Created in COMSOL Multiphysics 6.0

Radiation Effects in a PIN Diode

This tutorial performs steady-state and transient analysis of the response of a PIN diode to constant and pulsed radiation, respectively. The effect of radiation is modeled as spatially uniform generation of electron-hole pairs within the device. At high dose rates the separation of the generated charges causes the reduction of the interior electric field and prolonged storage of excess carriers. A quantitative prediction of this phenomenon is only possible with numerical simulation, since analytical solution is unattainable. Several techniques for achieving convergence in the cases of high reverse bias, field-dependent mobility, and time-dependent studies are demonstrated. The computed carrier concentrations and electric field distribution agree well with the reference paper.

Introduction

Radiation effects in semiconductor devices are of great scientific and engineering interests. This tutorial focuses on the steady-state and transient responses of a reverse biased PIN diode to ionizing radiation, following the treatment of Ref. 1, which models the radiation as a spatially uniform generation rate for electron-hole pairs within the device. At high dose rates, the interplay of electrostatics with contribution from the space charge of separated carriers, and charge transport with field-dependent mobilities, results in the intricate situation of much reduced interior electric field and extended storage of excess carriers. The inclusion of the field-dependent mobilities makes the equation system highly nonlinear and difficult to solve. Several techniques for achieving convergence are employed in the study settings with detailed discussions in the Modeling Instructions section.

Model Definition

Following Ref. 1, the PIN diode is constructed from a 300 um thick silicon wafer with heavy doping diffused into its two faces. The doping profile is shown in Figure 1, with parameters guessed from Fig. 3 of Ref. 1. As mentioned in the paper, recombination does not play a major role but is still included for completeness with a carrier lifetime of 100 us. Maxwell-Boltzmann statistics is used as suggested by Eq. (4) and (5) in Ref. 1.

The mobility models given by Eq. (15) and (16) in Ref. 1 differ by many orders of magnitude from the curves of carrier velocity vs. electric field shown in Fig. 2B in the same paper. Here we use similar expressions with modified coefficients to better match the curves in Fig. 2B.

In addition to the Semiconductor interface, an Events interface is added for the transient study to mark the end of the radiation pulse.

See the Modeling Instructions section for all the parameter, function and variable definitions, and detailed discussions on the techniques used to achieve convergence.

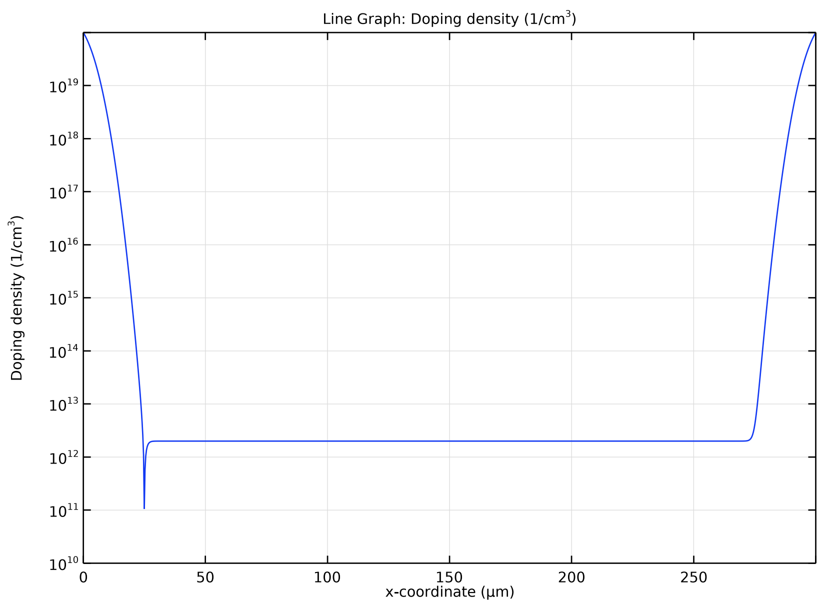


Figure 1: Doping profile.

Results and Discussion

Figure 2 and Figure 3 show the hole distribution and electric field distribution at various revers bias voltages, which compare well with Fig. 4A and 4B in the reference paper, respectively.

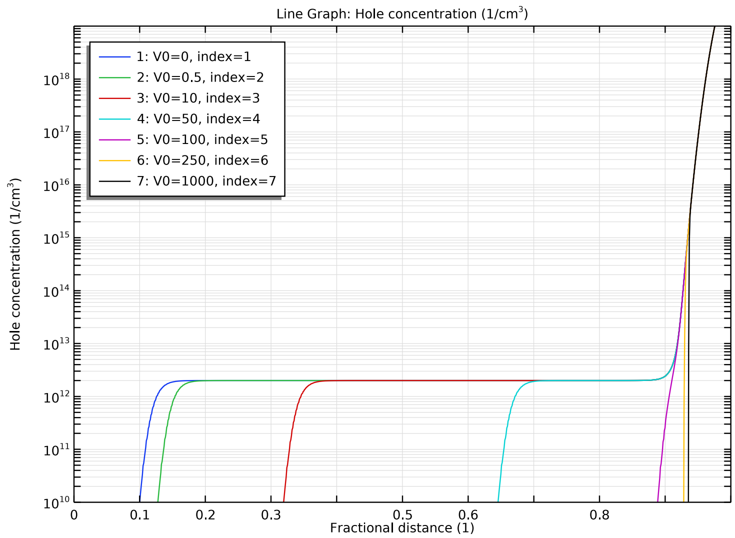


Figure 2: Hole distribution at various reverse bias voltages.

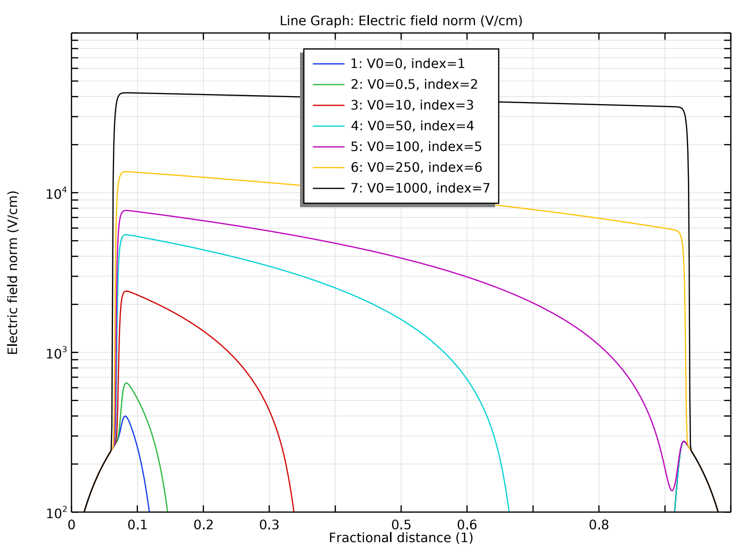


Figure 3: Electric field distribution at various reverse bias voltages.

Figure 4 and Figure 5 show the steady-state electric field and hole distribution for several ionization rates, which compare well with Fig. 5A and 5B in Ref. 1, respectively..

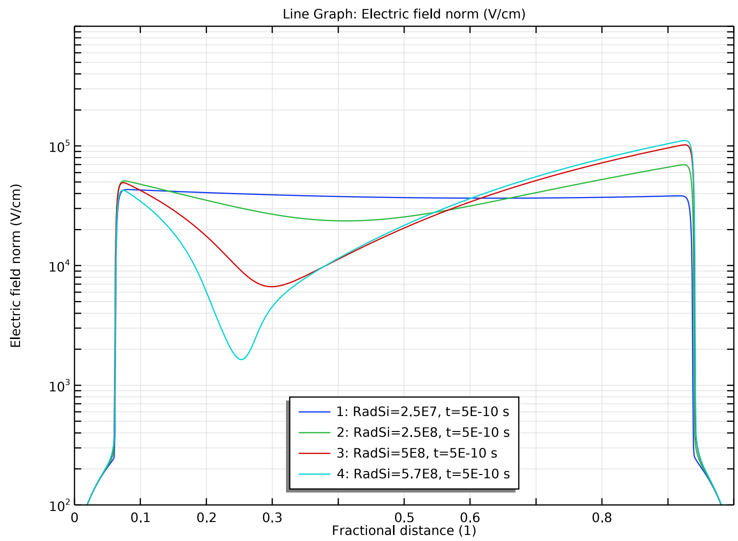


Figure 4: Steady-state electric field distribution for several ionization rates.

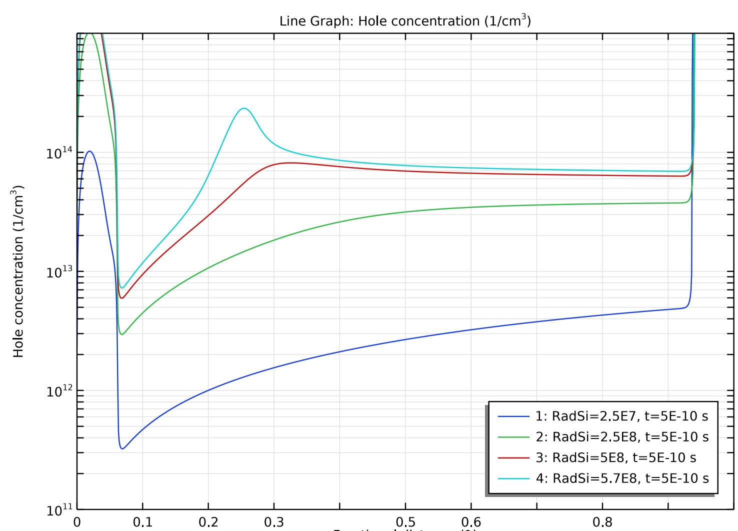


Figure 5: Steady-state hole distribution for several ionization rates.

[Figure 6](#) through [Figure 9](#) show the hole, electron, and electric field distributions at several times, and the photocurrent response at two ionization levels, which compare well with Fig. 7A–7C and Fig. 8 in the reference paper, respectively.

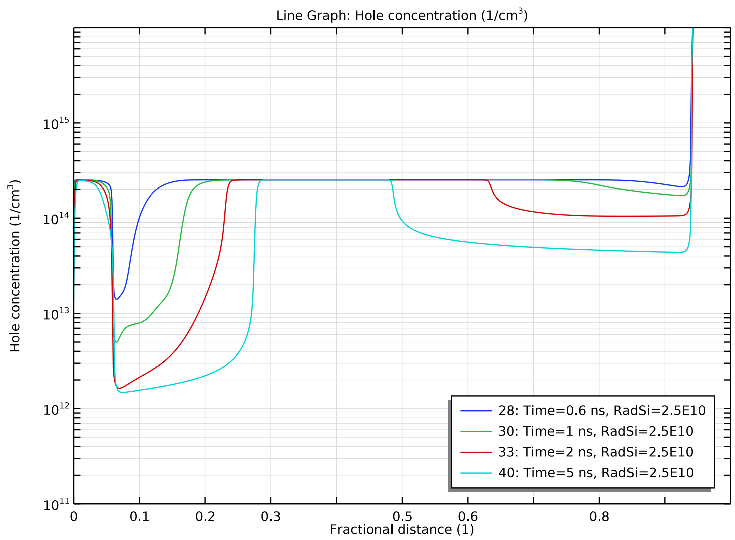


Figure 6: Hole distributions at several times.

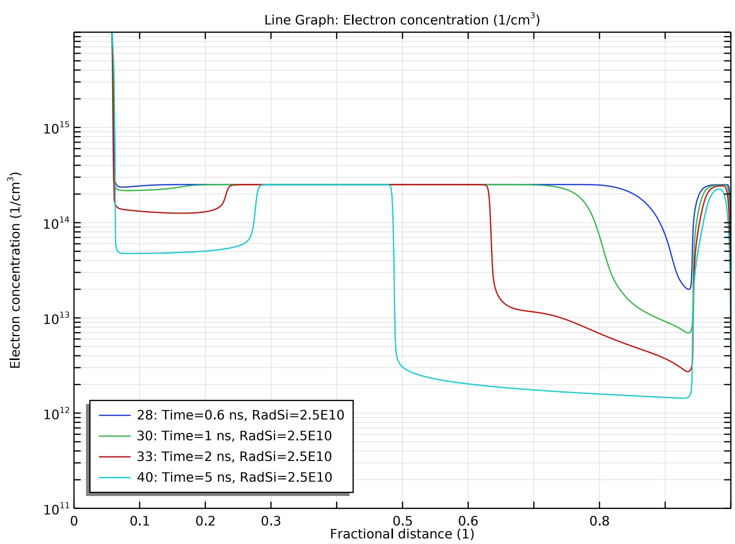


Figure 7: Electron distributions at several times.

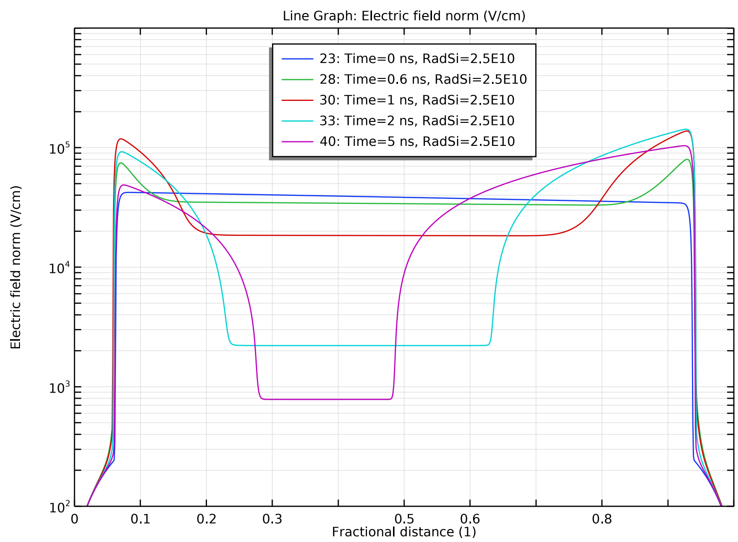


Figure 8: Electric field distributions at several times.

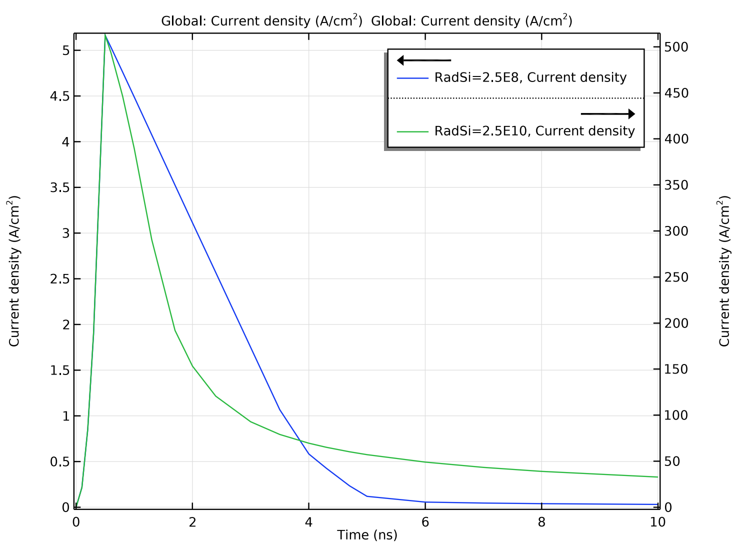


Figure 9: Photocurrent response at two ionization levels.

Reference

1. C.W. Gwyn, D.L. Scharfetter and J.L. Wirth, “The Analysis of Radiation Effects in Semiconductor Junction Devices,” presented at IEEE Conference on Nuclear and Space Radiation Effects, Columbus, Ohio, July 10–14, 1967.

Application Library path: `Semiconductor_Module/Photonic_Devices_and_Sensors/pin_radiation_effects`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **1D**.

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

3 Click **Add**.

Add an **Events** interface to capture the abrupt change in the slope at the end of the applied radiation pulse.

4 In the **Select Physics** tree, select **Mathematics>ODE and DAE Interfaces>Events (ev)**.

5 Click **Add**.

6 Click **Study**.

The **Semiconductor Equilibrium** study can be used to obtain a good initial condition for subsequent stationary or transient studies.

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

8 Click **Done**.

GEOMETRY 1

The Model Wizard exits and starts the COMSOL Desktop at the Geometry node. We can set the length scale here right away. Then enter some model parameters. In particular, the time parameter `t` lets stationary solvers recognize the built-in time variable of the same name and makes it convenient to set up the model using the same time-dependent expression for the generation rate due to the radiation dosage.

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**.

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
L	300[um]	3E-4 m	Device length
V0	1000[V]	1000 V	Applied voltage
Nds	1e20[cm^-3]	1E26 1/m³	Surface concentration of N-plus and P-plus doping
dj	25[um]	2.5E-5 m	Junction depth of N-plus and P-plus doping
Npi	2e12[cm^-3]	2E18 1/m³	Intrinsic doping concentration
tau	100[us]	1E-4 s	Carrier lifetime
mup0	480[cm^2/V/s]	0.048 m²/(V·s)	Low field, low doping, hole mobility
mun0	1350[cm^2/V/s]	0.135 m²/(V·s)	Low field, low doping, electron mobility
cp	1	1	Continuation parameter for mobility model
RadSi	0	0	Radiation dose rate in Rad(Si)/s
t	0[s]	0 s	Time parameter
tp	0.5[ns]	5E-10 s	Radiation pulse duration

Name	Expression	Value	Description
gR	4.03e13*RadSi[1/cm^3/s]*pw1(t/tp)		Generation rate due to radiation dose
index	1	1	Parameter for solution indexing
area	1[mm^2]	1E-6 m²	Cross-section area of the 1D model

The expression for the generation rate gR is red colored because the pulse function pw1 is not yet defined, which we will do next. Create a piecewise function without smoothing for the triangular pulse. Make the argument and the function unitless to avoid confusion.

Piecewise 1 (pw1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Piecewise**.

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

3 Find the **Intervals** subsection. In the table, enter the following settings:

Start	End	Function
0	1	x
1	2	0

4 Locate the **Units** section. In the **Arguments** text field, type 1.

5 In the **Function** text field, type 1.

Create a 300 um long interval to represent the 300 um thick wafer.

GEOMETRY 1

Interval 1 (i1)

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

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

3 In the table, enter the following settings:

Coordinates (µm)
0
L

Create a local variable node for the impact ionization and mobility models. The mobility models given by Eq. (15) and (16) in the reference paper differ by many orders of magnitude from the curves of carrier velocity vs. electric field shown in Fig. 2B in the same paper. Here we use similar expressions with modified coefficients to better match the curves in Fig. 2B. Note that the continuation parameter `cp` is used to control the amount of field dependence for aiding the solution process.

DEFINITIONS

Variables 1

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

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
E	semi.normE/1[V/cm]		Electric field intensity in V/cm
alphap	1.8e7[cm^-1]*exp(-3.2e6/E)	1/m	Ionization coefficient, holes
alphan	2.4e7[cm^-1]*exp(-1.6e6/E)	1/m	Ionization coefficient, electrons
NDt	(semi.Ndplus+semi.Naminus)/1[cm^-3]		Total ionized dopant concentration in 1/cm^3
mun	mun0/(1+81*NDt/(NDt+3.24e18))^0.5/(1+cp*(E/8e3)^4.9*(E+1.64e5)/(E+1))^(1/4.9)	$m^2/(V\cdot s)$	Electron mobility
mup	mup0/(1+350*NDt/(NDt+1.05e19))^0.5/(1+cp*(E/8.72e4)^1.15*(E+8.51e5)/(E+8.12e4))^(1/1.15)	$m^2/(V\cdot s)$	Hole mobility

Add the silicon material properties from the list of built-in materials. Some properties will be changed in the physics settings according to the reference paper.

ADD MATERIAL

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

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

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

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

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

Configure the physics settings. Enter the cross-section area for the 1D model. Use the default Maxwell-Boltzmann statistics as suggested by Eq. (4) and (5) in the reference paper. Use the local variables `mun` and `mup` defined above for the electron and hole mobilities.

SEMICONDUCTOR (SEMI)

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

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

3 In the A text field, type `area`.

Semiconductor Material Model 1

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

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

3 From the μ_n list, choose **User defined**. In the associated text field, type `mun`.

4 From the μ_p list, choose **User defined**. In the associated text field, type `mup`.

Add intrinsic and surface doping using the parameters defined earlier. For the surface doping remember to make a selection for the surface (boundary) from which dopants are diffused into the bulk.

Analytic Doping Model 1: Intrinsic

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

2 In the **Settings** window for **Analytic Doping Model**, type `Analytic Doping Model 1: Intrinsic` in the **Label** text field.

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

4 Locate the **Impurity** section. In the N_{A0} text field, type `Npi`.

Geometric Doping Model 1: P-plus

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

2 In the **Settings** window for **Geometric Doping Model**, type `Geometric Doping Model 1: P-plus` 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 **Profile away from the boundary** list, choose **Error function (erf)**.

5 Locate the **Impurity** section. In the N_{A0} text field, type `Nds`.

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

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

Geometric Doping Model 2: N-plus

1 Right-click **Geometric Doping Model 1: P-plus** and choose **Duplicate**.

2 In the **Settings** window for **Geometric Doping Model**, type `Geometric Doping Model 2: N-plus` in the **Label** text field.

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

4 In the N_{D0} text field, type `Nds`.

Boundary Selection for Doping Profile 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Semiconductor (semi)> Geometric Doping Model 1: P-plus** node, then click **Boundary Selection for Doping Profile 1**.

2 Select Boundary 2 only.

Boundary Selection for Doping Profile 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Semiconductor (semi)> Geometric Doping Model 2: N-plus** node, then click **Boundary Selection for Doping Profile 1**.

2 Select Boundary 1 only.

Add generation and recombination features using the parameters and variables defined above.

Trap-Assisted Recombination 1: SRH

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

2 In the **Settings** window for **Trap-Assisted Recombination**, type `Trap-Assisted Recombination 1: SRH` in the **Label** text field.

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

4 Locate the **Shockley-Read-Hall Recombination** section. From the τ_n list, choose **User defined**. In the associated text field, type `tau`.

5 From the τ_p list, choose **User defined**. In the associated text field, type `tau`.

Impact Ionization Generation 1

1 In the **Physics** toolbar, click **Domains** and choose **Impact Ionization Generation**.

2 In the **Settings** window for **Impact Ionization Generation**, locate the **Domain Selection** section.

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

4 Locate the **Impact Ionization Generation** section. From the **Impact ionization model** list, choose **User-defined**.

5 Find the **User-defined parameters** subsection. In the α_n text field, type `alphan`.

6 In the α_p text field, type `alphap`.

User-Defined Generation 1: Radiation effect

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

2 In the **Settings** window for **User-Defined Generation**, type `User-Defined Generation 1: Radiation effect` in the **Label** text field.

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

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

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

Finally create ohmic contacts, one grounded and the other driven with the voltage parameter `V0`.

Metal Contact 1: Ground

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

2 In the **Settings** window for **Metal Contact**, type `Metal Contact 1: Ground` in the **Label** text field.

3 Select Boundary 2 only.

Metal Contact 2: V0

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

2 In the **Settings** window for **Metal Contact**, type `Metal Contact 2: V0` in the **Label** text field.

3 Select Boundary 1 only.

4 Locate the **Terminal** section. In the V_0 text field, type `V0`.

Finish the physics setup by adding an explicit event at the end of the triangular pulse marked by the pulse duration `tp`.

EVENTS (EV)

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

Explicit Event 1

1 In the **Physics** toolbar, click **Global** and choose **Explicit Event**.

2 In the **Settings** window for **Explicit Event**, locate the **Event Timings** section.

3 In the t_i text field, type `tp`.

Use physics-controlled mesh. It is always recommended to double check the mesh resolution and to perform mesh refinement studies.

MESH 1

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

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

3 From the **Element size** list, choose **Extra fine**.

The field-dependent mobility model makes the equation system very nonlinear and difficult to solve. So we first assume field-independent mobility by setting the continuation parameter `cp` to zero. This helps an easier ramp up of the applied voltage `V0` from equilibrium to the operating voltage of 1000 V. Disable the Events interface which is only needed for the transient study of the pulsed radiation. Show default solver to change the continuation predictor from the default **Constant** to **Linear**. The **Linear** option helps accelerate the voltage sweep by using a linear extrapolation scheme to estimate the initial guess for the next swept parameter. The default **Constant** option uses the current solution as the initial guess for the next swept parameter, which is a more conservative approach and in most cases is appropriate for the highly nonlinear semiconductor equation system - for this model it is too conservative.

STUDY 1A: RAMP V0 WITH FIELD-INDEPENDENT MOBILITY

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

2 In the **Settings** window for **Study**, type `Study 1a: Ramp V0 with field-independent mobility` in the **Label** text field.

Step 1: Semiconductor Equilibrium

1 In the **Model Builder** window, under **Study 1a: Ramp V0 with field-independent mobility** click **Step 1: Semiconductor Equilibrium**.

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

3 In the table, clear the **Solve for** check box for **Events (ev)**.

Stationary

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>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 **Events (ev)**.
4 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.
5 From the **Sweep type** list, choose **All combinations**.
6 Click **Add**.
7 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
cp (Continuation parameter for mobility model)	0	

8 Click **Add**.
9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (Applied voltage)	`0 0.5 10 50 100 250 1000`	V

10 In the **Model Builder** window, click **Study 1a: Ramp V0 with field-independent mobility**.
11 In the **Settings** window for **Study**, locate the **Study Settings** section.
12 Clear the **Generate default plots** check box.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.
3 In the **Model Builder** window, expand the **Study 1a: Ramp V0 with field-independent mobility>Solver Configurations>Solution 1 (sol1)>Stationary Solver 2** node, then click **Parametric 1**.
4 In the **Settings** window for **Parametric**, click to expand the **Continuation** section.
5 From the **Predictor** list, choose **Linear**.
6 In the **Study** toolbar, click **Compute**.

Now that the voltage sweep is completed with field-independent mobility, we can use the set of solutions as the initial guess for the case of the full mobility model with field dependence. This is done by using a **Parametric Sweep** node to pair the swept voltage `V0` with a swept parameter `index`. Then use the parameter `index` to select the correct solution corresponding to each `V0` value, using the **Manual** option in the **Step 1: Stationary** node.

ADD STUDY

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

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

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Events (ev)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

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

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

STUDY 2

Step 1: Stationary

1 In the **Settings** window for **Stationary**, click to expand the **Values of Dependent Variables** section.

2 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

4 From the **Study** list, choose **Study 1a: Ramp V0 with field-independent mobility, Stationary**.

5 From the **Parameter value (V0 (V),cp)** list, choose **Manual**.

6 In the **Index** text field, type `index`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (Applied voltage)	0 0.5 10 50 100 250 1000	V

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
index (Parameter for solution indexing)	range(1,7)	

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

8 In the **Settings** window for **Study**, type Study 1b: Ramp V0 with full mobility model in the **Label** text field.

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

Plot the doping profile, hole distribution, and electric field distribution, to be compared with Fig. 3, 4A, and 4B in the reference paper, respectively.

RESULTS

Fig. 3 Doping Profile

1 In the **Model Builder** window, under **Results** click **Electric Potential (semi)**.

2 In the **Settings** window for **1D Plot Group**, type Fig. 3 Doping Profile in the **Label** text field.

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

Line Graph 1

1 In the **Model Builder** window, expand the **Fig. 3 Doping Profile** node, then click **Line Graph 1**.

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

3 In the **Expression** text field, type abs(semi.Ndoping).

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

5 Select the **Description** check box.

6 In the associated text field, type Doping density.

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

8 In the **Expression** text field, type x.

Fig. 3 Doping Profile

1 In the **Model Builder** window, click **Fig. 3 Doping Profile**.

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

3 Clear the **y-axis label** check box.

4 Locate the **Axis** section. Select the **y-axis log scale** check box.

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

6 In the **x minimum** text field, type `0`.

7 In the **x maximum** text field, type `300`.

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

9 In the **y maximum** text field, type `1e20`.

10 In the **Fig. 3 Doping Profile** toolbar, click **Plot**.

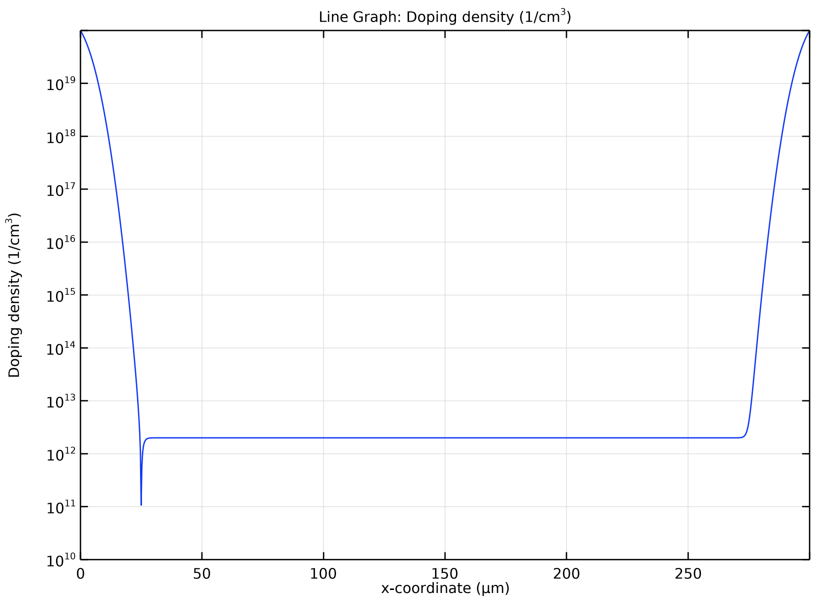


Fig. 4A Hole Distribution

1 Right-click **Fig. 3 Doping Profile** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Fig. 4A Hole Distribution` in the **Label** text field.

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

4 Locate the **Axis** section. In the **x maximum** text field, type `1`.

5 In the **y maximum** text field, type `1e19`.

6 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Line Graph 1

1 In the **Model Builder** window, expand the **Fig. 4A Hole Distribution** node, then click **Line Graph 1**.

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

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

4 Clear the **Description** check box.

5 Locate the **x-Axis Data** section. In the **Expression** text field, type `x/L`.

6 Select the **Description** check box.

7 In the associated text field, type `Fractional distance`.

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

9 In the **Fig. 4A Hole Distribution** toolbar, click **Plot**.

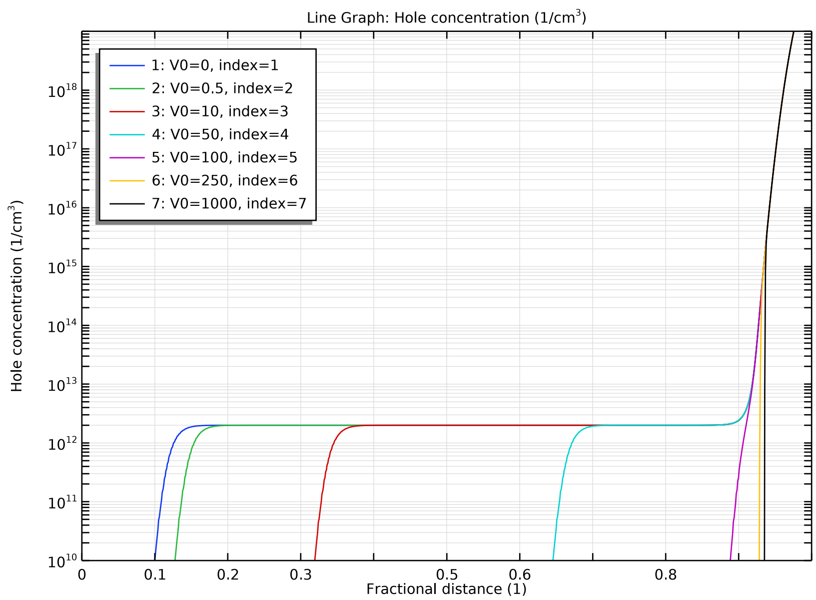


Fig. 4B Electric Field Distribution

1 In the **Model Builder** window, right-click **Fig. 4A Hole Distribution** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Fig. 4B Electric Field Distribution` in the **Label** text field.

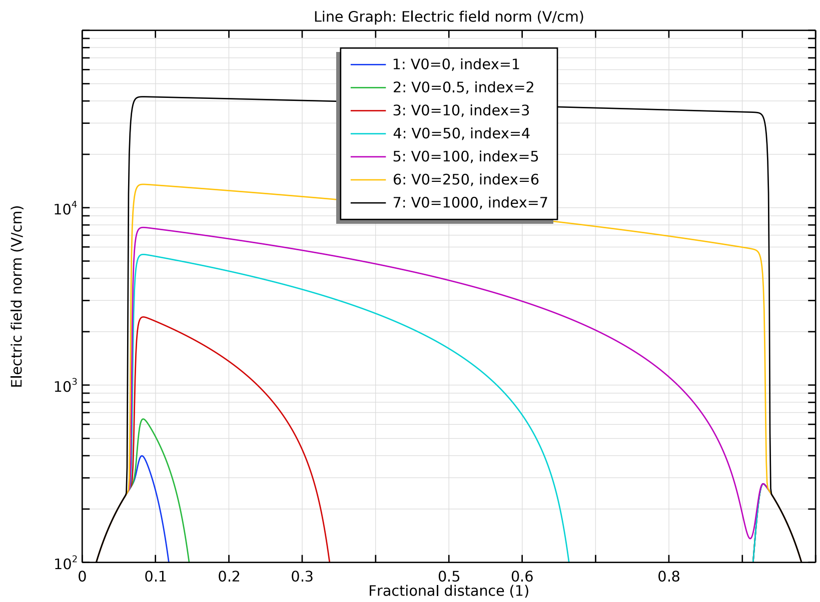
3 Locate the **Axis** section. In the **y minimum** text field, type `1e2`.

4 In the **y maximum** text field, type `1e5`.

5 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Line Graph 1

1. In the **Model Builder** window, expand the **Fig. 4B Electric Field Distribution** node, then click **Line Graph 1**.
2. In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
3. In the **Expression** text field, type `semi.normE`.
4. In the **Unit** field, type `V/cm`.
5. In the **Fig. 4B Electric Field Distribution** toolbar, click **Plot**.



With the diode fully reverse biased at 1000 V, we are ready to study the response of the device to steady-state radiation. In previous studies the time parameter `t` was `0[s]` as defined earlier, thus the pulse function `pw1(t/tp)` was zero and the generation rate due to radiation `gR` was also zero (Refer to the **Parameters 1** node for the definition). Now to specify nonzero radiation, just set the time parameter `t` to equal to the pulse duration `tp`, so that the pulse function `pw1(t/tp)` is unity. Then the dosage rate can be specified by the parameter `RadSi` directly in units of Rad(Si)/s.

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 **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Events (ev)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

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

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

STUDY 2: STEADY-STATE RADIATION EFFECT

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Study 2: Steady-state radiation effect` 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 **Study 2: Steady-state radiation effect** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Values of Dependent Variables** section.

3 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

5 From the **Study** list, choose **Study 1b: Ramp V0 with full mobility model, Stationary**.

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

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

8 Click + **Add**.

9 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
t (Time parameter)	tp	s

10 Click + **Add**.

11 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
RadSi (Radiation dose rate in Rad(Si)/s)	{0.25,2.5,5.0,5.7}*1e8	

As we will see, the field-dependent mobility gives rise to an interesting result for high dose rates, however it also makes the equation system very nonlinear and difficult to solve. In the previous pair of studies for voltage ramping, the difficulty is overcome by separating the solution process into two stages, with field-independent mobility in the first stage and full mobility in the second. In this current study of dose rate ramping, we show an alternative method to overcome the difficulty using a single study with full mobility.

The nonlinearity causes the **Automatic Newton** solver to converge slower than the ideal quadratic convergence behavior, which in turn causes the continuation solver to take too small steps for the swept parameter `RadSi`. So use the **Constant Newton** option instead, with an appropriate damping factor. In addition, provide a better initial step size for the continuation solver under the **Parametric 1** node to prevent it from taking too large a first step and then waste time in back tracking. Finally, use **Anderson acceleration** to further improve performance (by taking advantage of the information from earlier history of the nonlinear iteration) and use a smaller max number of iterations to reduce the time wasted in back tracking.

Solution 12 (sol12)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 12 (sol12)** node.
3 In the **Model Builder** window, expand the **Study 2: Steady-state radiation effect>Solver Configurations>Solution 12 (sol12)>Stationary Solver 1** node, then click **Fully Coupled 1**.
4 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.
5 From the **Nonlinear method** list, choose **Constant (Newton)**.
6 In the **Damping factor** text field, type `0.6`.
7 In the **Model Builder** window, under **Study 2: Steady-state radiation effect>Solver Configurations>Solution 12 (sol12)>Stationary Solver 1** click **Parametric 1**.
8 In the **Settings** window for **Parametric**, locate the **Continuation** section.
9 Select the **Tuning of step size** check box.
10 In the **Initial step size** text field, type `5e7`.
11 In the **Maximum step size** text field, type `1e8`.
12 From the **Predictor** list, choose **Linear**.
13 In the **Model Builder** window, under **Study 2: Steady-state radiation effect>Solver Configurations>Solution 12 (sol12)>Stationary Solver 1** click **Fully Coupled 1**.
14 In the **Settings** window for **Fully Coupled**, locate the **Method and Termination** section.
15 In the **Maximum number of iterations** text field, type `20`.

16 From the **Stabilization and acceleration** list, choose **Anderson acceleration**.

17 In the **Dimension of iteration space** text field, type `5`.

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

Plot the steady-state electric field distribution and hole distribution for several ionization rates, to be compared with Fig. 5A and 5B in the reference paper, respectively.

RESULTS

Fig. 5A Steady-State Electric Field Distribution vs. Dose Rate

1. In the **Model Builder** window, right-click **Fig. 4B Electric Field Distribution** and choose **Duplicate**.
2. In the **Settings** window for **1D Plot Group**, type `Fig. 5A Steady-State Electric Field Distribution vs. Dose Rate` in the **Label** text field.
3. Locate the **Data** section. From the **Dataset** list, choose **Study 2: Steady-state radiation effect/Solution 12 (sol12)**.
4. Locate the **Axis** section. In the **y maximum** text field, type `1e6`.
5. Locate the **Legend** section. From the **Position** list, choose **Lower middle**.
6. In the **Fig. 5A Steady-State Electric Field Distribution vs. Dose Rate** toolbar, click **Plot**.

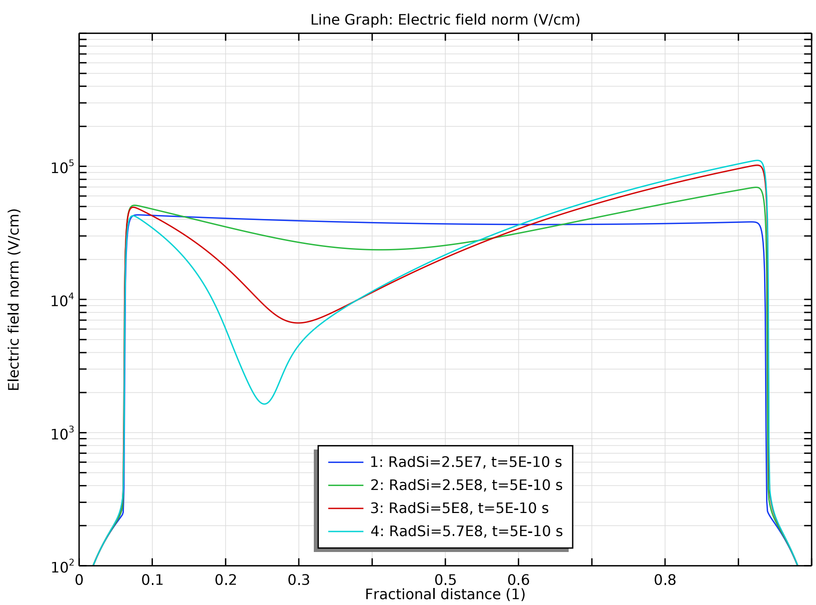


Fig. 5B Steady-State Hole Distribution vs. Dose Rate

1 In the **Model Builder** window, right-click **Fig. 4A Hole Distribution** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Fig. 5B  Steady-State Hole Distribution vs. Dose Rate` in the **Label** text field.

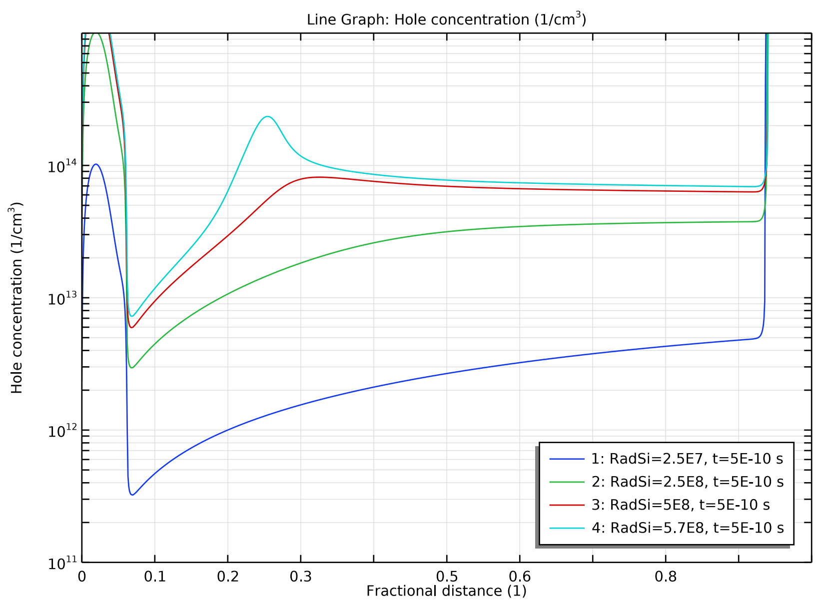
3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Steady-state radiation effect/Solution 12 (sol12)**.

4 Locate the **Axis** section. In the **y minimum** text field, type `1e11`.

5 In the **y maximum** text field, type `1e15`.

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

7 In the **Fig. 5B Steady-State Hole Distribution vs. Dose Rate** toolbar, click **Plot**.



In addition, plot the mobility versus the ionized impurity concentration and the drift velocity versus the electric field intensity, to be compared with the curves in Fig. 2A and 2B in the reference paper, respectively. Add datasets to plot the impurity-dependent and field-dependent curves on top of the simulated data points.

Fig. 2A Mobility vs. Doping

1 Right-click **Fig. 5B Steady-State Hole Distribution vs. Dose Rate** and choose **Duplicate**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1b: Ramp V0 with full mobility model/Parametric Solutions 1 (sol4)**.

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

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

6 In the associated text field, type `Doping (cm<SUP>-3</SUP>)`.

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

8 In the associated text field, type `Mobility (cm<SUP>2</SUP>/V-s)`.

9 Locate the **Axis** section. Select the **x-axis log scale** check box.

10 Clear the **y-axis log scale** check box.

11 In the **x minimum** text field, type `1e13`.

12 In the **x maximum** text field, type `1e20`.

13 In the **y minimum** text field, type `0`.

14 In the **y maximum** text field, type `1400`.

15 Locate the **Legend** section. From the **Position** list, choose **Upper right**.

Line Graph 1

1 In the **Model Builder** window, expand the **Fig. 2A Mobility vs. Doping** node, then click **Line Graph 1**.

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

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

4 From the **Unit** list, choose **cm^2/(V*s)**.

5 Locate the **x-Axis Data** section. In the **Expression** text field, type `NDt`.

6 In the **Description** text field, type `Ionized impurity concentration`.

7 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

8 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

9 From the **Positioning** list, choose **In data points**.

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

Line Graph 2

1 Right-click **Results>Fig. 2A Mobility vs. Doping>Line Graph 1** 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.mup`.

4 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle (reset)**.

Grid 1D 1: logNDt

1 In the **Results** toolbar, click **More Datasets** and choose **Grid>Grid 1D**.

2 In the **Settings** window for **Grid 1D**, type `Grid 1D 1: logNDt` in the **Label** text field.

3 Locate the **Data** section. From the **Source** list, choose **Function**.

4 From the **Function** list, choose **Piecewise 1 (pw1)**.

5 Locate the **Parameter Bounds** section. In the **Name** text field, type `logNDt`.

6 In the **Minimum** text field, type `13`.

7 In the **Maximum** text field, type `20`.

Line Graph 3

1 In the **Model Builder** window, right-click **Fig. 2A Mobility vs. Doping** and choose **Line Graph**.

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

3 From the **Dataset** list, choose **Grid 1D 1: logNDt**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `mun0[V*s/cm^2]/(1+81*10^logNDt/(10^logNDt+3.24e18))^0.5`.

5 Select the **Description** check box.

6 In the associated text field, type `Electron mobility`.

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

8 In the **Expression** text field, type `10^logNDt`.

9 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

10 In the **Width** text field, type `2`.

11 Locate the **Legends** section. Select the **Show legends** check box.

12 Find the **Include** subsection. Clear the **Solution** check box.

13 Select the **Description** check box.

Line Graph 4

1 Right-click **Line Graph 3** and choose **Duplicate**.

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

3 In the **Expression** text field, type `mup0[V*s/cm^2]/(1+350*10^logNDt/(10^logNDt+1.05e19))^0.5`.

4 In the **Description** text field, type `Hole mobility`.

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

6 In the **Fig. 2A Mobility vs. Doping** toolbar, click **Plot**.

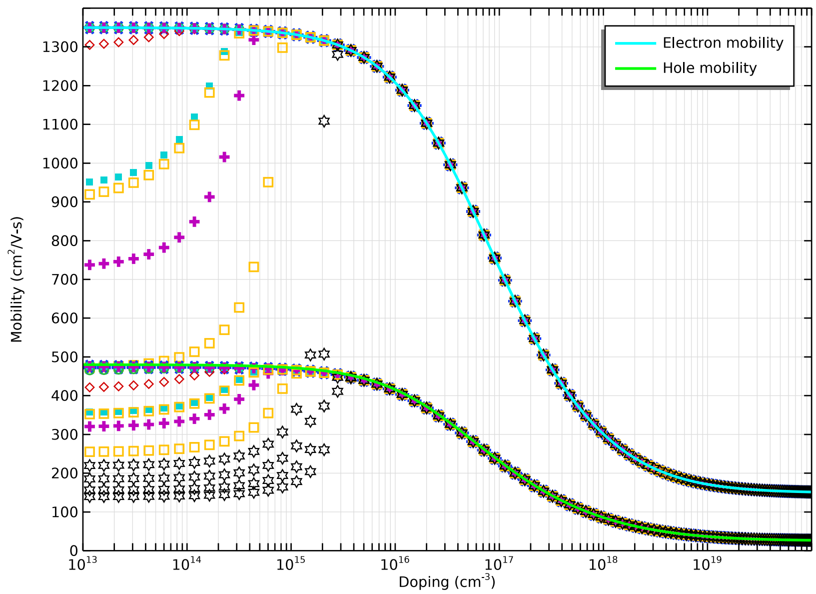


Fig. 2B Velocity vs. Electric Field

1 In the **Model Builder** window, right-click **Fig. 2A Mobility vs. Doping** and choose **Duplicate**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Steady-state radiation effect/Solution 12 (sol12)**.

4 Locate the **Plot Settings** section. In the **x-axis label** text field, type `Electric field (V/cm)`.

5 In the **y-axis label** text field, type `Drift velocity (cm/s)`.

6 Locate the **Axis** section. Clear the **x-axis log scale** check box.

7 In the **x minimum** text field, type `0`.

8 In the **x maximum** text field, type `1e5`.

9 In the **y maximum** text field, type `9e6`.

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

Line Graph 1

1 In the **Model Builder** window, expand the **Fig. 2B Velocity vs. Electric Field** node, then click **Line Graph 1**.

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

3 In the **Expression** text field, type semi.mun*semi.normE.

4 From the **Unit** list, choose **cm/s**.

5 Locate the **x-Axis Data** section. In the **Expression** text field, type semi.normE[cm/V].

6 Clear the **Description** check box.

Line Graph 2

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

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

3 In the **Expression** text field, type semi.mup*semi.normE.

4 From the **Unit** list, choose **cm/s**.

5 Locate the **x-Axis Data** section. In the **Expression** text field, type semi.normE[cm/V].

6 Clear the **Description** check box.

Grid 1D 1: E1

1 In the **Model Builder** window, right-click **Grid 1D 1: logNDt** and choose **Duplicate**.

2 In the **Settings** window for **Grid 1D**, type Grid 1D 1: E1 in the **Label** text field.

3 Locate the **Parameter Bounds** section. In the **Name** text field, type E1.

4 In the **Minimum** text field, type 0.

5 In the **Maximum** text field, type 1e5.

Line Graph 3

1 In the **Model Builder** window, under **Results>Fig. 2B Velocity vs. Electric Field** click **Line Graph 3**.

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

3 From the **Dataset** list, choose **Grid 1D 1: E1**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type E1*mun0[V*s/cm^2]/(1+(E1/8e3)^4.9*(E1+1.64e5)/(E1+1))^(1/4.9).

5 In the **Description** text field, type Electron velocity.

6 Locate the **x-Axis Data** section. In the **Expression** text field, type E1.

7 From the **Unit** list, choose **m**.

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

Line Graph 4

1 In the **Model Builder** window, click **Line Graph 4**.

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

3 From the **Dataset** list, choose **Grid 1D 1: E1**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `E1*mup0[V*s/cm^2]/(1+(E1/8.72e4)^1.15*(E1+8.51e5)/(E1+8.12e4))^(1/1.15)`.

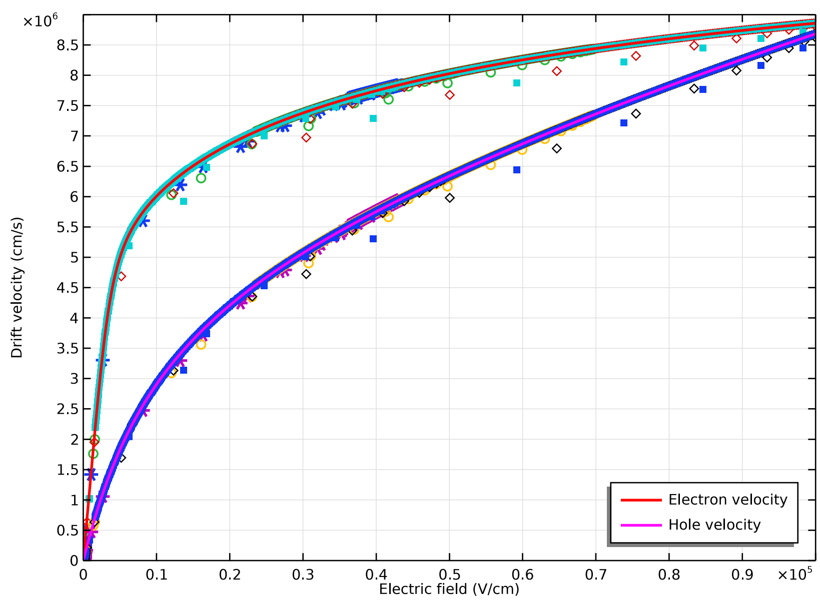
5 In the **Description** text field, type `Hole velocity`.

6 Locate the **x-Axis Data** section. In the **Expression** text field, type `E1`.

7 From the **Unit** list, choose **m**.

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Magenta**.

9 In the **Fig. 2B Velocity vs. Electric Field** toolbar, click **Plot**.



After completing the steady-state study, we are now ready to investigate the effect of pulsed radiation with the waveform given by the inset of Fig. 8 in the reference paper. This waveform is provided by the pulse function `pw1(t/tp)` in the model with a normalized height of unity. The peak dose rate is specified by the parameter `RadSi` directly in units of Rad(Si)/s. Tighten the tolerance to `1e-8`. Since the solution of the steady-state study is used as the initial condition, use the option of **Initial value based** for the scaling of the dependent variables, to get a proper scaling for the error estimate.

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> Time Dependent**.

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

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

STUDY 4

Step 1: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

2 From the **Time unit** list, choose **ns**.

3 In the **Output times** text field, type `0 0.1 0.2 0.3 0.5 0.6 0.8 1 1.3 1.7 2 2.4 3 3.5 4 4.3 4.7 5 6 7 8 10`.

4 From the **Tolerance** list, choose **User controlled**.

5 In the **Relative tolerance** text field, type `1.0E-8`.

6 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**.

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

8 From the **Study** list, choose **Study 1b: Ramp V0 with full mobility model, Stationary**.

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

10 Click **Add**.

11 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
RadSi (Radiation dose rate in Rad(Si)/s)	2.5e8 2.5e10	

12 In the **Model Builder** window, click **Study 4**.

13 In the **Settings** window for **Study**, type `Study 3: Pulsed radiation effect` in the **Label** text field.

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

Solution 13 (sol13)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 13 (sol13)** node, then click **Dependent Variables 1**.
3 In the **Settings** window for **Dependent Variables**, locate the **Scaling** section.
4 From the **Method** list, choose **Initial value based**.
5 In the **Study** toolbar, click **Compute**.

Plot the hole, electron, and electric field distributions at several times, and the photocurrent response at two ionization levels, to be compared with Fig. 7A ~ 7C and Fig. 8 in the reference paper, respectively.

RESULTS

Fig. 7A Hole Distribution at Several Times

1 In the **Model Builder** window, right-click **Fig. 5B Steady-State Hole Distribution vs. Dose Rate** and choose **Duplicate**.
2 In the **Settings** window for **1D Plot Group**, type `Fig. 7A  Hole Distribution at Several Times` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Study 3: Pulsed radiation effect/Solution 13 (sol13)**.
4 From the **Parameter selection (RadSi)** list, choose **Last**.
5 Locate the **Axis** section. In the **y maximum** text field, type `1e16`.
6 Locate the **Data** section. From the **Time selection** list, choose **From list**.
7 In the **Times (ns)** list, choose **0.6**, **1**, **2**, and **5**.

8 In the **Fig. 7A Hole Distribution at Several Times** toolbar, click **Plot**.

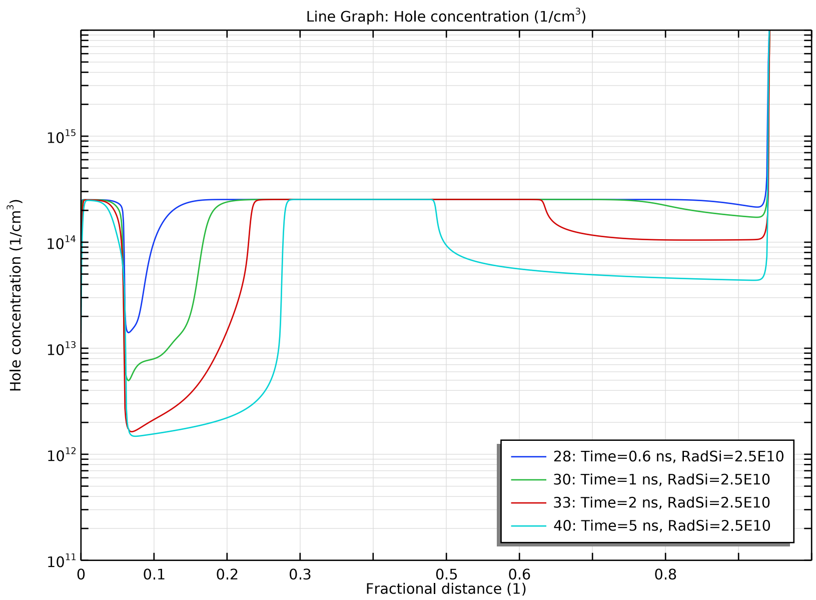


Fig. 7B Electron Distribution at Several Times

1 Right-click **Fig. 7A Hole Distribution at Several Times** and choose **Duplicate**.

2 In the **Model Builder** window, click **Fig. 7A Hole Distribution at Several Times 1**.

3 In the **Settings** window for **1D Plot Group**, type `Fig. 7B Electron Distribution at Several Times` in the **Label** text field.

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

Line Graph 1

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

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

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

4 In the **Fig. 7B Electron Distribution at Several Times** toolbar, click **Plot**.

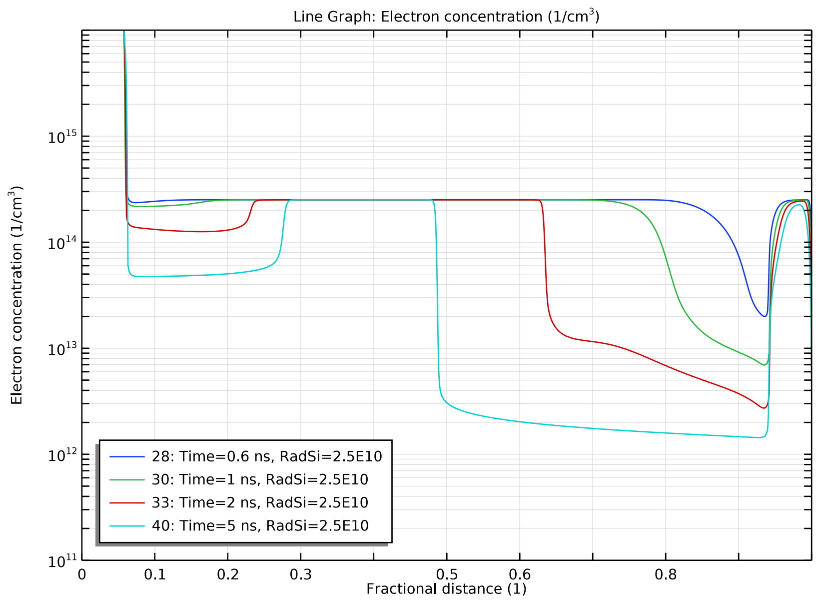


Fig. 7C Electric Field Distribution at Several Times

1 In the **Model Builder** window, right-click **Fig. 7B Electron Distribution at Several Times** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Fig. 7C Electric Field Distribution at Several Times` in the **Label** text field.

3 Locate the **Data** section. In the **Times (ns)** list, choose **0**, **0.6**, **1**, **2**, and **5**.

4 Locate the **Axis** section. In the **y minimum** text field, type `1e2`.

5 In the **y maximum** text field, type `1e6`.

6 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Line Graph 1

1 In the **Model Builder** window, expand the **Fig. 7C Electric Field Distribution at Several Times** node, then click **Line Graph 1**.

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

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

4 In the **Unit** field, type `V/cm`.

5 In the **Fig. 7C Electric Field Distribution at Several Times** toolbar, click **Plot**.

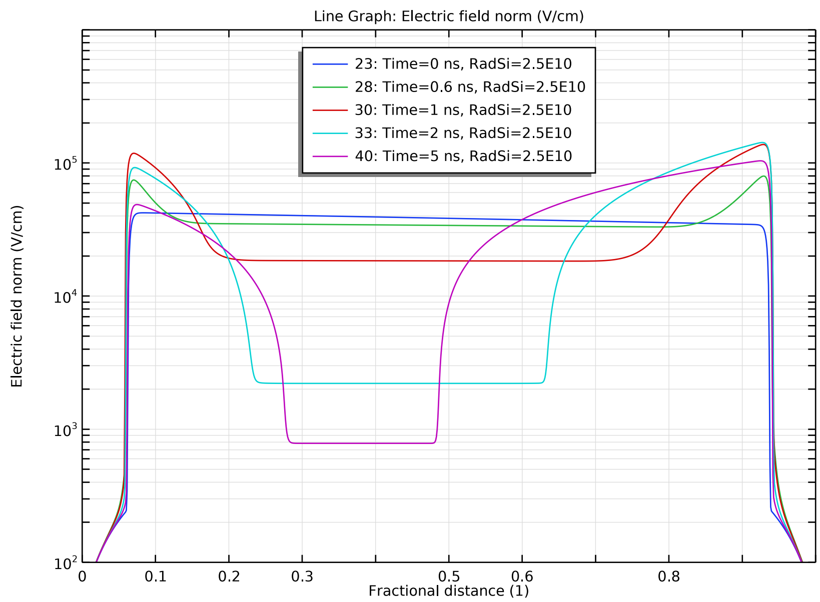


Fig. 8 Transient Photocurrent Response

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

2 In the **Settings** window for **1D Plot Group**, type `Fig. 8 Transient Photocurrent Response` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

4 Locate the **Plot Settings** section. Select the **Two y-axes** check box.

Global 1

1 Right-click **Fig. 8 Transient Photocurrent Response** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 3: Pulsed radiation effect/Solution 13 (sol13)**.

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

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

Expression	Unit	Description
`semi.I0_2/area`	`A/cm^2`	`Current density`

6 Click to expand the **Legends** section.

Global 2

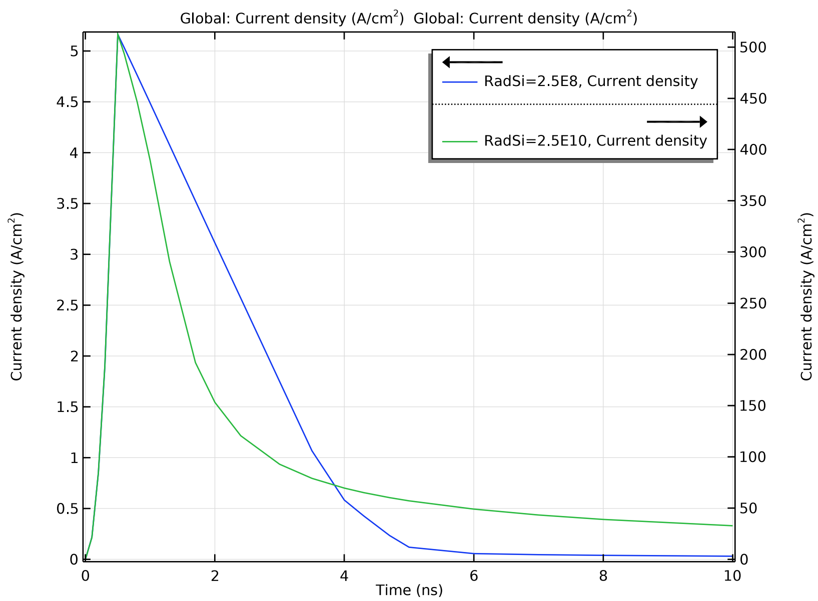
1 Right-click **Global 1** and choose **Duplicate**.

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

3 From the **Parameter selection (RadSi)** list, choose **Last**.

4 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** check box.

5 In the **Fig. 8 Transient Photocurrent Response** toolbar, click **Plot**.



Finally present the time evolution of the hole density profile and the drift velocity as the main mechanism of such evolution in one single condensed graph using the **Parametric Extrusion 1D** dataset.

Parametric Extrusion 1D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Parametric Extrusion 1D**.

2 In the **Settings** window for **Parametric Extrusion 1D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3: Pulsed radiation effect/Solution 13 (sol13)**.

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

Evolution of Hole Density Profile and Drift Velocity

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

2 In the **Settings** window for **2D Plot Group**, type `Evolution of Hole Density Profile and Drift Velocity` 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 `x:Distance  y:Time  z:log<SUB>10</SUB>(Hole Density(cm<SUP>-3</SUP>))  color:Drift Velocity(cm/s)`.

Surface 1

1 Right-click **Evolution of Hole Density Profile and Drift Velocity** and choose **Surface**.

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

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

4 From the **Unit** list, choose **cm/s**.

Height Expression 1

1 Right-click **Surface 1** and choose **Height Expression**.

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

3 From the **Height data** list, choose **Expression**.

4 In the **Expression** text field, type `semi.log10P`.

Filter 1

1 In the **Model Builder** window, right-click **Surface 1** and choose **Filter**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `semi.log10P>11 && semi.log10P<16`.

Contour 1

1 In the **Model Builder** window, right-click **Evolution of Hole Density Profile and Drift Velocity** and choose **Contour**.

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

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

4 Locate the **Levels** section. In the **Total levels** text field, type `10`.

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

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

7 Clear the **Color legend** check box.

Height Expression 1

1 In the **Model Builder** window, under **Results>Evolution of Hole Density Profile and Drift Velocity>Surface 1** click **Height Expression 1**.

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

3 Select the **Scale factor** check box.

4 Right-click **Results>Evolution of Hole Density Profile and Drift Velocity>Surface 1>Height Expression 1** and choose **Copy**.

Height Expression 1

In the **Model Builder** window, right-click **Contour 1** and choose **Paste Height Expression**.

Filter 1

In the **Model Builder** window, under **Results>Evolution of Hole Density Profile and Drift Velocity>Surface 1** right-click **Filter 1** and choose **Copy**.

Filter 1

In the **Model Builder** window, right-click **Contour 1** and choose **Paste Filter**.

Contour 2

1 Right-click **Contour 1** and choose **Duplicate**.

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

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

4 From the **Unit** list, choose **ns**.

5 Locate the **Levels** section. From the **Entry method** list, choose **Levels**.

6 In the **Levels** text field, type `0.1 0.2 0.5 1 2 3 4 5 8`.

7 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Gradient**.

8 From the **Top color** list, choose **Cyan**.

9 From the **Bottom color** list, choose **Magenta**.

10 Select the **Color legend** check box.

11 In the **Evolution of Hole Density Profile and Drift Velocity** toolbar, click **Plot**.

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