



Application Note

SiC Floating Field Ring Edge Termination

Updated 2017.06

© Crosslight Software Inc.

Abstract— A technology template for the simulation of floating field ring edge termination structures in silicon carbide power devices is presented. The example illustrates a multi-ring termination structure typical of those used in 1200V Silicon Carbide power MOSFETs using the Crosslight NOVATCAD suite of simulation tools. These structures pose several challenges to numerical simulation due to the very low equilibrium carrier densities associated with the wide-bandgap material as well as initially undefined potential of the field rings. These issues are handled transparently and robustly in the simulation tool. The example illustrates the use of the process simulation tool CSUPREM to generate the starting material and simulation grid. The structure is imported into the device simulator APSYS which is used to define the field ring structure and perform the avalanche breakdown analysis within a coupled Poisson-drift-diffusion framework with appropriate device ionization.

I. INTRODUCTION

Silicon carbide is rapidly becoming the material of choice for high-voltage and power semiconductor applications, due to its wide-bandgap and high critical electric field at breakdown. In practical applications, the breakdown voltage of planar p-n junctions is reduced from the theoretical maximum due to the occurrence of high field regions at the edge of the device. The reduced breakdown voltage originates from electric field crowding associated with the radius of curvature at the periphery of planar implanted or diffused junctions. To alleviate, these effects, various edge termination design techniques have been developed to reduce field crowding and increase the practical breakdown to or near the theoretical limit [1-2].

The floating field ring structure is widely used in high voltage applications due to both its effectiveness in reducing field crowding and the fact that no additional process steps are required to form the termination [3-4]. However, the design of field ring termination structures is difficult because of numerous interacting dependencies on ring width, ring depth, ring-to-ring spacing, ring and epitaxial layer doping and oxide charges. Proper optimization of these structures requires two-dimensional numerical simulation.

This application note presents template files useful for the analysis, design and optimization of floating field ring termination structures in SiC devices using the Crosslight NOVATCAD framework. The methodology is illustrated using a multi-ring termination structure that has been previously presented in the literature [4] and which is typical of those commonly used in commercial designs.

Author information

Gary M. Dolny, PhD is a scientific and technical consultant specializing in the areas of analog and power semiconductor devices and technologies. (gary.dolny.us@ieee.org)

II. DEVICE STRUCTURE

A simplified floating field ring termination structure is shown in Fig.1. Under reverse bias conditions, each floating ring within the depletion layer reaches an intermediate potential between zero and the applied voltage. The potential on any individual ring self-biases to achieve equilibrium with the adjacent material assuring zero net current flow. The presence of the rings increases the width of the depletion region at the surface, reducing the electric field at the junction periphery and improving the breakdown voltage. Thus, accurate simulation of the structure requires self-consistent calculation of the quasi-Fermi potential of each of the individual rings.

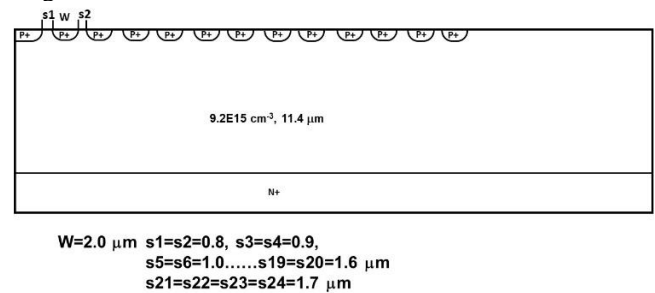


Fig.1 Typical multi-ring floating field ring termination

The actual simulation structure is shown in Fig. 2 and was based on the device described in [4]. The termination consists of 24 floating rings. The rings are approximated as a Gaussian profile in both x- and y-direction with a width of 2.0μm, a depth of 0.55μm and a surface concentration of $1 \times 10^{18} \text{cm}^{-3}$. The ring spacing is progressively varied from 0.8μm to 1.7μm as the distance from the main junction is increased. The epitaxial layer doping is $9.2 \times 10^{15} \text{cm}^{-3}$ and the thickness is 11.4 μm.

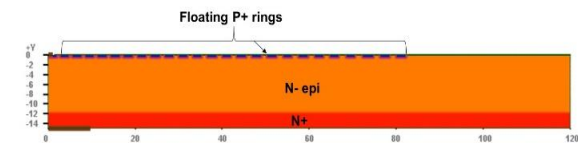


Fig.2 Multi-ring floating field ring termination used in simulation example illustrating structure aspect ratio

III. FIELD-RING SIMULATION

A.) Structure generation

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 field rings are defined analytically in the APSYS tool.

Grid generation is a challenge for simulation of floating field ring structures in silicon carbide due to the large difference between the physical extent of the simulation region compared to the minimum dimension needed to properly resolve the field ring spacings. In practical applications, the termination structure width may be well in excess of 100 μ m while the resolution necessary to properly capture the grid spacing is on the order of 0.1 μ m. The meshing strategy adopted in this example is to define a fine mesh in regions in the vicinity of the floating field rings and to use the ELIMINATE statements to remove unnecessary mesh lines in the bulk regions of the structure. Even with such a strategy node counts of >15,000 nodes may be required to accurately represent complex termination structures requiring several hours of simulation time. Reasonable approximations can be obtained with smaller node counts and correspondingly shorter run times.

For the purposes of this example the edge termination of figure 2 was simulated using two different gridding strategies. The first used a highly dense grid of ~18,000 nodes that was capable of accurately capturing the field ring spacings exactly as defined in Fig 1. The second used a coarser grid of ~10,000 nodes that required some approximations to the designed ring spacings. The comparison is presented in Table 1. The breakdown voltage predicted by the coarser grid agreed to within <1% of the dense mesh while the run time was reduced by nearly a factor of 2. A full listing of the input file is given in Appendix A.

Node count	Run time (sec)	Simulated BV (V)
10108	14061	1752
17955	26427	1736

Table 1 Simulation comparison vs node count

B.) Device simulation

The basic 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. The various doping statements generate the anode, the p+ floating field rings, and the top region of the substrate.

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 and SiO₂ as material 1. `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.

A key issue in the simulation of wide-bandgap devices are potential convergence issues due to the very low equilibrium carrier densities. The `set_minority_carrier` statement is used to artificially increase the minority carrier density thus alleviating this problem.

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. For this example, the well-known Chynoweth model was chosen with input parameters taken from [5].

The I-V characteristics are computed using the scan statements. Initially the cathode 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.

A full listing of the APSYS input file is given in Appendix B.

IV. SIMULATION RESULTS

The simulation results can be effectively analyzed with the Crosslight View Visualization tool. Representative output plots are shown in Figs 3-7. Fig. 3 plots the resultant I-V characteristic showing a breakdown voltage of 1752V which is about 95% of the ideal plane parallel junction breakdown. The two-dimensional equipotential contours are plotted in Fig. 4 while the maximum electric field and potential parallel to the surface at the bottom of the rings are plotted in Fig. 5 and 6. Fig. 7 plots the 2-dimensional current density at breakdown.

The plots show a relatively equal sharing of the electric field and uniform potential gradient in the termination region. The maximum electric field occurs at the innermost rings which determines the location of the maximum avalanche current density.

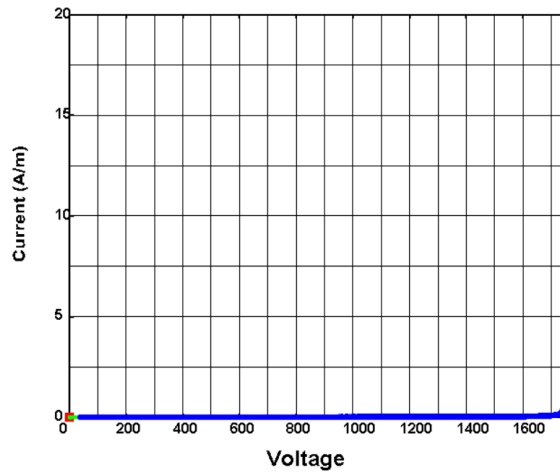


Fig. 3 Simulated BV_{dss} characteristic

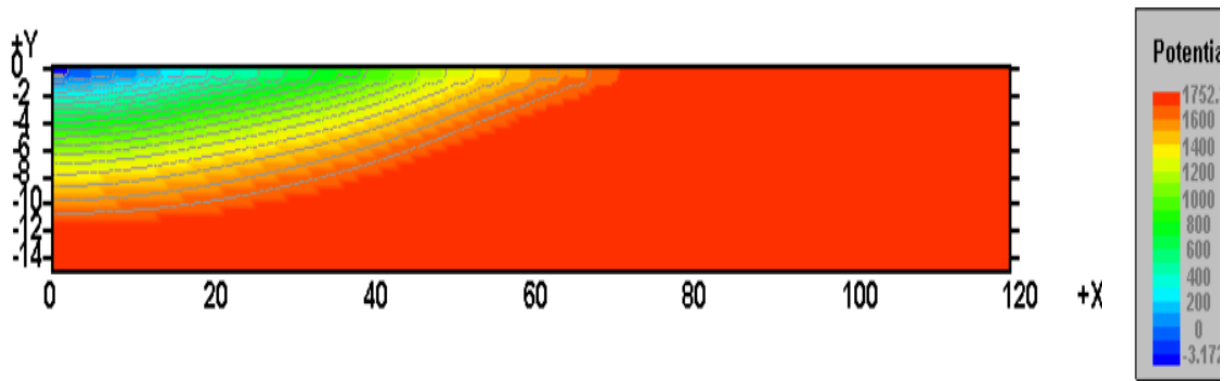


Fig 4. Equipotential contours at breakdown

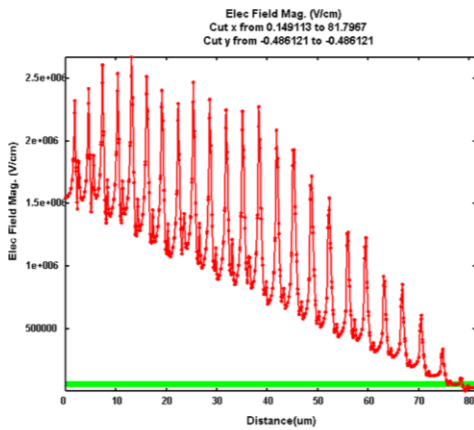


Fig 5. Subsurface electric field magnitude

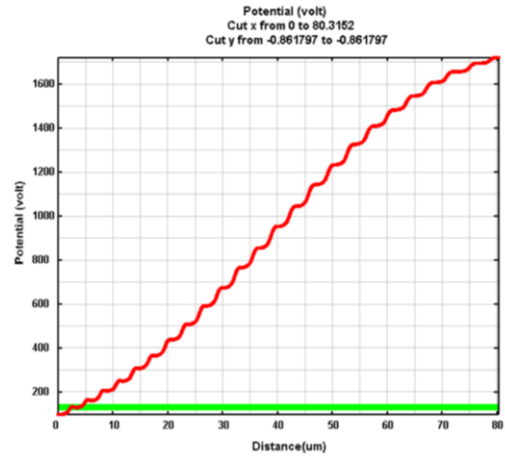
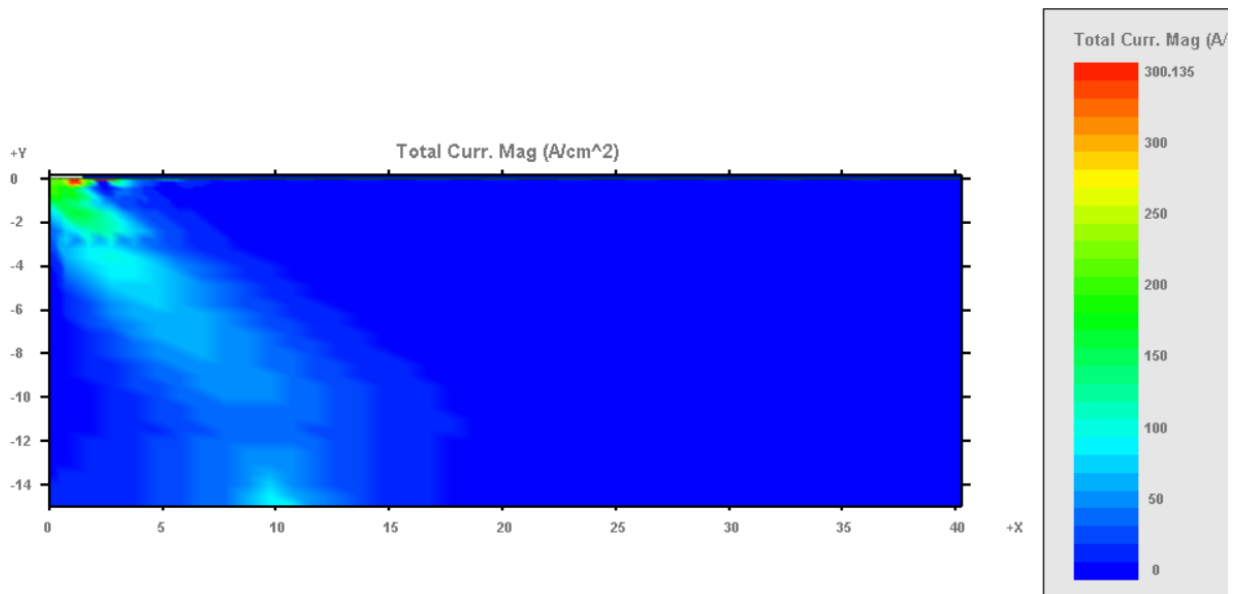


Fig. 6 Subsurface equipotential vs distance



Two-dimensional current density plot at breakdown

References

- [1] S. Woonjie, E van Brunt, B. J. Baliga, "A new edge termination technique for high-voltage devices in 4H-SiC—multiple floating zone junction termination extension", *IEEE Electron Device Letters*, vol. 32, no 7, pp. 880-882, July 2011.
- [2] C. Feng, J. Suda, T. Kimoto, "A space modulated junction termination extension for ultra-high-voltage p-i-n diodes in 4H-SiC", *IEEE Transactions on Electron Devices*, vol. 59, no 2, pp. 414-418, February 2012.
- [3] D. Sheridan et. al., "Design and fabrication of planar guard ring termination for high-voltage SiC diodes", *Solid State Electronics*, vol. 44, no 2, pp. 1367-1372, 2000.
- [4] P. Alexandrov, "Development of 4H-SiC high voltage unipolar switching devices", PhD dissertation, Rutgers University, 2010.
- [5] 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= 0.25      tag=lft
line x loc=     120.0      spacing= 0.25      tag=rht

line y loc=      0.0      spacing= 0.2      tag=top
line y loc=      0.4      spacing= 0.1
line y loc=      0.6      spacing= 0.1
line y loc=      2.0      spacing= 0.4
line y loc=     10.0      spacing= 0.5
line y loc=     15.0      spacing= 0.5      tag=bot
#line y loc=      5.0      spacing= 0.05      tabotg=bot
#line y loc=    345.0      spacing= 20.0

eliminate y.direction xlo=1 xhi=125 ylo=1 yhi=15 ntimes=1
eliminate y.direction xlo=1 xhi=125 ylo=3 yhi=15 ntimes=1
eliminate x.direction xlo=85 xhi=125 ylo=0.2 yhi=0.8 ntimes=1

option auto.mesh.implant=f

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=9.2e15

struct outf=1_sub.str

deposit nitride thick=1
diffuse time=1 temp=900 nitrogen
diffuse time=50 temp=950
etch nitride all

struct outf=2_drift.str
```



```
x_prof= ( 30.0, 32.0, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

$ Ring 11 and Ring 12 1.3um spacing,
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 33.3, 35.3, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 36.6, 38.6, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

$ Ring 13 and Ring 14 1.4um spacing,
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 40.0, 42.0, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 43.4, 45.4, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

$ Ring 15 and Ring 16 1.5um spacing,
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 46.9, 48.9, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 50.4, 52.4, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

$ Ring 17 and Ring 20 1.6um spacing,
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 54.0, 56.0, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 57.6, 59.6, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 61.2, 63.2, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 64.8, 66.8, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.0, 0.0 )

$ Ring 21 to Ring 24 1.7um spacin
doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
x_prof= ( 68.5, 70.5, 0.05, 0.05 )  &&
y_prof= (-0.55, 00.0, 0.00, 0.05 )

doping impurity=shal_dopant charge_type=acceptor max_conc=1.e24  &&
```



```
suprem_contact num=1 xrange=(0.000000 10) yrange=(-9999.000000 &&
9999.000000) touch_mater=1 side=lower
```

```
suprem_contact num=2 xrange=(0.0 1.0) yrange=(-9999.000000 &&
9999.000000) touch_mater=1 side=upper
```

```
contact num=1
contact num=2
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ Set minority carrier to improve convergence
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
```

```
set_minority_carrier virtual_eg_kt=25
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$
$ Impact ionization models
$ Choose coefficients from Loh et al, TED 2008
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ 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.]
```

```
$ 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.]
```

```
$ 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 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.]
```

```
$ 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.]
```

```
$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=2. var_tol=1.e-3 res_tol=1.e-4 &&  
max_iter=50 opt_iter=15 stop_iter=15 change_variable=yes
```

```
newton_par damping_step=5. &&  
var_tol=0.01 res_tol=0.01 change_variable=no  
$scan var=voltage_1 value_to=4000 &&  
$ init_step=0.5 max_step=20. min_step=1e-8 &&  
$ auto_finish=current_1 auto_until=1.e-2 auto_condition=above &&  
$ var2=time value2_to=10  
$scan var=current_1 value_to=1 &&  
$ init_step=1.1e-7 min_step=1.e-7 max_step=1.e4
```

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

```
$
```

```
$ Below is the original scan statement from the SBD simulation
```

```
$
```

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

```
scan var=voltage_1 value_to=3000 &&  
init_step=0.01 max_step=100 min_step=1e-8 &&  
auto_finish=current_2 auto_until=1e-3 auto_condition=above
```

```
scan var=current_1 value_to=2e1 &&  
init_step=1.1e-7 min_step=1.e-7 max_step=1.e4
```

```
end
```

