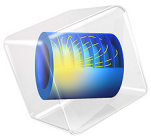
Created in COMSOL Multiphysics 5.6



GaAs PIN Photodiode

This model demonstrates how to use the Semiconductor Optoelectronics, Frequency Domain interface. This interface combines the Semiconductor interface with the Electromagnetic Waves, Frequency Domain interface, and is suitable for modeling direct band-gap optoelectronic semiconductor devices. A simple PIN photodiode device is modeled in this example.

Introduction

Photodiodes are semiconductor devices that convert incident light into a current. Incident photons with energy larger than the band gap can be absorbed by interacting with an electron in the valence band and promoting it across the band gap into the conduction band. Thus, each absorbed photon creates a hole in the valence band and an electron in the conduction band. If the device is appropriately designed, these extra photo-generated carriers can be separated and collected, resulting in a current from the device terminals.

Model Definition

This model simulates a simple rectangular GaAs PIN structure. The geometry and doping profile are shown in Figure 1, along with the energy level diagram for the device. The PIN structure is effective for photodiode devices due to the sloped nature of the conduction and valence bands, which have highest energy at the p-contact and lowest at the n-contact. When a photon is absorbed creating an electron and hole, the electron is swept toward the n-contact whilst the hole is swept in the opposite direction toward the p-contact. The p-contact is grounded and the n-contact is set to 2 V, and thus the device operates under reverse bias. This mode of operation is sometimes referred to as photoconductive mode, as the absorbed light is being used to generate a current. For a given wavelength of incident light, the current is linearly proportional to the irradiance. The reverse bias also increases both the slope of the energy levels and the width of the depletion layer, resulting in a reduced response time. However, this comes at the expense of an increased dark current, as more current flows in the absence of light due to the bias.

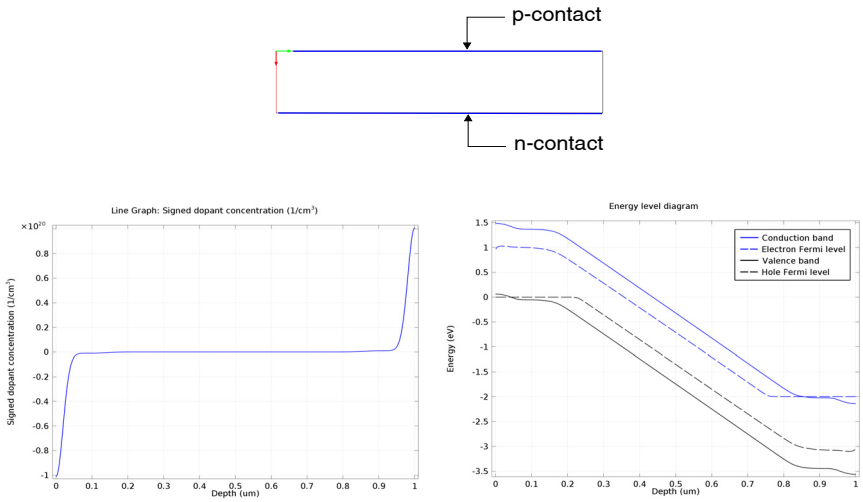


Figure 1: Device geometry, doping, and energy level diagram. Top pane: the device geometry is a simple rectangle with a p-contact on the top surface and an n-contact on the bottom surface. Lower-left pane: Signed dopant concentration taken along the red arrow indicated in the geometry diagram. Negative values correspond to net p-type doping and positive values correspond to net n-type doping. The PIN dopant profile is clearly visible, with highly doped p and n-type layers adjacent to the top and bottom surface, respectively. There is a wide intrinsic (undoped) region between approximately 0.15 and 0.85 μm from the surface. Lower-right pane: The resulting energy level diagram, taken along the red arrow indicated in the geometry diagram, showing the band edges and the quasi-Fermi levels. In the intrinsic region the quasi-Fermi electron level is below the conduction band and the quasi-Fermi hole level is above the valence band. This means that the conduction band is empty whilst the valence band is full, making this region well suited to absorbing photons.

The Semiconductor interface is used to define the doping and the electrical contacts. The Electromagnetic Waves, Frequency Domain interface is used to define the incident electromagnetic radiation. The Optical Transitions node configures the coupling between the two interfaces. The model is set to compute the absorption using a direct band-gap model which assumes parabolic bands, this is a reasonable approximation for the GaAs material used for this device. Both spontaneous and stimulated emission are computed, using the spontaneous lifetime of electron-hole pairs within the material to calculate the interaction strength between states in the conduction and valence bands with the same k-vector value. The frequency domain is represented using an extra dimension, which allows some properties to be visualized as a function of the photon energy. This is used to allow the spontaneous emission spectra to be plotted. The absorption of photons adds a generation term for electrons and holes to the carrier continuity equations, as well as

inducing a change in the susceptibility of the material. The two interfaces are coupled automatically via the Semiconductor-Electromagnetic Waves Coupling feature under the Multiphysics node in the model builder tree. This feature sets the electric field from the Electromagnetic Waves, Frequency Domain interface as the input for the absorption in the Semiconductor interface; whilst also amending the susceptibility in the Electromagnetic Waves, Frequency Domain interface to reflect the changes calculated in the Semiconductor interface. For a detailed guide on the coupling effects refer to the *Semiconductor Module User's Guide*.

In this model, a wavelength sweep is performed where the power of the incident light is held constant whilst the wavelength is varied from 875 nm to 475 nm. The band-gap of the GaAs material is 1.424 eV, which corresponds to a wavelength of ~872 nm. Therefore the incident photon energy is swept from just below the band-gap energy up to the middle of the blue range of the visible spectrum.

Results and Discussion

The current through the device per input optical power is plotted as a function of the incident photon wavelength in Figure 2. At the long wavelength end of the sweep there is not much current, which is to be expected as the longest wavelength has energy below the band gap and so should not be absorbed. As the wavelength is reduced, and thus the photon energy is increased, the current rapidly increases to a peak value of ~0.09 A/W at a wavelength of 725 nm before gradually reducing as the photon energy is further increased. This behavior can be explained by considering the parabolic shape of the conduction and valence bands and the rate of incident photons. The probability of absorbing a photon increases with increased photon energy, however as the incident power is constant the rate of photons decreases with increased photon energy. The rate of photon absorption depends on the product of the absorption probability and the rate of incident photons, leading to the current curve calculated by the model.

Some readers may be interested in checking the consistency between the input optical power and the output electrical current, in other words, the conservation of particles. As detailed in the Modeling Instructions, there are two factors to be considered: First, the out-of-plane thickness is fixed at 1 m for the wave optics interface, while it is set to 1 um for the semiconductor interface. Second, not all power is absorbed, as can be seen qualitatively in the next figure and can be evaluated quantitatively using global evaluations (see Modeling Instructions for the global evaluation).

Figure 3 shows the magnitude of the electric field throughout the device when the wavelength is set to 725 nm. As expected, the magnitude decreases as the wave traverses

the device. The change in magnitude appears to be approximately linear due to the 1 µm thickness of the device; if the absorbing region were thicker the exponential decay of the electric field magnitude would be more readily observed.

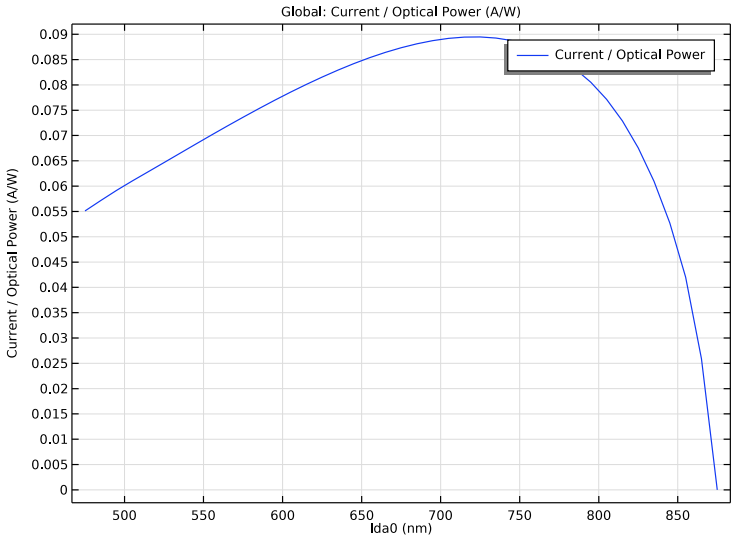


Figure 2: Current output per input optical power as a function of the incident wavelength.

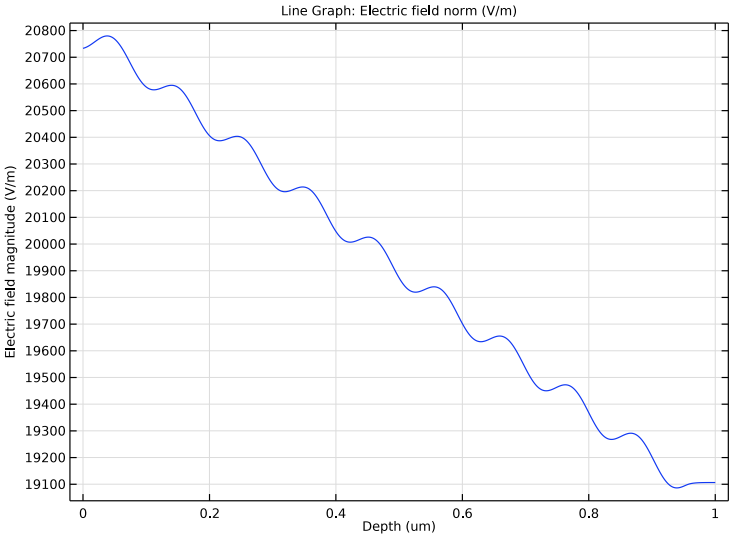


Figure 3: Magnitude of the electric field of the incident radiation throughout the device when the wavelength is set to 725 nm.

Figure 4 shows the spontaneous emission from the device when the incident wavelength was set to 725 nm. There is no emission with photon energies below the band-gap energy,

as expected. At the band-gap energy the emission abruptly begins, peaking with an emitted photon energy of ~1.505 eV which corresponds to a wavelength of 825 nm.

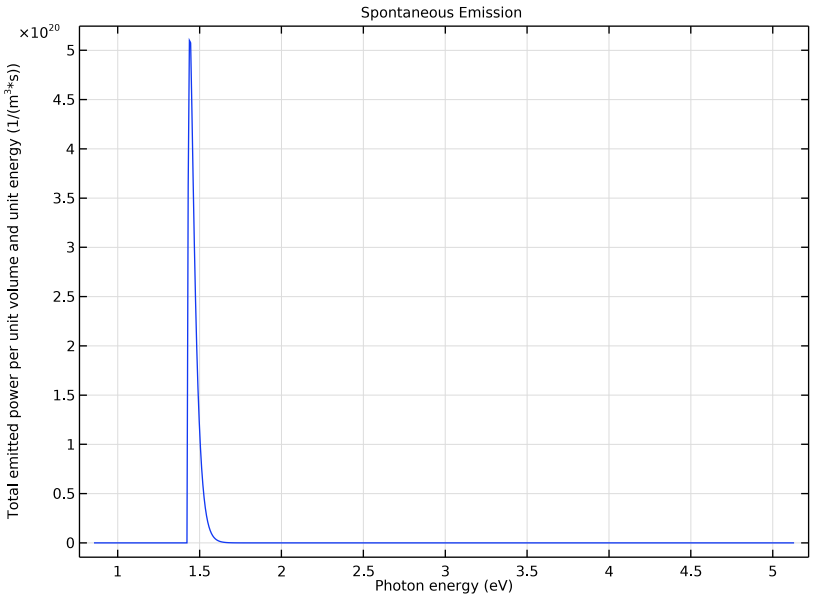


Figure 4: Spontaneous emission from the device when the incident wavelength is set to 725 nm.

Application Library path: `Semiconductor_Module/Photonic_Devices_and_Sensors/gaas_pin_photodiode`

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**.

2 In the **Select Physics** tree, select **Semiconductor>Semiconductor Optoelectronics, Frequency Domain**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Multiphysics>Frequency-Stationary**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

Input model parameters. Note in particular the parameters involving the out-of-plane thicknesses since this is a 2D model.

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
w_dom	5[um]	5E-6 m	Width
h_dom	1[um]	1E-6 m	Thickness
V_n	2[V]	2 V	n-contact voltage
V_p	0[V]	0 V	p-contact voltage
hbar0	h_const/(2*pi)	1.0546E-34 J·s	hbar without radians
lda0	870[nm]	8.7E-7 m	Incident wavelength
f0	c_const/lda0	3.4459E14 1/s	Incident frequency
omega0	2*pi*1[rad]*f0	2.1651E15 rad/s	Incident angular frequency
E_ph	f0*h_const	2.2833E-19 J	Incident photon energy
n0	3.5	3.5	Refractive index of GaAs (real component)
tau	2[ns]	2E-9 s	Spontaneous lifetime
d0	1[um]	1E-6 m	Out-of-plane thickness for the Semiconductor interface (the one for wave optics is fixed at 1 m)
Pin	10[uW]	1E-5 W	Incident power for out-of-plane thickness of d0 = 1 um

GEOMETRY 1

Create the model geometry. The length scale of um is appropriate and the geometry consists of a single rectangle. The physics of this model is 1D in nature with no variation in the horizontal direction. The reason why we use a 2D model is that there is no 1D wave optics interface.

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)

In the **Geometry** toolbar, click **Rectangle**.

Set the out-of-plane thickness for the semiconductor physics interface to `d0` = 1 um (the one for wave optics is hard-coded at 1 m). Switch to Fermi-Dirac carrier statistics, which is appropriate for the high doping concentrations used in this device.

SEMICONDUCTOR (SEMI)

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

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

3 In the *d* text field, type `d0`.

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

GEOMETRY 1

Rectangle 1 (r1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Rectangle 1 (r1)**.

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`.

5 Click **Build All Objects**.

Set up the doping, this is achieved with five doping features. Analytic Doping Model features are used to define the background doping and the main p and n sections of the device. Geometric Doping Models are used to create highly doped layers are the top and bottom of the device to increase the efficiency of the metal contacts.

Constant p doping

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

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

3 Select Domain 1 only.

4 Locate the **Impurity** section. In the N_{A0} text field, type `1e14[1/cm^3]`.

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 Select Domain 1 only.

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]`	X
`h_dom-0.1*h_dom`	Y

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

8 In the D text field, type `0.1*h_dom`.

9 Locate the **Profile** section. In the d_j text field, type `0.15*h_dom`.

10 From the N_b list, choose **Acceptor concentration (semi/adm1)**.

p+ Doping

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

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

3 Select Domain 1 only.

4 Locate the **Impurity** section. In the N_{A0} text field, type `1e20[1/cm^3]`.

5 Locate the **Profile** section. In the d_j text field, type `0.1*h_dom`.

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

Boundary Selection for Doping Profile 1

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

2 Select Boundary 3 only.

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 Select Domain 1 only.

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`.

8 In the D text field, type `0.1*h_dom`.

9 Locate the **Profile** section. In the d_j text field, type `0.15*h_dom`.

10 From the N_b list, choose **Acceptor concentration (semi/adm1)**.

n+ Doping

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

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

3 Select Domain 1 only.

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

5 In the N_{D0} text field, type `1e20[1/cm^3]`.

6 Locate the **Profile** section. In the d_j text field, type `0.1*h_dom`.

7 From the N_b list, choose **Acceptor concentration (semi/adm1)**.

Boundary Selection for Doping Profile 1

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

2 Select Boundary 2 only.

Apply metal contact boundary conditions to the top and bottom surfaces to form the p and n contacts.

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 2 only.

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

Add GaAs material from the Semiconductor Material Library and specify the real component of the refractive index.

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.

MATERIALS

GaAs - Gallium Arsenide (mat1)

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

2 In the table, click to select the cell at row number 8 and column number 4.

3 Right-click the **Refractive index, real part** row and choose **Edit**.

4 In the **Refractive index, real part** dialog box, type `n0` in the text field.

5 Click **OK**.

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

7 In the table, click to select the cell at row number 9 and column number 4.

8 Right-click the **Refractive index, imaginary part** row and choose **Edit**.

9 In the **Refractive index, imaginary part** dialog box, type `0` in the text field.

10 Click **OK**.

With the doping and electrical contacts defined, the next step is to configure the Optical Transitions feature. The default settings are appropriate for this model, all that is required is to set the spontaneous lifetime.

SEMICONDUCTOR (SEMI)

Optical Transitions 1

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

2 In the **Settings** window for **Optical Transitions**, locate the **Transition Matrix Element** section.

3 In the τ_{spon} text field, type `tau`.

Next configure the Electromagnetic Waves, Frequency Domain interface. Two Ports are required, one to excite the top surface of the device with incident radiation and one on the bottom surface to absorb the radiation. This is equivalent to having the electromagnetic wave pass through the device without any reflection from the exit surface. For the first port, the input power parameter `Pin` assumes the out-of-plane thickness of `d0` = 1 um. Scale it up to the out-of-plane thickness of 1[m] as hard-coded by the wave optics interface.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (ewfd)**.

Port 1

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

2 Select Boundary 3 only.

3 In the **Settings** window for **Port**, locate the **Port Properties** section.

4 In the P_{in} text field, type `Pin*1[m]/d0`.

5 Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

6 In the β text field, type `ewfd.k`.

Port 2

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

2 Select Boundary 2 only.

3 In the **Settings** window for **Port**, locate the **Port Mode Settings** section.

4 Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

5 In the β text field, type `ewfd.k`.

Periodic Condition 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Periodic Condition**.

Add the Periodic Condition feature to the sides of the device. This is equivalent to modeling a section of larger device which has greater lateral extent.

2 Select Boundaries 1 and 4 only.

Set a nonzero initial value for the electric field.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

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

3 Specify the $\mathbf{E}$ vector as

0	x
0	y
1	z

Configure the mesh, a mapped mesh with only one element in the horizontal direction is used for this effectively 1D model.

MESH 1

Mapped 1

In the **Mesh** toolbar, click **Mapped**.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundary 3 only.

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

4 In the **Number of elements** text field, type 1.

Distribution 2

1 In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.

2 Select Boundary 1 only.

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

4 In the **Number of elements** text field, type `500`.

5 Click **Build All**.

Create a nonlocal integration coupling to aid in evaluating the results.

DEFINITIONS (COMP1)

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 **Selection** list, choose **All domains**.

4 Locate the **Advanced** section. In the **Integration order** text field, type `1`.

Configure the study to sweep the wavelength and then compute.

STUDY 1: WAVELENGTH SWEEP

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

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

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

Step 1: Frequency-Stationary

1 In the **Model Builder** window, under **Study 1: Wavelength sweep** click **Step 1: Frequency-Stationary**.

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

3 In the **Frequency** text field, type `f0`.

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

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
lda0 (Incident wavelength)	`range(875[nm],-10[nm], 475[nm])`	`m`

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

Plot doping profile of the device and the energy level diagram.

RESULTS

Doping profile

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 profile` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (lda0)** list, choose **First**.

Line Graph 1

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

2 Select Boundary 1 only.

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

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

5 In the **Unit** field, type `1/cm^3`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Reversed arc length**.

Doping profile

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

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

3 Select the **x-axis label** check box.

4 In the associated text field, type `Depth (um)`.

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

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

Energy level diagram

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

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

3 Locate the **Data** section. From the **Parameter selection (lda0)** list, choose **Last**.

Conduction band

1 Right-click **Energy level diagram** and choose **Line Graph**.

2 Select Boundary 1 only.

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

4 In the **Expression** text field, type `semi.Ec_e`.

5 From the **Unit** list, choose **eV**.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Reversed arc length**.

7 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

8 In the table, enter the following settings:

Legends
Conduction band

9 Select the **Show legends** check box.

10 In the **Label** text field, type `Conduction band`.

Electron Quasi-Fermi energy

1 Right-click **Conduction band** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, type `Electron Quasi-Fermi energy` in the **Label** text field.

3 Locate the **y-Axis Data** section. In the **Expression** text field, type `semi.Efn_e`.

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

Legends
Electron Fermi level

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

6 From the **Color** list, choose **Blue**.

Valence band

1 In the **Model Builder** window, right-click **Conduction band** and choose **Duplicate**.

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

3 Locate the **y-Axis Data** section. In the **Expression** text field, type `semi.Ev_e`.

4 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

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

Legends
Valence band

Electron Quasi-Fermi energy 1

1 In the **Model Builder** window, right-click **Electron Quasi-Fermi energy** and choose **Duplicate**.

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

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

4 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

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

Legends
Hole Fermi level

Energy level diagram

1 In the **Model Builder** window, click **Energy level diagram**.

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

3 Select the **x-axis label** check box.

4 In the associated text field, type `Depth (um)`.

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

6 In the associated text field, type `Energy (eV)`.

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

8 In the **Title** text area, type `Energy level diagram`.

9 In the **Energy level diagram** toolbar, click **Plot**.

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

Plot the current per input optical power as a function of the wavelength.

Current as a function of wavelength

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 as a function of wavelength` in the **Label** text field.

Global 1

1 Right-click **Current as a function of wavelength** 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
`abs(semi.IO_1)/Pin`	`A/W`	`Current / Optical Power`

4 Locate the **x-Axis Data** section. From the **Unit** list, choose **nm**.

5 In the **Current as a function of wavelength** toolbar, click **Plot**.

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

Plot the electric field for a wavelength of 725 nm. This wavelength corresponds with the peak in the current.

Electric field

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

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

3 Locate the **Data** section. From the **Parameter selection (lda0)** list, choose **From list**.

4 In the **Parameter values (lda0 (m))** list, select **7.25E-7**.

Line Graph 1

1 Right-click **Electric field** and choose **Line Graph**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Line Graph**, locate the **x-Axis Data** section.

4 From the **Parameter** list, choose **Reversed arc length**.

Electric field

1 In the **Model Builder** window, click **Electric field**.

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

3 Select the **x-axis label** check box.

4 In the associated text field, type `Depth (um)`.

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

6 In the associated text field, type `Electric field magnitude (V/m)`.

7 In the **Electric field** toolbar, click  **Plot**.

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

For those who are interested in the conservation of number of particles, we can evaluate the rate of absorption of photons and compare with the rate of charged particles reaching the metal contact terminals. The rate of absorption can be computed in two different ways - either using the S-parameters of the wave optical ports or using the optical transition rates from the semiconductor model. All three rates evaluated below agree reasonably well.

Evaluation Group 1 - check particle conservation

1 In the **Results** toolbar, click  **Evaluation Group**.

2 In the **Settings** window for **Evaluation Group**, type `Evaluation Group 1 - check particle conservation` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (lda0)** list, choose **From list**.

4 In the **Parameter values (lda0 (m))** list, select **7.25E-7**.

Global Evaluation 1

1 Right-click **Evaluation Group 1 - check particle conservation** and choose **Global Evaluation**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`(1-abs(ewfd.S11)^2-abs(ewfd.S21)^2)*Pin/h_const/freq`	`1/s`	`Absorption rate (port)`
`intop1(semi.ot1.G_stim-semi.ot1.R_spon)*d0`	`1/s`	`Absorption rate (optical transition)`
`semi.IO_2/e_const`	`1/s`	`Charged particle arrival rate`

4 In the **Evaluation Group 1 - check particle conservation** toolbar, click **Evaluate**.

Plot the spontaneous emission, which in this device is due to unwanted recombination of carriers before they can be swept to the contacts. Although emission is not a design feature of photodiodes, it is useful to plot as an example of how to access quantities from the extra dimension which is used to represent the frequency domain. In order to access this data a new solution is required to hold the data from the extra dimension.

Study 1: Extra dimension

1 In the **Results** toolbar, click **More Datasets** and choose **Solution**.

2 In the **Settings** window for **Solution**, type `Study 1: Extra dimension` in the **Label** text field.

3 Locate the **Solution** section. From the **Component** list, choose **Extra Dimension from Optical Transitions 1 (semi_ot1_xdim)**.

Spontaneous emission

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1: Extra dimension (sol1)**.

4 From the **Parameter selection (lda0)** list, choose **From list**.

5 In the **Parameter values (lda0 (m))** list, select **7.25E-7**.

Line Graph 1

1 Right-click **Spontaneous emission** and choose **Line Graph**.

The spontaneous emission data is held in a variable **semi.ot1.dP_dE** which exists in the extra dimension. This data is plotted using the expression **comp1.atxd2(0,0.5e-6, semi.ot1.dP_dE)**, where the command **comp1.atxd#([coord],var)** retrieves the data from variable **var** as a function of the extra dimension from coordinate **coord** of the model geometry. In this example, the power emitted per unit volume and energy (semi.ot1.dP_dE) is obtained as a function of frequency (the extra dimension) from coordinate (0,0.5 um), which corresponds with the vertical center of the device. The numerical value **#** is required to let COMSOL know the dimension of the geometry to which the extra dimension is attached, in this case the model geometry is 2D so the value 2 is used. In addition, the tag comp1... tells COMSOL to look at component 1, in models with multiple components this allows for them to be individually addressed.

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

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

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `comp1.atxd2(0,0.5e-6,semi.ot1.dP_dE)`.

5 Select the **Description** check box.

6 In the associated text field, type `Total emitted power per unit volume and unit energy`.

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

8 In the **Expression** text field, type `hbar_const*comp1.atxd2(0,0.5e-6, semi.ot1.omega)`.

9 From the **Unit** list, choose **eV**.

10 Select the **Description** check box.

11 In the associated text field, type `Photon energy`.

Spontaneous emission

1 In the **Model Builder** window, click **Spontaneous emission**.

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

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

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

5 In the **Spontaneous emission** toolbar, click **Plot**.

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