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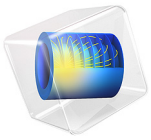

Breakdown in a MOSFET

This model shows how to use the time-dependent solver to model the breakdown of a MOSFET as a result of impact ionization. MOSFETs typically operate in three regimes depending on the drain-source voltage for a given gate voltage. Initially the current-voltage relation is linear; this is the ohmic region. As the drain-source voltage increases, the extracted current begins to saturate; this is the saturation region. As the drain-source voltage is further increased, the breakdown region is entered, where the current increases exponentially for a small increase in the applied voltage. This is due to impact ionization.

Introduction

Under high electric fields, charge carriers' energies can become greater than the gap energy. Under this condition, additional electron hole pairs are generated by the energy released when collisions occur. This process, called impact ionization, is responsible for the phenomenon of avalanche breakdown in semiconductors.

Practically speaking, the carrier generation rate due to impact ionization is given by:

$$R_n^{II} = R_p^{II} = -\frac{\alpha_n}{q}|\mathbf{J}_n| - \frac{\alpha_p}{q}|\mathbf{J}_p|$$

The Semiconductor Interface uses the model of Okuto and Crowell for α_n and α_p (Ref. 1) where:

$$\alpha_n = a_n(1 + c_n(T - T_{\text{ref}}))E_{||,n}\exp\left(-\left(\frac{b_n(1 + d_n(T - T_{\text{ref}}))}{E_{||,n}}\right)^2\right)$$

$$\alpha_p = a_p(1 + c_p(T - T_{\text{ref}}))E_{||,p}\exp\left(-\left(\frac{b_p(1 + d_p(T - T_{\text{ref}}))}{E_{||,p}}\right)^2\right)$$

And where $E_{||,n}$ and $E_{||,p}$ are the components of the electric field parallel to the electron and hole currents, respectively. T_{ref}, a_n, a_p, b_n, b_p, d_n, and d_p are material properties. Those values are defined in Ref. 1 for silicon, germanium, gallium arsenide, and gallium phosphate).

Model Definition

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

This model adds impact ionization generation to the device in which the drain voltage is swept under a constant gate voltage. The drain voltage is varied from 0 V to just over 11 V, which is the inception of avalanche breakdown in the 2D MOSFET.

After having loaded the original MOSFET model, a third study is added to the model in order to observe the effect of the impact ionization on the drain current. This study contains two study steps. The first step computes the stationary solution under a drain voltage and a gate voltage set to 0 V and 3 V, respectively. The second step is a transient step where the drain voltage is ramped from 0 V to 11.4 V for 1 ms under a gate voltage of 3 V. The solution obtained from the stationary step is used as the initial condition for the transient step.

Results and Discussion

Figure 1 shows the drain current as a function of the drain voltage under a gate voltage of 3V. The current initially starts to increase linearly before reaching saturation and eventually runaway as the carrier generation starts to break out.

Figure 2 shows the generation rate at Vds = 11.4 V. Note that the generation is localized mainly on a spot beneath the drain contact.

Figure 3 shows the logarithm of the generation rate at the same voltage (Vds = 11.4 V). Note that the generation is localized where the electrical field is more intense, that is, at the drain junction, and especially where the curvature of the junction is more pronounced.

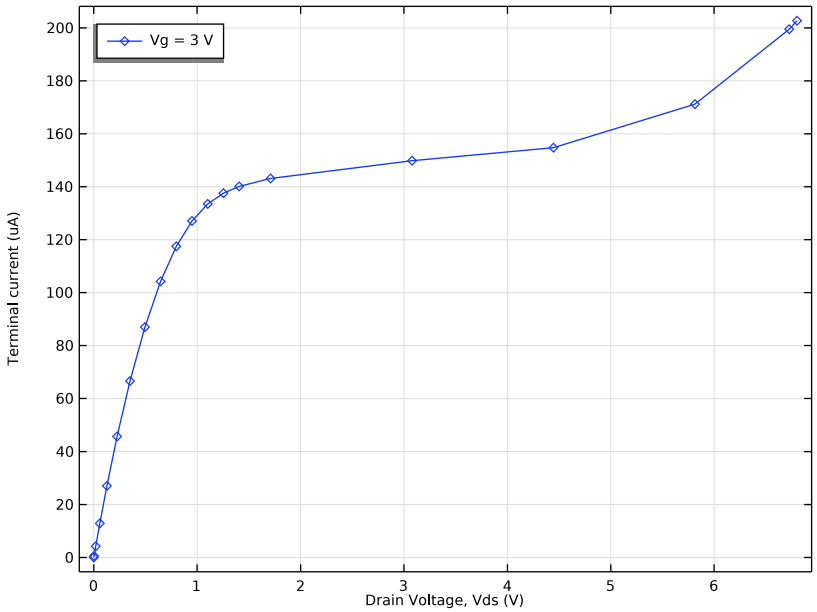

Figure 1: Plot of the terminal current vs. drain source voltage. When impact ionization is included, the current increases exponentially with increasing drain-source voltage.

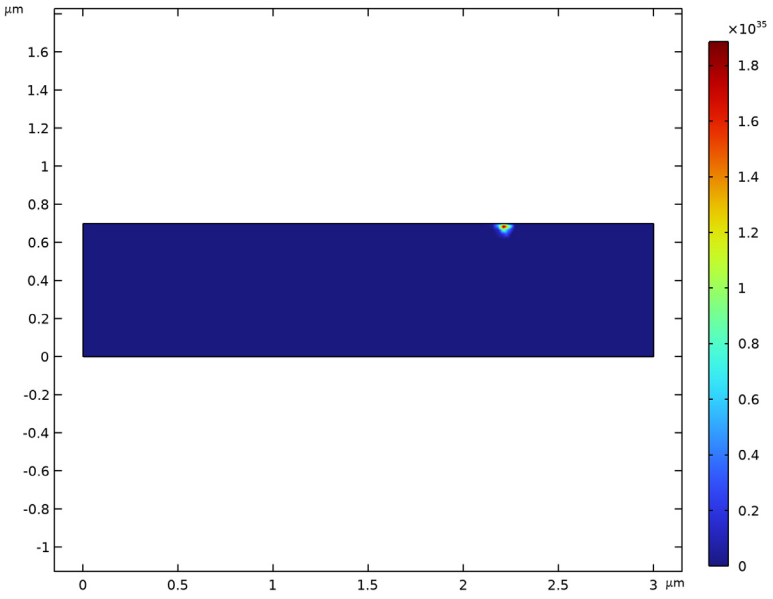

Figure 2: Plot of the impact ionization source which is largest beneath the drain contact.

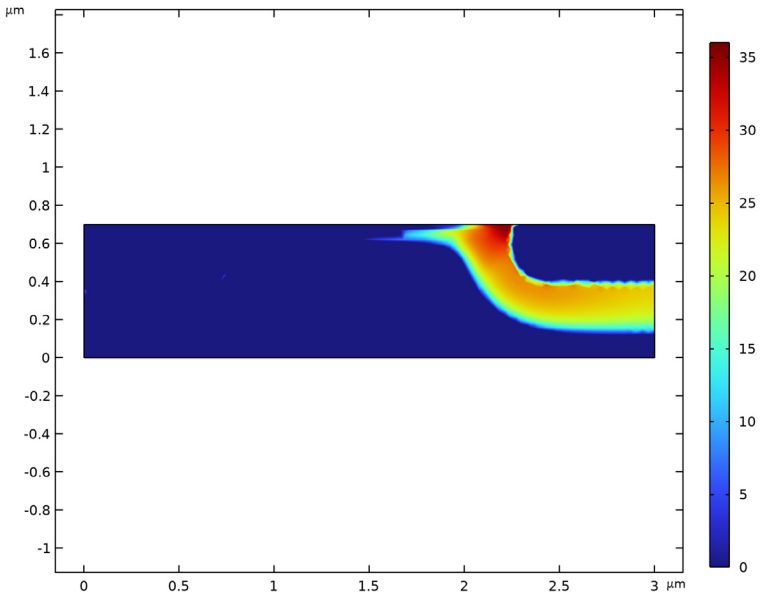

Figure 3: Plot of the logarithm of the impact ionization source which is largest beneath the drain.

Reference

1. Y. Okuto and C.R. Crowell, "Threshold Energy Effect on Avalanche Breakdown in Semiconductor Junctions," *Solid-State Electronics*, vol. 18, pp. 161–168, 1975.

Application Library path: `Semiconductor_Module/Transistors/mosfet_breakdown`

Modeling Instructions

ROOT

Load the MOSFET model.

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**.

GLOBAL DEFINITIONS

Configure the model's parameters for the breakdown study. Change the drain voltage to 0 V, this value will be used to determine the model's initial solution. Change the gate voltage to 3 V, which is the intermediate value from the previous MOSFET study. Also, add a value for the Breakdown voltage, `Vbreak`, to the model's parameters.

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
Vd	0[V]	0 V	Drain voltage
Vg	3[V]	3 V	Gate voltage
Vbreak	11.4[V]	11.4 V	Breakdown voltage

COMPONENT 1 (COMP1)

This study will sweep over Vd, in the previous MOSFET study this was achieved using an auxiliary sweep within a Stationary study step. For the breakdown model it is more appropriate to use a Time Dependent study step, as the stepping algorithm for this solver is better able to handle the highly nonlinear nature of the breakdown effects. In order to implement the same parameter sweep using a Time Dependent study step the drain voltage sweep is defined as a time dependent function, thus enabling the solver to perform the sweep as the solver steps through time. This is achieved by creating a new transient drain voltage variable, Vds, which is defined using a ramp function which increases as a function of time.

DEFINITIONS

Ramp 1 (rm1)

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

2 Right-click **Component 1 (comp1)>Definitions** and choose **Functions>Ramp**.

First create the ramp function. The has a gradient of 1000, such that its value increases from 0 to 1 over an argument range of 1e^{-3}.

3 In the **Settings** window for **Ramp**, locate the **Parameters** section.

4 In the **Slope** text field, type `1000`.

5 In the **Location** text field, type `5e-5`.

6 Select the **Cutoff** check box.

7 Click to expand the **Smoothing** section. Select the **Size of transition zone at start** check box.

8 Select the **Size of transition zone at cutoff** check box.

9 In the **Size of transition zone at start** text field, type `0.0001`.

10 In the **Size of transition zone at cutoff** text field, type `0.0001`.

Variables 1

1 In the **Home** toolbar, click a= **Variables** and choose **Local Variables**.

Now define the drain voltage sweep as a function of time using the ramp function. The time, in seconds, is used as the argument for the ramp, resulting in a function which increases from zero to one over a time interval of 1 ms. This is multiplied by `Vbreak` to create a drain voltage that sweeps between zero and the breakdown voltage linearly over 1 ms.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
`Vds`	`Vbreak*(rm1(t[1/s]))`	V	

SEMICONDUCTOR (SEMI)

Add a metal contact to the drain boundary. This extra boundary will be enabled to generate the initial solution in the first study step (stationary).

Metal Contact 4

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

Change the value of the drain voltage to Vds, the transient expression defined earlier. This boundary condition will be enabled only for the second study step (transient).

Metal Contact 2

1 In the **Model Builder** window, click **Metal Contact 2**.

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

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

Add the impact ionization feature to all domains. This feature will only be enabled in the second study step (transient).

Impact Ionization Generation 1

1 In the **Physics** toolbar, click **Domains** and choose **Impact Ionization Generation**.

2 In the **Settings** window for **Impact Ionization Generation**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

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

Step 1: Stationary

The stationary step is used to create the initial solution to the problem. In this step the impact ionization generation and the transient drain voltage are disabled.

1 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

2 Select the **Modify model configuration for study step** check box.

3 In the tree, select **Component 1 (comp1)>Semiconductor (semi)>Metal Contact 2**.

4 Click **Disable**.

5 In the tree, select **Component 1 (comp1)>Semiconductor (semi)>Impact Ionization Generation 1**.

6 Click **Disable**.

Add a transient step. This step will compute the solution of our problem starting from the initial solution obtained from the first step. Disable the stationary drain voltage to enable the transient voltage at the drain boundary.

Time Dependent

1 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 In the **Output times** text field, type `range(0,0.2/15,0.18)*1e-3 range(0.2,0.6/5,0.8)*1e-3 range(0.85,0.15/5,1)*1e-3`.

4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

5 In the tree, select **Component 1 (comp1)>Semiconductor (semi)>Metal Contact 4**.

6 Click **Disable**.

Solution 3 (sol3)

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

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

3 In the **Model Builder** window, under **Study 3>Solver Configurations>Solution 3 (sol3)** click **Time-Dependent Solver 1**.

4 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

5 Select the **Initial step** check box. In the associated text field, type `5e-6`.

6 Click to expand the **Absolute Tolerance** section. From the **Tolerance method** list, choose **Manual**.

7 In the **Absolute tolerance** text field, type `1e-6`.

Use a stop condition to cause the solver to stop when the current exceeds a certain value.

8 Right-click **Study 3>Solver Configurations>Solution 3 (sol3)>Time-Dependent Solver 1** and choose **Stop Condition**.

9 In the **Settings** window for **Stop Condition**, locate the **Output at Stop** section.

10 From the **Add solution** list, choose **Steps before and after stop**.

11 Locate the **Stop Expressions** section. Click **Add**.

12 In the table, enter the following settings:

Stop expression	Stop if	Active	Description
`root.comp1.semi.IO_2 >200e-6`	True (>=1)	√	`Stop expression 1`

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

14 In the **Settings** window for **Study**, locate the **Study Settings** section.

15 Clear the **Generate default plots** check box.

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

RESULTS

Id vs. Vd with impact ionization

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

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

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** check box. In the associated text field, type `Drain Voltage, Vds (V)`.

6 Select the **y-axis label** check box. In the associated text field, type `Terminal current (uA)`.

7 Click to expand the **Title** section. From the **Title type** list, choose **None**.

8 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

9 In the **Label** text field, type `Id vs. Vd with impact ionization`.

Global 1

1 Right-click **Id vs. Vd with impact ionization** 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.IO_2 - Terminal current - A**.

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

4 In the **Expression** text field, type `Vds`.

5 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`semi.IO_2`	uA	`Terminal current`

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

7 In the table, enter the following settings:

Legends
Vg = 3 V

8 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

9 In the **Id vs. Vd with impact ionization** toolbar, click **Plot**.

Impact Ionization

1 In the **Model Builder** window, right-click **Electric Potential (semi)** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Impact Ionization` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

Surface 1

1 In the **Model Builder** window, expand the **Impact Ionization** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `semi.Gii`.

Impact Ionization

1 In the **Model Builder** window, click **Impact Ionization**.

2 In the **Impact Ionization** toolbar, click **Plot**.

Impact Ionization log scale

1 Right-click **Impact Ionization** and choose **Duplicate**.

2 Right-click **Impact Ionization 1** and choose **Rename**.

3 In the **Rename 2D Plot Group** dialog box, type `Impact Ionization log scale` in the **New label** text field.

4 Click **OK**.

Surface 1

1 In the **Model Builder** window, expand the **Impact Ionization log scale** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `log10(-semi.Gii+eps)`.

4 Click to expand the **Range** section. Select the **Manual color range** check box.

5 In the **Maximum** text field, type 36.

6 In the **Impact Ionization log scale** toolbar, click  **Plot**.