Supplementary Materials to

Device Design Assessment of GaN Merged P-i-N Schottky Diodes

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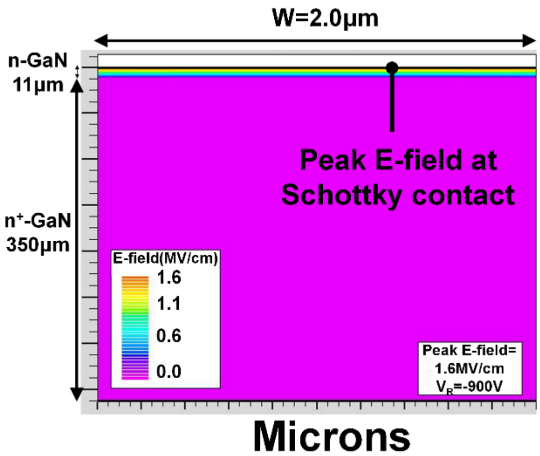
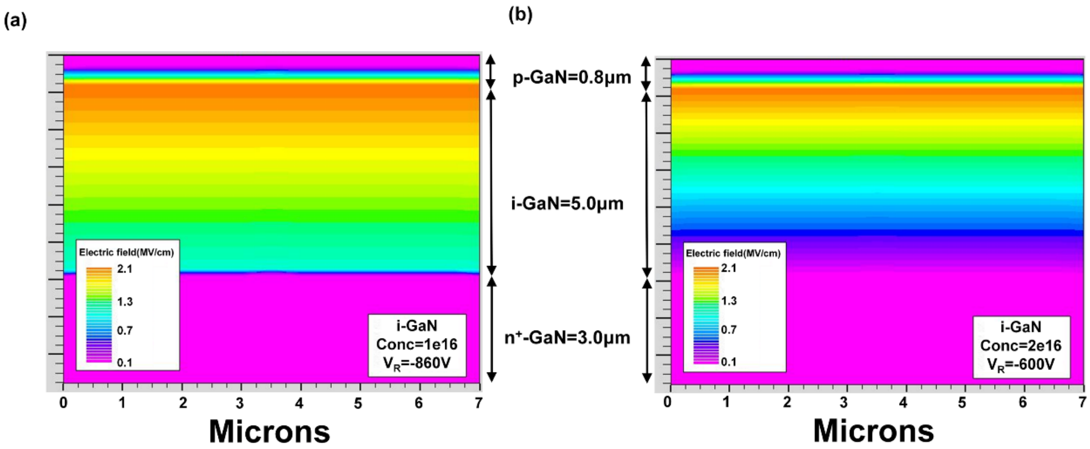
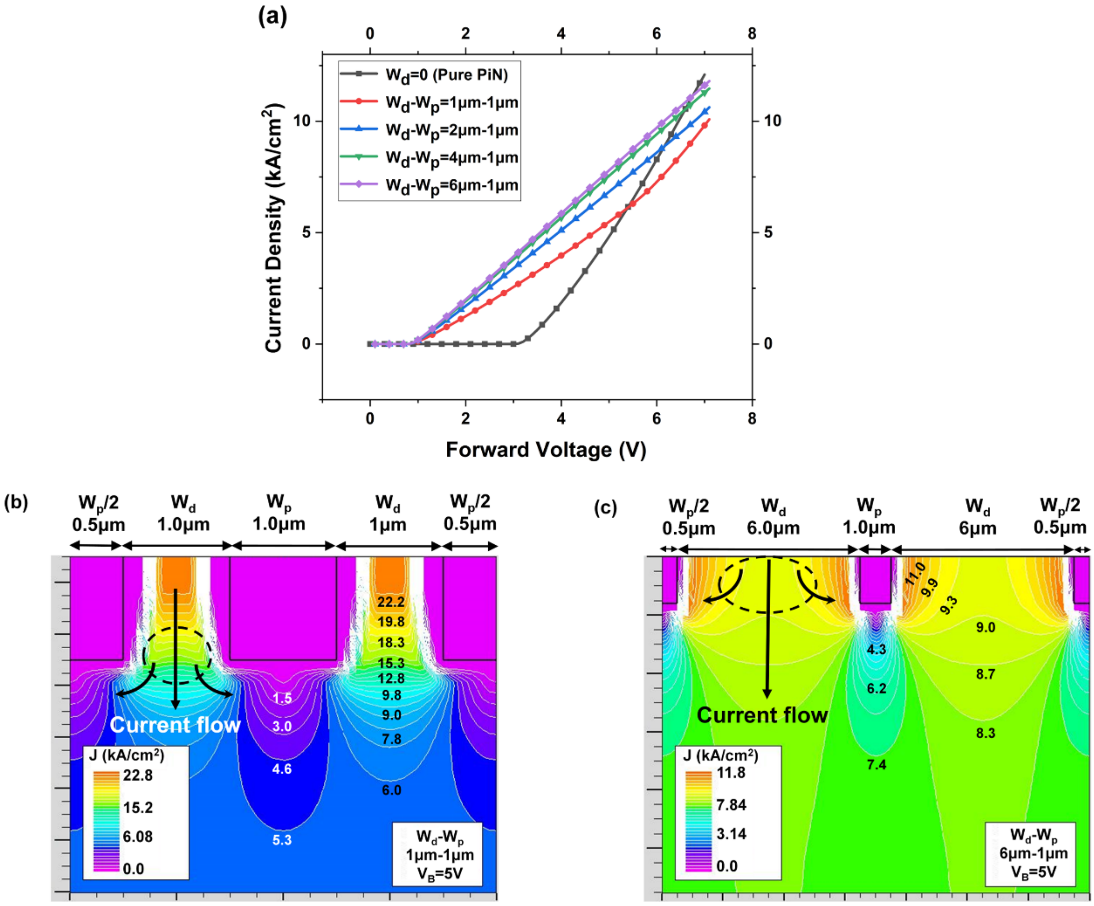
Supplementary Figures



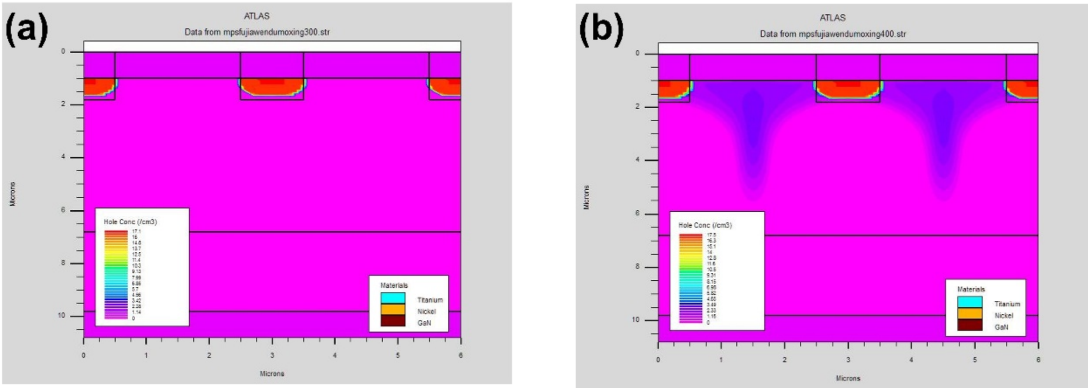
Supplementary FigureS1 | E-field distribution of SBD reported by S. Yang et al at -900V. A recently reported SBD device by S. Yang et al revealed the peak E-field for Schottky contact. According to our fitting process, SBD with same structure was simulated at -900V, showing the peak E-field at Schottky contact was about 1.6MV/cm. The above critical electrical field would serve as unambiguous criteria to determine the occurrence of breakdown in GaN MPS.



Supplementary FigureS2 | (a, b) E-field distribution of GaN P-i-N diode with i-GaN concentration of 2×10^{16} /cm^3 and 2×10^{16} /cm^3 Fig.1(**a**, **b**). In our report, when the i-GaN background concentration n=2×10^{16} cm^{-3}, the critical electrical field inside the MPS reached the breakdown criterial 2.1MV/cm for 600V reverse bias. When the i-GaN background concentration was reduced to 1×10^{16} cm^{-3}, the blocking voltage was increased to 860V given the same critical breakdown criterial 2.1MV/cm.



Supplementary FigureS3 | (a) **Forward characteristic of (2×10^{16} /cm^3) GaN MPS with various W_d while keeping W_p 1μm wide. (b, c) current density distribution of MPS with W_d-W_p=1 μm-1μm and W_d-W_p=6 μm-1μm at 5 V.** Fig.3S (**b, c**) compared the current density for MPS (i-GaN concentration of 2×10^{16} /cm^3) with W_d-W_p =1μm – 1μm and W_d-W_p =6μm – 1μm at 5 V. The conclusion of I-V characteristics is same to the MPS discussed with lower i-GaN concentration. It could be observed that the MPS with relatively high background concentration tends to exhibit higher current after turn-on, due to the higher intrinsic carrier concentration for conduction.



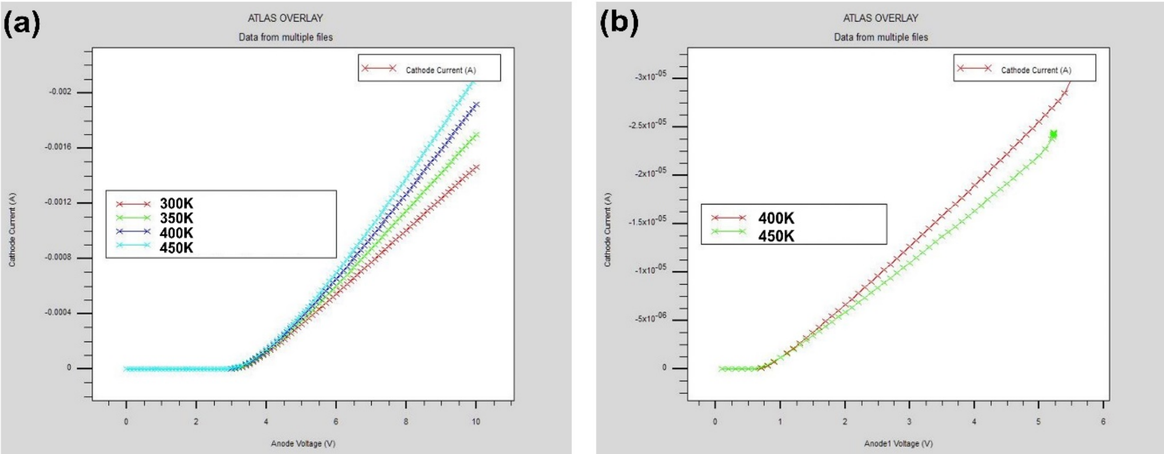
Temperature	Hole concentration near surface of P-GaN region	Hole concentration between p-GaN region
300K	1.2×10^{17} cm^{-3}	2×10^{-2} cm^{-3}
350K	2×10^{17} cm^{-3}	5×10^{0} cm^{-3}
400K	2.8×10^{17} cm^{-3}	4×10^{2} cm^{-3}
450K	3×10^{17} cm^{-3}	4.5×10^{4} cm^{-3}

Supplementary FigureS4 | (a, b) Hole concentration distribution of reverse biased GaN MPS at 300K and 400K, respectively. Table.1 Extracted hole concentration distribution at different temperature.

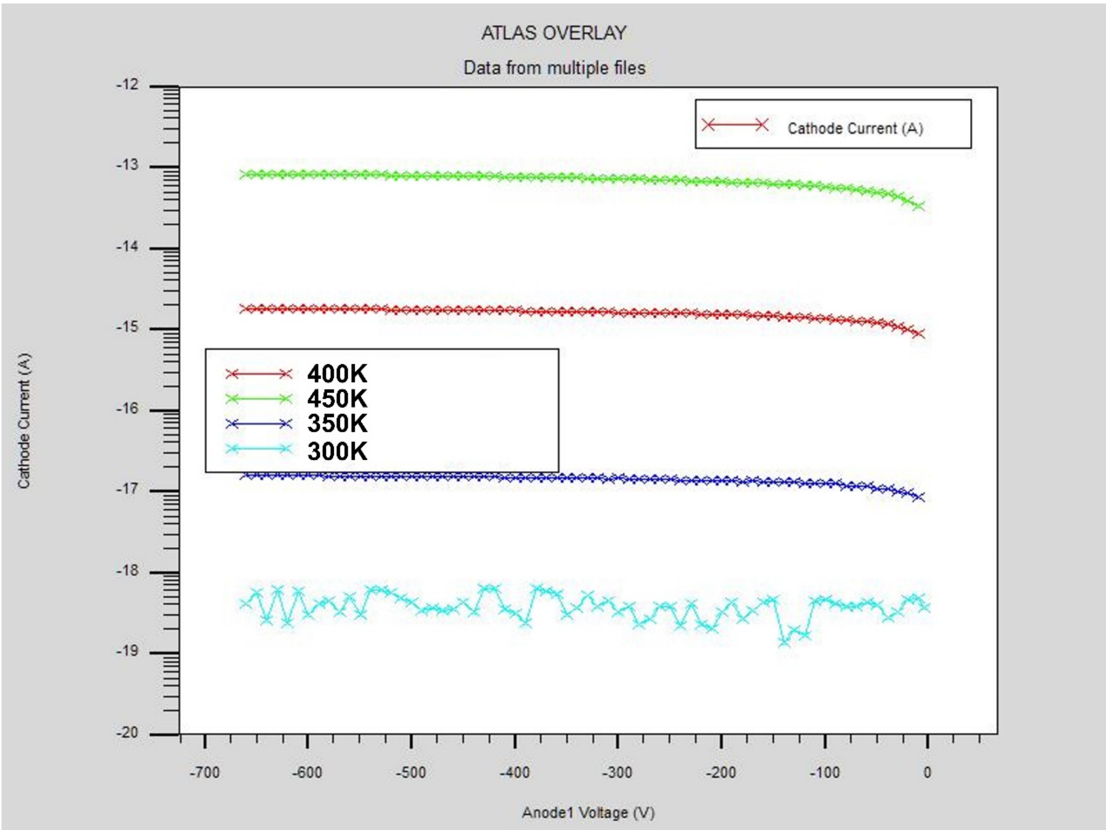
Temperature mainly affects the carrier mobility and incomplete ionization of holes in calculating process. Equation-1 indicates that carrier mobility is direct proportion to temperature. N is the dopant concentration, T is temperature, other parameters are material dependent constant.

$$\mu = MU1.ARORA \cdot \left(\frac{T}{300K}\right)^{ALPHA.ARORA} + \frac{MU2.ARORA\cdot\left(\frac{T}{300K}\right)^{BETA.ARORA}}{1+\frac{N}{NCRIT.ARORA\cdot\left(\frac{T}{300K}\right)^{GAMMA.ARORA}}} \quad (1)$$

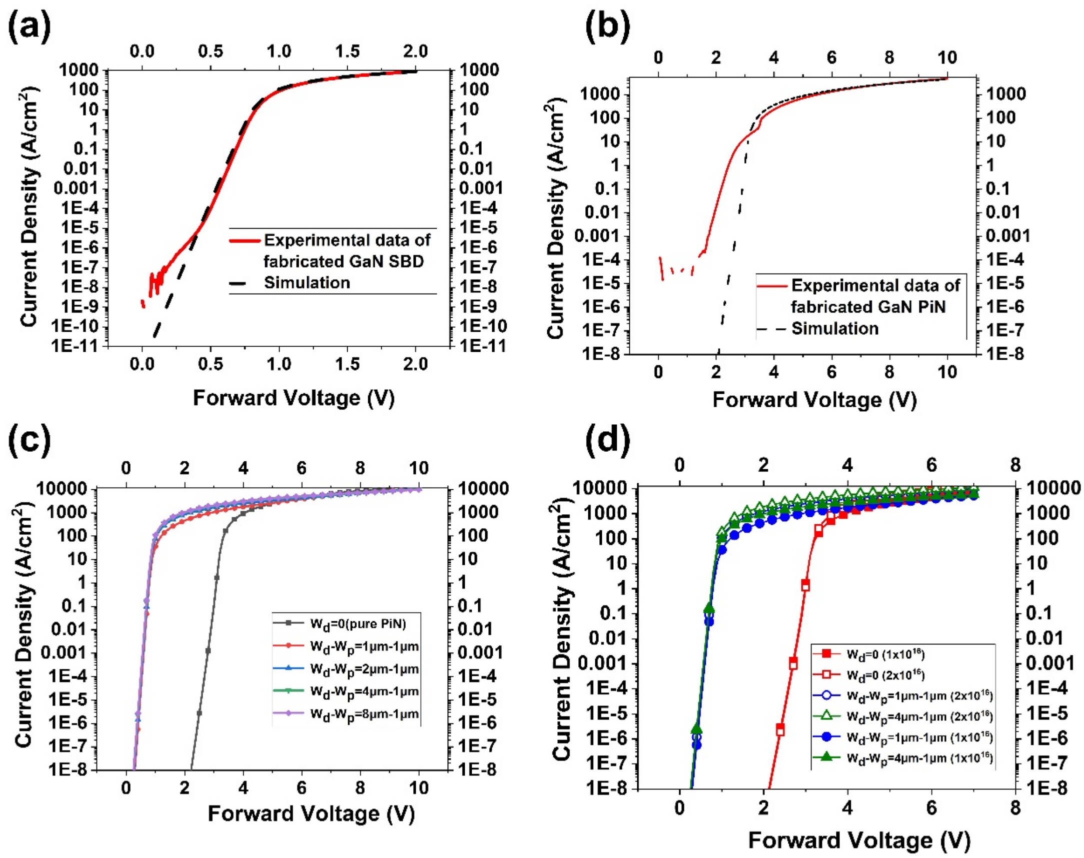
GaN MPS with 1×10^{16} cm^{-3} i-GaN concentration and W_d-W_p=2μm-1μm at -660V was simulated at different temperature. As shown in Fig.S4(a, b), holes were mainly concentrated near the surface of p-GaN region. The dopant concentration of Mg was 6×10^{17} cm^{-3}, and ionized hole concentration of 1.2×10^{17} cm^{-3} was obtained at 300K. With temperature increasing, more holes were ionized both near the surface and between p-GaN regions, as shown in Table.1. However, the area of ionized holes near the surface didn't change, space charge region which can afford electrical field around p-GaN was unaffected. On the other hand, lower ionized hole concentration between p-GaN regions compared with the one near the surface presented less influence on i-GaN layer and the Schottky contact was still protected, which indicated breakdown voltage of GaN MPS was less affected by temperature.



Supplementary FigureS5 | (a) Forward current of fabricated GaN PiN diode at four temperatures. (b) Forward current of fabricated GaN MPS diode at 400K and 450K. With increasing temperature, the PiN forward current increased due additional ionized acceptors. However, forward current of MPS reduced at low bias (SBD concept dominate) due to the scattering effect.



Supplementary FigureS6 | Reverse leakage current of GaN MPS with 1×10^{16} cm^{-3} i-GaN concentration and W_d-W_p=2μm-1μm at four temperatures. We have done some temperature-dependent leakage current simulation to demonstrate the leakage current level as a function of temperature, as follows. However, one should note that traps, sidewall leakage, impact ionization effects are barely reflected on the graph.



Supplementary FigureS7 | (a, b, c, d) Fig.1b, Fig. 2d, Fig.6ab in the manuscript were plotted in a log scale. As shown in (b), there is slight difference between two curves. The slightly lower leakage current occurred in the simulation curve was because the trap effects and sidewall leakage path were not taken into account compared with the experimental one. Despite this, the current level after turn-on matches each other quite well, which is actually the real application range of the device, and is of particular interest of our simulation. The Ron,diff at 300A/ cm^2 and 1kA/cm^2 is 4.5mΩ-cm^2/1.7mΩ-cm^2 and 4mΩ-cm^2/1.6mΩ-cm^2 ,respectively, which indicate our simulation result accords with the practical device. Log scales of Fig.6 (a, b) are plotted above. And we think plot Fig.6 (a, b) in liner scales can better show the difference of forward current level, so we keep the linear scale plots in the manuscript.

Supplementary code | Simulation code (consider thermal model) of GaN MPS at reverse bias with W_d-W_p =2μm – 1μm and i-GaN concentration of 1×10^{16}/cm^3.

```
go devedit
#
region reg=1 name=anode1 mat=Titanium elec.id=1    color=0xff7f pattern=0xf \
        polygon="0,0 0.5,0 0.5,1 0,1"
#
region reg=2 name=anode2 mat=Nickel elec.id=2 work.func=5.2 color=0xffff96 pattern=0xe \
        polygon="0.5,0 2.5,0 2.5,1 0.5,1"
#
region reg=3 name=anode3 mat=Titanium elec.id=3    color=0xff7f pattern=0xf \
        polygon="2.5,0 3.5,0 3.5,1 2.5,1"
#
```

```
region reg=4 name=anode4 mat=Nickel elec.id=4 work.func=5.2 color=0xffff96 pattern=0xe \
        polygon="3.5,0 5.5,0 5.5,1 3.5,1"
region reg=5 name=anode5 mat=Titanium elec.id=5    color=0xff7f pattern=0xf \
        polygon="5.5,0 6,0 6,1 5.5,1"
#
constr.mesh region=5 default
region reg=6 name=region1 mat=GaN color=0xcca3a3 pattern=0xd \
        polygon="0,1 6,1 6,9.8 0,9.8 "
impurity id=1 region.id=6 imp=donors \
x1=0 x2=6 y1=1 y2=9.8 \
peak.value=1e16 ref.value=1000000000000 comb.func=Multiply \
rolloff.y=both conc.func.y=constant \
rolloff.x=both conc.func.x=constant
#
region reg=7 name=region2 mat=GaN color=0xcca3a3 pattern=0xd \
        polygon="0,6.8 6,6.8 6,9.8 0,9.8"
impurity id=1 region.id=7 imp=donors \
x1=0 x2=6 y1=6.8 y2=9.8 \
peak.value=1e19 ref.value=1000000000000 comb.func=Multiply \
rolloff.y=both conc.func.y=constant \
rolloff.x=both conc.func.x=constant
#
region reg=8 name=cathode mat=Titanium elec.id=6 work.func=0 color=0xff7f pattern=0xf \
        polygon="0,9.8 6,9.8 6,10.8 0,10.8"
#
region reg=9 name=region3 mat=GaN color=0xcca3a3 pattern=0xd \
        polygon="0,1 0.5,1 0.5,1.8 0,1.8"
impurity id=2    region.id=9 imp=acceptors \
x1=0 x2=0.5 y1=1 y2=1.8 \
peak.value=6e17 ref.value=1000000000000 comb.func=Multiply \
rolloff.y=high conc.func.y=Constant \
rolloff.x=both conc.func.x=Constant
#
region reg=10 name=region4 mat=GaN color=0xcca3a3 pattern=0xd \
        polygon="2.5,1 3.5,1 3.5,1.8 2.5,1.8"
impurity id=2 region.id=10 imp=acceptors \
x1=2.5 x2=3.5 y1=1 y2=1.8 \
peak.value=6e17 ref.value=1000000000000 comb.func=Multiply \
rolloff.y=both conc.func.y=Constant \
rolloff.x=both conc.func.x=Constant
#
region reg=11 name=region5 mat=GaN color=0xcca3a3 pattern=0xd \
        polygon="5.5,1 6,1 6,1.8 5.5,1.8"
impurity id=2 region.id=11 imp=acceptors \
```

```
x1=5.5 x2=6 y1=1 y2=1.8 \
peak.value=6e17 ref.value=1000000000000 comb.func=Multiply \
rolloff.y=both conc.func.y=Constant \
rolloff.x=both conc.func.x=Constant
#
# Set Meshing Parameters
#
base.mesh height=0.1 width=0.1
#
bound.cond !apply max.slope=30 max.ratio=300 rnd.unit=0.001 line.straightening=1 align.points when=automatic
#
mesh
structure outf=mps.str
tonyplot mps.str

go atlas
init infile=mps.str
material material=GaN affinity=4.1 NC300=2.3E18 NV300=3.5E19 EG300=3.46 EGALPHA=4.73e-4 EGBETA=636 GCB=2 GVB=2 EDB=0.017 EAB=0.16 taun0=0.7e-9 taup0=2e-9 copt=1.1e-8 nsrhn=4e18 nsrhp=4e18 augn=3e-31 augp=3e-31 vsat=7e6

model conmob arora fldmob klaaug klasrh fermi bgn print mob.incompl conwell  temp=300 \

impact selber an1=1.5e5 an2=1.5e5 bn1=1.41e7 bn2=1.41e7 ap1=6.4e5 ap2=6.4e5 bp1=1.46e7 bp2=1.46e7 betan=1.0 betap=1.0 egran=1.6e6
mobility MU1N.ARORA=70 MU1P.ARORA=8 MU2N.ARORA=1200 MU2P.ARORA=80 ALPHAN.ARORA=-1.5 ALPHAP.ARORA=2 BETAN.ARORA=-1.5 BETAP.ARORA=-2.34 NCRITN.ARORA=1e13 NCRITP.ARORA=1e13



contact name=anode2 common=anode1 workf=5.2 surf.rec barrier
contact name=anode4 common=anode1 workf=5.2 surf.rec barrier
contact name=anode1
contact name=anode3 common=anode1
contact name=anode5 common=anode1

solve int
method newton trap maxtrap=30
log outfile=mps.log
solve vanode1=0 vstep=-10 vfinal=-660 name=anode1
save outf=mps.str
tonyplot mps.str
```

tonyplot mps.log
quit