EE210: Microelectronics-I

Lecture-7 : PN Junction Diode-3

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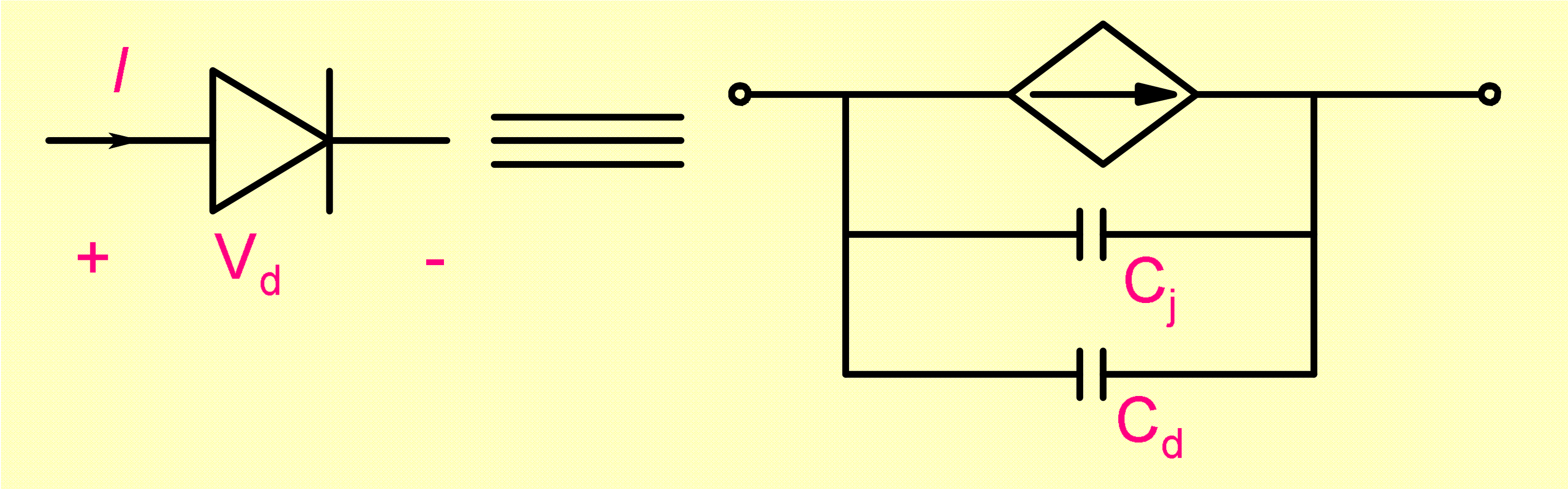
Diode Model: Forward Bias



$$I = I_S \times \left(\exp\left(\frac{V_d}{n V_T}\right) - 1 \right)$$

$$C_j = \frac{C_{j0}}{\left(1 - \frac{V_d}{V_{bi}}\right)^m}$$

$$C_d = \frac{I_F}{V_T} \cdot \tau$$

No. of parameters: 3+3+1

Temperature dependence of diode characteristics

$$I_D = I_S \times \{\exp(\frac{V_d}{V_T}) - 1\}$$

$$V_T = \frac{kT}{q}$$

$$I_S \propto n_i^2 \propto e^{-\frac{E_g}{kT}}$$

Reverse saturation current increases with temperature. For forward bias, even though V_T increases, current still increases because of greater influence of I_S

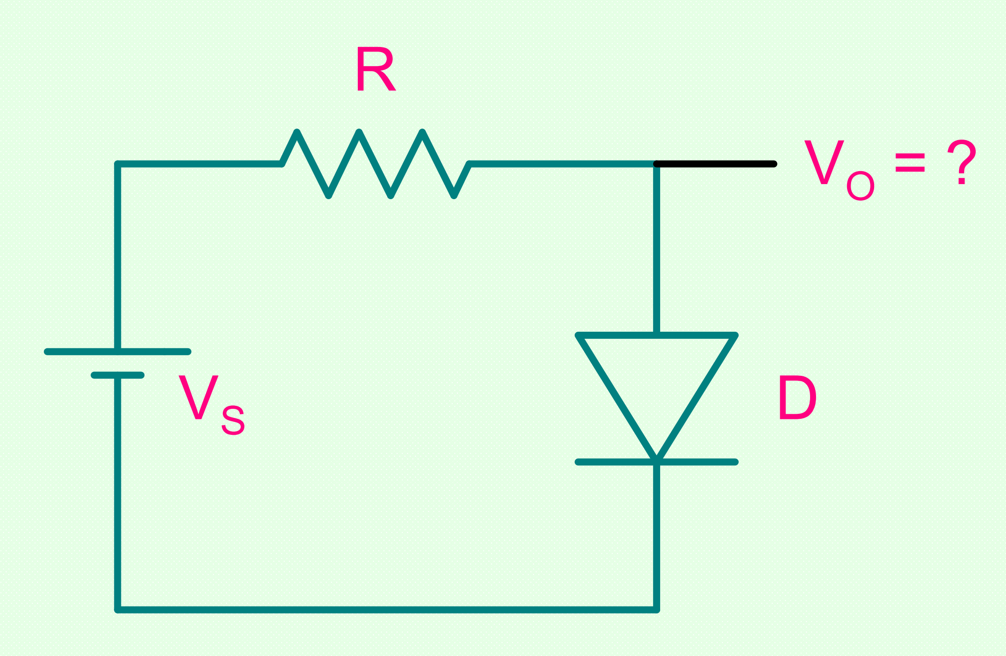
For a diode in forward bias at a fixed current I_O : $V_D = V_T \times \ln\left(I_O/I_S + 1\right)$

For Silicon diodes, V_D decreases at the rate of ~ -2mV/^{o}C

If the diode voltage is 0.7 at 27^{o}C, then at 100^{o}C it would be only :

$$0.7 - 2\times10^{-3}\times(100-27) = 0.554V$$

Analysis using non-linear diode model is not easy



$$V_S = I \times R + V_O \quad (1)$$

$$I = I_S \times \left(\exp\left(\frac{V_O}{nV_T}\right) - 1 \right) \quad (2)$$

$$\Rightarrow \quad V_O = nV_T \times \ln\left(\frac{\mathrm{I}}{\mathrm{I_S}} + 1\right) \quad (3)$$

$$\Rightarrow \quad V_S = I \times R + nV_T \times \ln\left(\frac{\mathrm{I}}{\mathrm{I_S}} + 1\right) \quad (4)$$

Iterative Method:

$$V_S = I \times R + V_O \quad (1)$$

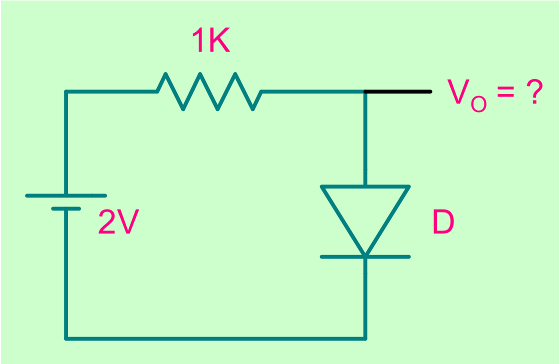
$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\} \quad (2)$$

Assume $$V_O = 0.6\mathrm{V}$$

Calculate $$I = \frac{V_S - V_O}{R}$$

Re-calculate $$V_O = nV_T \times \ln(\mathrm{I}/\mathrm{I_S} + 1)$$

Convergence: $$\frac{\Delta I}{I} \le \varepsilon$$



$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT / q \cong 26\ mV \ \text{ at } T = 300\text{K}$$

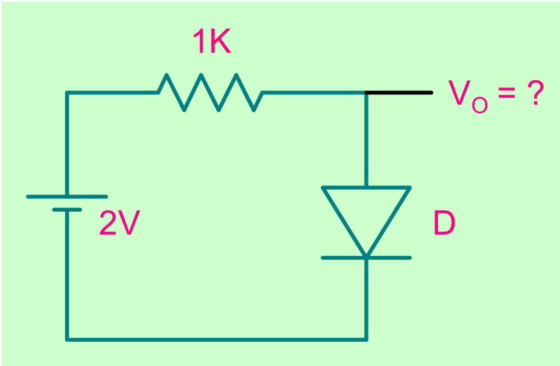
Assume V_O

$$I = \frac{V_S - V_O}{R}$$

$$V_O = nV_T \times \ln(I/I_S + 1)$$

$V_O = 0.5$	$V_O = 0.711$	$V_O = 0.707$
$I = 1.5 \times 10^{-3}$	$I = 1.289 \times 10^{-3}$	$I = 1.293 \times 10^{-3}$
$V_O = 0.711$	$V_O = 0.707$	$V_O = 0.707$

CONVERGENCE



$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

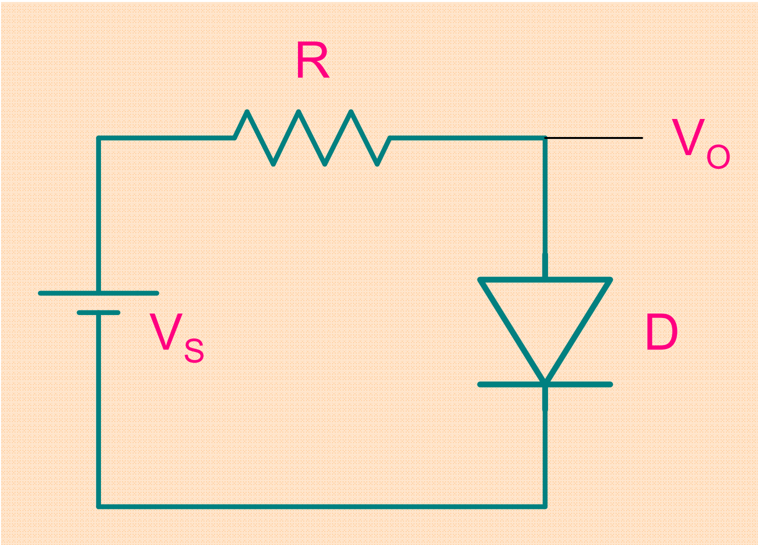
$$I_S = 2 \times 10^{-15}\ A$$

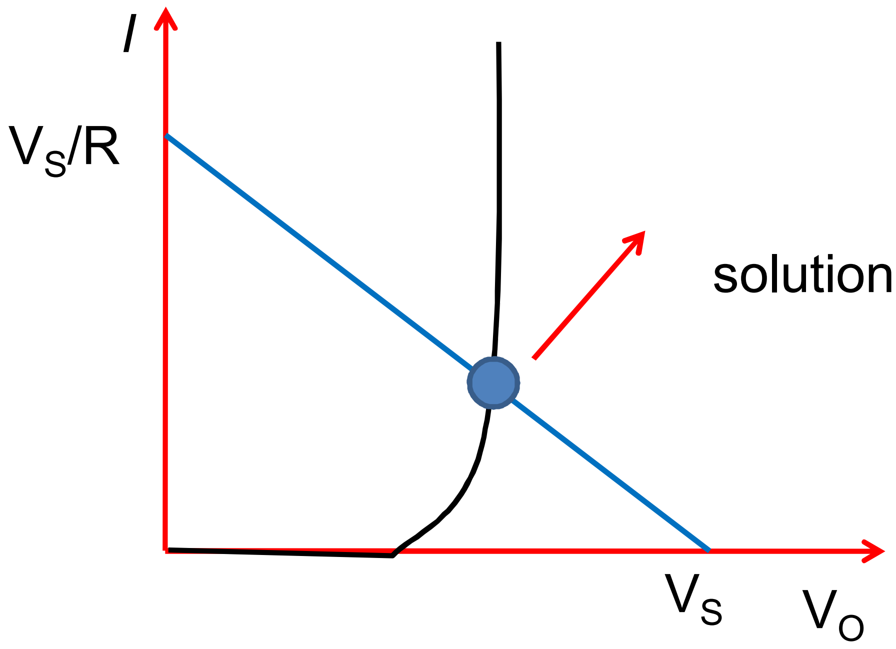
$$V_T = kT / q \cong 26\ mV \quad \text{at T} = 300\text{K}$$

Assume V_O	V_O = 1.0	V_O = 0.7	V_O = 0.707
$I = \frac{V_S - V_O}{R}$	I = 1.0 x 10^{-3}	I = 1.3 x 10^{-3}	I = 1.293 x 10^{-3}
$V_O = nV_T \times \ln(I/I_S + 1)$	V_O = 0.7	V_O = 0.707	V_O = 0.707

CONVERGENCE to the same Result

Graphical Method: Method of Load Line

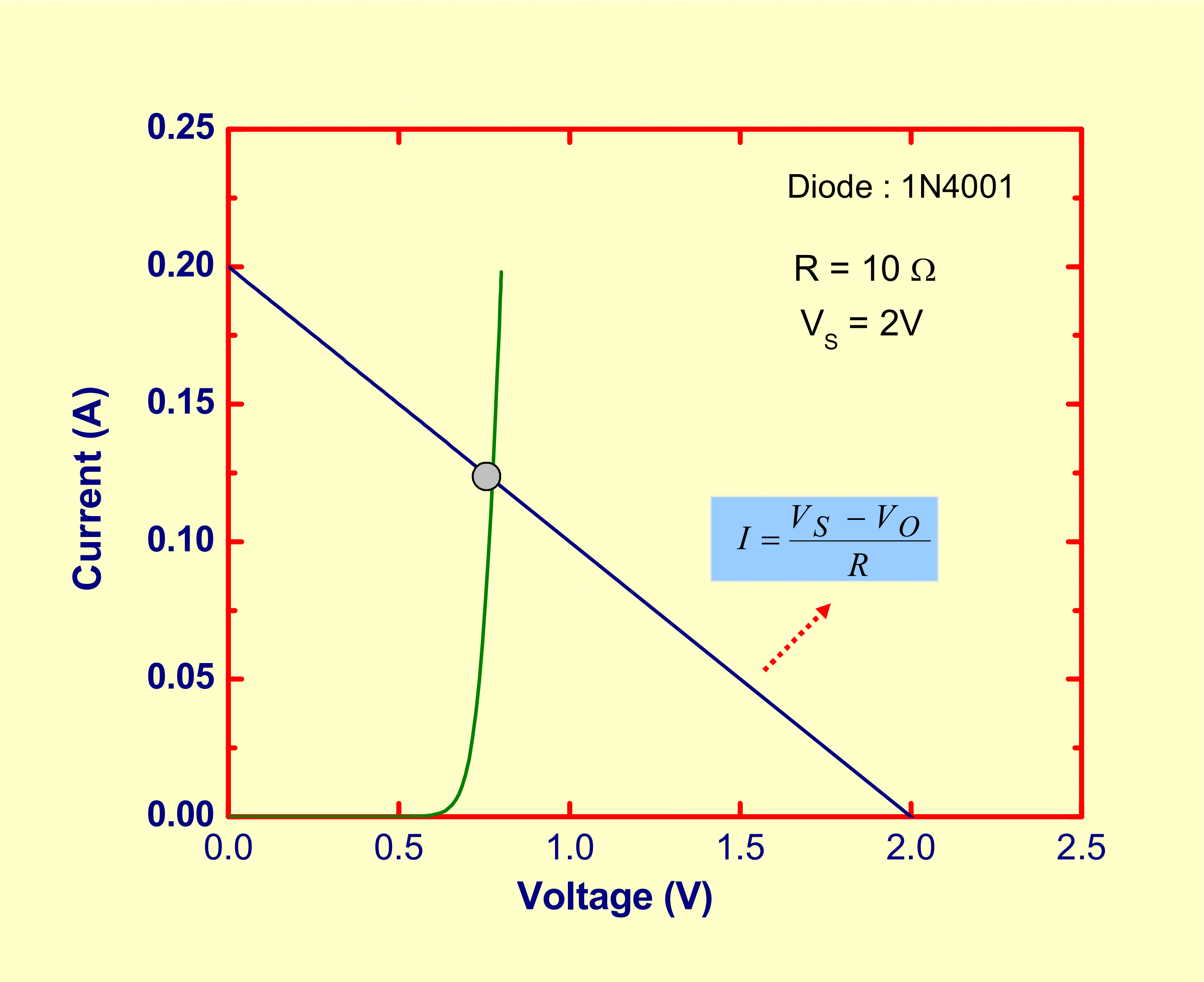




$$V_S = I \times R + V_O$$

$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\}$$

$$I = \frac{V_S - V_O}{R}$$



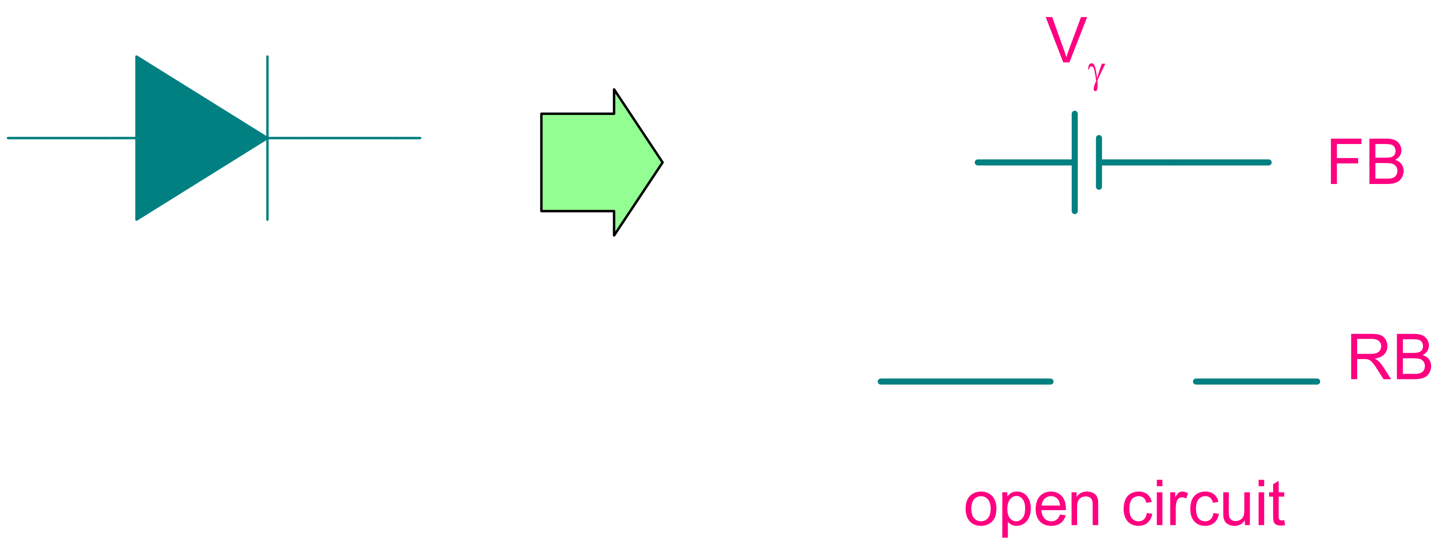
V_O = 0.77V; I = 0.12A

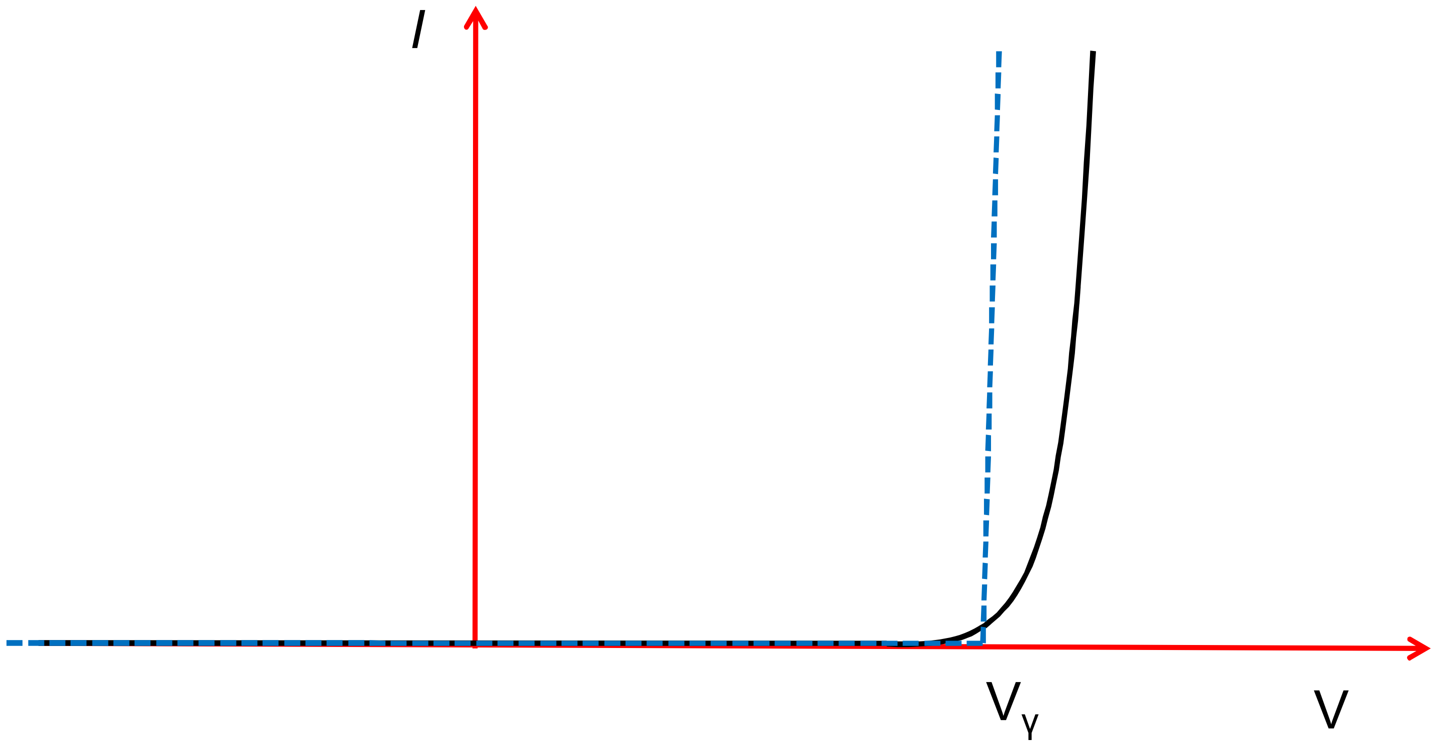
For “hand analysis” of circuits, we need simpler models!

•Analysis using a non-linear diode model is relatively difficult and time consuming.

•It also does not give a symbolic expression that can provide insight and help in the design of the circuit.

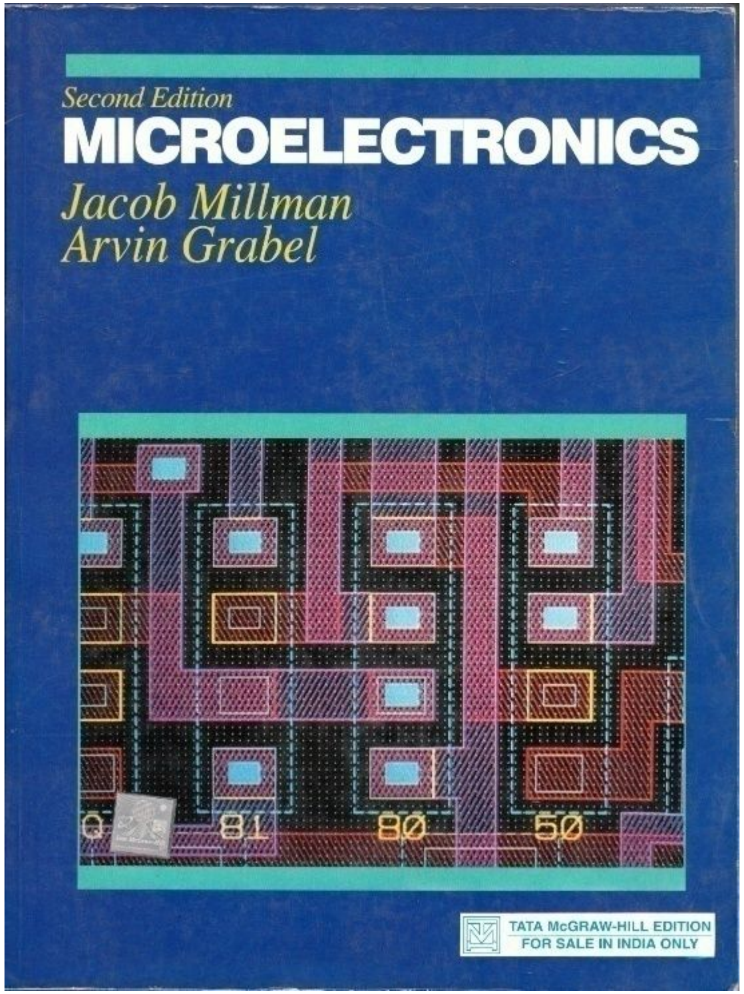
Need SIMPLER and LINEAR Device Models





Cut-in Voltage: V_γ

~0.6-0.7V



currents; for specified carrier densities, an increase in the area results in an increase in the current capacity of the junction.

Examination of Eq. (2-3) indicates that for forward bias, and for V_D several times V_T which makes $\epsilon^{V_D/\eta V_T} \gg 1$, I_D varies exponentially with applied voltage. For this case, Eq. (2-3) can be approximated by

$$I_D = I_S\, \epsilon^{V_D/\eta V_T} \qquad \text{A} \tag{2-5}$$

This result is expected as a decrease in the potential barrier permits carriers to diffuse more readily across the junction. Similarly, I_D is negative with magnitude I_S for reverse bias when V_D has a magnitude which is several times V_T. Both the negative sign, indicating current from n to p, and the constant current value for reverse bias are consistent with the discussion in Sec. 2-2.

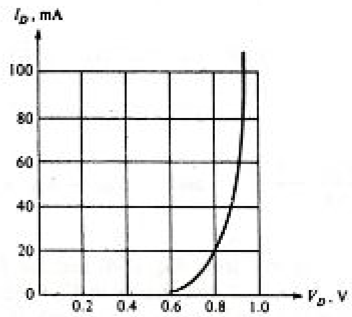
Often, because forward and reverse currents differ by several orders of magnitude, two different current scales are used to display the junction characteristic as in Fig. 2-4*b*. The dashed portion of the reverse-biased characteristic (note the broken scale) indicates that at a voltage $-V_Z$ the junction exhibits an abrupt departure from Eq. (2-3). At this voltage a large reverse current may exist and the junction is in its *breakdown* region. This phenomenon is discussed in Sec. 2-11.

The forward characteristic of the 1N4153, a fast-switching silicon diode, is depicted in Fig. 2-5. A noteworthy feature of this characteristic is the existence of a *cut-in*, *offset*, or *turn-on* voltage V_γ below which the current is small (less than 1 percent of rated current). From Fig. 2-5, V_γ is approximately 0.6 V; beyond V_γ, the current increases rapidly. The significance of the offset voltage is that the diode characteristic can be approximated as having negligible current for applied voltages less than V_γ.

The parameter η can be determined from the exponential nature of the volt-ampere characteristic. From Eq. (2-5), we have

$$\log I_D = \log I_S + \frac{0.43 V_D}{\eta V_T} \tag{2-6}$$

FIGURE 2-5
The forward volt-ampere characteristic of an 1N4153 silicon diode at 25°C.



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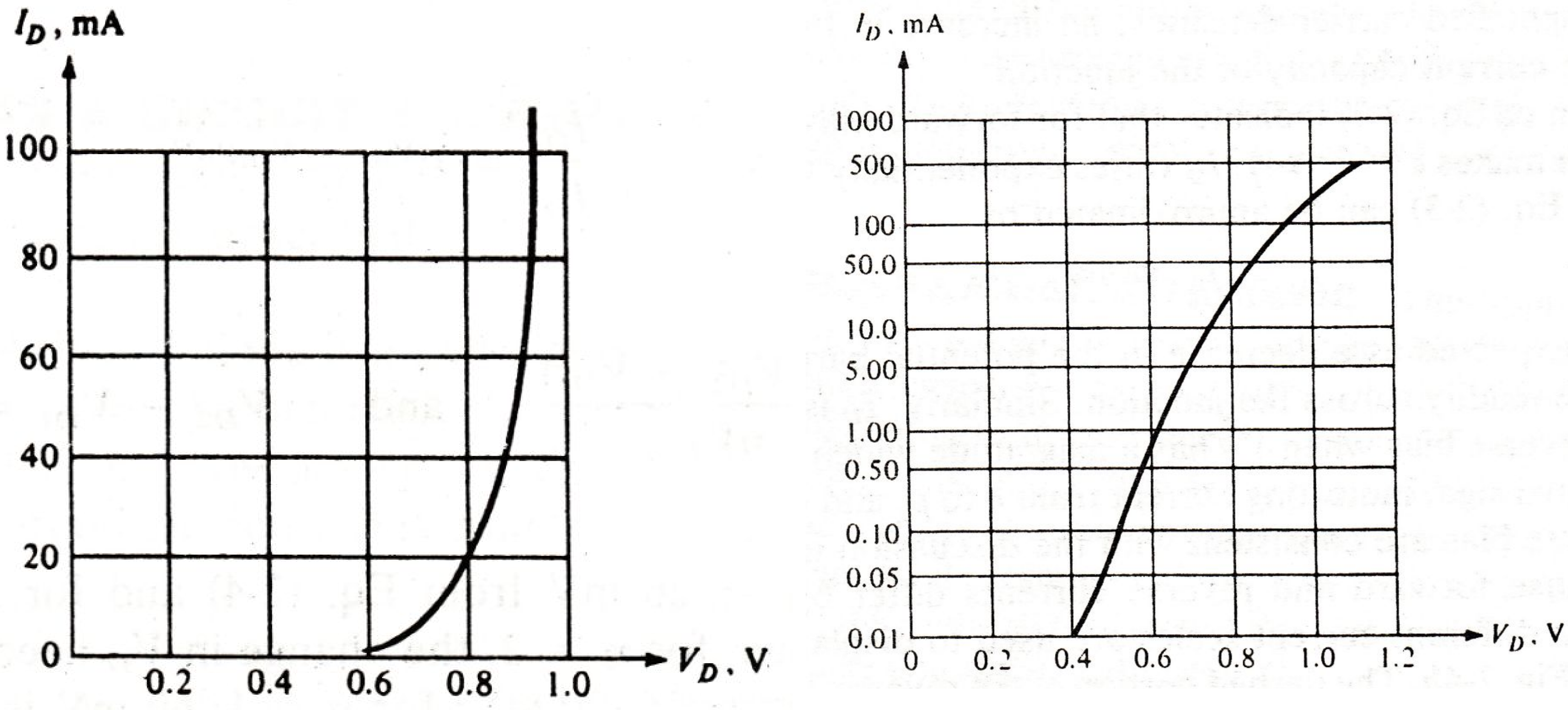


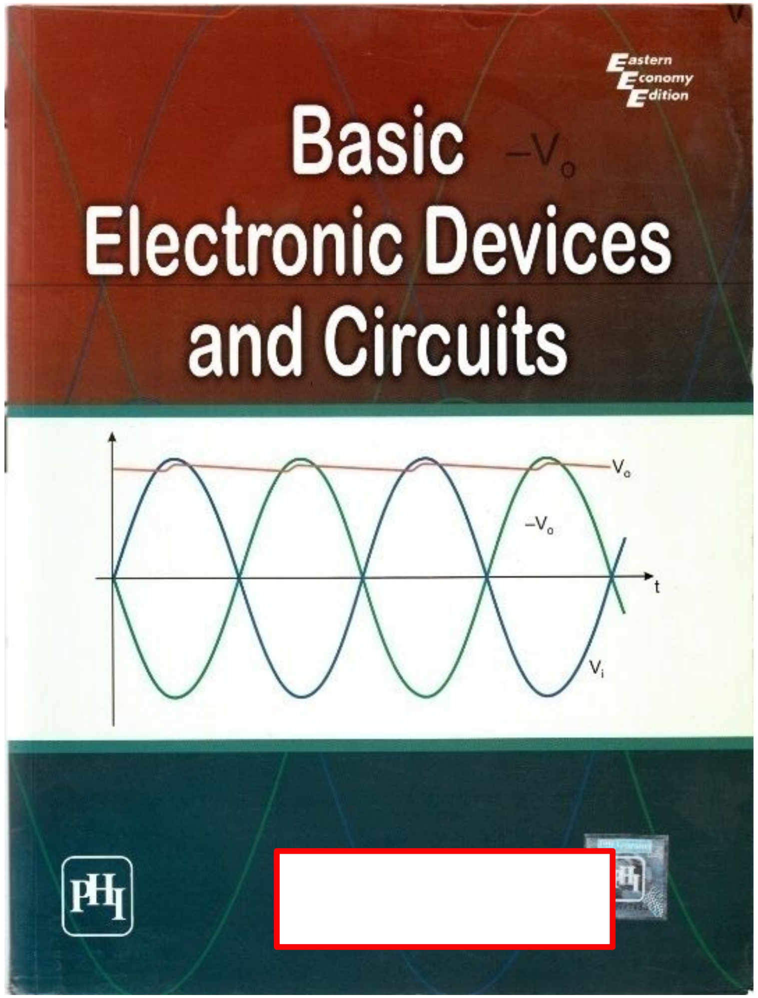
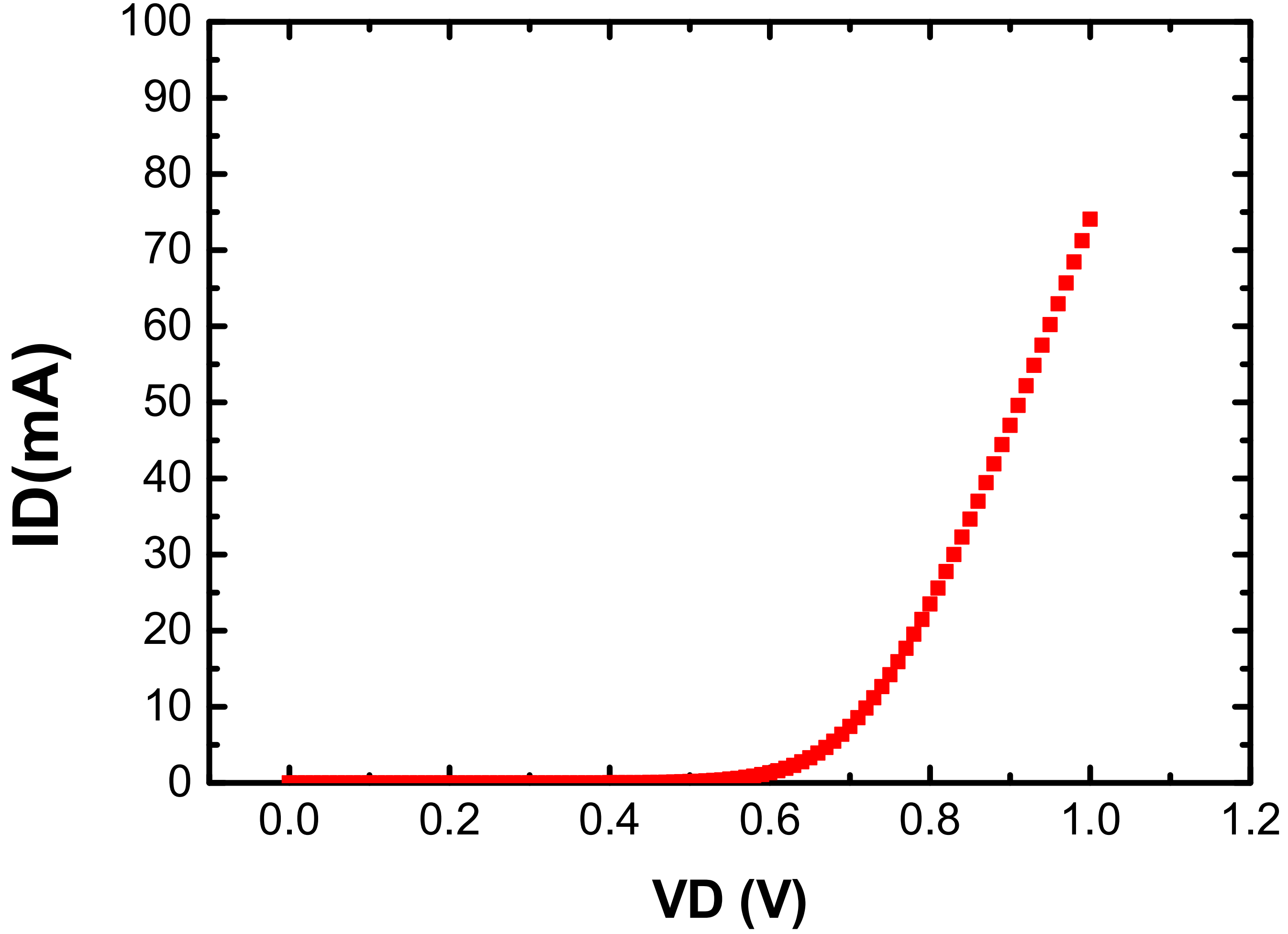
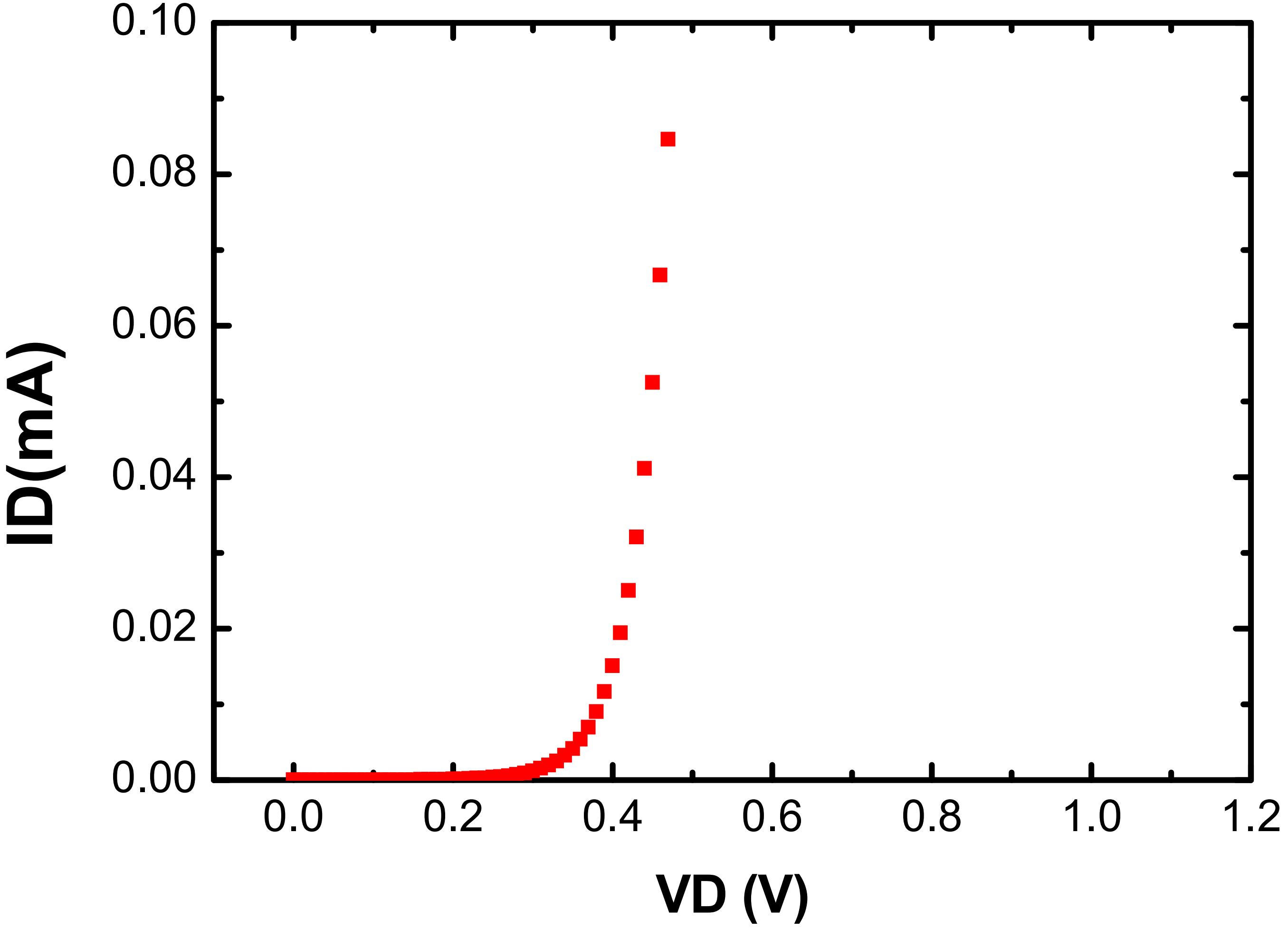


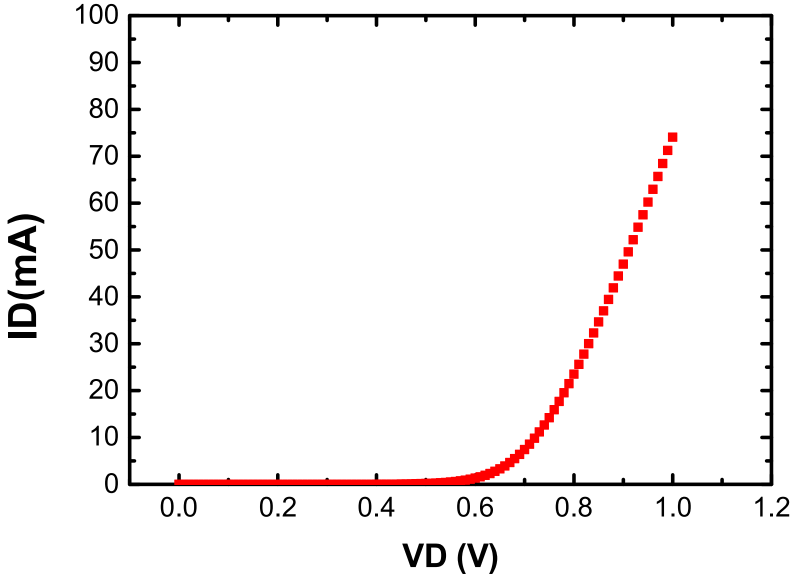
Figure 6.2 (a) shows the I–V curve under forward bias as obtained from the Shockley equation. Note that the current is negligibly small up to about 0.6 V and rises sharply beyond that. Under reverse bias, the Shockley equation predicts $I \approx -I_s$ which is negligibly small. However, as we have seen in Chapter 3, a real diode will

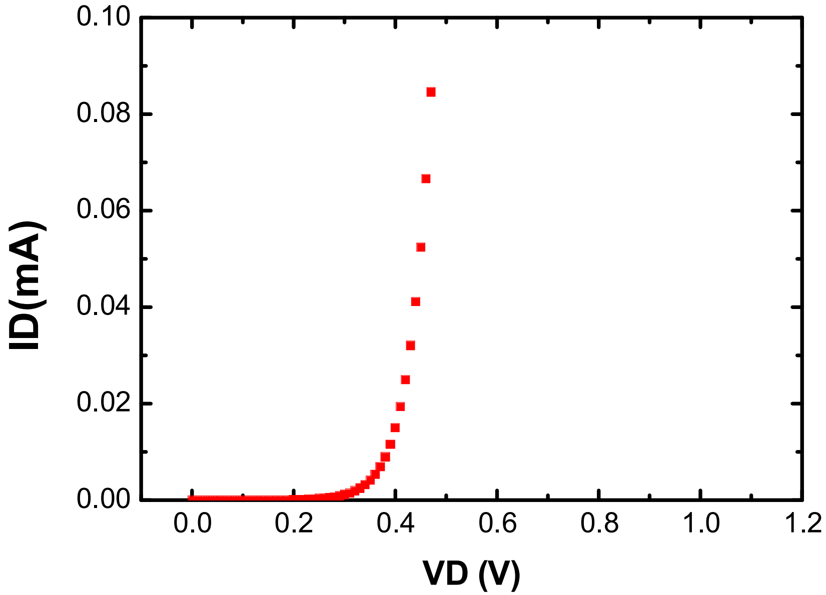


100
90
80
70
60
50
40
30
20
10
0
ID(mA)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
VD (V)

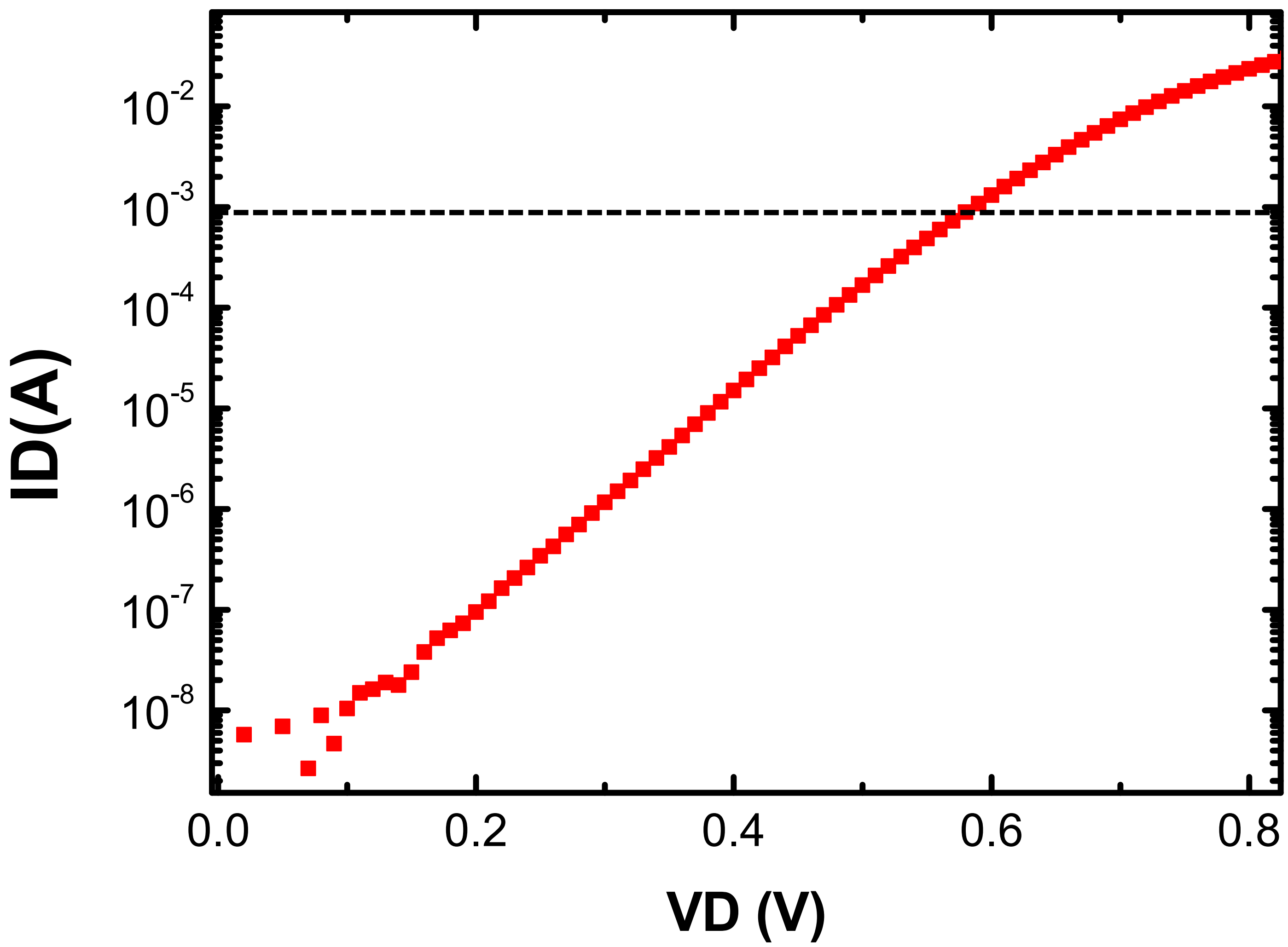


0.10
0.08
0.06
0.04
0.02
0.00
ID(mA)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
VD (V)

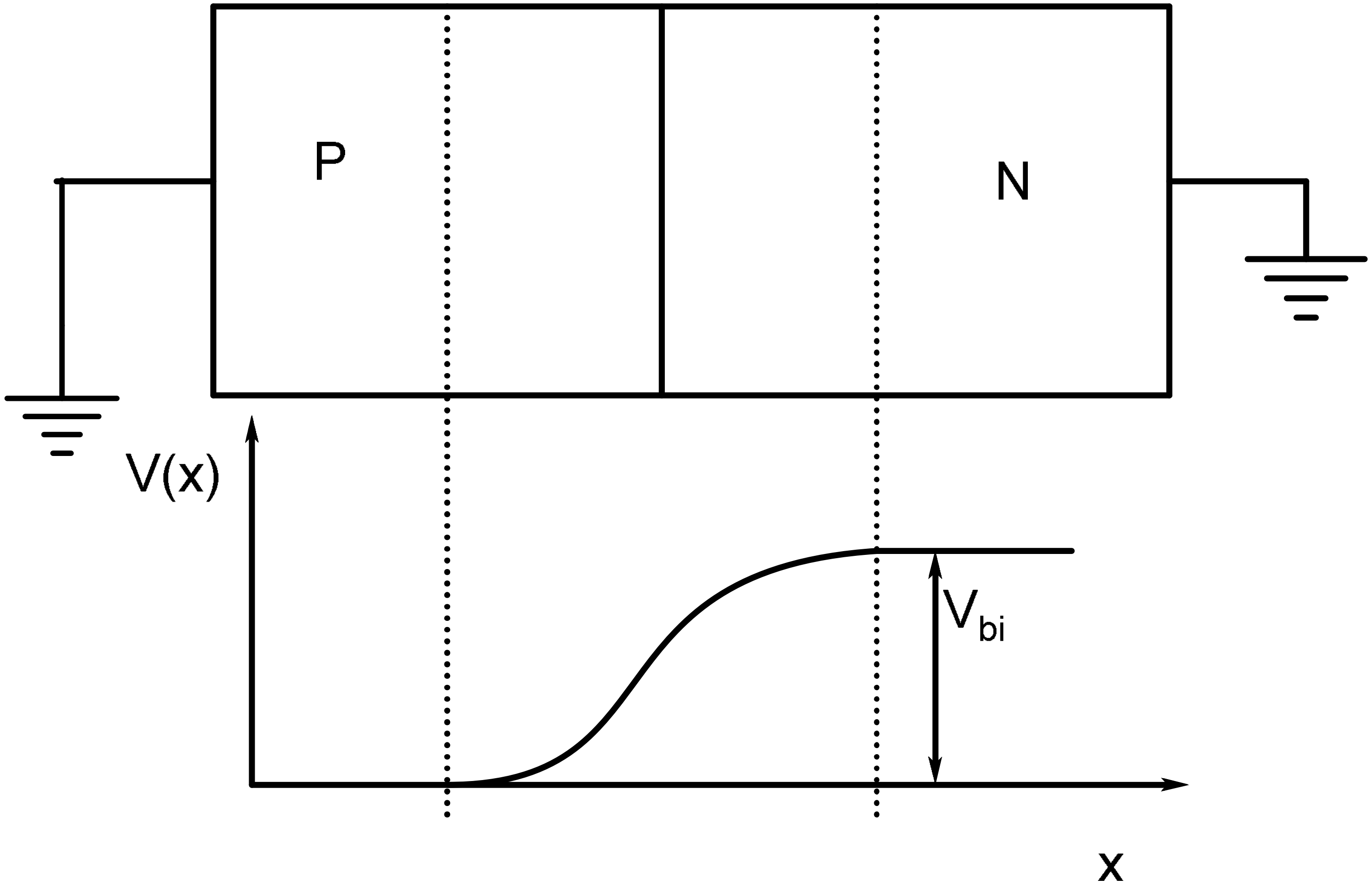




Both are identical diodes : 1N4007



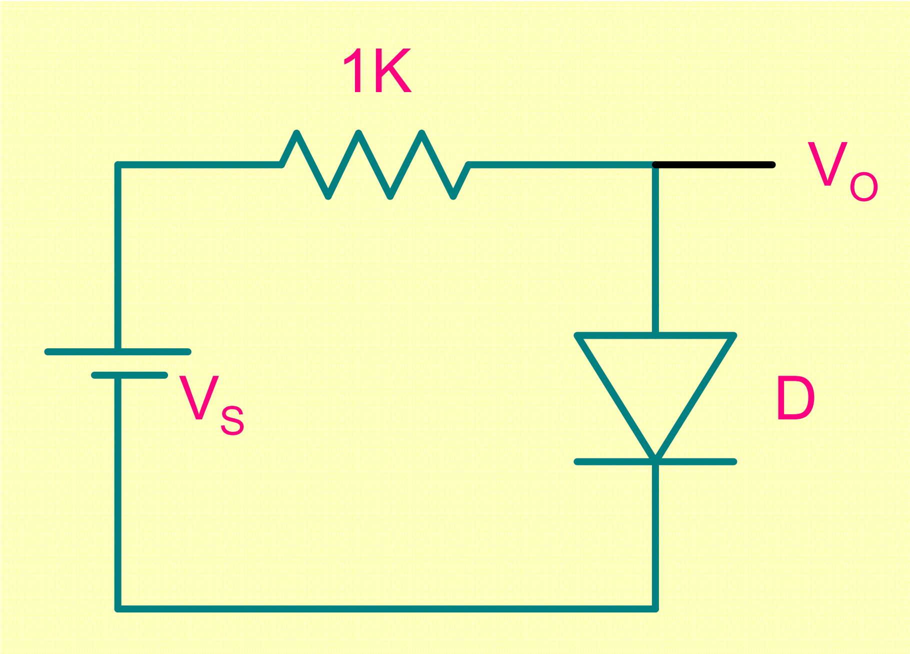
V_γ the cut-in or turn-on voltage depends on nature of diode and range of current considered



Misconception: $V_\gamma \sim V_{bi}$

"Learning is not just accumulation of knowledge
but the detection and correction of errors"

Constant diode voltage approximation becomes worse as applied voltage approaches the diode drop !



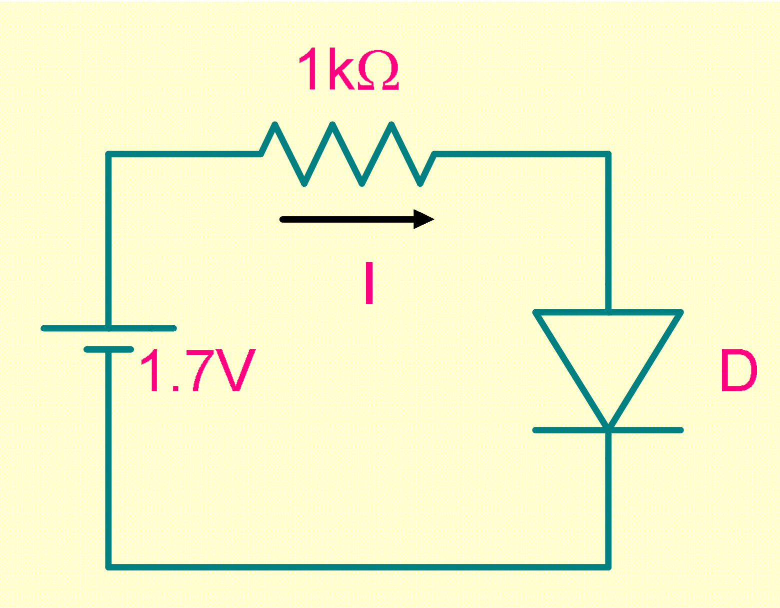
$$I = \frac{V - V_D}{R}$$

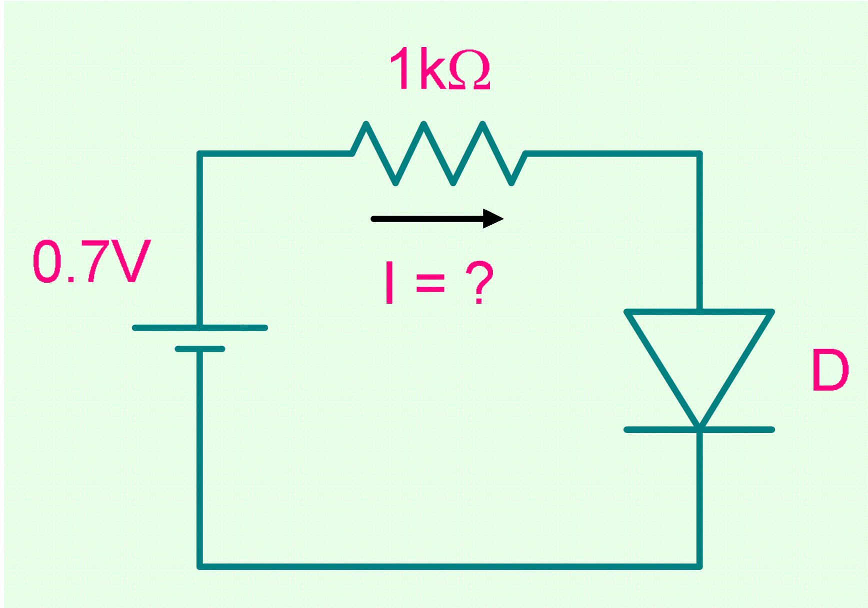
$$\Delta I = -\frac{\Delta V_D}{R}$$

$$\frac{\Delta I}{I} = -\left(\frac{\Delta V_D}{V - V_D}\right)$$

As $\mathbf{V}_s$ approaches $\mathrm{V_D} \rightarrow \left(\frac{\Delta I}{I}\right)$ increases

Error was ~9% with 1.7 V but 63% with 0.8V supply



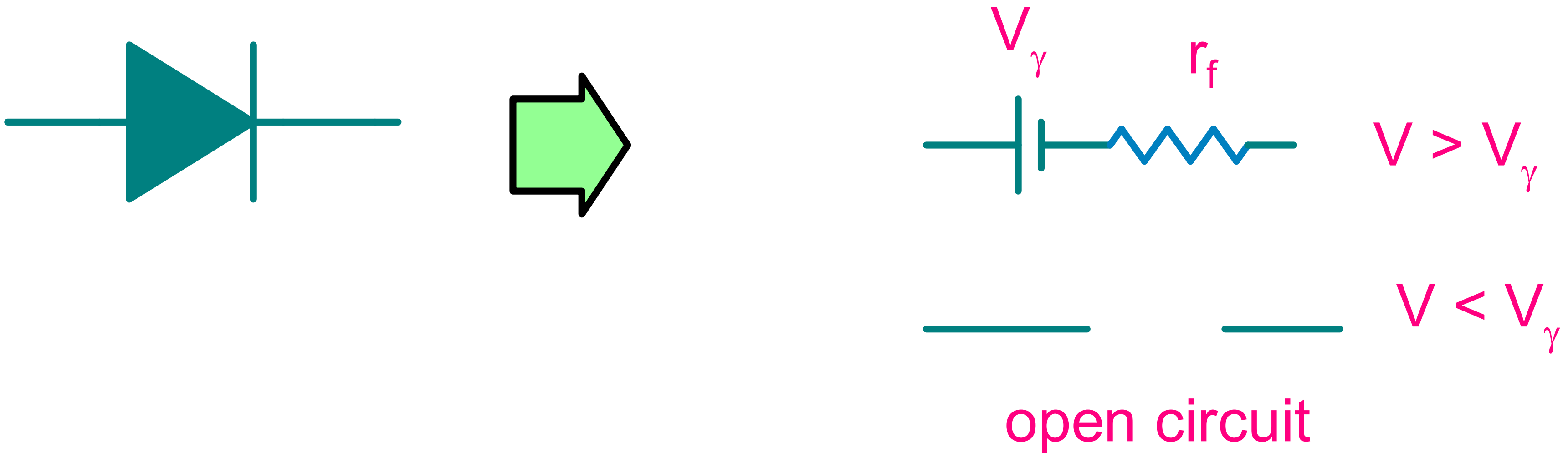


$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

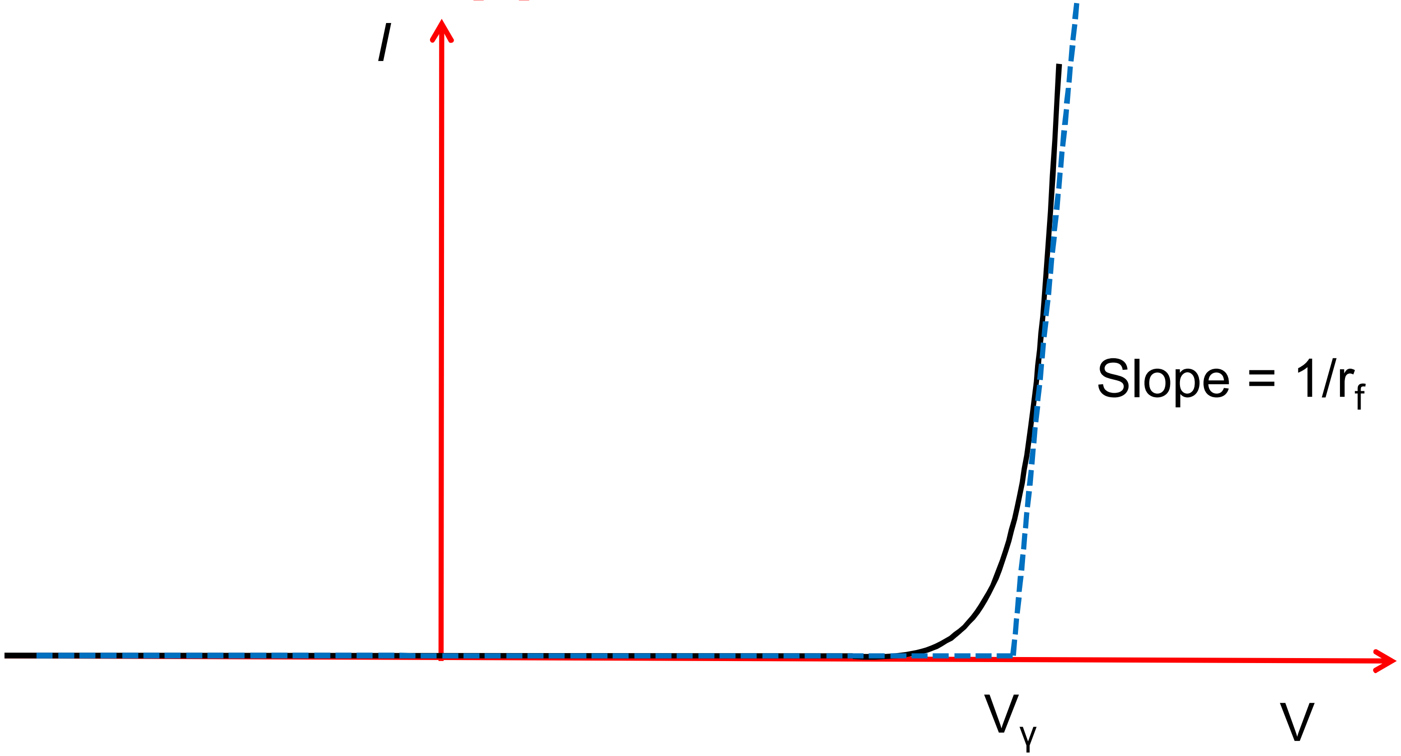
$$I_S = 2 \times 10^{-15}\ A$$

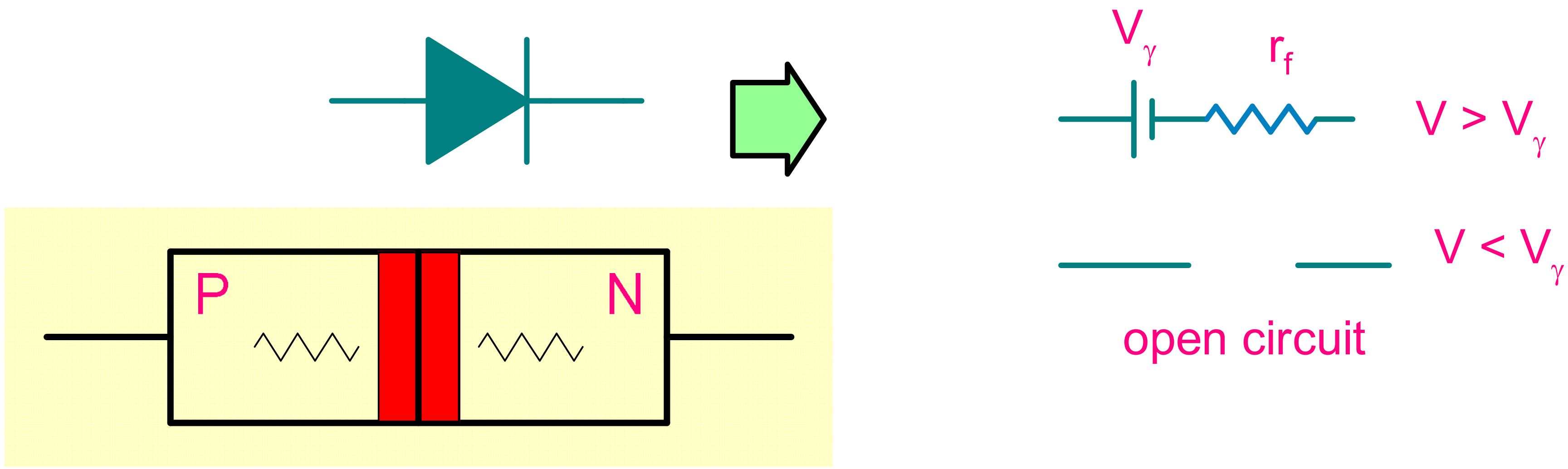
$$V_T = kT / q \cong 26\ mV \ \text{ at } \ \mathrm{T} = 300\mathrm{K}$$

A better Diode Model



Piece-Wise Linear approximation

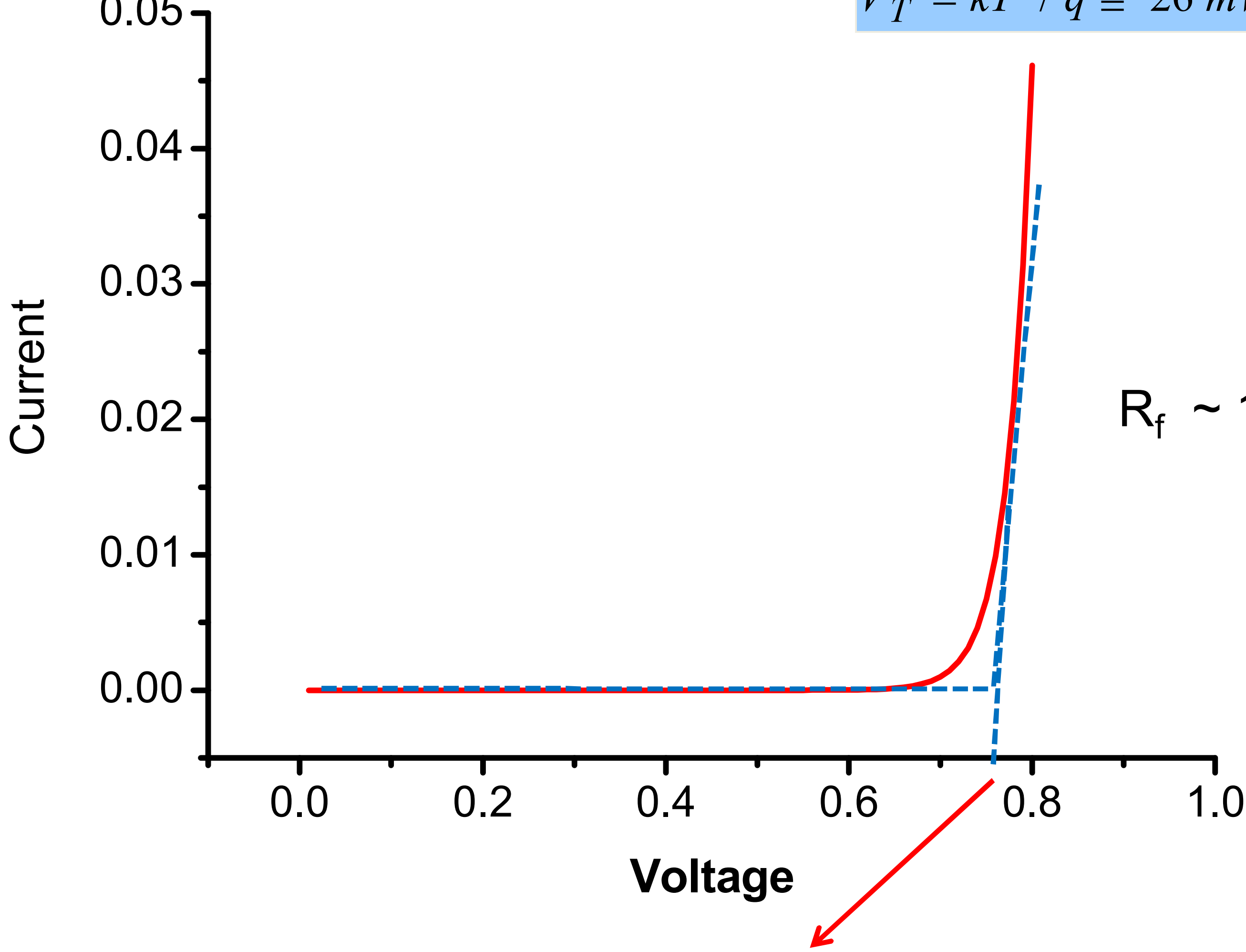




$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT / q \cong 26\ mV \quad \text{at } T = 300\text{K}$$



$R_f \sim 1.4\Omega$

$V_\gamma = 0.75V$

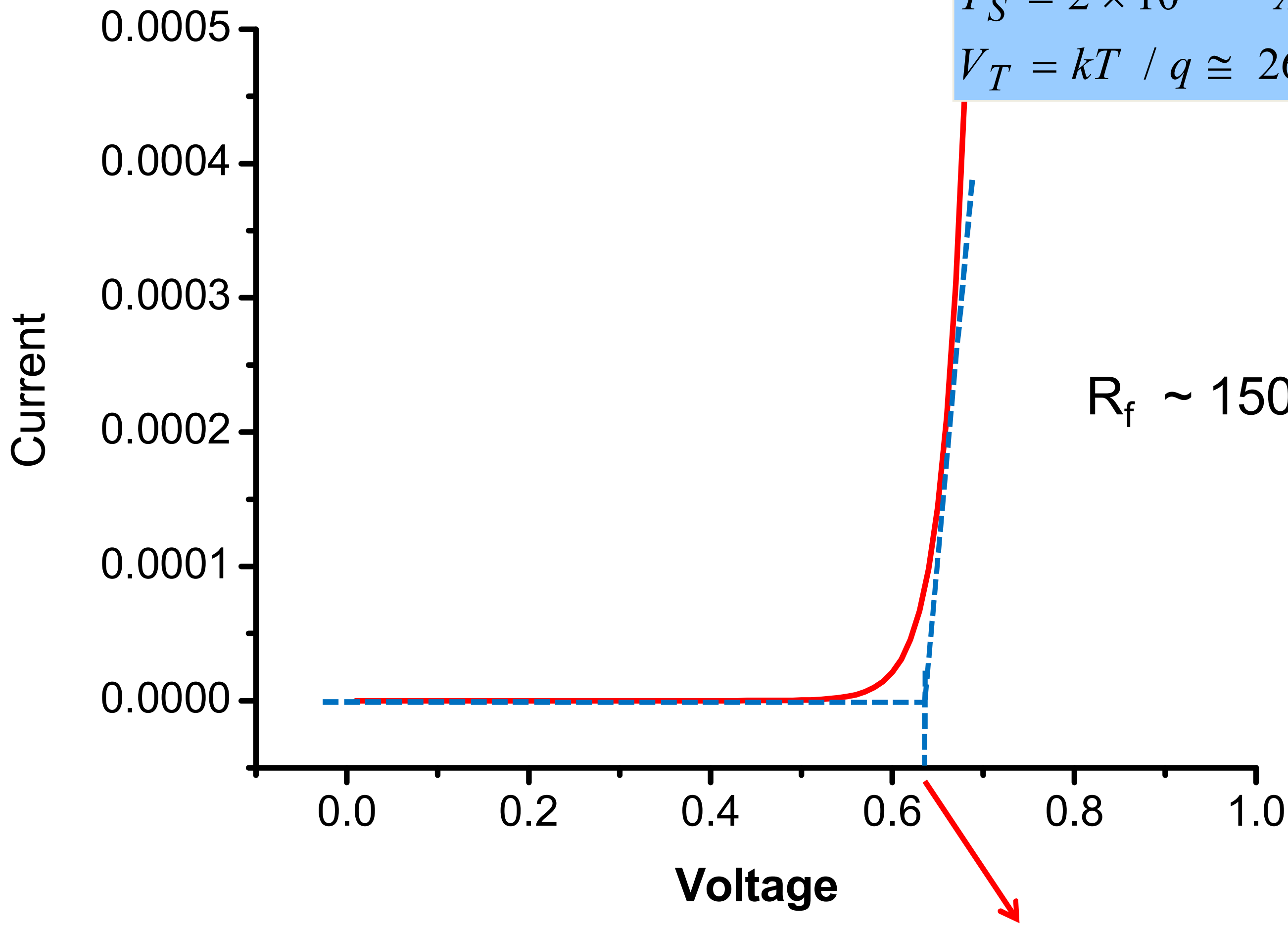
Current ~ 25mA

$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT / q \cong 26\ mV \ \text{ at } \ \mathrm{T} = 300\mathrm{K}$$

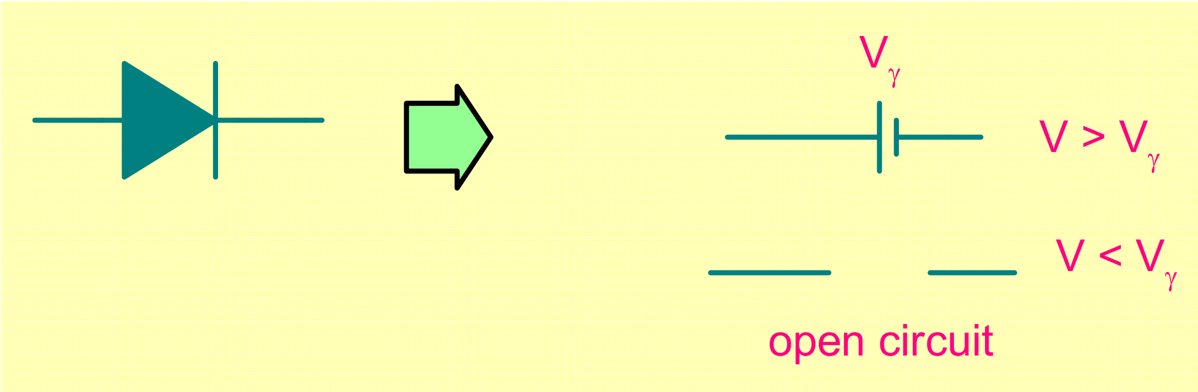
Current ~ 0.25mA



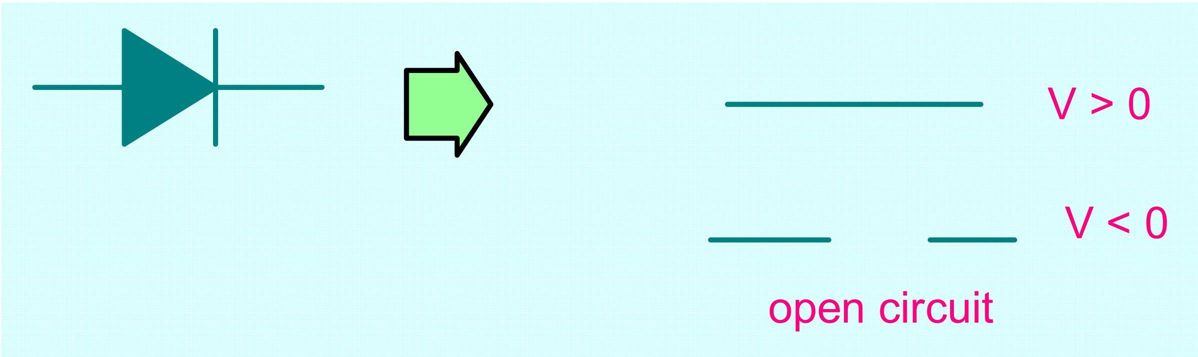
R_f ~ 150Ω

V_γ = 0.63V

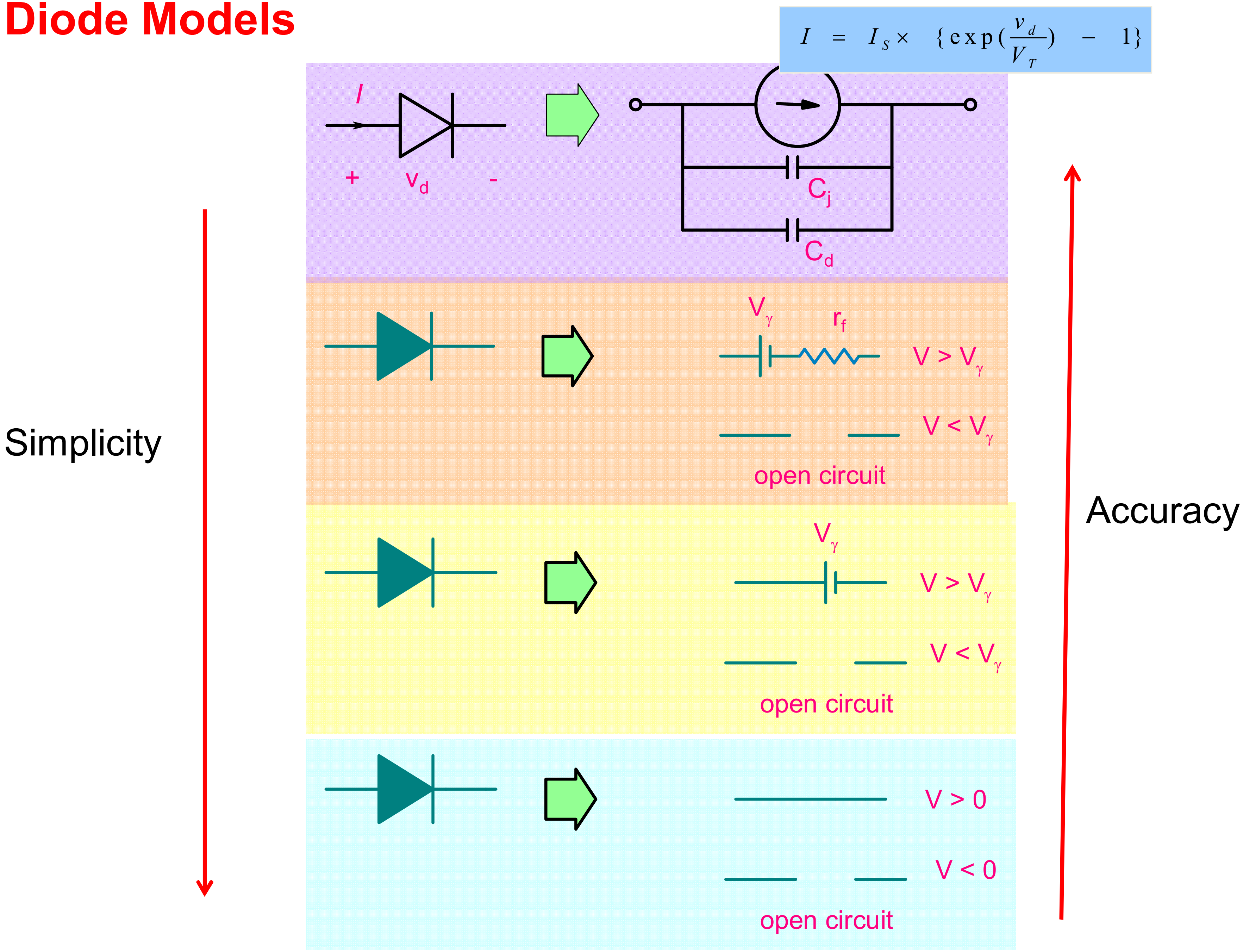
Even Simpler Diode Models



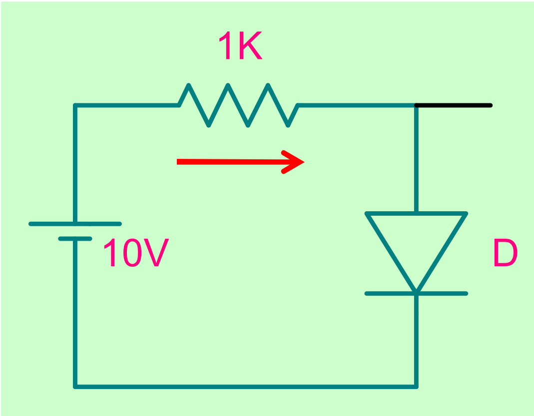
Ideal diode model

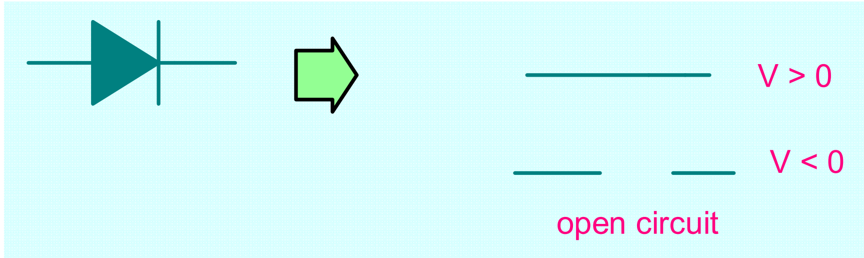


Diode Models



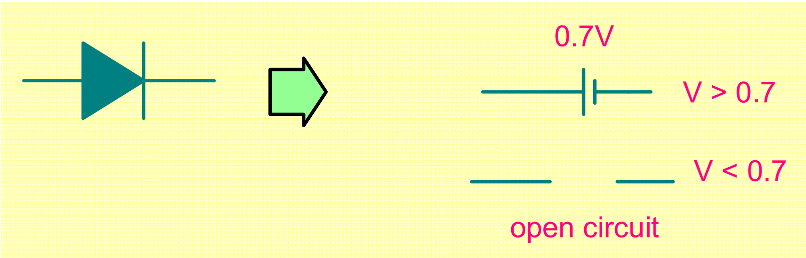
Use the simplest model that will yield results with desired accuracy





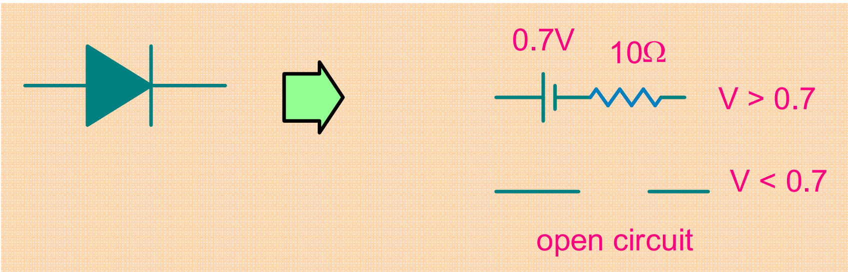
$$I = 10/10^3 = 10\,mA$$

8.2%



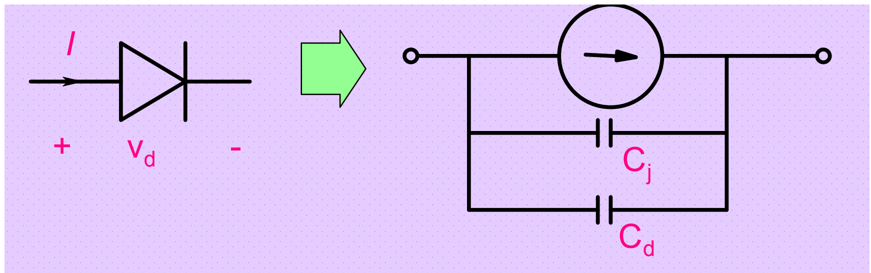
$$I = (10-0.7)/10^3 = 9.3\,mA$$

0.65%



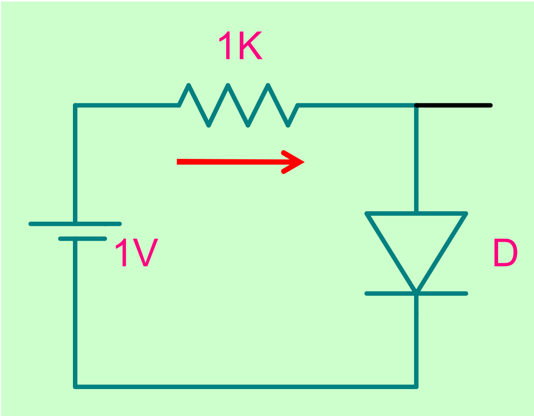
$$I = (10-0.7)/(10^3+10) = 9.208\,mA$$

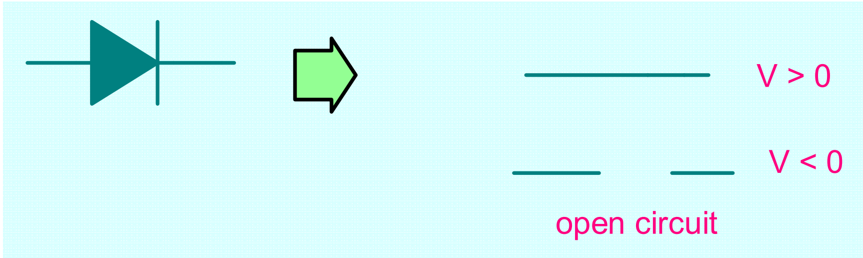
-0.34%



$$I = 9.24\,mA$$

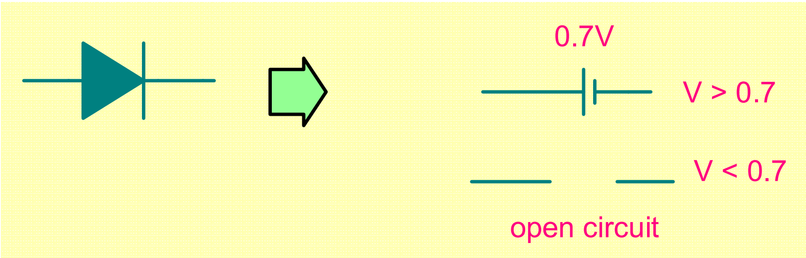
Use the simplest model that will yield results with desired accuracy





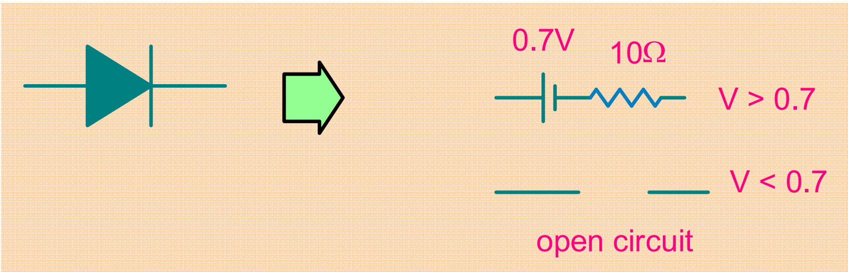
$$I = 1/10^3 = 1\,mA$$

~200%



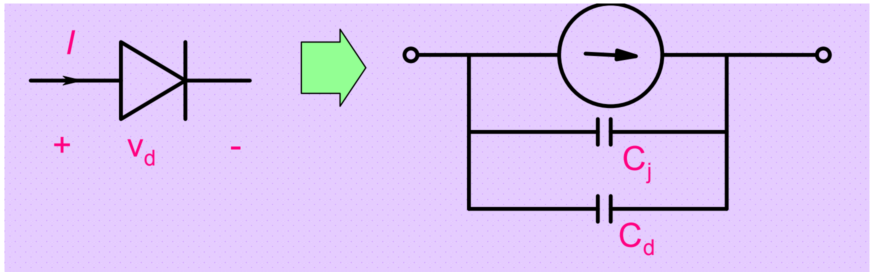
$$I = (1 - 0.7)/10^3 = 0.3\,mA$$

-8.8%



$$I = (1 - 0.7)/(10^3 + 10) = 0.297\,mA$$

-9.7%



$$I = 0.329\,mA$$

Diode: Small Signal Model (dc or low frequency)

Forward Bias

$$I_d = I_s e^{\frac{V_d}{nV_T}}$$

$$I_{DQ} + i_d = I_s e^{\frac{V_{DQ}+v_d}{nV_T}}$$

$$i_d = I_{DQ}\left(e^{\frac{v_d}{nV_T}} - 1\right)$$

$$i_d = I_{DQ}\left(\frac{v_d}{nV_T} + \frac{{v_d}^2}{2\left(nV_T\right)^2} + \ldots\ldots\ldots\right)$$

Small signal approx : $\dfrac{v_d}{nV_T} << 1$

$$i_d = I_{DQ}\left(\frac{v_d}{nV_T} + \frac{v_d^{\,2}}{2\left(nV_T\right)^2} + \dots\dots\dots\right)$$

$$i_d \cong \left(\frac{I_{DQ}}{nV_T}\right) v_d$$

$$i_d = \frac{v_d}{r_d}\ ;\ r_d = \frac{nV_T}{I_{DQ}}$$