Created in COMSOL Multiphysics 6.2

# Thermal Analysis of a Bipolar Transistor

This model demonstrates how to combine the Semiconductor interface with the Heat Transfer in Solids interface in order to include the effects of a nonuniform temperature throughout a semiconductor device.

**Note:** See the Bipolar Transistor model for a description of the bipolar transistor device and how the Semiconductor interface can be used to characterize its operation.

## *Introduction*

In this model, the Heat Transfer in Solids interface is added and configured to calculate the temperature distribution throughout the device. The Semiconductor interface provides the heat source used in the Heat Transfer in Solids interface; whilst the temperature distribution that is used in the Semiconductor interface is calculated by the Heat Transfer in Solids interface.

## *Model Definition*

The model geometry is the same as used in the Bipolar Transistor model. The Heat Transfer in Solids interface is configured to use the `semi.Q_tot` variable, which is the heating calculated in the Semiconductor interface, as the heat source throughout the model domain. Heat is transferred between the model domain and its environment via the contact boundaries. Since the packaging of the device is not explicitly modeled, the heat transfer coefficient for these boundaries is calculated assuming an effective thermal resistance of $R = 100$ K/W, which is a typical value for small-signal bipolar transistors. This means that a temperature difference of $100$ K between the device and the ambient temperature of its environment would result in a $1$ W heat flux through the contact boundaries. This heat flux is assumed to be distributed over the total area, $A$, of the contacts such that the effective heat transfer coefficient, $h_0$, for the contact boundaries is given by

$$h_0 = \frac{1}{RA}$$

The Semiconductor interface is configured to use an incomplete ionization model for the Dopant Ionization. Incomplete dopant ionization is an important temperature-dependent process that affects the carrier concentration, and thus currents, through the semiconductor material. In the Semiconductor interface, the temperature of the semiconductor material domains is usually set using the default Semiconductor Material Model node. This model adds a second Semiconductor Material Model node: the default node uses a constant material temperature, T0, which is specified in the parameters table; the additional node is set to use a temperature variable $T$, which is the temperature distribution calculated by the Heat Transfer in Solids interface.

This model sweeps the voltage applied to the base contact whilst the collector contact is held at a constant voltage of 3 V. The device is simulated in the common emitter configuration where the base and collector voltages are measured relative to the emitter, which serves as a common ground. Two studies are required to solve the fully coupled problem. The first study uses the default Semiconductor Material Model node, where the heating from the Semiconductor interface is used as the heat source in the Heat Transfer in Solids interface, but the Semiconductor interface uses a constant material temperature. Solutions from the first study are then used as initial conditions for the second study, which solves the fully coupled problem, where the temperature distribution calculated in the Heat Transfer in Solids interface is fed back into the material temperature used in the Semiconductor interface via the second Semiconductor Material Model node.

The Gummel Plot and Current Gain plot groups from the Bipolar Transistor model are then amended to show the result from the two new studies. Also, the semiconductor heat source, `semi.Q_tot`, is plotted as a surface plot. Finally, the resulting temperature throughout the semiconductor device is plotted in the same plot group as the voltage distribution. This allows the voltage and corresponding temperature throughout the device to be visualized simultaneously.

## *Results and Discussion*

Figure 1 is the Gummel plot, which shows the collector and base currents, plotted on a logarithmic $y$-axis as a function of the base voltage. The two datasets are nearly identical because the temperature throughout the device in the fully coupled study does not deviate more than a few degrees from the T0 value used in the initial study.

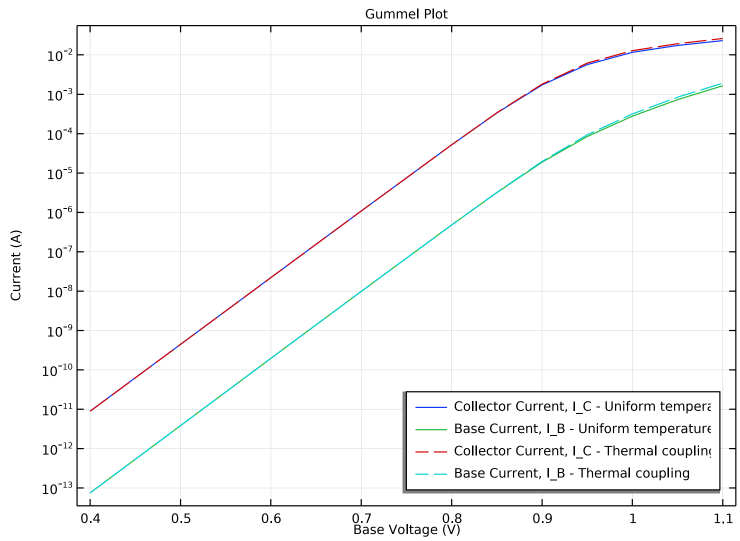


*Figure 1: Gummel plot showing the collector and base currents as a function of base voltage.*

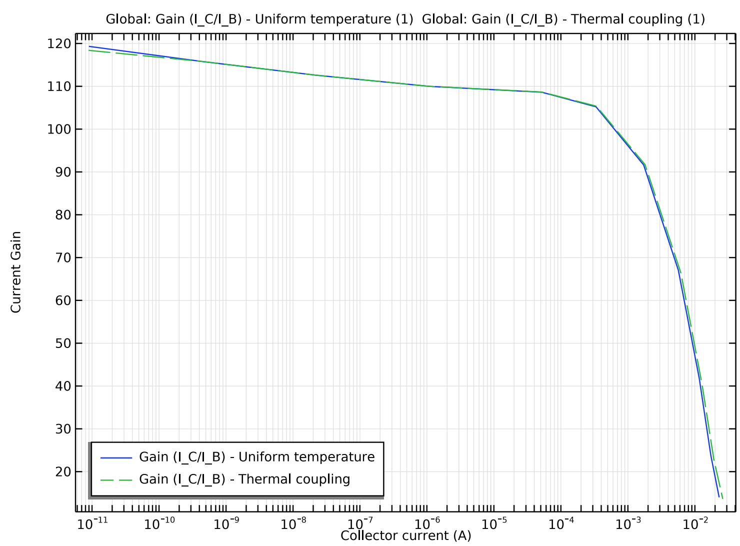


*Figure 2: Current gain curve showing the ratio of collector to base current as a function of base voltage.*

Figure 2 shows the current gain curve, which is the ratio of the collector to base current, as a function of the base voltage. The small magnitude of the base current for low values of the collector current lead to some numerical instability for collector currents less than approximately $10^{-10}$ A. Again, the two datasets are similar due to the small temperature difference between the initialization study and the fully coupled study.

The semiconductor heat source is shown in Figure 3. This is the heat source that is used by the Heat Transfer in Solids interface to calculated the temperature distribution throughout the device.

Figure 4 shows the voltage and temperature throughout the device. The top surface plot shows the voltage distribution, along with the electron and hole currents as black and white arrow plots, respectively. As expected, the hole current is between the base and emitter contacts, without entering the collector region, whilst the electron current is predominantly between the collector and emitter. The lower surface plot shows the corresponding temperature throughout the device, along with an arrow plot which shows the heat flux. The temperature is highest between the emitter and collector contacts, at the depth of the junction between the base and collector regions. This is the expected result as the majority of the current flows between these two contacts, and the base–collector junction creates a region with higher resistance than the surrounding bulk material. Thus the Joule heating, which is the predominant semiconductor heating mechanism in this model, is largest in this location. The heat flux also behaves as expected, as it flows from the peak temperature toward the contacts, which are the only boundaries that allow heat transfer in this simple model.

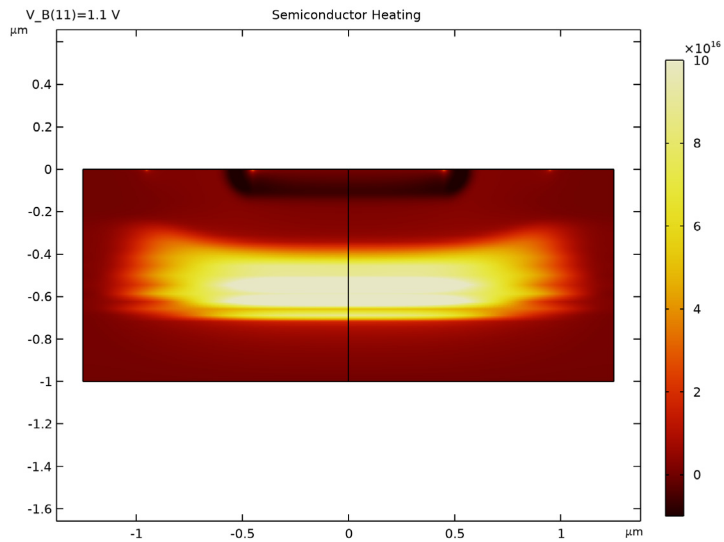


*Figure 3: Semiconductor heat source for a base voltage of 1.1 V and a collector voltage of 3 V.*

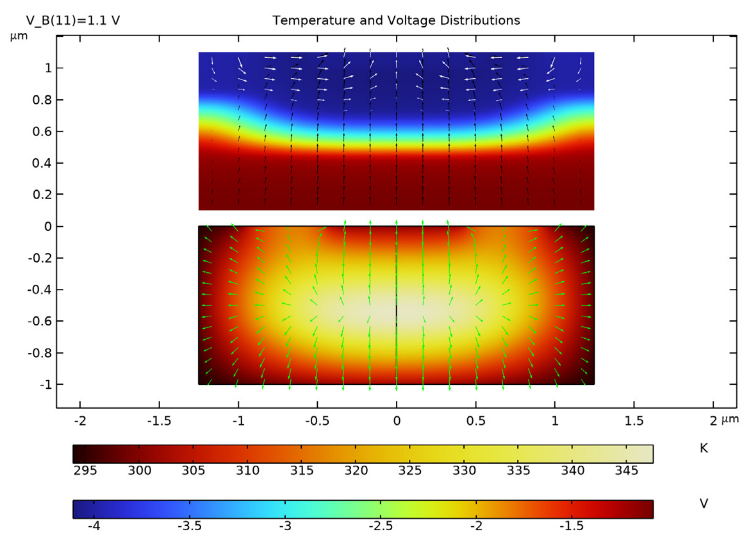


*Figure 4: Voltage and temperature for a base voltage of 1.1 V and a collector voltage of 3 V. Top panel: Voltage distribution with electron and hole currents shown in black and white arrows. Bottom panel: Corresponding temperature throughout the device, along with the heat flux shown as arrows.*

**Application Library path:** `Semiconductor_Module/Transistors/bipolar_transistor_thermal`

## *Modeling Instructions*

### ROOT

Open the bipolar_transistor model.

### APPLICATION LIBRARIES

1. From the **File** menu, choose **Application Libraries**.
2. In the **Application Libraries** window, select **Semiconductor Module>Transistors>bipolar_transistor** in the tree.
3. Click **Open**.

   Add some parameters which are required for the Heat Transfer physics. The effective thermal resistance of a fully packaged device is defined as the temperature difference between the device and its surroundings for a given heating power. This temperature difference is measured between the peak temperature within the device, which occurs at the p-n junction boundaries, and the ambient temperature of the environment in which the device is operating. In this model a value of 100 K/W is used, which means that a heat flux of 1 W would result in a temperature difference of 100 K. As only heat transferred to and from the device via the contacts is considered in this model, the effective thermal resistance is divided by the area of the contacts to give the thermal resistance per unit area. The reciprocal of this value gives the effective heat transfer coefficient, with units W/(m^2 K), which is used to specify the heat flux through the contact boundaries. Also added are an index parameters and a continuation parameter, both of which are used to set up the studies required by this 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 |
|---|---|---|---|
| V_C | 3[V] | 3 V | Applied voltage: collector |
| R | 100[K/W] | 100 K/W | Effective thermal resistance |
| h0 | 1/R/((w_cE+w_cB+w_cC)*l_BJT) | 1.6667E9 W/($m^2$·K) | Effective heat transfer coefficient for contacts |

Next, configure the Semiconductor Interface for thermal coupling. Incomplete Ionization is activated in the **Semiconductor Material Model** node, as this is an important temperature dependent phenomenon. A second **Semiconductor Material Model** node is required, these nodes specify the temperature used by the Semiconductor Interface. The existing node sets a constant temperature of **T0** and will be used in an initialization study in which the thermal effects are not coupled with the semiconductor equations; the additional node sets the temperature to **T** (using an available item from the drop-down menu after adding the Heat Transfer interface), which is the temperature output by the Heat Transfer in Solids interface, and is used in a second fully coupled study. Also, the base current and collector current nodes are disabled as they are not required in the thermal studies.

## COMPONENT 1 (COMP1)

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

## SEMICONDUCTOR (SEMI)

### *Semiconductor Material Model 1*

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Semiconductor (semi)** node, then click **Semiconductor Material Model 1**.

2 In the **Settings** window for **Semiconductor Material Model**, click to expand the **Dopant Ionization** section.

3 From the **Dopant ionization** list, choose **Incomplete ionization**.

4 Right-click **Component 1 (comp1)>Semiconductor (semi)> Semiconductor Material Model 1** and choose **Duplicate**.

### *Base Current*

1 In the **Model Builder** window, right-click **Base Current** and choose **Disable**.

Add the Heat Transfer in Solids Interface and configure the thermal physics. The out-of-plane thickness in the Heat Transfer in Solids Interface needs to be set to the same value as in the Semiconductor Interface. The heating calculated by the Semiconductor Interface, given by variable **semi.Q_tot** (as an available item in the drop-down menu), is coupled into the Heat Transfer in Solids Interface using a Heat Source node. Also, a Heat Flux node is used to include the effects of heat transfer through the contact boundaries.

### 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 **Heat Transfer>Heat Transfer in Solids (ht)**.

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

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

### HEAT TRANSFER IN SOLIDS (HT)

1 In the **Settings** window for **Heat Transfer in Solids**, locate the **Physical Model** section.

2 In the $d_z$ text field, type `l_BJT`.

3 Click to expand the **Discretization** section. From the **Temperature** list, choose **Linear**.

#### *Initial Values 1*

1 In the **Model Builder** window, under **Component 1 (comp1)>Heat Transfer in Solids (ht)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the $T$ text field, type `T0`.

#### *Heat Source 1*

1 In the **Physics** toolbar, click **Domains** and choose **Heat Source**.

2 Select Domain 1 only.

3 In the **Settings** window for **Heat Source**, locate the **Heat Source** section.

4 From the $Q_0$ list, choose **Total heat source (semi)**.

#### *Heat Flux 1*

1 In the **Physics** toolbar, click **Boundaries** and choose **Heat Flux**.

2 Select Boundaries 2, 3, 5, and 6 only.

3 In the **Settings** window for **Heat Flux**, locate the **Heat Flux** section.

4 From the **Flux type** list, choose **Convective heat flux**.

5 In the $h$ text field, type `h0`.

6 In the $T_{ext}$ text field, type `T0`.

### SEMICONDUCTOR (SEMI)

*Semiconductor Material Model 2*

1 In the **Model Builder** window, under **Component 1 (comp1)>Semiconductor (semi)** click **Semiconductor Material Model 2**.

2 Select Domain 1 only.

3 In the **Settings** window for **Semiconductor Material Model**, locate the **Model Input** section.

4 From the $T$ list, choose **Temperature (ht)**.

Add a study to perform a sweep on V_C with incomplete ionization.

### ADD STUDY

1 In the **Home** 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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

### INCOMPLETE IONIZATION: V_C SWEEP, V_B=0 V, V_E=0 V

1 In the **Model Builder** window, click **Study 5**.

2 In the **Settings** window for **Study**, type `Incomplete Ionization: V_C Sweep, V_B=0 V, V_E=0 V` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

*Step 1: Stationary*

1 In the **Model Builder** window, under **Incomplete Ionization: V_C Sweep, V_B=0 V, V_E=0 V** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** check box.

4 In the tree, select **Component 1 (comp1)>Semiconductor (semi)> Semiconductor Material Model 2**.

5 Right-click and choose **Disable**.

6 In the tree, select **Component 1 (comp1)>Heat Transfer in Solids (ht)**.

7 Right-click and choose **Disable in Solvers**.

8 Click to expand the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

9 From the **Method** list, choose **Solution**.

10 From the **Study** list, choose **V_C Sweep, V_B=0 V, V_E=0 V, Stationary**.

11 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

12 Click **Add**.

13 In the table, enter the following settings:

| Parameter name | Parameter value list | Parameter unit |
|---|---|---|
| V_B (Applied voltage: base) | 0 | V |

14 Click **Add**.

15 In the table, enter the following settings:

| Parameter name | Parameter value list | Parameter unit |
|---|---|---|
| V_E (Applied voltage: emitter) | 0 | V |

16 Click **Add**.

17 In the table, enter the following settings:

| Parameter name | Parameter value list | Parameter unit |
|---|---|---|
| V_C (Applied voltage: collector) | 0.5 1 2 3 | V |

18 From the **Sweep type** list, choose **All combinations**.

19 In the **Home** toolbar, click **Compute**.

### ADD STUDY

1 In the **Home** 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>Stationary**.

4 Click **Add Study** in the window toolbar.

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

### INCOMPLETE IONIZATION: V_B SWEEP, V_C=3 V, V_E=0 V

1 In the **Model Builder** window, click **Study 6**.

2 In the **Settings** window for **Study**, type `Incomplete Ionization: V_B Sweep, V_C=3 V, V_E=0 V` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

1 In the **Model Builder** window, under **Incomplete Ionization: V_B Sweep, V_C=3 V, V_E=0 V** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 In the table, clear the **Solve for** check box for **Heat Transfer in Solids (ht)**.

4 Locate the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

5 From the **Method** list, choose **Solution**.

6 From the **Study** list, choose **Incomplete Ionization: V_C Sweep, V_B=0 V, V_E=0 V, Stationary**.

7 Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

8 Click **Add**.

9 In the table, enter the following settings:

| Parameter name | Parameter value list | Parameter unit |
|---|---|---|
| V_B (Applied voltage: base) | `range(0.4,0.1,0.7) range(0.8,0.05,1.1)` | V |

10 In the **Home** toolbar, click **Compute**.

11 Right-click **Incomplete Ionization: V_B Sweep, V_C=3 V, V_E=0 V>Step 1: Stationary** and choose **Copy**.

### ADD STUDY

1 In the **Home** 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 **Empty Study**.

4 Click **Add Study** in the window toolbar.

### FULL THERMAL COUPLING: V_B SWEEP, V_C=3 V, V_E=0 V

1 In the **Settings** window for **Study**, type `Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

3 Right-click **Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V** and choose **Paste Stationary**.

1 In the **Model Builder** window, under **Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 In the table, select the **Solve for** check box for **Heat Transfer in Solids (ht)**.

4 In the **Home** toolbar, click **Compute**.

Amend the Gummel Plot graph to show the results from this model. The dataset used for the existing Global plot is set to the solution from the Thermal initialization study and a second Global plot is added to show the data from the fully coupled solution.

## RESULTS

### *Global 1*

1 In the **Model Builder** window, expand the **Results>Gummel Plot, I_C and I_B as a function of V_BE** node, then click **Global 1**.

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

3 From the **Dataset** list, choose **Incomplete Ionization: V_B Sweep, V_C=3 V, V_E=0 V/ Solution 6 (sol6)**.

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

| Expression | Unit | Description |
|---|---|---|
| `abs(semi.IO_3)` | A | Collector Current, I_C - Uniform temperature |
| `abs(semi.IO_2)` | A | Base Current, I_B - Uniform temperature |

5 Right-click **Global 1** and choose **Duplicate**.

### *Global 2*

1 In the **Model Builder** window, click **Global 2**.

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

3 From the **Dataset** list, choose **Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V/ Solution 7 (sol7)**.

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

| Expression | Unit | Description |
|---|---|---|
| `abs(semi.IO_3)` | A | `Collector Current, I_C - Thermal coupling` |
| `abs(semi.IO_2)` | A | `Base Current, I_B - Thermal coupling` |

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

**6** In the **Expression** text field, type `V_B`.

**7** Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

### *Gummel Plot, I_C and I_B as a function of V_BE*

**1** In the **Model Builder** window, click **Gummel Plot, I_C and I_B as a function of V_BE**.

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

**3** From the **Dataset** list, choose **None**.

**4** Locate the **Legend** section. From the **Position** list, choose **Lower right**.

**5** In the **Gummel Plot, I_C and I_B as a function of V_BE** toolbar, click **Plot**.

Amend the Current Gain graph in a similar way.

### *Global 1*

**1** In the **Model Builder** window, expand the **Results>Current Gain** node, then click **Global 1**.

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

**3** From the **Dataset** list, choose **Incomplete Ionization: V_B Sweep, V_C=3 V, V_E=0 V/Solution 6 (sol6)**.

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

| Expression | Unit | Description |
|---|---|---|
| `abs(semi.IO_3/semi.IO_2)` | 1 | `Gain (I_C/I_B) - Uniform temperature` |

**5** Right-click **Global 1** and choose **Duplicate**.

### *Global 2*

**1** In the **Model Builder** window, click **Global 2**.

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

**3** From the **Dataset** list, choose **Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V/Solution 7 (sol7)**.

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

| Expression | Unit | Description |
|---|---|---|
| `abs(semi.IO_3/semi.IO_2)` | 1 | `Gain (I_C/I_B) - Thermal coupling` |

5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

### *Current Gain*

1 In the **Model Builder** window, click **Current Gain**.

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

3 From the **Position** list, choose **Lower left**.

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

Note that, because of the coupling, the gain curve is more susceptible to numerical fluctuations than the previous curve. This effect could be lessened by reducing the solver absolute tolerance, however this significantly increases the time required to solve the model.

Create a mirrored dataset to represent the entire bipolar transistor (recall that, due to symmetry, only one half of the device is modeled).

### *Mirror 2D 1*

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 2D**.

2 In the **Settings** window for **Mirror 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Full Thermal Coupling: V_B Sweep, V_C=3 V, V_E=0 V/ Solution 7 (sol7)**.

Plot the total heat source from the Semiconductor Interface.

### *Semiconductor Heat Source*

1 In the **Results** toolbar, click **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Semiconductor Heat Source` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 1**.

### *Surface 1*

1 Right-click **Semiconductor Heat Source** and choose **Surface**.

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

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

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Thermal>ThermalDark** in the tree.

6 Click **OK**.

7 In the **Settings** window for **Surface**, click to expand the **Range** section.

8 Select the **Manual color range** check box.

9 In the **Maximum** text field, type `1e17`.

10 In the **Minimum** text field, type `-1e16`.

11 Click to expand the **Quality** section. From the **Resolution** list, choose **No refinement**.

12 From the **Smoothing** list, choose **Everywhere**.

13 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

14 In the **Title** text area, type `Semiconductor Heating`.

15 In the **Semiconductor Heat Source** toolbar, click **Plot**.

16 Click the **Zoom Extents** button in the **Graphics** toolbar.

Notice how the heating is most intense around the base-collector junction directly between the emitter and collector contact. This is to be expected, as the majority of the current flows between these two contacts and the base-collector junction causes a region of higher electrical resistance than the surrounding bulk material.

Plot the temperature distribution and the resulting heat flux. Also plot the voltage and the resulting electron and hole currents. Both plots are shown in the same plot group, with the voltage data offset in the *y* direction using a deformation.

*Temperature and Voltage*

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Temperature and Voltage` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 1**.

*Temperature*

1 Right-click **Temperature and Voltage** and choose **Surface**.

2 In the **Settings** window for **Surface**, type `Temperature` in the **Label** text field.

3 Locate the **Coloring and Style** section. Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Thermal>ThermalDark** in the tree.

5 Click **OK**.

*Heat Flux*

1 In the **Model Builder** window, right-click **Temperature and Voltage** and choose **Arrow Surface**.
2 In the **Settings** window for **Arrow Surface**, type `Heat Flux` in the **Label** text field.
3 Locate the **Coloring and Style** section. From the **Arrow length** list, choose **Logarithmic**.
4 From the **Color** list, choose **Green**.

*Voltage*

1 Right-click **Temperature and Voltage** and choose **Surface**.
2 In the **Settings** window for **Surface**, type `Voltage` in the **Label** text field.
3 Locate the **Expression** section. In the **Expression** text field, type `V`.
4 Locate the **Quality** section. From the **Resolution** list, choose **No refinement**.
5 From the **Smoothing** list, choose **Everywhere**.

*Deformation 1*

1 Right-click **Voltage** and choose **Deformation**.
2 In the **Settings** window for **Deformation**, locate the **Expression** section.
3 In the **x-component** text field, type `0`.
4 In the **y-component** text field, type `1.1`.
5 Locate the **Scale** section.
6 Select the **Scale factor** check box. In the associated text field, type `1`.
7 In the **Temperature and Voltage** toolbar, click **Plot**.
8 Click the **Zoom Extents** button in the **Graphics** toolbar.

*Electron Current*

1 In the **Model Builder** window, right-click **Temperature and Voltage** and choose **Arrow Surface**.
2 In the **Settings** window for **Arrow Surface**, type `Electron Current` in the **Label** text field.
3 Locate the **Expression** section. In the **x-component** text field, type `semi.JnX`.
4 In the **y-component** text field, type `semi.JnY`.
5 Locate the **Coloring and Style** section. From the **Arrow length** list, choose **Logarithmic**.
6 From the **Color** list, choose **Black**.

*Deformation 1*

1 Right-click **Electron Current** and choose **Deformation**.

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

3 In the **x-component** text field, type `0`.

4 In the **y-component** text field, type `1.1`.

5 Locate the **Scale** section.

6 Select the **Scale factor** check box. In the associated text field, type `1`.

### *Electron Current*

In the **Model Builder** window, right-click **Electron Current** and choose **Duplicate**.

### *Hole Current*

1 In the **Model Builder** window, under **Results>Temperature and Voltage** click **Electron Current 1**.

2 In the **Settings** window for **Arrow Surface**, type `Hole Current` in the **Label** text field.

3 Locate the **Expression** section. In the **x-component** text field, type `semi.JpX`.

4 In the **y-component** text field, type `semi.JpY`.

5 Locate the **Coloring and Style** section. From the **Color** list, choose **White**.

### *Temperature and Voltage*

1 In the **Model Builder** window, click **Temperature and Voltage**.

2 In the **Settings** window for **2D Plot Group**, click to expand the **Title** section.

3 From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Temperature and Voltage Distributions`.

5 Locate the **Color Legend** section. Select the **Show units** check box.

6 From the **Position** list, choose **Bottom**.

7 In the **Temperature and Voltage** toolbar, click **Plot**.

8 Click the **Zoom Extents** button in the **Graphics** toolbar.

The value of V_B for which the results are plotted can be varied by clicking on the **Temperature and Voltage** node and changing the **Parameter value (V_B)** selection in the **Data** section. Try several different values of V_B. Notice how the peak temperature is always located around the base-collector junction. The fluxes, shown as arrow plots, also behave as expected: The heat flux is from the peak temperature at the base-collector junction toward the contacts, which are the only boundaries that allow heat transfer in this simple model; the hole current flows from the base to the emitter without entering the collector region, whilst the electron current flows predominantly between the collector and emitter.