Created in COMSOL Multiphysics 6.3

Tunnel Diode

Introduction

A tunnel diode, also known as an Esaki diode, is a heavily doped p–n junction diode with negative resistance due to tunneling, a quantum mechanical effect. A tunnel diode enables electrons to “tunnel” through the potential barrier at the junction, allowing for fast switching, which is beneficial in high-frequency applications.

At equilibrium, the Fermi levels of the p-type and n-type regions are aligned. By applying a forward bias, electrons can tunnel through the barrier due to the narrow depletion region. Therefore, electrons from the conduction band at the n-type region tunnel directly into the valence band of the p-type region. By raising the voltage further, the current reaches a peak value. After this point, the Fermi levels start to get misaligned and the tunneling current decreases, creating a negative resistance region. As the voltage continues to rise, the diode transitions to a standard operation, where current increases with voltage.

This model shows how to model the band-to-band tunneling effect in a tunnel diode.

Model Definition

This model employs a manual approach to simulate the tunneling effect in a tunnel diode. A User-Defined Recombination domain feature is used to make electrons disappear from the conduction band on the n-side and holes disappear from the valence band on the p-side, to mimic the effect of the electrons from the conduction band on the n-side tunneling into the valence band on the p-side. The rate of recombination can be computed with different levels of complexity. The current model takes the simplest approach as in Ref. 1, Section 8.2.1, where the tunneling current density is defined as

$$J_t = \frac{q^2\xi}{36\pi\hbar^2}\sqrt{\frac{2m^*}{E_g}}D_t\exp\left(-\frac{4\sqrt{2m^*}E_g^{3/2}}{3q\hbar\xi}\right) \tag{1}$$

where the quantity D_t is an overlap integral, which modulates the shape of the I–V curve. It has the dimension of energy, depending on the temperature and the degeneracy, V_n and V_p, and is defined as

$$D_t \equiv \int[F_C(E) - F_V(E)]\left[1 - \exp\left(\frac{2E_S}{\bar{E}}\right)\right]dE \tag{2}$$

where $F_C(E)$ and $F_V(E)$ are the Fermi–Dirac distribution functions, E_S is the smaller of the conduction and valence band energy levels, and $\bar{E}$ is an energy-related component given by

$$\overline{E} \equiv \frac{\sqrt{2}q\ \hbar\ \xi}{\pi\sqrt{m^* E_g}} \tag{3}$$

The average electric field, ξ, is taken as half of the peak electric field from the simulation. The limits of the energy integration are also obtained from the numerical results.

The model is represented as a 1D domain with two 20 nm thick layers of highly n-doped and p-doped regions. The domains in which the electrons and holes disappear are selected in advance by visually estimating the approximate location where tunneling occurs. The recombination rates are assumed to be uniform within the domains.

The Modeling Instructions section describes the setup in detail.

Results and Discussion

Figure 1 shows the current density versus applied voltage of the tunnel diode under forward bias. The plot shows the tunneling current increase at a low forward voltage, followed by the negative resistance region where tunneling decreases, leading to a drop in the current density.

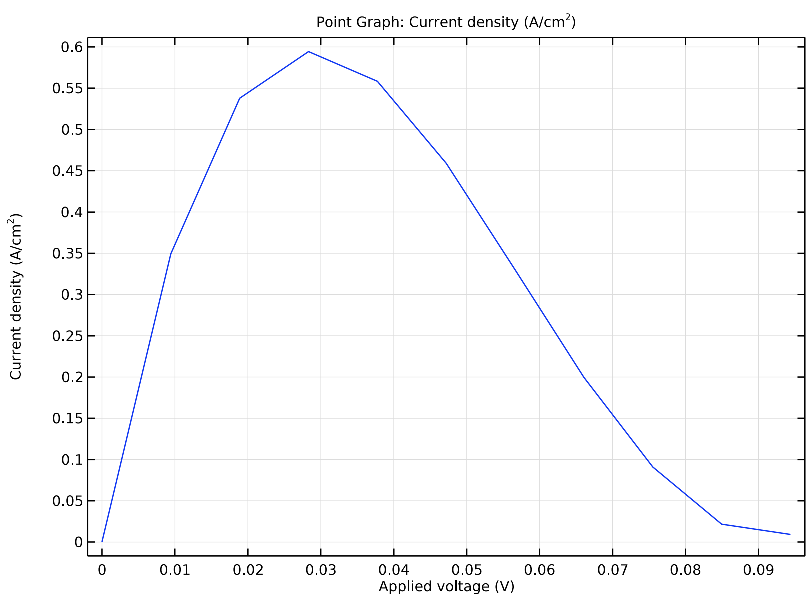


Figure 1: Current density versus applied voltage of the tunnel diode.

Reference

1. S.M. Sze and K.K. Ng, *Physics of Semiconductor Devices*, 3rd ed., John Wiley & Sons, 2007.

Application Library path: `Semiconductor_Module/Device_Building_Blocks/tunnel_diode`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1. In the **Model Wizard** window, click **1D**.
2. In the **Select Physics** tree, select **Semiconductor** > **Semiconductor (semi)**.
3. Click **Add**.
4. Click **Study**.
5. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Semiconductor Equilibrium**.
6. Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1. In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2. In the **Settings** window for **Parameters**, locate the **Parameters** section.
3. In the table, enter the following settings:

Name	Expression	Value	Description
T0	300[K]	300 K	Temperature
Na	2e19[cm^-3]	2E25 1/m³	p-doping
Nd	2e19[cm^-3]	2E25 1/m³	n-doping

Name	Expression	Value	Description
V0	0[V]	0 V	Applied voltage
mstar	2*me_const/(1/0.044+1/0.036)	3.6073E-32 kg	Effective mass
d	5[nm]	5E-9 m	Depth of tunneling layer

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 **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **nm**.

4 In the **Model Builder** window, click **Interval 1 (i1)**.

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

6 In the table, enter the following settings:

Coordinates (nm)
-d*4
-d*2
-d
0
d
d*2
d*4

ADD MATERIAL

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

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

3 In the tree, select **Semiconductors** > **Ge - Germanium**.

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

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

DEFINITIONS

Integration 1 (intop1)

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

2 In the **Settings** window for **Integration**, type `intop_p` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 2 only.

Integration 2 (intop_p2)

1 Right-click **Integration 1 (intop_p)** and choose **Duplicate**.

2 In the **Settings** window for **Integration**, type `intop_n` in the **Operator name** text field.

3 Locate the **Source Selection** section. Click **Clear Selection**.

4 Select Boundary 6 only.

Integration 3 (intop_n2)

1 Right-click **Integration 2 (intop_n)** and choose **Duplicate**.

2 In the **Settings** window for **Integration**, type `intop_0` in the **Operator name** text field.

3 Locate the **Source Selection** section. Click **Clear Selection**.

4 Select Boundary 4 only.

Variables 1

1 In the **Model Builder** window, 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
Ecn	intop_n(semi.Ec)	V	Conduction band energy level
Evp	intop_p(semi.Ev)	V	Valence band energy level
Efn	intop_n(semi.Efn)	V	Electron quasi-Fermi energy level
Efp	intop_p(semi.Efp)	V	Hole quasi-Fermi energy level
E0	intop_0(semi.normE)/2	V/m	Average electric field
Eg	intop_0(semi.Eg)	V	Band gap voltage at the junction

Name	Expression	Unit	Description
Ebar	(sqrt(2)*hbar_const*E0)/(pi*sqrt(mstar*Eg*e_const))	V	Energy-related factor
Jt0	e_const^3*E0/(36*pi*hbar_const^2)*sqrt(2*mstar/(Eg*e_const))*exp(-(4*sqrt(2*mstar*Eg*e_const)*(Eg*e_const))/(3*e_const*hbar_const*E0))	S/m²	Prefactor of tunneling current density
Vth	intop_0(semi.Vth)	V	Thermal potential at the junction
D0	integrate((1/(1+exp((V_-Efn)/Vth))-1/(1+exp((V_-Efp)/Vth)))*(1-exp((-2*min(V_-Ecn,Evp-V_))/Ebar)),V_,Ecn,Evp)	V	Overlap integral
Jt	Jt0*D0	A/m²	Tunneling current density
Rt	Jt/e_const/d	1/(m³·s)	Recombination rate

SEMICONDUCTOR (SEMI)

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

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

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

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 **Model Input** section.

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

Analytic Doping Model 1

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

2 Select Domains 1–3 only.

3 In the **Settings** window for **Analytic Doping Model**, locate the **Impurity** section.

4 In the N_{A0} text field, type `Na`.

Analytic Doping Model 2

1 Right-click **Analytic Doping Model 1** and choose **Duplicate**.

2 In the **Settings** window for **Analytic Doping Model**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

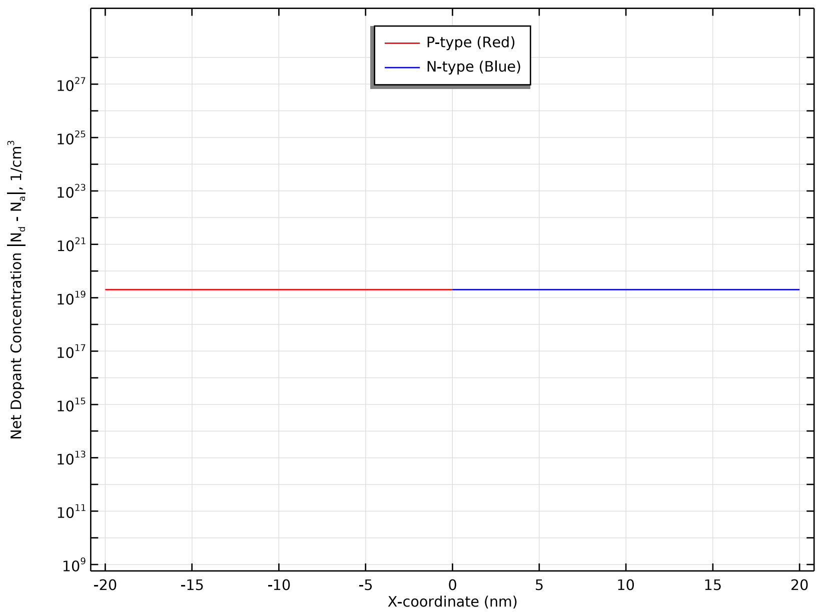
4 Select Domains 4–6 only.

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

6 In the N_{D0} text field, type `Nd`.

Here you can plot the preview of the doping profile for the p–n junction.

7 Click the **Plot Net Doping Profile for All** button in the window toolbar.



Metal Contact 1

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

2 Select Boundary 7 only.

Metal Contact 2

1 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 In the V_0 text field, type `V0`.

Trap-Assisted Recombination 1

1 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**. From the τ_p list, choose **User defined**.

Define two User-Defined Recombination domain features. Use the first one to make electrons disappear from the conduction band on the n-side and the second one to make holes disappear from the valence band on the p-side. This mimics the band-to-band tunneling across a p–n junction. The domains where the electrons and holes disappear are defined approximately.

User-Defined Recombination 1

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

2 Select Domain 5 only.

3 In the **Settings** window for **User-Defined Recombination**, locate the **User-Defined Recombination** section.

4 In the $R_{n,0}$ text field, type `Rt`.

User-Defined Recombination 2

1 Right-click **User-Defined Recombination 1** and choose **Duplicate**.

2 In the **Settings** window for **User-Defined Recombination**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Select Domain 2 only.

5 Locate the **User-Defined Recombination** section. In the $R_{n,0}$ text field, type `0[1/(m^3*s)]`.

6 In the $R_{p,0}$ text field, type `Rt`.

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 **Fine**.

STUDY 1: EQUILIBRIUM

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

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

Step 1: Semiconductor Equilibrium

1 In the **Model Builder** window, under **Study 1: Equilibrium** click **Step 1: Semiconductor Equilibrium**.

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

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

4 In the **Relative tolerance** text field, type `1.0E-6`.

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

RESULTS

Evaluation Group 1

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

Point Evaluation 1

1 Right-click **Evaluation Group 1** and choose **Point Evaluation**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Point Evaluation**, locate the **Expressions** section.

4 In the table, enter the following settings:

Expression	Unit	Description
`semi.Ev-semi.Efp`	V	

Point Evaluation 2

1 In the **Model Builder** window, right-click **Evaluation Group 1** and choose **Point Evaluation**.

2 Select Boundary 7 only.

3 In the **Settings** window for **Point Evaluation**, locate the **Expressions** section.

4 In the table, enter the following settings:

Expression	Unit	Description
`semi.Efn-semi.Ec`	V	

Evaluation Group 1

1 In the **Model Builder** window, click **Evaluation Group 1**.

2 In the **Evaluation Group 1** toolbar, click **Evaluate**.

Now take the evaluated values of Vn and Vp from the first study, as they reflect the degrees of the degeneracy of n+-side and p+-side, respectively.

GLOBAL DEFINITIONS

Parameters 2: from Result of Study 1 (Eval Group 1)

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add** > **Parameters**.

2 In the **Settings** window for **Parameters**, type `Parameters 2: from Result of Study 1 (Eval Group 1)` in the **Label** text field.

3 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
Vp_	0.060325[V]	0.060325 V	
Vn_	0.034063[V]	0.034063 V	

ADD STUDY

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

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

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

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

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

STUDY 2: SWEEP VP

In the **Settings** window for **Study**, type `Study 2: Sweep Vp` in the **Label** text field.

Step 1: Stationary

1 In the **Model Builder** window, under **Study 2: Sweep Vp** click **Step 1: Stationary**.

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

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

4 In the **Relative tolerance** text field, type `1E-6`.

5 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**.

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

7 From the **Study** list, choose **Study 1: Equilibrium, Semiconductor Equilibrium**.

8 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

9 Click **Add**.

10 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (Applied voltage)	`(Vn_+Vp_)*range(0,0.1,1)`	V

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

RESULTS

Net Dopant Concentration (semi) 1

In the **Model Builder** window, under **Results** right-click **Net Dopant Concentration (semi) 1** and choose **Delete**.

J-V

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Sweep Vp/Solution 2 (sol2)**.

Point Graph 1

1 Right-click **J-V** and choose **Point Graph**.

2 Select Boundary 1 only.

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

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

5 In the **Unit** field, type `A/cm^2`.

6 Select the **Description** checkbox. In the associated text field, type `Current density`.

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

8 In the **Expression** text field, type `V0`.

9 Select the **Description** checkbox.

10 In the **J-V** toolbar, click **Plot**.

Jx and Jt

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Sweep Vp/Solution 2 (sol2)**.

4 From the **Parameter selection (V0)** list, choose **From list**.

5 In the **Parameter values (V0 (V))** list, select **0.037755**.

Line Graph 1

1 Right-click **Jx and Jt** and choose **Line Graph**.

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 `semi.JX`.

5 In the **Unit** field, type `A/cm^2`.

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

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

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

9 Find the **Include** subsection. Clear the **Solution** checkbox.

10 Select the **Description** checkbox.

Line Graph 2

1 Right-click **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 `Jt`.

4 In the **Jx and Jt** toolbar, click **Plot**.