CROSSLIGHT

Application Note

SiC MOSFET Simulation

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*Abstract--***A technology template for the device simulation of a 3.3 kV Silicon Carbide (SiC) MOS power transistor using the Crosslight NOVATCAD suite of simulation tools is provided. The example illustrates the use of the process simulation tool CSUPREM to generate the basic mesh, epitaxial layer, and gate structure. This structure is imported into the device simulator APSYS in which the doped layers are added using analytic approximations. A methodology to simulate the SiC MOS electrical characteristics including the drain transfer curves, gate transfer curves, on-state resistance, and breakdown voltage is demonstrated. Simulation results are displayed and analyzed using the CrosslightView plotting tool.**

I. INTRODUCTION

Silicon carbide has become a leading candidate to replace silicon in high voltage power switching applications based on its superior material properties including high breakdown field, high thermal conductivity and high electron saturation velocity. In order to properly understand and optimize these devices fast and accurate TCAD modeling is essential. This application note presents template files useful for the analysis, design and optimization of SiC MOSFET devices using the Crosslight NOVATCAD framework. CSUPREM is used to generate the simulation grid, epitaxial layer and gate structure. This is imported into the APSYS device simulator where the doped regions are introduced analytically. Template files for simulating device I_d-V_g, I_d-V_d, and drain breakdown characteristics (BV_{dss}) are provided.

Fig. 1. shows schematic cross-section of the unit cell of a typical 3.3 kV SiC MOSFET [1]. The device is formed on a 30 μm thick n-type epitaxial drift layer with a doping concentration of $3x10^{15}$ cm^{-3}. The channel length is assumed to be 1.0 μm and the width of the JFET region is 1.5 μm. The total cell pitch is 5.5 μm. The gate oxide is 50 nm thick while the gate contact is formed from n+ doped polysilicon.

The simulation structure is shown in Fig. 2. Because of symmetry only the half-cell is simulated to minimize node count and run time.

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The p-well region is approximated as a two-step Gaussian profile. The shallower profile sets the surface dopant concentration of approximately $2x10^{17}$ cm^{-3} and thus determines the threshold voltage. The deeper profile is more highly doped and serves to prevent punch-through from the drain-to-source under high-voltage operation. The total well depth is 1.0 μm. Shallower, higher concentration profiles form the n+ source and p+ body tie regions.

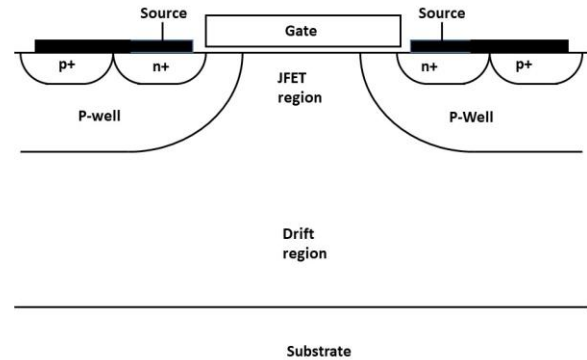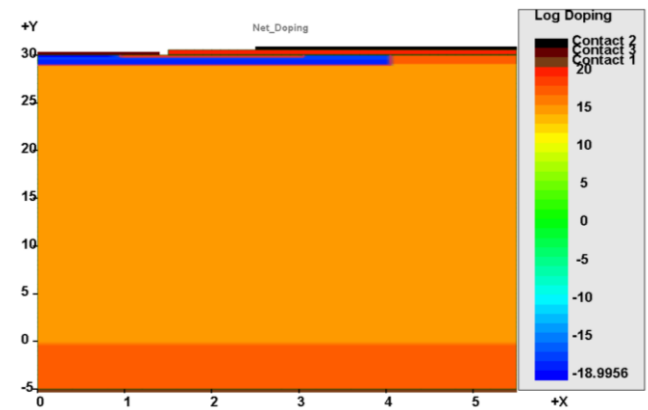**Fig. 1 Schematic Cross Section of SiC MOSFET**

Fig. 2 Simulation Cross Section

II. STRUCTURE GENERATION

A. Initial set-up

CSUPREM is used as a convenient method to define the material regions, generate the simulation grid and specify the epitaxial layer doping. Minimal process simulation is actually performed since the well and source regions are defined analytically in the APSYS tool. The

meshing strategy implements a coarse mesh deep in the structure with much finer spacings near the surface and at the edge of the p-well where the highest electric fields occur. This is easily accomplished using the RATIO command in the initial mesh setup. This example employs approximately 5000 mesh points which provides a good compromise between required accuracy and sufficiently fast run time. The CSUPREM input file is provided in Appendix A.

B. Physical model selection

The most important physical models necessary for accurate simulation of SiC MOSFET devices are bulk mobility, inversion layer mobility, and impact ionization. These models have been discussed in detail in the literature [2-3].

The bulk mobility model is based on a modified Arora formulation to capture both impurity and temperature dependence.

$$\mu_n = \mu_{min} + \frac{\mu_d}{1+(\frac{N_t}{N_0})^a} \qquad (1)$$

The electron mobility temperature dependence is modeled as

$$\mu(T) = \mu_{300}(\frac{T}{300})^{-2.4} \qquad (2)$$

In (1) μ_d= 791cm^2/V-sec, μ_{min}= 33cm^2/V-sec, N_0= 1.94x10^{17}cm^{-3}, a=0.61 and T is the Kelvin temperature. The mobility coefficients are defined for the x-direction, which is parallel to the wafer surface. These are defined using the low_field_mobility statement in APSYS as illustrated below.

```
low_field_mobility_model
el_doping_dependence_model=arora
&&
el_ar_d=0.0791  el_ar_umin=0.0033
el_ar_n=1.94E+23 el_ar_a=0.61
```

The anisotropy in the low field mobility is captured as

$$\mu_y = 1.2\mu_x \qquad (3)$$

The inversion layer mobility is SiC is determined by a number of scattering mechanisms the most important of which are the surface phonon scattering and the surface roughness scattering due to structural disprder at the SiC/SiO2 interface. These effects are captured in APSYS using the Lombardi mobility model as illustrated below.

```
mobility_xy
elec_field_model=lombardi
hole_field_model=lombardi &&
elec_lombardi_b=1.00E+06
elec_lombardi_alpha=1.746E+05 &&
elec_lombardi_beta=0.043
elec_lombardi_delta=3.0E+14 &&
dir=y factor_elec=1.2 mater=1
```

The model coefficients are calibrated to the measured data but are similar to those presented by Kimoto and Cooper [4].

Impact ionization calculations use Selberher's formulation of the Chynoweth model [5]

$$\alpha_{n,p} = \alpha_{n,p}^{\infty}e^{-(\frac{Fn}{F})^{\kappa}} \qquad (4)$$

The ionization coefficients are taken from Loh et. al. [6]

III. SiC SIMULATION IN NOVATCAD

A. Forward I-V simulation

The SiC MOSFET device structure generated with the CSUPREM export statement is the input structure for the device simulations. The load_mesh statement is used to enter the device structure into APSYS while the doping statements generate the P-well, source, body tie and JFET regions. The subsequent suprem_to_apsys_material command maps the CSUPREM materials into the APSYS materials. suprem_mater is the original material number in the CSUPREM file, which by default defines 4H-SiC as material 26. apsys_mater is the corresponding material number in APSYS. The load_macro statements are used to describe the properties of the various materials used in the structure as defined in the materials database. The suprem_contact statements are used to

define the electrodes on the mesh imported from CSUPREM.

The `interface` statement is used to specify the oxide charge, in units of $1/m^2$. The location of the interface must correspond to the physical interface between the gate oxide and the SiC active layer. The carrier mobilities are set by the `low_field_mobility` and `mobility_xy` statements described previously.

Fig. 3 illustrates the simulated forward Id-Vd characteristics for the SiC MOSFET of Fig. 2. The Id-Vg characteristics are shown in Fig. 4. The data show a threshold voltage of 6.3 V. The simulated on-state resistance at Vg=15 V is 14.5 mohm-cm^2 which is typical of commercial 3.3 kV rated SiC MOSFETs [1]. The simulation data include the effect of a lumped resistance equal to the actual substrate resistance.
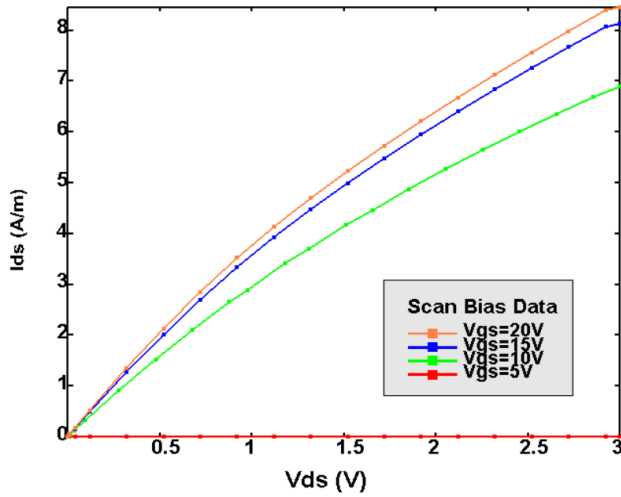
Fig. 3 Id-Vd Simulation Vgsmax=20V, 5V increments

A complete listing of the APSYS input file for the Id-Vd simulations is given in appendix B. Appendix C presents the Id-Vg input file.

b.) Reverse Simulations

The APSYS input file for the reverse simulations is provided in Appendix D. A key issue in the reverse simulation of wide-bandgap devices is the potential problem of convergence due to
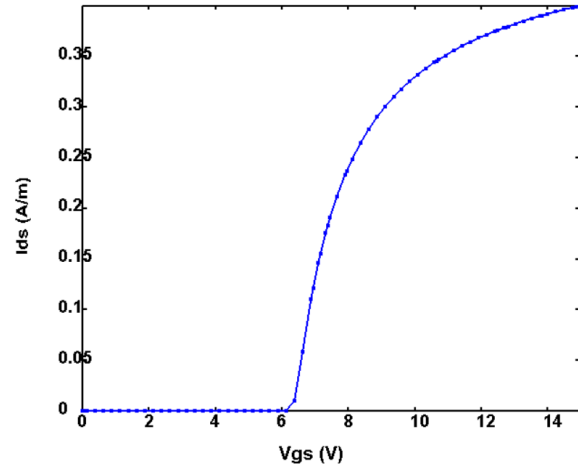
Fig. 4 Id-Vg Simulation Vds=0.1V,

the very low equilibrium carrier densities. The `set_minority_carrier` statement is used to artificially increase the minority carrier density thus alleviating this problem. The I-V characteristics are computed using the scan statements. Initially the drain voltage is swept until a specified avalanche current is reached as defined by the `auto_finish` and `auto_until` statements. After this the simulation switches to a current boundary condition to allow the rest of the I-V curve computed.

Accurate simulation of breakdown voltage requires proper choice of the impact ionization model and its associated parameters. NOVATCAD provides a number of different models commonly found in the literature to allow the user flexibility to choose the most appropriate model for a given simulation and to provide properly calibrated input parameters. The well-known Chynoweth model with the appropriate input parameters described previously is specified by the `impact_chynoweth` statement. The simulated reverse I-V characteristics are shown in Fig. 5. The simulated breakdown voltage is 4.0 kV in good agreement with the measured value from [1].
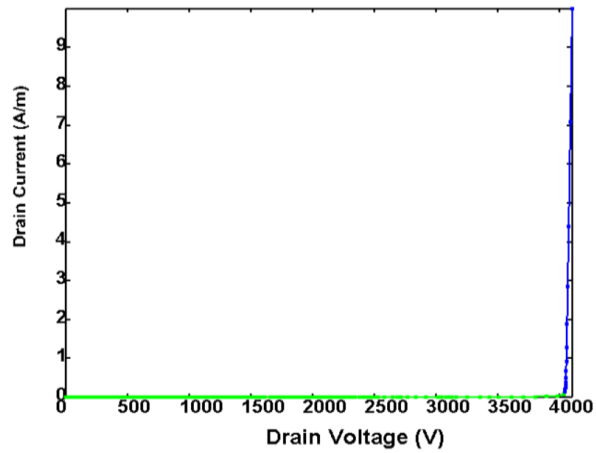
Fig. 5 BVdss Simulation

References

[1] K. Hamada, S. Hino, and T. Kitani, "Low On-Resistance SiC MOSFET with a 3.3 kV Blocking Voltage", *Mitsubishi Electric Advance*, Vol 149, pp 14-17, March 2015.

[2] T. Hatakeyama, K. Fukuda, and H. Okumura, "Physical Models for SiC and Their Application to Device Simulations of SiC Insulated-Gate Bipolar Transistors", *IEEE Trans Electron Devices*, vol. 60, no. 2, pp. 613-621, Feb. 2013.

[3] N. D. Arora, J. R. Hauser, and D. J. Roulston, "Electron and hole mobili-ties in silicon as a function of concentration and temperature", *IEEE Transactions on Electron Devices*, vol. 29, no. 2, pp. 292-295, February 1982.

[4] T. Kimoto and J. Cooper, "Fundamentals of Silicon Carbide Technology, Growth Characterization, Devices and Applications", *Wiley-IEEE Press*, pp. 329-350, 2014.

[5] S.Selberher,, *Analysis and Simulation of Semiconductor Devices* Springer-Verlag, 1984.

[6] W.K. Loh et.al., "Ionization coefficients in 4H-SiC", *IEEE Transactions on Electron Devices*, vol. 55, no 8, pp. 1984-1989, August 2008.

Appendix A: CSUPREM Input File

```
#################################################
#
#  Grid structure
#
#################################################


line x loc=     0.0      spacing=  0.1      tag=lft
line x loc=     5.5      spacing=  0.1      tag=rht

line y loc=     0.0      spacing=  0.5      tag=top
line y loc=     5.0      spacing=  0.5      tag=bot


eliminate y.direction xlo=0 xhi=10 ylo=1 yhi=5 ntimes=2
option  auto.mesh.implant=f

#################################################
#
#  Define structure as SiC
#
#################################################


region  4H-SiC xlo=lft xhi=rht ylo=top yhi=bot
bound exposed xlo=lft xhi=rht ylo=top yhi=top
bound backside xlo=lft xhi=rht ylo=bot yhi=bot

#################################################
#
#  Initialize substrate
#
#################################################

init phosphorus conc=1.e18



#################################################
#
#  SiC epi layer
#
#################################################

deposit 4H-SiC thick=20 meshlayer=40 phosphorus conc=3e15
deposit 4H-SiC thick=9.5 meshlayer=25 phosphorus conc=3e15
ratio.layer=0.8
```

```
deposit 4H-SiC thick=0.5 meshlayer=10 phosphorus conc=3e15
diffuse time=1 temp=900 nitrogen


################################################
#
#   Deposit gate oxide
#
################################################

deposit oxide thick=0.05 divisions=5


################################################
#
#   Deposit and pattern gate
#
################################################

deposit poly thick=0.5 divisions=5 phosphorus conc=1E20
etch poly left p1.x=1.5

################################################
#
#   Etch source region contacts
#
################################################

etch oxide left p1.x=1.5

################################################
#
#   Set activation and save final structure
#
################################################

activation.mode phosphorus fraction=1 force.activation=t
activation.mode boron fraction=0.65 force.activation=t

struct outf=Suprem_SIC_MOS.str

export outf=SiC_MOS.aps xpsize=0.001


quit
```

Appendix B: SiC MOSFET Id-Vd Simulation Input File

```
begin

$------- Polarity of Posititive Current Flow -----------
convention positive_current_flow=inward
temperature temp=300

load_mesh mesh_inf=SiC_MOS.aps  suprem_import=yes
output sol_outf=MOS_Id_Vd.out
more_output space_charge=yes

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Define the doping profiles analytically

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$ Well
doping impurity=shal_dopant charge_type=acceptor max_conc=3e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 30.0, 0.0, 0.00 )
$ Retrograde
doping impurity=shal_dopant charge_type=acceptor max_conc=8e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 29.5, 0.0, 0.00 )
$ Source
doping impurity=shal_dopant charge_type=donor max_conc=1.e25  &&
  x_prof= ( 1.0, 3.0, 0.01, 0.01 )  &&
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )
$ JFET
doping impurity=shal_dopant charge_type=donor max_conc=1.e23  &&
  x_prof= ( 0.0, 5.5, 0.01, 0.01 )  &&
  y_prof= ( 29.1, 30.0, 0.0, 0.00 )
$Body tie
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e25  &&
  x_prof= ( 0.0, 0.8, 0.01, 0.01 )  &&
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Do the material mapping

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
```

```
suprem_property user_material_mapping = yes

suprem_to_apsys_material suprem_mater=26  apsys_mater=1
suprem_to_apsys_material suprem_mater=4 apsys_mater=3
suprem_to_apsys_material suprem_mater=1 apsys_mater=2

material_label_define label=4h_sic mater=   1
load_macro name=4h_sic mater=    1

material_label_define label=sio2 mater=   2
load_macro name= sio2 mater= 2

material_label_define label=poly mater=   3
load_macro name= poly mater= 3




$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$ Define the contacts
$
$ Drain/Substrate= 1
$ Gate= 2
$ Source= 3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

suprem_contact num=1 xrange=(0.000000 10.000000)  yrange=(-9999.000000
&&
9999.000000) touch_mater=1 side=lower

suprem_contact num=2 xrange=(2.5 10.000000)  yrange=(-9999.000000 &&
9999.000000) touch_mater=3 side=upper

suprem_contact num=3 xrange=(0.0 1.4)  yrange=(-9999.000000 &&
9999.000000) touch_mater=1 side=upper

contact num=1
contact num=2
contact num=3


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$  Set the bulk mobility parameters to accommodate mobility anisotropy
$  Adjust low-field bulk mobilityfor a-axis =1/1.2 x c-axis values
$  Get proper c-axis mobility from mobility anisotropy dir_y
factor_elec=1.2
```

```
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

low_field_mobility_model el_doping_dependence_model=arora &&
el_ar_d=0.0791 el_ar_umin=0.0033 el_ar_n=1.94E+23 el_ar_a=0.61

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Set the channel mobility parameters
$  Use optimized Lombardi coefficients based on Kimoto and Cooper

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


mobility_xy elec_field_model=lombardi hole_field_model=lombardi &&
elec_lombardi_b=1.00E+06  elec_lombardi_alpha=2.2E+05 &&
elec_lombardi_beta=0.043 elec_lombardi_delta=8.0E+14 &&
dir=y factor_elec=1.2 mater=1

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Define the oxide fixed charge

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


interface model=charge within_y=(29.9, 30.1) within_x=(1.5, 5.5) &&
 fix_charge=1e14


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$   Equilibrium solution
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$

newton_par damping_step=5. max_iter=150 print_flag=3 &&
var_tol=0.1 res_tol=0.1
equilibrium
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$
$
$   Rds solution--Set Vgs=15V to calibrate to
$   published data for 3.3 kV MOSFET
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$


newton_par damping_step=8.    &&
  var_tol=0.01 res_tol=0.01 change_variable=yes

$-------------------------------------------------------------
$ Vg=5.0 Trace
$-------------------------------------------------------------

scan var=voltage_2 value_to=5 min_step=1e-9 max_step=0.5 &&
init_step=0.001

scan var=voltage_1 value_to=3 min_step=1e-6 max_step=0.2 &&
init_step=0.001

scan var=voltage_1 value_to=0 min_step=1e-6 max_step=0.2 &&
init_step=0.001

$-------------------------------------------------------------
$ Vg=10.0 Trace
$-------------------------------------------------------------

scan var=voltage_2 value_to=10 min_step=1e-9 max_step=0.5 &&
init_step=0.001

scan var=voltage_1 value_to=3 min_step=1e-6 max_step=0.2 &&
init_step=0.001

scan var=voltage_1 value_to=0 min_step=1e-6 max_step=0.2 &&
init_step=0.001

$-------------------------------------------------------------
$ Vg=15.0 Trace
$-------------------------------------------------------------

scan var=voltage_2 value_to=15 min_step=1e-9 max_step=0.5 &&
init_step=0.001

scan var=voltage_1 value_to=3 min_step=1e-6 max_step=0.2 &&
init_step=0.001

scan var=voltage_1 value_to=0 min_step=1e-6 max_step=0.2 &&
init_step=0.001
```

```
$-------------------------------------------------------------
$ Vg=20.0 Trace
$-------------------------------------------------------------

scan var=voltage_2 value_to=20 min_step=1e-9 max_step=0.5 &&
init_step=0.001

scan var=voltage_1 value_to=3 min_step=1e-6 max_step=0.2 &&
init_step=0.001

end
```

Appendix C: SiC MOSFET Id-Vg Simulation Input File

```
begin

$------- Polarity of Posititive Current Flow -----------
convention positive_current_flow=inward
temperature temp=300

load_mesh mesh_inf=SiC_MOS.aps   suprem_import=yes
output sol_outf=MOS_Id_Vg.out
more_output space_charge=yes

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$

$  Define the doping profiles analytically

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$

$ Well
doping impurity=shal_dopant charge_type=acceptor max_conc=3e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 30.0, 0.0, 0.00 )
$ Retrograde
doping impurity=shal_dopant charge_type=acceptor max_conc=8e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 29.5, 0.0, 0.00 )
$ Source
doping impurity=shal_dopant charge_type=donor max_conc=1.e25  &&
  x_prof= ( 1.0, 3.0, 0.01, 0.01 )  &&
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )
$ JFET
doping impurity=shal_dopant charge_type=donor max_conc=1.e23  &&
  x_prof= ( 0.0, 5.5, 0.01, 0.01 )  &&
  y_prof= ( 29.1, 30.0, 0.0, 0.00 )
$Body tie
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e25  &&
  x_prof= ( 0.0, 0.8, 0.01, 0.01 )  &&
```

```
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$

$  Do the material mapping

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$


suprem_property user_material_mapping = yes

suprem_to_apsys_material suprem_mater=26  apsys_mater=1
suprem_to_apsys_material suprem_mater=4 apsys_mater=3
suprem_to_apsys_material suprem_mater=1 apsys_mater=2

material_label_define label=4h_sic mater=   1
load_macro name=4h_sic mater=   1

material_label_define label=sio2 mater=   2
load_macro name= sio2 mater= 2

material_label_define label=poly mater=   3
load_macro name= poly mater= 3



$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$ Define the contacts
$
$ Drain/Substrate= 1
$ Gate= 2
$ Source= 3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$

suprem_contact num=1 xrange=(0.000000 10.000000)  yrange=(-9999.000000
&&
9999.000000) touch_mater=1 side=lower

suprem_contact num=2 xrange=(2.5 10.000000)  yrange=(-9999.000000 &&
9999.000000) touch_mater=3 side=upper

suprem_contact num=3 xrange=(0.0 1.4)  yrange=(-9999.000000 &&
9999.000000) touch_mater=1 side=upper

contact num=1
```

```
contact num=2
contact num=3

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Set the bulk mobility parameters to accommodate mobility anisotropy
$  Adjust low-field bulk mobilityfor a-axis =1/1.2 x c-axis values
$  Get proper c-axis mobility from mobility anisotropy dir_y
factor_elec=1.2

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

low_field_mobility_model el_doping_dependence_model=arora &&
el_ar_d=0.0791 el_ar_umin=0.0033 el_ar_n=1.94E+23 el_ar_a=0.61


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Set the channel mobility parameters
$  Use optimized Lombardi coefficients based on Kimoto and Cooper

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


mobility_xy elec_field_model=lombardi hole_field_model=lombardi &&
elec_lombardi_b=1.00E+06  elec_lombardi_alpha=2.2E+05 &&
elec_lombardi_beta=0.043 elec_lombardi_delta=8.0E+14 &&
dir=y factor_elec=1.2 mater=1

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Define the oxide fixed charge

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


interface model=charge within_y=(29.9, 30.1) within_x=(1.5, 5.5) &&
 fix_charge=1e14
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$   Equilibrium solution
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

newton_par damping_step=5. max_iter=150 print_flag=3 &&
var_tol=0.1 res_tol=0.1
equilibrium

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$   Id-Vg solution--Set drain voltage to 0.1V
$   and sweep Vg.
$
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


newton_par damping_step=8.   &&
  var_tol=0.01 res_tol=0.01 change_variable=yes

$Set the gate voltage
scan var=voltage_1 value_to=0.1  &&
     init_step=0.01 max_step=1.0 min_step=1e-8

$ Sweep the drain voltage
scan var=voltage_2 value_to=15  &&
     init_step=0.01 max_step=0.25 min_step=1e-8


end
```

Appendix D: SiC MOSFET BVdss Simulation Input File

```
begin

$------- Part 1: Polarity of Potistive Current Flow -----------
convention positive_current_flow=inward
temperature temp=300

load_mesh mesh_inf=SiC_MOS.aps  suprem_import=yes
output sol_outf=MOS_BV.out
more_output impact_ionization=yes space_charge=yes

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$  Define well and source doping profiles analytically

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


$ Well
doping impurity=shal_dopant charge_type=acceptor max_conc=3e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 30.0, 0.0, 0.00 )
$ Retrograde
doping impurity=shal_dopant charge_type=acceptor max_conc=8e23  &&
  x_prof= ( 0.0, 4.0, 0.01, 0.01 )  &&
  y_prof= ( 29.0, 29.5, 0.0, 0.00 )
$ Source
doping impurity=shal_dopant charge_type=donor max_conc=1.e25  &&
  x_prof= ( 1.0, 3.0, 0.01, 0.01 )  &&
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )
$ JFET
doping impurity=shal_dopant charge_type=donor max_conc=1.e23  &&
  x_prof= ( 0.0, 5.5, 0.01, 0.01 )  &&
  y_prof= ( 29.1, 30.0, 0.0, 0.00 )
$Body tie
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e25  &&
  x_prof= ( 0.0, 1.0, 0.01, 0.01 )  &&
  y_prof= ( 29.8, 30.0, 0.0, 0.00 )

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$  Do the material mapping

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


suprem_property user_material_mapping = yes
```

```
suprem_to_apsys_material suprem_mater=26  apsys_mater=1
suprem_to_apsys_material suprem_mater=4 apsys_mater=3
suprem_to_apsys_material suprem_mater=1 apsys_mater=2

material_label_define label=4h_sic mater=   1
load_macro name=4h_sic mater=   1

material_label_define label=sio2 mater=   2
load_macro name= sio2 mater= 2

material_label_define label=poly mater=   3
load_macro name= poly mater= 3




$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ Define the contacts
$
$ Substrate= 1
$ Gate= 2
$ Source= 3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

suprem_contact num=1 xrange=(0.000000 10.000000)  yrange=(-9999.000000
&&
9999.000000) touch_mater=1 side=lower

suprem_contact num=2 xrange=(2.5 10.000000)  yrange=(-9999.000000 &&
9999.000000) touch_mater=3 side=upper

suprem_contact num=3 xrange=(0.0 1.4)  yrange=(-9999.000000 &&
9999.000000) touch_mater=1 side=upper

contact num=1
contact num=2
contact num=3



$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$  Set the bulk mobility parameters
$  Adjust for a-axis =1/1.2 x c-axis values
$  Get proper c-axis mobility from mobility anisotropy dir_y
factor_elec=1.2

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

low_field_mobility_model el_doping_dependence_model=arora &&
el_ar_d=0.0791 el_ar_umin=0.0033 el_ar_n=1.94E+23 el_ar_a=0.61
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Set the channel mobility parameters
$  Use optimized Lombardi coefficients based on Kimoto and Cooper

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$



mobility_xy elec_field_model=lombardi hole_field_model=lombardi &&
elec_lombardi_b=1.00E+06  elec_lombardi_alpha=2.2E+05 &&
elec_lombardi_beta=0.043 elec_lombardi_delta=8.0E+14 &&
dir=y factor_elec=1.2 mater=1




$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$  Set virtual minority carrier concentration to improve convergence
$  This is critical for wide-bandgap BV simulation
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$


set_minority_carrier virtual_eg_kt=25



$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$
$    Impact ionization models for SiC
$    Choose coefficients from Loh et al, TED 2008
$    in this example
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$

$  Originals from Crosslight Example
$impact_chynoweth mater = 1 hole_setnum = 1  &&
$    hole_set1 =  [1.12e+09,1.72e+09,1.]  &&
$    elec_setnum = 1 elec_set1 =   [4.60e+07,1.78e+09,1.]
```

```
$  Old Silvaco defaults
$impact_chynoweth mater = 1 hole_setnum = 1   &&
$     hole_set1 =   [5.18e+08,1.4e+09,1.]   &&
$     elec_setnum = 1 elec_set1 =   [1.660e+08,1.27e+09,1.]


$ Loh/GE Coefficinets
impact_chynoweth mater = 1 hole_setnum = 1   &&
   hole_set1 =   [3.51e+08,1.03e+09,1.09]   &&
    elec_setnum = 1 elec_set1 =   [2.78e+08,1.05e+09,1.37]



$ From Hatakeyama's paper  a axis coefficients
$impact_chynoweth mater = 1 hole_setnum = 1   &&
$   hole_set1 =   [2.96E+09,1.6E+09,1.]   &&
$   elec_setnum = 1 elec_set1 =   [2.1e9,1.7E+09,1.]



$ From Hatakeyama's paper  C axis coefficients
$impact_chynoweth mater = 1 hole_setnum = 1   &&
$     hole_set1 =   [3.41e+10,2.5E+09,1.]   &&
$     elec_setnum = 1 elec_set1 =   [1.76e+10,3.3E+09,1.]



$impact_lackner elec_a_coef=2.10E+09 elec_critical_field=1.7E+09 &&
$                 hole_a_coef=2.96e+09 hole_critical_field=1.6E+09

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$  Equilibrium solution
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


newton_par damping_step=5. max_iter=150 &&
var_tol=0.1 res_tol=0.1
$
equilibrium
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$  Reverse Simulation
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


newton_par damping_step=5.    &&
  var_tol=0.01 res_tol=0.01 change_variable=no



scan var=voltage_1 value_to=5000 &&
   init_step=0.01 max_step=100 min_step=1e-8 &&
   auto_finish=current_1 auto_until=0.1 auto_condition=above
```

```
scan var=current_1 value_to=10   &&
   init_step=1e-1 min_step=1.e-10 max_step=1.e4



end
```