Created in COMSOL Multiphysics 5.6

Forward Recovery of a PIN Diode

This model is licensed under the COMSOL Software License Agreement 5.6. All trademarks are the property of their respective owners. See www.comsol.com/trademarks. This tutorial simulates the turn-on transient (forward recovery) of a simple PIN diode, based on the book "Fundamentals of Power Semiconductor Devices" by B.J. Baliga (p. 242, 2008 edition; Ref. 1). The diode is current driven with a constant ramp rate of $1 \cdot 10^9$, $2 \cdot 10^9$, and $1 \cdot 10^{10}$ A/cm²/s and a steady state current density of 100 A/cm². The resulting time evolution of the device voltage and electron concentration compare well to those shown in the book (Figs. 5.30–5.31). For a more sophisticated example including band gap narrowing, carrier-carrier scattering, and external load circuit elements, see the tutorial *Reverse Recovery of a PIN Diode*.

Introduction

The PIN diode structure is an important building block for power electronic circuits. The process of switching the PIN rectifier from the off-state to the on-state is referred to as the forward recovery. During the turn-on time interval with a specified current input, the device voltage shows an initial spike, due to the amount of time required to accumulate extra charge carriers in the drift region for the diode to be fully turned on. This tutorial follows the approach in Ref. 1, where an idealized linearly ramped-on current input (with a specified max on-current) is used. For a more sophisticate example that uses the circuit capability of COMSOL Multiphysics to simulate the inductive load with a flyback diode in a more realistic fashion, see the tutorial *Reverse Recovery of a PIN Diode* That tutorial also includes band gap narrowing and carrier-carrier scattering effects.

Model Definition

The model simulates a diode of 80 μ m length and 1 mm cross-section area. The background n-doping is $5 \cdot 10^{13}$ /cm³ and the peak n- and p-doping at the exterior boundaries is $1 \cdot 10^{19}$ /cm³. **Shockley-Read-Hall recombination** is included. The device is grounded at the right endpoint and current driven from the left endpoint.

A **Ramp** function with a **Cutoff** is used to specify the linear current ramp up to the max oncurrent. The **Events** interface is used to mark the abrupt change in the slope of the applied current at the end of the current ramp, so that the time-dependent solver can take appropriate actions.

The **Semiconductor Equilibrium** study step is used for the initial condition. Then a **Time Dependent** study step is used to simulate the forward recovery, with an **Auxiliary sweep** to study a few different current ramp rates.

Results and Discussion

Figure 1 and Figure 2 show the time evolution of the device voltage and the electron concentration at a few selected time points, respectively. They exhibit the typical behavior as expected from the initial accumulation of extra charge carriers in the drift region. The figures compare well with the corresponding figures in Ref. 1.



Figure 1: Time evolution of the device voltage.



Figure 2: Time evolution of the electron concentration.

Reference

1. B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, 2008 ed., Springer, pp. 242–243.

Application Library path: Semiconductor_Module/Device_Building_Blocks/ pin_forward_recovery

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click 🙆 Model Wizard.

MODEL WIZARD

I In the Model Wizard window, click — ID.

- 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 of the applied voltage.

- 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.

- 7 In the Select Study tree, select Preset Studies for Some Physics Interfaces> Semiconductor Equilibrium.
- 8 Click **M** Done.

GEOMETRY I

The Model Wizard exits and starts the COMSOL Desktop at the Geometry node. We can set the length scale here right away.

- I In the Model Builder window, under Component I (compl) click Geometry I.
- 2 In the Settings window for Geometry, locate the Units section.
- **3** From the **Length unit** list, choose **µm**.

Import global parameters from a text file.

GLOBAL DEFINITIONS

Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- **3** Click **b** Load from File.
- **4** Browse to the model's Application Libraries folder and double-click the file pin_forward_recovery.txt.

Build a simple 1D line interval of 80 um long.

GEOMETRY I

Interval I (i1)

- I In the Model Builder window, under Component I (comp1) right-click Geometry I 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		
80		

Add silicon material.

ADD MATERIAL

- I 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.

MATERIALS

Si - Silicon (mat1) Enter the cross-section area for the 1D model.

SEMICONDUCTOR (SEMI)

- I In the Model Builder window, under Component I (compl) click Semiconductor (semi).
- 2 In the Settings window for Semiconductor, locate the Cross-Section Area section.
- **3** In the *A* text field, type area.

Set up doping - first the background doping.

Analytic Doping Model I

- I In the Physics toolbar, click Domains and choose Analytic Doping Model.
- 2 In the Settings window for Analytic Doping Model, locate the Domain Selection section.
- **3** From the **Selection** list, choose **All domains**.
- 4 Locate the Impurity section. From the Impurity type list, choose Donor doping (n-type).
- **5** In the N_{D0} text field, type 5e13[1/cm^3].

Then the P and N doping.

Geometric Doping Model I

- I In the Physics toolbar, click Domains and choose Geometric Doping Model.
- 2 In the Settings window for Geometric Doping Model, locate the Domain Selection section.

- 3 From the Selection list, choose All domains.
- **4** Locate the **Impurity** section. In the N_{A0} text field, type 1e19[1/cm^3].
- **5** Locate the **Profile** section. In the d_j text field, type 10[um].
- **6** From the N_b list, choose **Donor concentration (semi/adml)**.

Boundary Selection for Doping Profile 1

- I In the Model Builder window, expand the Geometric Doping Model I node, then click Boundary Selection for Doping Profile I.
- 2 Select Boundary 1 only.

Geometric Doping Model 2

- I In the Physics toolbar, click Domains and choose Geometric Doping Model.
- 2 In the Settings window for Geometric Doping Model, locate the Domain Selection section.
- 3 From the Selection list, choose All domains.
- 4 Locate the Impurity section. From the Impurity type list, choose Donor doping (n-type).
- 5 In the N_{D0} text field, type 1e19[1/cm^3].
- **6** Locate the **Profile** section. In the d_j text field, type 10[um].
- 7 From the N_b list, choose Donor concentration (semi/adml).

Boundary Selection for Doping Profile I

- I In the Model Builder window, expand the Geometric Doping Model 2 node, then click Boundary Selection for Doping Profile I.
- **2** Select Boundary 2 only.

Add ohmic contacts.

Metal Contact I

- I In the Physics toolbar, click Boundaries and choose Metal Contact.
- 2 Select Boundary 2 only.

Metal Contact 2

- I In the Physics toolbar, click Boundaries and choose Metal Contact.
- 2 Select Boundary 1 only.
- 3 In the Settings window for Metal Contact, locate the Terminal section.
- 4 From the Terminal type list, choose Current.

5 In the I_0 text field, type J_on*area*rm1(t/t_on).

The ramp function rm1 is not yet defined and turns the expression to yellow colored. Let us define it now.

DEFINITIONS

Ramp I (rm1)

- I In the Home toolbar, click f Functions and choose Global>Ramp.
- 2 In the Settings window for Ramp, locate the Parameters section.
- **3** Select the **Cutoff** check box.

Add SRH recombination.

SEMICONDUCTOR (SEMI)

Trap-Assisted Recombination I

- I In the Physics toolbar, click Domains and choose Trap-Assisted Recombination.
- **2** In the Settings window for Trap-Assisted Recombination, locate the Domain Selection section.
- 3 From the Selection list, choose All domains.
- 4 Locate the Shockley-Read-Hall Recombination section. From the τ_n list, choose User defined. In the associated text field, type 1[us].
- **5** From the τ_p list, choose **User defined**. In the associated text field, type 1[us].

Add an event to mark the end of the applied current ramp, so that the time-dependent solver can take appropriate actions.

EVENTS (EV)

In the Model Builder window, under Component I (compl) click Events (ev).

Explicit Event 1

I 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 t_on.

Exclude the Events interface from the initial study step.

STUDY I

Step 1: Semiconductor Equilibrium

- I In the Model Builder window, under Study I click Step I: 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).

Add a time dependent study step with Auxiliary sweep, to simulate a few different current ramp rates.

Time Dependent

- I In the Study toolbar, click Study Steps and choose Time Dependent> Time Dependent.
- 2 In the Settings window for Time Dependent, locate the Study Settings section.
- **3** From the **Time unit** list, choose **ns**.
- 4 In the **Output times** text field, type range(0,1,99).
- 5 From the Tolerance list, choose User controlled.
- 6 In the Relative tolerance text field, type 1e-5.
- 7 Click to expand the Study Extensions section. Select the Auxiliary sweep check box.
- 8 Click + Add.
- **9** In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
dJdt (Desired current density	1e9 2e9 1e10	A/cm^2/s
ramp rate)		

IO In the **Study** toolbar, click **= Compute**.

Plot the time evolution of the device voltage, to see the different amount of spiking for the different current ramp rates.

RESULTS

V(t)

- I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type V(t) in the Label text field.

Global I

- I Right-click V(t) 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.VO_2	V	Terminal voltage

4 In the V(t) toolbar, click **I** Plot.



Plot the electron concentration at a few selected time points, to see the initial buildup of the charge carriers in the drift region.

Electron Concentration

- I In the Model Builder window, right-click Carrier Concentrations (semi) and choose Duplicate.
- 2 Click the y-Axis Log Scale button in the Graphics toolbar.
- **3** In the **Settings** window for **ID Plot Group**, type Electron Concentration in the **Label** text field.
- 4 Locate the Data section. From the Parameter selection (dJdt) list, choose Last.
- 5 From the Time selection list, choose Manual.
- 10 | FORWARD RECOVERY OF A PIN DIODE

- 6 In the Parameter indices (1-100) text field, type 3 7 10 15.
- 7 Locate the Plot Settings section. Clear the y-axis label check box.
- 8 Locate the Axis section. Select the Manual axis limits check box.
- 9 In the x maximum text field, type 31.
- **IO** In the **y minimum** text field, type -2e14.
- II In the **y maximum** text field, type 1e16.

Electron Concentration

- I In the Model Builder window, click Electron Concentration.
- 2 In the Settings window for Line Graph, click to expand the Legends section.
- **3** From the **Legends** list, choose **Automatic**.

Hole Concentration

In the Model Builder window, right-click Hole Concentration and choose Delete.

Electron Concentration

- I In the Model Builder window, click Electron Concentration.
- **2** In the **Electron Concentration** toolbar, click **I Plot**.

