

# DEVSIM

Version: Beta 0.01

User Guide

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# **Part I**

# **User Guide**



# Chapter 1

## Release Notes

Please see *Chapter 11, Installation* on page 67 for information on installing DEVSIM on your system. If you require assistance with this product, please contact us using the information in the [front cover](#) of this manual.

*DEVSIM is now an open source distribution. The documentation is in the process of being updated to reflect this.*



## Chapter 2

# Introduction

### 2.1 Overview

DEVSIM is a technology computer-aided design (TCAD) software for semiconductor device simulation. While geared toward this application, it may be used where the control volume approach is appropriate for solving systems of partial-differential equations (PDE's) on a static mesh. After introducing DEVSIM, the rest of the manual discusses the key components of the system, and instructions for their use.

### 2.2 Goals

The primary goal of DEVSIM is to give the user as much flexibility and control as possible. In this regard, few models are coded into the program binary. They are implemented in human-readable scripts that can be modified if necessary.

DEVSIM is embedded within a scripting language interface (*Chapter 8, User Interface on page 53*). This provides control structures and language syntax in a consistent and intuitive manner. Taking a hierarchical approach, the user is provided an environment where they can implement new models on their own. This is without requiring extensive vendor support or use of compiled programming languages.

SYMDIFF (*Chapter 9, SYMDIFF on page 57*) is the symbolic expression parser used to allow the formulation of device equations in terms of models and parameters. Using symbolic differentiation, the required partial derivatives can be generated, or provided by the user. DEVSIM then assembles these equations over the mesh.

## 2.3 Structures

**Devices** A device refers to a discrete structure being simulated. It is composed of the following types of objects.

**Regions** A region defines a portion of the device of a specific material. Each region has its own system of equations being solved.

**Interfaces** Interfaces connect two regions together. At the interfaces, equations are specified to account for how the flux in each device region crosses the region boundary.

**Contacts** Contacts specify the boundary conditions required for device simulation. It also specifies how terminal currents are integrated into an external circuit.

## 2.4 Equation assembly

Equation assembly of models is discussed in *Chapter 3, Equation and Models on page 9*.

## 2.5 Parameters

Parameters may be specified globally, or for a specific device or region. Alternatively, parameters may be based on the material type of the regions. Usage is discussed in *Chapter 4, Model Parameters on page 33*.

## 2.6 Circuits

Circuit boundary conditions allow multi-device simulation. They are also required for setting sources and their response for AC and noise analysis. Circuit elements, such as voltage sources, current sources, resistors, capacitors, and inductors may be specified. This is further discussed in *Chapter 5, Circuits on page 37*.

## 2.7 Meshing

Meshing is discussed in *Chapter 6, Meshing on page 41*.

## 2.8 Analysis

DEVSIM offers a range of simulation algorithms. They are discussed in more detail in *Chapter 7, Solver on page 49*.



**DC** The DC operating point analysis is useful for performing steady-state simulation for a different bias conditions.

**AC** At each DC operating point, a small-signal AC analysis may be performed. An AC source is provided through a circuit and the response is then simulated. This is useful for both quasi-static capacitance simulation, as well as RF simulation.

**Noise/Sensitivity** Noise analysis may be used to evaluate how internal noise sources are observed in the terminal currents of the device or circuit. Using this method, it is also possible to simulate how the device response changes when device parameters are changed.

**Transient** DEVSIM is able to simulate the nonlinear transient behavior of devices, when the bias conditions change with time.

## 2.9 Scripting interface

The scripting interface to DEVSIM is discussed in *Chapter 8, User Interface* on page 53.

## 2.10 Expression parser

The expression parser is discussed in *Chapter 9, SYMDIFF* on page 57.

## 2.11 Visualization and postprocessing

Visualization is discussed in *Chapter 10, Visualization* on page 65.

## 2.12 Installation

Installation is discussed in *Chapter 11, Installation* on page 67.

## 2.13 Additional information

Additional information is discussed in *Chapter 12, Additional Information* on page 69.

## 2.14 Examples

Examples are discussed in the remaining chapters beginning with *Chapter 13, Example Overview* on page 73.



## Chapter 3

# Equation and Models

### 3.1 Overview

DEVSIM uses the control volume approach for assembling partial-differential equations (PDE's) on the simulation mesh. DEVSIM is used to solve equations of the form:

$$\frac{\partial X}{\partial t} + \nabla \cdot \vec{Y} + Z = 0 \quad (3.1)$$

Internally, it transforms the PDE's into an integral form.

$$\int \frac{\partial X}{\partial t} \partial r + \int \vec{Y} \cdot \partial \vec{s} + \int Z \partial r = 0 \quad (3.2)$$

Equations involving the divergence operators are converted into surface integrals, while other components are integrated over the device volume.

In Figure 3.1, 2D mesh elements are depicted. The shaded area around the center node is referred to as the node volume, and it is used for the volume integration. The lines from the center node to other nodes are referred to as edges. The flux through the edge are integrated with respect to the perpendicular bisectors (dashed lines) crossing each triangle edge.

In this form, we refer to a model integrated over the edges of triangles as edge models. Models integrated over the volume of each triangle vertex are referred to as node models. Element edge models are a special case where variables at other nodes off the edge may cause the flux to change.

There are a default set of models created in each region upon initialization of a device, and are typically based on the geometrical attributes. These are described in the following sections. Models required for describing the device behavior are created using the equation parser described in [Chapter 9, SYMDIFF on page 57](#). For special situations, custom matrix assembly is also available and is discussed in [Section 3.5, Custom matrix assembly on page 17](#).

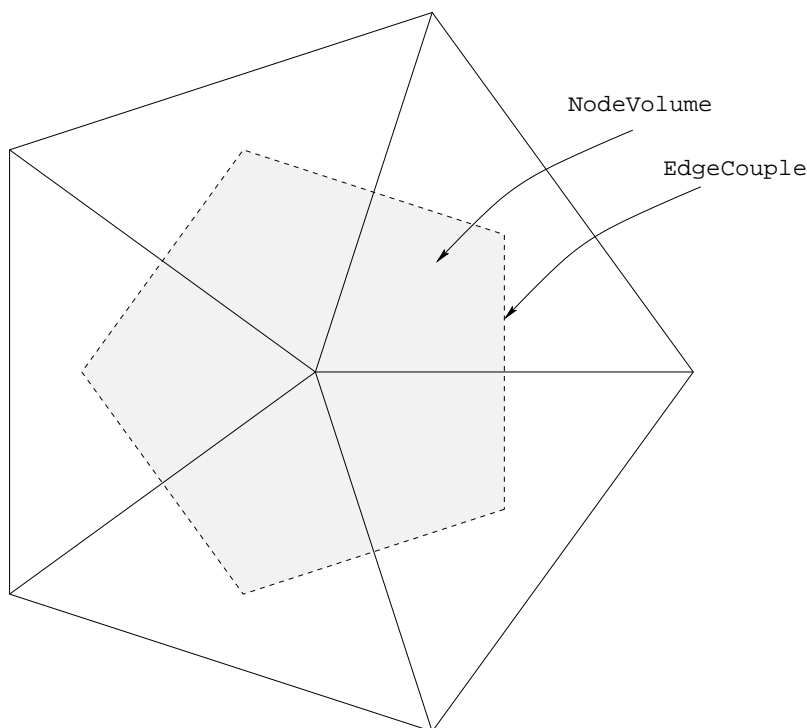


Figure 3.1: Mesh elements in 2D.

## 3.2 Bulk models

### 3.2.1 Node models

Node models may be specified in terms of other node models, mathematical functions, and parameters on the device. The simplest model is the node solution, and it represents the solution variables being solved for. Node models automatically created for a region are listed in Table 3.1.

In this example, we present an implementation of Shockley Read Hall recombination [1].

```

USRH="-ElectronCharge*(Electrons*Holes - n_i^2)/(taup*(Electrons + n1) \
      + taun*(Holes + p1))"
dUSRHdn="simplify(diff(%s, Electrons))" % USRH
dUSRHdp="simplify(diff(%s, Holes))" % USRH
ds.node_model(device='MyDevice', region='MyRegion', name="USRH", equation=USRH)
ds.node_model(device='MyDevice', region='MyRegion', name="USRH:Electrons", equation=dUSRHdn)
ds.node_model(device='MyDevice', region='MyRegion', name="USRH:Holes", equation=dUSRHdp)

```

The first model specified, USRH, is the recombination model itself. The derivatives with respect to electrons and holes are USRH:Electrons and USRH:Holes, respectively. In this particular example Electrons and Holes have already been defined as solution variables. The remaining variables in the equation have already been specified as parameters.

The `diff` function tells the equation parser to take the derivative of the original expression, with respect to the variable specified as the second argument. During equation assembly, these

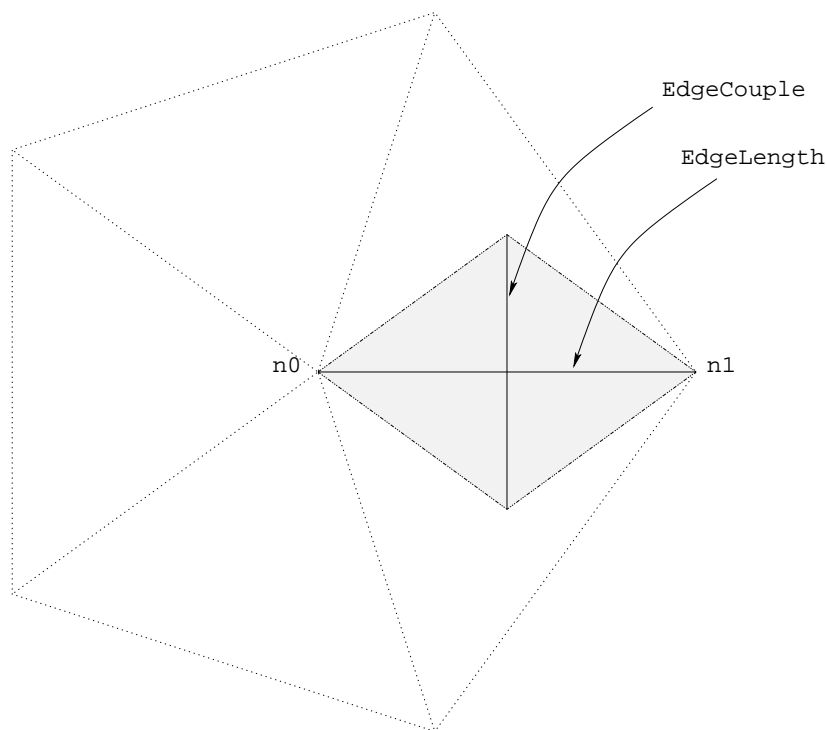


Figure 3.2: Edge model constructs in 2D.

derivatives are required in order to converge upon a solution. The `simplify` function tells the expression parser to attempt to simplify the expression as much as possible.

### 3.2.2 Edge models

Edge models may be specified in terms of other edge models, mathematical functions, and parameters on the device. In addition, edge models may reference node models defined on the ends of the edge. As depicted in Figure 3.2, edge models are with respect to the two nodes on the edge, `n0` and `n1`.

For example, to calculate the electric field on the edges in the region, the following scheme is employed:

```
ds.edge_model(device="device", region="region", name="ElectricField",
              equation="(Potential@n0 - Potential@n1)*EdgeInverseLength")
ds.edge_model(device="device", region="region",
              name="ElectricField:Potential@n0", equation="EdgeInverseLength")
ds.edge_model(device="device", region="region",
              name="ElectricField:Potential@n1", equation="-EdgeInverseLength")
```

In this example, `EdgeInverseLength` is a built-in model for the inverse length between nodes on an edge. `Potential@n0` and `Potential@n1` is the `Potential` node solution on the nodes at the end of the edge. These edge quantities are created using the [edge\\_from\\_node\\_model](#) command (page 24). In addition, the [edge\\_average\\_model](#) command (page 24) can be used to create edge models in terms of node model quantities.

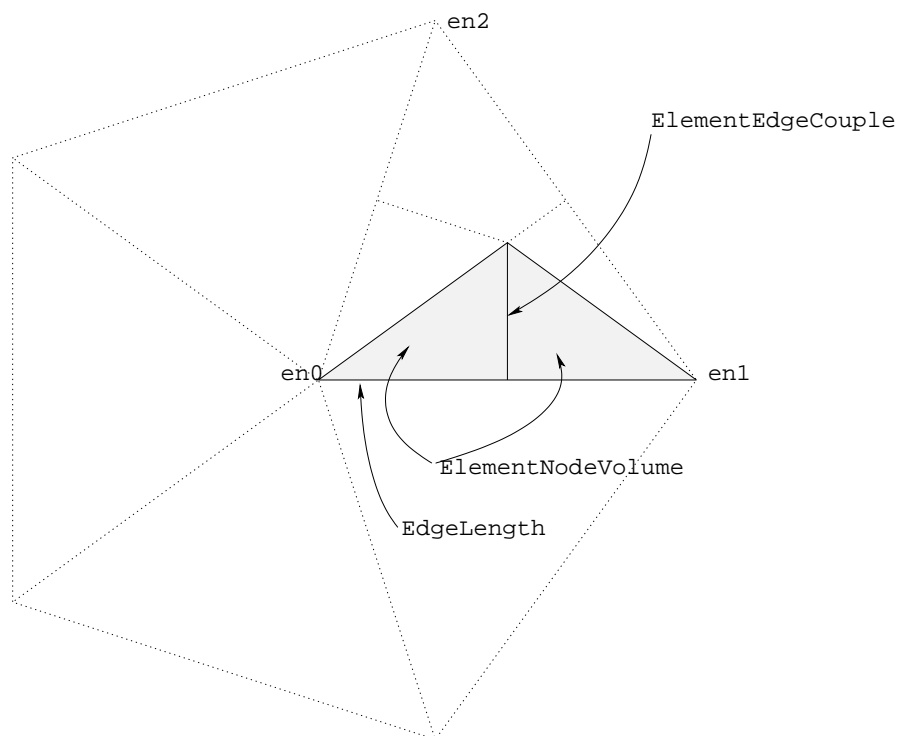


Figure 3.3: Element edge model constructs in 2D.

Edge models automatically created for a region are listed in Table 3.2.

### 3.2.3 Element edge models

Element edge models are used when the edge quantities cannot be specified entirely in terms of the quantities on both nodes of the edge, such as when the carrier mobility is dependent on the normal electric field. In 2D, element edge models are evaluated on each triangle edge. As depicted in Figure 3.3, edge models are with respect to the three nodes on each triangle edge and are denoted as `en0`, `en1`, and `en2`. Derivatives are with respect to each node on the triangle.

In 3D, element edge models are evaluated on each tetrahedron edge. Derivatives are with respect to the nodes on both triangles on the tetrahedron edge. Element edge models automatically created for a region are listed in Table 3.3.

As an alternative to treating integrating the element edge model with respect to `ElementEdgeCouple`, the integration may be performed with respect to `ElementNodeVolume`. See `equation` command (page 20) for more information.

### 3.2.4 Model derivatives

To converge upon the solution, derivatives are required with respect to each of the solution variables in the system. DEVSIM will look for the required derivatives. For a model `model`, the derivatives with respect to solution variable `variable` are presented in Table 3.4.

Node Model	Description
AtContactNode	Evaluates to 1 if node is a contact node, otherwise 0
NodeVolume	The volume of the node. Used for volume integration of node models on nodes in mesh
NSurfaceNormal <sub>x</sub>	The surface normal to points on the interface or contact (2D and 3D)
NSurfaceNormal <sub>y</sub>	The surface normal to points on the interface or contact (2D and 3D)
NSurfaceNormal <sub>z</sub>	The surface normal to points on the interface or contact (3D)
SurfaceArea	The surface area of a node on interface and contact nodes, otherwise 0
x	x position of the node
y	y position of the node (2D and 3D)
z	z position of the node (3D only)

Table 3.1: Node models defined on each region of a device.

Edge Model	Description
EdgeCouple	The length of the perpendicular bisector of an element edge. Used to perform surface integration of edge models on edges in mesh.
EdgeInverseLength	Inverse of the EdgeLength.
EdgeLength	The distance between the two nodes of an edge
unitx	x component of the unit vector along an edge
unity	y component of the unit vector along an edge (2D and 3D)
unitz	z component of the unit vector along an edge (3D only)

Table 3.2: Edge models defined on each region of a device.

### 3.2.5 Conversions between model types

The `edge_from_node_model` command (page 24) is used to create edge models referring to the nodes connecting the edge. For example, the edge models `Potential@n0` and `Potential@n1` refer to the `Potential` node model on each end of the edge.

The `edge_average_model` command (page 24) creates an edge model which is either the arithmetic mean, geometric mean, gradient, or negative of the gradient of the node model on each edge.

When an edge model is referred to in an element edge model expression, the edge values are implicitly converted into element edge values during expression evaluation. In addition, derivatives of the edge model with respect to the nodes of an element edge are required, they are converted as well. For example, `edgemodel:variable@n0` and `edgemodel:variable@n1` are implicitly converted to `edgemodel:variable@en0` and `edgemodel:variable@en1`, respectively.

The `element_from_edge_model` command (page 26) is used to create directional components of an edge model over an entire element. The `derivative` option is used with this command to create the derivatives with respect to a specific node model. The `element_from_node_model` command (page 27) is used to create element edge models referring to each node on the element of the element edge.

Element Edge Model	Description
ElementEdgeCouple	The length of the perpendicular bisector of an edge. Used to perform surface integration of element edge model on element edge in the mesh.
ElementNodeVolume	The node volume at either end of each element edge.

Table 3.3: Element edge models defined on each region of a device.

Model Type	Derivatives Required
Node Model	model:variable
Edge Model	model:variable@n0 model:variable@n1
Element Edge Model	model:variable@en0 model:variable@en1 model:variable@en2 model:variable@en3 (3D)

Table 3.4: Required derivatives for equation assembly. `model` is the name of the model being evaluated, and `variable` is one of the solution variables being solved at each node.

### 3.2.6 Equation assembly

Bulk equations are specified in terms of the node, edge, and element edge models using the `equation` command (page 20). Node models are integrated with respect to the node volume. Edge models are integrated with the perpendicular bisectors along the edge onto the nodes on either end.

Element edge models are treated as flux terms and are integrated with respect to `ElementEdgeCouple` using the `element_model` option. Alternatively, they may be treated as source terms and are integrated with respect to `ElementNodeVolume` using the `volume_model` option.

In this example, we are specifying the Potential Equation in the region to consist of a flux term named `PotentialEdgeFlux` and to not have any node volume terms.

```
ds.equation(device="device", region="region", name="PotentialEquation",
            variable_name="Potential", edge_model="PotentialEdgeFlux", variable_update="log_damp" )
```

In addition, the solution variable coupled with this equation is `Potential` and it will be updated using logarithmic damping.

## 3.3 Interface

### 3.3.1 Interface models

Figure 3.4 depicts an interface in DEVSIM. It is a collection of overlapping nodes existing in two regions, `r0` and `r1`.

Interface models are node models specific to the interface being considered. They are unique from bulk node models, in the sense that they may refer to node models on both sides of the interface. They are specified using the `interface_model` command (page 29). Interface models may



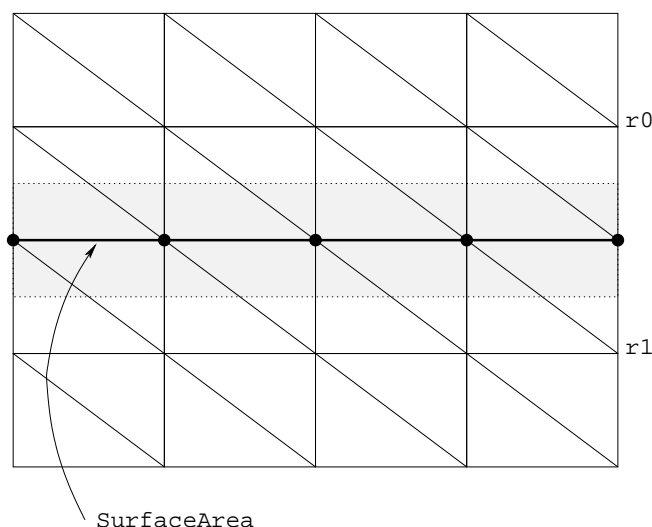


Figure 3.4: Interface constructs in 2D. Interface node pairs are located at each •. The SurfaceArea model is used to integrate flux term models.

Model Type	Model Name	Derivatives Required
Node Model (region 0)	nodemodel@r0	nodemodel:variable@r0
Node Model (region 1)	nodemodel@r1	nodemodel:variable@r1
Interface Node Model	inodemodel	inodemodel:variable@r0 inodemodel:variable@r1

Table 3.5: Required derivatives for interface equation assembly. The node model name `nodemodel` and its derivatives `nodemodel:variable` are suffixed with `@r0` and `@r1` to denote which region on the interface is being referred to.

refer to node models or parameters on either side of the interface using the syntax `nodemodel@r0` and `nodemodel@r1` to refer to the node model in the first and second regions of the interface. The naming convention for node models, interface node models, and their derivatives are shown in Table 3.5.

```
ds.interface_model(device="device", interface="interface",
                  name="continuousPotential", equation="Potential@r0-Potential@r1")
```

### 3.3.2 Interface model derivatives

For a given interface model, `model`, the derivatives with respect to the variable `variable` in the regions are

- `model:variable@r0`
- `model:variable@r1`

```
ds.interface_model(device="device", interface="interface",
```

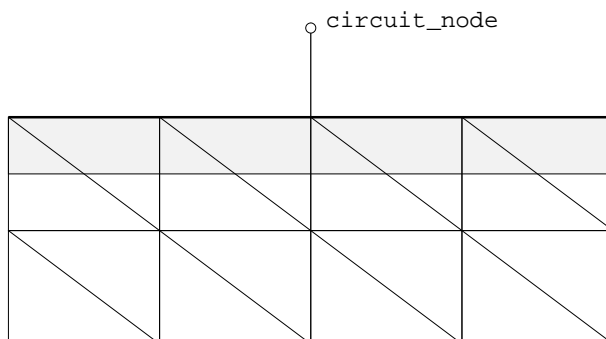


Figure 3.5: Contact constructs in 2D.

```

name="continuousPotential:Potential@r0", equation="1")
ds.interface_model(device="device", interface="interface",
name="continuousPotential:Potential@r1", equation="-1")

```

### 3.3.3 Interface equation assembly

There are two types of interface equations considered in DEVSIM. They are both activated using the [interface\\_equation](#) command (page 21).

In the first form, *continuous*, the equations for the nodes on both sides of the interface are integrated with respect to their volumes and added into the same equation. An additional equation is then specified to relate the variables on both sides. In this example, continuity in the potential solution across the interface is enforced, using the *continuousPotential* model defined in the previous section.

```

ds.interface_equation(device="device", interface="interface", name="PotentialEquation",
variable_name="Potential", interface_model="continuousPotential",
type="continuous")

```

In the second form, *fluxterm*, a flux term is integrated over the surface area of the interface and added to the first region, and subtracted from the second.

## 3.4 Contact

### 3.4.1 Contact models

Figure 3.5 depicts how a contact is treated in a simulation. It is a collection of nodes on a region. During assembly, the specified models form an equation, which replaces the equation applied to these nodes for a bulk node.

Contact models are equivalent to node and edge models, and are specified using the [contact\\_node\\_model](#) command (page 21) and the [contact\\_edge\\_model](#) command (page 21), respectively. The key difference is that the models are only evaluated on the contact nodes for the contact specified.

### 3.4.2 Contact model derivatives

The derivatives are equivalent to the discussion in [Section 3.2.4, Model derivatives on page 12](#). If external circuit boundary conditions are being used, the model `model` derivative with respect to the circuit node `node` name should be specified as `model:node`.

### 3.4.3 Contact equation assembly

The `contact_equation` command (page 19) is used to specify the boundary conditions on the contact nodes. The models specified replace the models specified for bulk equations of the same name. For example, the node model specified for the contact equation is assembled on the contact nodes, instead of the node model specified for the bulk equation. Contact equation models not specified are not assembled, even if the model exists on the bulk equation for the region attached to the contact.

As an example

```
ds.contact_equation(device="device", contact="contact", name="PotentialEquation",
                    variable_name="Potential", node_model="contact_bc",
                    edge_charge_model="DField")
```

Current models refer to the instantaneous current flowing into the device. Charge models refer to the instantaneous charge at the contact.

During a transient, small-signal or ac simulation, the time derivative is taken so that the net current into a circuit node is

$$I(t) = i(t) + \frac{\partial q(t)}{\partial t} \quad (3.3)$$

where  $i$  is the integrated current and  $q$  is the integrated charge.

## 3.5 Custom matrix assembly

The `custom_equation` command (page 19) command is used to register callbacks to be called during matrix and right hand side assembly. The Python procedure must expect to receive two arguments and return two lists. For example a procedure named `myassemble` registered with

```
ds.custom_equation(name="test1", procedure="myassemble")
```

must expect to receive two arguments

```
def myassemble(what, timemode):
    .
    .
    .
    return [rcv, rv]
```

where `what` may be passed as one of

MATRIXONLY  
 RHS  
 MATRIXANDRHS

and `timemode` may be passed as one of

DC  
 TIME

When `timemode` is DC, the time-independent part of the equation is returned. When `timemode` is TIME, the time-derivative part of the equation is returned. The simulator will scale the time-derivative terms with the proper frequency or time scale.

The return value from the procedure must return two lists of the form

```
[1 1 1.0 2 2 1.0 1 2 -1.0 2 1 -1.0 2 2 1.0] [1 1.0 2 1.0 2 -1.0]
```

where the length of the first list is divisible by 3 and contains the row, column, and value to be assembled into the matrix. The second list is divisible by 2 and contains the right-hand side entries. Either list may be empty.

The [get\\_circuit\\_equation\\_number](#) command (page 38) may be used to get the equation numbers corresponding to circuit node names. The [get\\_equation\\_numbers](#) command (page 20) may be used to find the equation number corresponding to each node index in a region.

The matrix and right hand side entries should be scaled by the `NodeVolume` if they are assembled into locations in a device region. Row permutations, required for contact and interface boundary conditions, are automatically applied to the row numbers returned by the Python procedure.

## 3.6 Cylindrical Coordinate Systems

In 2D, models representing the edge couples, surface areas and node volumes may be generated using the following commands:

- [cylindrical\\_edge\\_couple](#) command (page 22)
- [cylindrical\\_node\\_volume](#) command (page 22)
- [cylindrical\\_surface\\_area](#) command (page 23)

In order to change the integration from the default models to cylindrical models, the following parameters may be set

```
set_parameter(name="node_volume_model",          value="CylindricalNodeVolume")
set_parameter(name="edge_couple_model",          value="CylindricalEdgeCouple")
set_parameter(name="element_edge_couple_model", value="ElementCylindricalEdgeCouple")
set_parameter(name="element_node0_volume_model", value="ElementCylindricalNodeVolume@en0")
set_parameter(name="element_node1_volume_model", value="ElementCylindricalNodeVolume@en1")
```

## 3.7 Equation commands

### contact\_equation

```
ds.contact_equation(device=STRING, contact=STRING, name=STRING,
                    variable_name=STRING,
                    circuit_node=STRING,
                    edge_charge_model=STRING,
                    edge_current_model=STRING,
                    edge_model=STRING,
                    element_charge_model=STRING,
                    element_current_model=STRING,
                    element_model=STRING,
                    node_charge_model=STRING,
                    node_current_model=STRING,
                    node_model=STRING)
```

device=	Device on which to apply this command
contact=	Contact on which to apply this command
name=	Name of the contact equation being created
variable_name=	The variable name is used to determine the bulk equation we are replacing at this contact
circuit_node=	Name of the circuit we integrate the flux into
edge_charge_model=	Name of the edge model used to determine the charge at this contact
edge_current_model=	Name of the edge model used to determine the current flowing out of this contact
edge_model=	Name of the edge model being integrated at each edge at this contact
element_charge_model=	Name of the element edge model used to determine the charge at this contact
element_current_model=	Name of the element edge model used to determine the current flowing out of this contact
element_model=	Name of the element edge model being integrated at each edge at this contact
node_charge_model=	Name of the node model used to determine the charge at this contact
node_current_model=	Name of the node model used to determine the current flowing out of this contact
node_model=	Name of the node_model being integrated at each node at this contact

### custom\_equation

```
ds.custom_equation(name=STRING, procedure=STRING)
```

**name=** Name of the custom equation being created  
**procedure=** The Python procedure to be called. See [Section 3.5, Custom matrix assembly](#) on page 17 for a description of how the function should be structured.

## equation

```
ds.equation(device=STRING, region=STRING, name=STRING,
            variable_name=STRING, node_model=STRING,
            edge_model=STRING, time_node_model=STRING,
            element_model=STRING, volume_model=STRING,
            variable_update=OPTION)
```

**device=** Device on which to apply this command  
**region=** Region on which to apply this command  
**name=** Name of the equation being created  
**variable\_name=** Name of the node\_solution being solved  
**node\_model=** Name of the node\_model being integrated at each node in the device volume  
**edge\_model=** Name of the edge model being integrated over each edge in the device volume  
**time\_node\_model=** Name of the time dependent node\_model being integrated at each node in the device volume  
**element\_model=** Name of the element\_model being integrated over each edge in the device volume  
**volume\_model=** Name of the element\_model being integrated over the volume of each edge in the device volume  
**variable\_update=** update type for circuit variable  
     "default" Variable can be positive or negative  
     "log\_damp" Variable update is damped  
     "positive" Solution update results in positive quantity

## get\_equation\_numbers

```
ds.get_equation_numbers(device=STRING, region=STRING, equation=STRING,
                       variable=STRING)
```

**device=** Device on which to apply this command  
**region=** Region on which to apply this command  
**equation=** Name of the equation (optional)  
**variable=** Name of the variable (optional)

Returns a list of the equation numbers corresponding to each node in a region. Values are only valid when during the course of a solve.

**interface\_equation**

```
ds.interface_equation(device=STRING, interface=STRING, name=STRING,
                      variable_name=STRING,
                      interface_model=STRING,
                      type=OPTION)
```

device=	Device on which to apply this command
interface=	Interface on which apply this command
name=	Name of the interface equation being created
variable_name=	The variable name is used to determine the bulk equation we are coupling this interface to
interface_model=	When specified, the bulk equations on both sides of the interface are integrated together. This model is then used to specify how nodal quantities on both sides of the interface are balanced
type=	Specifies the type of boundary condition
"continuous"	Equations of the same name in the two regions are added. The interface_model is an additional equation is created to specify how quantities across the interface are solved
"fluxterm"	The interface_model is added to the bulk equation in the first region, and subtracted from the second

**3.8 Model commands****contact\_edge\_model**

```
ds.contact_edge_model(device=STRING, contact=STRING, name=STRING,
                      equation=STRING, display_type=OPTION)
```

device=	Device on which to apply this command
contact=	Contact on which to apply this command
name=	Name of the contact edge model being created
equation=	Equation used to describe the contact edge model being created
display_type=	Option for output display in graphical viewer
"nodisplay"	Data on edge will not be displayed
"scalar"	Data on edge is a scalar quantity
"vector"	Data on edge is a vector quantity (default)

**contact\_node\_model**

```
ds.contact_node_model(device=STRING, contact=STRING, name=STRING,
                      equation=STRING, display_type=OPTION)
```

device=	Device on which to apply this command
contact=	Contact on which to apply this command
name=	Name of the contact node model being created
equation=	Equation used to describe the contact node model being created
display_type=	Option for output display in graphical viewer
"nodisplay"	Data on node will not be displayed
"scalar"	Data on node is a scalar quantity (default)

### cylindrical\_edge\_couple

`ds.cylindrical_edge_couple(device=STRING, region=STRING)`

device= Device on which to apply this command  
 region= Region on which to apply this command  
 This model is only available in 2D. The created variables are

- ElementCylindricalEdgeCouple (Element Edge Model)
- CylindricalEdgeCouple (Edge Model)

The [set\\_parameter](#) command (page 34) must be used to set

- raxis\_variable, the variable (x or y) which is the radial axis variable in the cylindrical coordinate system
- raxis\_zero, the location of the z axis for the radial axis variable

### cylindrical\_node\_volume

`ds.cylindrical_node_volume(device=STRING, region=STRING,  
                               zaxis_variable=STRING, raxis_zero=STRING)`

device= Device on which to apply this command  
 region= Region on which to apply this command  
 This model is only available in 2D. The created variables are

- ElementCylindricalNodeVolume@en0 (Element Edge Model)
- ElementCylindricalNodeVolume@en1 (Element Edge Model)
- CylindricalNodeVolume (Edge Model)

The ElementCylindricalNodeVolume@en0 and ElementCylindricalNodeVolume@en1 represent the node volume at each end of the element edge.

The [set\\_parameter](#) command (page 34) must be used to set

- raxis\_variable, the variable (x or y) which is the radial axis variable in the cylindrical coordinate system
- raxis\_zero, the location of the z axis for the radial axis variable



**cylindrical\_surface\_area**

```
ds.cylindrical_surface_area(device=STRING, region=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

This model is only available in 2D. The created variables are

- CylindricalSurfaceArea (Node Model)

and is the cylindrical surface area along each contact and interface node in the device region.

The [set\\_parameter](#) command (page 34) must be used to set

- `raxis_variable`, the variable (x or y) which is the radial axis variable in the cylindrical coordinate system
- `raxis_zero`, the location of the z axis for the radial axis variable

**delete\_edge\_model**

```
ds.delete_edge_model(device=STRING, region=STRING,  
                     name=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

name= Name of the edge model being deleted

**delete\_interface\_model**

```
ds.delete_interface_model(device=STRING, interface=STRING,  
                          name=STRING)
```

device= Device on which to apply this command

interface= Interface on which apply this command

name= Name of the interface model being deleted

**delete\_node\_model**

```
ds.delete_node_model(device=STRING, region=STRING,  
                     name=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

name= Name of the node model being deleted

**edge\_average\_model**

```
ds.edge_average_model(device=STRING, region=STRING,
                      node_model=STRING, edge_model=STRING,
                      average_type=STRING, derivative=STRING)
```

device=	Device on which to apply this command
region=	Region on which to apply this command
node_model=	The node model from which we are creating the edge model. If derivative is specified, the edge model is created from nodeModel:derivativeModel
edge_model=	The edge model name being created. If derivative is specified, the edge models created are edgeModel:derivativeModel@n0 edgeModel:derivativeModel@n1, which are the derivatives with respect to the derivative model on each side of the edge
derivative=	The node model of the variable for which the derivative is being taken. The node model nodeModel:derivativeModel is used to create the resulting edge models.
average_type=	The node models on both sides of the edge are averaged together to create one of the following types of averages.
"arithmetic"	The edge model is the average of the node model on both sides (default)
"geometric"	The edge model is the square root of the product of the node model evaluated on each side
"gradient"	The edge model is the gradient along the edge with respect to the distance between the two nodes.
"negative_gradient"	The edge model is the negative of the gradient along the edge

For a node model, creates an 2 edge models referring to the node model value at both ends of the edge. For example, to calculate electric field:

```
ds.edge_average_model(device=device, region=region, node_model="Potential",
                      edge_model="ElectricField", average_type="negative_gradient")
```

and the derivatives ElectricField:Potential@n0 and ElectricField:Potential@n1 are then created from

```
ds.edge_average_model(device=device, region=region, node_model="Potential",
                      edge_model="ElectricField", average_type="negative_gradient",
                      derivative="Potential")
```

**edge\_from\_node\_model**

```
ds.edge_from_node_model(device=STRING, region=STRING,
                        node_model=STRING)
```

device=	Device on which to apply this command
region=	Region on which to apply this command
node_model=	The node model from which we are creating the edge model

For a node model, creates an 2 edge models referring to the node model value at both ends of the edge. For example, to calculate electric field:

```
ds.edge_from_node_model(device=device, region=region, node_model="Potential")
```

### edge\_model

```
ds.edge_model(device=STRING, region=STRING, name=STRING,
              equation=STRING, display_type=OPTION)
```

device=	Device on which to apply this command
region=	Region on which to apply this command
name=	Name of the edge model being created
equation=	Equation used to describe the edge model being created
display_type=	Option for output display in graphical viewer
"nodisplay"	Data on edge will not be displayed
"scalar"	Data on edge is a scalar quantity (default)
"vector"	Data on edge is a vector quantity (deprecated)

The `vector` option uses an averaging scheme for the edge values projected in the direction of each edge. For a given model, `model`, the generated components in the visualization files is:

- `model_x_onNode`
- `model_y_onNode`
- `model_z_onNode` (3D)

This averaging scheme does not produce accurate results, and it is recommended to use the [element\\_from\\_edge\\_model](#) command (page 26) to create components better suited for visualization. See [Chapter 10, Visualization](#) on page 65 for more information about creating data files for external visualization programs.

### element\_model

```
ds.element_model(device=STRING, region=STRING, name=STRING,
                 equation=STRING, display_type=OPTION)
```

device=	Device on which to apply this command
region=	Region on which to apply this command
name=	Name of the element edge model being created
equation=	Equation used to describe the element edge model being created
display_type=	Option for output display in graphical viewer
"nodisplay"	Data on edge will not be displayed
"scalar"	Data on edge is a scalar quantity (default)

**element\_from\_edge\_model**

```
ds.element_from_edge_model(device=STRING, region=STRING,
                           edge_model=STRING,
                           derivative=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 edge\_model= The edge model from which we are creating the element model  
 derivative= The variable we are taking with respect to edge\_model

For an edge model `emodel`, creates an element models referring to the directional components on each edge of the element:

- `emodel_x`
- `emodel_y`

If the derivative variable option is specified, the `emodel@n0` and `emodel@n1` are used to create:

- `emodel_x:variable@en0`
- `emodel_y:variable@en0`
- `emodel_x:variable@en1`
- `emodel_y:variable@en1`
- `emodel_x:variable@en2`
- `emodel_y:variable@en2`

in 2D for each node on a triangular element. and

- `emodel_x:variable@en0`
- `emodel_y:variable@en0`
- `emodel_z:variable@en0`
- `emodel_x:variable@en1`
- `emodel_y:variable@en1`
- `emodel_z:variable@en1`
- `emodel_x:variable@en2`
- `emodel_y:variable@en2`
- `emodel_z:variable@en2`

- `emodel_x:variable@en3`
- `emodel_y:variable@en3`
- `emodel_z:variable@en3`

in 3D for each node on a tetrahedral element.

The suffix `en0` refers to the first node on the edge of the element and `en1` refers to the second node. `en2` and `en3` specifies the derivatives with respect the variable at the nodes opposite the edges on the element being considered.

### **element\_from\_node\_model**

```
ds.element_from_node_model(device=STRING, region=STRING,
                           node_model=STRING)
```

`device=` Device on which to apply this command  
`region=` Region on which to apply this command  
`node_model=` The node model from which we are creating the edge model

This command creates an element edge model from a node model so that each corner of the element is represented. A node model, `nmodel`, would be accessible as

- `nmodel@en0`
- `nmodel@en1`
- `nmodel@en2`
- `nmodel@en3` (3D)

where `en0`, and `en1` refers to the nodes on the element's edge. In 2D, `en2` refers to the node on the triangle node opposite the edge. In 3D, `en2` and `en3` refers to the nodes on the nodes off the element edge on the tetrahedral element.

### **get\_edge\_model\_list**

```
ds.get_edge_model_list(device=STRING, region=STRING)
```

`device=` Device on which to apply this command  
`region=` Region on which to apply this command  
Returns a list of the edge models on the device region

### **get\_edge\_model\_values**

```
ds.get_edge_model_values(device=STRING, region=STRING,
                         name=STRING)
```

`device=` Device on which to apply this command  
`region=` Region on which to apply this command  
`name=` Name of the edge model values being returned as a list

**get\_element\_model\_list**

```
ds.get_edge_model_list(device=STRING, region=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
Returns a list of the element edge models on the device region

**get\_element\_model\_values**

```
ds.get_edge_model_values(device=STRING, region=STRING,  
                        name=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
name= Name of the element edge model values being returned as a list

**get\_interface\_model\_list**

```
ds.get_interface_model_values(device=STRING, interface=STRING)
```

device= Device on which to apply this command  
interface= Interface on which apply this command  
Returns a list of the interface models on the interface

**get\_interface\_model\_values**

```
ds.get_interface_model_values(device=STRING, interface=STRING,  
                             name=STRING)
```

device= Device on which to apply this command  
interface= Interface on which apply this command  
name= Name of the interface model values being returned as a list

**get\_node\_model\_list**

```
ds.get_node_model_list(device=STRING, region=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
Returns a list of the node models on the device region

**get\_node\_model\_values**

```
ds.get_node_model_values(device=STRING, region=STRING,
                        name=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 name= Name of the node model values being returned as a list

**interface\_model**

```
ds.interface_model(device=STRING, interface=STRING,
                  name=STRING, equation=STRING)
```

device= Device on which to apply this command  
 interface= Interface on which apply this command  
 equation= Equation used to describe the interface node model being created

**interface\_normal\_model**

```
ds.interface_normal_model(device=STRING, region=STRING, interface=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 interface= Interface on which apply this command  
 This model creates the following edge models:

- `iname_distance`
- `iname_normal_x` (2D and 3D)
- `iname_normal_y` (2D and 3D)
- `iname_normal_z` (3D only)

where `iname` is the name of the interface. The normals are of the closest node on the interface. The sign is toward the interface.

**node\_model**

```
ds.node_model(device=STRING, region=STRING, name=STRING,
              equation=STRING, display_type=OPTION)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 name= Name of the node model being created  
 equation= Equation used to describe the node model being created  
 display\_type= Option for output display in graphical viewer  
   "nodisplay" Data on node will not be displayed  
   "scalar" Data on node is a scalar quantity (default)

**node\_solution**

```
ds.node_solution(device=STRING, region=STRING, name=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
name= Name of the solution being created

**print\_node\_values**

```
ds.print_node_values(device=STRING, region=STRING,  
                    name=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
name= Name of the node model values being printed to the screen

**print\_edge\_values**

```
ds.print_edge_values(device=STRING, region=STRING,  
                    name=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
name= Name of the edge model values being printed to the screen

**print\_element\_values**

```
ds.print_element_values(device=STRING, region=STRING,  
                      name=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
name= Name of the element edge model values being printed to the screen

**register\_function**

```
ds.register_function(name=STRING, nargs=STRING)
```

name= Name of the function  
nargs= Number of arguments to the function  
This command is used to register a new Python procedure for evaluation by SYMDIFF.



**set\_node\_values**

```
ds.set_node_values(device=STRING, region=STRING, name=STRING,
                  init_from=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 name= Name of the node model being initialized  
 init\_from= Node model we are using to initialize the node solution

**syndiff**

```
ds.syndiff(expr=STRING)
```

expr= Expression to send to SYMDIFF

This command returns an expression. All strings are treated as independent variables. It is primarily used for defining new functions to the parser.

**vector\_element\_model**

```
ds.vector_element_model(device=STRING, region=STRING,
                      element_model=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 element\_model= The element model for which we are calculating the vector components

This command creates element edge models from an element model which represent the vector components on the element edge. An element model, `emodel`, would then have

- `emodel_x`
- `emodel_y`
- `emodel_z` (3D only)

The primary use of these components are for visualization.

**vector\_gradient**

```
ds.vector_gradient(device=STRING, region=STRING,
                  node_model=STRING, calc_type=STRING)
```

device= Device on which to apply this command  
 region= Region on which to apply this command  
 node\_model= The node model from which we are creating the edge model  
 calc\_type= The node model from which we are creating the edge model  
   "default" Consider all nodes for calculating the gradient field (default)  
   "avoidzero" Do not take gradient at nodes where the node\_model is zero

Used for noise analysis. The `avoidzero` option is important for noise analysis, since a node model value of zero is not physical for some contact and interface boundary conditions. For a given node model, `model`, a node model is created in each direction:

- `model_gradx` (1D)
- `model_grady` (2D and 3D)
- `model_gradz` (3D)

It is important not to use these models for simulation, since DEVSIM, does not have a way of evaluating the derivatives of these models. The models can be used for integrating the impedance field, and other postprocessing. The `element_from_edge_model` command (page 26) command can be used to create gradients for use in a simulation.

## 3.9 Geometry commands

### **get\_device\_list**

```
ds.get_device_list()
```

Gets a list of devices on the simulation.

### **get\_region\_list**

```
ds.get_region_list(device=STRING, contact=STRING, interface=STRING)
```

<code>device=</code>	Device on which to apply this command
<code>contact=</code>	If specified, gets the name of the region belonging to this contact on the device (optional)
<code>interface=</code>	If specified, gets the name of the region belonging to this interface on the device (optional)

### **get\_contact\_list**

```
ds.get_contact_list(device=STRING)
```

<code>device=</code>	Device on which to apply this command
----------------------	---------------------------------------

### **get\_interface\_list**

```
ds.get_interface_list(device=STRING)
```

<code>device=</code>	Device on which to apply this command
----------------------	---------------------------------------

## Chapter 4

# Model Parameters

Parameters can be set using the commands in [Section 4.4, Material commands](#) on page 34. There are two complementary formalisms for doing this.

### 4.1 Parameters

Parameters are set globally, on devices, or on regions of a device. The models on each device region are automatically updated whenever parameters change.

```
ds.set_parameter(device="device", region="region", name="ThermalVoltage", value=0.0259)
```

### 4.2 Material database entries

Alternatively, parameters may be set based on material types. A database file is used for getting values on the regions of the device.

```
ds.create_db(filename="foodb")
ds.add_db_entry(material="global", parameter="q", value=1.60217646e-19,
               unit=coul, description="Electron Charge")
ds.add_db_entry(material="Si", parameter="one", value=1, unit="", description="")
ds.close_db
```

When a database entry is not available for a specific material, the parameter will be looked up on the `global` material entry.

### 4.3 Discussion

Both parameters and material database entries may be used in model expressions. Parameters have precedence in this situation. If a parameter is not found, then DEVSIM will also look for a circuit node by the name used in the model expression.

## 4.4 Material commands

### get\_dimension

```
ds.get_dimension (device=STRING)
```

device= Device on which to apply this command

### get\_parameter

```
ds.get_parameter (device=STRING, region=STRING, name=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

name= Name of the parameter name being retrieved

Note that the `device` and `region` options are optional. If the region is not specified, the parameter is retrieved for the entire device. If the device is not specified, the parameter is retrieved for all devices. If the parameter is not found on the region, it is retrieved on the device. If it is not found on the device, it is retrieved over all devices.

### get\_parameter\_list

```
ds.get_parameter_list (device=STRING, region=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

Note that the `device` and `region` options are optional. If the region is not specified, the parameter is retrieved for the entire device. If the device is not specified, the parameter is retrieved for all devices. Unlike the [get\\_parameter](#) command (page 34), parameter names on the the device are not retrieved if they do not exist on the region. Similarly, the parameter names over all devices are not retrieved if they do not exist on the device.

### set\_parameter

```
ds.set_parameter (device=STRING, region=STRING, name=STRING, value=STRING)
```

device= Device on which to apply this command

region= Region on which to apply this command

name= Name of the parameter name being retrieved

value= value to set for the parameter

Note that the `device` and `region` options are optional. If the region is not specified, the parameter is set for the entire device. If the device is not specified, the parameter is set for all devices.

**get\_material**

```
ds.get_material (device=STRING, region=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
Returns the material for the specified region

**set\_material**

```
ds.set_material (device=STRING, region=STRING, material=STRING)
```

device= Device on which to apply this command  
region= Region on which to apply this command  
material= New material name  
Sets the new material for a region.

**create\_db**

```
ds.create_db (filename=STRING)
```

filename= filename to create for the db

**open\_db**

```
ds.open_db (filename=STRING, permission=OPTION)
```

filename= filename to create for the db  
permissions= permissions on the db  
"readwrite" Open file for reading and writing  
"readonly" Open file for read only (default)

**close\_db**

```
ds.close_db()
```

Closes the database so that its entries are no longer available.

**save\_db**

```
ds.save_db()
```

Saves any new or modified db entries to the database file.

**add\_db\_entry**

```
ds.add_db_entry (material=STRING, parameter=STRING, \  
                value=STRING, unit=STRING, description=STRING)
```

material=     Material name requested. global refers to all regions whose material does not have the parameter name specified

parameter=    Parameter name

value=        Value assigned for the parameter

unit=         String describing the units for this parameter name

description=   Description of the parameter for this material type.

The `save_db` command is used to commit these added entries permanently to the database.

**get\_db\_entry**

```
ds.get_db_entry (material=STRING, parameter=STRING)
```

material=     Material name

parameter=    Parameter name

This command returns a list containing the value, unit, and description for the requested material db entry.

## Chapter 5

# Circuits

### 5.1 Circuit elements

Circuit elements are manipulated using the commands in [Section 5.3, Circuit commands](#) on [page 37](#). Using the [circuit\\_element](#) command ([page 38](#)) to add a circuit element will implicitly create the nodes being references.

A simple resistor divider with a voltage source would be specified as:

```
ds.circuit_element(name="V1", n1="1", n2="0", value=1.0)
ds.circuit_element(name="R1", n1="1", n2="2", value=5.0)
ds.circuit_element(name="R2", n1="2", n2="0", value=5.0)
```

Circuit nodes are created automatically when referred to by these commands. Voltage sources create an additional circuit node of the form `V1.I` to account for the current flowing through it.

### 5.2 Connecting devices

For devices to contribute current to an external circuit, the [contact\\_equation](#) command ([page 19](#)) should use the `circuit_node` option to specify the circuit node in which to integrate its current. This option does not create a node in the circuit. No circuit boundary condition for the contact equation will exist if the circuit node does not actually exist in the circuit. The [circuit\\_node\\_alias](#) command ([page 38](#)) may be used to associate the name specified on the contact equation to an existing circuit node on the circuit.

The circuit node names may be used in any model expression on the regions and interfaces. However, the simulator will only take derivatives with respect to circuit nodes names on models used to compose the contact equation.

### 5.3 Circuit commands

Circuit commands are for adding circuit elements to the simulation.

**add\_circuit\_node**

```
ds.add_circuit_node (name=STRING, value=FLOAT,  
                    variable_update=OPTION)
```

name=	Name of the circuit node being created
variable_update=	update type for circuit variable
"default"	Variable can be positive or negative
"log_damp"	Variable update is damped
"positive"	Solution update results in positive quantity
value=	initial value

**circuit\_alter**

```
ds.circuit_alter (name=STRING, param=STRING,  
                 value=FLOAT)
```

name=	Name of the circuit element being modified
param=	parameter being modified (default <i>value</i> )
value=	value for the parameter

**circuit\_element**

```
ds.circuit_element (name=STRING, value=FLOAT,  
                   n1=STRING, n2=STRING, aereal=FLOAT, acimag=FLOAT)
```

name=	Name of the circuit element being created. A prefix of "V" is for voltage source, "I" for current source, "R" for resistor, "L" for inductor, and "C" for capacitor.
value=	value for the default parameter of the circuit element
n1=	circuit node
n2=	circuit node
aereal=	real part of AC source for voltage
acimag=	imaginary part of AC source for voltage

**circuit\_node\_alias**

```
ds.circuit_node_alias (node=STRING, alias=STRING)
```

node=	circuit node being aliased
alias=	alias for the circuit node

**get\_circuit\_equation\_number**

```
ds.get_circuit_equation_number (node=STRING)
```



node= Circuit node

Returns the row number correspond to circuit node in a region. Values are only valid when during the course of a solve.

### **get\_circuit\_node\_list**

Gets the list of the nodes in the circuit.

```
get_circuit_node_list()
```

### **get\_circuit\_node\_value**

```
ds.get_circuit_node_value(solution=STRING, node=STRING)
```

solution= name of the solution. "dcop" is the name for the DC solution and is  
the default

node= circuit node of interest

### **get\_circuit\_solution\_list**

```
ds.get_circuit_solution_list()
```

Gets the list of available circuit solutions.

### **set\_circuit\_node\_value**

```
ds.set_circuit_node_value(solution=STRING, node=STRING,  
                           value=FLOAT)
```

solution= name of the solution. "dcop" is the name for the DC solution and is  
the default

node= circuit node of interest

value= new value



## Chapter 6

# Meshing

### 6.1 1D mesher

DEVSIM has an internal 1D mesher and the proper sequence of commands follow in this example.

```
ds.create_1d_mesh(mesh="cap")
ds.add_1d_mesh_line(mesh="cap", pos=0, ps=0.1, tag="top")
ds.add_1d_mesh_line(mesh="cap", pos=0.5, ps=0.1, tag="mid")
ds.add_1d_mesh_line(mesh="cap", pos=1, ps=0.1, tag="bot")
ds.add_1d_contact(mesh="cap", name="top", tag="top")
ds.add_1d_contact(mesh="cap", name="bot", tag="bot")
ds.add_1d_interface(mesh="cap", name="MySiOx", tag="mid")
ds.add_1d_region(mesh="cap", material="Si", region="MySiRegion", tag1="top", tag2="mid")
ds.add_1d_region(mesh="cap", material="Ox", region="MyOxRegion", tag1="mid", tag2="bot")
ds.finalize_mesh(mesh="cap")
ds.create_device(mesh="cap", device="device")
```

The [create\\_1d\\_mesh](#) command (page 44) is first used to initialize the specification of a new mesh by the name specified with the `mesh` option. The [add\\_1d\\_mesh\\_line](#) command (page 44) is used to specify the end points of the 1D structure, as well as the location of points where the spacing changes. The `tag` is used to create reference labels used for specifying the contacts, interfaces and regions.

The [add\\_1d\\_contact](#) command (page 45), [add\\_1d\\_interface](#) command (page 45) and [add\\_1d\\_region](#) command (page 45) are used to specify the contacts, interfaces and regions for the device.

Once the meshing commands have been completed, the [finalize\\_mesh](#) command (page 44) is called to create a mesh structure and then [create\\_device](#) command (page 47) is used to create a device using the mesh.

## 6.2 2D mesher

Similar to the 1D mesher, the 2D mesher uses a sequence of non-terminating mesh lines are specified in both the x and y directions to specify a mesh structure. As opposed to using tags, the regions are specified using `add_2d_region` command (page 46) as box coordinates on the mesh coordinates. The contacts and interfaces are specified using boxes, however it is best to ensure the the interfaces and contacts encompass only one line of points.

```
ds.create_2d_mesh(mesh="cap")
ds.add_2d_mesh_line(mesh="cap", dir="y", pos=-0.001, ps=0.001)
ds.add_2d_mesh_line(mesh="cap", dir="x", pos=xmin, ps=0.1)
ds.add_2d_mesh_line(mesh="cap", dir="x", pos=xmax, ps=0.1)
ds.add_2d_mesh_line(mesh="cap", dir="y", pos=ymin, ps=0.1)
ds.add_2d_mesh_line(mesh="cap", dir="y", pos=ymax, ps=0.1)
ds.add_2d_mesh_line(mesh="cap", dir="y", pos=+1.001, ps=0.001)
ds.add_2d_region(mesh="cap", material="gas", region="gas1", yl=-.001, yh=0.0)
ds.add_2d_region(mesh="cap", material="gas", region="gas2", yl=1.0, yh=1.001)
ds.add_2d_region(mesh="cap", material="Oxide", region="r0", xl=xmin, xh=xmax,
    yl=ymin, yh=ymin)
ds.add_2d_region(mesh="cap", material="Silicon", region="r1", xl=xmin, xh=xmax,
    yl=ymin, yh=ymin)
ds.add_2d_region(mesh="cap", material="Silicon", region="r2", xl=xmin, xh=xmax,
    yl=ymin, yh=ymax)

ds.add_2d_interface(mesh="cap", name="i0", region0="r0", region1="r1")
ds.add_2d_interface(mesh="cap", name="i1", region0="r1", region1="r2", xl=0, xh=1,
    yl=ymin, yh=ymin, bloat=1.0e-10)
ds.add_2d_contact(mesh="cap", name="top", region="r0", yl=ymin, yh=ymin, bloat=1.0e-10)
ds.add_2d_contact(mesh="cap", name="bot", region="r2", yl=ymax, yh=ymax, bloat=1.0e-10)
ds.finalize_mesh(mesh="cap")
ds.create_device(mesh="cap", device="device")
```

In the current implementation of the software, it is necessary to create a region on both sides of the contact in order to create a contact using `add_2d_contact` command (page 46) or an interface using `add_2d_interface` command (page 46).

Once the meshing commands have been completed, the `finalize_mesh` command (page 44) is called to create a mesh structure and then `create_device` command (page 47) is used to create a device using the mesh.

## 6.3 Using an external mesher

The Gmsh meshing software (see [Section 12.1.1, Gmsh on page 69](#)) can be used to create a 1D, 2D, or 3D mesh suitable for use in DEVSIM. When creating the mesh file using the software, use physical group names to map the difference entities in the resulting mesh file to a group name. In this example, a mos structure is read in:

```

ds.create_gmsh_mesh(file="gmsh_mos2d.msh", mesh="mos2d")
ds.add_gmsh_region(mesh="mos2d" gmsh_name="bulk", region="bulk", material="Silicon")
ds.add_gmsh_region(mesh="mos2d" gmsh_name="oxide", region="oxide", material="Silicon")
ds.add_gmsh_region(mesh="mos2d" gmsh_name="gate", region="gate", material="Silicon")
ds.add_gmsh_contact(mesh="mos2d" gmsh_name="drain_contact", region="bulk", name="drain")
ds.add_gmsh_contact(mesh="mos2d" gmsh_name="source_contact", region="bulk", name="source")
ds.add_gmsh_contact(mesh="mos2d" gmsh_name="body_contact", region="bulk", name="body")
ds.add_gmsh_contact(mesh="mos2d" gmsh_name="gate_contact", region="gate", name="gate")
ds.add_gmsh_interface(mesh="mos2d" gmsh_name="gate_oxide_interface", region0="gate",
    region1="oxide", name="gate_oxide")
ds.add_gmsh_interface(mesh="mos2d" gmsh_name="bulk_oxide_interface", region0="bulk",
    region1="oxide", name="bulk_oxide")
ds.finalize_mesh(mesh="mos2d")
ds.create_device(mesh="mos2d", device="mos2d")

```

Once the meshing commands have been completed, the `finalize_mesh` command (page 44) is called to create a mesh structure and then `create_device` command (page 47) is used to create a device using the mesh.

## 6.4 Loading and saving results

The `write_devices` command (page 47) is used to create an ASCII file suitable for saving data for restarting the simulation later. The "devsim" format encodes structural information, as well as the commands necessary for generating the models and equations used in the simulation. The "devsimdata" format is used for storing numerical information for use in other programs for analysis. The `load_devices` command (page 47) is then used to reload the device data for restarting the simulation.

## 6.5 Meshing commands

### create\_gmsh\_mesh

```
ds.create_gmsh_mesh(mesh=STRING, file=STRING)
```

file= name of the Gmsh mesh file being read into DEVSIM  
 mesh= name of the mesh being generated

### add\_gmsh\_contact

```
ds.add_gmsh_contact(mesh=STRING, gmsh_name=STRING,
    name=STRING, region=STRING)
```

gmsh\_name= physical group name in the Gmsh file  
mesh= name of the mesh being generated  
name= name of the contact begin created  
region= region that the contact is attached to

### **add\_gmsh\_interface**

```
ds.add_gmsh_interface(mesh=STRING, gmsh_name=STRING,  
                      name=STRING, region0=STRING, region1=STRING)
```

gmsh\_name= physical group name in the Gmsh file  
mesh= name of the mesh being generated  
name= name of the interface begin created  
region0= first region that the interface is attached to  
region1= second region that the interface is attached to

### **add\_gmsh\_region**

```
ds.add_gmsh_region(mesh=STRING, gmsh_name=STRING,  
                   name=STRING, region=STRING, material=STRING)
```

gmsh\_name= physical group name in the Gmsh file  
mesh= name of the mesh being generated  
region= name of the region begin created  
material= material for the region being created

### **create\_1d\_mesh**

```
ds.create_1d_mesh(mesh=STRING)
```

mesh= name of the 1D mesh being created

### **finalize\_mesh**

```
ds.finalize_mesh(mesh=STRING)
```

mesh= Mesh to finalize

Finalize the 1D or 2D mesh so no additional mesh specifications can be added and devices can be created.

### **add\_1d\_mesh\_line**

```
ds.add_1d_mesh_line mesh=STRING, tag=STRING, pos=FLOAT,  
                    ns=FLOAT, ps=FLOAT)
```

mesh= Mesh to add the line to  
tag= Text label for the position  
pos= Position for the mesh point  
ns= Spacing from this point in the negative direction (defaults to ps value)  
ps= Spacing from this point in the positive direction

### **add\_1d\_interface**

```
ds.add_1d_mesh_interface mesh=STRING, tag=STRING, name=STRING)
```

mesh= Mesh to add the interface to  
tag= Text label for the position to add the interface  
name= Name for the interface being created

### **add\_1d\_contact**

```
ds.add_1d_mesh_contact mesh=STRING, tag=STRING, name=STRING)
```

mesh= Mesh to add the contact to  
tag= Text label for the position to add the contact  
name= Name for the contact being created

### **add\_1d\_region**

```
ds.add_1d_region mesh=STRING, tag1=STRING, tag2=STRING,  
                region=STRING, material=STRING)
```

mesh= Mesh to add the line to  
tag1= Text label for the position bounding the region being added  
tag2= Text label for the position bounding the region being added  
region= Name for the region being created  
material= Material for the region being created

### **create\_2d\_mesh**

```
ds.create_2d_mesh mesh=STRING)
```

mesh= name of the 2D mesh being created

### **add\_2d\_mesh\_line**

```
ds.add_2d_mesh_line mesh=STRING, pos=FLOAT,  
                    ns=FLOAT, ps=FLOAT)
```

mesh= Mesh to add the line to  
pos= Position for the mesh point  
ns= Spacing from this point in the negative direction (defaults to ps value)  
ps= Spacing from this point in the positive direction

**add\_2d\_region**

```
ds.add_2d_region mesh=STRING, region=STRING,  
                material=STRING,  
                xl=FLOAT, xh=FLOAT,  
                yl=FLOAT, yh=FLOAT,  
                bloat=FLOAT)
```

mesh=	Mesh to add the region to
region=	Name for the region being created
material=	Material for the region being created
xl=	x position for corner of bounding box (default -MAXDOUBLE)
xh=	x position for corner of bounding box (default +MAXDOUBLE)
yl=	y position for corner of bounding box (default -MAXDOUBLE)
yh=	y position for corner of bounding box (default +MAXDOUBLE)
bloat=	Extend bounding box by this amount when search for mesh to include in region (default 1e-10)

**add\_2d\_interface**

```
ds.add_2d_interface mesh=STRING, name=STRING,  
                   region0=STRING, region1=STRING,  
                   xl=FLOAT, xh=FLOAT,  
                   yl=FLOAT, yh=FLOAT,  
                   bloat=FLOAT)
```

mesh=	Mesh to add the interface to
interface=	Name for the interface being created
region0=	Name of the region included in the interface
region1=	Name of the region included in the interface
xl=	x position for corner of bounding box (default -MAXDOUBLE)
xh=	x position for corner of bounding box (default +MAXDOUBLE)
yl=	y position for corner of bounding box (default -MAXDOUBLE)
yh=	y position for corner of bounding box (default +MAXDOUBLE)
bloat=	Extend bounding box by this amount when search for mesh to include in region (default 1e-10)

**add\_2d\_contact**

```
ds.add_2d_contact(mesh=STRING, name=STRING,  
                 region=STRING,  
                 xl=FLOAT, xh=FLOAT,  
                 yl=FLOAT, yh=FLOAT,  
                 bloat=FLOAT)
```



mesh=        Mesh to add the contact to  
 contact=     Name for the contact being created  
 region=      Name of the region included in the contact  
 xl=          x position for corner of bounding box (default -MAXDOUBLE)  
 xh=          x position for corner of bounding box (default +MAXDOUBLE)  
 yl=          y position for corner of bounding box (default -MAXDOUBLE)  
 yh=          y position for corner of bounding box (default +MAXDOUBLE)  
 bloat=       Extend bounding box by this amount when search for mesh to include in region (default 1e-10)

### **create\_device**

`ds.create_device mesh=STRING, device=STRING)`

mesh=        name of the mesh being used to create a device  
 device=      name of the device being created

### **load\_devices**

`ds.load_devices(file=STRING)`

file=    name of the file to load the meshes from

### **write\_devices**

`ds.write_devices(file=STRING, device=STRING, type=OPTION)`

file=                name of the file to write the meshes to  
 device=              name of the device to write (optional)  
 type=                format to use  
   "devsim"            DEVSIM format  
   "devsim\_data"       DEVSIM output format with numerical data for all models  
   "floops"            Floops format (for visualization in Postmini)  
   "tecplot"           Tecplot format (for visualization in Tecplot)  
   "vtk"                VTK format (for visualization in ParaView and VisIt)



# Chapter 7

## Solver

### 7.1 Solver

DEVSIM uses Newton methods to solve the system of PDE's. All of the analyses are performed using the `solve` command (page 51).

### 7.2 DC analysis

A DC analysis is performed using the `solve` command (page 51).

```
solve(type="dc", absolute_error=1.0e10, relative_error=1e-7 maximum_iterations=30)
```

### 7.3 AC analysis

An AC analysis is performed using the `solve` command (page 51). A circuit voltage source is required to set the AC source.

### 7.4 Noise/Sensitivity analysis

An noise analysis is performed using the `solve` command. A circuit node is specified in order to find its sensitivity to changes in the bulk quantities of each device. If the circuit node is named V1.I. A noise simulation is performed using:

```
solve(type="noise", frequency=1e5, output_node="V1.I")
```

Noise and sensitivity analysis is performed using the `solve` command (page 51). If the equation begin solved is PotentialEquation, the names of the scalar impedance field is then:

- V1.I\_PotentialEquation\_real
- V1.I\_PotentialEquation\_imag

and the vector impedance fields evaluated on the nodes are

- `V1.I_PotentialEquation_real_gradx`
- `V1.I_PotentialEquation_imag_gradx`
- `V1.I_PotentialEquation_real_grady` (2D and 3D)
- `V1.I_PotentialEquation_imag_grady` (2D and 3D)
- `V1.I_PotentialEquation_real_gradz` (3D only)
- `V1.I_PotentialEquation_imag_gradz` (3D only)

## 7.5 Transient analysis

Transient analysis is performed using the `solve` command (page 51). DEVSIM supports time-integration of the device PDE's. The three methods are supported are:

- BDF1
- TRBDF
- BDF2

## 7.6 Solver commands

### **get\_contact\_current**

```
ds.get_contact_current(device=STRING, contact=STRING, equation=STRING)
```

<code>device=</code>	Device on which to apply this command
<code>contact=</code>	Contact on which to apply this command
<code>equation=</code>	Name of the contact equation from which we are retrieving the current

### **get\_contact\_charge**

```
ds.get_contact_charge(device=STRING, contact=STRING, equation=STRING)
```

<code>device=</code>	Device on which to apply this command
<code>contact=</code>	Contact on which to apply this command
<code>equation=</code>	Name of the contact equation from which we are retrieving the charge

**solve**

```
ds.solve(type=OPTION,
        solver_type=OPTION,
        absolute_error=FLOAT,
        relative_error=FLOAT,
        charge_error=FLOAT,
        maximum_iterations=INTEGER,
        frequency=FLOAT,
        output_node=STRING,
        gamma=FLOAT,
        tdelta=FLOAT)
```

type=	type of solve being performed
"dc"	DC steady state simulation
"ac"	Small-signal AC simulation
"noise"	Small-signal AC simulation
"transient_dc"	Perform DC steady state and keep calculate charge at initial time step
"transient_bdf1"	Perform transient simulation using backward difference integration
"transient_bdf2"	Perform transient simulation using backward difference integration
"transient_tr"	Perform transient simulation using trapezoidal integration
solver_type=	Linear solver type
"direct"	Use LU factorization (default)
"iterative"	Use iterative solver
absolute_error=	Required update norm in the solve
relative_error=	Required relative update in the solve
charge_error=	Relative error between projected and solved charge during transient simulation
gamma=	Scaling factor for transient time step (default 1.0)
tdelta=	time step
maximum_iterations=	Maximum number of iterations in the DC solve
frequency=	Frequency for small-signal AC simulation
output_node=	Output circuit node for noise simulation
	A small-signal AC source is set with the circuit voltage source.



## Chapter 8

# User Interface

### 8.1 Starting DEVSIM

Refer to *Chapter 11, Installation on page 67* for instructions on how to install DEVSIM. Once installed, DEVSIM may be invoked using the following command

```
devsim
```

for an interactive shell or

```
devsim filename.py
```

for batch mode where `filename.py` is the name of script being run. DEVSIM output is printed to the screen. To capture the output of the program, shell redirection commands may be used to direct the output to a file.

### 8.2 Python Language

#### 8.2.1 Introduction

Python is the scripting language employed as the text interface to DEVSIM. Documentation and tutorials for the language are available from [2] A paper discussing the general benefits of using scripting languages may be found in [3].

#### 8.2.2 DEVSIM commands

All of commands are in the `ds` namespace. In order to invoke a command, the command should be prefixed with `ds.`, or the following may be placed at the beginning of the script:

```
from ds import *
```

For details concerning error handling, please see *Section 8.4, Error handling on page 55*.

### 8.2.3 Other packages

DEVSIM is able to load Python packages. It is important to note that binary extensions loaded into DEVSIM must be compatible with the operating system which it was compiled for. To load an extension, it is first necessary to provide the path as an environment variable, or at program run time.

For example, if the Python packages on your system are available in “/usr/share/tcltk”, it is necessary to set the environment variable in “csh” as

```
setenv PYTHONPATH /usr/share/tcltk
```

or in “bash”

```
export PYTHONPATH=/usr/share/tcltk
```

In the Python script, this may be done using using the appropriate paths for your system

```
import sys
sys.path.append("/usr/share/tcltk")
```

Please see [Python](#) on page 69 for more information on obtaining a copy of Python for your computer's operating system.

### 8.2.4 Advanced usage

In this manual, more advanced usage of the Python language may be used. The reader is encouraged to use a suitable reference to clarify the proper use of the scripting language constructs, such as control structures.

## 8.3 Unicode Support

Internally, DEVSIM uses UTF-8 encoding, and expects model equations and saved mesh files to be written using this encoding. Users are encouraged to use the standard ASCII character set if they do not wish to use this feature. When reading a Unicode encoded script, the built in Python interpreter should be made aware of the encoding of the source encoding using this on the first or second line of the script

```
# -*- coding: utf-8 -*-
```

This option is only required on systems, such as Microsoft Windows, which do not default to this encoding. Care should be taken when using Unicode names for visualization using the tools in [Chapter 10, Visualization](#) on page 65, as this character set may not be supported.



## 8.4 Error handling

### 8.4.1 Python errors

When a syntax error occurs in a Python script an exception may be thrown. If it is uncaught, then DEVSIM will terminate. More details may be found in an appropriate reference. An exception that is thrown by DEVSIM is of the type `ds.error`. It may be caught.

### 8.4.2 Fatal errors

When DEVSIM enters a state in which it may not recover. The interpreter should throw a Python exception with a message `DEVSIM_FATAL`. At this point DEVSIM may enter an inconsistent state, so it is suggested not to attempt to continue script execution if this occurs.

In rare situations, the program may behave in an erratic manner, print a message, such as `UNEXPECTED` or terminate abruptly. Please report this to DEVSIM LLC using the contact information in the [front cover](#) of this manual.

### 8.4.3 Floating Point Exceptions

During model evaluation, DEVSIM will attempt to detect floating point issues and return an error with some diagnostic information printed to the screen, such as the symbolic expression being evaluated. Floating point errors may be characterized as invalid, division by zero, and numerical overflow. This is considered to be a fatal error.

### 8.4.4 Solver errors

When using the [solve](#) command (page 51), the solver may not converge and a message will be printed and an exception may be thrown. The solution will be restored to its previous value before the simulation began. This exception may be caught and the bias conditions may be changed so the simulation may be continued. For example:

```
try:
    solve(type="dc", absolute_error=abs_error,
          relative_error=rel_error, maximum_iterations=max_iter)
except ds.error as msg:
    if msg[0].find("Convergence failure") != 0:
        raise
    ##### put code to modify step here.
```

### 8.4.5 Verbosity

The [set\\_parameter](#) command (page 34) may be used to set the verbosity globally, per device, or per region. Setting the `debug_level` parameter to `info` results in the default level of information to the screen. Setting this option to `verbose` or any other name results in more information to the screen which may be useful for debugging.

The following example sets the default level of debugging for the entire simulation, except that the gate region will have additional debugging information.

```
ds.set_parameter(name="debug_level", value="info")
ds.set_parameter(device="device" region="gate", name="debug_level", value="verbose")
```

## 8.5 Parallelization

Routines for the evaluating of models have been parallelized. In order to select the number of threads to use

```
ds.set_parameter(name="threads_available", value=2)
```

where the value specified is the number of threads to be used. By default, DEVSIM does not use threading. For regions with a small number of elements, the time for switching threads is more than the time to evaluate in a single thread. To set the minimum number of elements for a calculation, set the following parameter.

```
ds.set_parameter(name="threads_task_size", value=1024)
```

## Chapter 9

# SYMDIFF

### 9.1 Overview

SYMDIFF is a tool capable of evaluating derivatives of symbolic expressions. Using a natural syntax, it is possible to manipulate symbolic equations in order to aid derivation of equations for a variety of applications. It has been tailored for use within DEVSIM.

### 9.2 Syntax

#### 9.2.1 Variables and numbers

Variables and numbers are the basic building blocks for expressions. A variable is defined as any sequence of characters beginning with a letter and followed by letters, integer digits, and the `_` character. Note that the letters are case sensitive so that `a` and `A` are not the same variable. Any other characters are considered to be either mathematical operators or invalid, even if there is no space between the character and the rest of the variable name.

Examples of valid variable names are:

`a`, `dog`, `var1`, `var_2`

Numbers can be integer or floating point. Scientific notation is accepted as a valid syntax. For example:

`1.0`, `1.0e-2`, `3.4E-4`

Expression	Description
(exp1)	Parenthesis for changing precedence
+exp1	Unary Plus
-exp1	Unary Minus
!exp1	Logical Not
exp1 ^ exp2	Exponentiation
exp1 * exp2	Multiplication
exp1 / exp2	Division
exp1 + exp2	Addition
exp1 - exp2	Subtraction
exp1 < exp2	Test Less
exp1 <= exp2	Test Less Equal
exp1 > exp2	Test Greater
exp1 >= exp2	Test Greater Equal
exp1 == exp2	Test Equality
exp1 != exp2	Test Inequality
exp1 && exp2	Logical And
exp1    exp2	Logical Or
variable	Independent Variable
number	Integer or decimal number

Table 9.1: Basic expressions involving unary, binary, and logical operators.

### 9.2.2 Basic expressions

In Table 9.1, the basic syntax for the language is presented. An expression may be composed of variables and numbers tied together with mathematical operations. Order of operations is from bottom to top in order of increasing precedence. Operators with the same level of precedence are contained within horizontal lines.

In the expression  $a + b * c$ , the multiplication will be performed before the addition. In order to override this precedence, parenthesis may be used. For example, in  $(a + b) * c$ , the addition operation is performed before the multiplication.

The logical operators are based on non zero values being true and zero values being false. The test operators are evaluate the numerical values and result in 0 for false and 1 for true.

*It is important to note since values are based on double precision arithmetic, testing for equality with values other than 0.0 may yield unexpected results.*

Function	Description
B(exp1)	Bernoulli Function
dBdx(exp1)	derivative of Bernoulli function
derfcdx(exp1)	derivative of complementary error function
derfdx(exp1)	derivative error function
dFermidx(exp1)	derivative of Fermi Integral
dInvFermidx(exp1)	derivative of InvFermi Integral
dot2d(exp1x, exp1y, exp2x, exp2y)	$\exp1x \cdot \exp2x + \exp1y \cdot \exp2y$
erfc(exp1)	complementary error function
erf(exp1)	error function
exp(exp1)	exponent
Fermi(exp1)	Fermi Integral
ifelse(test, exp1, exp2)	if test is true, then evaluate exp1, otherwise exp2
if(test, exp)	if test is true, then evaluate exp, otherwise 0
InvFermi(exp1)	inverse of the Fermi Integral
log(exp1)	natural log
max(exp1, exp2)	maximum of the two arguments
min(exp1, exp2)	minimum of the two arguments
pow(exp1, exp2)	take exp1 to the power of exp2
sgn(exp1)	sign function
step(exp1)	unit step function
kahan3(exp1, exp2, exp3)	Extended precision addition of arguments
kahan4(exp1, exp2, exp3, exp4)	Extended precision addition of arguments

Table 9.2: Predefined Functions.

### 9.2.3 Functions

In Table 9.2 are the built in functions of SYMDIFF. Note that the `pow` function uses the `,` operator to separate arguments. In addition an expression like `pow(a,b+y)` is equivalent to an expression like `a^(b+y)`. Both `exp` and `log` are provided since many derivative expressions can be expressed in terms of these two functions. It is possible to nest expressions within functions and vice-versa.

Command	Description
<code>diff(obj1, var)</code>	Take derivative of <code>obj1</code> with respect to variable <code>var</code>
<code>expand(obj)</code>	Expand out all multiplications into a sum of products
<code>help</code>	Print description of commands
<code>scale(obj)</code>	Get constant factor
<code>sign(obj)</code>	Get sign as 1 or -1
<code>simplify(obj)</code>	Simplify as much as possible
<code>subst(obj1,obj2,obj3)</code>	substitute <code>obj3</code> for <code>obj2</code> into <code>obj1</code>
<code>unscaledval(obj)</code>	Get value without constant scaling
<code>unsignedval(obj)</code>	Get unsigned value
<code>sum</code>	sum of all the values over the entire region or interface

Table 9.3: Commands.

### 9.2.4 Commands

Commands are shown in Table 9.3. While they appear to have the same form as functions, they are special in the sense that they manipulate expressions and are never present in the expression which results. For example, note the result of the following command

```
> diff(a*b, b)
a
```

Command	Description
<code>clear(name)</code>	Clears the name of a user function
<code>declare(name(arg1, arg2, ...))</code>	declare function name taking dummy arguments arg1, arg2, .... Derivatives assumed to be 0
<code>define(name(arg1, arg2, ...), obj1, obj2, ...)</code>	declare function name taking arguments arg1, arg2, . . . having corresponding derivatives obj1, obj2, ...

Table 9.4: Commands for user functions.

### 9.2.5 User functions

Commands for specifying and manipulating user functions are listed in Table 9.4. They are used in order to define new user function, as well as the derivatives of the functions with respect to the user variables. For example, the following expression defines a function named `f` which takes one argument.

```
> define(f(x), 0.5*x)
```

The list after the function prototype is used to define the derivatives with respect to each of the independent variables. Once defined, the function may be used in any other expression. In additions the any expression can be used as an arguments. For example:

```
> diff(f(x*y),x)
((0.5 * (x * y)) * y)
> simplify((0.5 * (x * y)) * y)
(0.5 * x * (y^2))
```

The chain rule is applied to ensure that the derivative is correct. This can be expressed as

$$\frac{\partial}{\partial x} f(u, v, \dots) = \frac{\partial u}{\partial x} \cdot \frac{\partial}{\partial u} f(u, v, \dots) + \frac{\partial v}{\partial x} \cdot \frac{\partial}{\partial v} f(u, v, \dots)$$

The `declare` command is required when the derivatives of two user functions are based on one another. For example:

```
> declare(cos(x))
cos(x)
> define(sin(x), cos(x))
sin(x)
> define(cos(x), -sin(x))
cos(x)
```

When declared, a functions derivatives are set to 0, unless specified with a `define` command. It is now possible to use these expressions as desired.

```
> diff(sin(cos(x)),x)
(cos(cos(x)) * (-sin(x)))
> simplify(cos(cos(x)) * (-sin(x)))
(-cos(cos(x)) * sin(x))
```

### 9.2.6 Macro assignment

The use of macro assignment allows the substitution of expressions into new expressions. Every time a command is successfully used, the resulting expression is assigned to a special macro definition, `$_`.

In this example, the result of the each command is substituted into the next.

```
> a+b
(a + b)
> $_-b
((a + b) - b)
> simplify($_)
a
```

In addition to the default macro definition, it is possible to specify a variable identifier by using the `$` character followed by an alphanumeric string beginning with a letter. In addition to letters and numbers, a `_` character may be used as well. A macro which has not previously assigned will implicitly use 0 as its value.

This example demonstrates the use of macro assignment.

```
> $a1 = a + b
(a + b)
> $a2 = a - b
(a - b)
> simplify($a1+$a2)
(2 * a)
```

## 9.3 Invoking SYMDIFF from DEVSIM

### 9.3.1 Equation parser

The `syndiff` command (page 31) should be used when defining new functions to the parser. Since you do not specify regions or interfaces, it considers all strings as being independent variables, as opposed to models. [Section 3.8, Model commands on page 21](#) presents commands which have the concepts of models. A “;” should be used to separate each statement.

This is a sample invocation from DEVSIM

```
% syndiff(expr="subst(dog * cat, dog, bear)")
(bear * cat)
```

### 9.3.2 Evaluating external math

The `register_function` command (page 30) is used to evaluate functions declared or defined within SYMDIFF. A Python procedure may then be used taking the same number of arguments. For example:



```
from math import cos
from math import sin
syndiff(expr="declare(sin(x))")
syndiff(expr="define(cos(x), -sin(x))")
syndiff(expr="define(sin(x), cos(x))")
register_function(name=cos, nargs=1)
register_function(name=sin, nargs=1)
```

The `cos` and `sin` function may then be used for model evaluation. For improved efficiency, it is possible to create procedures written in C or C++ and load them into Python.

### 9.3.3 Models

When used with the model commands discussed in [Section 3.8, Model commands](#) on [page 21](#), DEVSIM has been extended to recognize model names in the expressions. In this situation, the derivative of a model named, `model`, with respect to another model, `variable`, is then `model:variable`.

During the element assembly process, DEVSIM evaluates all models of an equation together. While the expressions in models and their derivatives are independent, the software uses a caching scheme to ensure that redundant calculations are not performed. It is recommended, however, that users developing their own models investigate creating intermediate models in order to improve their understanding of the equations that they wish to be assembled.



## Chapter 10

# Visualization

### 10.1 Introduction

DEVSIM is able to create files for visualization tools. Information about acquiring these tools are presented in *Chapter 12.1, Third Party Software Availability* on page 69.

### 10.2 Using Tecplot

The `write_devices` command (page 47) is used to create an ASCII file suitable for use in Tecplot. Edge quantities are interpolated onto the node positions in the resulting structure. Element edge quantities are interpolated onto the centers of each triangle or tetrahedron in the mesh.

```
write_devices(file="mos_2d_dd.dat", type="tecplot")
```

### 10.3 Using Postmini

The `write_devices` command (page 47) is used to create an ASCII file suitable for use in Postmini. Edge and element edge quantities are interpolated onto the node positions in the resulting structure.

```
write_devices(file="mos_2d_dd.flps", type="floops")
```

### 10.4 Using ParaView

The `write_devices` command (page 47) is used to create an ASCII file suitable for use in ParaView. Edge quantities are interpolated onto the node positions in the resulting structure. Element edge quantities are interpolated onto the centers of each triangle or tetrahedron in the mesh.

```
write_devices(file="mos_2d_dd", type="vtk")
```

One `vtu` file per device region will be created, as well as a `vtm` file which may be used to load all of the device regions into ParaView.

## 10.5 Using Visit

Visit supports reading the Tecplot and ParaView formats. When using the `vtk` option on the `write_devices` command (page 47), a file with a `visit` filename extension is created to load the files created for ParaView.

## 10.6 DEVSIM

DEVSIM has several commands for getting information on the mesh. Those related to post processing are described in [Section 3.8, Model commands on page 21](#) and [Section 3.9, Geometry commands on page 32](#).

See [Section 6.4, Loading and saving results on page 43](#) for information about loading and saving mesh information to a file.

# Chapter 11

## Installation

### 11.1 Supported platforms

DEVSIM is has been compiled and tested on the platforms in Table [11.1](#). If you require a version of DEVSIM on a different software platform, please contact us using the information in the [front cover](#) of this manual.

### 11.2 Directory Structure

A `devsim` directory is created with the following sub directories.

`bin` contains the devsim binary

`doc` contains product documentation

`lib` contains runtime libraries

`examples` contains example scripts

### 11.3 Running DEVSIM

See *Chapter 8, User Interface* on page [53](#) for instructions on how to invoke DEVSIM.

Platform	Bits	OS Version
Microsoft Windows	32,64	Windows XP Windows 7
Linux	32,64	Ubuntu 8.04 (LTS) Ubuntu 10.04 (LTS) Ubuntu 12.04 (LTS) Centos 5 (Red Hat Enterprise 5 compatible)
Apple Mac OS X	32,64	Mac OS X 10.6 (Snow Leopard)

Table 11.1: Current platforms for DEVSIM.

## Chapter 12

# Additional Information

### 12.1 Third Party Software Availablilty

#### 12.1.1 Gmsh

Gmsh [4] is available from <http://geuz.org/gmsh/>.

#### 12.1.2 ParaView

ParaView is an open source visualization tool available at <http://www.paraview.org>.

#### 12.1.3 Postmini

Postmini is available from <http://home.comcast.net/~john.faricelli/tcad.htm>.

#### 12.1.4 SQLite3

SQLite3 is the database engine used for the material database and is available from <http://www.sqlite.com>. It may be accessed from DEVSIM using

```
import sqlite3
```

#### 12.1.5 Python

A Python distribution is not required for using DEVSIM, however additional packages from Python may be loaded into DEVSIM. Python is distributed with many operating system distributions. Additional information is available at <http://www.python.org>. It should be stressed that binary packages must be compatible with the Python distribution used by DEVSIM.

#### 12.1.6 Tecplot

Tecplot is a visualization tool available from <http://www.tecplot.com>.

### 12.1.7 VisIt

VisIt is a visualization tool available from <https://wci.llnl.gov/codes/visit/>.

## 12.2 Third Party Licenses

### 12.2.1 SuperLU

SuperLU [5] is used within DEVSIM and their copyright is reproduced here:

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SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.



## **Part II**

# **Examples**



## Chapter 13

# Example Overview

In the following chapters, examples are presented for the use of DEVSIM to solve some simulation problems. Examples are also located in the DEVSIM distribution and their location is mentioned in *Section 11.2, Directory Structure on page 67*.

The following example directories are contained in the distribution.

**capacitance** These are 1D and 2D capacitor simulations, using the internal mesher. A description of these examples is presented in *Chapter 14, Capacitor on page 75*.

**diode** This is a collection of 1D, 2D, and 3D diode structures using the internal mesher, as well as Gmsh. These examples are discussed in *Chapter 15, Diode on page 85*.

**bioapp1** This is a biosensor application.

**vector\_potential** This is a 2d magnetic field simulation solving for the magnetic potential. The simulation script is `vector_potential/twowire.py`. A simulation result for two wires conducting current is shown in *Figure 13.1*.

**mobility** This is an advanced example using electric field dependent mobility models.

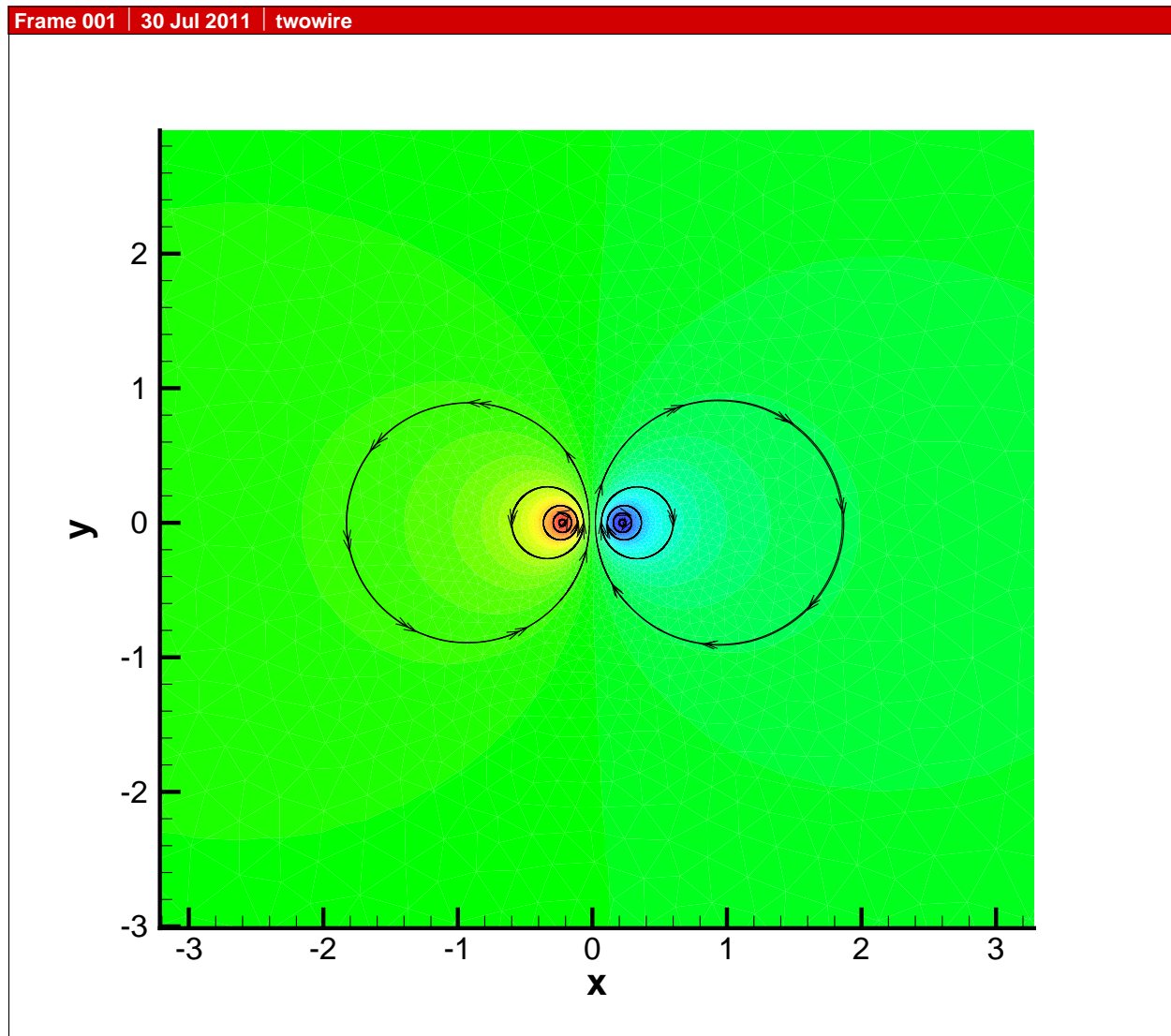


Figure 13.1: Simulation result for solving for the magnetic potential and field. The coloring is by the Z component of the magnetic potential, and the stream traces are for components of magnetic field.

# Chapter 14

## Capacitor

### 14.1 Overview

In this chapter, we present a capacitance simulations. The purpose is to demonstrate the use of DEVSIM with a rather simple example. The first example in [Section 14.2, 1D Capacitor on page 75](#) is called `cap1d.py` and is located in the `examples/capacitance` directory distributed with DEVSIM. In this example, we have manually taken the derivative expressions. In other examples, we will show use of SYMDIFF to create the derivatives in an automatic fashion. The second example is in [Section 14.3, 2D Capacitor on page 79](#).

### 14.2 1D Capacitor

#### 14.2.1 Equations

In this example, we are solving Poisson's equation. In differential operator form, the equation to be solved over the structure is:

$$\epsilon \nabla^2 \psi = 0 \quad (14.1)$$

and the contact boundary equations are

$$\psi_i - V_c = 0 \quad (14.2)$$

where  $\psi_i$  is the potential at the contact node and  $V_c$  is the applied voltage.

#### 14.2.2 Creating the mesh

The following statements create a one-dimensional mesh which is 1 m long with a 0.1 m spacing. A contact is placed at 0 and 1 and are named `contact1` and `contact2` respectively.

```
from ds import *
device="MyDevice"
region="MyRegion"
```

```
###
```

```

### Create a 1D mesh
###
create_1d_mesh (mesh="mesh1")
add_1d_mesh_line (mesh="mesh1", pos=0.0, ps=0.1, tag="contact1")
add_1d_mesh_line (mesh="mesh1", pos=1.0, ps=0.1, tag="contact2")
add_1d_contact (mesh="mesh1", name="contact1", tag="contact1")
add_1d_contact (mesh="mesh1", name="contact2", tag="contact2")
add_1d_region (mesh="mesh1", material="Si", region=region, tag1="contact1", tag2="contact2")
finalize_mesh (mesh="mesh1")
create_device (mesh="mesh1", device=device)

```

### 14.2.3 Setting device parameters

In this section, we set the value of the permittivity to that of  $\text{SiO}_2$ .

```

###
### Set parameters on the region
###
set_parameter(device=device, region=region, name="Permittivity", value=3.9*8.85e-14)

```

### 14.2.4 Creating the models

Solving for the Potential,  $\psi$ , we first create the solution variable.

```

###
### Create the Potential solution variable
###
node_solution(device=device, region=region, name="Potential")

```

In order to create the edge models, we need to be able to refer to Potential on the nodes on each edge.

```

###
### Creates the Potential@n0 and Potential@n1 edge model
###
edge_from_node_model(device=device, region=region, node_model="Potential")

```

We then create the ElectricField model with knowledge of Potential on each node, as well as the EdgeInverseLength of each edge. We also manually calculate the derivative of ElectricField with Potential on each node and name them ElectricField:Potential@n0 and ElectricField:Potential@n1.

```

###
### Electric field on each edge, as well as its derivatives with respect to
### the potential at each node
###
edge_model(device=device, region=region, name="ElectricField",
           equation="(Potential@n0 - Potential@n1)*EdgeInverseLength")

edge_model(device=device, region=region, name="ElectricField:Potential@n0",

```

```
equation="EdgeInverseLength")
```

```
edge_model(device=device, region=region, name="ElectricField:Potential@n1",
equation="-EdgeInverseLength")
```

We create DField to account for the electric displacement field.

```
###
```

```
### Model the D Field
```

```
###
```

```
edge_model(device=device, region=region, name="DField",
equation="Permittivity*ElectricField")
```

```
edge_model(device=device, region=region, name="DField:Potential@n0",
equation="diff(Permittivity*ElectricField, Potential@n0)")
```

```
edge_model(device=device, region=region, name="DField:Potential@n1",
equation="-DField:Potential@n0")
```

The bulk equation is now created for the structure using the models and parameters we have previously defined.

```
###
```

```
### Create the bulk equation
```

```
###
```

```
equation(device=device, region=region, name="PotentialEquation", variable_name="Potential",
edge_model="DField", variable_update="default")
```

### 14.2.5 Contact boundary conditions

We then create the contact models and equations. We use the Python `foreach` looping construct and variable substitutions to create a unique model for each contact, `contact1_bc` and `contact2_bc`.

```
###
```

```
### Contact models and equations
```

```
###
```

```
for c in ("contact1", "contact2"):
```

```
    contact_node_model(device=device, contact=c, name="%s_bc" % c,
equation="Potential - %s_bias" % c)
```

```
    contact_node_model(device=device, contact=c, name="%s_bc:Potential" % c,
equation="1")
```

```
    contact_equation(device=device, contact=c, name="PotentialEquation",
variable_name="Potential",
node_model="%s_bc" % c, edge_charge_model="DField")
```

In this example, the contact bias is applied through parameters named `contact1.bias` and `contact2.bias`. When applying the boundary conditions through circuit nodes, models with respect to their names and their derivatives would be required.

### 14.2.6 Setting the boundary conditions

```
###
### Set the contact
###
set_parameter(device=device, region=region, name="contact1_bias", value=1.0e-0)
set_parameter(device=device, region=region, name="contact2_bias", value=0.0)

###
### Solve
###
solve(type="dc", absolute_error=1.0, relative_error=1e-10, maximum_iterations=30)

###
### Print the charge on the contacts
###
for c in ("contact1", "contact2"):
    print("contact: %s charge: %1.5e"
          % (c, get_contact_charge(device=device, contact=c, equation="PotentialEquation")))
```

### 14.2.7 Running the simulation

We run the simulation and see the results.

```
capacitance> devsim cap1d.py
-----

DEVSIM

Version: Beta 0.01

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-----

contact2
(region: MyRegion)
(contact: contact1)
(contact: contact2)
Region "MyRegion" on device "MyDevice" has equations 0:10
Device "MyDevice" has equations 0:10
number of equations 11
Iteration: 0
  Device: "MyDevice" RelError: 1.00000e+00 AbsError: 1.00000e+00
    Region: "MyRegion" RelError: 1.00000e+00 AbsError: 1.00000e+00
      Equation: "PotentialEquation" RelError: 1.00000e+00 AbsError: 1.00000e+00
Iteration: 1
  Device: "MyDevice" RelError: 2.77924e-16 AbsError: 1.12632e-16
    Region: "MyRegion" RelError: 2.77924e-16 AbsError: 1.12632e-16
      Equation: "PotentialEquation" RelError: 2.77924e-16 AbsError: 1.12632e-16
contact: contact1 charge: 3.45150e-13
contact: contact2 charge: -3.45150e-13
```

Which corresponds to our expected result of  $3.45150 \cdot 10^{-13} \text{ F/cm}^2$  for a homogenous capacitor.



## 14.3 2D Capacitor

This example is called `cap2d.py` and is located in the `examples/capacitance` directory distributed with DEVSIM. This file uses the same physics as the 1d example, but with a 2d structure. The mesh is built using the DEVSIM internal mesher. An air region exists with two electrodes in the simulation domain.

## 14.4 Defining the mesh

```
from ds import *
device="MyDevice"
region="MyRegion"

xmin=-25
x1  =-24.975
x2  =-2
x3  =2
x4  =24.975
xmax=25.0

ymin=0.0
y1  =0.1
y2  =0.2
y3  =0.8
y4  =0.9
ymax=50.0

create_2d_mesh(mesh=device)
add_2d_mesh_line(mesh=device, dir="y", pos=ymin, ps=0.1)
add_2d_mesh_line(mesh=device, dir="y", pos=y1 , ps=0.1)
add_2d_mesh_line(mesh=device, dir="y", pos=y2 , ps=0.1)
add_2d_mesh_line(mesh=device, dir="y", pos=y3 , ps=0.1)
add_2d_mesh_line(mesh=device, dir="y", pos=y4 , ps=0.1)
add_2d_mesh_line(mesh=device, dir="y", pos=ymax, ps=5.0)

device=device
region="air"

add_2d_mesh_line(mesh=device, dir="x", pos=xmin, ps=5)
add_2d_mesh_line(mesh=device, dir="x", pos=x1 , ps=2)
add_2d_mesh_line(mesh=device, dir="x", pos=x2 , ps=0.05)
add_2d_mesh_line(mesh=device, dir="x", pos=x3 , ps=0.05)
add_2d_mesh_line(mesh=device, dir="x", pos=x4 , ps=2)
add_2d_mesh_line(mesh=device, dir="x", pos=xmax, ps=5)

add_2d_region(mesh=device, material="gas" , region="air", yl=ymin, yh=ymax, xl=xmin, xh=xmax)
add_2d_region(mesh=device, material="metal", region="m1" , yl=y1 , yh=y2 , xl=x1 , xh=x4)
add_2d_region(mesh=device, material="metal", region="m2" , yl=y3 , yh=y4 , xl=x2 , xh=x3)
```

```
# must be air since contacts don't have any equations
add_2d_contact(mesh=device, name="bot", region="air", yl=y1, yh=y2, xl=x1, xh=x4)
add_2d_contact(mesh=device, name="top", region="air", yl=y3, yh=y4, xl=x2, xh=x3)
finalize_mesh(mesh=device)
create_device(mesh=device, device=device)
```

## 14.5 Setting up the models

```
###
### Set parameters on the region
###
set_parameter(device=device, region=region, name="Permittivity", value=3.9*8.85e-14)

###
### Create the Potential solution variable
###
node_solution(device=device, region=region, name="Potential")

###
### Creates the Potential@n0 and Potential@n1 edge model
###
edge_from_node_model(device=device, region=region, node_model="Potential")

###
### Electric field on each edge, as well as its derivatives with respect to
### the potential at each node
###
edge_model(device=device, region=region, name="ElectricField",
            equation="(Potential@n0 - Potential@n1)*EdgeInverseLength")

edge_model(device=device, region=region, name="ElectricField:Potential@n0",
            equation="EdgeInverseLength")

edge_model(device=device, region=region, name="ElectricField:Potential@n1",
            equation="-EdgeInverseLength")

###
### Model the D Field
###
edge_model(device=device, region=region, name="DField",
            equation="Permittivity*ElectricField")

edge_model(device=device, region=region, name="DField:Potential@n0",
            equation="diff(Permittivity*ElectricField, Potential@n0)")

edge_model(device=device, region=region, name="DField:Potential@n1",
            equation="-DField:Potential@n0")
```

```

###
### Create the bulk equation
###
equation(device=device, region=region, name="PotentialEquation", variable_name="Potential",
        edge_model="DField", variable_update="default")

###
### Contact models and equations
###
for c in ("top", "bot"):
    contact_node_model(device=device, contact=c, name="%s_bc" % c,
        equation="Potential - %s_bias" % c)

    contact_node_model(device=device, contact=c, name="%s_bc:Potential" % c,
        equation="1")

    contact_equation(device=device, contact=c, name="PotentialEquation",
        variable_name="Potential",
        node_model="%s_bc" % c, edge_charge_model="DField")

###
### Set the contact
###
set_parameter(device=device, name="top_bias", value=1.0e-0)
set_parameter(device=device, name="bot_bias", value=0.0)

edge_model(device=device, region="m1", name="ElectricField", equation="0")
edge_model(device=device, region="m2", name="ElectricField", equation="0")
node_model(device=device, region="m1", name="Potential", equation="bot_bias;")
node_model(device=device, region="m2", name="Potential", equation="top_bias;")

#solve -type dc -absolute_error 1.0 -relative_error 1e-10 -maximum_iterations 100 -solver_type iterative
solve(type="dc", absolute_error=1.0, relative_error=1e-10, maximum_iterations=30, solver_type="direct")

```

## 14.6 Fields for visualization

Before writing the mesh out for visualization, the `element_from_edge_model` is used to calculate the electric field at each triangle center in the mesh. The components are the `ElectricField_x` and `ElectricField_y`.

```

element_from_edge_model(edge_model="ElectricField", device=device, region=region)
print(get_contact_charge(device=device, contact="top", equation="PotentialEquation"))
print(get_contact_charge(device=device, contact="bot", equation="PotentialEquation"))

```

```
write_devices(file="cap2d.msh", type="devsim")
write_devices(file="cap2d.dat", type="tecplot")
```

## 14.7 Running the simulation

-----

DEVSIM

Version: Beta 0.01

Copyright 2009-2013 Devsim LLC

-----

```
Creating Region air
Creating Region m1
Creating Region m2
Adding 8281 nodes
Adding 23918 edges with 22990 duplicates removed
Adding 15636 triangles with 0 duplicate removed
Adding 334 nodes
Adding 665 edges with 331 duplicates removed
Adding 332 triangles with 0 duplicate removed
Adding 162 nodes
Adding 321 edges with 159 duplicates removed
Adding 160 triangles with 0 duplicate removed
Contact bot in region air with 334 nodes
Contact top in region air with 162 nodes
Region "air" on device "MyDevice" has equations 0:8280
Region "m1" on device "MyDevice" has no equations.
Region "m2" on device "MyDevice" has no equations.
Device "MyDevice" has equations 0:8280
number of equations 8281
Iteration: 0
  Device: "MyDevice" RelError: 1.00000e+00 AbsError: 1.00000e+00
    Region: "air" RelError: 1.00000e+00 AbsError: 1.00000e+00
      Equation: "PotentialEquation" RelError: 1.00000e+00 AbsError: 1.00000e+00
Iteration: 1
  Device: "MyDevice" RelError: 1.25144e-12 AbsError: 1.73395e-13
    Region: "air" RelError: 1.25144e-12 AbsError: 1.73395e-13
      Equation: "PotentialEquation" RelError: 1.25144e-12 AbsError: 1.73395e-13
3.35017166004e-12
-3.35017166004e-12
```

A visualization of the results is shown in Figure [14.1](#).

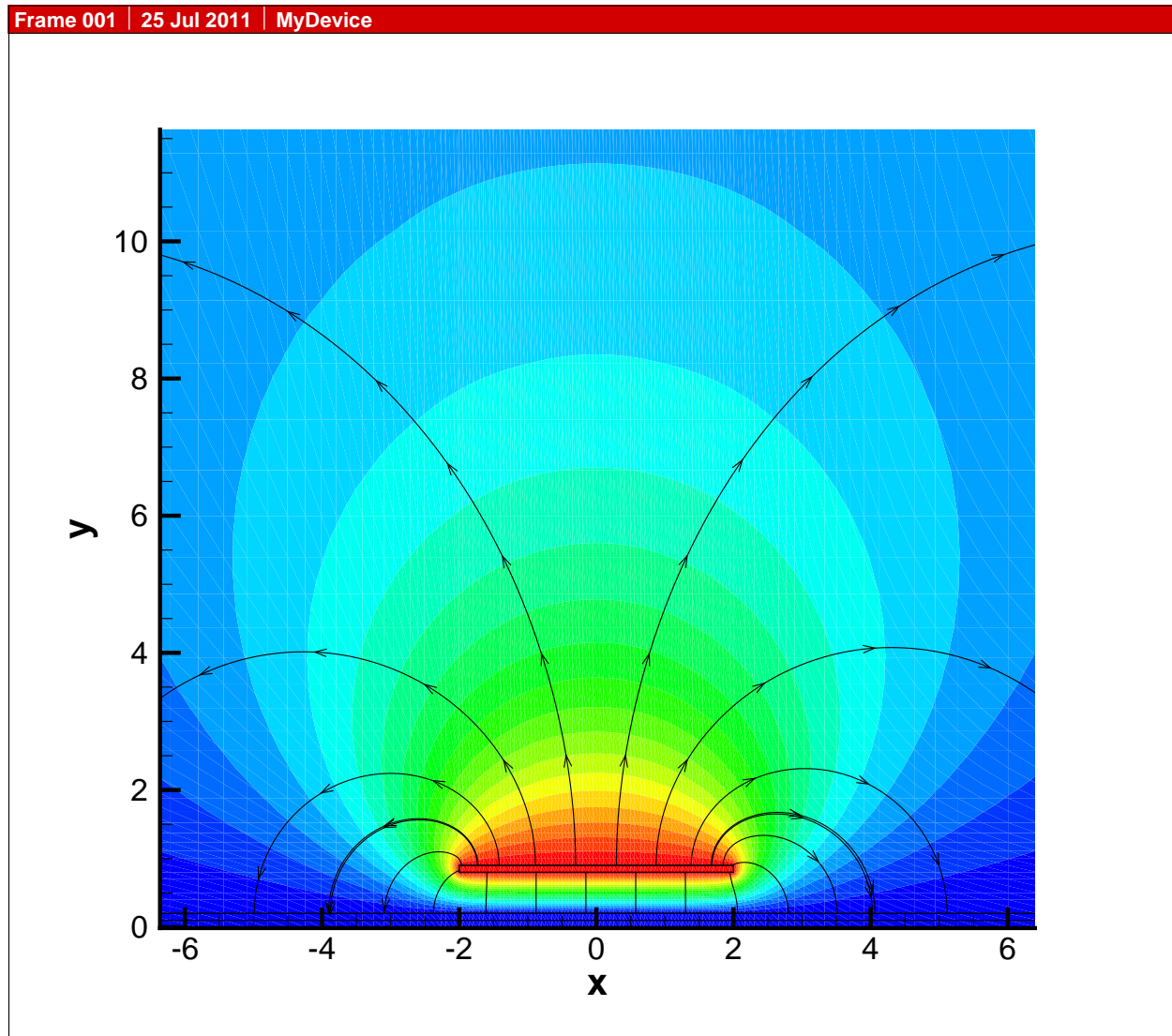


Figure 14.1: Capacitance simulation result. The coloring is by Potential, and the stream traces are for components of ElectricField.



# Chapter 15

## Diode

The diode examples are located in the `examples/diode`. They demonstrate the use of packages located in the `python_packages` directory to simulate drift-diffusion using the Scharfetter-Gummel method [6].

### 15.1 1D diode

#### 15.1.1 Using the python packages

For these examples, python modules are provided to supply the appropriate model and parameter settings. A listing is shown in Table 15.1. The `python_packages` must be in your path, and may be set using the methods described in *Section 8.2.3, Other packages on page 54*. The example files in the DEVSIM distribution set the path properly when loading modules.

For this example, `diode_1d.py`, the following line is used to import the relevant physics.

```
from ds import *
from simple_physics import *
```

#### 15.1.2 Creating the mesh

This creates a mesh  $10^{-6}$  cm long with a junction located at the midpoint. The name of the device is `MyDevice` with a single region names `MyRegion`. The contacts on either end are called `top` and `bot`.

```
def createMesh(device, region):
    create_1d_mesh(mesh="dio")
    add_1d_mesh_line(mesh="dio", pos=0, ps=1e-7, tag="top")
    add_1d_mesh_line(mesh="dio", pos=0.5e-5, ps=1e-9, tag="mid")
    add_1d_mesh_line(mesh="dio", pos=1e-5, ps=1e-7, tag="bot")
    add_1d_contact (mesh="dio", name="top", tag="top")
    add_1d_contact (mesh="dio", name="bot", tag="bot")
    add_1d_region (mesh="dio", material="Si", region=region, tag1="top", tag2="bot")
    finalize_mesh(mesh="dio")
    create_device(mesh="dio", device=device)
```

model_create	Creation of models and their derivatives
ramp	Ramping bias and automatic stepping
simple_dd	Functions for calculating bulk electron and hole current
simple_physics	Functions for setting up device physics

Table 15.1: Python package files.

```
device="MyDevice"
region="MyRegion"

createMesh(device, region)
```

## 15.2 Physical Models and Parameters

```
####
#### Set parameters for 300 K
####
SetSiliconParameters(device, region, 300)
set_parameter(device=device, region=region, name="taun", value=1e-8)
set_parameter(device=device, region=region, name="taup", value=1e-8)

####
#### NetDoping
####
CreateNodeModel(device, region, "Acceptors", "1.0e18*step(0.5e-5-x)")
CreateNodeModel(device, region, "Donors", "1.0e18*step(x-0.5e-5)")
CreateNodeModel(device, region, "NetDoping", "Donors-Acceptors")
print_node_values(device=device, region=region, name="NetDoping")

####
#### Create Potential, Potential@n0, Potential@n1
####
CreateSolution(device, region, "Potential")

####
#### Create potential only physical models
####
CreateSiliconPotentialOnly(device, region)

####
#### Set up the contacts applying a bias
####
for i in get_contact_list(device=device):
    set_parameter(device=device, name=GetContactBiasName(i), value=0.0)
    CreateSiliconPotentialOnlyContact(device, region, i)
```



```

####
#### Initial DC solution
####
solve(type="dc", absolute_error=1.0, relative_error=1e-12, maximum_iterations=30)

####
#### drift diffusion solution variables
####
CreateSolution(device, region, "Electrons")
CreateSolution(device, region, "Holes")

####
#### create initial guess from dc only solution
####
set_node_values(device=device, region=region, name="Electrons", init_from="IntrinsicElectrons")
set_node_values(device=device, region=region, name="Holes", init_from="IntrinsicHoles")

###
### Set up equations
###
CreateSiliconDriftDiffusion(device, region)
for i in get_contact_list(device=device):
    CreateSiliconDriftDiffusionAtContact(device, region, i)

###
### Drift diffusion simulation at equilibrium
###
solve(type="dc", absolute_error=1e10, relative_error=1e-10, maximum_iterations=30)

####
#### Ramp the bias to 0.5 Volts
####
v = 0.0
while v < 0.51:
    set_parameter(device=device, name=GetContactBiasName("top"), value=v)
    solve(type="dc", absolute_error=1e10, relative_error=1e-10, maximum_iterations=30)
    PrintCurrents(device, "top")
    PrintCurrents(device, "bot")
    v += 0.1

####
#### Write out the result
####
write_devices(file="diode_1d.dat", type="tecplot")

```

### 15.2.1 Plotting the result

A plot showing the doping profile and carrier densities are shown in Figure 15.1. The potential and electric field distribution is shown in Figure 15.2. The current distributions are shown in Figure 15.3.

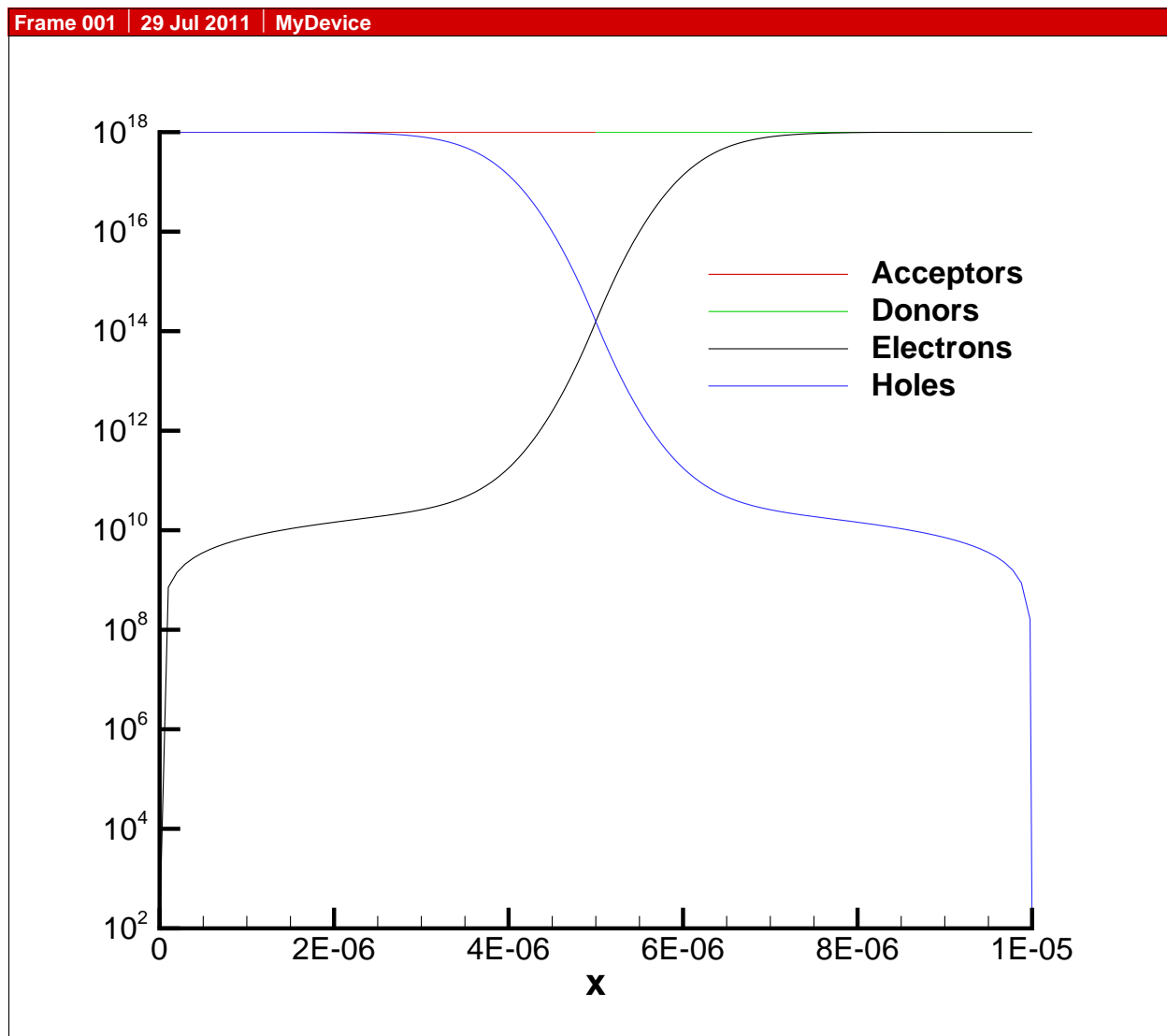


Figure 15.1: Carrier density versus position in 1D diode.

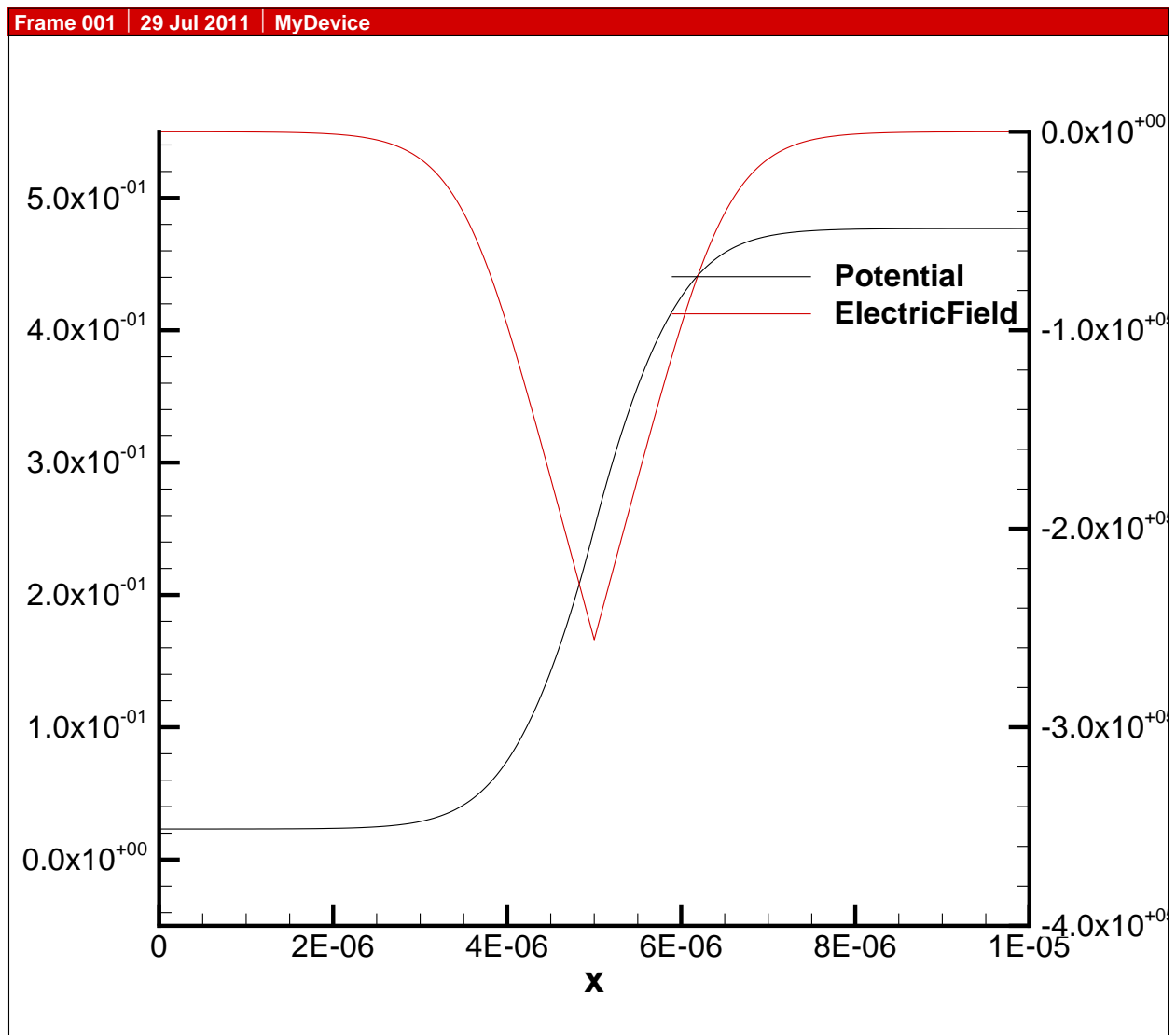


Figure 15.2: Potential and electric field versus position in 1D diode.

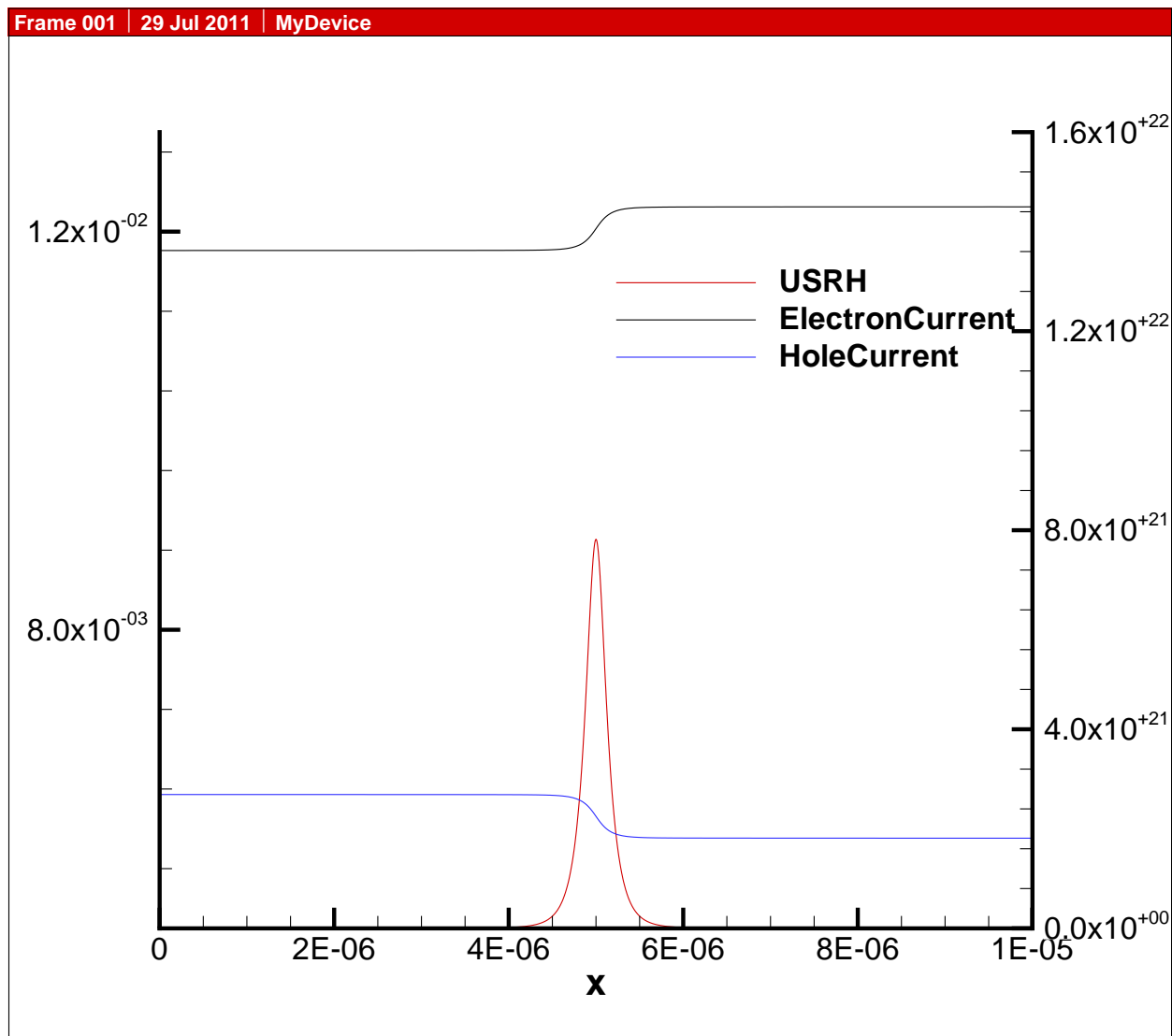


Figure 15.3: Electron and hole current and recombination.



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