Created in COMSOL Multiphysics 6.2

Caughey–Thomas Mobility

This example demonstrates how to use the Caughey–Thomas high-field saturation model for the electron and hole mobility. Field-dependent mobility makes a problem which is already highly nonlinear even more nonlinear. The Semiconductor physics interface automatically creates a suggested solver sequence for better convergence when a built-in field-dependent mobility model is used.

Introduction

With an increase in the parallel component of the applied field, carriers can gain energies above the ambient thermal energy and then transfer energy gained from the field to the lattice by optical phonon emission. This effect leads to a saturation of the carriers velocity.

The Caughey–Thomas mobility model adds high field velocity saturation to an existing mobility model (or to a constant input mobility), based on equations presented in Ref. 1.

The electron ($\mu_{n,ct}$) and hole ($\mu_{p,ct}$) mobilities are determined by the following equations:

$$\mu_{n,ct} = \frac{\mu_{in,n}}{\left(1+\left(\frac{\mu_{in,n}F_n}{v_{\mathrm{sat},n}}\right)^{\alpha_n}\right)^{1/\alpha_n}} \qquad \mu_{p,ct} = \frac{\mu_{in,p}}{\left(1+\left(\frac{\mu_{in,p}F_p}{v_{\mathrm{sat},p}}\right)^{\alpha_p}\right)^{1/\alpha_p}}$$

$$\alpha_n = \alpha_{0,n}\left(\frac{T}{T_{\mathrm{ref}}}\right)^{\beta_{1,n}} \qquad \alpha_p = \alpha_{0,p}\left(\frac{T}{T_{\mathrm{ref}}}\right)^{\beta_{1,p}}$$

$$v_{\mathrm{sat},n} = v_{0,n}\left(\frac{T}{T_{\mathrm{ref}}}\right)^{\beta_{2,n}} \qquad v_{\mathrm{sat},p} = v_{0,p}\left(\frac{T}{T_{\mathrm{ref}}}\right)^{\beta_{2,p}}$$

Here T is the lattice temperature, $\mu_{in,n}$ and $\mu_{in,p}$ are the electron and hole input mobilities, respectively, and F_n and F_p are the driving forces for electrons and holes, respectively (several options are available, the default is $F_n = E_{\|,n}$ and $F_p = E_{\|,p}$, where $E_{\|,n}$ is the magnitude of the component of the electric field parallel to the electron current and $E_{\|,p}$ is the magnitude of the component of the electric field parallel to the hole current). All other parameters in the model are material properties (note that $v_{0,n}$ and $v_{0,p}$ are the saturation velocities for electrons and holes at the reference temperature T_{ref} and have units of m/s). The material properties for Silicon are also obtained from Ref. 1.

Model Definition

The model represents a simplified channel region of a 2D MOSFET, where the n-doped drain and source are located on the left and right side of the geometry, respectively; see

Figure 1. The gate is positioned on top of the p-doped silicon section, which is located at the center of the device.

The model consists of sweeping the drain to source voltage form 0 V to 1 V under a gate to source voltage of 0 V. Sweeping the drain voltage creates a significant electric field at the left side of the gate at the p–n junction.

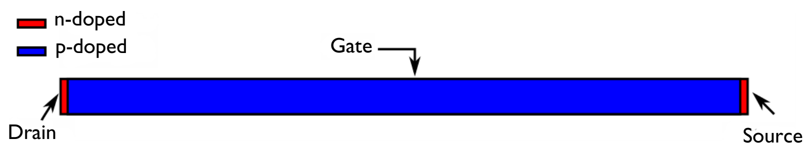

Figure 1: Schematic of the modeled device.

The field-dependent mobility models are very nonlinear and difficult to solve in a fully coupled manner. The Semiconductor physics interface automatically creates a suggested solver sequence when the built-in field-dependent mobility models are used. This suggested solver sequence alternately solves the main dependent variables with the electric field variables fixed and then updates the electric field variables afterward, using the Segregated solver. By default, 3 iterations are used; however, depending on the model, more iterations may be needed. For this model, 4 iterations are used for better accuracy.

Results and Discussion

Figure 2 shows the effect of the Caughey–Thomas mobility model on the solution. The comparison of the constant mobility (the driving forces F_n and F_p are multiplied by 0) and the Caughey–Thomas mobility model (F_n and F_p multiplied by 1) shows a more pronounced saturation effect for the Caughey–Thomas model.

Figure 3 shows that the electron mobility varies substantially along the device. The electron mobility is 3 order of magnitude lower in the vicinity of the drain–gate junction as a consequence of the high electric field generated by the applied potential on the drain contact.

Figure 4 and Figure 5 show the effect of the mobility model on the electron drift velocity. Figure 4 shows the electron drift velocity for the Caughey–Thomas mobility model (F_n and F_p multiplied by 1) and Figure 5 for the constant mobility model (F_n and F_p multiplied by 0). A comparison of the two figures clearly shows an important reduction of the electron drift velocity when the field effect is taken into account.

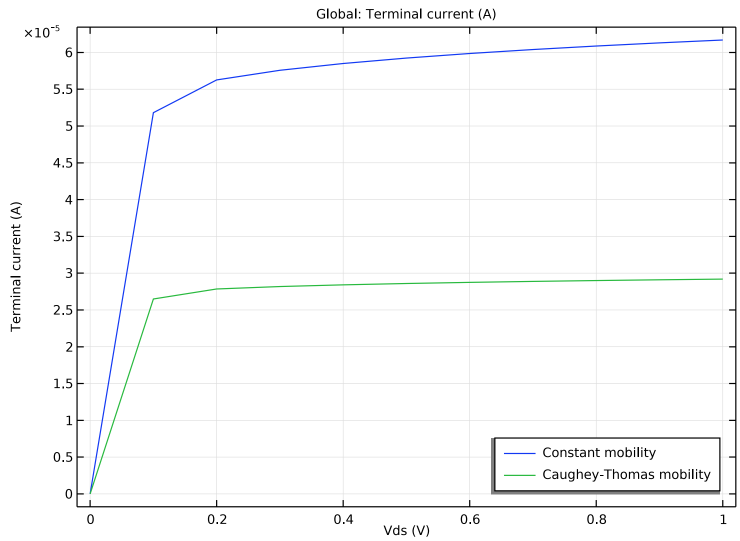

Figure 2: Comparison of the terminal current for the constant mobility and Caughey–Thomas mobility. The current is lower and levels off more rapidly due to the fact that the mobility decreases when the electric field is high.

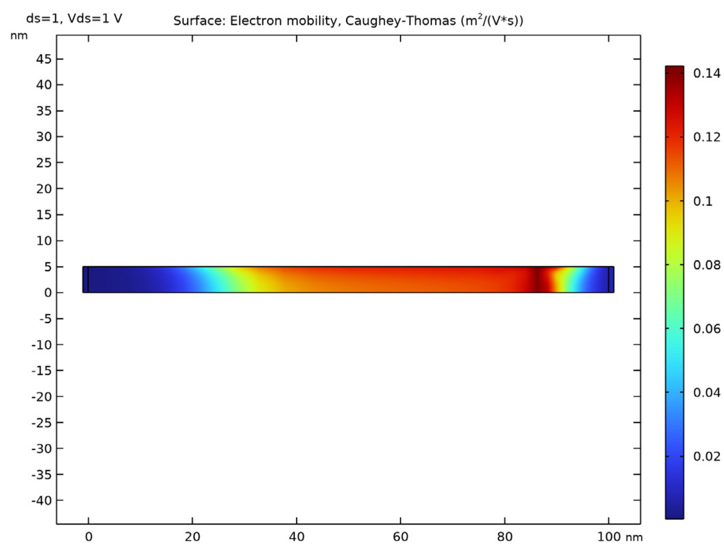

Figure 3: Plot of the electron mobility at a drain–source voltage of 1 V. The mobility varies by 3 orders of magnitude over the modeling domain.

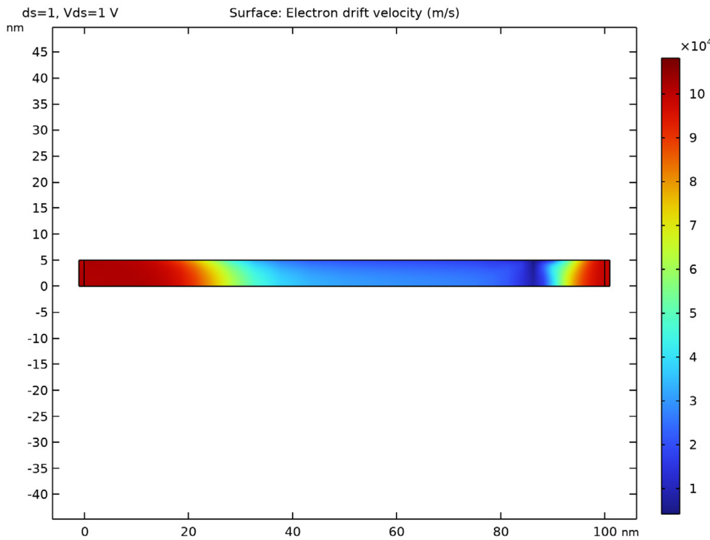

Figure 4: Plot of the electron drift velocity using Caughey–Thomas mobility. The drift velocity barely exceeds 1 x 10^5 m/s.

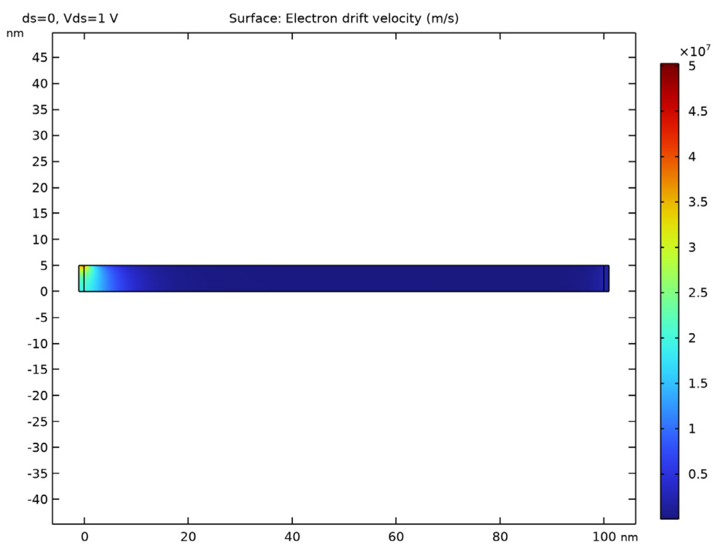

Figure 5: Plot of the electron drift velocity for the constant mobility case. Since the mobility does not decrease as the electric field increases, the drift velocity becomes very high.

Reference

1. C. Canali, G. Majni, R. Minder, and G. Ottaviani, "Electron and Hole Drift Velocity Measurements in Silicon and Their Empirical Relation to Electric Field and Temperature", *IEEE Transactions on Electron Devices*, vol. 22, no. 11, pp. 1045–1047, 1975.

Note: Note the correction in: G. Ottaviani, "Correction to 'Electron and hole drift velocity measurements in silicon and their empirical relation to electric field and temperatures'," *IEEE Transactions on Electron Devices*, vol. 23, no. 9, p. 1113, 1976.

Application Library path: `Semiconductor_Module/Transistors/caughey_thomas_mobility`

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 (semi)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Stationary**.

6 Click **Done**.

Enter model parameters.

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**
`Wfin`	`10[nm]`	1E-8 m	`Height`
`Lg`	`100[nm]`	1E-7 m	`Width`
`tox`	`1[nm]`	1E-9 m	`Gate oxide thickness`
`Vds`	`0[V]`	0 V	`Drain source voltage`
`Vgs`	`0[V]`	0 V	`Gate source voltage`
`ds`	`0`	0	`Continuation parameter`

Create model geometry representing a simplified channel region of a field effect transistor.

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

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

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `Lg`.

4 In the **Height** text field, type `Wfin/2`.

Rectangle 2 (r2)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Height** text field, type `Wfin/2`.

4 Locate the **Position** section. In the **x** text field, type `-1`.

Rectangle 3 (r3)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Height** text field, type `Wfin/2`.

4 Locate the **Position** section. In the **x** text field, type `Lg`.

5 Click **Build All Objects**.

Add the built-in silicon material properties.

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.

Enter physics settings.

SEMICONDUCTOR (SEMI)

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

2 In the **Settings** window for **Semiconductor**, click to expand the **Continuation Settings** section.

3 In the C_p text field, type `ds`.

Analytic Doping Model 1

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

2 Select Domains 1 and 3 only.

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

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

5 In the N_{D0} text field, type `1e19[1/cm^3]`.

Analytic Doping Model 2

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

2 Select Domain 2 only.

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

4 In the N_{A0} text field, type `1e15[1/cm^3]`.

Metal Contact 1

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 `Vds`.

Metal Contact 2

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

2 Select Boundary 10 only.

Thin Insulator Gate 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Thin Insulator Gate**.
2 Select Boundary 6 only.
3 In the **Settings** window for **Thin Insulator Gate**, locate the **Terminal** section.
4 In the V_0 text field, type `Vgs`.
5 Locate the **Gate Contact** section. In the ε_{ins} text field, type `3.9`.
6 In the d_{ins} text field, type `tox`.

Semiconductor Material Model 1

In the **Model Builder** window, click **Semiconductor Material Model 1**.

Caughey-Thomas Mobility Model (E) 1

1 In the **Physics** toolbar, click **Attributes** and choose **Caughey-Thomas Mobility Model (E)**.
2 In the **Settings** window for **Caughey-Thomas Mobility Model (E)**, click to expand the **Continuation Settings** section.
3 From the **Continuation type** list, choose **Use interface continuation parameter**.

Do not forget to select the mobility model in the Semiconductor Material Model node, otherwise the mobility model subnode has no effect.

Semiconductor Material Model 1

1 In the **Model Builder** window, 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 **Electron mobility, Caughey-Thomas (semi/smm1/mmct1)**.
4 From the μ_p list, choose **Hole mobility, Caughey-Thomas (semi/smm1/mmct1)**.

   Optionally use the finite element log formulation to compute this model.
5 In the **Model Builder** window, click **Semiconductor (semi)**.
6 In the **Settings** window for **Semiconductor**, click to expand the **Discretization** section.
7 From the **Formulation** list, choose **Finite element, log formulation (linear shape function)**.

Set up a user-defined mesh.

MESH 1

Mapped 1

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

2 In the **Settings** window for **Mapped**, click to expand the **Reduce Element Skewness** section.

3 Select the **Adjust edge mesh** check box.

Distribution 1

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

2 Select Boundaries 1, 4, and 10 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type `20`.

6 In the **Element ratio** text field, type `5`.

7 From the **Growth rate** list, choose **Exponential**.

8 Select the **Reverse direction** check box.

Distribution 2

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

2 Select Boundaries 3 and 9 only.

Distribution 3

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

2 Select Boundary 6 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type `50`.

6 In the **Element ratio** text field, type `25`.

7 From the **Growth rate** list, choose **Exponential**.

8 Select the **Symmetric distribution** check box.

Set up an auxiliary sweep for the `ds` parameter, with the value 0 for constant mobility and 1 for mobility model.

STUDY 1

Step 1: Stationary

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

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vds (Drain source voltage)		V

6 Click **Add**.

7 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vds (Drain source voltage)	`range(0,0.1,1)`	V
ds (Continuation parameter)	`0 1`	

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

9 From the **Reuse solution from previous step** list, choose **Auto**.

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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 1>Solver Configurations>Solution 1 (sol1)>Stationary Solver 1** node, then click **Segregated 1**.

4 In the **Settings** window for **Segregated**, locate the **General** section.

5 In the **Number of iterations** text field, type 4.

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

RESULTS

Electron Concentration (semi)

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

1D Plot Group 5

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

Global 1

1 Right-click **1D Plot Group 5** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Semiconductor>Terminals>semi.I0_1 - Terminal current - A**.

3 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Vds**.

4 In the **1D Plot Group 5** toolbar, click **Plot**.

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

6 In the table, enter the following settings:

Legends
Constant mobility
Caughey-Thomas mobility

7 In the **1D Plot Group 5** toolbar, click **Plot**.

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

1D Plot Group 5

1 In the **Model Builder** window, click **1D Plot Group 5**.

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

3 From the **Position** list, choose **Lower right**.

2D Plot Group 6

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

Surface 1

1 Right-click **2D Plot Group 6** and choose **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Semiconductor>Mobility>semi.mun_ct - Electron mobility, Caughey-Thomas - $m^2/(V \cdot s)$**.

3 In the **2D Plot Group 6** toolbar, click **Plot**.

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

2D Plot Group 6

In the **Model Builder** window, right-click **2D Plot Group 6** and choose **Duplicate**.

Surface 1

1 In the **Model Builder** window, expand the **2D Plot Group 7** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `semi.mun_ct*semi.smm1.mmct1.Fn`.

4 Select the **Description** check box. In the associated text field, type `Electron drift velocity`.

5 In the **2D Plot Group 7** toolbar, click **Plot**.

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

2D Plot Group 7

1 In the **Model Builder** window, click **2D Plot Group 7**.

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

3 From the **Parameter value (ds)** list, choose **0**.

4 In the **2D Plot Group 7** toolbar, click **Plot**.

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