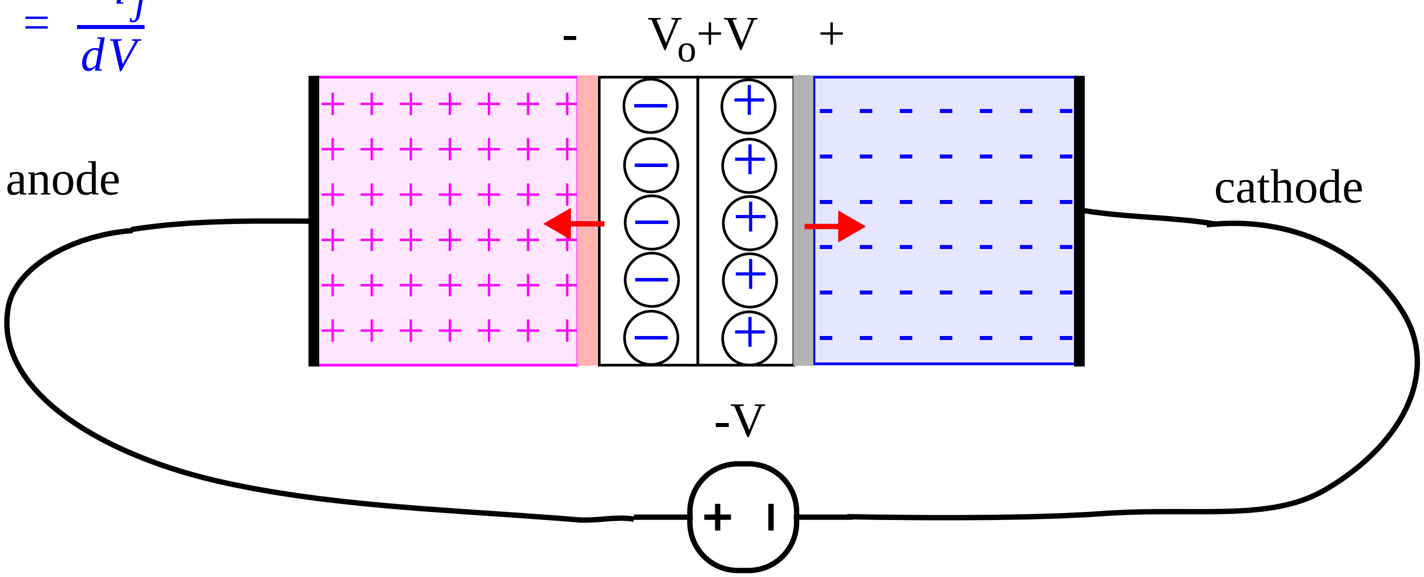
Reverse Biased Capacitance

- The charge at the p-n junction, q_j, changes with applied voltage
- The depletion region is "sort of" like a parallel plate capacitor

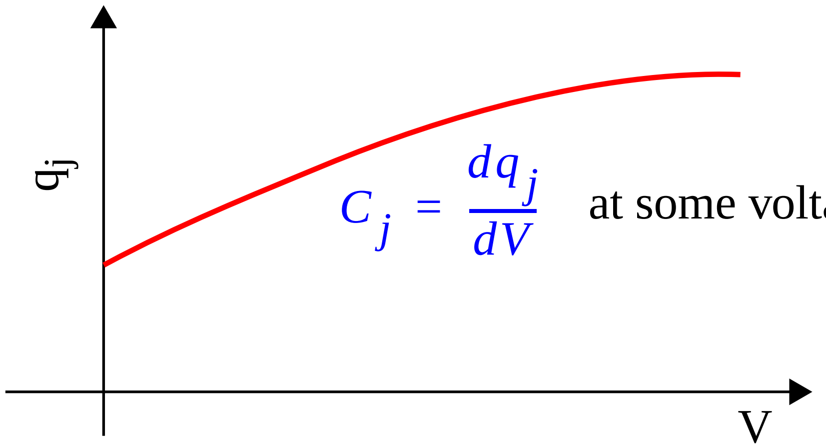
$$C_j = \frac{dq_j}{dV}$$



- Because the depletion region changes with applied voltage, (roughly speaking) the distance between +q and -q changes, hence capacitance changes
- Does C_j increase or decrease with negative applied voltage?

Reverse Biased Capacitance

- How can we tell from this voltage vs. charge plot that the capacitance is a nonlinear function of the applied voltage?



$$C_j = \frac{dq_j}{dV}$$ at some voltage bias point

- What does this capacitance represent?

Depletion Capacitance

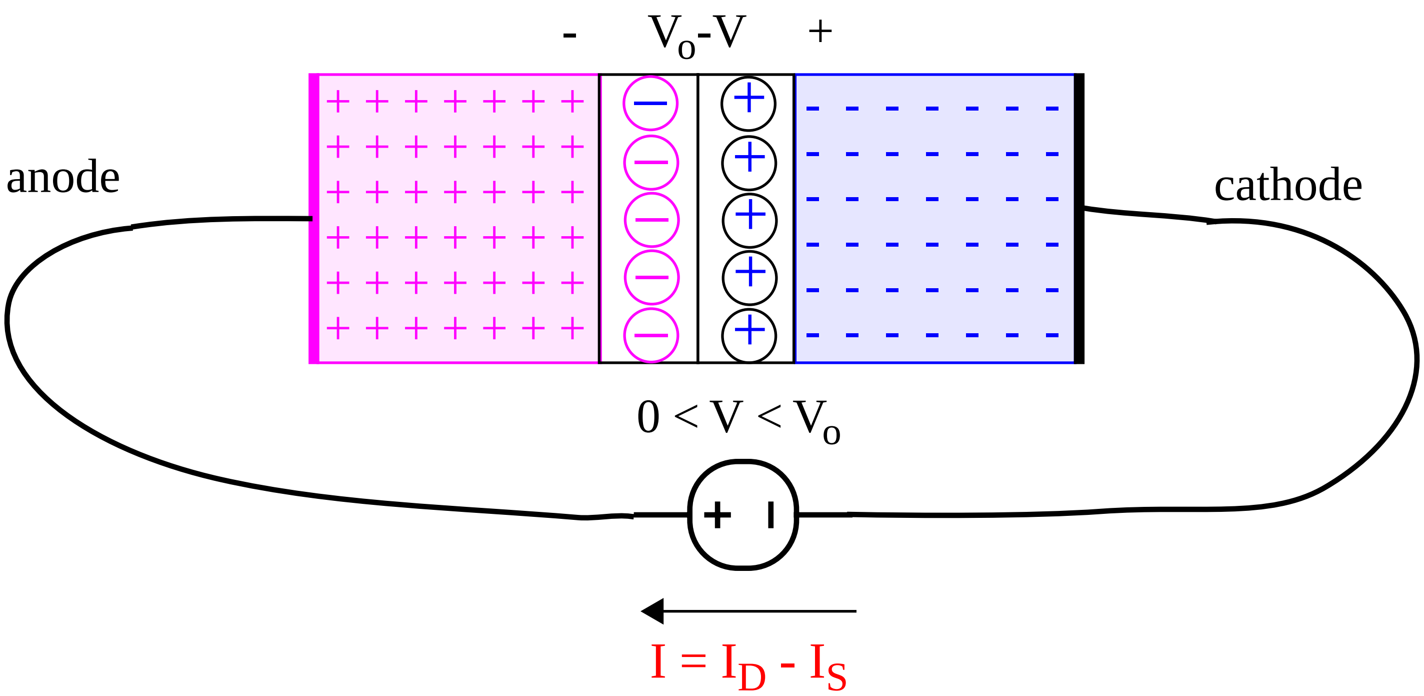
Often called Junction Capacitance

$$C_j = \frac{K}{(V_o - V_D)^m}$$

- V_o is the built-in voltage
- Applied only for negative external voltage, V_D.
- K is a constant that is a function of the Si doping, etc.
- m is a constant that depends on how the junction was formed (how the impurities were added) --- varies between 1/3 and 1/2 for Si diodes

Positive Applied Voltage

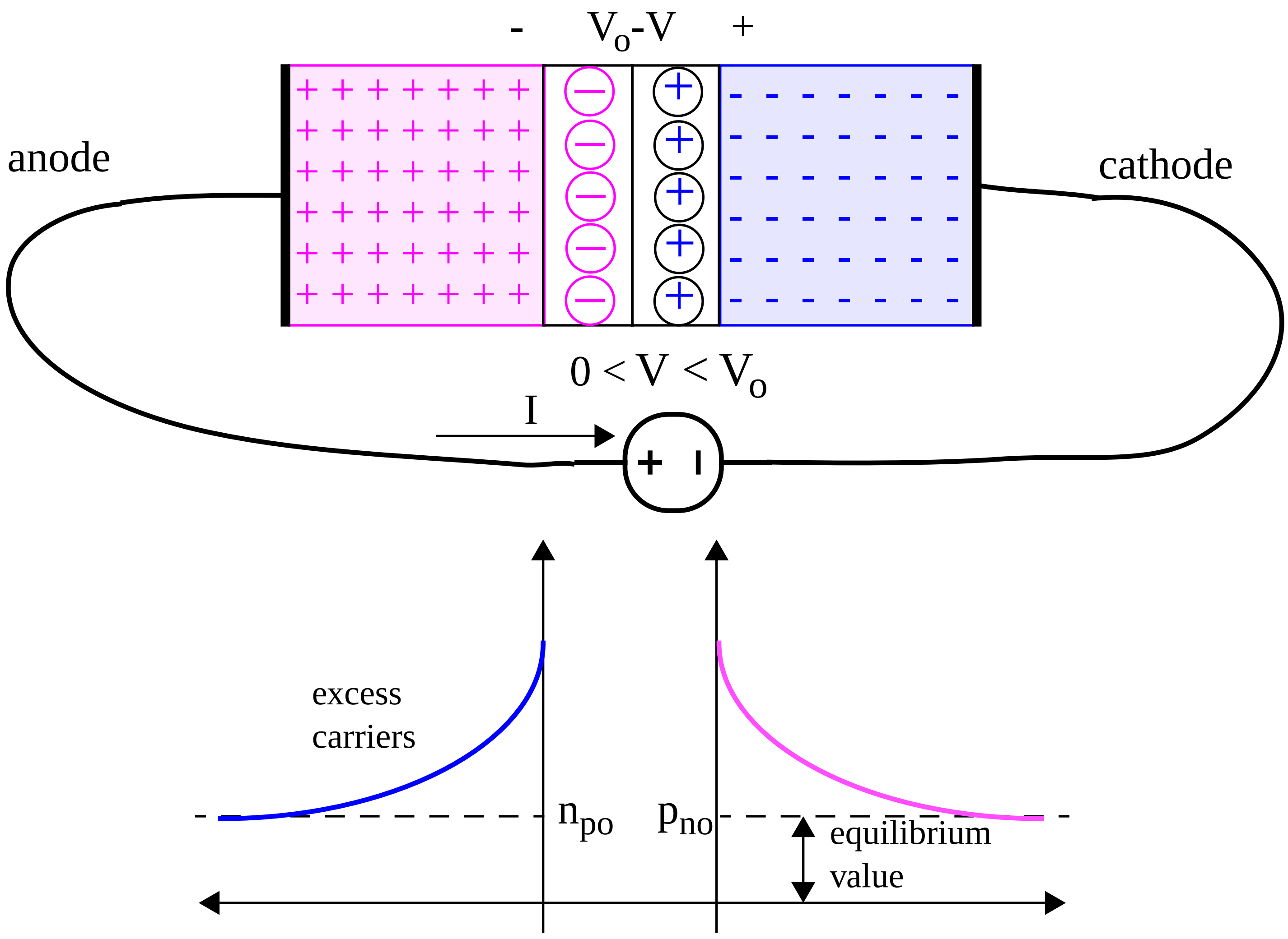
- A positive external voltage will reduce the barrier and allow more carriers to diffuse
- The depletion region width is also reduced



- Now the diffusion current dominates the drift current

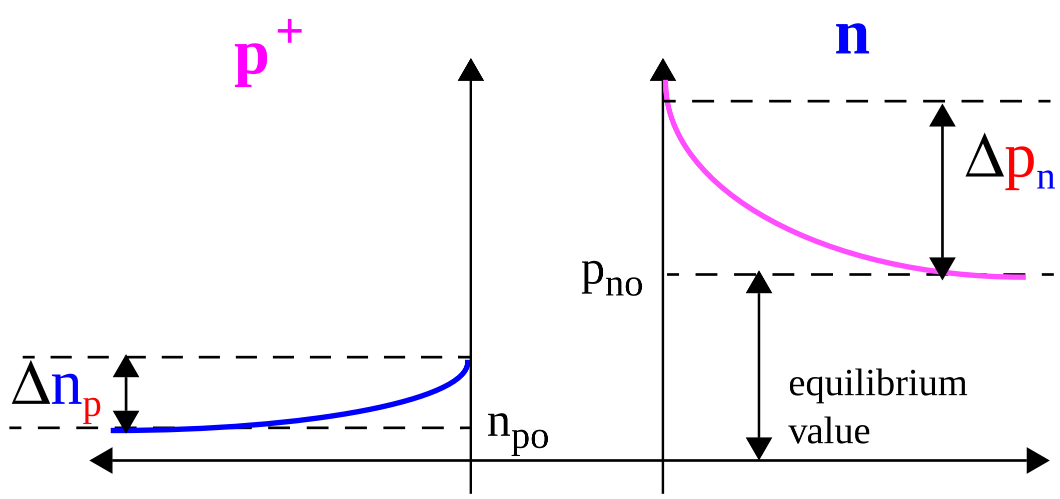
Positive Applied Voltage

- With a lower potential barrier, more free carriers are able to diffuse



Positive Applied Voltage - p^+n diode

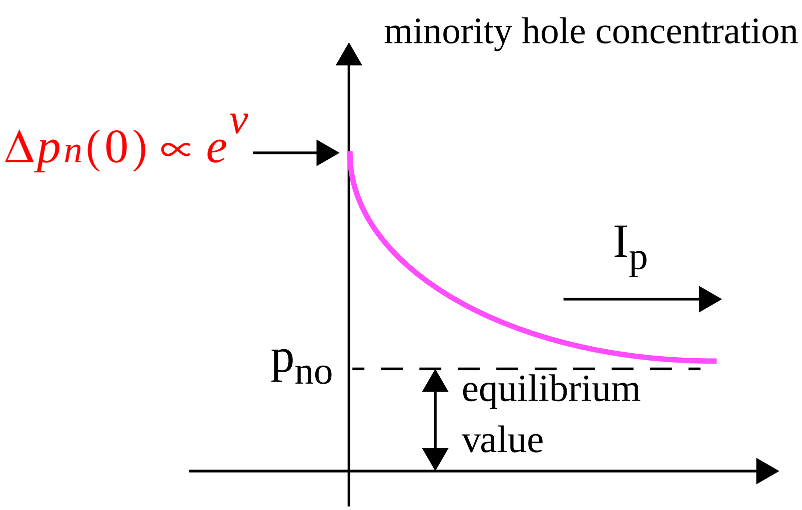
- The lower doped region is sometimes called “the base”.
- For the asymmetrical doping of p and n regions the minority carrier concentrations in both regions differ. The excess carrier concentrations will differ as well.
- $\Delta p_n >> \Delta n_p$ Why?



Positive Applied Voltage

- At steady state for V>0, the excess carrier distributions correspond to diffusion currents that comprise the external diode current, I
- Excess carriers decay exponentially with distance (due to recombination), therefore the minority carrier distributions are exponential
- The minority carrier injection at the edge of the depletion region increases exponentially with increasing voltage

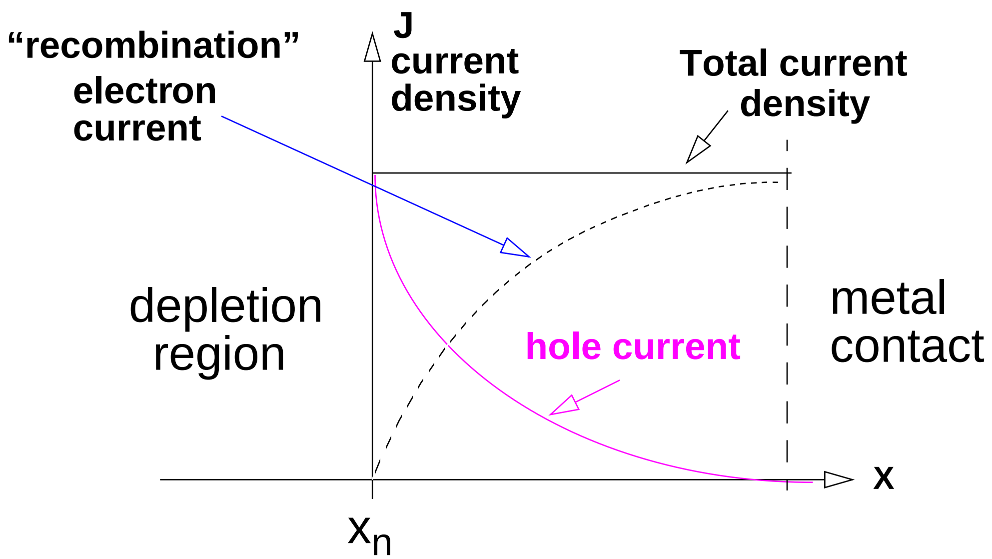
- The total excess charge, Q_p, is directly proportional to e^v because it varies exponentially with distance

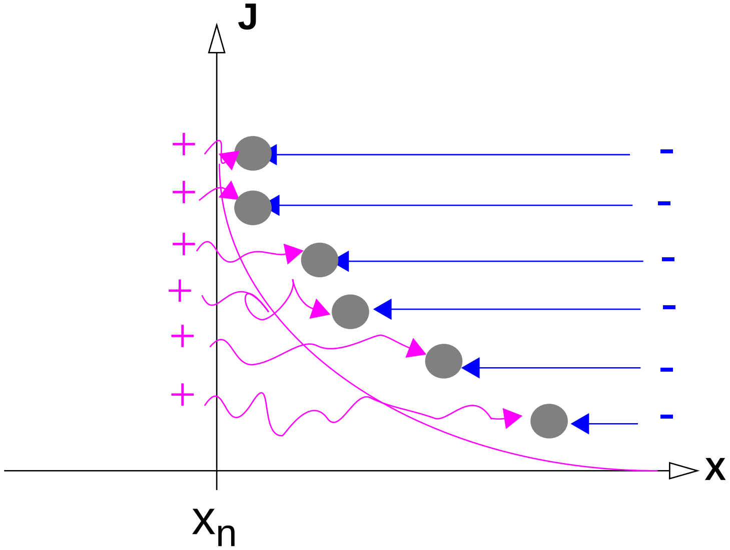


Forward Bias - "Recombination Current"

- Diffusion current within the neutral region is bigger closer to the depletion layer where the gradient is bigger. What about current continuity?

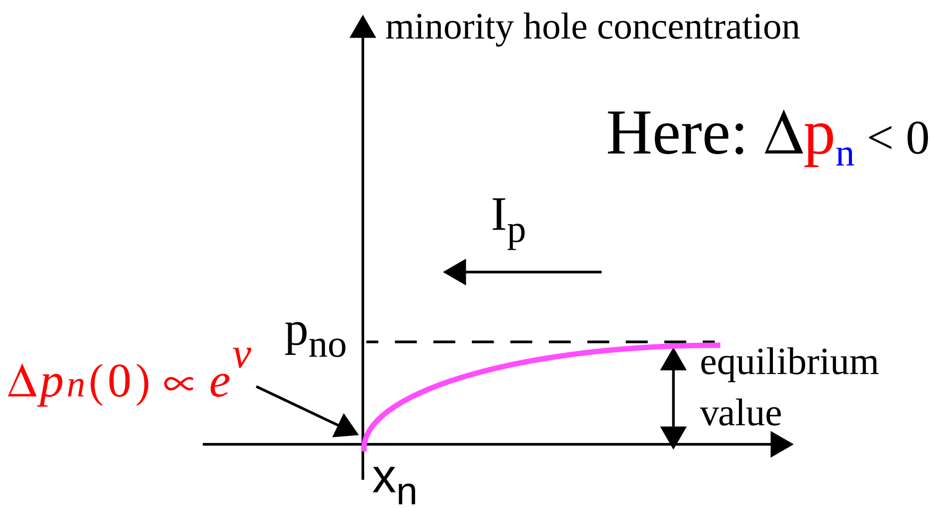
- The charge transport through the forward biased diode can be attributed to acts of recombination!
- Minority holes injected into the n region attract electrons from the contact. The electron-hole pairs diffuse according to the hole gradient until the pair recombines. In equilibrium, each time such a recombination occurs, a new hole is injected. Thus, the each act of recombination corresponds to an act of transport of an elementary charge. Similar thing happens at the p side of the junction... (at low current levels, recombination in the depletion region is also an important mechanism contributing to the overall current).

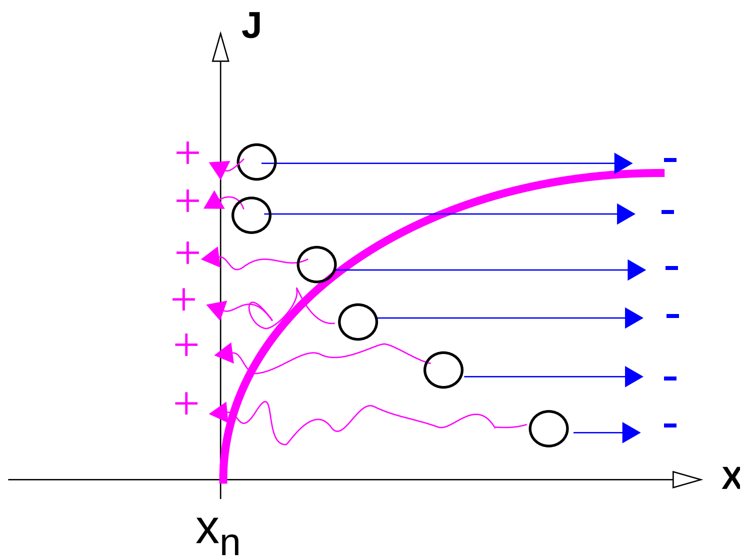




Reverse Bias - "Generation Current"

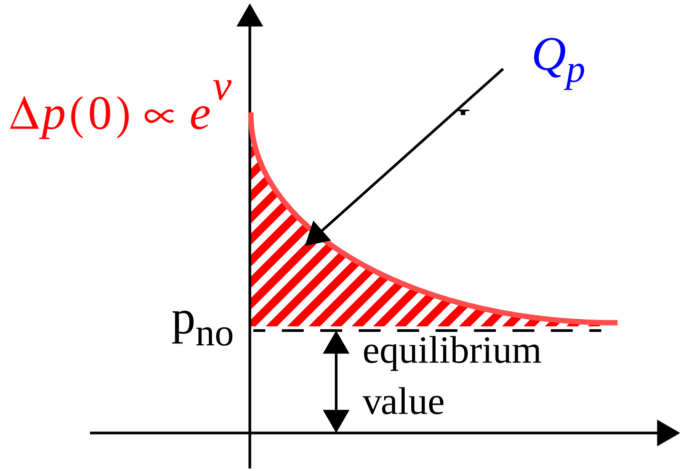
- Diffusion current within the neutral region is bigger closer to the depletion layer where the gradient is bigger.
- In equilibrium, each time generation occurs, a new electron-hole pair starts diffusing towards the depletion region. At x_n, the pair is separated: hole is swept through the depletion layer and electron goes to contact of n region. Thus, each act of generation corresponds to an act of transport of an elementary charge. Similar thing happens at the p side of the junction...
(generation in the depletion region is also an important mechanism contributing to the overall current in Si diodes, especially for large reverse bias voltage, when the depletion layer is wide).
- The charge transport through the reverse biased diode can be attributed to acts of generation! The explanation based on the drift current (given earlier) is still valid: generated holes and electrons drift through the depletion layer.





Positive Applied Voltage

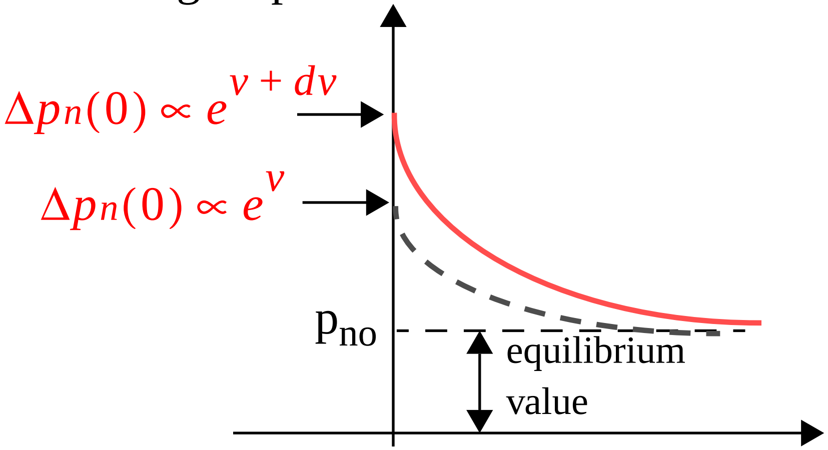
- The minority carrier charges have an average lifetime of τ, before they recombine
- What is the rate at which charge must be flowing in from the external circuit to replenish the lost charge?



- What does this charge flow represent?

Diffusion Capacitance

- The change in this charge with change in voltage represents the diffusion capacitance



- By definition

$$C = \frac{dQ}{dV}$$

- Since Q is directly proportional to I_A, the current at operating point A, then

$$C \propto \frac{dI_A}{dV}$$

- And since I is an exponential function of voltage

$$C \propto I_A$$

- Diffusion Capacitance (nonlinear function of voltage):

$$C_d = k_c I_A$$

Positive Applied Voltage

- From $I \propto e^{v}$
- One can derive the complete expression for the steady state diode current:

$$i = I_S\left(e^{v/nV_T} - 1\right)$$

- I_S is saturation current (component due to drift) which depends on area of the junction and temperature --- why?
- I_S is on the order of 10^{-15}Amps for ICs, but doubles with every 5° C increase in temperature
- n varies between 1 and 2, and depends on how the junction is formed
- V_T is the thermal voltage, KT/q

$$q \equiv 1.602 \times 10^{-19} C \qquad K \equiv 1.38 \times 10^{-23} \frac{j}{°K}$$

- At room temperature, 20°C, V_T = 25.2mV

Positive Applied Voltage

- Does the equation agree with the physical explanation when v=0 and v<<0?

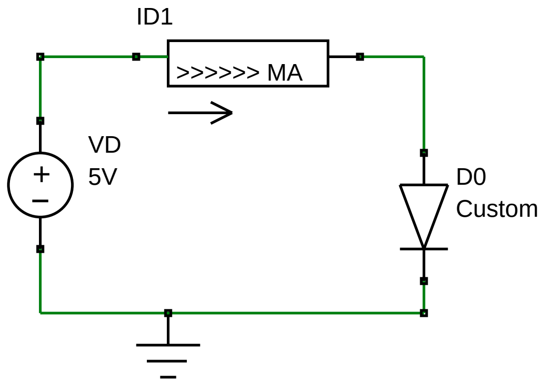
$$i = I_S\left(e^{v/nV_T} - 1\right)$$

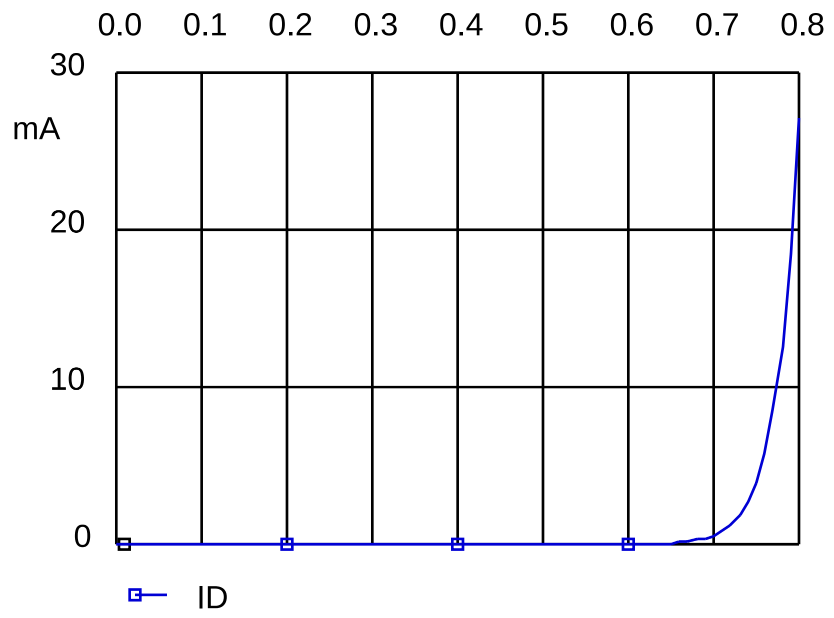
- What's the expression look like for v >> V_T?

Positive Applied Voltage

- Since the current varies exponentially with voltage, the look of the curve as compared to an ideal curve depends very much on the range over which the plot is made
- One might say that the turn-on voltage is 0.7 volts in this plot, but this really depends on how you view the current scale
- Note that V_o is NOT the turn-on voltage

$V_o = V_j = 1.0v$





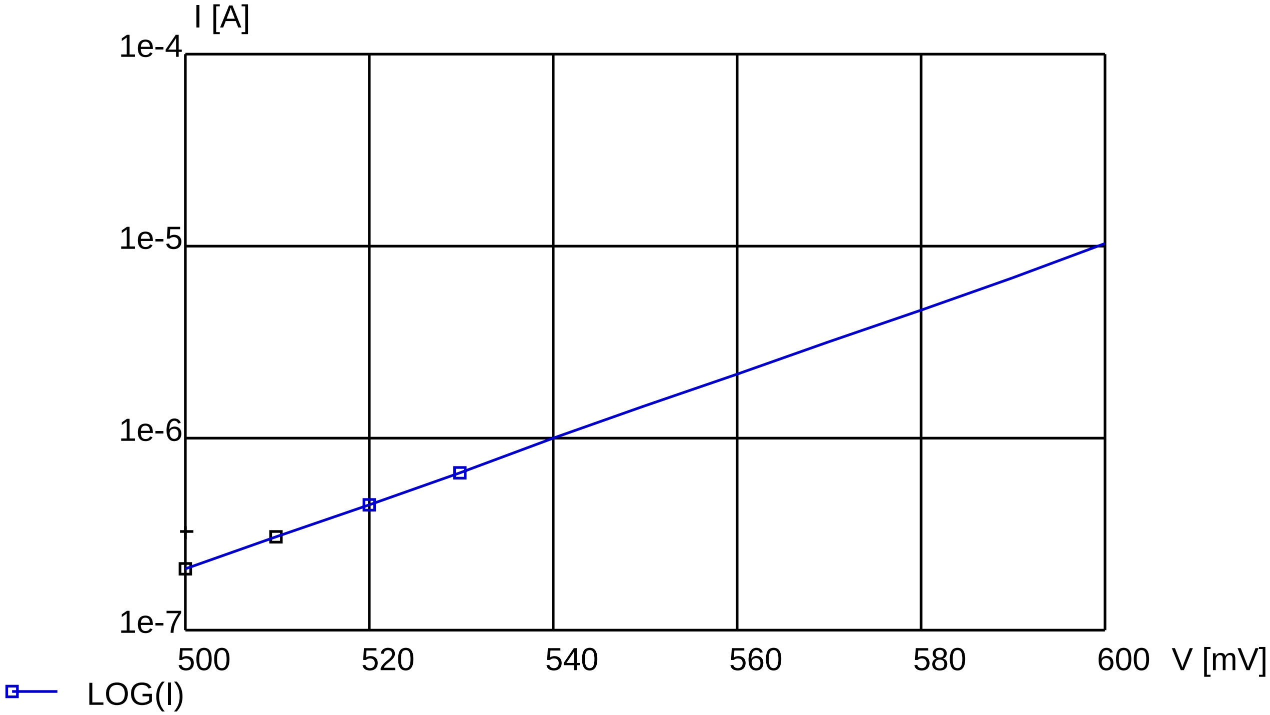
Positive Applied Voltage

- On a semi-log scale, it is easy to see that an order of magnitude change in current corresponds to ~60mV (n=1) change in voltage at room temperature

$$I_1 = I_S e^{V_1/nV_T}$$

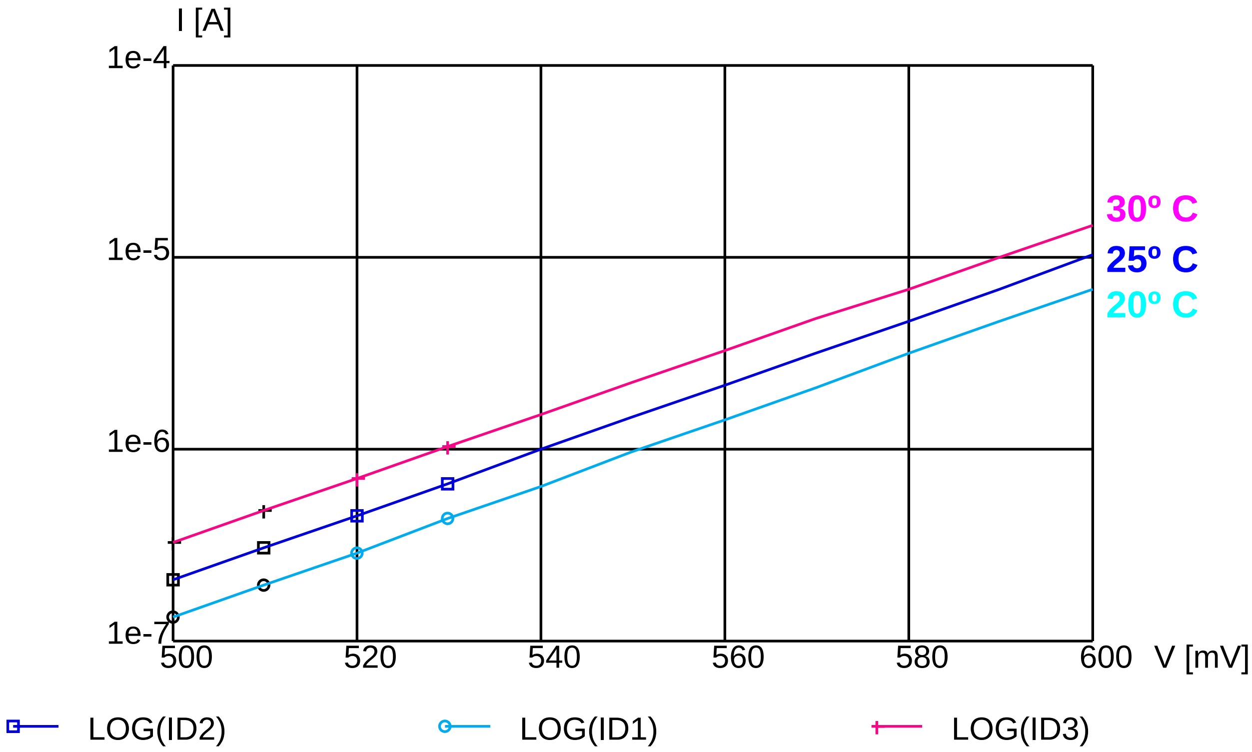
$$I_2 = I_S e^{V_2/nV_T}$$

$$V_2 - V_1 = nV_T \ln\left(\frac{I_2}{I_1}\right) = 2.3nV_T \log\left(\frac{I_2}{I_1}\right)$$



Variation with Temperature

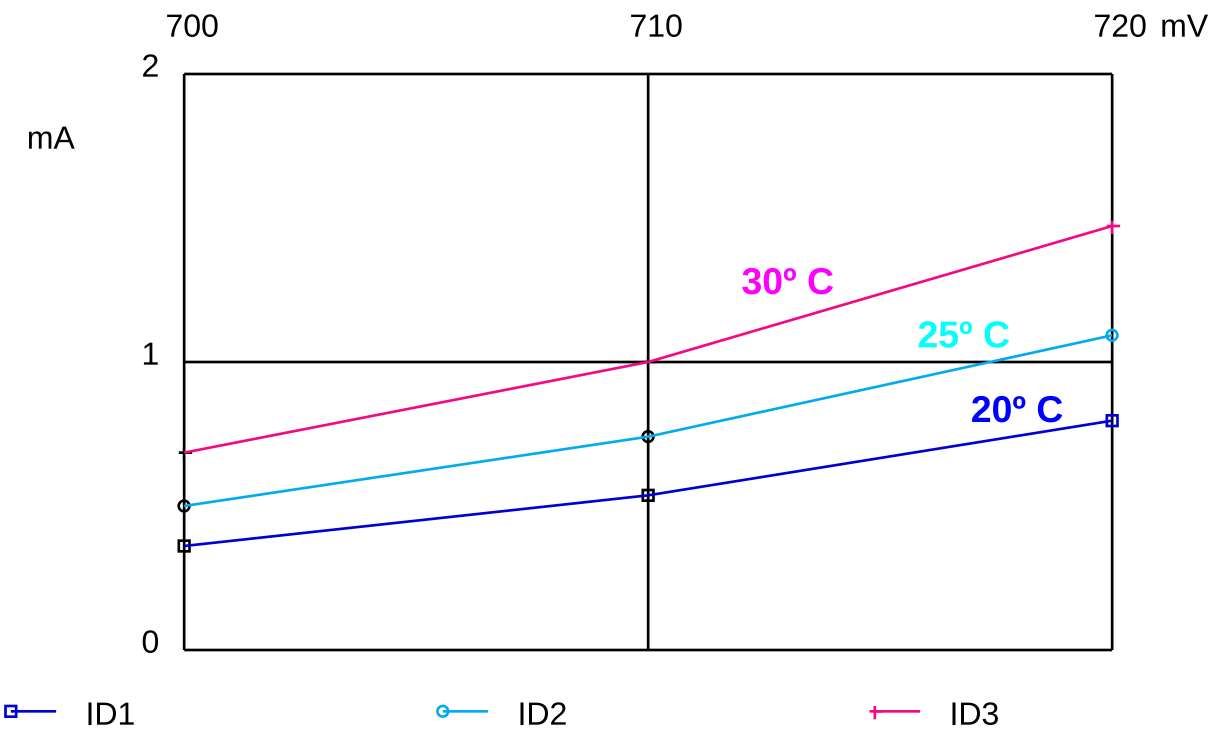
- The diode characteristic varies with temperature since I_S and V_T vary with T
- The change in voltage is *approximately* 2mV for every 1° C increase



Variation with Temperature

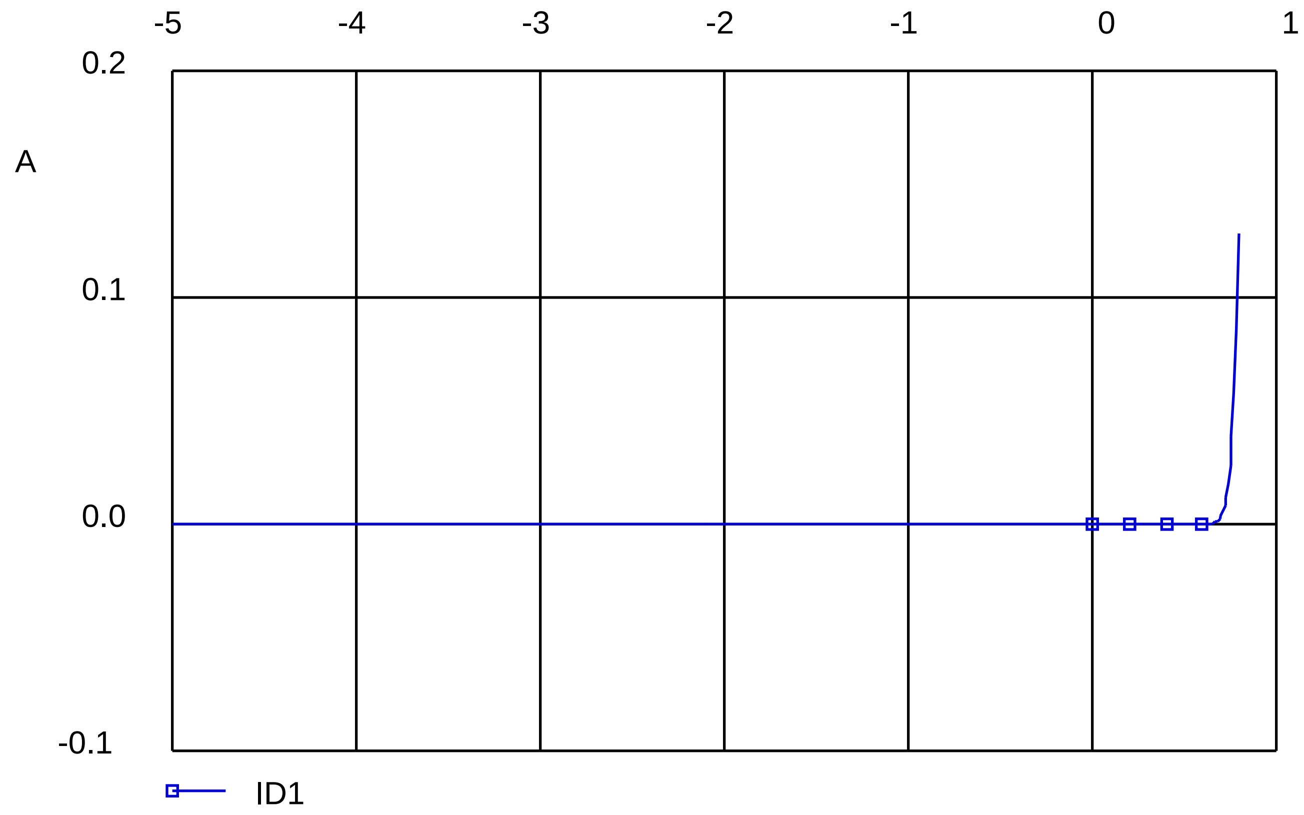
- The change in voltage is approximately 2mV for every 1º C increase

Linear Scale for I_D $-2mV/°C$



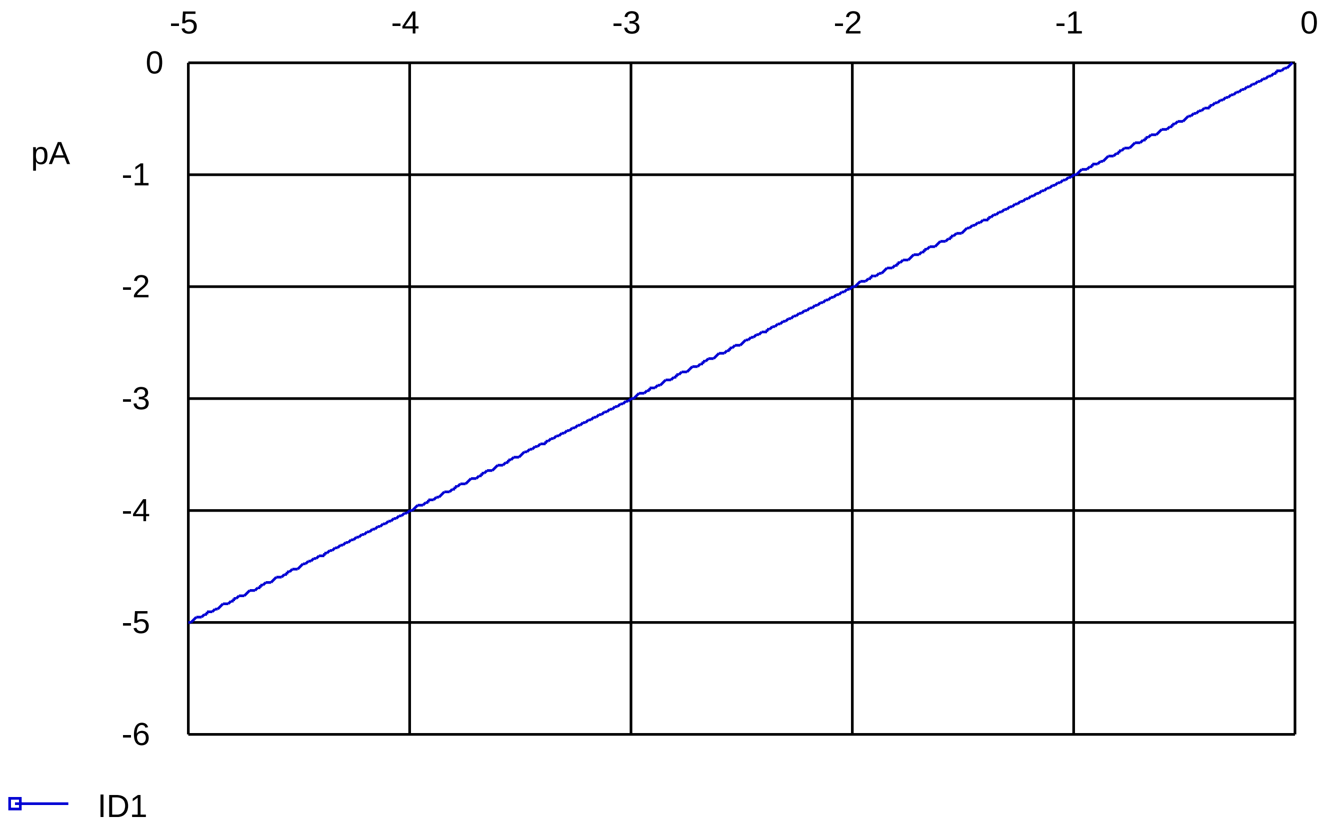
Complete Characteristic

- The reverse current is approximately, I_S, but it can be much larger than this value as V becomes more negative



Reverse Characteristic

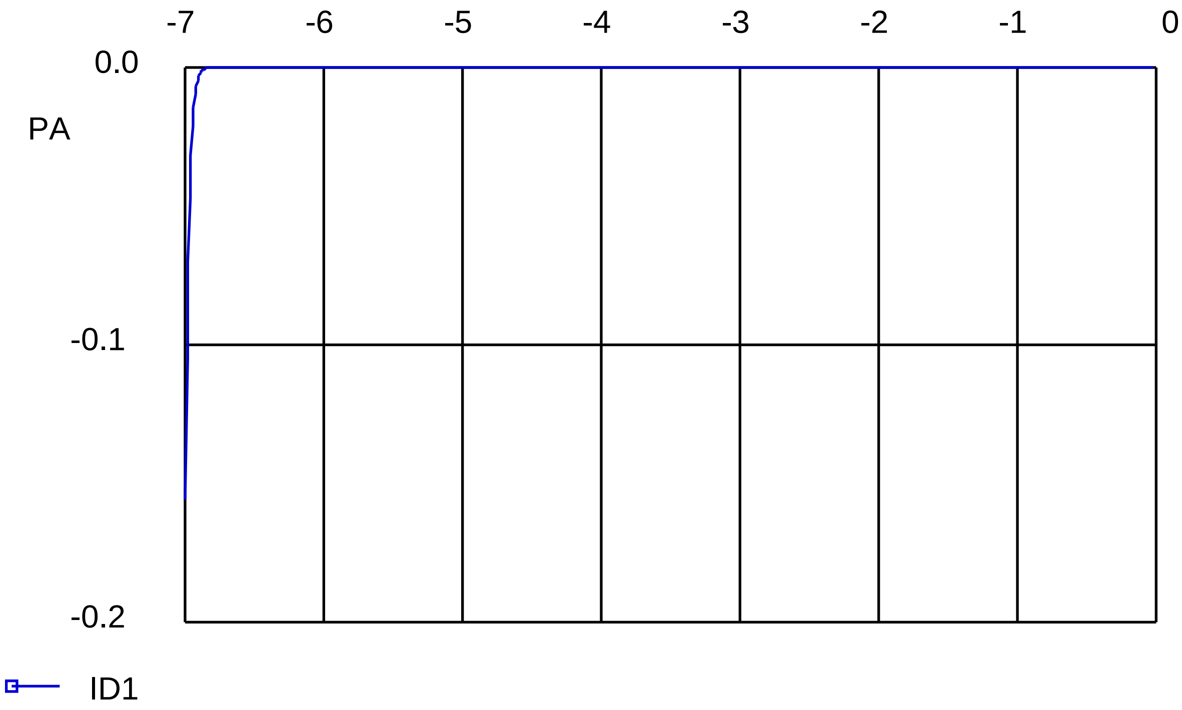
- A plot of the reverse characteristic only shows the increase in saturation current with reverse bias



- The SPICE model we use is linear for this portion of characteristics.

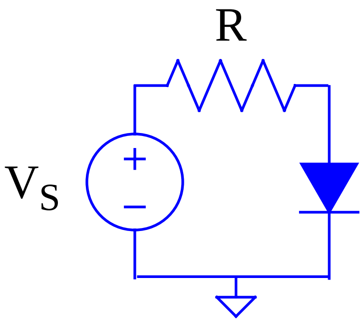
Breakdown Characteristic

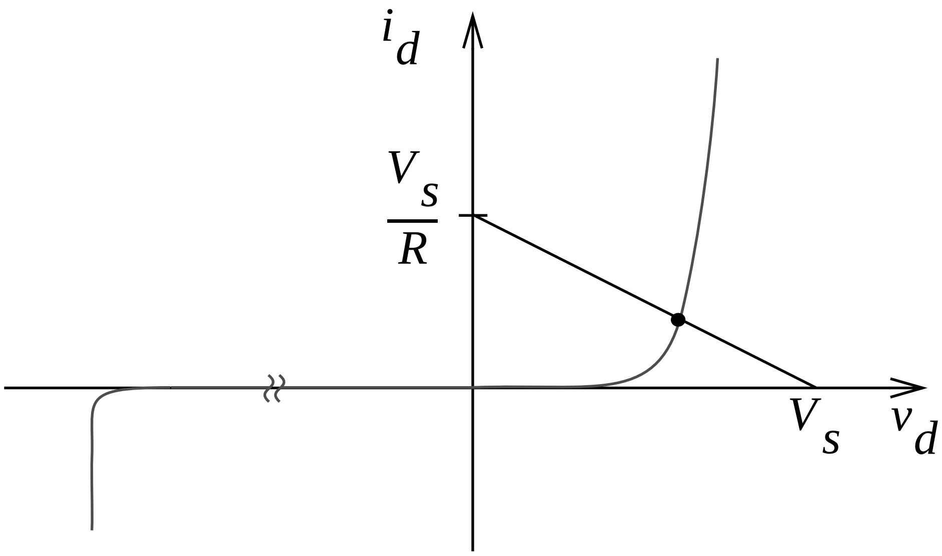
- A plot of the reverse characteristic including breakdown



Diode Circuits

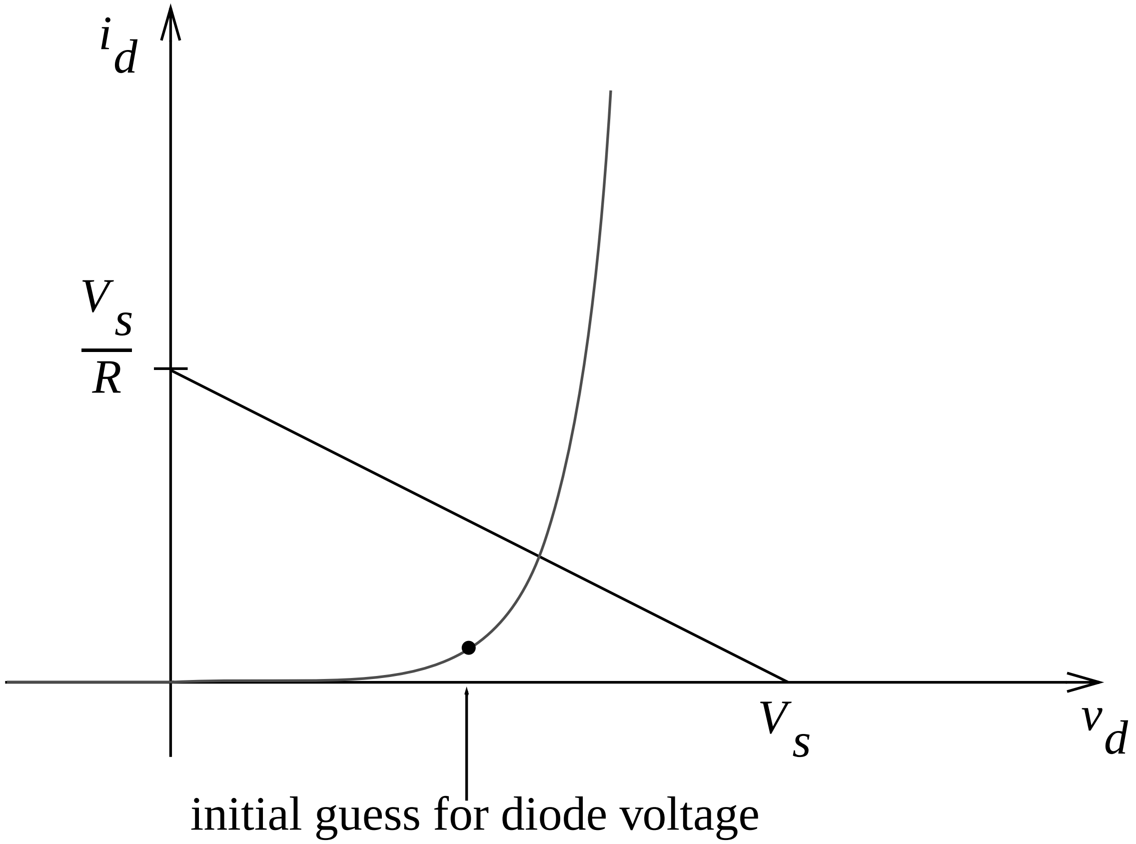
- Solving for the loop current requires solving a nonlinear equation in the circuit below
- Superimpose Thevenin characteristic on diode i-v curve





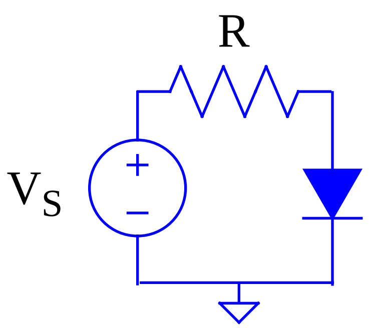
Diode Circuits in SPICE

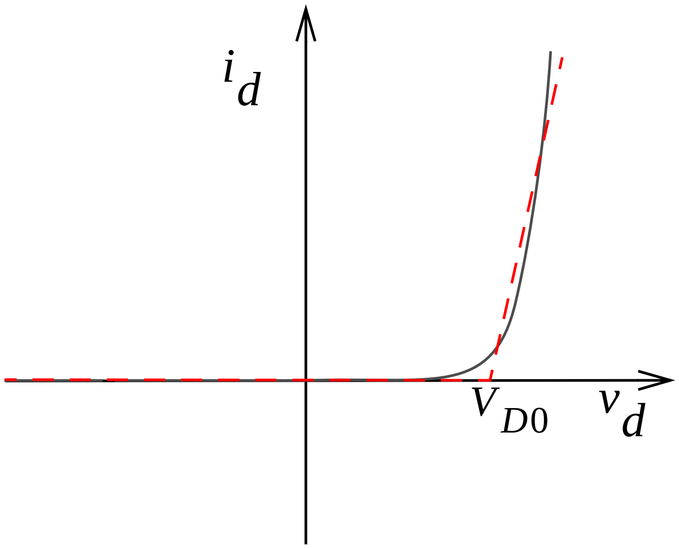
- SPICE solves these circuit problems via Newton-Raphson iteration



Simplified Diode Models

- For hand calculations we generally use a simplified diode model
- A two-piece piecewise-linear model is the most obvious choice

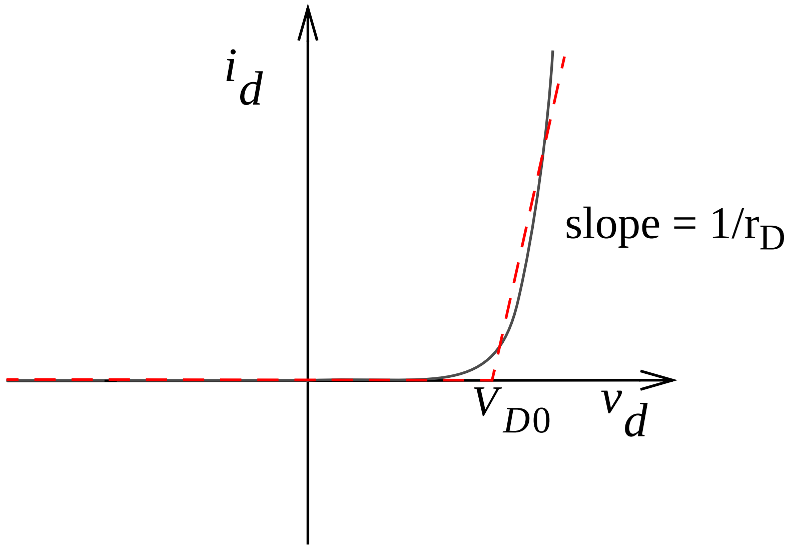


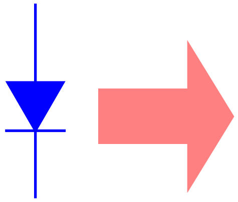


- What are the equations for this straight-line characteristic?

Simplified Diode Models

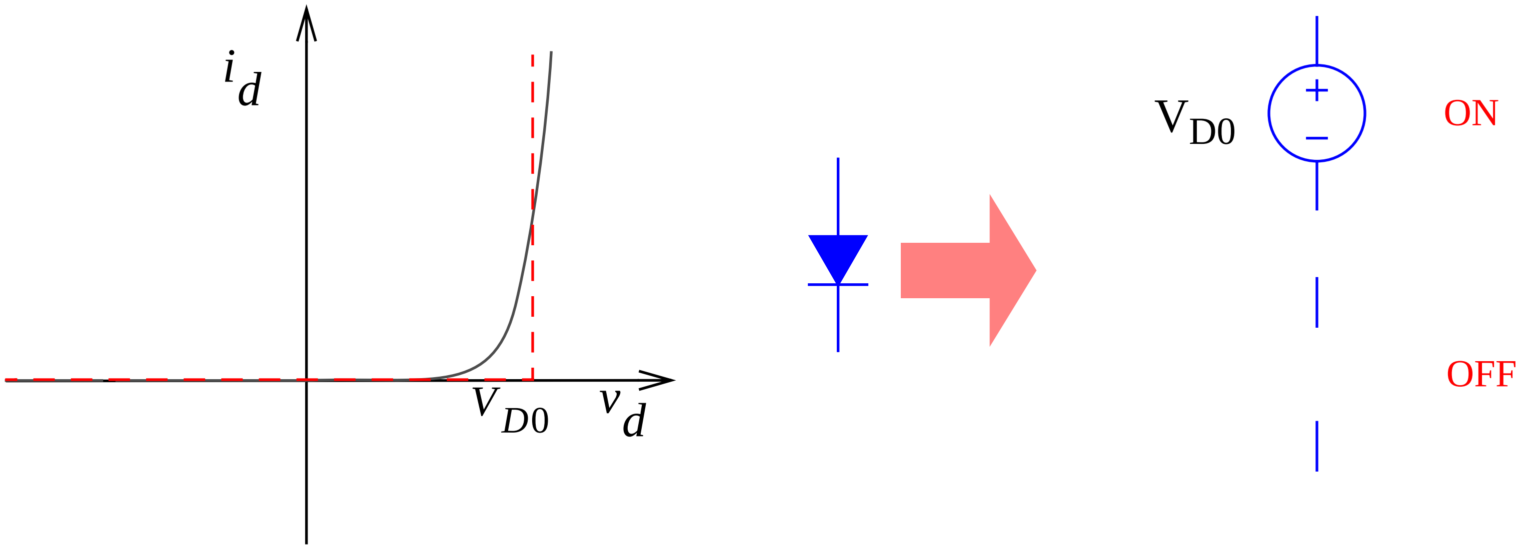
- What does the diode equivalent circuit model look like?





Even Simpler Model

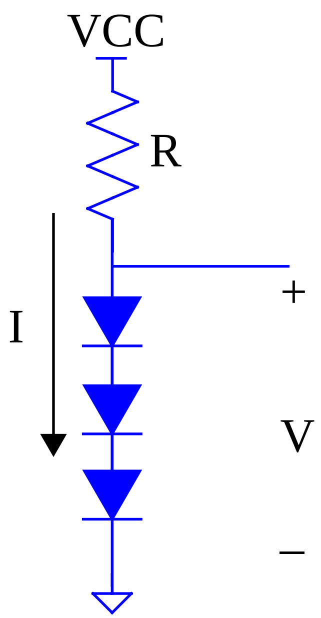
- To further simplify a hand analysis, we generally rely on the following model:



- The value of V_{D0}, the “on”-voltage, is based on the current level for which one would consider the diode to be “on” ---- typically ~ 0.7 volts

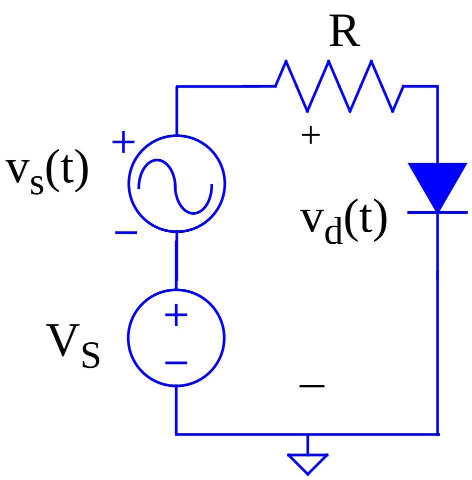
Example

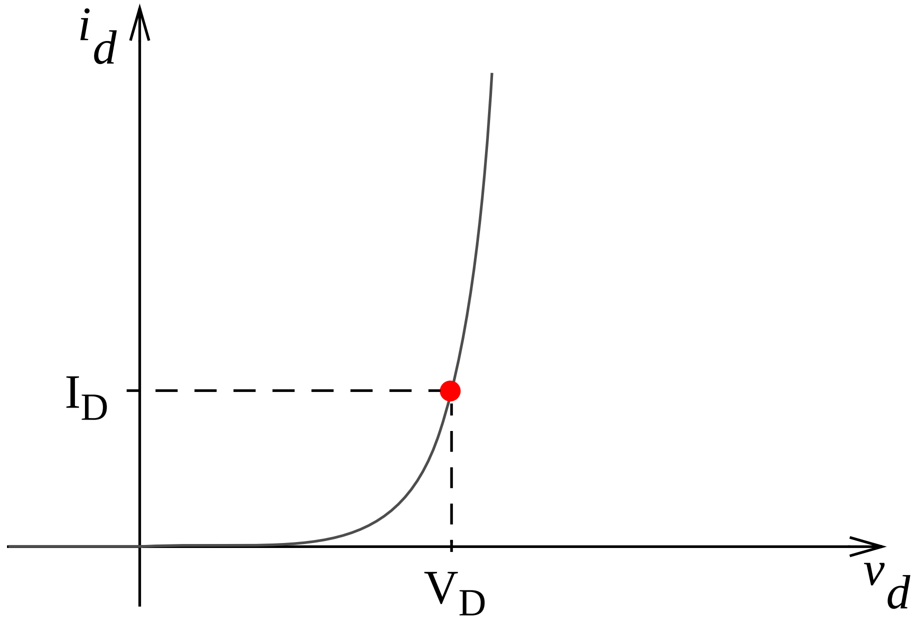
- Solve for the current, I, and the voltage, V, in the circuit below:



Small Signal Diode Model

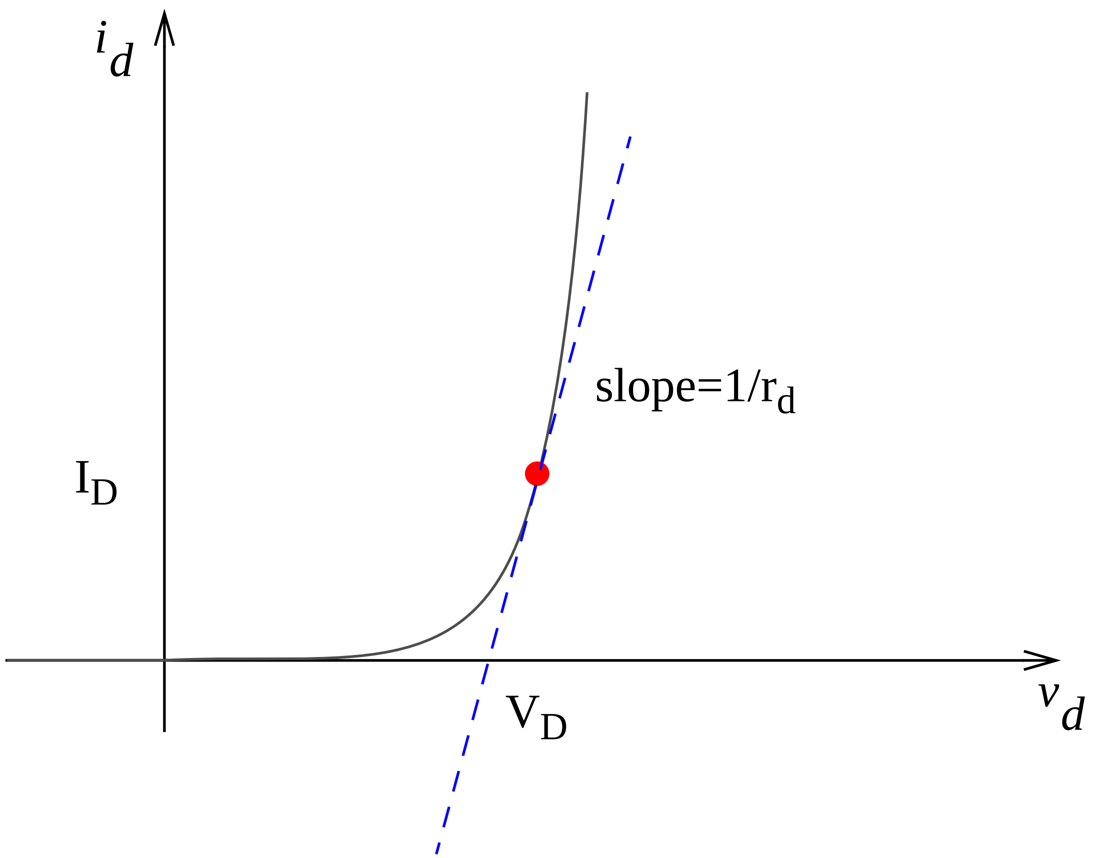
- For analog design we're often interested in the small signal response
- Especially for transistor circuits, we will bias a nonlinear circuit to a dc operating point, then model it as linear for the small ac analog signals
- Model the diode as a single piecewise linear segment that passes through the bias point





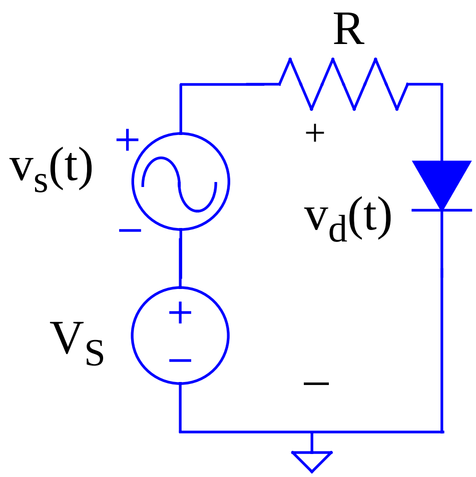
Small Signal Diode Model

- With a piecewise linear tangential approximation passing through the bias point, the model represents the exact dc solution
- If the ac signal is small, we can assume that the diode variation in current due to a small variation in voltage follows the piecewise linear approximation



Small Signal Diode Model

- This approximation, if valid, allows us to analyze the ac and dc responses separately



Small Signal Diode Model