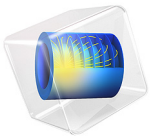
Created in COMSOL Multiphysics 5.6



GaAs P-N Junction Infrared LED

This model simulates an LED that emits in the infrared part of the electromagnetic spectrum. The device structure is made up of a single p-n junction formed by a layer of p-type doping near the top surface of an otherwise n-type wafer. This kind of device geometry is simple and cheap to produce and similar LEDs are found in many household applications, for example, the IR emitters in TV remote controls. In this model the Optical Transition feature is used to calculate the electroluminescence from the device. The electronic properties are computed and the efficiency of the light production is assessed. Also, by visualizing the spacial distribution of the radiative recombination it is possible to make design suggestions to maximize the total efficiency of the output light.

Introduction

Infrared LEDs are widely used in many optoelectronic applications, but perhaps the most familiar in a household setting is for use in remote controls. Although more efficient light production can be achieved using complicated device structures, simple p-n junctions are still used for many IR emitters due to their low cost and ease of manufacture.

In this model, a simple p-n junction infrared LED is modeled. The device geometry is cylindrically symmetric, which enables a 3D visualization of the results with a much shorter computation time than would be required for a full 3D model. This model shows an example of how to use the Semiconductor Initialization study to create a refined mesh in cylindrical geometry, this is useful because this study step automatically refines the mesh around p-n junction. A second Stationary study is then used to sweep the bias applied to the device, allowing the current-voltage curve and optical emission characteristics to be calculated.

Model Definition

The device is made using 60 μm diameter circular chip of GaAs. Although, due to the crystalline nature of semiconductor materials, actual LED chips are likely to be fabricated using rectangular chips, only the circular active region formed by the p- and n-type doping is included in this simulation. This is in order to allow cylindrical symmetry, which considerably reduces computation time. Because the r=0 axis is an axis of symmetry, the device geometry is represented by a 30 μm wide rectangle with a thickness of 10 μm. The bottom 7.5 μm of the device are n-doped and the top 2.5 μm are p-doped. A rectangular trench has been etched down to the n-type layer at the right hand side of the domain to allow an electrical contact to be deposited onto the n-type side of the p-n junction, creating a ring of metal around the edge of the device. The p-type contact is deposited

directly on the top surface in the center of the device, creating a metal disk. This configuration is shown in Figure 1.

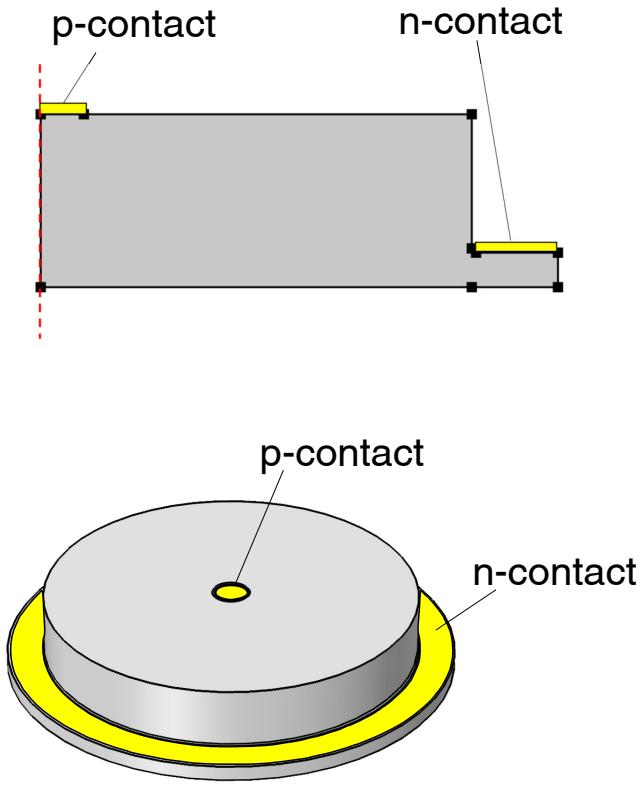


Figure 1: Device geometry. Top: Geometry view showing one half of a 2D cross section through the diameter of the device. The axis of symmetry is shown as a red dashed line. Bottom: The 3D device geometry.

An **Optical Transitions** feature is added to the domain to allow the electroluminescence to be calculated. This is achieved by clearing the **Stimulated Emission** check box within the feature, such that only the **Spontaneous Emission** will be calculated. In the absence of any optical excitement from an incident electromagnetic field the spontaneous emission will be the electroluminescence due to the carrier dynamics of the injected current.

An **Auger Recombination** feature has been added to include a nonradiative recombination mechanism. This is only one possible nonradiative recombination mechanism, in reality a variety of other processes may be present, such as lattice/impurity scattering and phonon interactions. However, for the purpose of this demonstration model Auger recombination

is sufficient to capture the important behavior that the efficiency of the radiative emission drastically reduces with increased current densities.

The model uses two studies. The first study is a Semiconductor Initialization study, which is used to automatically refine the mesh around the gradient of the dopant concentration. This is useful because the refined mesh is denser around the p-n junctions, which is where a smaller resolution is required.

The second study sweeps the voltage bias across the device from 0 V to 1.5 V. The current-voltage curve is plotted, to show that the device is indeed a diode, and the emission rate throughout the device is calculated.

Results and Discussion

The default mesh, with the size set to **Fine**, is shown in Figure 2. The refined mesh, output by the first study, is shown in Figure 3 and the doping is shown in Figure 4. From these two figures it can be seen that the mesh has been refined in region of the p-n junction as desired.

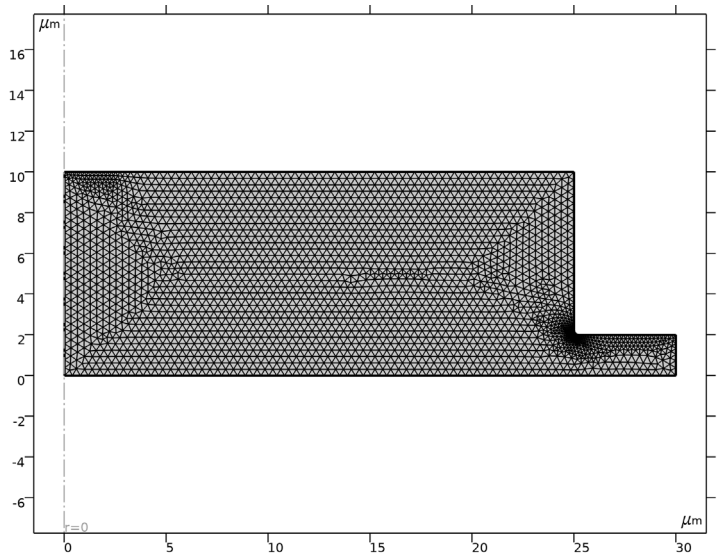


Figure 2: Default physics induced mesh after the size node has been set to Finer.

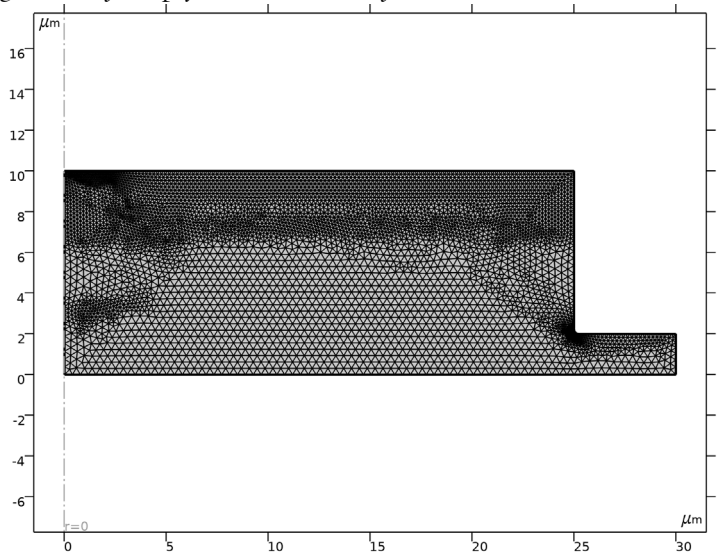


Figure 3: Refined mesh output by the Semiconductor Initialization study step in the first study. The mesh density is increased in the p-n junction region.

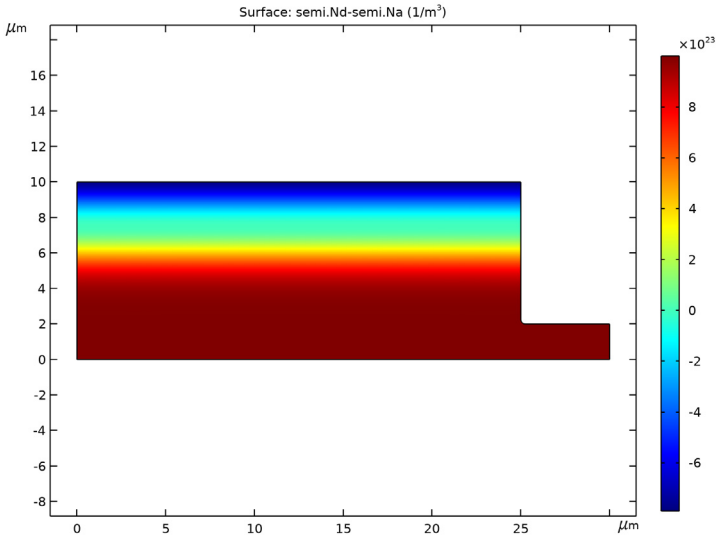


Figure 4: Signed dopant concentration shows the p-type surface layer in blue and the n-type region in red. The doping gradually transitions from n-type to p-type over a range of a few μm to create a wide region in which light emission can occur.

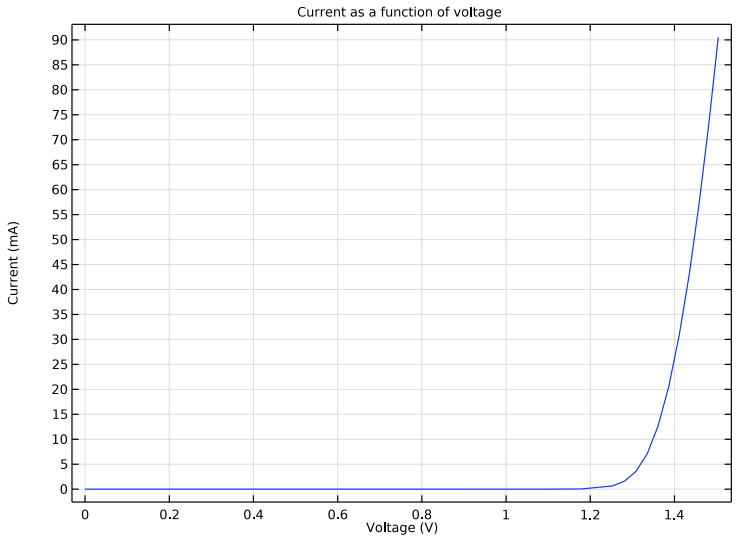


Figure 5: Current as a function of voltage showing diode behavior with a turn-on voltage just above 1.2 V.

Figure 5 shows the current as a function of the voltage bias. The device is clearly a diode, with a turn-on voltage of around 1.2 V.

Figure 6 and Figure 7 show the emission rate throughout the device for a voltage of 1.5 V and 1.2 V. At the larger bias the emission has become concentrated toward the center of the device.

Figure 8 shows the total rate of emission, integrated over the entire domain of the device, as a function of the current. The sublinear curve is characteristic of a LED droop, a phenomenon where the efficiency of LEDs decreases with increased current density. This reduction in efficiency is even more apparent in Figure 9, which shows the Internal Quantum Efficiency (IQE) as a function of the current. The IQE is the ratio of the emission rate to the carrier injection rate, and gives the proportion of injected carriers which radiatively recombine to emit light. Initially the IQE is very low, as no current flows, however as soon as current begins to flow the IQE is initially quite high. As the current increases the IQE drops drastically to plateau at a value of 0.075. In this model, Auger recombination has been included as a nonradiative recombination mechanism. The rate of Auger recombination is proportional to the cube of the carrier density, whilst the radiative emission rate is proportional to the square of the carrier density. This means that as the carrier density is increased by the increasing current a larger proportion of the carriers recombine via the Auger mechanism, leading to the observed drastic reduction in IQE.

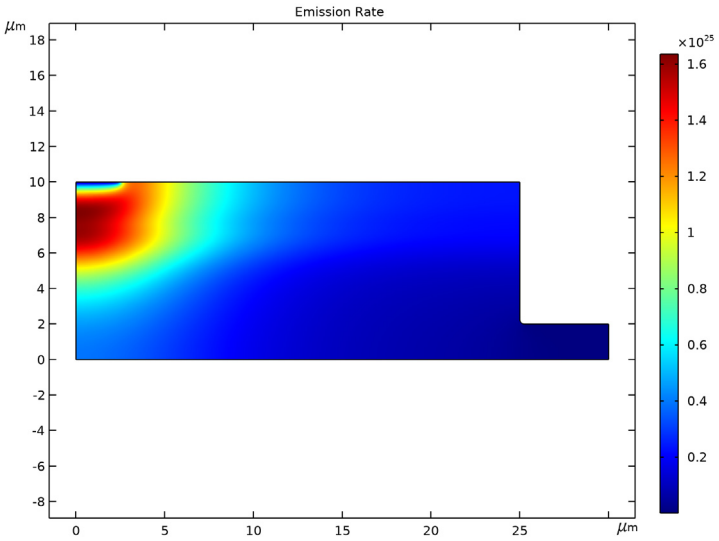


Figure 6: Emission rate throughout the device at a voltage bias of 1.5 V.

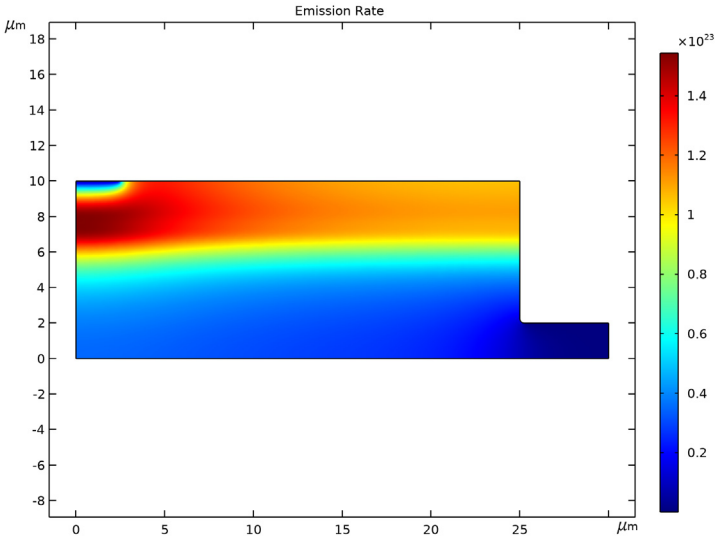


Figure 7: Emission rate throughout the device at a voltage bias of 1.2 V.

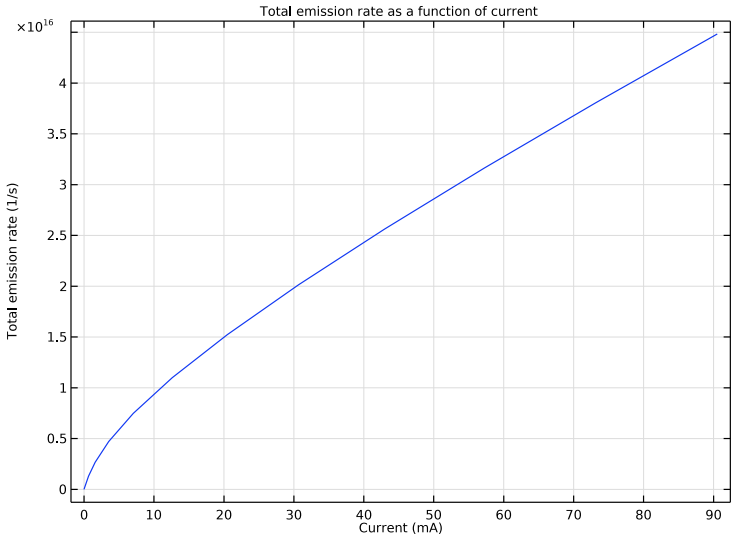


Figure 8: Total emission rate as a function of current. The sublinear curve is indicative of LED droop.

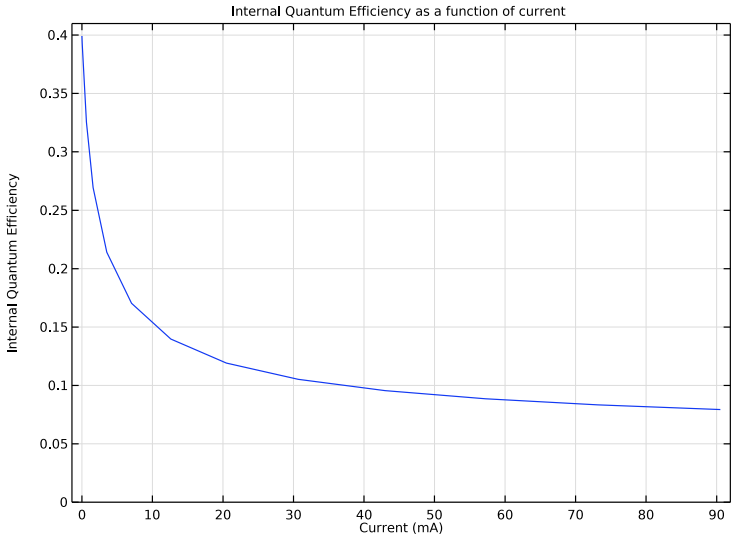


Figure 9: Internal Quantum Efficiency as a function of current. The drastic drop in efficiency corresponds with the sublinear increase in total emission.

The IQE is only a measure of the efficiency of the radiative recombination within the device. In order to assess the actual efficiency of the device as a light source other considerations need to be included. Specifically, it is important to consider where within the device the light is emitted from. As the p-contact on the top surface is opaque, emission underneath the p-contact may not contribute to the emitted light intensity from the device. From Figure 6 and Figure 7, which show the spacial distribution of the radiative emission, it can be seen that the emission becomes concentrated toward the center of the device with increasing voltages. This is more apparent in Figure 10, which shows a 3D visualization of the data from Figure 6. The IQE, shown in Figure 9, indicates that efficient operation of the LED would occur with low currents below 5 mA. This would be the desirable range of operation current for a remote control device, where intensity of the emission is not important compared to increased battery lifetime. These currents corresponds to voltages between 1.2 and 1.3 V and so the emission will be distributed similar to that shown in Figure 7, where the emission occurs throughout the entire p-type layer. For these voltages the position of the p-contact does not block most of the light emission from leaving the device. However, if the LED was to be used in a situation where total brightness was more important than efficiency it could be desirable to drive the device with a larger current. This could be the case if the LED was providing illumination for an infrared night-vision security camera, for example. In this case, although increasing the current increases the total rate of emission, the localization of the emission to the region underneath the p-contact could significantly reduce the total light emitted. For such a scenario it would be advantageous to change the material used for the p-contact so that it was transparent to IR light, or perhaps amened the geometry of the p-contact. For example, a ring shaped p-contact, which would allow the brightest emission on the central axis to leave the device, could be considered.

This example highlights the importance of simulation tools when designing optoelectronic semiconductor devices, as it is much cheaper to simulate several designs before committing to manufacture a device.

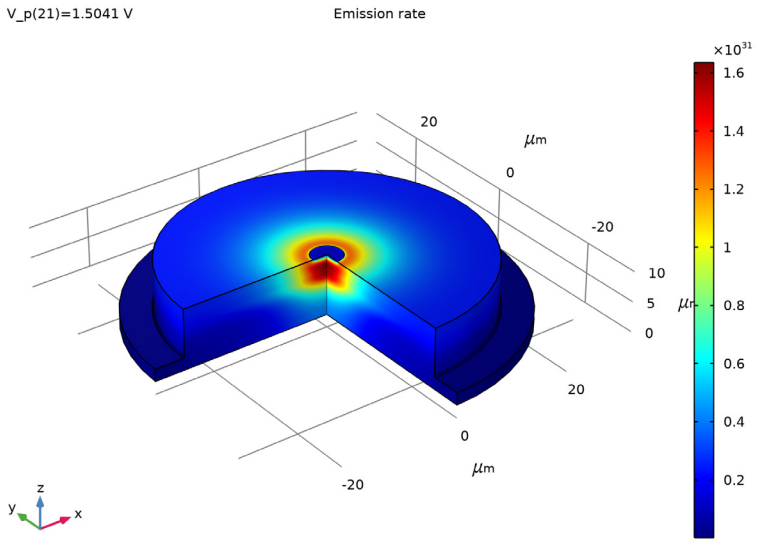


Figure 10: Emission rate throughout the device for an applied voltage of 1.5 V. This figure is a 3D visualization of the data in Figure 6.

Application Library path: `Semiconductor_Module/Photonic_Devices_and_Sensors/gaas_pn_junction_infrared_led_diode`

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 **Semiconductor>Semiconductor (semi)**.

3 Click **Add**.

4 Click **Study**.

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

6 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
V_n	0[V]	0 V	n voltage
V_p	1.5[V]	1.5 V	p voltage
w_dom	25[um]	2.5E-5 m	Domain width
h_dom	10[um]	1E-5 m	Domain height
w_con_n	w_dom/5	5E-6 m	Width of n contact
h_con_n	h_dom/5	2E-6 m	Height of n contact
w_con_p	w_dom/10	2.5E-6 m	Width of p contact
h_p	h_dom/4	2.5E-6 m	Height of surface p-type layer
r_fill	0.25[um]	2.5E-7 m	Fillet radius

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**.

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_dom.

4 In the **Height** text field, type h_dom.

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_con_n`.

4 In the **Height** text field, type `h_con_n`.

5 Locate the **Position** section. In the **r** text field, type `w_dom`.

Union 1 (uni1)

1 In the **Geometry** toolbar, click  **Booleans and Partitions** and choose **Union**.

2 Click in the **Graphics** window and then press Ctrl+A to select both objects.

3 In the **Settings** window for **Union**, locate the **Union** section.

4 Clear the **Keep interior boundaries** check box.

Polygon 1 (pol1)

1 In the **Geometry** toolbar, click  **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 In the table, enter the following settings:

r (µm)	z (µm)
0	h_dom
w_con_p	h_dom

Fillet 1 (fil1)

1 In the **Geometry** toolbar, click  **Fillet**.

2 On the object **uni1**, select Point 4 only.

It might be easier to select the correct point by using the **Selection List** window. To open this window, in the **Home** toolbar click **Windows** and choose **Selection List**. (If you are running the cross-platform desktop, you find **Windows** in the main menu.)

3 In the **Settings** window for **Fillet**, locate the **Radius** section.

4 In the **Radius** text field, type `r_fill`.

5 Click **Build All Objects**.

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

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>GaAs - Gallium Arsenide**.

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

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

SEMICONDUCTOR (SEMI)

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

2 In the **Settings** window for **Semiconductor**, locate the **Model Properties** section.

3 From the **Carrier statistics** list, choose **Fermi-Dirac**.

p Doping

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

2 In the **Settings** window for **Analytic Doping Model**, type `p Doping` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **All domains**.

4 Locate the **Distribution** section. From the list, choose **Box**.

5 Locate the **Impurity** section. In the N_{A0} text field, type `1e18[1/cm^3]`.

6 Locate the **Uniform Region** section. Specify the r_0 vector as

`0[um]`	R
`h_dom-h_p`	Z

7 In the W text field, type `w_dom`.

8 In the H text field, type `h_p`.

9 Locate the **Profile** section. From the **Specify profile length scale** list, choose **Decay length**.

10 In the l_d text field, type `2[um]`.

n Doping

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

2 In the **Settings** window for **Analytic Doping Model**, type `n Doping` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **All domains**.

4 Locate the **Distribution** section. From the list, choose **Box**.

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

6 In the N_{D0} text field, type `1e18[1/cm^3]`.

7 Locate the **Uniform Region** section. In the W text field, type `w_dom+w_con_n`.

8 In the H text field, type `h_dom-h_p`.

9 Locate the **Profile** section. From the **Specify profile length scale** list, choose **Decay length**.

10 In the l_d text field, type `2[um]`.

p Contact

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

2 In the **Settings** window for **Metal Contact**, type `p Contact` in the **Label** text field.

3 Select Boundary 3 only.

4 Locate the **Terminal** section. In the V_0 text field, type `V_p`.

n Contact

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

2 In the **Settings** window for **Metal Contact**, type `n Contact` in the **Label** text field.

3 Select Boundary 7 only.

4 Locate the **Terminal** section. In the V_0 text field, type `V_n`.

Optical Transitions 1

1 In the **Physics** toolbar, click **Domains** and choose **Optical Transitions**.

2 Select Domain 1 only.

3 In the **Settings** window for **Optical Transitions**, locate the **Optical Transitions** section.

4 Clear the **Stimulated absorption and emission** check box.

Auger Recombination 1

1 In the **Physics** toolbar, click **Domains** and choose **Auger Recombination**.

2 Select Domain 1 only.

MATERIALS

GaAs - Gallium Arsenide (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **GaAs - Gallium Arsenide (mat1)**.

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Auger recombination factor, electrons	Cn	`1e-31[cm^6/s]`	m^6/s	Auger recombination
Auger recombination factor, holes	Cp	`1e-31[cm^6/s]`	m^6/s	Auger recombination

Add a nonlocal integration coupling for use in postprocessing the results.

DEFINITIONS (COMP1)

Integration 1 (intop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 Select Domain 1 only.

Use a semiconductor initialization study to refine the mesh.

STUDY 1: MESH REFINEMENT

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

2 In the **Settings** window for **Study**, type `Study 1: Mesh Refinement` in the **Label** text field.

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

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

COMPONENT 1 (COMP1)

Compare the two meshes, note that the refined mesh is denser around the p-n junction.

MESH 1

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

2 Right-click **Component 1 (comp1)>Meshes>Mesh 1** and choose **Build All**.

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

LEVEL 1 ADAPTED MESH 1

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

Before adding and configuring the main voltage sweep study, confirm the doping profile using a 2D surface plot.

RESULTS

Doping

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

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

Surface 1

1 Right-click **Doping** and choose **Surface**.

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

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

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

The doping should look like Figure 4.

Add a study to perform the voltage sweep.

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.

STUDY 2: VOLTAGE SWEEP

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

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

3 Clear the **Generate default plots** check box.

4 In the **Label** text field, type `Study 2: Voltage Sweep`.

Step 1: Stationary

1 In the **Model Builder** window, under **Study 2: Voltage Sweep** click **Step 1: 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
V_p (p voltage)	`log(range(1,0.25,3.5))` `log(range(3.6,0.1,4.5))`	V

Solution 5 (sol5)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 5 (sol5)** node.

3 Right-click **Stationary Solver 1** and choose **Segregated**.

4 In the **Model Builder** window, expand the **Study 2: Voltage Sweep>Solver Configurations> Solution 5 (sol5)>Stationary Solver 1>Segregated 1** node, then click **Segregated Step**.

5 In the **Settings** window for **Segregated Step**, click to expand the **Method and Termination** section.

6 From the **Nonlinear method** list, choose **Automatic (Newton)**.

7 In the **Model Builder** window, right-click **Segregated 1** and choose **Lower Limit**.

8 In the **Settings** window for **Lower Limit**, locate the **Lower Limit** section.

9 In the **Lower limits (field variables)** text field, type `comp1.Ne 1 comp1.Ph 1`.

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

Plot the current-voltage curve to see that the device behaves as a diode.

RESULTS

Current vs. Voltage

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Voltage Sweep/ Solution 5 (sol5)**.

4 Locate the **Plot Settings** section. Select the **x-axis label** check box.

5 In the associated text field, type `Voltage (V)`.

6 Select the **y-axis label** check box.

7 In the associated text field, type `Current (mA)`.

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

9 In the **Title** text area, type `Current as a function of voltage`.

Global 1

1 Right-click **Current vs. Voltage** and choose **Global**.

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`	`mA`	`Terminal current`

4 Click to expand the **Legends** section. Clear the **Show legends** check box.

5 In the **Current vs. Voltage** toolbar, click **Plot**.

Plot the electroluminescence emission rate throughout the device, the effects of varying the voltage can be seen by changing the value of **V_p** for which the results are plotted. At voltages just above the turn on voltage the emission is spread out radially but it becomes more concentrated under the central p-contact as the voltage is increased.

Emission Rate

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Voltage Sweep/ Solution 5 (sol5)**.

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

5 In the **Title** text area, type `Emission Rate`.

Surface 1

1 Right-click **Emission Rate** and choose **Surface**.

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

3 In the **Expression** text field, type `semi.ot1.R_spon`.

4 In the **Unit** field, type `1/(cm^3*s)`.

5 In the **Emission Rate** toolbar, click **Plot**.

The default plot shows the case for **V_p=1.5V**. However, cycling through several values of **V_p** allows data for other values to be viewed. This is done by selecting the desired value from the list, for example:

Emission Rate

1 In the **Model Builder** window, click **Emission Rate**.

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

3 From the **Parameter value (V_p (V))** list, choose **1.2528**.

4 In the **Emission Rate** toolbar, click **Plot**.

The internal efficiency of the device can be assessed using two graphs, one that shows the total emission rate as a function of current and one that calculates the Internal Quantum Efficiency. The total emission rate can be plotted by using the integration operator to integrate the emission rate variable throughout the entire domain.

Emission Rate vs. Current

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Voltage Sweep/ Solution 5 (sol5)**.

4 Locate the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Total emission rate as a function of current`.

6 Locate the **Plot Settings** section. Select the **x-axis label** check box.

7 In the associated text field, type `Current (mA)`.

8 Select the **y-axis label** check box.

9 In the associated text field, type `Total emission rate (1/s)`.

Global 1

1 Right-click **Emission Rate vs. Current** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`intop1(semi.ot1.R_spon)`	`1/s`	

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

5 In the **Expression** text field, type `semi.IO_1`.

6 From the **Unit** list, choose **mA**.

7 Locate the **Legends** section. Clear the **Show legends** check box.

8 In the **Emission Rate vs. Current** toolbar, click **Plot**.

The Internal Quantum Efficiency (IQE) is the proportion of injected carriers which radiatively recombine within the device. It is found by dividing the total rate of radiative transitions, calculated using the integration operator as in the previous graph, by the rate at which carriers are injected, calculated by dividing the current at the p-contact by the electron charge.

Internal Quantum Efficiency

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Voltage Sweep/ Solution 5 (sol5)**.

4 Locate the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Internal Quantum Efficiency as a function of current`.

6 Locate the **Plot Settings** section. Select the **x-axis label** check box.

7 In the associated text field, type `Current (mA)`.

8 Select the **y-axis label** check box.

9 In the associated text field, type `Internal Quantum Efficiency`.

Remove the first few points of the voltage sweep result where the current and emission rate are too small to be computed accurately.

10 Locate the **Data** section. From the **Parameter selection (V_p)** list, choose **Manual**.

11 Click **Range**.

12 In the **Integer Range** dialog box, type `5` in the **Start** text field.

13 In the **Stop** text field, type `21`.

14 Click **Replace**.

Global 1

1 Right-click **Internal Quantum Efficiency** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`intop1(semi.ot1.R_spon)/(semi.IO_1/e_const)`	1	

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

5 In the **Expression** text field, type `semi.IO_1`.

6 From the **Unit** list, choose **mA**.

7 Locate the **Legends** section. Clear the **Show legends** check box.

Internal Quantum Efficiency

1 In the **Model Builder** window, click **Internal Quantum Efficiency**.

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 `0`.

5 In the **Internal Quantum Efficiency** toolbar, click **Plot**.

Finally, the data can be visualized in 3D due to the cylindrical symmetry. To do this, create a new dataset to hold the revolved data.

Revolution 2D 1

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

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

3 From the **Dataset** list, choose **Study 2: Voltage Sweep/Solution 5 (sol5)**.

4 Click to expand the **Revolution Layers** section. In the **Start angle** text field, type `270`.

5 In the **Revolution angle** text field, type `270`.

Now a 3D plot group can be used to visualize the results. By default the data is plotted for **V_p = 1.5 V**, however this can be changed in the same way as for the previous graphs.

Emission Rate 3D

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Emission Rate 3D` in the **Label** text field.

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

4 In the **Title** text area, type `Emission rate`.

Volume 1

1 Right-click **Emission Rate 3D** and choose **Volume**.

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

3 In the **Expression** text field, type `semi.ot1.R_spon`.

4 In the **Emission Rate 3D** toolbar, click **Plot**.

It is important to note that the Internal Quantum Efficiency is a metric of the efficiency of the radiative recombination within the device, and not of the actual efficiency of the output light. External factors, such as the wavelength and direction of the emission must be included when assessing the total efficiency of the device. For example, if emission is localized underneath the top p-contact then the device may not function well as the light cannot pass through the opaque metal contact.

This demonstrates both the importance of considering the entire device geometry when designing an optoelectronic device, as well as how COMSOL can be used to optimize designs. For example, for the simple device used in this model we can see from the Emission Rate versus Current graph that the total emission rate does not increase linearly with current. This is familiar behavior and is known as "LED droop". This results in the drastic drop of in efficiency with increasing current shown in the Internal Quantum Efficiency graph. However, we can also view the spacial distribution of the emission in the Emission Rate and Emission Rate 3D graphs. In these plots we see that at higher currents the emission becomes concentrated underneath the surface p-contact. This allows design changes to be made if required. For example, if efficiency was not a major concern and instead the goal was to have a high brightness then running the device with a large current could be acceptable. However, this would require either a transparent p-contact or changes to the p-contact geometry to prevent the emission from being wasted on the underside of the contact. One option which you can try is to change the p-contact geometry such that it forms a ring, if you do this and re-solve the simulation you will see that this geometry would be better for a high-brightness design.