



DEVSIM Manual

Release 1.0.0-rc1

Devsim LLC

Nov 02, 2018

Contents

List of Figures	vii
------------------------	------------

List of Tables	ix
-----------------------	-----------

1 Front Matter	1
-----------------------	----------

1.1 Contact	1
1.2 Copyright	1
1.3 Documentation License	1
1.4 Disclaimer	1
1.5 Trademark	1

2 Release Notes	3
------------------------	----------

2.1 Introduction	3
2.2 1.0.0-rc1 Nov 02, 2018	3
2.3 July 20, 2018	4
2.4 May 15, 2017	5
2.5 February 6, 2016	6
2.6 November 24, 2015	7
2.7 November 1, 2015	7
2.8 September 6, 2015	8
2.9 August 10, 2015	8
2.10 July 16, 2015	8
2.11 June 7, 2015	9
2.12 October 4, 2014	9
2.13 December 25, 2013	9
2.14 September 8, 2013	10
2.15 August 14, 2013	10
2.16 July 29, 2013	11

3 Introduction	13
-----------------------	-----------

3.1 Overview	13
3.2 Goals	13
3.3 Structures	13
3.4 Equation assembly	14
3.5 Parameters	14
3.6 Circuits	14
3.7 Meshing	14

3.8	Analysis	14
3.9	Scripting interface	15
3.10	Expression parser	15
3.11	Visualization and postprocessing	15
3.12	Installation	15
3.13	Additional information	15
3.14	Examples	15
4	Equation and Models	17
4.1	Overview	17
4.2	Bulk models	21
4.3	Interface	24
4.4	Contact	26
4.5	Custom matrix assembly	28
4.6	Cylindrical Coordinate Systems	29
5	Model Parameters	31
5.1	Parameters	31
5.2	Material database entries	31
5.3	Discussion	31
6	Circuits	33
6.1	Circuit elements	33
6.2	Connecting devices	33
7	Meshing	35
7.1	1D mesher	35
7.2	2D mesher	36
7.3	Using an external mesher	37
7.4	Loading and saving results	38
8	Solver	39
8.1	Solver	39
8.2	DC analysis	39
8.3	AC analysis	39
8.4	Noise/Sensitivity analysis	39
8.5	Transient analysis	40
9	User Interface	41
9.1	Starting DEVSIM	41
9.2	Python Language	41
9.3	Error handling	42
10	SYMDIFF	45
10.1	Overview	45
10.2	Syntax	45
10.3	Invoking SYMDIFF from DEVSIM	50
11	Visualization	51

11.1	Introduction	51
11.2	Using Tecplot	51
11.3	Using Postmini	51
11.4	Using Paraview	51
11.5	Using VisIt	52
11.6	DEVSIM	52
12	Installation	53
12.1	Availability	53
12.2	Supported platforms	53
12.3	Binary availability	53
12.4	Source code availability	54
12.5	Directory Structure	54
12.6	Running DEVSIM	54
13	Additional Information	55
13.1	DEVSIM License	55
13.2	SYMDIFF	55
13.3	External Software Tools	55
13.4	Library Availabilty	56
14	Command Reference	59
14.1	Circuit Commands	59
14.2	Equation Commands	60
14.3	Geometry Commands	65
14.4	Material Commands	65
14.5	Meshing Commands	68
14.6	Model Commands	74
14.7	Solver Commands	85
15	Example Overview	87
15.1	capacitance	87
15.2	diode	87
15.3	bioapp1	87
15.4	genius	87
15.5	vector_potential	88
15.6	mobility	88
16	Capacitor	89
16.1	Overview	89
16.2	1D Capacitor	89
16.3	Setting device parameters	90
16.4	2D Capacitor	93
16.5	Defining the mesh	93
16.6	Setting up the models	94
16.7	Fields for visualization	96
16.8	Running the simulation	96
17	Diode	99

17.1	1D diode	99
17.2	Physical Models and Parameters	100
	Bibliography	105
	Index	107

List of Figures

4.1	Mesh elements in 2D.	18
4.2	Edge model constructs in 2D.	19
4.3	Element edge model constructs in 2D.	20
4.4	Interface constructs in 2D. Interface node pairs are located at each •. The <code>SurfaceArea</code> model is used to integrate flux term models.	25
4.5	Contact constructs in 2D.	27
15.1	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.	88
16.1	Capacitance simulation result. The coloring is by <code>Potential</code> , and the stream traces are for components of <code>ElectricField</code>	98
17.1	Carrier density versus position in 1D diode.	102
17.2	Potential and electric field versus position in 1D diode.	103
17.3	Electron and hole current and recombination.	104

List of Tables

4.1	Node models defined on each region of a device.	21
4.2	Edge models defined on each region of a device.	22
4.3	Element edge models defined on each region of a device.	23
4.4	Required derivatives for equation assembly. <code>model</code> is the name of the model being evaluated, and <code>variable</code> is one of the solution variables being solved at each node.	23
4.5	Required derivatives for interface equation assembly. The node model name <code>nodemodel</code> and its derivatives <code>nodemodel:variable</code> are suffixed with <code>@r0</code> and <code>@r1</code> to denote which region on the interface is being referred to.	24
10.1	Basic expressions involving unary, binary, and logical operators.	46
10.2	Predefined Functions.	47
10.3	Commands.	48
10.4	Commands for user functions.	48
12.1	Current platforms for DEVSIM.	53
12.2	Directory structure for DEVSIM.	54
17.1	Python package files.	99

Chapter 1

Front Matter

1.1 Contact

Web:	https://devsim.com
Email:	info@devsim.com
Open Source Project:	https://devsim.org

1.2 Copyright

Copyright © 2009–2018 DEVSIM LLC

1.3 Documentation License

This work is licensed under the Creative Commons Attribution-NoDerivatives 4.0 International License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nd/4.0/>.

1.4 Disclaimer

DEVSIM LLC MAKES NO WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, WITH REGARD TO THIS MATERIAL, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

1.5 Trademark

DEVSIM is a registered trademark and SYMDIFF is a trademark of DEVSIM LLC. All other product or company names are trademarks of their respective owners.

Chapter 2

Release Notes

2.1 Introduction

DEVSIM download and installation instructions are located in *Installation* (page 53). The following sections list bug fixes and enhancements over time. The official website for this project is located at <https://devsim.org>.

2.2 1.0.0-rc1 Nov 02, 2018

2.2.1 Version

Due to the numerous changes in the Python API, the version number has been updated to having a major revision of 1. We adopt the semantic version numbering presented at <https://semver.org>. The version number can be accessed through the Python interface using the `devsim.__version__` variable.

2.2.2 Python Support

DEVSIM is now loaded as a shared library from any compatible Python interpreter. Previously, DEVSIM binaries contained an embedded Python interpreter. The following versions of Python are supported in this release

- 2.7
- 3.6
- 3.7

By first setting the `PYTHONPATH` variable to the `lib` directory in the DEVSIM distribution, `devsim` is loaded by using

```
import devsim
```

from Python. Previous versions of devsim used the `ds` module, the manual will be updated to reflect the change in module name.

Many of the examples in the distribution rely on the `python_packages` module, which is available by using:

```
import devsim.python_packages
```

The default version of Python for use in scripts is 3.7, however scripts written for earlier versions of Python 3 should work. Python 2.7 is deprecated for future development.

Anaconda Python 3.7 is the recommended distribution and is available from <https://continuum.io>. The Intel Math Kernel Library is required for the official DEVSIM releases. These may be installed in Anaconda using the following command:

```
conda install mkl
```

Some of the examples and tests also use `numpy`, which is available using:

```
conda install numpy
```

Please see *User Interface* (page 41) and *Installation* (page 53) for more information.

2.3 July 20, 2018

2.3.1 Documentation

The documentation has a new license, which is described in *Copyright* (page 1). The source files are now available for download from: https://github.com/devsim/devsim_documentation.

2.3.2 Python 3 Support

Python 3 executable, `devsim_py3` is now supplied in addition to standard Python 2 executable, `devsim`.

2.3.3 Element Information

The `devsim.get_element_node_list()` (page 65) retrieves a list of nodes for every element on a region, contact, or interface.

2.3.4 Interface Boundary Condition

The `type=hybrid` option is now available for the `devsim.interface_equation()` (page 64) command. Please see *Interface equation assembly* (page 26) for information about boundary conditions.

2.3.5 Interface Equation Coupling

The `name0`, and `name1` options are now available for the `devsim.interface_equation()` (page 64) command. They make it possible to change the equation coupling in each region.

2.3.6 Interface and Contact Surface Area

Contact surface area is no longer included in `SurfaceArea` node model. It is now placed in `ContactSurfaceArea`. These are listed in [Table 4.1](#).

2.3.7 Bug Fixes

- The `devsim.interface_equation()` (page 64) command is fixed for `type=fluxterm` boundary conditions on the interface.
- The `devsim.get_material()` (page 66), and `devsim.set_material()` (page 67) now properly handle the `contact` option.
- Interface equation assembly properly skips nodes when an interface node is shared with a contact.

2.3.8 Extended Precision

The following new parameters are available:

- `extended_solver`, extended precision matrix for Newton and linear Solver
- `extended_model`, extended precision model evaluation
- `extended_equation`, extended precision equation assembly

When compiled with 128-bit extended precision support, these options enable calculations to be performed with higher precision. Default geometric models, are also calculated with extended precision.

```
devsim.set_parameter(name = "extended_solver", value=True)
devsim.set_parameter(name = "extended_model", value=True)
devsim.set_parameter(name = "extended_equation", value=True)
```

Currently, the Linux and gcc-based Apple Mac OS X versions have extended precision support.

2.4 May 15, 2017

2.4.1 Platforms

- The Ubuntu 16.04 (LTS) platform is now supported.
- The Ubuntu 12.04 (LTS), Centos 5 (Red Hat 5 compatible) platforms are no longer supported. These platforms are no longer supported by their vendors.

- Apple Mac OS X compiled with `flat_namespace` to allow substitution of dynamically linked libraries.
- Microsoft Windows 7 is compiled using Microsoft Visual Studio 2017.

2.4.2 Binary Releases

- Releases available from <https://github.com/devsim/devsim/releases>.
- Centos 6 released is linked against the Intel Math Kernel Library.
- Microsoft Windows 7 release is linked against the Intel Math Kernel Library
- Apple Mac OS X can optionally use the Intel Math Kernel Library.
- Anaconda Python 2.7 is the recommended distribution.
- Please see release notes for more information.

2.4.3 Bug Fixes

- 3d element edge derivatives were not being evaluated correctly
- 3d equation model evaluation for element edge models

2.4.4 Enhancements

- Build scripts are provided to build on various platforms.
- DEVSIM mesh format stores elements, instead of just nodes, for contact and interfaces
- The `devsim.create_gmsh_mesh()` (page 73) command can be used to create a device from a provided list of elements.

2.4.5 Example Availability

- BJT simulation example available from https://github.com/devsim/devsim_bjt_example.

2.5 February 6, 2016

DEVSIM is now covered by the Apache License, Version 2.0 [ApacheSoftwareFoundation]. Please see the NOTICE and LICENSE file for more information.

2.6 November 24, 2015

2.6.1 Python Help

The Python interpreter now has documentation for each command, derived from the documentation in the manual. For example, help for the `devsim.solve()` (page 85) can be found using:

```
help("devsim.solve")
```

2.6.2 Manual Updates

The manual has been updated so that commands are easier to find in the index. Every command now has a short description. Cross references have been fixed. The date has been added to the front page.

2.7 November 1, 2015

2.7.1 Convergence Info

The `devsim.solve()` (page 85) now supports the `info` option. The `solve` command will then return convergence information.

2.7.2 Python Interpreter Changes

The way DEVSIM commands are loaded into the `devsim` module has been changed. It is now possible to see the full list of DEVSIM commands by typing

```
help('devsim')
```

in the Python interpreter.

2.7.3 Platform Improvements and Binary Availability

Many improvements have been made in the way binaries are generated for the Linux, Apple Mac OS X, and Microsoft Windows platforms.

For Linux (see `linux.txt`):

- Create Centos 5, (Red Hat Enterprise Linux 5 compatible) build
- Build uses Intel Math Kernel Library math libraries (community edition)
- Build uses any compatible Python 2.7, including Anaconda
- Build compatible with newer Linux distributions.

For Apple Mac OS X (see `macos.txt`):

- Uses the system Python 2.7 on Mac OS X 10.10 (Yosemite)
- Provide instructions to use Anaconda Python

For Microsoft Windows (see `windows.txt`):

- Uses any compatible Python 2.7, including Anaconda
- Build uses Intel Math Kernel Library Community Edition

Binary releases are available for these platforms at <https://devsim.org>.

2.8 September 6, 2015

The `devsim.set_node_values()` (page 83) takes a new option, `values`. It is a list containing values to set for all of the nodes in a region.

The following new commands have been added:

- `devsim.get_equation_list()` (page 63)
- `devsim.get_contact_equation_list()` (page 63)
- `devsim.get_interface_equation_list()` (page 64)
- `devsim.delete_equation()` (page 62)
- `devsim.delete_contact_equation()` (page 61)
- `devsim.delete_interface_equation()` (page 62)
- `devsim.get_equation_command()` (page 63)
- `devsim.get_contact_equation_command()` (page 63)
- `devsim.get_interface_equation_command()` (page 64)

2.9 August 10, 2015

The `devsim.create_contact_from_interface()` (page 72) may be used to create a contact at the location of an interface. This is useful when contact boundary conditions are needed for a region connected to the interface.

2.10 July 16, 2015

The `devsim.set_node_value()` (page 83) was not properly setting the value. This issue is now resolved.

2.11 June 7, 2015

The `devsim.equation()` (page 62) now supports the `edge_volume_model`. This makes it possible to integrate edge quantities properly so that it is integrated with respect to the volume on nodes of the edge. To set the node volumes for integration, it is necessary to define a model for the node volumes on both nodes of the edge. For example:

```
devsim.edge_model(device="device", region="region", name="EdgeNodeVolume",
    equation="0.5*EdgeCouple*EdgeLength")
set_parameter(name="edge_node0_volume_model", value="EdgeNodeVolume")
set_parameter(name="edge_node1_volume_model", value="EdgeNodeVolume")
```

For the cylindrical coordinate system in 2D, please see *Cylindrical Coordinate Systems* (page 29).

Mac OS X 10.10 (Yosemite) is now supported. Regression results in the source distribution are for a 2014 Macbook Pro i7 running this operating system.

2.12 October 4, 2014

2.12.1 Platform Availability

The software is now supported on the Microsoft Windows. Please see *Supported platforms* (page 53) for more information.

2.13 December 25, 2013

2.13.1 Binary Availability

Binary versions of the DEVSIM software are available for download from <http://sourceforge.net/projects/devsim>. Current versions available are for

- Mac OS X 10.10 (Yosemite)
- Red Hat Enterprise Linux 6
- Ubuntu 12.04 (LTS)

Please see *Installation* (page 53) for more information.

2.13.2 Platforms

Mac OS X 10.10 (Yosemite) is now supported. Support for 32 bit is no longer supported on this platform, since the operating system is only released as 64 bit.

Regression data will no longer be maintained in the source code repository for 32 bit versions of Ubuntu 12.04 (LTS) and Red Hat Enterprise Linux 6. Building and running on these platforms will still be supported.

2.13.3 Source code improvements

The source code has been improved to compile on Mac OS X 10.10 (Yosemite) and to comply with C++11 language standards. Some of the structure of the project has been reorganized. These changes to the infrastructure will help to keep the program maintainable and useable into the future.

2.14 September 8, 2013

2.14.1 Convergence

If the simulation is diverging for 5 or more iterations, the simulation stops.

2.14.2 Bernoulli Function Derivative Evaluation

The dBdx math function has been improved to reduce overflow.

2.14.3 Default Edge Model

The `edge_index` is now a default edge models created on a region [Table 4.2](#).

2.15 August 14, 2013

2.15.1 SYMDIFF functions

The `vec_max` and `vec_min` functions have been added to the SYMDIFF parser ([Table 10.2](#)). The `vec_sum` function replaces `sum`.

2.15.2 Default Node Models

The `coordinate_index` and `node_index` are now part of the default node models created on a region ([Table 4.1](#)).

2.15.3 Set Node Value

It is now possible to use the `devsim.set_node_value()` ([page 83](#)) to set a uniform value or indexed value on a node model.

2.15.4 Fix Edge Average Model

Fixed issue with `devsim.edge_average_model()` ([page 77](#)) during serialization to the DEVSIM format.

2.16 July 29, 2013

2.16.1 DEVSIM is open source

DEVSIM is now an open source project and is available from <https://github.com/devsim/devsim>. License information may be found in *DEVSIM License* (page 55). If you would like to participate in this project or need support, please contact us using the information in *Contact* (page 1). Installation instructions may be found in *Installation* (page 53).

2.16.2 Build

The Tcl interpreter version of DEVSIM is now called `devsim_tcl`, and is located in `/src/main/` of the build directory. Please see the `INSTALL` file for more information.

2.16.3 Contact Material

Contacts now require a material setting (e.g. `metal`). This is for informational purposes. Contact models still look up parameter values based on the region they are located.

2.16.4 External Meshing

Please see *Using an external mesher* (page 37) for more information about importing meshes from other tools.

Genius **Mesh Import** DEVSIM can now read meshes written from Genius Device Simulator. More information about Genius is in *Genius* (page 37).

Gmsh **Mesh Import** DEVSIM reads version 2.1 and 2.2 meshes from Gmsh. Version 2.0 is no longer supported. Please see *Gmsh* (page 38) for more information.

2.16.5 Math Functions

The `acosh`, `asinh`, `atanh`, are now available math functions. Please see [Table 10.2](#).

2.16.6 Test directory structure

Platform specific results are stored in a hierarchical fashion.

Chapter 3

Introduction

3.1 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.

DEVSIM is available from <https://devsim.org>. The source code is available under the terms of the Apache License Version 2.0 [ApacheSoftwareFoundation]. Examples are released under the Apache License Version 2.0 [ApacheSoftwareFoundation]. Contributions to this project are welcome in the form of bug reporting, documentation, modeling, and feature implementation.

3.2 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 has a scripting language interface (*User Interface* (page 41)). This provides control structures and language syntax in a consistent and intuitive manner. 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 (*SYMDIFF* (page 45)) 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.

3.3 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 An `interface` connects two regions together. At the interfaces, equations are specified to account for how the flux in each device region crosses the region boundary.

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

3.4 Equation assembly

Equation assembly of models is discussed in *Equation and Models* (page 17).

3.5 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 *Model Parameters* (page 31).

3.6 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 *Circuits* (page 33).

3.7 Meshing

Meshing is discussed in *Meshing* (page 35).

3.8 Analysis

DEVSIM offers a range of simulation algorithms. They are discussed in more detail in *Solver* (page 39).

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.

3.9 Scripting interface

The scripting interface to DEVSIM is discussed in *User Interface* (page 41).

3.10 Expression parser

The expression parser is discussed in *SYMDIFF* (page 45).

3.11 Visualization and postprocessing

Visualization is discussed in *Visualization* (page 51).

3.12 Installation

Installation is discussed in *Installation* (page 53).

3.13 Additional information

Additional information is discussed in *Additional Information* (page 55).

3.14 Examples

Examples are discussed in the remaining chapters beginning with *Example Overview* (page 87).

Chapter 4

Equation and Models

4.1 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:

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

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

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

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

In Fig. 4.1, 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 *SYMDIFF* (page 45). For special situations, custom matrix assembly is also available and is discussed in *Custom matrix assembly* (page 28).

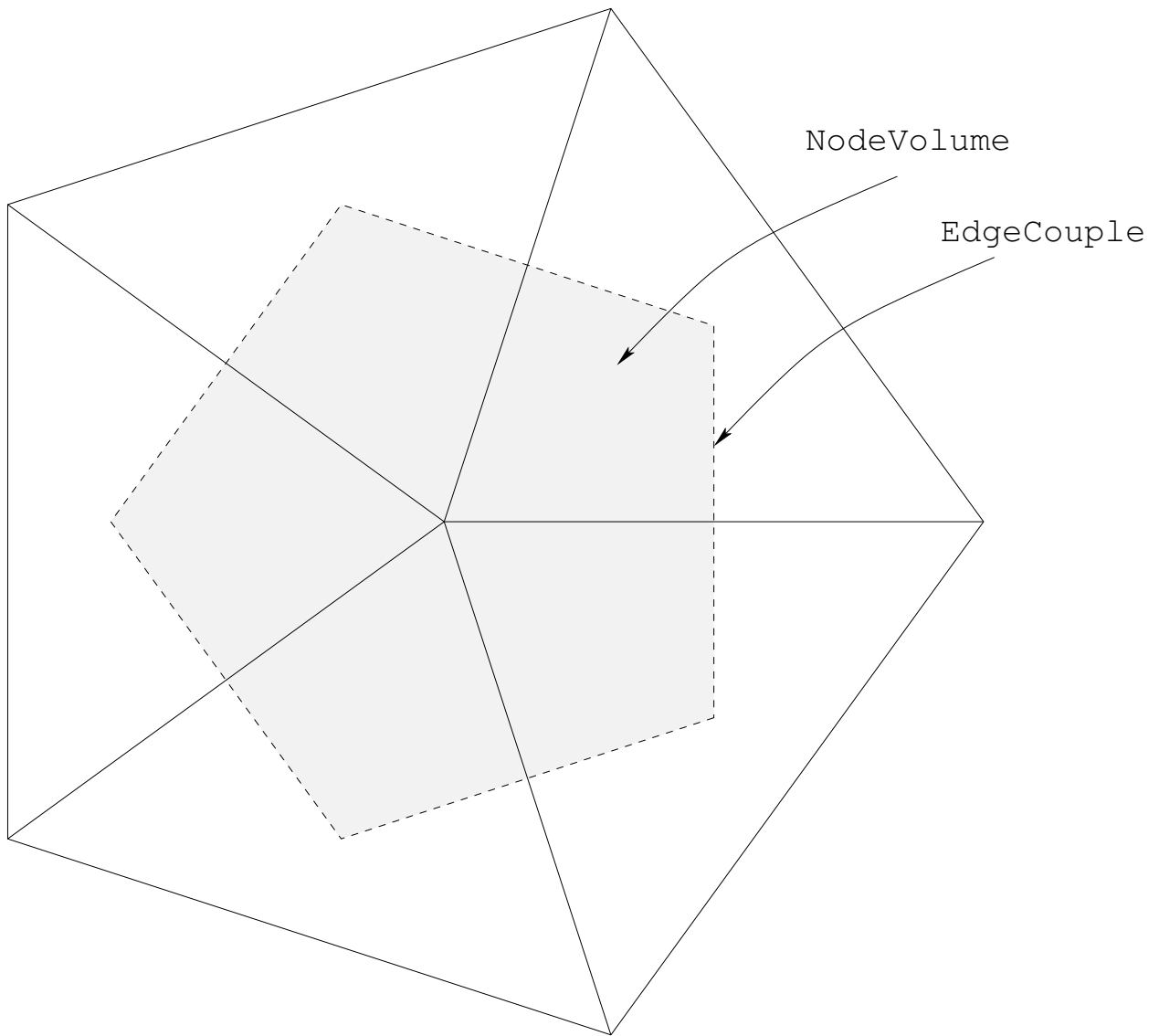


Fig. 4.1: Mesh elements in 2D.

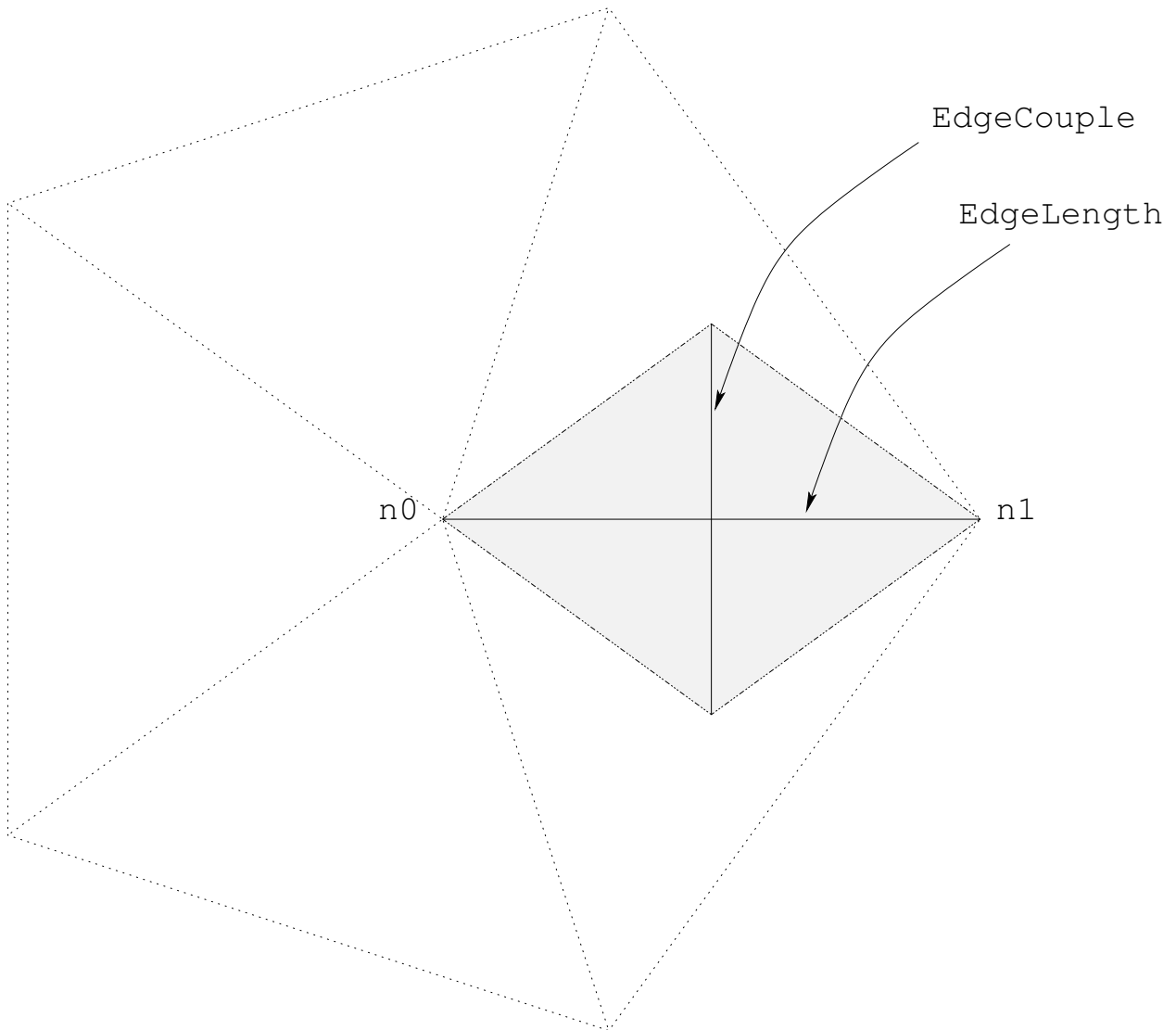


Fig. 4.2: Edge model constructs in 2D.

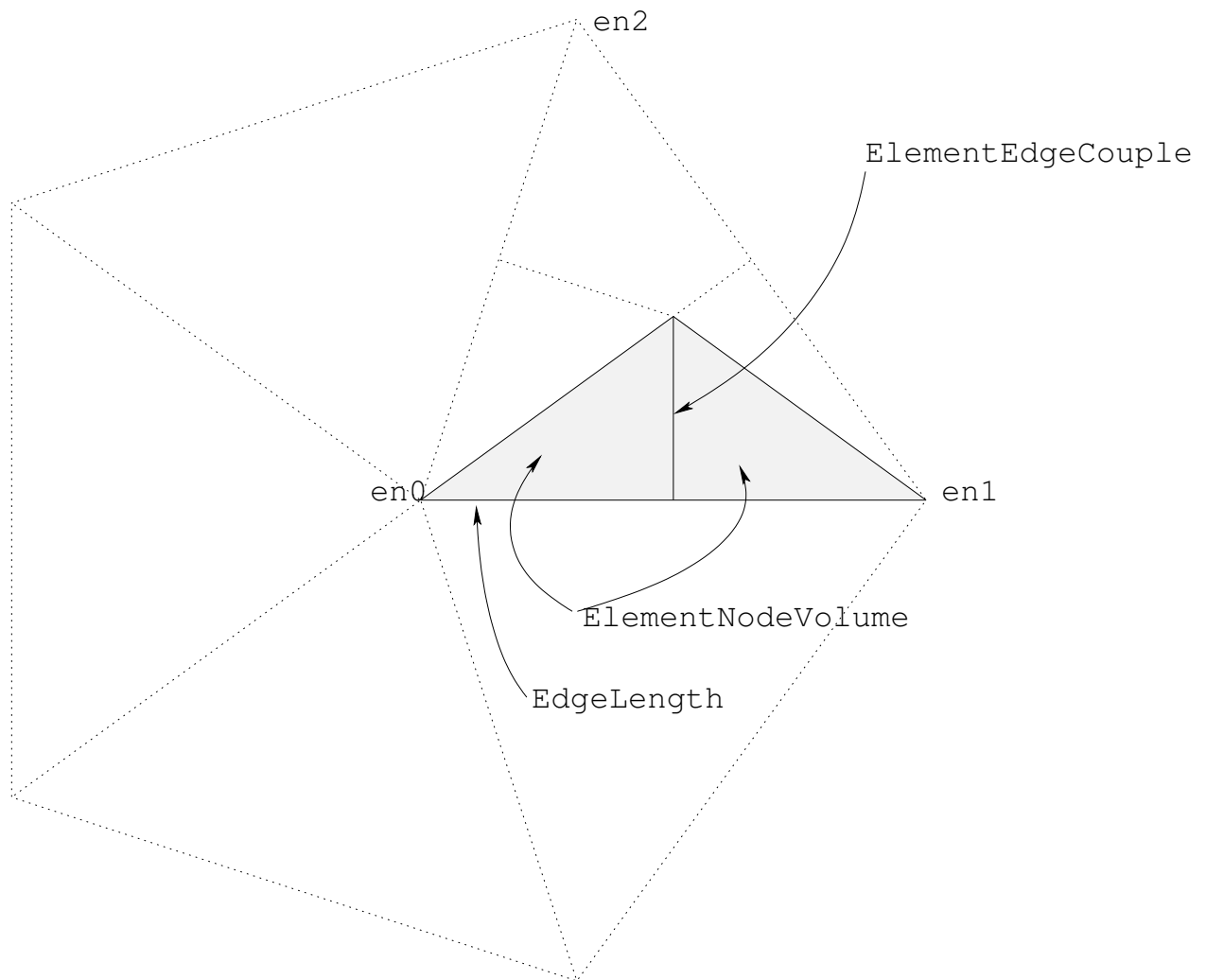


Fig. 4.3: Element edge model constructs in 2D.

4.2 Bulk models

4.2.1 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 4.1.

In this example, we present an implementation of Shockley Read Hall recombination [MKC02].

```
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
devsim.node_model(device='MyDevice', region='MyRegion',
  name="USRH", equation=USRH)
devsim.node_model(device='MyDevice', region='MyRegion',
  name="USRH:Electrons", equation=dUSRHdn)
devsim.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 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.

Table 4.1: Node models defined on each region of a device.

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_x	The surface normal to points on the interface or contact (2D and 3D)
NSurfaceNormal_y	The surface normal to points on the interface or contact (2D and 3D)
NSurfaceNormal_z	The surface normal to points on the interface or contact (3D)
SurfaceArea	The surface area of a node on interface nodes, otherwise 0
ContactSurfaceArea	The surface area of a node on contact nodes, otherwise 0
coordinate_index	Coordinate index of the node on the device
node_index	Index of the node in the region
x	x position of the node
y	y position of the node
z	z position of the node

4.2.2 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 Fig. 4.2, edge models are with respect to the two nodes on the edge, n_0 and n_1 .

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

```
devsim.edge_model(device="device", region="region", name="ElectricField",
    equation="(Potential@n0 - Potential@n1)*EdgeInverseLength")
devsim.edge_model(device="device", region="region",
    name="ElectricField:Potential@n0", equation="EdgeInverseLength")
devsim.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 `devsim.edge_from_node_model()` (page 77). In addition, the `devsim.edge_average_model()` (page 77) can be used to create edge models in terms of node model quantities.

Edge models automatically created for a region are listed in Table 4.2.

Table 4.2: Edge 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
edge_index	Index of the edge on the region
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)

4.2.3 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 Fig. 4.3, edge models are with respect to the three nodes on each triangle edge and are denoted as e_{n0} , e_{n1} , and e_{n2} . 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 4.3.

As an alternative to treating integrating the element edge model with respect to `ElementEdgeCouple`, the integration may be performed with respect to `ElementNodeVolume`. See `devsim.equation()` (page 62) for more information.

Table 4.3: Element edge models defined on each region of a device.

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.

4.2.4 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 4.4.

Table 4.4: 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.

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

4.2.5 Conversions between model types

The `devsim.edge_from_node_model()` (page 77) 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 `devsim.edge_average_model()` (page 77) 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 `devsim.element_from_edge_model()` (page 78) 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 `devsim.element_from_node_model()` (page 79) is used to create element edge models referring to each node on the element of the element edge.

4.2.6 Equation assembly

Bulk equations are specified in terms of the node, edge, and element edge models using the `devsim.equation()` (page 62). 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.

```
devsim.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.

Table 4.5: 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.

Model Type	Model Name	Derivatives Required
Node Model (region 0)	<code>nodemodel@r0</code>	<code>nodemodel:variable@r0</code>
Node Model (region 1)	<code>nodemodel@r1</code>	<code>nodemodel:variable@r1</code>
Interface Node Model	<code>inodemodel</code>	<code>inodemodel:variable@r0</code> , <code>inodemodel:variable@r1</code>

4.3 Interface

4.3.1 Interface models

Fig. 4.4 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 `devsim.interface_model()` (page 81). Interface models may 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 4.5.

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

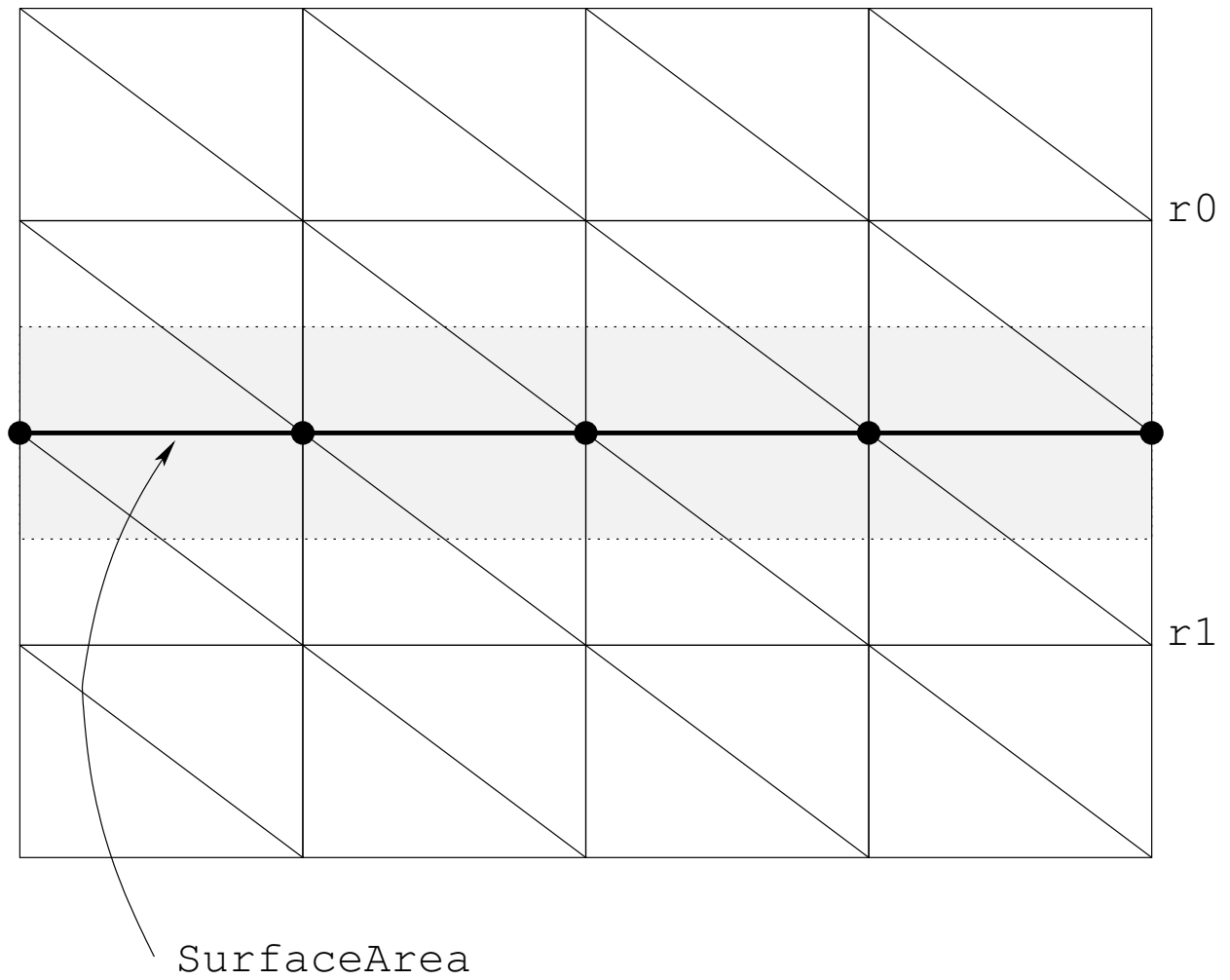


Fig. 4.4: Interface constructs in 2D. Interface node pairs are located at each \bullet . The `SurfaceArea` model is used to integrate flux term models.

4.3.2 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`

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

4.3.3 Interface equation assembly

There are three types of interface equations considered in DEVSIM. They are both activated using the `devsim.interface_equation()` (page 64).

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.

```
devsim.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.

In the third form, `hybrid`, equations for nodes on both sides of the interface are added into the equation for the node in the first region. The equation for the node on the second interface is integrated in the second region, and the fluxterm is subtracted in the second region.

4.4 Contact

4.4.1 Contact models

Fig. 4.5 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 `devsim.contact_node_model()` (page 74) and the `devsim.contact_edge_model()` (page 74), respectively. The key difference is that the models are only evaluated on the contact nodes for the contact specified.

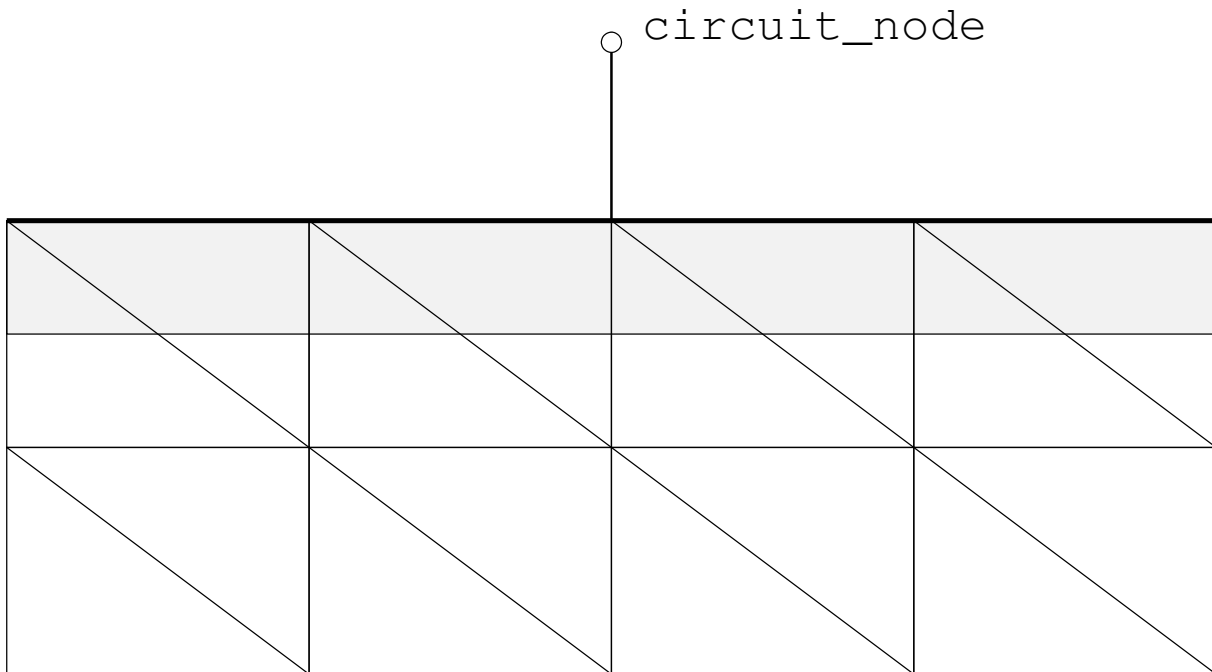


Fig. 4.5: Contact constructs in 2D.

4.4.2 Contact model derivatives

The derivatives are equivalent to the discussion in *Model derivatives* (page 23). 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`.

4.4.3 Contact equation assembly

The `devsim.contact_equation()` (page 60) 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

```
devsim.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

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

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

4.5 Custom matrix assembly

The `devsim.custom_equation()` (page 61) 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

```
devsim.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 `devsim.get_circuit_equation_number()` (page 60) may be used to get the equation numbers corresponding to circuit node names. The `devsim.get_equation_numbers()` (page 63) 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.

4.6 Cylindrical Coordinate Systems

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

- `devsim.cylindrical_edge_couple()` (page 74)
- `devsim.cylindrical_node_volume()` (page 75)
- `devsim.cylindrical_surface_area()` (page 75)

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="edge_node0_volume_model",
  value="CylindricalEdgeNodeVolume@n0")
set_parameter (name="edge_node1_volume_model",
  value="CylindricalEdgeNodeVolume@n1")
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")
```


Chapter 5

Model Parameters

Parameters can be set using the commands in *Material Commands* (page 65). There are two complementary formalisms for doing this.

5.1 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.

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

5.2 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.

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

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

5.3 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.

Chapter 6

Circuits

6.1 Circuit elements

Circuit elements are manipulated using the commands in *Circuit Commands* (page 59). Using the `devsim.circuit_element()` (page 59) to add a circuit element will implicitly create the nodes being references.

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

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

6.2 Connecting devices

For devices to contribute current to an external circuit, the `devsim.contact_equation()` (page 60) should use the `circuitnode` 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 `devsim.circuit_node_alias()` (page 60) 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.

Chapter 7

Meshing

7.1 1D mesher

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

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

The *devsim.create_1d_mesh()* (page 72) is first used to initialize the specification of a new mesh by the name specified with the *command* option. The *devsim.add_1d_mesh_line()* (page 68) is used to specify the end points of the 1D structure, as well as the location of points where the spacing changes. The *command* is used to create reference labels used for specifying the contacts, interfaces and regions.

The *devsim.add_1d_contact()* (page 68), *devsim.add_1d_interface()* (page 68) and *devsim.add_1d_region()* (page 69) are used to specify the contacts, interfaces and regions for the device.

Once the meshing commands have been completed, the *devsim.finalize_mesh()* (page 73) is called to create a mesh structure and then *devsim.create_device()* (page 72) is used to create a device using the mesh.

7.2 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 `devsim.add_2d_region()` (page 70) 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.

```

devsim.create_2d_mesh(mesh="cap")
devsim.add_2d_mesh_line(mesh="cap", dir="y", pos=-0.001, ps=0.001)
devsim.add_2d_mesh_line(mesh="cap", dir="x", pos=xmin, ps=0.1)
devsim.add_2d_mesh_line(mesh="cap", dir="x", pos=xmax, ps=0.1)
devsim.add_2d_mesh_line(mesh="cap", dir="y", pos=ymin, ps=0.1)
devsim.add_2d_mesh_line(mesh="cap", dir="y", pos=ymin, ps=0.1)
devsim.add_2d_mesh_line(mesh="cap", dir="y", pos=ymin, ps=0.1)
devsim.add_2d_mesh_line(mesh="cap", dir="y", pos=ymin, ps=0.1)
devsim.add_2d_region(mesh="cap", material="gas", region="gas1", yl=-.001,
↪yh=0.0)
devsim.add_2d_region(mesh="cap", material="gas", region="gas2", yl=1.0, yh=1.
↪001)
devsim.add_2d_region(mesh="cap", material="Oxide", region="r0", xl=xmin,
↪xh=xmax,
    yl=ymin, yh=ymin)
devsim.add_2d_region(mesh="cap", material="Silicon", region="r1", xl=xmin,
↪xh=xmax,
    yl=ymin, yh=ymin)
devsim.add_2d_region(mesh="cap", material="Silicon", region="r2", xl=xmin,
↪xh=xmax,
    yl=ymin, yh=ymin)

devsim.add_2d_interface(mesh="cap", name="i0", region0="r0", region1="r1")
devsim.add_2d_interface(mesh="cap", name="i1", region0="r1", region1="r2",
    xl=0, xh=1, yl=ymin, yh=ymin, bloot=1.0e-10)
devsim.add_2d_contact(mesh="cap", name="top", region="r0", yl=ymin, yh=ymin,
    bloot=1.0e-10, material="metal")
devsim.add_2d_contact(mesh="cap", name="bot", region="r2", yl=ymin, yh=ymin,
    bloot=1.0e-10, material="metal")
devsim.finalize_mesh(mesh="cap")
devsim.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 `devsim.add_2d_contact()` (page 69) or an interface using `devsim.add_2d_interface()` (page 69).

Once the meshing commands have been completed, the `devsim.finalize_mesh()` (page 73) is called to create a mesh structure and then `devsim.create_device()` (page 72) is used to create a device using the mesh.

7.3 Using an external mesher

DEVSIM supports reading meshes from Genius Device Simulator and Gmsh. These meshes may only contain points, lines, triangles, and tetrahedra. Hybrid meshes or uniform meshes containing other elements are not supported at this time.

7.3.1 Genius

Meshes from the Genius Device Simulator software (see *Genius* (page 55)) can be imported using the CGNS format. In this example, `devsim.create_genius_mesh()` (page 72) returns region and boundary information which can be used to setup the device.

```

mesh_name = "nmos_iv"
result = create_genius_mesh(file="nmos_iv.cgns", mesh=mesh_name)

contacts = {}
for region_name, region_info in result['mesh_info']['regions'].iteritems():
    add_genius_region(mesh=mesh_name, genius_name=region_name,
                      region=region_name, material=region_info['material'])
    for boundary, is_electrode in region_info['boundary_info'].iteritems():
        if is_electrode:
            if boundary in contacts:
                contacts[boundary].append(region_name)
            else:
                contacts[boundary] = [region_name, ]

for contact, regions in contacts.iteritems():
    if len(regions) == 1:
        add_genius_contact(mesh=mesh_name, genius_name=contact, name=contact,
                           region=regions[0], material='metal')
    else:
        for region in regions:
            add_genius_contact(mesh=mesh_name, genius_name=contact,
                               name=contact+'@'+region, region=region, material='metal')

for boundary_name, regions in result['mesh_info']['boundaries'].iteritems():
    if (len(regions) == 2):
        add_genius_interface(mesh=mesh_name, genius_name=boundary_name,
                              name=boundary_name, region0=regions[0], region1=regions[1])

finalize_mesh(mesh=mesh_name)
create_device(mesh=mesh_name, device=mesh_name)

```

Example locations are available on *genius* (page 87).

7.3.2 Gmsh

The Gmsh meshing software (see *Gmsh* (page 55)) 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:

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

Once the meshing commands have been completed, the *devsim.finalize_mesh()* (page 73) is called to create a mesh structure and then *devsim.create_device()* (page 72) is used to create a device using the mesh.

7.3.3 Custom mesh loading using scripting

It is also possible to arbitrarily load a mesh from a Python using the *devsim.create_gmsh_mesh()* (page 73). This is explained in the Notes section of the command.

7.4 Loading and saving results

The *devsim.write_devices()* (page 74) 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 *devsim_data* format is used for storing numerical information for use in other programs for analysis. The *devsim.load_devices()* (page 73) is then used to reload the device data for restarting the simulation.

Chapter 8

Solver

8.1 Solver

DEVSIM uses Newton methods to solve the system of PDE's. All of the analyses are performed using the `devsim.solve()` (page 85).

8.2 DC analysis

A DC analysis is performed using the `devsim.solve()` (page 85).

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

8.3 AC analysis

An AC analysis is performed using the `devsim.solve()` (page 85). A circuit voltage source is required to set the AC source.

8.4 Noise/Sensitivity analysis

An noise analysis is performed using the `devsim.solve()` (page 85) 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 `devsim.solve()` (page 85). 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)

8.5 Transient analysis

Transient analysis is performed using the `devsim.solve()` (page 85). DEVSIM supports time-integration of the device PDE's. The three methods are supported are:

- BDF1
- TRBDF
- BDF2

Chapter 9

User Interface

9.1 Starting DEVSIM

Refer to *Installation* (page 53) for instructions on how to install DEVSIM. Once installed, DEVSIM may be invoked using the following command

By first setting the `PYTHONPATH` variable to the `lib` directory in the DEVSIM distribution, `devsim` is loaded by using

```
import devsim
```

from Python.

Many of the examples in the distribution rely on the `python_packages` module, which is available by using:

```
import devsim.python_packages
```

The default version of Python for use in scripts is 3.7, however scripts written for earlier versions of Python 3 should work. Python 2.7 is deprecated for future development.

9.2 Python Language

9.2.1 Introduction

Python is the scripting language employed as the text interface to DEVSIM. Documentation and tutorials for the language are available from [pyt]. A paper discussing the general benefits of using scripting languages may be found in [Ous98].

9.2.2 DEVSIM commands

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

```
from devsim import *
```

For details concerning error handling, please see *Error handling* (page 42).

9.2.3 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.

9.2.4 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. Python 3 interpreters handle UTF-8 encoding well. For the deprecated Python 2 interpreter, it is necessary to put the following line at the beginning of the python script.

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

On some systems, such as Microsoft Windows, it may be necessary to set the following environment variable before running a script containing UTF-8 characters.

```
SET PYTHONIOENCODING=utf-8
```

Care should be taken when using UTF-8 characters in names for visualization using the tools in *Visualization* (page 51), as this character set may not be supported.

9.3 Error handling

9.3.1 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 `devsim.error`. It may be caught.

9.3.2 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 using the contact information in *Contact* (page 1).

9.3.3 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.

9.3.4 Solver errors

When using the `devsim.solve()` (page 85), 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 devsim.error as msg:
    if msg[0].find("Convergence failure") != 0:
        raise
    ##### put code to modify step here.
```

9.3.5 Verbosity

The `set_parameter()` 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.

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

9.3.6 Parallelization

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

```
devsim.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.

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

The Intel Math Kernel Library is parallelized, the number of thread may be controlled by setting the MKL_NUM_THREADS environment variable.

Chapter 10

SYMDIFF

10.1 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.

10.2 Syntax

10.2.1 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`

10.2.2 Basic expressions

Table 10.1: Basic expressions involving unary, binary, and logical operators.

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

In Table 10.1, 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.

10.2.3 Functions

Table 10.2: Predefined Functions.

Function	Description
<code>acosh(exp1)</code>	Inverse Hyperbolic Cosine
<code>asinh(exp1)</code>	Inverse Hyperbolic Sine
<code>atanh(exp1)</code>	Inverse Hyperbolic Tangent
<code>B(exp1)</code>	Bernoulli Function
<code>dBdx(exp1)</code>	derivative of Bernoulli function
<code>derfcdx(exp1)</code>	derivative of complementary error function
<code>derfdx(exp1)</code>	derivative error function
<code>dFermidx(exp1)</code>	derivative of Fermi Integral
<code>dInvFermidx(exp1)</code>	derivative of InvFermi Integral
<code>dot2d(exp1x, exp1y, exp2x, exp2y)</code>	$exp1x*exp2x+exp1y*exp2y$
<code>erfc(exp1)</code>	complementary error function
<code>erf(exp1)</code>	error function
<code>exp(exp1)</code>	exponent
<code>Fermi(exp1)</code>	Fermi Integral
<code>ifelse(test, exp1, exp2)</code>	if test is true, then evaluate exp1, otherwise exp2
<code>if(test, exp)</code>	if test is true, then evaluate exp, otherwise 0
<code>InvFermi(exp1)</code>	inverse of the Fermi Integral
<code>log(exp1)</code>	natural log
<code>max(exp1, exp2)</code>	maximum of the two arguments
<code>min(exp1, exp2)</code>	minimum of the two arguments
<code>pow(exp1, exp2)</code>	take exp1 to the power of exp2
<code>sgn(exp1)</code>	sign function
<code>step(exp1)</code>	unit step function
<code>kahan3(exp1, exp2, exp3)</code>	Extended precision addition of arguments
<code>kahan4(exp1, exp2, exp3, exp4)</code>	Extended precision addition of arguments
<code>vec_max</code>	maximum of all the values over the entire region or interface
<code>vec_min</code>	minimum of all the values over the entire region or interface
<code>vec_sum</code>	sum of all the values over the entire region or interface

In Table 10.2 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.

10.2.4 Commands

Table 10.3: Commands.

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

Commands are shown in [Table 10.3](#). 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
```

10.2.5 User functions

Table 10.4: Commands for user functions.

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 <code>arg1, arg2, ...</code> . Derivatives assumed to be 0
<code>define(name(arg1, arg2, ...), obj1, obj2, ...)</code>	declare function name taking arguments <code>arg1, arg2, ...</code> having corresponding derivatives <code>obj1, obj2, ...</code>

Commands for specifying and manipulating user functions are listed in [Table 10.4](#). 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

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

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))
```

10.2.6 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)
```

10.3 Invoking SYMDIFF from DEVSIM

10.3.1 Equation parser

The `devsim.symdiff()` (page 84) 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. *Model Commands* (page 74) presents commands which have the concepts of models. A `;` should be used to separate each statement.

This is a sample invocation from DEVSIM

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

10.3.2 Evaluating external math

The `devsim.register_function()` (page 83) 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
symdiff(expr="declare(sin(x))")
symdiff(expr="define(cos(x), -sin(x))")
symdiff(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.

10.3.3 Models

When used with the model commands discussed in *Model Commands* (page 74), 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 11

Visualization

11.1 Introduction

DEVSIM is able to create files for visualization tools. Information about acquiring these tools are presented in *External Software Tools* (page 55).

11.2 Using Tecplot

The `devsim.write_devices()` (page 74) 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")
```

11.3 Using Postmini

The `devsim.write_devices()` (page 74) 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")
```

11.4 Using Paraview

The `devsim.write_devices()` (page 74) 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.

11.5 Using VisIt

VisIt supports reading the Tecplot and ParaView formats. When using the `vtk` option on the `devsim.write_devices()` (page 74), a file with a `visit` filename extension is created to load the files created for ParaView.

11.6 DEVSIM

DEVSIM has several commands for getting information on the mesh. Those related to post processing are described in *Model Commands* (page 74) and *Geometry Commands* (page 65).

See *Loading and saving results* (page 38) for information about loading and saving mesh information to a file.

Chapter 12

Installation

12.1 Availability

Information about the open source version of DEVSIM is available from <https://devsim.org>. This site contains up-to-date information about where to obtain compiled and source code versions of this software. It also contains information about how to get support and participate in the development of this project.

12.2 Supported platforms

DEVSIM is compiled and tested on the platforms in Table 12.1. If you require a version on a different software platform, please contact us.

Table 12.1: Current platforms for DEVSIM.

Platform	Bits	OS Version
Microsoft Windows	64	Microsoft Windows 7, Microsoft Windows 10
Linux	64	Ubuntu 14.04 (LTS)
		Ubuntu 16.04 (LTS)
		Red Hat Enterprise Linux 6 (Centos 6 compatible)
Apple Mac OS X	64	Mac OS X 10.13 (High Sierra)

12.3 Binary availability

Compiled packages for the the platforms in Table 12.1 are currently available from <https://github.com/devsim/devsim/releases>. The prerequisites on each platform are described in the `linux.txt`, `macos.txt`, and `windows.txt`.

12.4 Source code availability

DEVSIM is also available in source code form from <https://github.com/devsim/devsim>.

12.5 Directory Structure

A DEVSIM directory is created with the following sub directories listed in [Table 12.2](#).

Table 12.2: Directory structure for DEVSIM.

bin	contains the devsim tcl binary
lib/devsim	contains the devsim interpreter modules
lib/devsim/python_packages	contains runtime libraries
doc	contains product documentation
examples	contains example scripts
testing	contains additional examples used for testing

12.6 Running DEVSIM

See *User Interface* (page 41) for instructions on how to invoke DEVSIM.

Chapter 13

Additional Information

13.1 DEVSIM License

Individual files are covered by the license terms contained in the comments at the top of the file. Contributions to this project are subject to the license terms of their authors. In general, DEVSIM is covered by the Apache License, Version 2.0 [ApacheSoftwareFoundation]. Please see the NOTICE and LICENSE file for more information.

13.2 SYMDIFF

SYMDIFF is available from <https://syndiff.org> and is covered by the terms of the Apache License, Version 2.0 [ApacheSoftwareFoundation].

13.3 External Software Tools

13.3.1 Genius

Genius is available in commercial and open source versions from <http://www.cogenda.com>.

13.3.2 Gmsh

Gmsh [GR09] is available from <http://gmsh.info>.

13.3.3 Paraview

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

13.3.4 Tecplot

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

13.3.5 VisIt

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

13.4 Library Availability

The following tools are used to build DEVSIM.

13.4.1 BLAS and LAPACK

These are the basic linear algebra routines used directly by DEVSIM and by SuperLU. Reference versions are available from <http://www.netlib.org>. There are optimized versions available from other vendors.

13.4.2 CGNS

CGNS (CFD Generalized Notation System) is an open source library, which implements the storage format used to read Genius Device Simulator meshes. It is available from <http://www.cgns.org>.

13.4.3 Python

A Python distribution is required for using DEVSIM and is distributed with many operating system. Additional information is available at <https://www.python.org>. It should be stressed that binary packages must be compatible with the Python distribution used by DEVSIM.

13.4.4 SQLite3

SQLite3 is an open source database engine used for the material database and is available from <https://www.sqlite.org>.

13.4.5 SuperLU

SuperLU [DEG+99] is used within DEVSIM and is available from <http://crd-legacy.lbl.gov/~xiaoye/SuperLU>:

Copyright (c) 2003, The Regents of the University of California, through Lawrence Berkeley National Laboratory (subject to receipt of any required approvals from U.S. Dept. of Energy)

All rights reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

(1) Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer. (2) Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution. (3) Neither the name of Lawrence Berkeley National Laboratory, U.S. Dept. of Energy nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS "AS IS" AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT OWNER OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

13.4.6 Tcl

Tcl is the original parser for DEVSIM and is superseded by Python. It is still used for some of the tests. Tcl is available from <http://www.tcl.tk>.

13.4.7 zlib

zlib is an open source compression library available from <https://zlib.net>.

Chapter 14

Command Reference

14.1 Circuit Commands

Commands are for adding circuit elements to the simulation.

`devsim.add_circuit_node` (*name*, *value*, *variable_update*)

Adds a circuit node for use in circuit or multi-device simulation

Parameters

name [str] Name of the circuit node being created

value [Float, optional] initial value (default 0.0)

variable_update [{ 'default', 'log_damp', 'positive' }] update type for circuit variable

`devsim.circuit_alter` (*name*, *param*, *value*)

Alter the value of a circuit element parameter

Parameters

name [str] Name of the circuit node being created

param [str, optional] parameter being modified (default 'value')

value [Float] value for the parameter

`devsim.circuit_element` (*name*, *value*, *n1*, *n2*, *acreal*, *acimag*)

Adds a circuit element external to the devices

Parameters

name [str] 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 [Float, optional] value for the default parameter of the circuit element (default 0.0)

n1 [str] circuit node

n2 [str] circuit node

acreal [Float, optional] real part of AC source for voltage (default 0.0)

acimag [Float, optional] imag part of AC source for voltage (default 0.0)

`devsim.circuit_node_alias` (*node*, *alias*)

Create an alias for a circuit node

Parameters

node [str] circuit node being aliased

alias [str] alias for the circuit node

`devsim.get_circuit_equation_number` (*node*)

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

Parameters

node [str] circuit node

`devsim.get_circuit_node_list` ()

Gets the list of the nodes in the circuit.

`devsim.get_circuit_node_value` (*solution*, *node*)

Gets the value of a circuit node for a given solution type.

Parameters

solution [str, optional] name of the solution. 'dcop' is the name for the DC solution (default 'dcop')

node [str] circuit node of interest

`devsim.get_circuit_solution_list` ()

Gets the list of available circuit solutions.

`devsim.set_circuit_node_value` (*solution*, *node*, *value*)

Sets the value of a circuit node for a given solution type.

Parameters

solution [str, optional] name of the solution. 'dcop' is the name for the DC solution (default 'dcop')

node [str] circuit node of interest

value [Float, optional] new value (default 0.0)

14.2 Equation Commands

Commands for manipulating equations on contacts, interface, and regions

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

Create a contact equation on a device

Parameters

- device** [str] The selected device
- contact** [str] Contact on which to apply this command
- name** [str] Name of the contact equation being created
- variable_name** [str, optional] The variable name is used to determine the bulk equation we are replacing at this contact (deprecated)
- circuit_node** [str, optional] Name of the circuit we integrate the flux into
- edge_charge_model** [str, optional] Name of the edge model used to determine the charge at this contact
- edge_current_model** [str, optional] Name of the edge model used to determine the current flowing out of this contact
- edge_model** [str, optional] Name of the edge model being integrated at each edge at this contact
- element_charge_model** [str, optional] Name of the element edge model used to determine the charge at this contact
- element_current_model** [str, optional] Name of the element edge model used to determine the current flowing out of this contact
- element_model** [str, optional] Name of the element edge model being integrated at each edge at this contact
- node_charge_model** [str, optional] Name of the node model used to determine the charge at this contact
- node_current_model** [str, optional] Name of the node model used to determine the current flowing out of this contact
- node_model** [str, optional] Name of the node_model being integrated at each node at this contact

`devsim.custom_equation` (*name, procedure*)

Custom equation assembly. See *Custom matrix assembly* (page 28) for a description of how the function should be structured.

Parameters

- name** [str] Name of the custom equation being created
- procedure** [str] The procedure to be called

`devsim.delete_contact_equation` (*device, contact, name*)

This command deletes an equation from a contact.

Parameters

- device** [str] The selected device
- contact** [str] Contact on which to apply this command
- name** [str] Name of the contact equation being deleted

`devsim.delete_equation` (*device, region, name*)

This command deletes an equation from a region.

Parameters

- device** [str] The selected device
- region** [str] The selected region
- name** [str] Name of the equation being deleted

`devsim.delete_interface_equation` (*device, interface, name*)

This command deletes an equation from an interface.

Parameters

- device** [str] The selected device
- interface** [str] Interface on which to apply this command
- name** [str] Name of the interface equation being deleted

`devsim.equation` (*device, region, name, variable_name, node_model, edge_model, edge_volume_model, time_node_model, element_model, volume_model, variable_update*)

Specify an equation to solve on a device

Parameters

- device** [str] The selected device
- region** [str] The selected region
- name** [str] Name of the equation being created
- variable_name** [str] Name of the node_solution being solved
- node_model** [str, optional] Name of the node_model being integrated at each node in the device volume
- edge_model** [str, optional] Name of the edge model being integrated over each edge in the device volume
- edge_volume_model** [str, optional] Name of the edge model being integrated over the volume of each edge in the device volume
- time_node_model** [str, optional] Name of the time dependent node_model being integrated at each node in the device volume
- element_model** [str, optional] Name of the element_model being integrated over each edge in the device volume

volume_model [str, optional] Name of the `element_model` being integrated over the volume of each edge in the device volume

variable_update [str, optional] update type for circuit variable (default 'default')

Notes

The integration variables can be changed in 2D for cylindrical coordinate systems by setting the appropriate parameters as described in *Cylindrical Coordinate Systems* (page 29).

In order to set the node volumes for integration of the `edge_volume_model`, it is possible to do something like this:

```
devsim.get_contact_equation_command(device, contact, name)
```

This command gets the options used when creating this contact equation.

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

name [str] Name of the contact equation being command options returned

```
devsim.get_contact_equation_list(device, contact)
```

This command gets a list of equations on the specified contact.

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

```
devsim.get_equation_command(device, region, name)
```

This command gets the options used when creating this equation.

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the equation being command options returned

```
devsim.get_equation_list(device, region)
```

This command gets a list of equations on the specified region.

Parameters

device [str] The selected device

region [str] The selected region

```
devsim.get_equation_numbers(device, region, equation, variable)
```

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.

Parameters

device [str] The selected device
region [str] The selected region
equation [str, optional] Name of the equation
variable [str, optional] Name of the variable

`devsim.get_interface_equation_command` (*device, interface, name*)

This command gets the options used when creating this interface equation.

Parameters

device [str] The selected device
interface [str] Interface on which to apply this command
name [str] Name of the interface equation being command options returned

`devsim.get_interface_equation_list` (*device, interface*)

This command gets a list of equations on the specified interface.

Parameters

device [str] The selected device
interface [str] Interface on which to apply this command

`devsim.interface_equation` (*device, interface, name, name0, name1, variable_name, interface_model, type*)

Command to specify an equation at an interface

Parameters

device [str] The selected device
interface [str] Interface on which to apply this command
name [str] Name of the interface equation being created
name0 [str, optional] Name of the equation coupling in region 0 being created (default 'name')
name1 [str, optional] Name of the equation coupling in region 1 being created (default 'name')
variable_name [str, optional] The variable name is used to determine the bulk equation we are coupling this interface to (deprecated)
interface_model [str] 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 [str] Specifies the type of boundary condition

14.3 Geometry Commands

Commands for getting information about the device structure.

`devsim.get_contact_list (device)`

Gets a list of contacts on a device.

Parameters

device [str] The selected device

`devsim.get_device_list ()`

Gets a list of devices on the simulation.

`devsim.get_element_node_list (device, region, contact, interface)`

Gets a list of nodes for each element on a device, region, contact, or interface.

Parameters

device [str] The selected device

region [str] The selected region

contact [str, optional] If specified, gets the element nodes for the contact on the specified region

interface [str, optional] If specified, gets the element nodes for the interface on the specified region

`devsim.get_interface_list (device)`

Gets a list of interfaces on a device.

Parameters

device [str] The selected device

`devsim.get_region_list (device, contact, interface)`

Gets a list of regions on a device, contact, or interface.

Parameters

device [str] The selected device

contact [str, optional] If specified, gets the name of the region belonging to this contact on the device

interface [str, optional] If specified, gets the name of the regions belonging to this interface on the device

14.4 Material Commands

Commands for manipulating parameters and material properties

`devsim.add_db_entry (material, parameter, value, unit, description)`

Adds an entry to the database

Parameters

- material** [str] Material name requested. `global` refers to all regions whose material does not have the parameter name specified
- parameter** [str] Parameter name
- value** [str] Value assigned for the parameter
- unit** [str] String describing the units for this parameter name
- description** [str] Description of the parameter for this material type.

Notes

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

`devsim.close_db()`

Closes the database so that its entries are no longer available

`devsim.create_db(filename)`

Create a database to store material properties

Parameters

- filename** [str] filename to create for the db

`devsim.get_db_entry(material, parameter)`

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

Parameters

- material** [str] Material name
- parameter** [str] Parameter name

`devsim.get_dimension(device)`

Get the dimension of the device

Parameters

- device** [str, optional] The selected device

`devsim.get_material(device, region, contact)`

Returns the material for the specified region

Parameters

- device** [str, optional] The selected device
- region** [str, optional] The selected region
- contact** [str, optional] Contact on which to apply this command

`devsim.get_parameter(device, region, name)`

Get a parameter on a region, device, or globally.

Parameters

- device** [str, optional] The selected device
- region** [str, optional] The selected region
- name** [str] Name of the parameter name being retrieved

Notes

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.

`devsim.get_parameter_list (device, region)`

Get list of parameter names on region, device, or globally

Parameters

- device** [str, optional] The selected device
- region** [str, optional] The selected region

Notes

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 `ds.getParameter()`, 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.

`devsim.open_db (filename, permissions)`

Open a database storing material properties

Parameters

- filename** [str] filename to create for the db
- permissions** [str, optional] permissions on the db (default 'readonly')

`devsim.save_db ()`

Saves any new or modified db entries to the database file

`devsim.set_material (device, region, contact, material)`

Sets the new material for a region

Parameters

- device** [str, optional] The selected device
- region** [str, optional] The selected region
- contact** [str, optional] Contact on which to apply this command

material [str] New material name

`devsim.set_parameter` (*device, region, name, value*)

Set a parameter on region, device, or globally

Parameters

device [str, optional] The selected device

region [str, optional] The selected region

name [str] Name of the parameter name being retrieved

value [any] value to set for the parameter

Notes

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.

14.5 Meshing Commands

Commands for reading and writing meshes

`devsim.add_1d_contact` (*material, mesh, name, tag*)

Add a contact to a 1D mesh

Parameters

material [str] material for the contact being created

mesh [str] Mesh to add the contact to

name [str] Name for the contact being created

tag [str] Text label for the position to add the contact

`devsim.add_1d_interface` (*mesh, tag, name*)

Add an interface to a 1D mesh

Parameters

mesh [str] Mesh to add the interface to

tag [str] Text label for the position to add the interface

name [str] Name for the interface being created

`devsim.add_1d_mesh_line` (*mesh, tag, pos, ns, ps*)

Add a mesh line to a 1D mesh

Parameters

mesh [str] Mesh to add the line to

tag [str, optional] Text label for the position

- pos** [str] Position for the mesh point
- ns** [Float, optional] Spacing from this point in the negative direction (default ps value)
- ps** [Float] Spacing from this point in the positive direction

`devsim.add_1d_region` (*mesh, tag1, tag2, region, material*)

Add a region to a 1D mesh

Parameters

- mesh** [str] Mesh to add the line to
- tag1** [str] Text label for the position bounding the region being added
- tag2** [str] Text label for the position bounding the region being added
- region** [str] Name for the region being created
- material** [str] Material for the region being created

`devsim.add_2d_contact` (*name, material, mesh, region, xl, xh, yl, yh, bloat*)

Add an interface to a 2D mesh

Parameters

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

`devsim.add_2d_interface` (*mesh, name, region0, region1, xl, xh, yl, yh, bloat*)

Add an interface to a 2D mesh

Parameters

- mesh** [str] Mesh to add the interface to
- name** [str] Name for the interface being created
- region0** [str] Name of the region included in the interface
- region1** [str] Name of the region included in the interface
- xl** [Float, optional] x position for corner of bounding box (default -MAXDOUBLE)
- xh** [Float, optional] x position for corner of bounding box (default +MAXDOUBLE)

yl [Float, optional] y position for corner of bounding box (default -MAXDOUBLE)

yh [Float, optional] y position for corner of bounding box (default +MAXDOUBLE)

bloat [Float, optional] Extend bounding box by this amount when search for mesh to include in region (default 1e-10)

`devsim.add_2d_mesh_line` (*mesh, pos, ns, ps*)

Add a mesh line to a 2D mesh

Parameters

mesh [str] Mesh to add the line to

pos [str] Position for the mesh point

ns [Float] Spacing from this point in the negative direction

ps [Float] Spacing from this point in the positive direction

`devsim.add_2d_region` (*mesh, region, material, xl, xh, yl, yh, bloat*)

Add a region to a 2D mesh

Parameters

mesh [str] Mesh to add the region to

region [str] Name for the region being created

material [str] Material for the region being created

xl [Float, optional] x position for corner of bounding box (default -MAXDOUBLE)

xh [Float, optional] x position for corner of bounding box (default +MAXDOUBLE)

yl [Float, optional] y position for corner of bounding box (default -MAXDOUBLE)

yh [Float, optional] y position for corner of bounding box (default +MAXDOUBLE)

bloat [Float, optional] Extend bounding box by this amount when search for mesh to include in region (default 1e-10)

`devsim.add_genius_contact` (*genius_name, material, mesh, name, region*)

Create a contact for an imported Genius mesh

Parameters

genius_name [str] boundary condition name in the Genius CGNS file

material [str] material for the contact being created

mesh [str] name of the mesh being generated

name [str] name of the contact being created

region [str] region that the contact is attached to

`devsim.add_genius_interface` (*genius_name, mesh, name, region0, region1*)

Create an interface for an imported Genius mesh

Parameters

genius_name [str] boundary condition name in the Genius CGNS file

mesh [str] name of the mesh being generated

name [str] name of the interface begin created

region0 [str] first region that the interface is attached to

region1 [str] second region that the interface is attached to

`devsim.add_genius_region` (*genius_name, mesh, region, material*)

Create a region for an imported Genius mesh

Parameters

genius_name [str] region name in the Genius CGNS file

mesh [str] name of the mesh being generated

region [str] name of the region begin created

material [str] material for the region being created

`devsim.add_gmsh_contact` (*gmsh_name, material, mesh, name, region*)

Create a mesh to import a Gmsh mesh

Parameters

gmsh_name [str] physical group name in the Gmsh file

material [str] material for the contact being created

mesh [str] name of the mesh being generated

name [str] name of the contact begin created

region [str] region that the contact is attached to

`devsim.add_gmsh_interface` (*gmsh_name, mesh, name, region0, region1*)

Create an interface for an imported Gmsh mesh

Parameters

gmsh_name [str] physical group name in the Gmsh file

mesh [str] name of the mesh being generated

name [str] name of the interface begin created

region0 [str] first region that the interface is attached to

region1 [str] second region that the interface is attached to

`devsim.add_gmsh_region` (*gmsh_name, mesh, region, material*)

Create a region for an imported Gmsh mesh

Parameters

gmsh_name [str] physical group name in the Gmsh file

mesh [str] name of the mesh being generated

region [str] name of the region begin created

material [str] material for the region being created

`devsim.create_1d_mesh` (*mesh*)

Create a mesh to create a 1D device

Parameters

mesh [str] name of the 1D mesh being created

`devsim.create_2d_mesh` (*mesh*)

Create a mesh to create a 2D device

Parameters

mesh [str] name of the 2D mesh being created

`devsim.create_contact_from_interface` (*device, region, interface, material, name*)

Creates a contact on a device from an existing interface

Parameters

device [str] The selected device

region [str] The selected region

interface [str] Interface on which to apply this command

material [str] material for the contact being created

name [str] name of the contact begin created

`devsim.create_device` (*mesh, device*)

Create a device from a mesh

Parameters

mesh [str] name of the mesh being used to create a device

device [str] name of the device being created

`devsim.create_genius_mesh` (*file, mesh*)

This command reads in a Genius mesh written in the CGNS format

Parameters

file [str] name of the Genius mesh file being read into DEVSIM

mesh [str] name of the mesh being generated

Notes

If successful, this command will return a dictionary containing information about the regions and boundaries in the mesh. Please see the example in [Genius](#) (page 37) for an example of how this information can be used for adding contacts and interfaces to the structure being created.

If the CGNS file was created with HDF as the underlying storage format, it may be necessary to convert it to ADF using the `hdf2adf` command before reading it into DEVSIM. This command is available as part of the CGNS library when it is compiled with HDF support. Please *CGNS* (page 56) for availability. }

`devsim.create_gmsh_mesh` (*mesh, file, coordinates, elements, physical_names*)

Create a mesh to import a Gmsh mesh

Parameters

mesh [str] name of the mesh being generated

file [str, optional] name of the Gmsh mesh file being read into DEVSIM

coordinates [list, optional] List of coordinate positions on mesh.

elements [list, optional] List of elements on the mesh.

physical_names [list, optional] List of names for each contact, interface, and region on mesh.

Notes

This file will import a Gmsh format mesh from a file. Alternatively, the mesh structure may be passed in as arguments:

`coordinates` is a float list of positions in the mesh. Each coordinate adds an x, y, and z position so that the coordinate list length is 3 times the number of coordinates.

`physical_names` is a list of contact, interface, and region names. It is referenced by index by the `elements` list.

`elements` is a list of elements. Each element adds

- Element Type (float)
 - 0 node
 - 1 edge
 - 2 triangle
 - 3 tetrahedron
- Physical Index
 - This indexes into the `physical_names` list.
- Nodes
 - Each node of the element indexes into the `coordinates` list.

`devsim.finalize_mesh` (*mesh*)

Finalize a mesh so no additional mesh specifications can be added and devices can be created.

Parameters

mesh [str] Mesh to finalize

`devsim.load_devices` (*file*)

Load devices from a DEVSIM file

Parameters

file [str] name of the file to load the meshes from

`devsim.write_devices` (*file, device, type*)

Write a device to a file for visualization or restart

Parameters

file [str] name of the file to write the meshes to

device [str, optional] name of the device to write

type [{ 'devsim', 'devsim_data', 'floops', 'tecplot', 'vtk' }] format to use

14.6 Model Commands

Commands for defining and evaluating models

`devsim.contact_edge_model` (*device, contact, name, equation, display_type*)

Create an edge model evaluated at a contact

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

name [str] Name of the contact edge model being created

equation [str] Equation used to describe the contact edge model being created

display_type [{ 'vector', 'nodisplay', 'scalar' }] Option for output display in graphical viewer

`devsim.contact_node_model` (*device, contact, name, equation, display_type*)

Create a node model evaluated at a contact

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

name [str] Name of the contact node model being created

equation [str] Equation used to describe the contact node model being created

display_type [{ 'scalar', 'nodisplay' }] Option for output display in graphical viewer

`devsim.cylindrical_edge_couple` (*device, region*)

This command creates the `EdgeCouple` model for 2D cylindrical simulation

Parameters

device [str] The selected device

region [str] The selected region

Notes

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

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

The `ds.set_parameter()` 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

`devsim.cylindrical_node_volume` (*device, region*)

This command creates the `NodeVolume` model for 2D cylindrical simulation

Parameters

device [str] The selected device

region [str] The selected region

Notes

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

- `ElementCylindricalNodeVolume@en0` (Element Edge Model)
- `ElementCylindricalNodeVolume@en1` (Element Edge Model)
- `CylindricalEdgeNodeVolume@n0` (Edge Model)
- `CylindricalEdgeNodeVolume@n1` (Edge Model)
- `CylindricalNodeVolume` (Node Model)

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

The `ds.set_parameter()` 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

`devsim.cylindrical_surface_area` (*device, region*)

This command creates the `SurfaceArea` model for 2D cylindrical simulation

Parameters

device [str] The selected device

region [str] The selected region

Notes

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 `ds.set_parameter()` 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

`devsim.debug_triangle_models` (*device, region*)

Debugging command used in the development of DEVSIM and used in regressions.

Parameters

device [str] The selected device

region [str] The selected region

`devsim.delete_edge_model` (*device, region, name*)

Deletes an edge model from a region

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the edge model being deleted

`devsim.delete_element_model` (*device, region, name*)

Deletes a element model from a region

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the node model being deleted

`devsim.delete_interface_model` (*device, interface, name*)

Deletes an interface model from an interface

Parameters

device [str] The selected device

interface [str] Interface on which to apply this command

name [str] Name of the interface model being deleted

`devsim.delete_node_model (device, region, name)`

Deletes a node model from a region

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the node model being deleted

`devsim.edge_average_model (device, region, node_model, edge_model, derivative, average_type)`

Creates an edge model based on the node model values

Parameters

device [str] The selected device

region [str] The selected region

node_model [str] 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 [str] 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 [str, optional] 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 [str, optional] The node models on both sides of the edge are averaged together to create one of the following types of averages. (default 'arithmetic')

Notes

For a node model, creates 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")
```

`devsim.edge_from_node_model (device, region, node_model)`

For a node model, creates an 2 edge models referring to the node model value at both ends of the edge.

Parameters

device [str] The selected device

region [str] The selected region

node_model [str] The node model from which we are creating the edge model

Notes

For example, to calculate electric field:

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

`devsim`.**edge_model** (*device, region, name, equation, display_type*)

Creates an edge model based on an equation

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the edge model being created

equation [str] Equation used to describe the edge model being created

display_type [str, optional] Option for output display in graphical viewer (default 'scalar')

Notes

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 `ds.element_from_edge_model()` to create components better suited for visualization. See [Visualization](#) (page 51) for more information about creating data files for external visualization programs.

`devsim`.**element_from_edge_model** (*device, region, edge_model, derivative*)

Creates element edge models from an edge model

Parameters

device [str] The selected device

region [str] The selected region

edge_model [str] The edge model from which we are creating the element model

derivative [str, optional] The variable we are taking with respect to `edge_model`

Notes

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.

`devsim.element_from_node_model` (*device, region, node_model*)

Creates element edge models from a node model

Parameters

device [str] The selected device

region [str] The selected region

node_model [str] The node model from which we are creating the edge model

Notes

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.

`devsim.element_model` (*device, region, name, equation, display_type*)

Create a model evaluated on element edges.

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the element edge model being created

equation [str] Equation used to describe the element edge model being created

display_type [str, optional] Option for output display in graphical viewer (default 'scalar')

`devsim.get_edge_model_list` (*device, region*)

Returns a list of the edge models on the device region

Parameters

device [str] The selected device

region [str] The selected region

`devsim.get_edge_model_values` (*device, region, name*)

Get the edge model values calculated at each edge.

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the edge model values being returned as a list

`devsim.get_element_model_list` (*device, region*)

Returns a list of the element edge models on the device region

Parameters

device [str] The selected device

region [str] The selected region

`devsim.get_element_model_values` (*device, region, name*)

Get element model values at each element edge

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the element edge model values being returned as a list

`devsim.get_interface_model_list` (*device, interface*)

Returns a list of the interface models on the interface

Parameters

device [str] The selected device

interface [str] Interface on which to apply this command

`devsim.get_interface_model_values` (*device, interface, name*)

Gets interface model values evaluated at each interface node.

Parameters

device [str] The selected device

interface [str] Interface on which to apply this command

name [str] Name of the interface model values being returned as a list

`devsim.get_node_model_list` (*device, region*)

Returns a list of the node models on the device region

Parameters

device [str] The selected device

region [str] The selected region

`devsim.get_node_model_values` (*device, region, name*)

Get node model values evaluated at each node in a region.

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the node model values being returned as a list

`devsim.interface_model` (*device, interface, equation*)

Create an interface model from an equation.

Parameters

device [str] The selected device

interface [str] Interface on which to apply this command

equation [str] Equation used to describe the interface node model being created

`devsim.interface_normal_model` (*device, region, interface*)

Creates edge models whose components are based on direction and distance to an interface

Parameters

device [str] The selected device

region [str] The selected region

interface [str] Interface on which to apply this command

Notes

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.

`devsim.node_model` (*device, region, name, equation, display_type*)

Create a node model from an equation.

Parameters

device [str] The selected device

region [str] The selected region

name [str] Name of the node model being created

equation [str] Equation used to describe the node model being created

display_type [str, optional] Option for output display in graphical viewer (default 'scalar')

`devsim.node_solution` (*device, region, name*)

Create node model whose values are set.

Parameters

device [str] The selected device

region [str] The selected region
name [str] Name of the solution being created

`devsim.print_edge_values (device, region, name)`

Print edge values for debugging.

Parameters

device [str] The selected device
region [str] The selected region
name [str] Name of the edge model values being printed to the screen

`devsim.print_element_values (device, region, name)`

Print element values for debugging.

Parameters

device [str] The selected device
region [str] The selected region
name [str] Name of the element edge model values being printed to the screen

`devsim.print_node_values (device, region, name)`

Print node values for debugging.

Parameters

device [str] The selected device
region [str] The selected region
name [str] Name of the node model values being printed to the screen

`devsim.register_function (name, nargs)`

This command is used to register a new Python procedure for evaluation by SYMDIFF.

Parameters

name [str] Name of the function
nargs [str] Number of arguments to the function

`devsim.set_node_value (device, region, name, index, value)`

A uniform value is used if index is not specified. Note that equation based node models will lose this value if their equation is recalculated.

Parameters

device [str] The selected device
region [str] The selected region
name [str] Name of the node model being whose value is being set
index [int] Index of node being set
value [Float] Value of node being set

`devsim.set_node_values` (*device, region, name, init_from, values*)

Set node model values from another node model, or a list of values.

Parameters

- device** [str] The selected device
- region** [str] The selected region
- name** [str] Name of the node model being initialized
- init_from** [str, optional] Node model we are using to initialize the node solution
- values** [list, optional] List of values for each node in the region.

`devsim.symdiff` (*expr*)

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

Parameters

- expr** [str] Expression to send to SYMDIFF

`devsim.vector_element_model` (*device, region, element_model*)

Create vector components from an element edge model

Parameters

- device** [str] The selected device
- region** [str] The selected region
- element_model** [str] The element model for which we are calculating the vector components

Notes

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.

`devsim.vector_gradient` (*device, region, node_model, calc_type*)

Creates the vector gradient for noise analysis

Parameters

- device** [str] The selected device
- region** [str] The selected region
- node_model** [str] The node model from which we are creating the edge model

calc_type [str, optional] The node model from which we are creating the edge model (default 'default')

Notes

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 `ds.element_from_edge_model()` command can be used to create gradients for use in a simulation.

14.7 Solver Commands

Commands for simulation

`devsim.get_contact_charge` (*device, contact, equation*)

Get charge at the contact

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

equation [str] Name of the contact equation from which we are retrieving the charge

`devsim.get_contact_current` (*device, contact, equation*)

Get current at the contact

Parameters

device [str] The selected device

contact [str] Contact on which to apply this command

equation [str] Name of the contact equation from which we are retrieving the current

`devsim.solve` (*type, solver_type, absolute_error, relative_error, charge_error, gamma, tdelta, maximum_iterations, frequency, output_node, info*)

Call the solver. A small-signal AC source is set with the circuit voltage source.

Parameters

type [{ 'dc', 'ac', 'noise', 'transient_dc', 'transient_bdf1', 'transient_bdf2', 'transient_tr' } required] type of solve being performed

solver_type [{ 'direct', 'iterative' } required] Linear solver type

absolute_error [Float, optional] Required update norm in the solve (default 0.0)

relative_error [Float, optional] Required relative update in the solve (default 0.0)

charge_error [Float, optional] Relative error between projected and solved charge during transient simulation (default 0.0)

gamma [Float, optional] Scaling factor for transient time step (default 1.0)

tdelta [Float, optional] time step (default 0.0)

maximum_iterations [int, optional] Maximum number of iterations in the DC solve (default 20)

frequency [Float, optional] Frequency for small-signal AC simulation (default 0.0)

output_node [str, optional] Output circuit node for noise simulation

info [bool, optional] Solve command return convergence information (default False)

Chapter 15

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 *Directory structure for DEVSIM*. (page 54).

The following example directories are contained in the distribution.

15.1 capacitance

These are 1D and 2D capacitor simulations, using the internal mesher. A description of these examples is presented in *Capacitor* (page 89).

15.2 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 *Diode* (page 99).

15.3 bioapp1

This is a biosensor application.

15.4 genius

This directory has examples importing meshes from Genius Device Simulator.

15.5 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 Fig. 15.1.

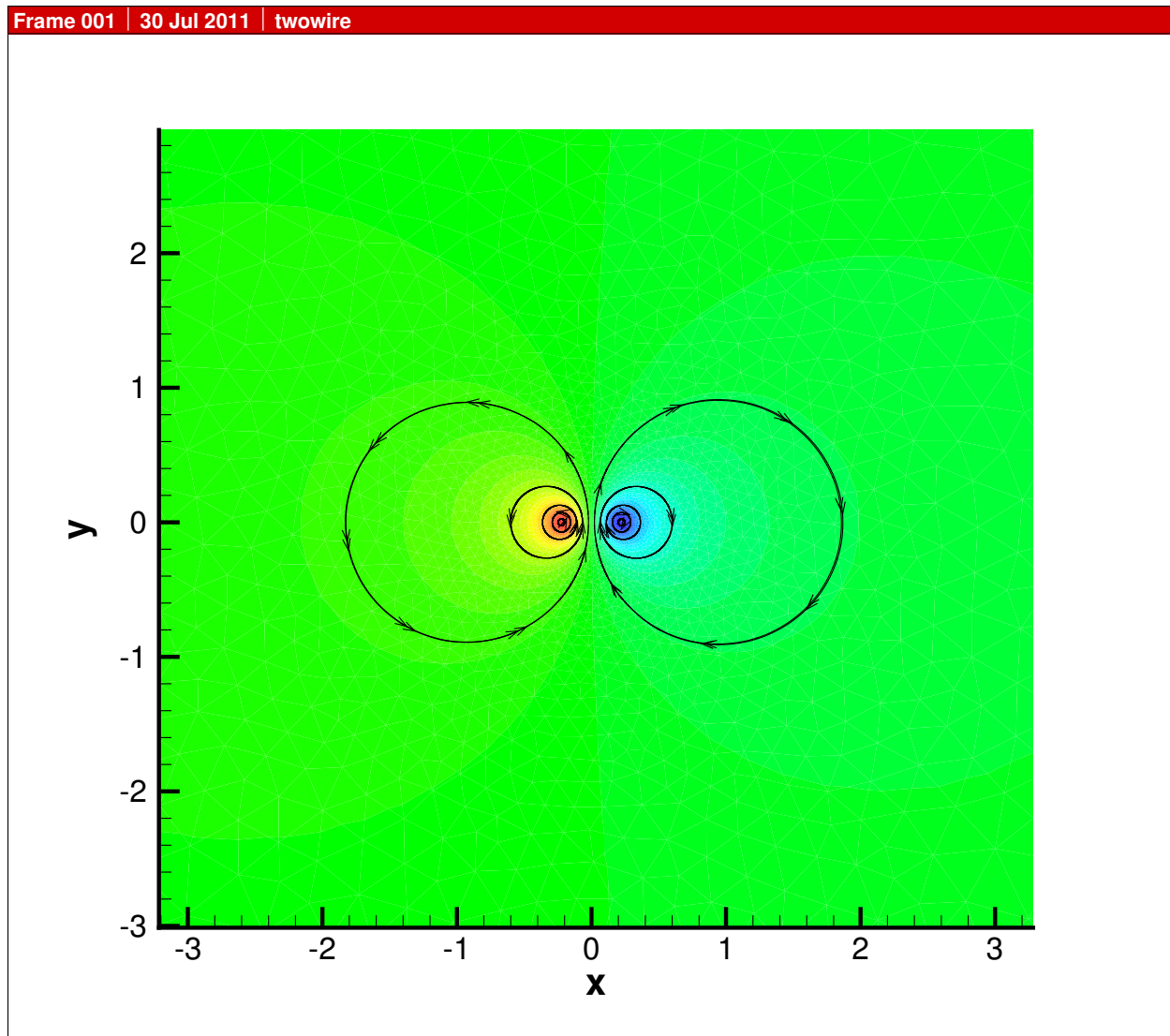


Fig. 15.1: Simulation result for solving for the magnetic potential and field. The coloring is by the Z component of the magnetic potential, and the stream traces are for components of magnetic field.

15.6 mobility

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

Chapter 16

Capacitor

16.1 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 *1D Capacitor* (page 89) 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 *2D Capacitor* (page 93).

16.2 1D Capacitor

16.2.1 Equations

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

$$\epsilon \nabla^2 \psi = 0$$

and the contact boundary equations are

$$\psi_i - V_c = 0$$

where ψ_i is the potential at the contact node and V_c is the applied voltage.

16.2.2 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 devsim 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",
  material="metal")
add_1d_contact (mesh="mesh1", name="contact2", tag="contact2",
  material="metal")
add_1d_region (mesh="mesh1", material="Si", region=region,
  tag1="contact1", tag2="contact2")
finalize_mesh (mesh="mesh1")
create_device (mesh="mesh1", device=device)

```

16.3 Setting device parameters

In this section, we set the value of the permittivity to that of SiO_2 .

```

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

```

16.3.1 Creating the models

Solving for the Potential, ψ , 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")

```

16.3.2 Contact boundary conditions

We then create the contact models and equations. We use the Python for loop 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,

```

(continues on next page)

(continued from previous page)

```

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.

16.3.3 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")))

```

16.3.4 Running the simulation

We run the simulation and see the results.

```

capacitance> python cap1d.py
-----

DEVSIM

Version: Beta 0.01

Copyright 2009-2013 Devsim LLC

-----

```

(continues on next page)

(continued from previous page)

```

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 3.451510^{-13} F/cm² for a homogenous capacitor.

16.4 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.

16.5 Defining the mesh

```

from devsim 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

```

(continues on next page)

(continued from previous page)

```

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", material="metal", yl=y1,
↳yh=y2, xl=x1, xh=x4)
add_2d_contact(mesh=device, name="top", region="air", material="metal", yl=y3,
↳yh=y4, xl=x2, xh=x3)
finalize_mesh(mesh=device)
create_device(mesh=device, device=device)

```

16.6 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")

```

(continues on next page)

(continued from previous page)

```

###
### 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")

```

(continues on next page)

(continued from previous page)

```

###
### 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=30,
    solver_type="direct")

```

16.7 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")

```

16.8 Running the simulation

```

-----

DEVSIM

Version: Beta 0.01

Copyright 2009-2013 Devsim LLC

-----

```

(continues on next page)

(continued from previous page)

```
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 [Fig. 16.1](#).

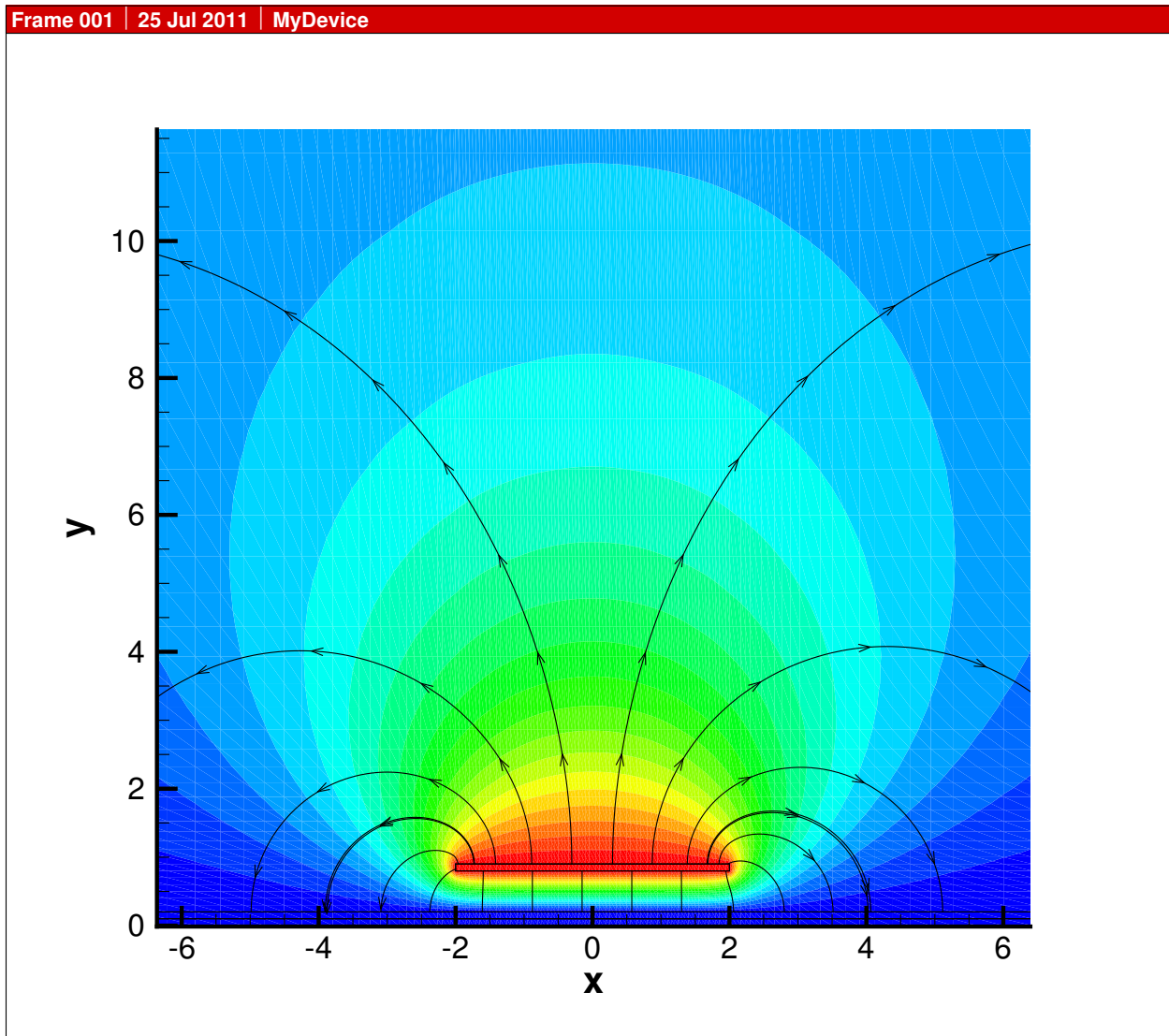


Fig. 16.1: Capacitance simulation result. The coloring is by Potential, and the stream traces are for components of ElectricField.

Chapter 17

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 [SG69].

17.1 1D diode

17.1.1 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 17.1. The `devsim.python_packages` module is part of the distribution. The example files in the DEVSIM distribution set the path properly when loading modules.

Table 17.1: Python package files.

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

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

```
from devsim import *
from simple_physics import *
```

17.1.2 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_ld_mesh(mesh="dio")
    add_ld_mesh_line(mesh="dio", pos=0, ps=1e-7, tag="top")
    add_ld_mesh_line(mesh="dio", pos=0.5e-5, ps=1e-9, tag="mid")
    add_ld_mesh_line(mesh="dio", pos=1e-5, ps=1e-7, tag="bot")
    add_ld_contact (mesh="dio", name="top", tag="top", material="metal")
    add_ld_contact (mesh="dio", name="bot", tag="bot", material="metal")
    add_ld_region (mesh="dio", material="Si", region=region, tag1="top", tag2=
↪"bot")
    finalize_mesh(mesh="dio")
    create_device(mesh="dio", device=device)

device="MyDevice"
region="MyRegion"

createMesh(device, region)

```

17.2 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)

```

(continues on next page)

(continued from previous page)

```

####
#### 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_ld.dat", type="tecplot")

```

17.2.1 Plotting the result

A plot showing the doping profile and carrier densities are shown in Fig. 17.1. The potential and electric field distribution is shown in Fig. 17.2. The current distributions are shown in Fig. 17.3.

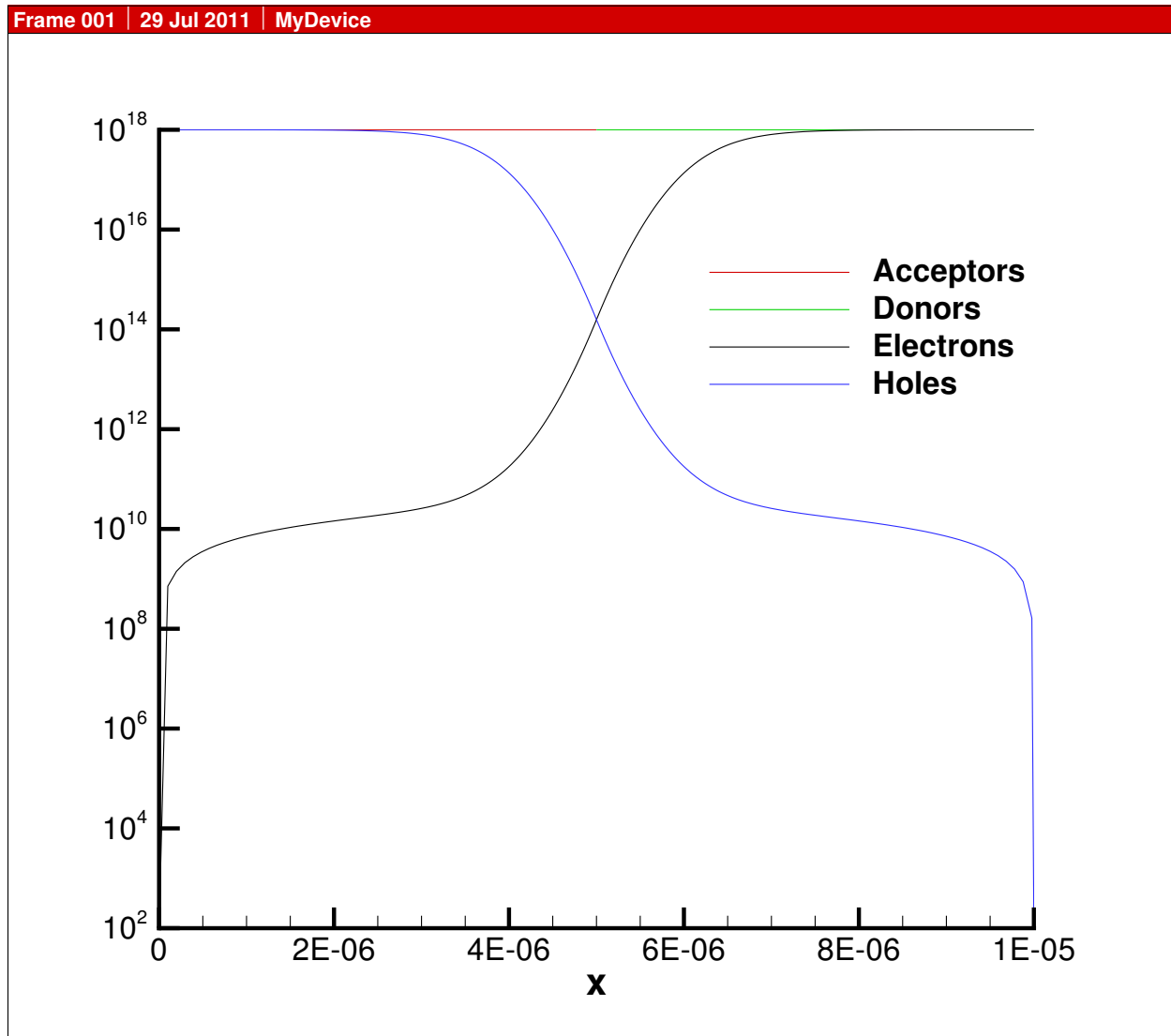


Fig. 17.1: Carrier density versus position in 1D diode.

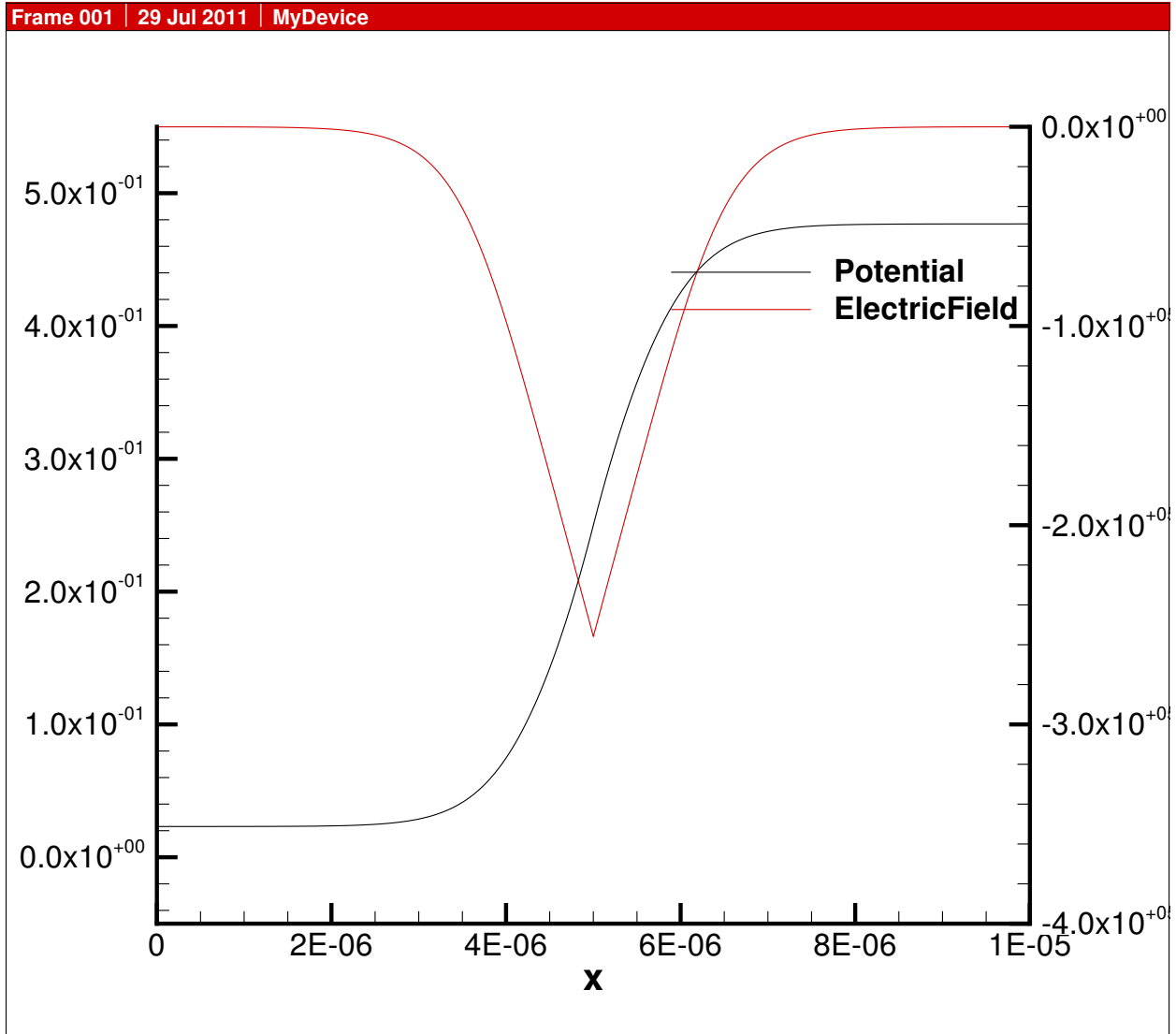


Fig. 17.2: Potential and electric field versus position in 1D diode.

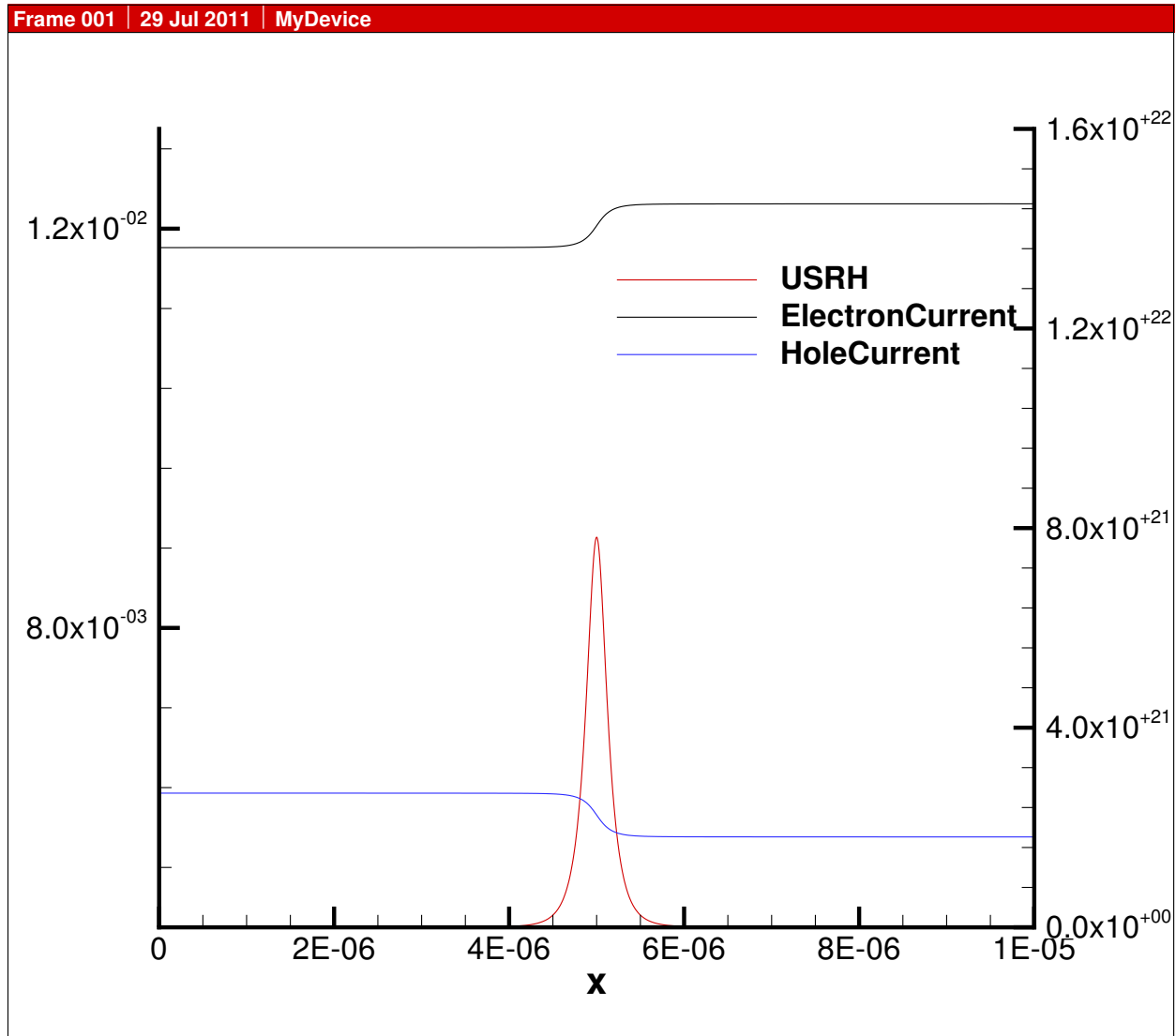


Fig. 17.3: Electron and hole current and recombination.

Bibliography

- [pyt] Python programming language — official website. <http://www.python.org>.
- [DEG+99] James W. Demmel, Stanley C. Eisenstat, John R. Gilbert, Xiaoye S. Li, and Joseph W. H. Liu. A supernodal approach to sparse partial pivoting. *SIAM J. Matrix Analysis and Applications*, 20(3):720–755, 1999.
- [GR09] C. Geuzaine and J.-F. Remacle. Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. *International Journal for Numerical Methods in Engineering*, 2009.
- [MKC02] Richard S. Muller, Theodore I. Kamins, and Mansun Chan. *Device Electronics for Integrated Circuits*. John Wiley & Sons, 3 edition, 2002.
- [Ous98] John K. Ousterhout. Scripting: higher level programming for the 21st century. *IEEE Computer*, 31:23–30, 1998.
- [SG69] D. L. Scharfetter and H. K. Gummel. Large-signal analysis of a silicon Read diode oscillator. *IEEE Trans. Electron Devices*, ED-16(1):64–77, January 1969.
- [ApacheSoftwareFoundation] Apache Software Foundation. Apache License, Version 2.0. URL: <http://www.apache.org/licenses/LICENSE-2.0.html>.

Index

A

add_1d_contact() (in module devsim), 68
add_1d_interface() (in module devsim), 68
add_1d_mesh_line() (in module devsim), 68
add_1d_region() (in module devsim), 69
add_2d_contact() (in module devsim), 69
add_2d_interface() (in module devsim), 69
add_2d_mesh_line() (in module devsim), 70
add_2d_region() (in module devsim), 70
add_circuit_node() (in module devsim), 59
add_db_entry() (in module devsim), 65
add_genius_contact() (in module devsim), 70
add_genius_interface() (in module devsim), 70
add_genius_region() (in module devsim), 71
add_gmsh_contact() (in module devsim), 71
add_gmsh_interface() (in module devsim), 71
add_gmsh_region() (in module devsim), 71

C

circuit_alter() (in module devsim), 59
circuit_element() (in module devsim), 59
circuit_node_alias() (in module devsim), 60
close_db() (in module devsim), 66
contact_edge_model() (in module devsim), 74
contact_equation() (in module devsim), 60
contact_node_model() (in module devsim), 74
create_1d_mesh() (in module devsim), 72
create_2d_mesh() (in module devsim), 72
create_contact_from_interface() (in module devsim), 72
create_db() (in module devsim), 66
create_device() (in module devsim), 72
create_genius_mesh() (in module devsim), 72
create_gmsh_mesh() (in module devsim), 73
custom_equation() (in module devsim), 61
cylindrical_edge_couple() (in module devsim), 74
cylindrical_node_volume() (in module devsim), 75
cylindrical_surface_area() (in module devsim), 75

D

debug_triangle_models() (in module devsim), 76
delete_contact_equation() (in module devsim), 61
delete_edge_model() (in module devsim), 76
delete_element_model() (in module devsim), 76
delete_equation() (in module devsim), 62
delete_interface_equation() (in module devsim), 62
delete_interface_model() (in module devsim), 76
delete_node_model() (in module devsim), 77
devsim (module), 59, 60, 65, 68, 74, 85

E

edge_average_model() (in module devsim), 77
edge_from_node_model() (in module devsim), 77
edge_model() (in module devsim), 78
element_from_edge_model() (in module devsim), 78
element_from_node_model() (in module devsim), 79
element_model() (in module devsim), 80
equation() (in module devsim), 62

F

finalize_mesh() (in module devsim), 73

G

get_circuit_equation_number() (in module devsim), 60
get_circuit_node_list() (in module devsim), 60
get_circuit_node_value() (in module devsim), 60
get_circuit_solution_list() (in module devsim), 60
get_contact_charge() (in module devsim), 85
get_contact_current() (in module devsim), 85
get_contact_equation_command() (in module devsim), 63
get_contact_equation_list() (in module devsim), 63
get_contact_list() (in module devsim), 65
get_db_entry() (in module devsim), 66
get_device_list() (in module devsim), 65
get_dimension() (in module devsim), 66

- get_edge_model_list() (in module devsim), 80
 - get_edge_model_values() (in module devsim), 80
 - get_element_model_list() (in module devsim), 80
 - get_element_model_values() (in module devsim), 81
 - get_element_node_list() (in module devsim), 65
 - get_equation_command() (in module devsim), 63
 - get_equation_list() (in module devsim), 63
 - get_equation_numbers() (in module devsim), 63
 - get_interface_equation_command() (in module devsim), 64
 - get_interface_equation_list() (in module devsim), 64
 - get_interface_list() (in module devsim), 65
 - get_interface_model_list() (in module devsim), 81
 - get_interface_model_values() (in module devsim), 81
 - get_material() (in module devsim), 66
 - get_node_model_list() (in module devsim), 81
 - get_node_model_values() (in module devsim), 81
 - get_parameter() (in module devsim), 66
 - get_parameter_list() (in module devsim), 67
 - get_region_list() (in module devsim), 65
- I**
- interface_equation() (in module devsim), 64
 - interface_model() (in module devsim), 81
 - interface_normal_model() (in module devsim), 82
- L**
- load_devices() (in module devsim), 73
- N**
- node_model() (in module devsim), 82
 - node_solution() (in module devsim), 82
- O**
- open_db() (in module devsim), 67
- P**
- print_edge_values() (in module devsim), 83
 - print_element_values() (in module devsim), 83
 - print_node_values() (in module devsim), 83
- R**
- register_function() (in module devsim), 83
- S**
- save_db() (in module devsim), 67
 - set_circuit_node_value() (in module devsim), 60
 - set_material() (in module devsim), 67
 - set_node_value() (in module devsim), 83
 - set_node_values() (in module devsim), 83
 - set_parameter() (in module devsim), 68
 - solve() (in module devsim), 85
 - syndiff() (in module devsim), 84
- V**
- vector_element_model() (in module devsim), 84
 - vector_gradient() (in module devsim), 84
- W**
- write_devices() (in module devsim), 74