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MOSFET with Mobility Models

This tutorial shows how to add several linked mobility models to the basic MOSFET example, including two field-dependent mobility models which are very nonlinear and difficult to solve in a fully coupled manner. When such built-in field-dependent mobility models are used, the Semiconductor physics interface automatically creates a suggested solver sequence. Convergence is readily achieved by this autogenerated solver sequence which uses the Segregated solver to alternately solve the main dependent variables with the electric field variables fixed, and then update the electric field variables subsequently.

Introduction

The response of the charged carriers to electric fields and their subsequent momentum loss due to a host of physical processes can be a very important factor in semiconductor simulation. There are numerous physical processes that act to remove momentum from charged carriers within a semiconductor device. These include, but are not limited to, lattice vibrations (L), ionized impurity ions (I), carrier concentrations (C), and surface effects (S). The effect of these individual microscopic processes are generally combined into the macroscopic quantity, the carrier mobility, found in the transport equations. In addition, the presence of large electric fields (E) within the device can serve to significantly reduce the carrier mobility in those regions.

In some cases a constant value for the mobility can be used, measured for a particular semiconductor material. However, in many devices, the physics demands that you model the effects described above as they can drastically alter the value of the carrier mobility in certain parts of the device.

This model adds three mobility models to the basic MOSFET model to explore the effect of these processes on the I–V characteristics. Please review the MOSFET model in the Application Libraries first.

Model Definition

The geometry and operation of the device are discussed for the DC Characteristics of a MOS Transistor (MOSFET) model.

There are several mobility models available for use within the Semiconductor interface. They are provided to cover all the basic processes and physics that may be present in your model that may affect the carrier mobility.

In general, the correct use of mobility models in semiconductor simulations is not straightforward. There exist several families of models that need to be used and combined in particular ways. The implementation within the Semiconductor interface aims to simplify their use by providing a mechanism to "chain" mobility models together in the appropriate way. In addition, flexibility is provided so that custom or complex user-defined mobility models can be implemented with ease.

In this tutorial model three mobility models are added and linked together. The mobility models are listed below together with a small description. For more information, see the "Mobility Models" theory section in the *Semiconductor Module User's Guide*.

Arora mobility model (LI)

The Arora mobility model (Ref. 1) is an empirical model that aims to model both phonon (L) and ionized impurity scattering (I). This model calculates carrier mobilities based solely on provided model parameters, therefore it can be used on its own or as an intermediate step for other mobility models. In this example it is used as an input into the Lombardi surface mobility model.

Lombardi Surface Mobility Model (S)

The Lombardi surface mobility model (Ref. 3) adds surface scattering (S) resulting from surface acoustic phonons and from surface roughness. Mobility contributions corresponding to these effects are combined with the input mobility using Matthiessen's rule. This model is not a standalone model as it adjusts a supplied base mobility to include the described effects. The model accepts input mobilities of type L (power law mobility model), LI (Arora mobility model), or C (Fletcher mobility model (Ref. 2)) as well as a user-defined mobility. The Lombardi model is used as an input for the Caughey–Thomas mobility model.

Caughey–Thomas Mobility Model (E)

The Caughey–Thomas mobility model (Ref. 4) adds high field velocity scattering (E) to an existing mobility model (or to a constant input mobility). It also cannot be used as a standalone model, and it accepts input mobilities of type L (power law mobility model), LI (Arora mobility model), C (Fletcher mobility model), or S (Lombardi) as well as a user-defined input mobility.

Once linked together, the model uses the output from the Caughey–Thomas model as the mobility used within the transport equations. This mobility contains contributions from all three mobility models.

Numerous combinations of mobility models can be used and linked together depending upon the particular device being modeled. Simple, low bias p–n junction devices may only require lattice and ionized impurity models, whereas highly doped devices with high field regions close to contacts such as certain MOSFET devices may require the inclusion of carrier concentrations, surface effects, and high-field effect.

Model	Physics	Example 1 (all models)	Example 2 (LI+S+E)	Example 3 (L+S)
Constant				
Power Law	Lattice (L)			(L)
Arora	Lattice + Impurity (LI)	(LI)	(LI)	
Fletcher	Carrier conc. (C)	(LI+C)		
Lombardi	Surface (S)	(LI+C+S)	(LI+S)	(L+S)
Caughey-Thomas	High E-field (E)	(LI+C+S+E)	(LI+S+E)	

Figure 1: Mobility model linking scheme and examples.

The mobility models link together as shown in Figure 1. A particular mobility model can be combined to include the physics of any mobility model below it in the table; mobility models cannot link to models above them in the table. Mobility models can be skipped as you go down the table if that process is not important. The tutorial model links the mobility models as shown in example 2.

Some of the mobility models are highly nonlinear, in particular the Fletcher, Lombardi, and Caughey–Thomas models. As a result, the implementation of these models is designed such that their effect can be slowly introduced via a continuation parameter. This allows models to be solved with small contributions from these models initially, with a gradual ramp up to their full effect.

In addition, for the field-dependent mobility models (Lombardi and Caughey–Thomas), convergence can be helped by using the Segregated solver to first solve the main dependent variables with the electric field variables kept constant, and then update the electric field variables in a second Segregated Step, and alternate between the first and second steps for a few iterations. The Semiconductor physics interface automatically generates a suggested solver sequence to do this when Lombardi and/or Caughey–Thomas mobility models are used.

The model in this tutorial uses the automatically generated solver sequence.

Results and Discussions

Figure 2 compares the I–Vd (Vg=2 V) characteristics with constant mobility and with the added mobility models.

Mobility models generally model processes that remove or limit the momentum of the carriers, therefore a reduction in the drain current is expected when they are included in the model, as shown clearly in the figure.

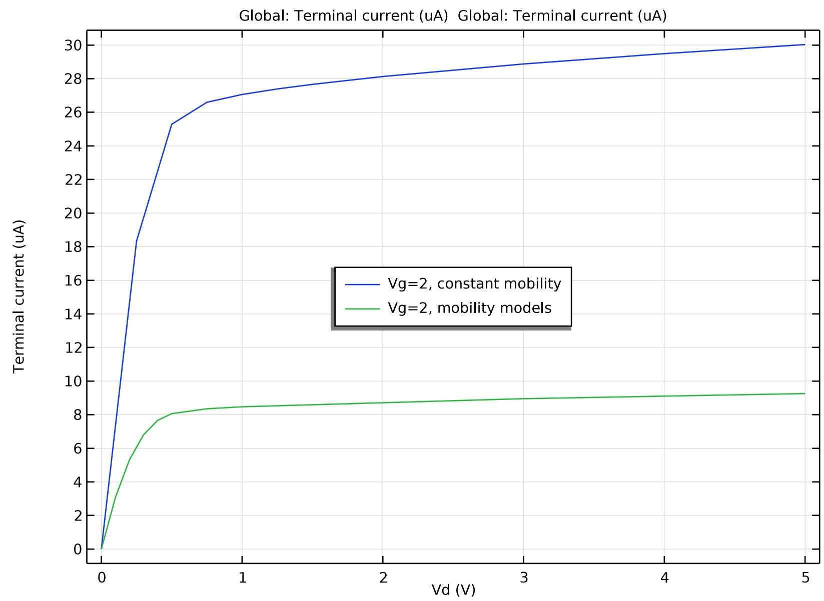

Figure 2: I–Vd (Vg=2V) characteristics comparing a model with constant mobility and with added mobility models.

References

1. N.D. Arora, J.R. Hauser, and D.J. Roulston, "Electron and Hole Mobilities in Silicon as a Function of Concentration and Temperature," *IEEE Transactions on Electron Devices*, vol. 29, no. 2, pp. 292–295, 1982.

2. J.M. Dorkel and Ph. Leturcq, "Carrier Mobilities in Silicon Semi-empirically Related to Temperature, Doping and Injection Level," *Solid-State Electronics*, vol. 24, no. 9, pp. 821–825, 1981.

3. C. Lombardi, S. Manzini, A. Saporito, and M. Vanzi, “A physically based mobility model for numerical simulation of nonplanar devices,” *IEEE Transactions on Computer-Aided Design*, vol. 7, no. 11, pp. 1164–1171, 1988.

4. 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 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/mosfet_mobility`

Modeling Instructions

ROOT

Open the existing MOSFET model (filename: mosfet.mph).

APPLICATION LIBRARIES

1 From the **File** menu, choose **Application Libraries**.

2 In the **Application Libraries** window, select **Semiconductor Module>Transistors>mosfet** in the tree.

3 Click **Open**.

Add the Arora mobility model. This models lattice and ionized impurity scattering effects. This model does not take any inputs other than the model parameters.

COMPONENT 1 (COMP1)

In the **Model Builder** window, expand the **Component 1 (comp1)** node.

SEMICONDUCTOR (SEMI)

Semiconductor Material Model 1

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

Arora Mobility Model (LI) 1

1 In the **Physics** toolbar, click **Attributes** and choose **Arora Mobility Model (LI)**.

Next add the Lombardi surface mobility model. This mobility model takes the output from the Arora model as its input, along with additional model parameters.

Semiconductor Material Model 1

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

Lombardi Surface Mobility Model (S) 1

1 In the **Physics** toolbar, click **Attributes** and choose **Lombardi Surface Mobility Model (S)**.

To connect the output of the Arora model to the input of the Lombardi model, you select the appropriate values for the input mobilities within the Lombardi model.

2 In the **Settings** window for **Lombardi Surface Mobility Model (S)**, locate the **Input Mobilities** section.

3 From the $\mu_{n,in}$ list, choose **Electron mobility, Arora (semi/smm1/mmar1)**.

4 From the $\mu_{p,in}$ list, choose **Hole mobility, Arora (semi/smm1/mmar1)**.

Next add the Caughey-Thomas mobility model. This mobility model takes the output from the Lombardi (or the Arora model) as its input, along with additional model parameters.

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)**, locate the **Input Mobilities** section.

3 From the $\mu_{n,in}$ list, choose **Electron mobility, Lombardi (semi/smm1/mmls1)**.

4 From the $\mu_{p,in}$ list, choose **Hole mobility, Lombardi (semi/smm1/mmls1)**.

To connect the output of the Lombardi model to the input of the Caughey-Thomas model, again you select the appropriate values for the input mobilities.

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)**.

Add a new stationary study to solve the model with the mobility models. This will allow comparison between the currents with and without the mobility models.

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 **Add Study** in the window toolbar.

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

STUDY 3 - MOBILITY MODELS

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

2 In the **Settings** window for **Study**, type `Study 3 - mobility models` in the **Label** text field.

Step 1: Stationary

Set up the study to sweep over the drain voltage `Vd`. A range together with manual values will allow resolution only where it is needed.

1 In the **Model Builder** window, under **Study 3 - mobility models** 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 From the **Sweep type** list, choose **All combinations**.

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vd (Drain voltage)	`range(0,0.1,0.5) 0.75 1 3 5`	V

7 In the table, click to select the cell at row number 1 and column number 3.

Our initial solution (Vd = 0V, Vg = 2V) has already been computed in study 2.

8 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**.

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

10 From the **Study** list, choose **Study 2, Stationary**.

11 From the **Parameter value (Vd (V),Vg (V))** list, choose **1: Vd=0 V, Vg=2 V**.

The field-dependent mobility models are very nonlinear and difficult to solve in a fully coupled manner. The Semiconductor 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 update the electric field variables afterward, using the Segregated solver. By default 3 iterations is used, however depending on the model, more iterations may be needed. let us take a look at the suggested solver setup.

Solution 3 (sol3)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node.

   Observe that the default number of iterations for the Segregated solver is 3.

3 In the **Model Builder** window, expand the **Study 3 - mobility models>Solver Configurations>Solution 3 (sol3)>Stationary Solver 1>Segregated 1** node, then click **Segregated Step 1**.

4 In the **Settings** window for **Segregated Step**, click to expand the **Method and Termination** section.

   Observe that the main variables are solved in the first Segregated Step with the Automatic Newton solver.

   Click on **Segregated Step 2**, and observe that the electric field variables are updated in the second Segregated Step with the Constant Newton solver.

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

   Next, duplicate the I-V plot and compare the current obtained with and without the mobility models.

RESULTS

Id vs. Vd

In the **Model Builder** window, under **Results** right-click **Id vs. Vd** and choose **Duplicate**.

Id vs. Vd 1

1 In the **Model Builder** window, expand the **Results>Id vs. Vd 1** node, then click **Id vs. Vd 1**.

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

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

4 In the **Parameter values (Vg (V))** list, select **2**.

Global 1

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

Global 2

1 In the **Model Builder** window, click **Global 2**.
2 In the **Settings** window for **Global**, locate the **Data** section.
3 From the **Dataset** list, choose **Study 3 - mobility models/Solution 3 (sol3)**.
4 In the **Id vs. Vd 1** 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
`Vg=2, mobility models`

Global 1

1 In the **Model Builder** window, click **Global 1**.
2 In the **Settings** window for **Global**, locate the **Legends** section.
3 From the **Legends** list, choose **Manual**.
4 In the table, enter the following settings:

Legends
`Vg=2, constant mobility`

5 In the **Id vs. Vd 1** toolbar, click **Plot**.