EEE6206 Power Semiconductor Devices:

Design examples

6.5kV p-i-n Diode Design example

- A customer requires a 6500V 30A rated diode die for a HVDC application.
- Design and compare the room temperature on-state voltage drop for silicon p-i-n Non Punch Through and Punch Through designs to a 4H-Silicon Carbide NPT Schottky diode
- Assume a 1V built in potential of the Schottky junction and that the designs must consider sufficient pass band voltages of 20%
- Consider high injection lifetime=5μs, and an operating current density=30A/cm^2

Part 1: 6.5kV NPT PiN diode design

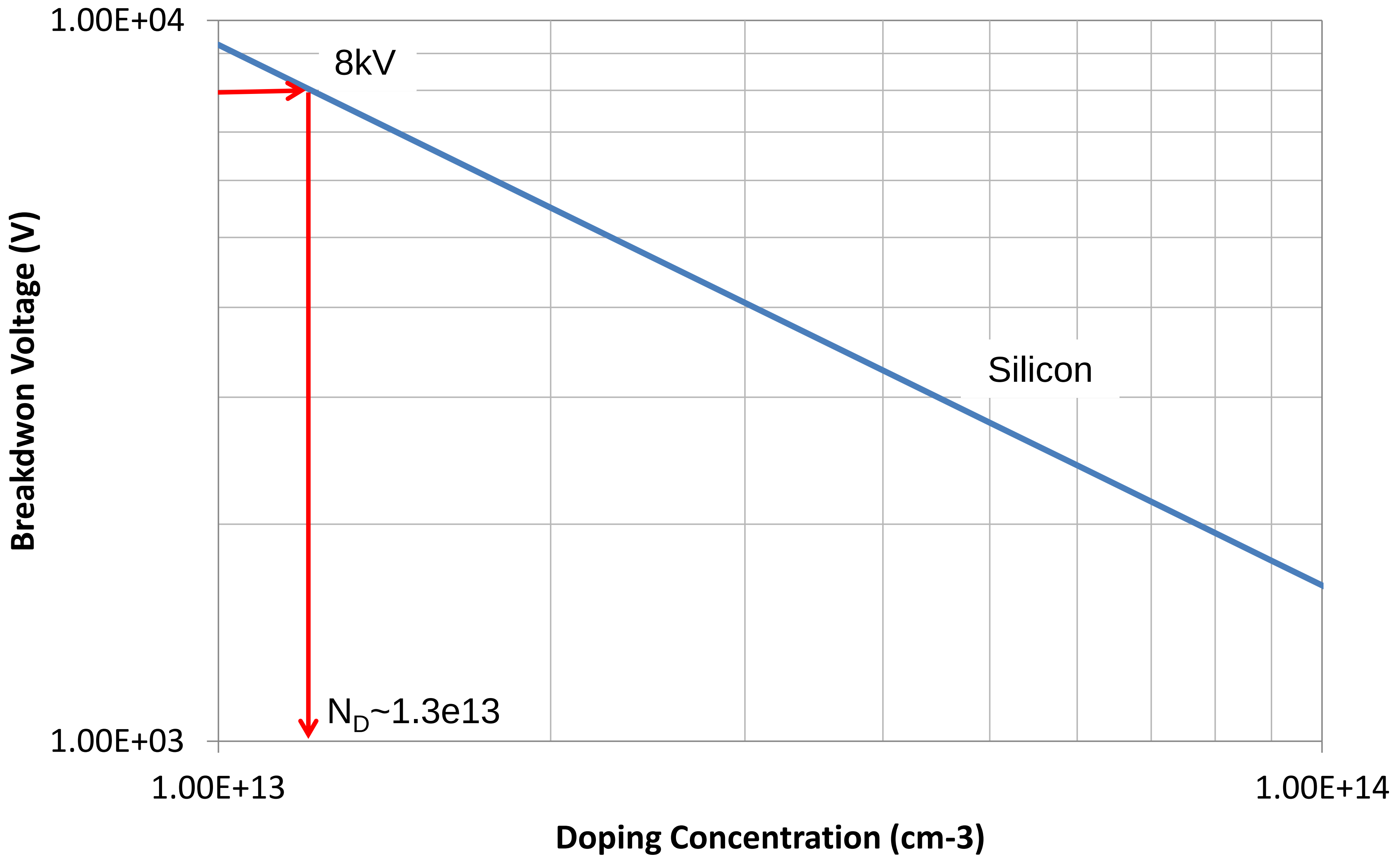
Obtaining the drift region parameters

- Calculated the breakdown voltage required for the voltage rating:

$$Pass\ Band\ Voltage = V_{rated} \times \text{passband}$$
$$= 6500\ \times 0.2 = 1300V$$
$$Required\ Breakdown\ Voltage = 7800V$$

- Use doping vs breakdown voltage curve to select approximate n- doping concentration for the NPT design

Maximum Breakdown Voltage with respect to drift region doping concentration: Approximate doping concentration



Check viability of the drift region parameters

- From this doping concentration calculate its viability for the application
  - Critical electric field strength

$$E_c(Silicon) = 4010{N_D}^{1/8}$$

$$= 4010 \times (1.3 \times 10^{13})^{1/8} = 174.7kV/cm$$

  - Breakdown Voltage

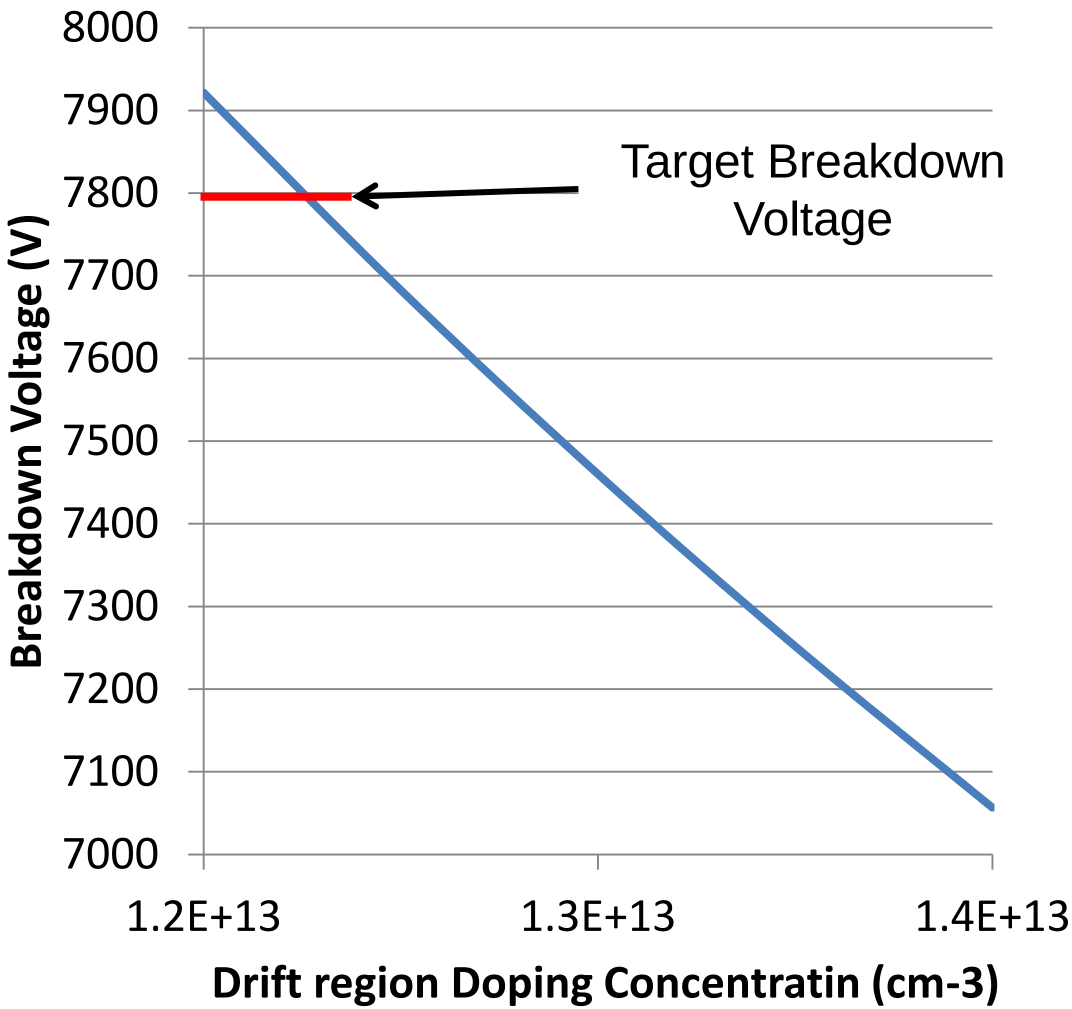
$$BV = \frac{{E_c}^2 \varepsilon_s}{2qN_D}$$

$$BV = \frac{(174.7 \times 10^3)^2 \times 11.7 \times 8.85 \times 10^{-14}}{2 \times 1.63 \times 10^{-19} \times 1.3 \times 10^{13}} = 7456.8\,V$$

- Target=7800V Calculated 7456.8
- 7% difference, calculated point too far away, reduce dopant concentration (N_D) and re-iterate

Doping concentration iteration: Silicon

Nd	Ec	BV
1.20E+13	1.73E+05	7.92E+03
1.25E+13	1.74E+05	7.68E+03
1.30E+13	1.75E+05	7.46E+03
1.35E+13	1.76E+05	7.25E+03
1.40E+13	1.76E+05	7.06E+03



- Required n- drift region doping=1.2E13
- BV~7.92kV Target 7800V minimum

Calculate n- region (i) thickness

- Maximum depletion layer width at breakdown

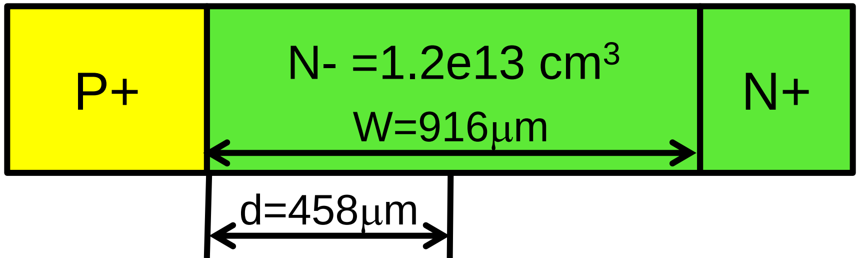
$$W_{max} = \sqrt{\frac{2\varepsilon_s BV}{qN_D}}$$

$$W_{max} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times 7922}{1.63 \times 10^{-19} \times 1.2 \times 10^{13}}}$$

$$= 0.0916cm$$

$$= 915.8\mu m$$

NPT Silicon cross-section



On state characteristic

- Current flow through the diode is due to bipolar conduction
  - Both carrier types in the presence of an electric field
  - Need to use ambipolar diffusion lengths and diffusion coefficients…
- Calculate $\frac{d}{L_a}$ ratio:

$$d(half\ drift\ length) = \frac{W}{2} = \frac{915.8}{2} = 457.9\mu m$$

$$L_a = \sqrt{D_a \tau_H}$$

$$D_a = \frac{2D_n}{1+\frac{\mu_n}{\mu_p}} \qquad D_n = \left(\frac{kT}{q}\right)\mu_n = \frac{1.38\times10^{-23}\times300}{1.63\times10^{-19}} \times 1450$$

$$= 36.8\ cm^2/s$$

Voltage dropped across the i region

$$D_a = \frac{2D_n}{1+\frac{\mu n}{\mu p}} \qquad D_a = \frac{2\times 36.8}{1+\frac{1450}{470}} = 18cm^2/s$$

$$L_a = \sqrt{D_a \tau_H}$$

$$L_a = \sqrt{18 \times 5 \times 10^{-6}} = 9.49 \times 10^{-3}\ cm$$

$$\frac{d}{L_a}\text{ ratio} = \frac{457.9\times 10^{-4}}{9.49\times 10^{-3}} = 4.79$$

- The device is classes as a long base (ratio >2). Therefore the voltage drop across the n- region is given by

$$V_i = \frac{3\pi kT}{8q} e^{\left(\frac{d}{L_a}\right)} = \frac{3\pi \times 1.38 \times 10^{-23} \times 300}{8 \times 1.62 \times 10^{-19}} exp^{(4.79)} = 3.58V$$

Forward voltage drop: Function F(d/La)

- To obtain the forward voltage drop firstly we need to calculate the function $\mathrm{F}\left(\frac{d}{L_a}\right)$

$$F\left(\frac{d}{L_a}\right) = \frac{(d/L_a)\tanh(d/L_a)}{\sqrt{1 - 0.25 tanh^4(d/L_a)}} exp^{-qV_m/2kT}$$

$$= \frac{(4.79)\tanh(4.79)}{\sqrt{1 - 0.25 \times tanh^4(4.79)}} exp\left[\frac{-1.63 \times 10^{-19} \times 3.58}{2 \times 1.38 \times 10^{-23} \times 300}\right]$$

$$= 1.28 \times 10^{-30}$$

Forward Voltage Drop

$$J_T = \frac{2qD_a n_i}{d} F\left(\frac{d}{L_a}\right) exp^{\left(\frac{qV_{on}}{2kT}\right)}$$

- Therefore

$$V_{on} = ln\left(\frac{J_T d}{2qD_a n_i F\left(\frac{d}{L_a}\right)}\right) \times \frac{2kT}{q}$$

$$V_{on} = ln\left(\frac{30 \times 457.9 \times 10^{-4}}{2 \times 1.63 \times 10^{-19} \times 18 \times 1 \times 10^{-10} \times 1.28 \times 10^{-30}}\right) \times \frac{2 \times 1.38 \times 10^{-23}}{1.63 \times 10^{-19}} = 4.36V$$

Forward Voltage Drop of a 6.5kV rated NPT PiN diode = **4.36V @30A/cm²**

Part 2: 4H-SiC NPT Schottky diode

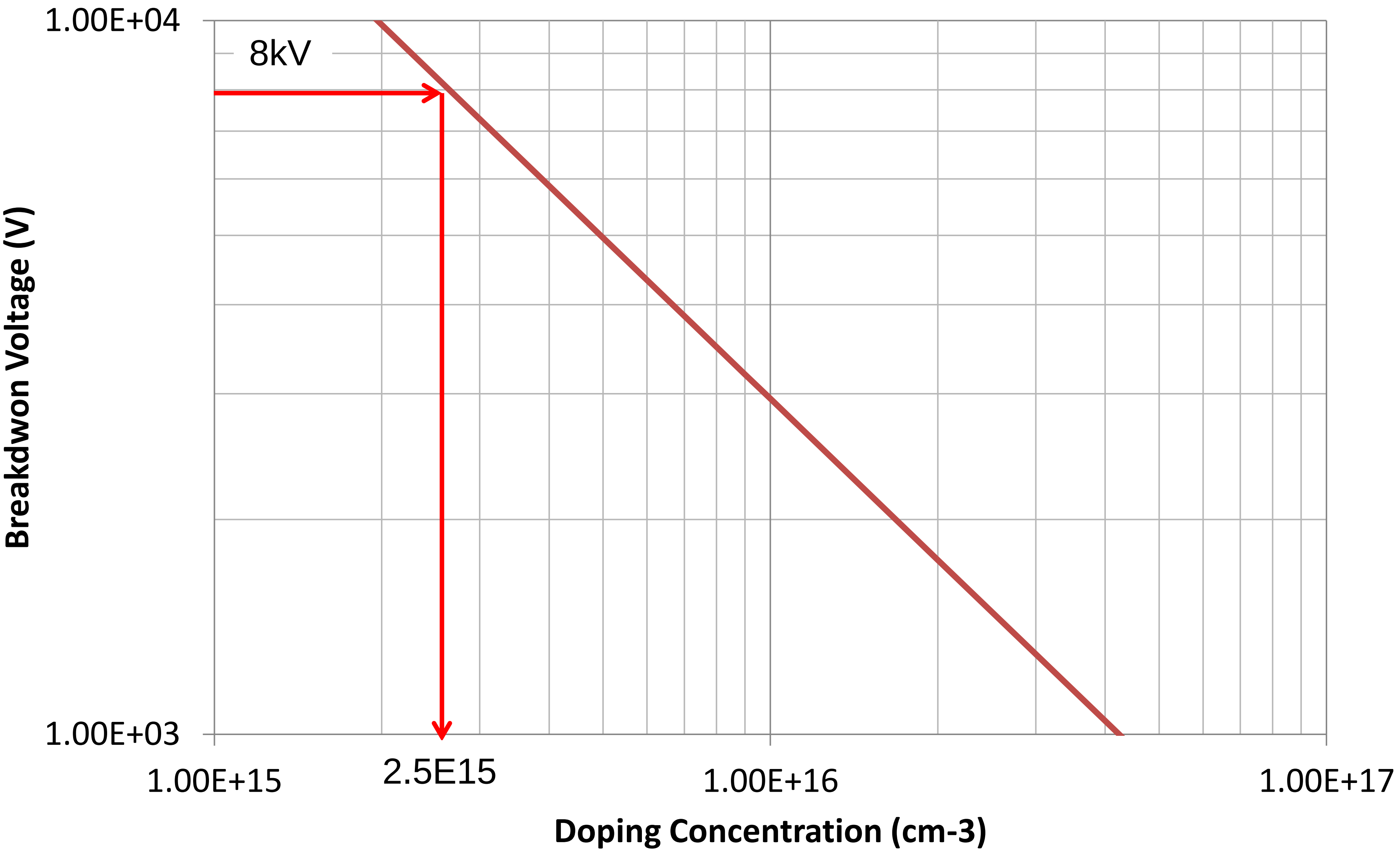
4H-SiC Schottky Diode: Drift region design

- Rated voltage same a Si PiN diode, Target breakdown voltage is the same:

$$Required\ Breakdown\ Voltage = 7800V$$

- Use doping vs breakdown voltage of 4H-SiC curve to select approximate n- doping concentration for a NPT Schottky design

Maximum Breakdown Voltage with respect to drift region doping concentration: Approximate doping concentration



Check viability of the drift region parameters

- From this doping concentration calculate its viability for the application
  - Critical electric field strength

$$E_c(4H - SiC) = 3.3 \times 10^4 {N_D}^{1/8}$$

$$= 3.3 \times 10^4 \times (2.5 \times 10^{15})^{1/8} = 2.775 MV/cm$$

  - Breakdown Voltage

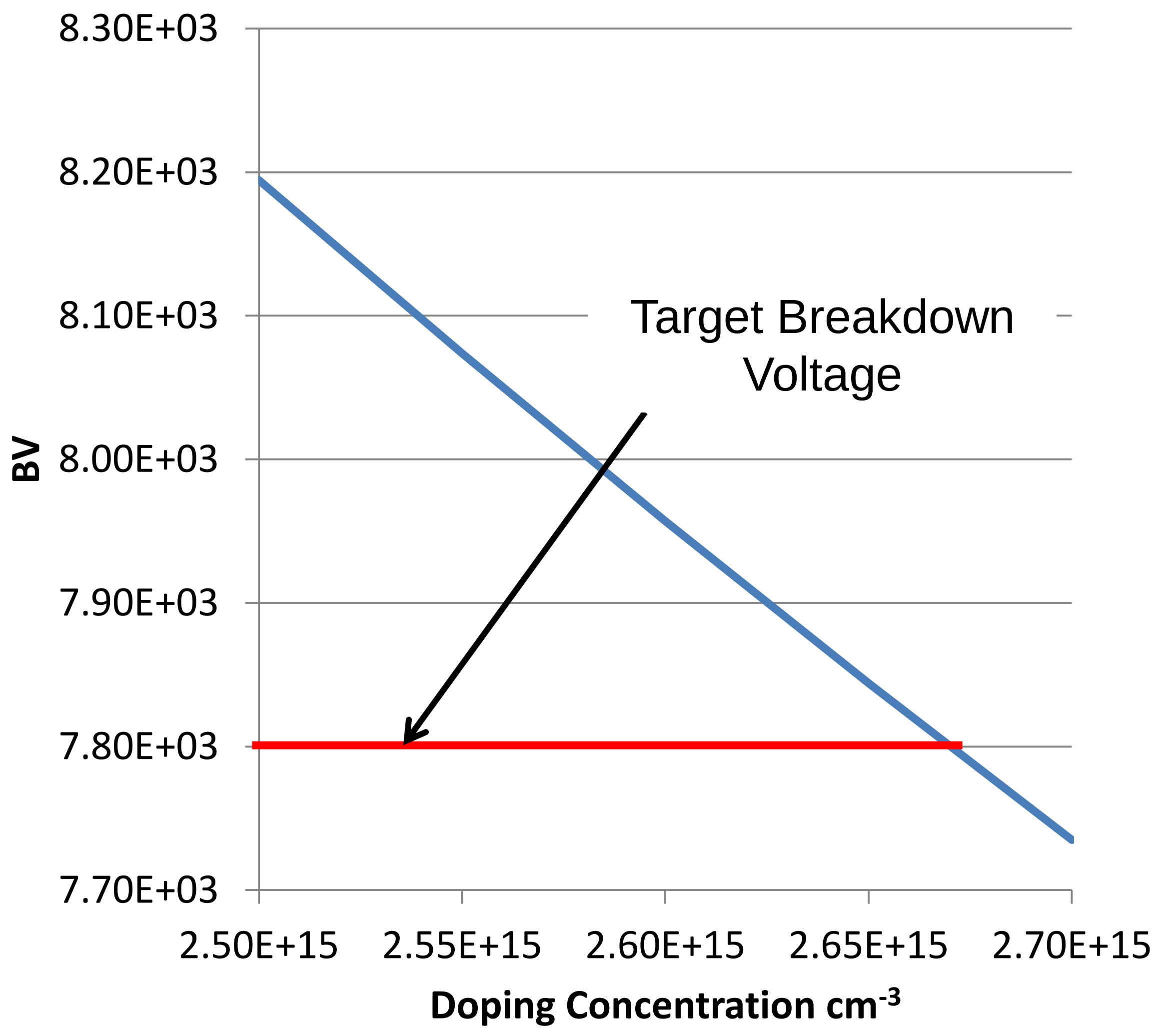
$$BV = \frac{{E_c}^2 \varepsilon_s}{2qN_D}$$

$$BV = \frac{(2.775 \times 10^6)^2 \times 9.8 \times 8.85 \times 10^{-14}}{2 \times 1.63 \times 10^{-19} \times 2.5 \times 10^{15}} = 8194V$$

- Target=7800V Calculated 8194
- 5% difference, calculated point too far away, increase dopant concentration (N_D) and re-iterate

Doping concentration iteration: Silicon Carbide (4H-SiC)

Nd	Ec	BV
2.50E+15	2.77E+06	8.19E+03
2.55E+15	2.78E+06	8.07E+03
2.60E+15	2.79E+06	7.96E+03
2.65E+15	2.80E+06	7.84E+03
2.70E+15	2.80E+06	7.73E+03



- Required n- drift region doping=2.65E15
- BV~7840V Target 7800V minimum ~0.6% difference

Calculate n- region (i) thickness for the SiC Schottky

- Maximum depletion layer width at breakdown

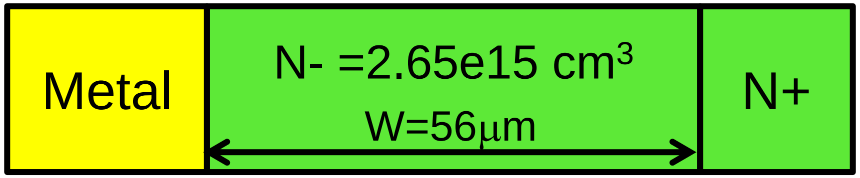
$$W_{max} = \sqrt{\frac{2\varepsilon_s BV}{qN_D}}$$

$$W_{max} = \sqrt{\frac{2 \times 9.8 \times 8.85 \times 10^{-14} \times 7840}{1.63 \times 10^{-19} \times 2.65 \times 10^{15}}}$$

$$= 0.00559cm$$

$$= 55.96\mu m$$

NPT 4H SiC cross-section

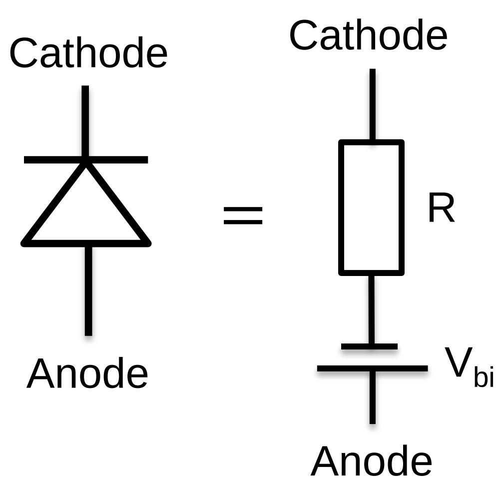


On-state Characteristic

- On state current flow through the Schottky is by majority carriers therefore we calculate its on-state resistance

$$\rho = \frac{1}{q\mu_n N_D} = \frac{1}{1.63 \times 10^{-19} \times 1450 \times 2.65 \times 10^{16}} = 1.6\Omega - cm$$

$$R = \rho \frac{L}{area} = 1.6 \times \frac{55.96 \times 10^{-4}}{1} = 8.94m\Omega$$



- Forward Voltage drop at 30A

$$V_f = (IR\ ) + V_{bi}$$
$$V_f = (30 \times 8.73 \times 10^{-3}\ \ ) + 1$$

$$\underline{\boldsymbol{V_f = 1.27V@30A/cm^2}}$$

Part 5: 6.5kV PT PiN diode design

Part 3: Si Punch Through design

- Rated voltage same a Si PiN diode, Target breakdown voltage is the same:

$$Required\ Breakdown\ Voltage = 7800V$$

- For the design we need to decide how much to reduce the drift region by
  - Aim for a 30% reduction in drift region length in comparison to the Silicon NPT design

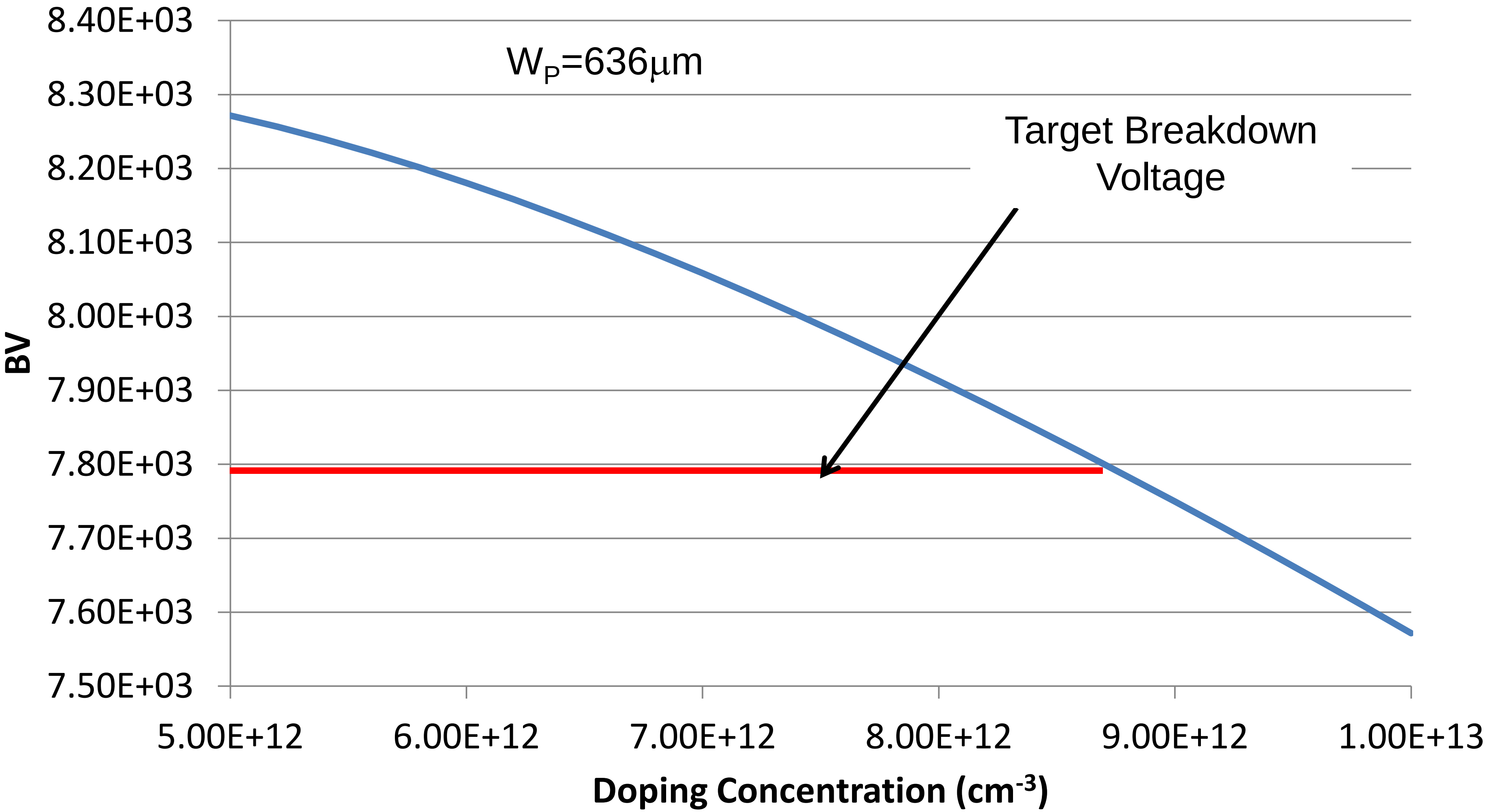
$$W_p = 0.6 \times W_{NPT} = 0.6 \times 916 = 636\mu m$$

- Using the relationship:

$$BV_{PT} = E_c W_p - \frac{q N_D {W_p}^2}{2\varepsilon_s}$$

- To obtain the drift region concentration for the PT structure…

Doping concentration iteration: Silicon PT design



- Required n- drift region doping=8.6E12
- BV~7816V Target 7800V minimum ~0.2% difference
- Design is PT: Therefore depletion layer thickness limited by the PT width

$$Max\ Depletion\ Width = WPT = 636\mu m$$

On-state forward drop

- Calculate $\frac{d}{L_a}$ ratio:

$$d = \frac{W}{2} = \frac{636\mu m}{2} = 318\mu m$$

- Ambiploar diffusion constant same as NPT design as carrier mobility's are constant

$$D_a = 18\ cm^2/s$$

$$L_a = 9.49 \times 10^{-3}\ cm$$

$$\frac{d}{L_a} \text{ ratio} = \frac{318 \times 10^{-4}}{9.49 \times 10^{-3}} = 3.35$$

- The device is classes as a long base(ratio >2). Therefore the voltage drop of the i region is given by:…

Forward voltage drop: Function F(d/La)

$$V_i = \frac{3\pi kT}{8q} e^{\left(\frac{d}{L_a}\right)} = \frac{3\pi \times 1.38 \times 10^{-23} \times 300}{8 \times 1.62 \times 10^{-19}} exp^{(3.35)} = 0.853V$$

- To calculate forward voltage drop we need to calculate the function $\mathrm{F}\left(\frac{d}{L_a}\right)$

$$F\left(\frac{d}{L_a}\right) = \frac{(d/L_a)\tanh(d/L_a)}{\sqrt{1 - 0.25tanh^4(d/L_a)}} exp^{-qV_m/2kT}$$

$$= \frac{(3.35)\tanh(3.35)}{\sqrt{1 - 0.25 \times tanh^4(3.35)}} exp\left[\frac{-1.63 \times 10^{-19} \times 0.853}{2 \times 1.38 \times 10^{-23} \times 300}\right]$$

$$= 1.97 \times 10^{-7}$$

Forward Voltage Drop

$$J_T = \frac{2qD_a n_i}{d} F\left(\frac{d}{L_a}\right) exp^{\left(\frac{qV_{on}}{2kT}\right)}$$

- Therefore

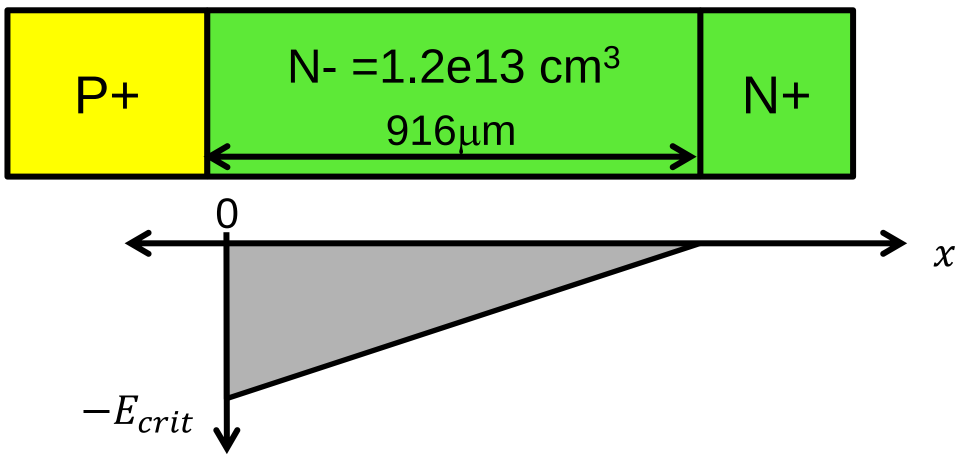
$$V_{on} = ln\left(\frac{J_T d}{2qD_a n_i F\left(\frac{d}{L_a}\right)}\right) \times \frac{2kT}{q}$$

$$V_{on} = ln\left(\frac{30 \times 318 \times 10^{-4}}{2 \times 1.63 \times 10^{-19} \times 18 \times 1 \times 10^{-10} \times 1.97 \times 10^{-7}}\right) \times \frac{2 \times 1.38 \times 10^{-23}}{1.63 \times 10^{-19}} = 2.1V$$

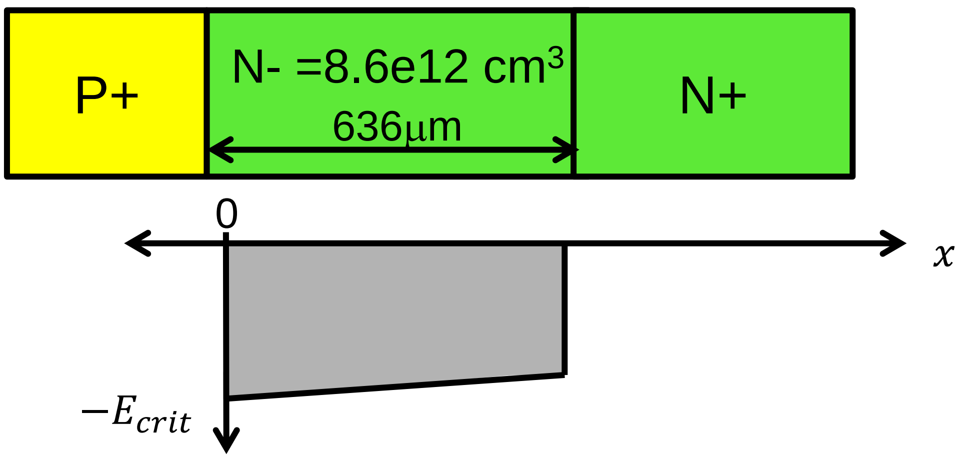
Forward Voltage Drop of a 6.5kV rated PT PiN diode = **2.1V @30A/cm²**

6.5kV rated diode designs

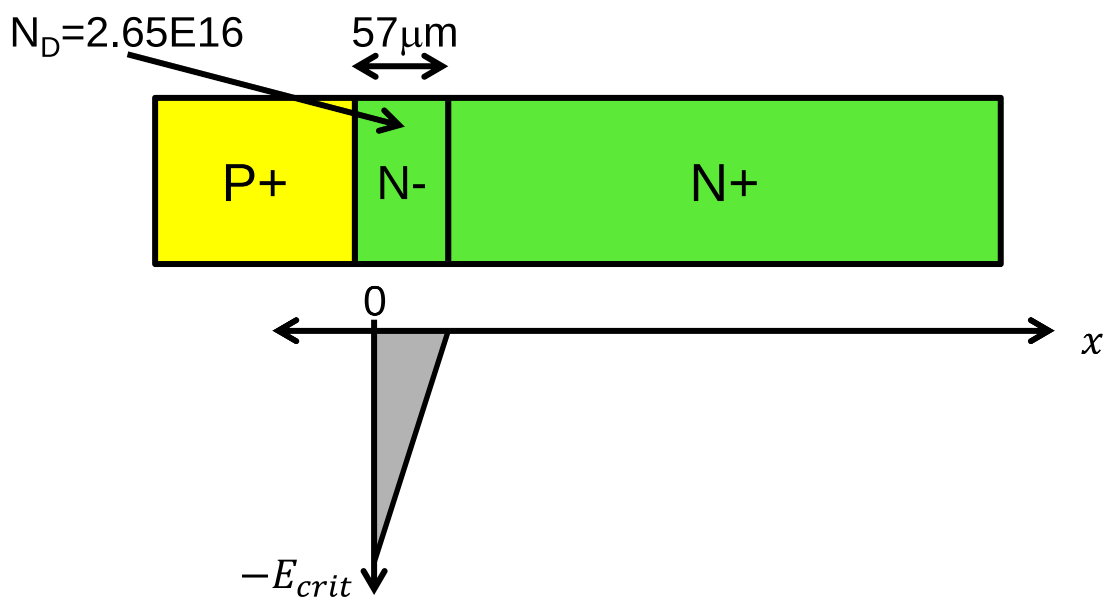
NPT Silicon



PT Silicon



NPT Silicon Carbide



6500V Characteristic comparison

Design	N_D	W	BV	V_f at 30A
Silicon PiN (NPT)	1.2e13 cm^3	916μm	7920 V	4.36 V
Silicon Carbide Schottky	2.65e15 cm^3	57μm	7840 V	1.27 V
Silicon (PT)	8.6e12 cm^3	636μm	7816 V	2.1 V

1200V p-i-n Diode Design example

- A customer requires a 1200V 100A rated diode die for an automotive application.
- Design and compare the room temperature on-state voltage drop for silicon p-i-n Non Punch Through and Punch Through designs to a 4H-Silicon Carbide NPT Schottky diode
- Assume a 0.9V built in potential of the Schottky junction and that the designs must consider sufficient pass band voltages of 20%
- Consider high injection lifetime=0.25μs, and an operating current density=100A/cm^2

Solutions

- Voltage rating=1200V; passband=240
  - Target Breakdown voltage = 1440V
- Drift region parameters:
  - Si NPT: 1.18e14, 125μm
  - 4HSiC: 2.54e16, 7.8μm
  - Si NPT (30% reduction) 7.8e13, 87.3μm
- On state forward drop:
  - Si NPT:
    - d/La = 2.94 – Long base diode eq 2 to calculate Vm
    - F(d/La) = 4.94e-5
    - Von @ 100A/cm2 = 1.33V

- Si PT:
  - d/La = 1.99 - Short base diode eq 1 to calculate Vm
  - F(d/La) = 2.25e-2
  - Von @ 100A/cm2 = 0.996V
- 4H-SiC NPT:
  - Rho = 0.167 Ω-cm
  - Resistance = 0.129mΩ
  - Von = 0.913V

1200V Characteristic comparison

Design	N_D	W	BV	V_f at 100A
Silicon PiN (NPT)	1.18e14 cm^3	125μm	1431 V	1.33V
Silicon Carbide Schottky	2.54e16 cm^3	7.8μm	1439 V	0.913V
Silicon (PT)	7.8e13 cm^3	87μm	1441 V	0.996V