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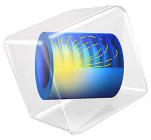


Lombardi Surface Mobility

This example demonstrates how to use the Lombardi surface scattering model for the electron mobility in a simple MOSFET. The additional nonlinearity introduced by the field dependence of the mobility is readily overcome by the autogenerated solver sequence upon detection of such mobility models by the Semiconductor physics interface. The current density profile and total current flowing into the terminal is compared with the constant mobility case.

Introduction

Surface acoustic phonons and surface roughness have an important effect on the carrier mobility, especially in the thin inversion layer under the gate in MOSFETs. The Lombardi surface mobility model adds surface scattering resulting from these effects to an existing mobility model using Matthiessen's rule. The mobility model is based on the equations presented in Ref. 1.

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

$$\frac{1}{\mu_{n,lo}} = \frac{1}{\mu_{in,n}} + \frac{1}{\mu_{ac,n}} + \frac{1}{\mu_{sr,n}} \qquad \frac{1}{\mu_{p,lo}} = \frac{1}{\mu_{in,p}} + \frac{1}{\mu_{ac,p}} + \frac{1}{\mu_{sr,p}}$$

$$\mu_{ac,n} = \frac{\mu_{1,n}}{\left(\frac{E_{\perp,n}}{E_{ref}}\right)} + \frac{\mu_{2,n}\left(\frac{N}{N_{ref}}\right)^{\beta_n}}{\left(\frac{E_{\perp,n}}{E_{ref}}\right)^{1/3}\left(\frac{T}{T_{ref}}\right)} \qquad \mu_{ac,p} = \frac{\mu_{1,p}}{\left(\frac{E_{\perp,p}}{E_{ref}}\right)} + \frac{\mu_{2,p}\left(\frac{N}{N_{ref}}\right)^{\beta_p}}{\left(\frac{E_{\perp,p}}{E_{ref}}\right)^{1/3}\left(\frac{T}{T_{ref}}\right)}$$

$$\mu_{sr,n} = \frac{\delta_n}{E_{\perp,n}^2} \qquad \mu_{sr,p} = \frac{\delta_p}{E_{\perp,p}^2}$$

$$N = N_a^- + N_d^+$$

where T is the lattice temperature, $\mu_{in,n}$ and $\mu_{in,p}$ are the electron and hole input mobilities, N_a^- is the ionized acceptor concentration, N_d^+ is the ionized donor concentration, $E_{\perp,n}$ is the component of the electric field perpendicular to the electron current and $E_{\perp,p}$ is the component of the electric field perpendicular to the hole current. All other parameters in the model are material properties (note that δ_n and δ_p have units of V/s). The material properties for silicon are also obtained from Ref. 1.

Model Definition

The model represents a 2D MOSFET where the n-doped drain and source contacts are located at the top right and top left of the geometry, respectively; see Figure 1. The gate is positioned above the p-doped silicon section which is located at the center of the device.

The model sweeps the drain voltage form 0 V to 1 V with an applied gate voltage of 1 V. We expect a significant perpendicular (to the currents) electric field underneath the gate contact. In order to ensure convergence of the nonlinear model, the Semiconductor physics interface creates a Segregated solver to first solve the main dependent variables with the electron and hole perpendicular components of the field ($\boldsymbol{E}_{\perp,n}$ and $\boldsymbol{E}_{\perp,p}$) fixed, and then update the electric field variables separately.

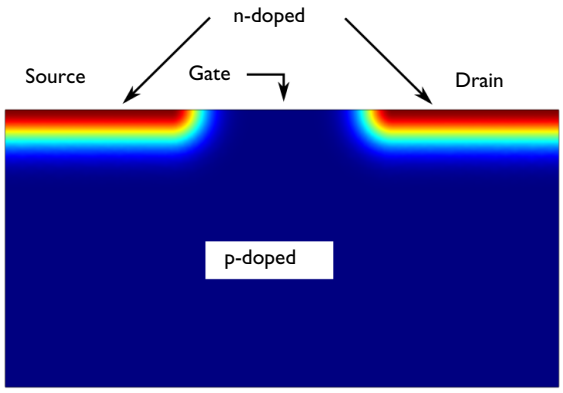


Figure 1: Schematic of the modeled device.

Results and Discussion

Figure 2 shows the effect of the Lombardi surface mobility model on the solution. The comparison of the constant mobility (the perpendicular fields are multiplied by 0) and the Lombardi surface mobility ($\boldsymbol{E}_{\perp,n}$ and $\boldsymbol{E}_{\perp,p}$ multiplied by 1) models shows a more pronounced saturation effect for the Lombardi surface mobility model than for the constant mobility model (without field dependent parameters).

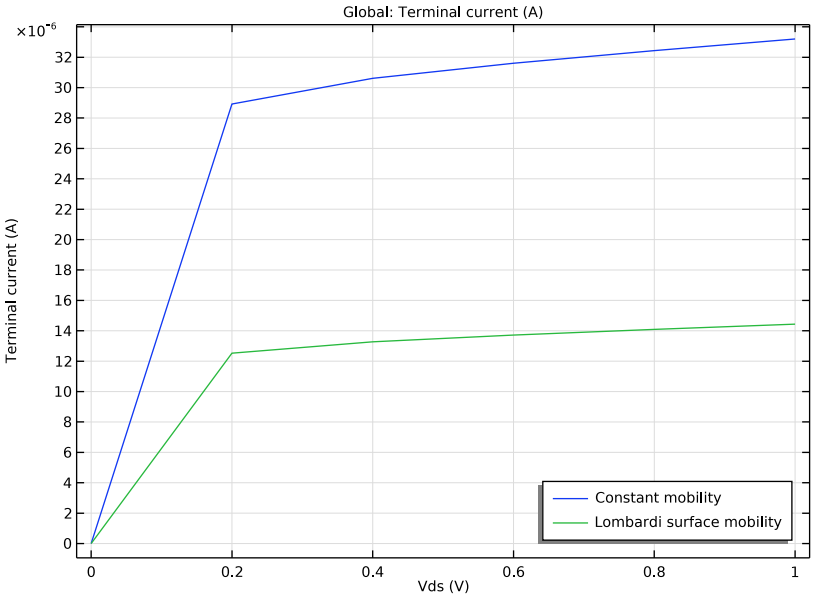


Figure 2: Plot of terminal current for the constant mobility and surface mobility cases. The current is reduced when the surface mobility model is active.

Figure 3 shows that the electron current density varies substantially in the inversion layer depending on the used mobility model. The Lombardi surface mobility model (top) shows a lower current density in comparison to the one observed with the constant mobility model (bottom).

Figure 4 shows that the electron mobility also varies along the device. As a consequence of the surface scattering effect, the electron mobility is smaller in the vicinity of the gate contact.

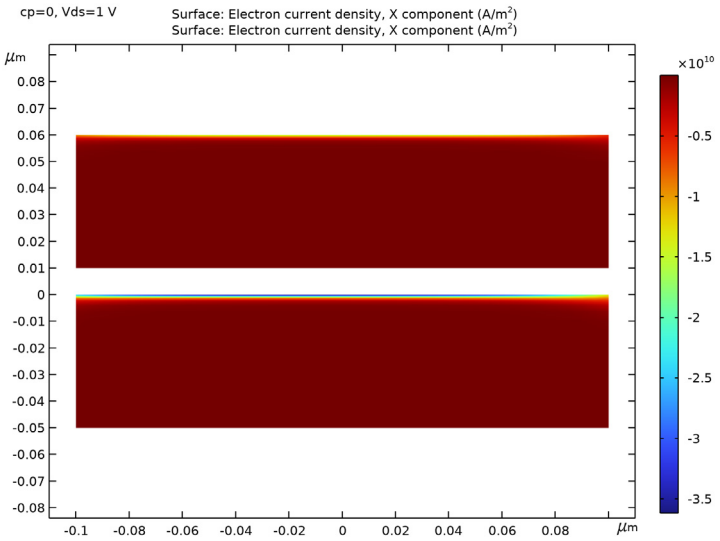


Figure 3: Plot of the electron current density on the same scale with the Lombardi surface mobility model active (top) and without (bottom).

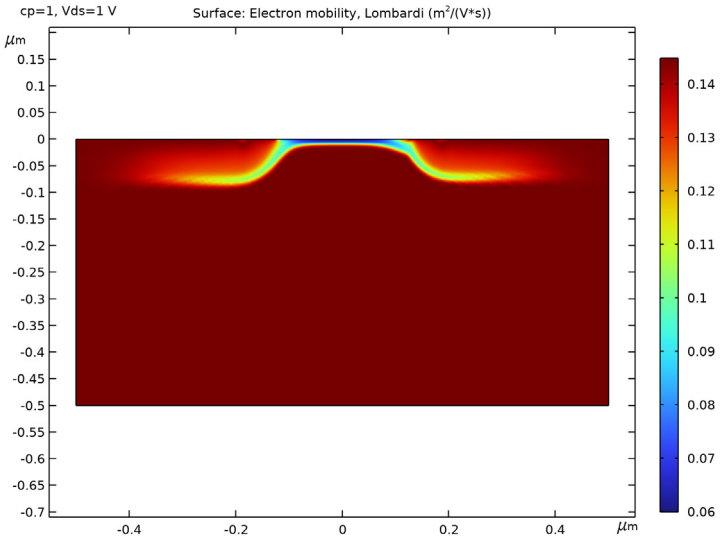


Figure 4: Plot of the electron mobility for a drain-source voltage of 1 volt with the Lombardi surface mobility model active.

Reference

1. C.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. 1164–117, 1988.

Application Library path: `Semiconductor_Module/Transistors/lombardi_surface_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
Vds	0[V]	0 V	Drain-source voltage

Name	Expression	Value	Description
Vgs	1[V]	1 V	Gate-source voltage
cp	0	0	Continuation parameter

Create model geometry representing a simplified MOSFET.

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 **µm**.

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 **Height** text field, type `0.5`.

4 Locate the **Position** section. In the **x** text field, type `-0.5`.

5 In the **y** text field, type `-0.5`.

6 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (µm)
Layer 1	0.01

7 Clear the **Layers on bottom** check box.

8 Select the **Layers on top** check box.

9 Click **Build All Objects**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **x** text field, type `-0.12`.

6 Locate the **Endpoint** section. In the **x** text field, type `0.12`.

Line Segment 2 (ls2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **x** text field, type `-0.18`.

6 Locate the **Endpoint** section. In the **x** text field, type `-0.5`.

Line Segment 3 (ls3)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **x** text field, type `0.18`.

6 Locate the **Endpoint** section. In the **x** text field, type `0.5`.

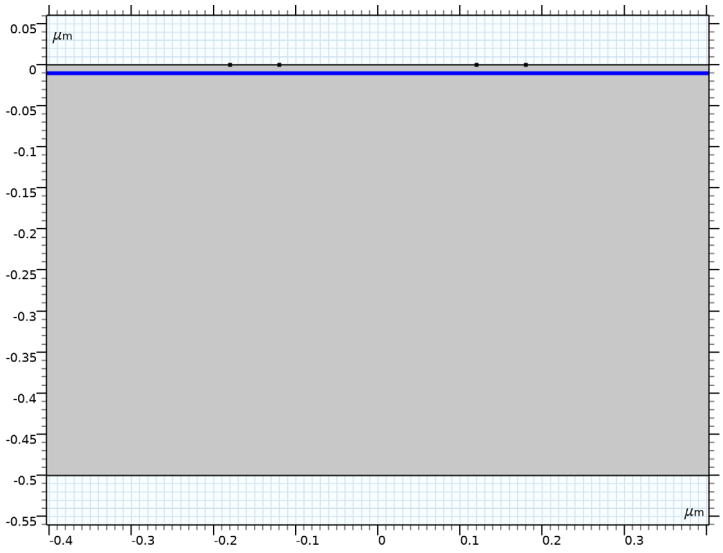
7 Click **Build All Objects**.

Mesh Control Edges 1 (mce1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Mesh Control Edges**.

2 On the object **fin**, select Boundary 4 only.

It might be easier to select the correct boundary by using the **Selection List** window. To open this window, in the **Home** toolbar click **Windows** and choose **Selection List**. (If you are running the cross-platform desktop, you find **Windows** in the main menu.)



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 `cp`.

Metal Contact 1

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

2 Select Boundaries 2 and 3 only.

Metal Contact 2

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

2 Select Boundary 7 only.

3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.

4 In the V_0 text field, type `Vds`.

Thin Insulator Gate 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Thin Insulator Gate**.

2 Select Boundary 5 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 `4.2`.

6 In the d_{ins} text field, type `5[nm]`.

7 In the Φ text field, type `4.5[V]`.

Analytic Doping Model 1

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

2 Select Domain 1 only.

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

4 In the N_{A0} text field, type `5e17[1/cm^3]`.

Analytic Doping Model 2

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

2 Select Domain 1 only.

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

4 From the list, choose **Box**.

5 Locate the **Uniform Region** section. Specify the r_0 vector as

`0.2[um]`	X
`0[um]`	Y

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

7 Locate the **Uniform Region** section. In the W text field, type `0.3[um]`.

8 In the D text field, type `0.2[um]`.

9 Locate the **Impurity** section. In the N_{D0} text field, type `1e19[1/cm^3]`.

10 Locate the **Profile** section. In the d_j text field, type `0.1[um]`.

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

Analytic Doping Model 3

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

2 Select Domain 1 only.

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

4 From the list, choose **Box**.

5 Locate the **Uniform Region** section. Specify the r_0 vector as

`-0.5[um]`	X
`0[um]`	Y

6 In the W text field, type `0.3[um]`.

7 In the D text field, type `0.2[um]`.

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

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

10 Locate the **Profile** section. In the d_j text field, type `0.1[um]`.

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

Trap-Assisted Recombination 1

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

2 Select Domain 1 only.

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)**.

2 In the **Settings** window for **Lombardi Surface Mobility Model (S)**, 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, Lombardi (semi/smm1/mmls1)**.

Set up a user-defined mesh.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Size

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

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

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `0.04`.

5 In the **Maximum element growth rate** text field, type `1.04`.

Size 1

In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Size 1** and choose **Delete**.

Size 2

In the **Model Builder** window, right-click **Size 2** and choose **Delete**.

Free Triangular 1

In the **Model Builder** window, right-click **Free Triangular 1** and choose **Delete**.

Edge 1

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

2 Select Boundaries 3–7 only.

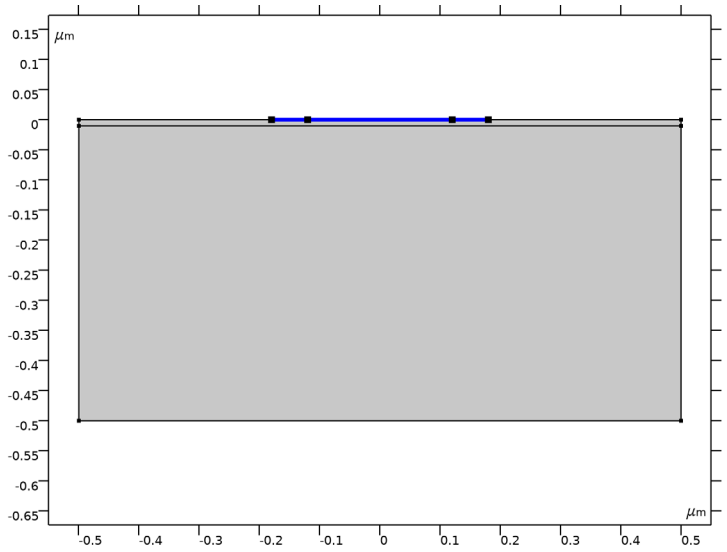
3 In the **Settings** window for **Edge**, click to expand the **Control Entities** section.

4 Clear the **Smooth across removed control entities** check box.

Size 1

1 Right-click **Edge 1** and choose **Size**.

2 Select Boundaries 4–6 only.



3 In the **Settings** window for **Size**, locate the **Element Size** section.

4 From the **Calibrate for** list, choose **Semiconductor**.

5 Click the **Custom** button.

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

7 In the associated text field, type `0.005`.

Copy Edge 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Copying Operations> Copy Edge**.

2 In the **Settings** window for **Copy Edge**, locate the **Source Boundaries** section.

3 Click  **Paste Selection**.

4 In the **Paste Selection** dialog box, type `3-7` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Copy Edge**, locate the **Destination Boundaries** section.

7 Click to select the  **Activate Selection** toggle button.

8 Select Boundary 11 only.

9 Click to expand the **Control Entities** section. Clear the **Smooth across removed control entities** check box.

Mapped 1

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

2 In the **Settings** window for **Mapped**, locate the **Domain Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domain 2 only.

5 Click to expand the **Control Entities** section. Clear the **Smooth across removed control entities** check box.

6 Click to expand the **Reduce Element Skewness** section. Select the **Adjust edge mesh** check box.

Distribution 1

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

2 Select Boundary 9 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 `6`.

6 In the **Element ratio** text field, type 7.

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

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

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.

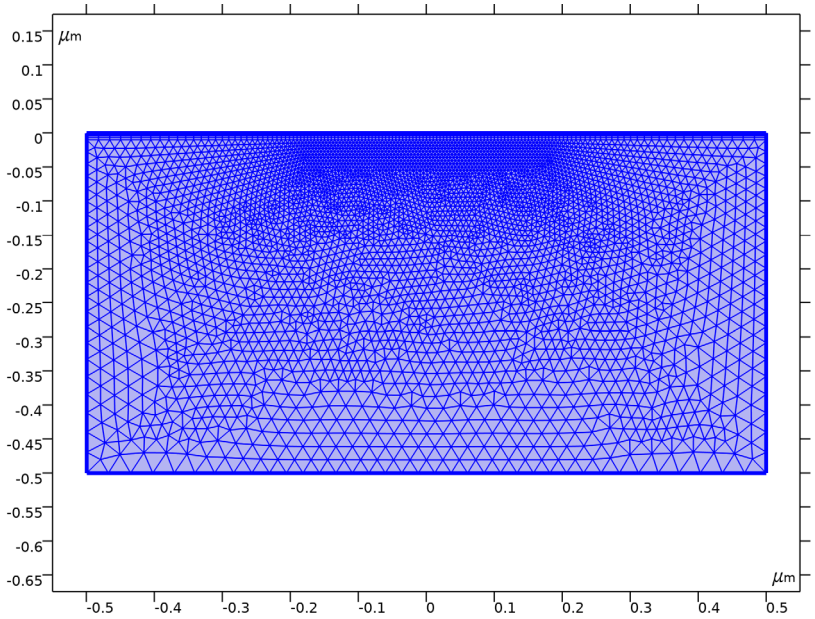
2 In the **Settings** window for **Free Triangular**, click to expand the **Control Entities** section.

3 Clear the **Smooth across removed control entities** check box.

4 Click **Build All**.

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

The user-defined mesh is shown in the image below. The mapped mesh with the specific distribution helps create layers of thin elements underneath the gate, where the large gradient of the carrier concentration should be resolved by the mesh.



STUDY 1

Step 1: Stationary

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

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 Click + **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Vds (Drain-source voltage)	`range(0,0.2,1)`	V
cp (Continuation parameter)	`0 1`	

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

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

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 the default is sufficient. Take a look at the autogenerated solver sequence.

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.

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

4 In the **Model Builder** window, expand the **Study 1>Solver Configurations> Solution 1 (sol1)>Stationary Solver 1>Segregated 1** node, then click **Segregated Step 1**.

5 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.

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

RESULTS

Electron Concentration (semi)

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

Add a 1D plot to compare the I-V curves with and without the mobility model.

1D Plot Group 4

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

Global 1

1 Right-click **1D Plot Group 4** 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_2 - Terminal current - A**.

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

4 In the **1D Plot Group 4** 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
Lombardi surface mobility

1D Plot Group 4

1 In the **Model Builder** window, click **1D Plot Group 4**.

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

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

Add a 2D plot to compare the current density profiles with and without the mobility model.

Electron current density comparison

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

2 In the **Settings** window for **2D Plot Group**, type `Electron current density comparison` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (cp)** list, choose **0**.

For this plot group, we will zoom in to a region underneath the gate to look at the current density profile. In order not to interfere with the zoom settings of other plot groups, we use a different view setting for this plot group by selecting "New".

4 Locate the **Plot Settings** section. From the **View** list, choose **New view**.

5 Clear the **Plot dataset edges** check box.

Surface 1

1 Right-click **Electron current density comparison** 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> Currents and charge>Electron current>Electron current density - A/m²>semi.JnX - Electron current density, X component**.

Filter 1

1 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 `(y>-0.05[um])&&(x>-0.1[um])&&(x<0.1[um])`.

4 In the **Electron current density comparison** toolbar, click **Plot**.

Surface 2

1 In the **Model Builder** window, under **Results>Electron current density comparison** right-click **Surface 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Deformation 1

1 Right-click **Surface 2** and choose **Deformation**.

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

3 In the **X component** text field, type `0`.

4 In the **Y component** text field, type `0.06`.

5 Locate the **Scale** section. Select the **Scale factor** check box.

6 In the associated text field, type `1`.

7 In the **Electron current density comparison** toolbar, click **Plot**.

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

Add a 2D plot to show the electron mobility.

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_ls - Electron mobility, Lombardi - m²/(V·s)**.

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

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