)**.

Boundary Selection for Doping Profile 1

1 In the **Model Builder** window, expand the **Geometric Doping Model 1** node, then click **Boundary Selection for Doping Profile 1**.

2 Select Boundary 1 only.

Add Shockley-Read-Hall recombination using default parameters for silicon.

Trap-Assisted Recombination 1

1 In the **Physics** toolbar, click **Domains** and choose **Trap-Assisted Recombination**.

2 In the **Settings** window for **Trap-Assisted Recombination**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

Add the photo-generation and use the spatially varying variable defined above for the generation rate.

User-Defined Generation 1

1 In the **Physics** toolbar, click **Domains** and choose **User-Defined Generation**.

2 In the **Settings** window for **User-Defined Generation**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Locate the **User-Defined Generation** section. In the $G_{n,0}$ text field, type `G_ph`.

5 In the $G_{p,0}$ text field, type `G_ph`.

Add two metal contacts with one grounded and the other a voltage applied.

Metal Contact 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.

2 Select Boundary 2 only.

Metal Contact 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Metal Contact**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.

4 In the V_0 text field, type `V0`.

The modeling domain is quite large compared to the length scale of the steep gradients of physical quantities near the surface of the device. So we will adjust the mesh in order to resolve the gradients.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Finer**.

4 Right-click **Component 1 (comp1)>Mesh 1** and choose **Edit Physics-Induced Sequence**.

Size 1

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

2 Select Boundary 1 only.

3 In the **Settings** window for **Size**, click to expand the **Element Size Parameters** section.

4 Locate the **Element Size** section. Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** check box. In the associated text field, type `10[nm]`.

Add a **Stationary** study step to sweep the applied voltage.

STUDY 1

Step 2: Stationary

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (applied voltage)	`range(0,0.05,0.5)` `range(0.51,0.01,0.61)`	V

6 In the **Study** toolbar, click **Compute**.

RESULTS

Net Dopant Concentration (semi)

In the **Model Builder** window, under **Results** right-click **Net Dopant Concentration (semi)** and choose **Delete**.

Doping

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Locate the **Data** section. From the **Parameter selection (V0)** list, choose **First**.

Line Graph 1

1 Right-click **Doping** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Semiconductor>Carriers and dopants> Dopant concentrations>semi.Nd - Donor concentration - 1/m³**.

5 Locate the **y-Axis Data** section. In the **Unit** field, type `1/cm^3`.

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

7 In the **Expression** text field, type `x`.

8 Click to expand the **Legends** section. Select the **Show legends** check box.

9 From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
Donor

11 Right-click **Line Graph 1** and choose **Duplicate**.

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

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

3 In the **Expression** text field, type `semi.Na`.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
Acceptor

5 In the **Doping** toolbar, click **Plot**.

6 Click the **y-Axis Log Scale** button in the **Graphics** toolbar.

Zoom in to show the doping profile near the surface in more detail.

Doping

1 In the **Model Builder** window, click **Doping**.

2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

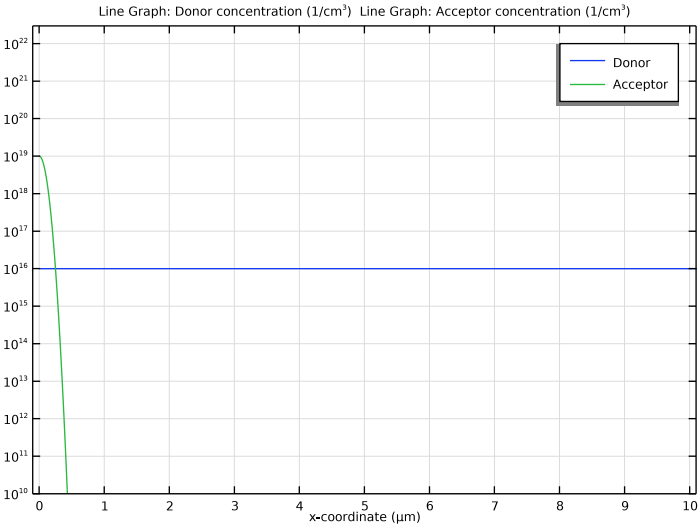
3 Select the **Manual axis limits** check box.

4 In the **x minimum** text field, type `-0.1`.

5 In the **x maximum** text field, type `10.1`.

6 In the **y minimum** text field, type `1e10`.

7 In the **Doping** toolbar, click **Plot**.



Plot the generation and recombination rates.

8 Right-click **Doping** and choose **Duplicate**.

Generation/Recombination rates

1 In the **Model Builder** window, under **Results** click **Doping 1**.

2 In the **Settings** window for **1D Plot Group**, type `Generation/Recombination rates` in the **Label** text field.

3 Locate the **Axis** section. Clear the **Manual axis limits** check box.

Line Graph 1

1 In the **Model Builder** window, expand the **Generation/Recombination rates** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Semiconductor>Generation and recombination>semi.Rsrh - Shockley–Read–Hall recombination term - 1/(m³·s)**.

3 Locate the **y-Axis Data** section. In the **Unit** field, type `1/(cm^3*s)`.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
Recombination

Line Graph 2

In the **Model Builder** window, right-click **Line Graph 2** and choose **Delete**.

Line Graph 1

In the **Model Builder** window, under **Results>Generation/Recombination rates** right-click **Line Graph 1** and choose **Duplicate**.

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Semiconductor>Generation and recombination>semi.udg1.Gn - User-defined generation rate, electrons - 1/(m³·s)**.

3 Locate the **Legends** section. In the table, enter the following settings:

Legends
Generation

4 In the **Generation/Recombination rates** toolbar, click **Plot**.

Generation/Recombination rates

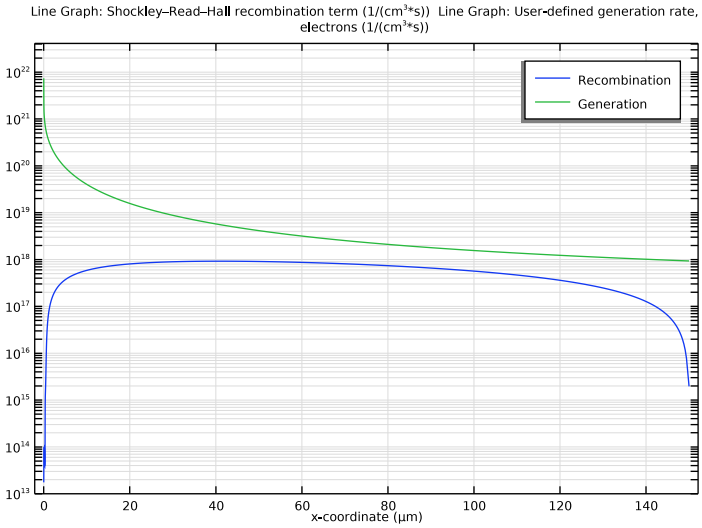
1 In the **Model Builder** window, click **Generation/Recombination rates**.

2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** check box.

4 In the **y minimum** text field, type `1e13`.

5 In the **Generation/Recombination rates** toolbar, click **Plot**.



Plot the I-V curve.

I-V curve

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `I-V curve` in the **Label** text field.

3 Locate the **Legend** section. Clear the **Show legends** check box.

Global 1

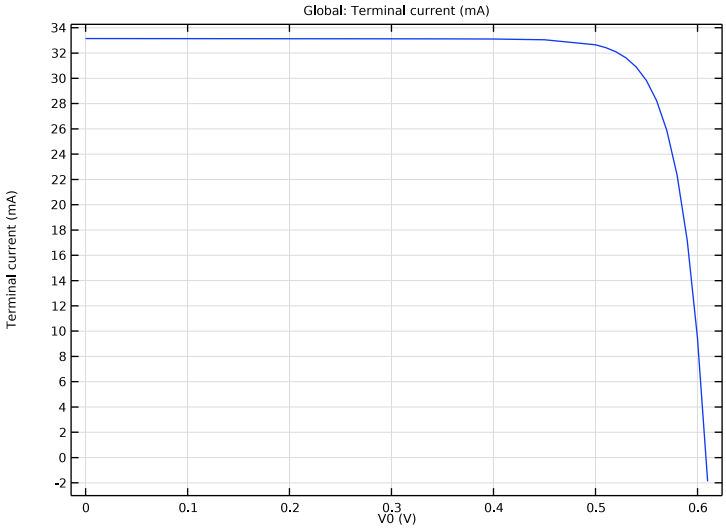
1 Right-click **I-V curve** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Semiconductor> Terminals>semi.IO_1 - Terminal current - A**.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`semi.IO_1`	`mA`	`Terminal current`

4 In the **I-V curve** toolbar, click **Plot**.



Plot the P-V curve.

I-V curve

In the **Model Builder** window, right-click **I-V curve** and choose **Duplicate**.

P-V curve

1 In the **Model Builder** window, expand the **Results>I-V curve 1** node, then click **I-V curve 1**.

2 In the **Settings** window for **1D Plot Group**, type `P-V curve` in the **Label** text field.

Global 1

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

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

3 In the table, enter the following settings:

Expression	Unit	Description
`semi.IO_1*VO`	`mW`	`Power`

P-V curve

1 In the **Model Builder** window, click **P-V curve**.

2 In the **P-V curve** toolbar, click **Plot**.

The I-V and P-V curves can be combined in a single figure, by copying the I-V plot into this plot group. The scales of the two curves can be separated by using the **Two y-axes** option.

Global 1

In the **Model Builder** window, under **Results>I-V curve** right-click **Global 1** and choose **Copy**.

P-V and I-V curves

1. In the **Model Builder** window, under **Results** right-click **P-V curve** and choose **Paste Global**.
2. In the **Model Builder** window, click **P-V curve**.
3. In the **Settings** window for **1D Plot Group**, type `P-V and I-V curves` in the **Label** text field.
4. Locate the **Plot Settings** section. Select the **Two y-axes** check box.
5. In the table, select the **Plot on secondary y-axis** check box for **Global 2**.
6. Click the **Zoom Extents** button in the **Graphics** toolbar.
7. Locate the **Axis** section. Select the **Manual axis limits** check box.
8. In the **y minimum** text field, type `0`.
9. In the **Secondary y minimum** text field, type `0`.
10. Locate the **Legend** section. Select the **Show legends** check box.
11. From the **Position** list, choose **Middle left**.
12. In the **P-V and I-V curves** toolbar, click **Plot**.