1897
VICTORIA UNIVERSITY OF
WELLINGTON
TE HERENGA WAKA
NEW ZEALAND

XMUT204 Electronic Design

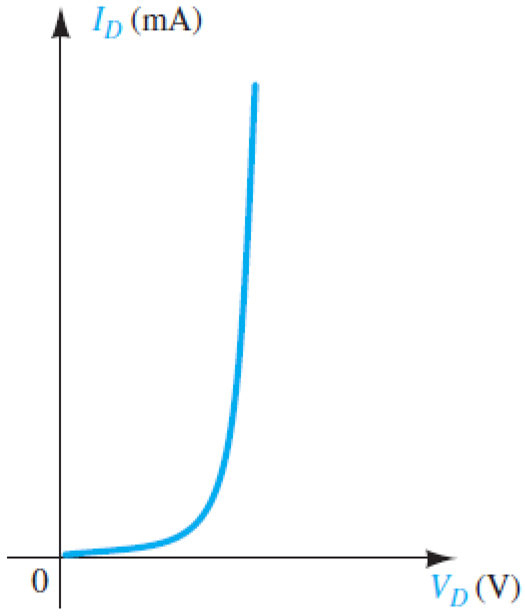
Lecture 2b - Diode Models and Circuit Analysis

Overview

1. Load line analysis.
2. Ideal diode model.
3. States of diode operation.
4. Refining ideal diode model.
5. More sophisticated model.

1. Load Line Analysis

- A graphical technique to find operating current and voltages in a circuit -> important for circuit & device design.
- The analysis is based of V-I curve graph superimposed with a straight line derived from circuit parameters such as voltage source and resistance.
- Simultaneously plotting two graphs and finding their intersection.

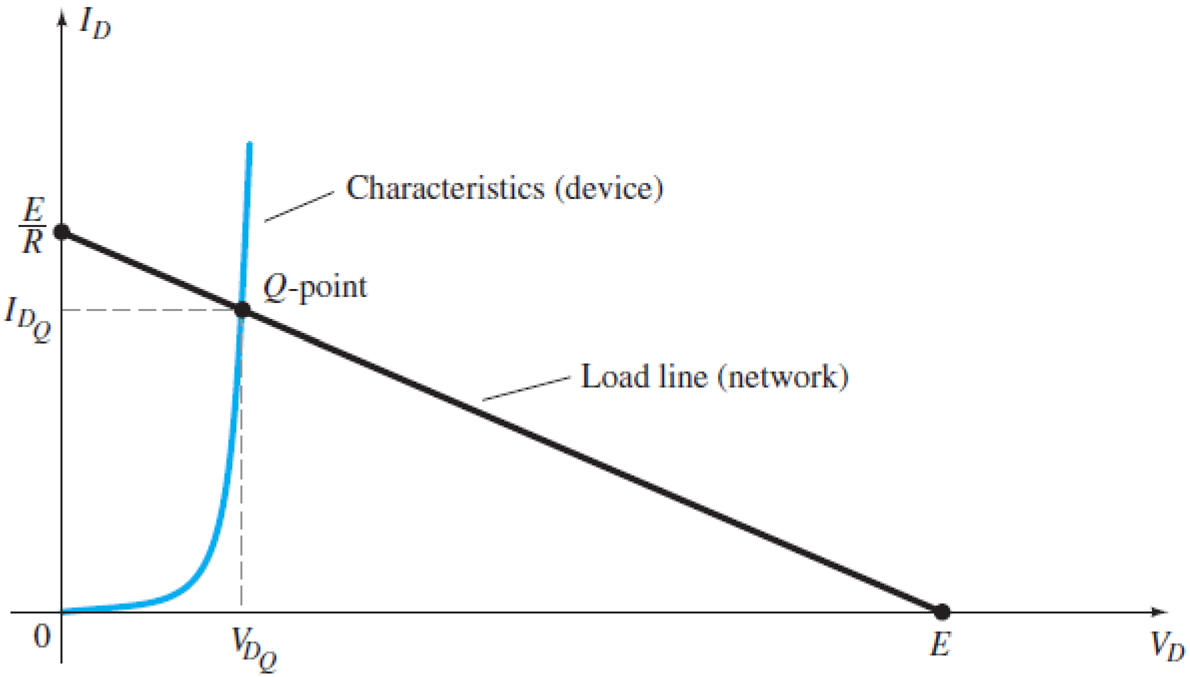


(b)

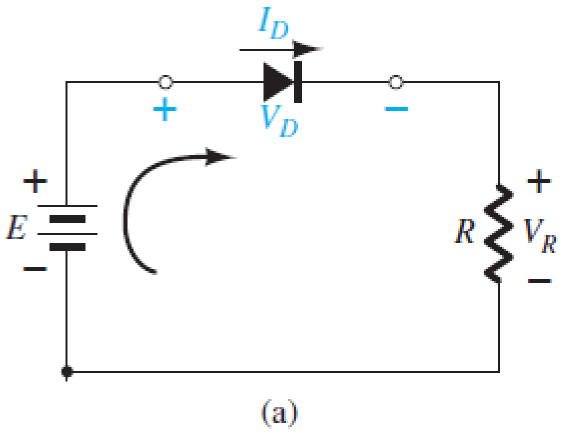
1. Load Line Analysis

In case of a diode:

- I-V curve for the specific diode in the circuit (non-linear).
- Line defined by KVL applied around the circuit loop.



1. Load Line Analysis (cont.)

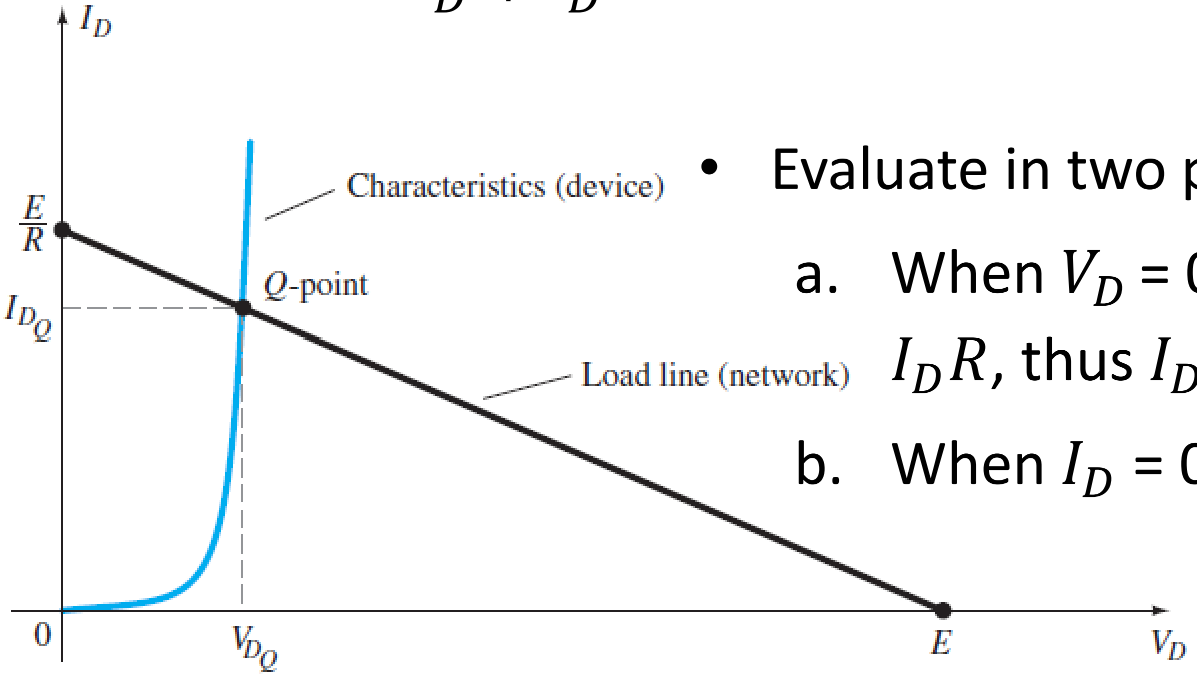


- Apply KVL across the circuit:

$$E - V_D - V_R = 0$$

- So

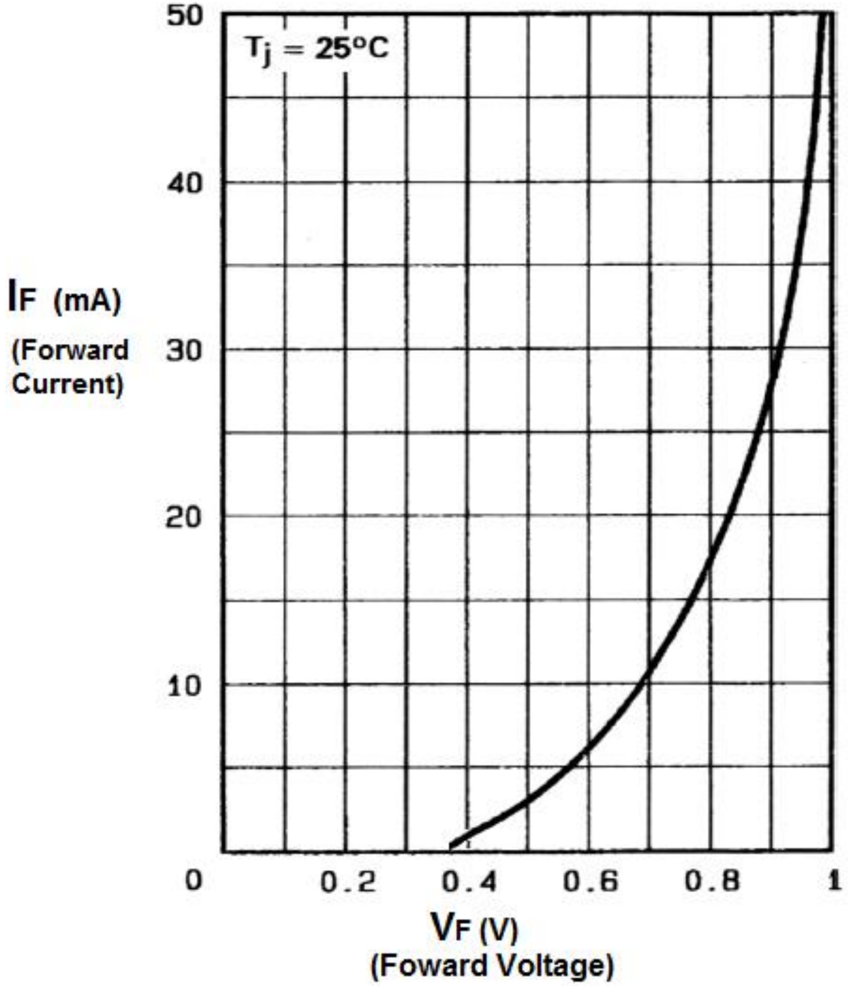
$$E = V_D + I_D R$$

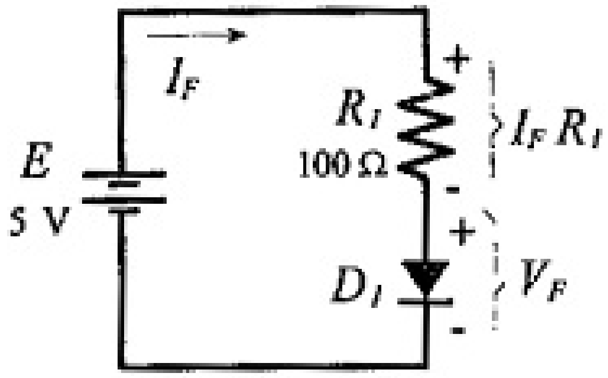


- Evaluate in two points:
  a. When $V_D = 0$ V, we have $E = I_D R$, thus $I_D = E/R$.
  b. When $I_D = 0$, we have $V_D = E$.

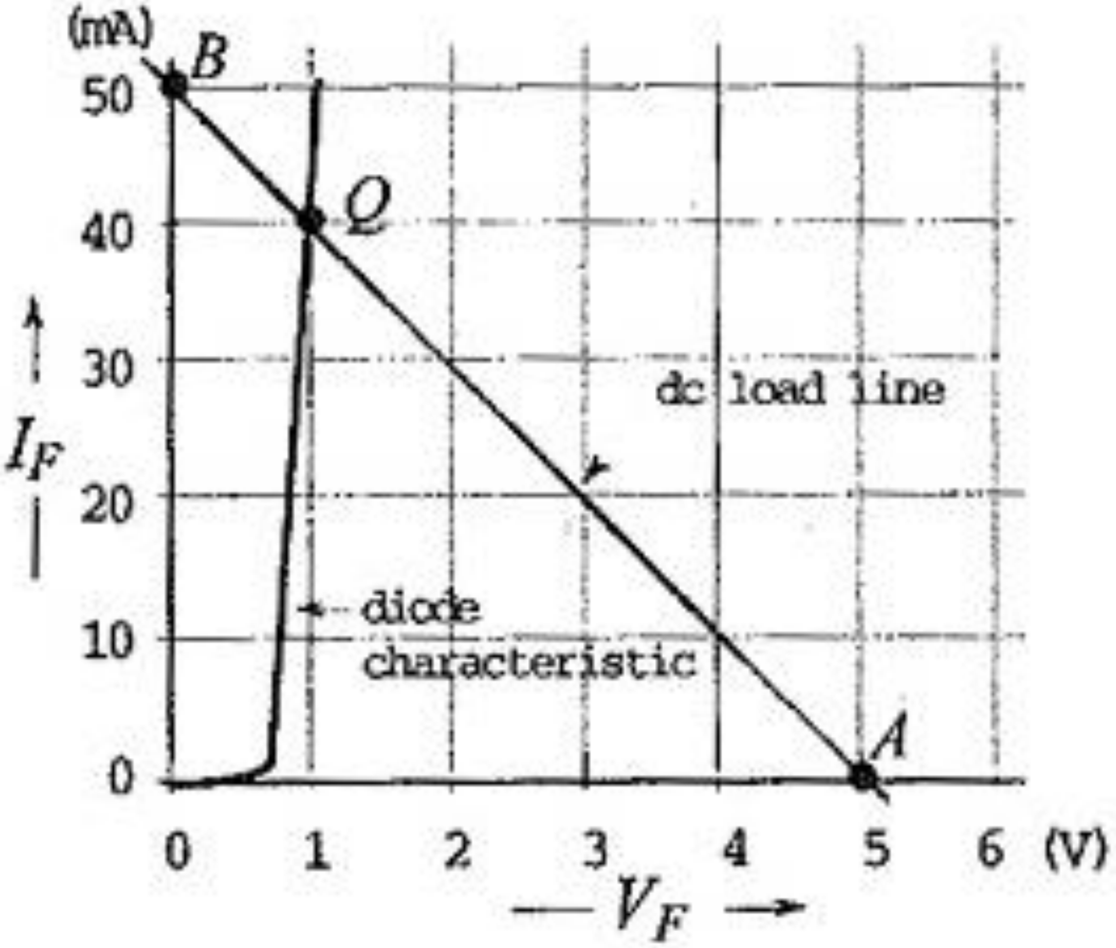
Example for Tutorial 1 – Diode Load Line

1. Sketch the load line if the diode is forward biased by a 10 V power supply and a 1 kΩ current limiting resistor is placed in series. Determine in your sketch the operating condition of the diode. [5 marks]





- The graph for the load line analysis is given in the figure below



- Extreme points in the graph for the biasing of the diode are:

$$I_F(\text{max}) = \frac{V_F}{R_D} = \frac{5}{100} = 50\ \text{mA}$$

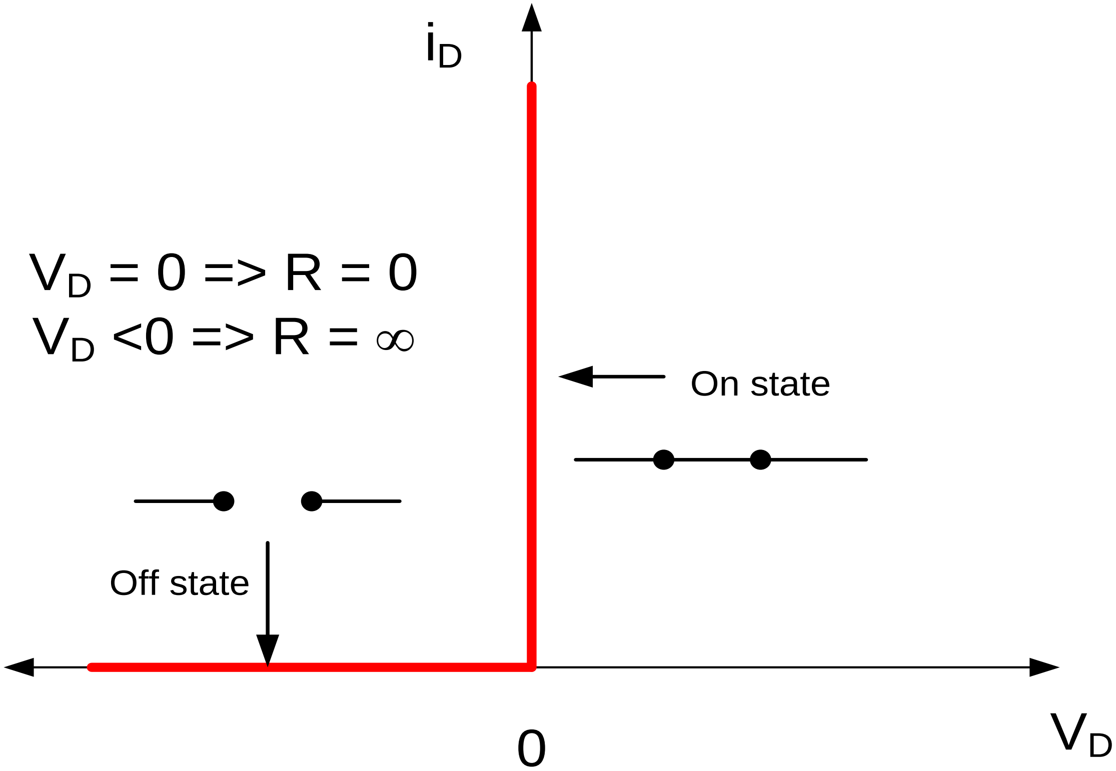
And

$$V_F(\text{max}) = I_F \times R_D = (50\ \text{mA})(100\ \Omega) = 5\ \text{V}$$

- Notice that the maximum forward voltage of the diode is 5 V at point A in the graph and the maximum forward current of the diode is 50 mA at point B.
- The recommended operating condition of the diode is supposed to be designed at point Q in the graph.

2. The Ideal Diode Model

- An element that has zero resistance (short circuit) in forward bias and infinite resistance (open circuit) in reverse bias.
- This model allows current to flow in only one direction and is only dependant on the polarity of the bias voltage.



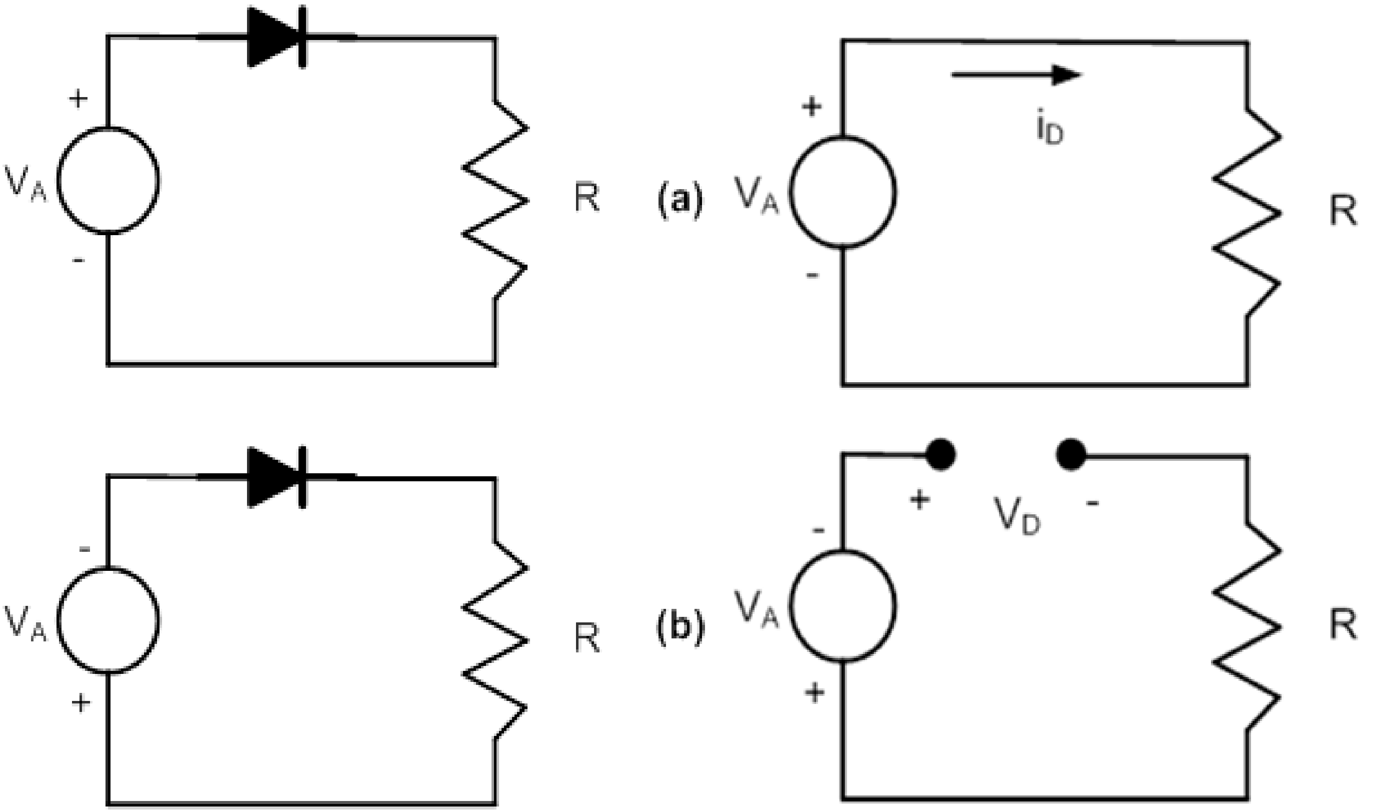
$V_D = 0 \Rightarrow R = 0$

$V_D < 0 \Rightarrow R = \infty$

On state

Off state

3. Ideal Diode Model Operation



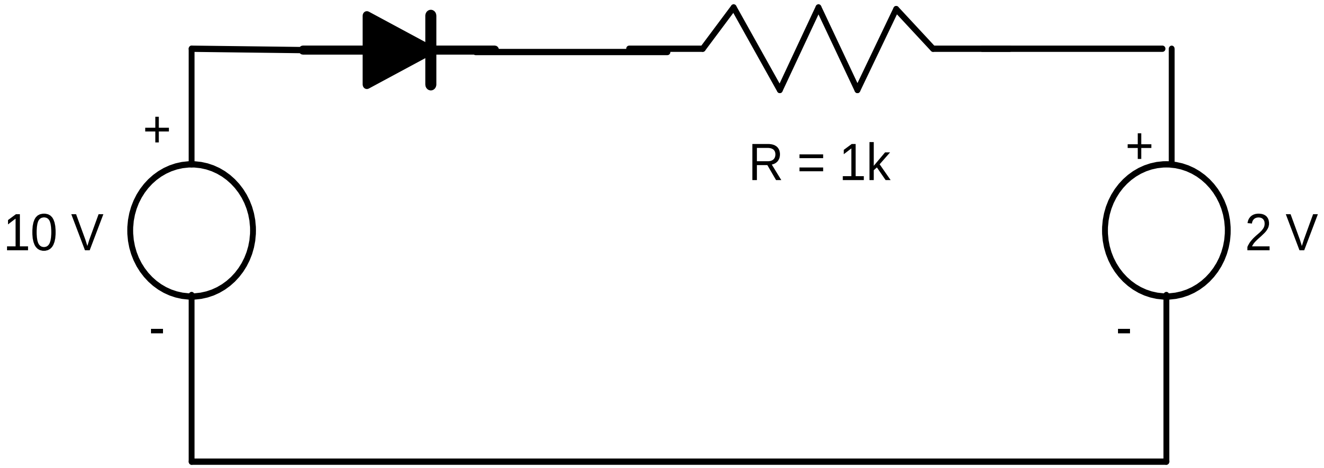
Forward bias

Reverse bias

- The ideal diode models on the right for a diode in forwards bias (a) and reverse bias (b).

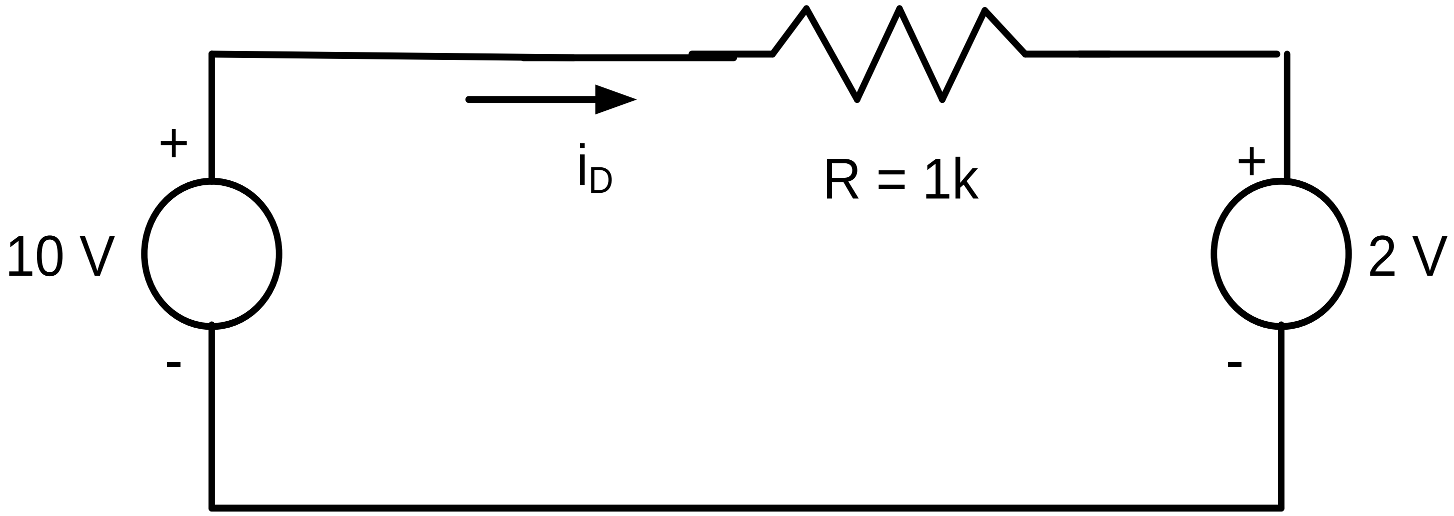
The Assumed States Method (using Ideal Diode Model)

1. Identify all possible state combinations.
2. Analyse each state by replacing the diode with the corresponding short or open circuit.
3. Determine which state is consistent for each diode: ON with i_D > 0 or OFF with V_D < 0.



State 1: Diode ON

- The diode is now simply a short and a KVL around the circuit will give: $10 - i_D R - 2 = 0$, so that i_D = 8 mA.
- As this value of i_D is consistent with the forward biased case, it would appear that this is the correct state of the diode.

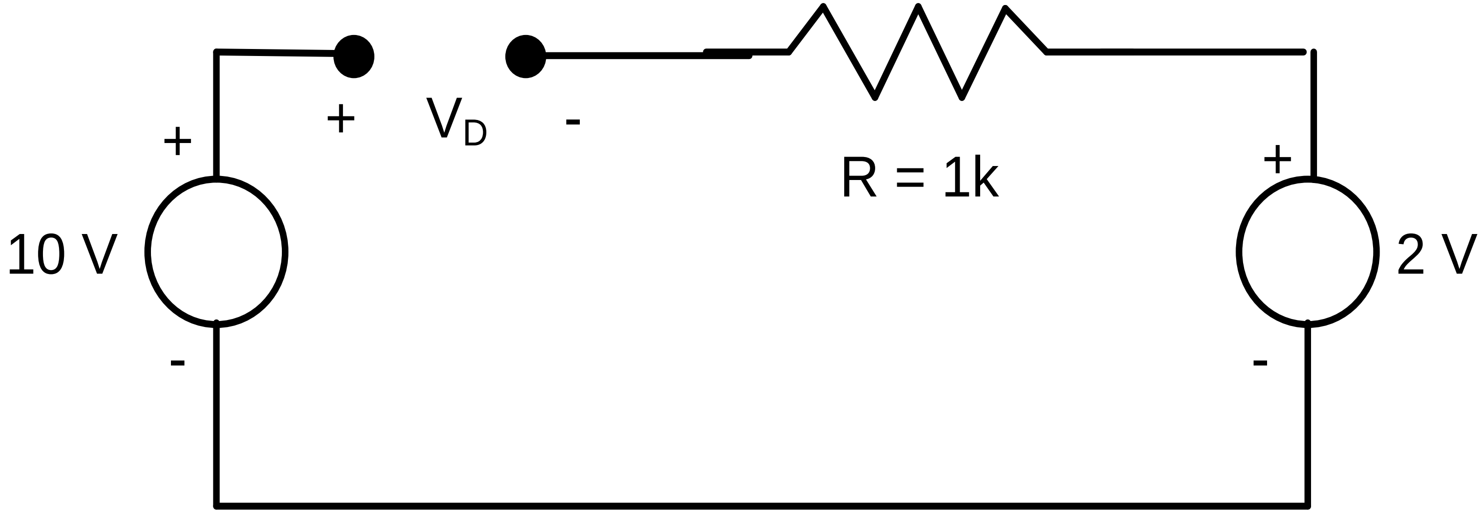


State 2: Diode OFF

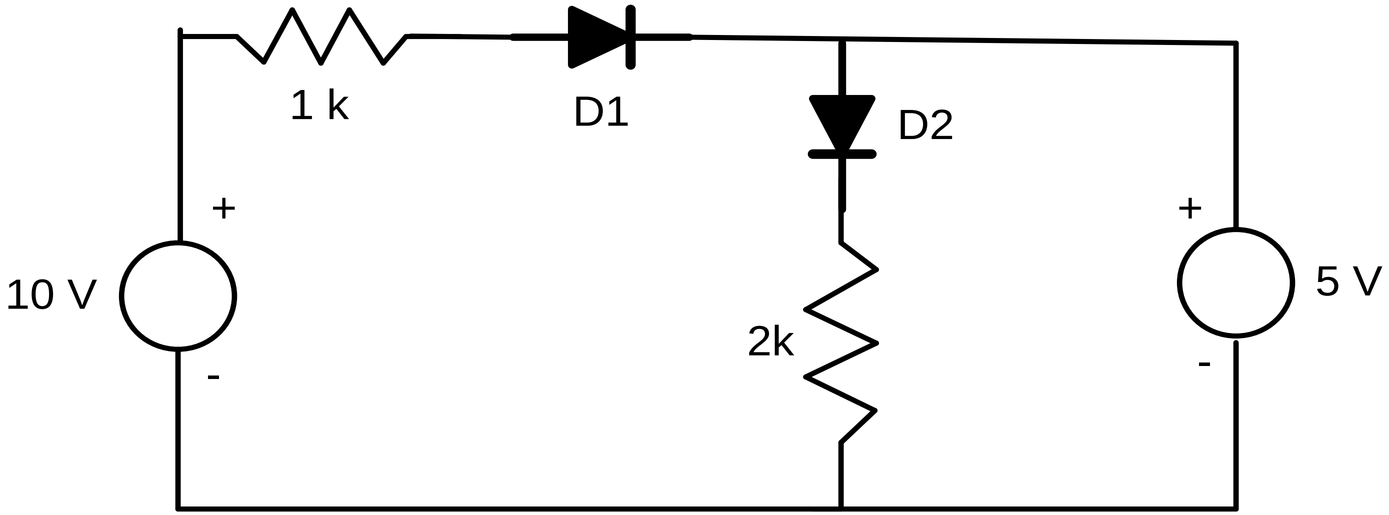
- The diode is now an open circuit and a KVL around the circuit will now give:

$$10 - V_D - i_D R - 2 = 0 \quad \text{(with } i_D = 0\text{)}$$

- We can then calculate V_D to yield V_D = 8 V.
- This is not consistent with the assumed state of the diode OFF ($V_D < 0$) so we can accept that *this is not the state of the diode*.



Analysis of Assumed States Method (with two diodes)

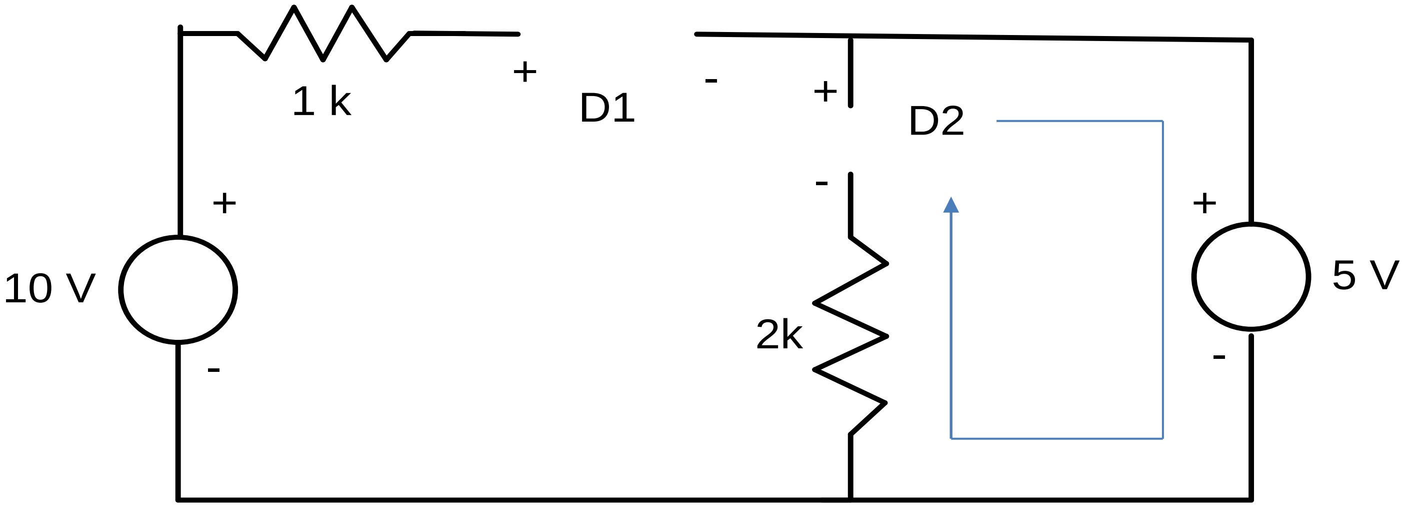


State	Diode 1	Diode 2	Consistent?
1	OFF	OFF	No
2	OFF	ON	No
3	ON	OFF	No
4	ON	ON	Yes

First assumed state: Both diodes OFF

- Perform a KVL around any of the loops.
- For the right-hand loop, we will get:

$$5 - V_{D_2} - V_{R_{2k\Omega}} = 0$$



First assumed state: Both diodes OFF (cont.)

- But, the voltage over the 2 kΩ resistor is zero, so that the voltage over diode D_2 will be:

$$V_{D_2} = 5\text{ V}$$

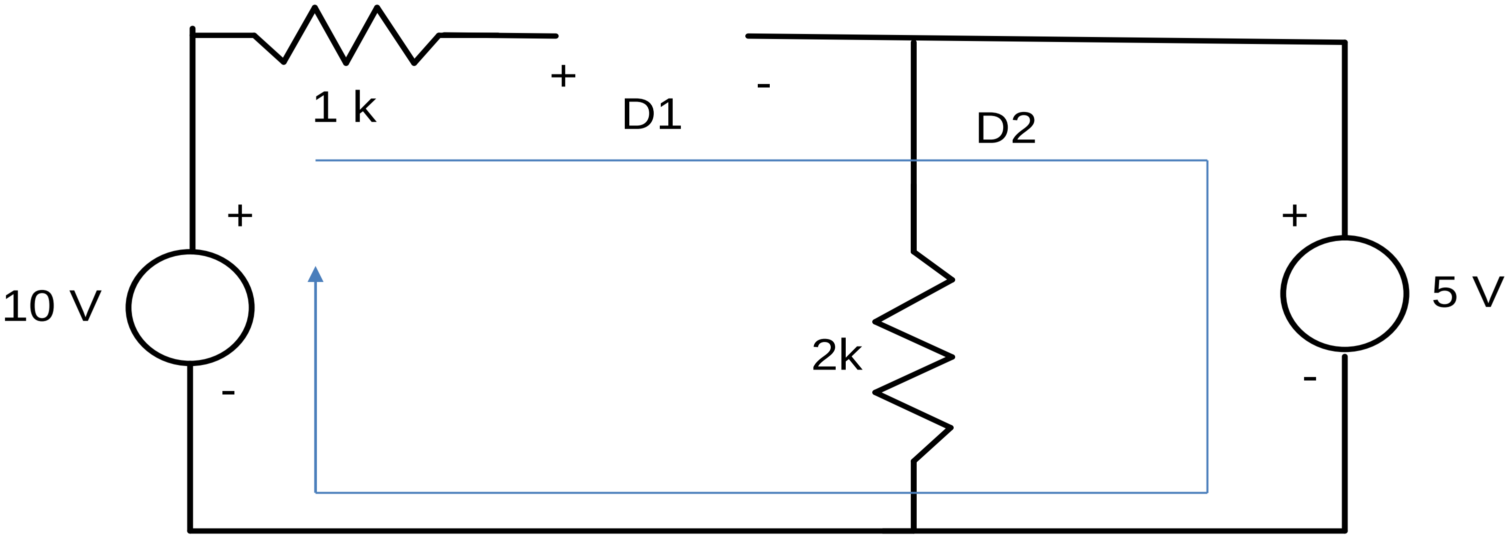
- This result that the voltage over D_2 is positive is not consistent with our model that the voltage over a diode that is OFF must be < 0 V.
- So that the *first assumed state is not consistent*.

State	**Diode 1**	**Diode 2**	**Consistent?**
1	OFF	OFF	No

Second assumed state: D_1 = OFF and D_2 = ON

- We can do a KVL by going around the outer loop:

$$10 - V_{R_{1\mathrm{k}\Omega}} - V_{D_1} - 5 = 0$$



Second assumed state: D_1 = OFF and D_2 = ON (cont.)

- But the current through the 1 kΩ resistor will be zero so $V_{R_{1\mathrm{k}\Omega}}$= 0 and we have:

$$V_{D1} = -5 + 10 = 5\text{ V}$$

- However, this calculation that V_{D1} = 5 V which is > 0 V is not consistent with the second assumed state which was that D_1 is OFF (meaning V_{D1} must be < 0 V).
- So that *this state is not consistent*.

State	**Diode 1**	**Diode 2**	**Consistent?**
2	OFF	ON	No

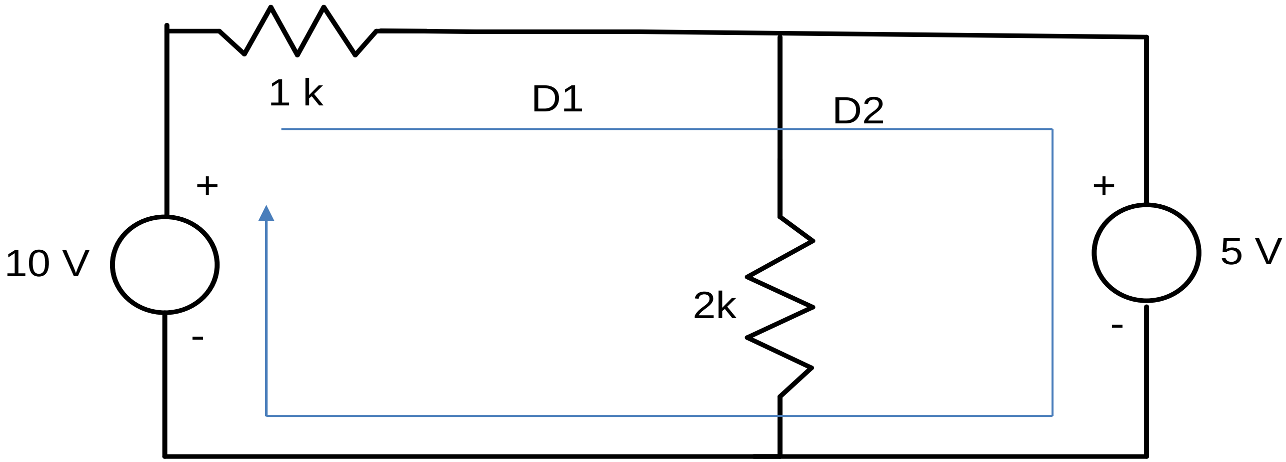
Third assumed state: D_1 = ON and D_2 = OFF

- We have already shown for State 1 that the case of D_2 = OFF is *not consistent*.
- So without having to do any calculations we can say:

States	**Diode 1**	**Diode 2**	**Consistent?**
3	ON	OFF	No

Fourth assumed state: D_1 On and D_2 On

- The last remaining state will be both the diodes on, yielding a circuit containing two shorts as follows:



- A KVL can be written for the outer loop as:

$$10 - (1000)I_{D1} - 5 = 0$$

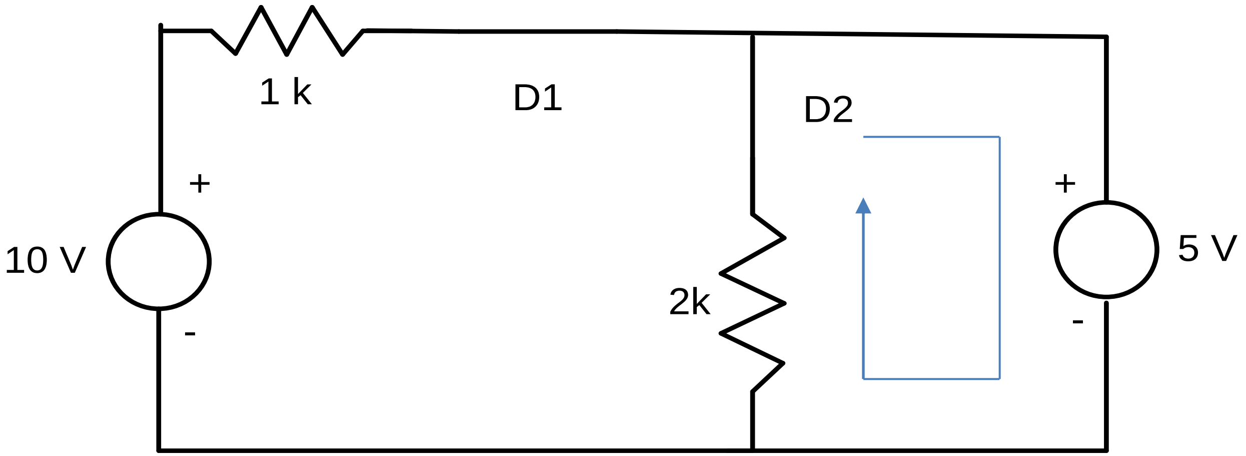
- Solving for I_{D1}, we get I_{D1} = 5/1000 = 5 mA.

Fourth assumed state: D_1 On and D_2 On (cont.)

- This value of $I_{D1} > 0$ is then consistent with a diode that is on and so far this state seems consistent.
- We can also evaluate the right hand loop by KVL:

$$5 - (2000)I_{D_2} = 0 \text{ so that } I_{D_2} = 5/2000 = 2.5 \text{ mA}$$

- Value is again consistent with a diode that is ON
- State 4 with both diodes ON is the *only consistent state* of the circuit.



Fourth assumed state: D_1 On and D_2 On (cont.)

State	**Diode 1**	**Diode 2**	**Consistent?**
4	ON	ON	Yes

- The currents through the two diodes will be ~ 5 mA through D_1 and ~ 2.5 mA through D_2.
- We can also calculate the voltage drop over the two resistors:

$$V_{R_1} = (5\text{ mA})(1000\ \Omega) = 5\text{ V}$$

$$V_{R_2} = (2.5\text{ mA})(2000\ \Omega) = 5\text{ V}$$

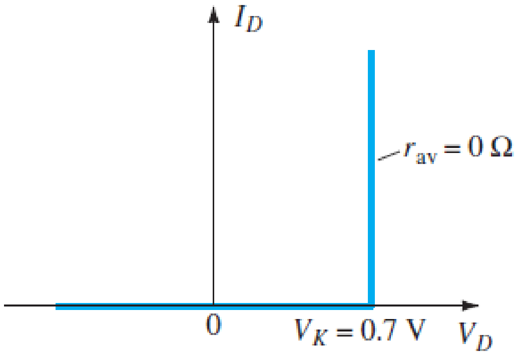
- and of course $V_{D_1} = V_{D_2}$ = 0 V from the model.

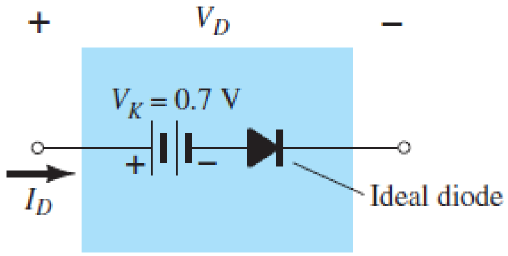
4. Refining the Ideal Diode Model

- The ideal diode plus voltage drop model.

$$V_D = \text{Ideal Diode} + V_T$$

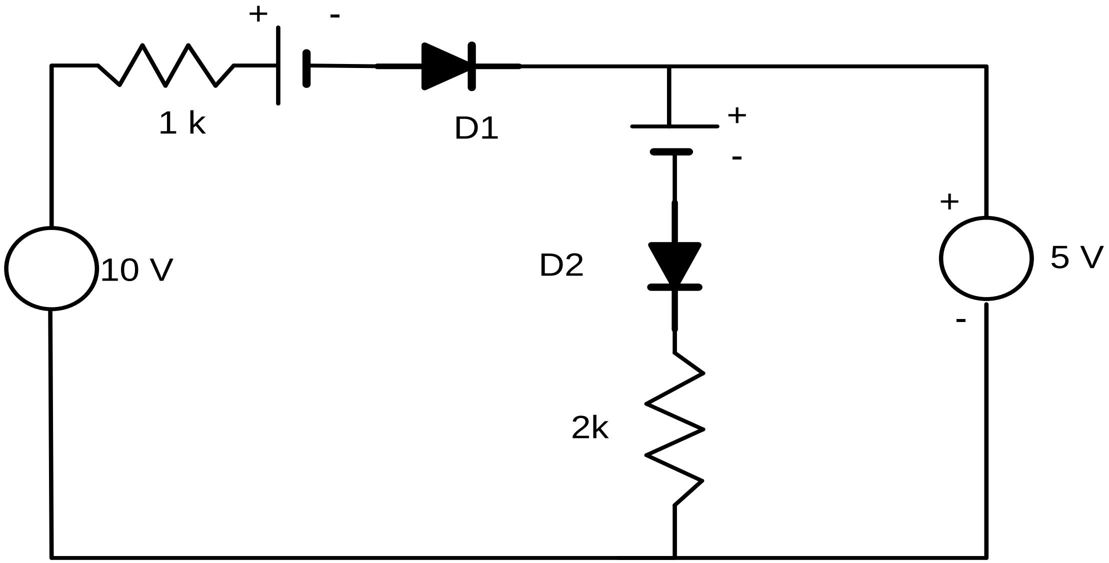
- Thermal voltage V_T = 0.7 V for Silicon diode, or 0.6 V for Germanium diode.





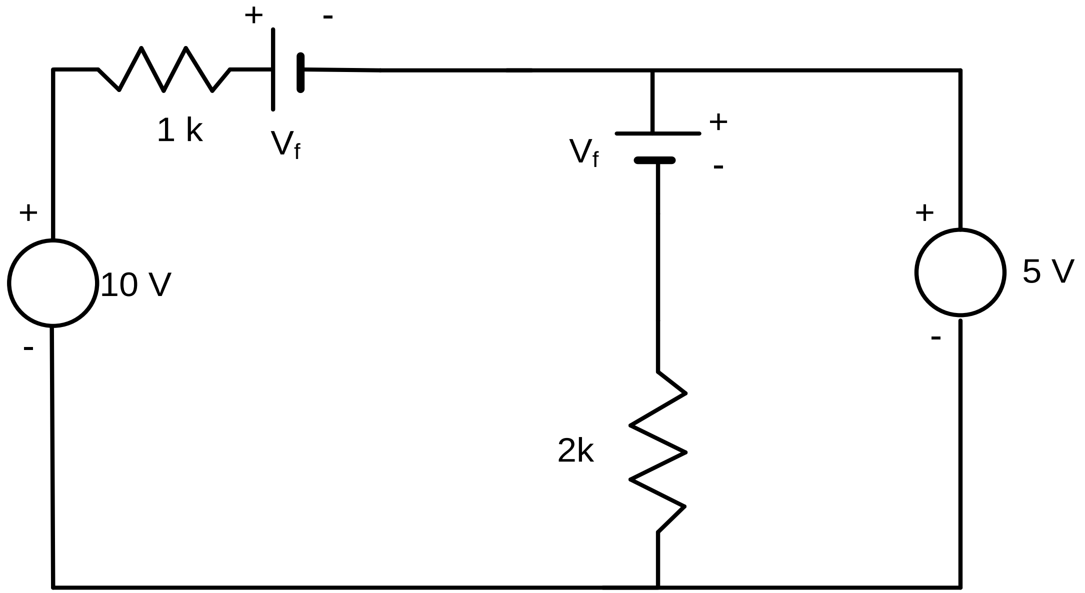
4. Refining the Ideal Diode Model

- Analyse this circuit using the ideal diode plus voltage drop model.
- Like previous models analysis, but with more precise model.



4. Refining the Ideal Diode Model

- Assume that both diodes are on.
- Replace with diode model for ideal diode plus voltage drop.



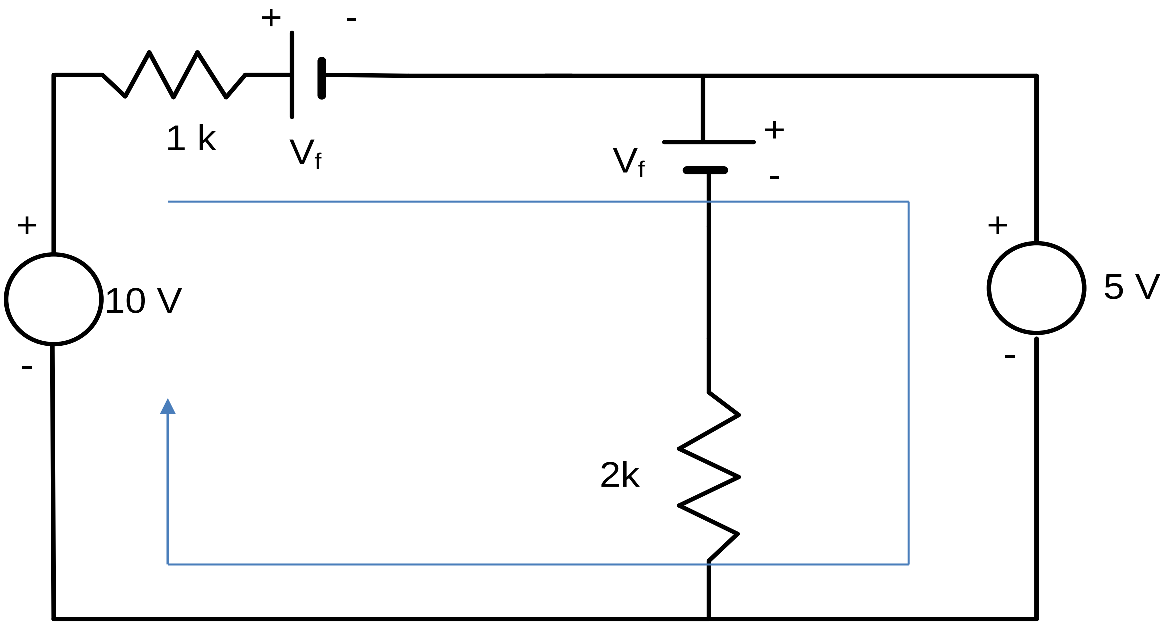
4. Refining the Ideal Diode Model (cont..)

- Writing a KVL around the outer loop:

$$10 - I_{D_1} R_1 - V_f - 5 = 0$$

- Thus:

$$I_{D_1} = (5 - V_f)/1000$$



4. Refining the Ideal Diode Model (cont..)

- Current I_{D_1} will then be > 0 when V_f < 5 V
- Expect this is to be the case, as V_f ~ 0.7 V for a Silicon diode.
- The assumption that diode D_1 is on is then correct.
- If we assume the value of V_f = 0.7 V for these diodes, the value of I_{D_1} will be 4.3 mA.

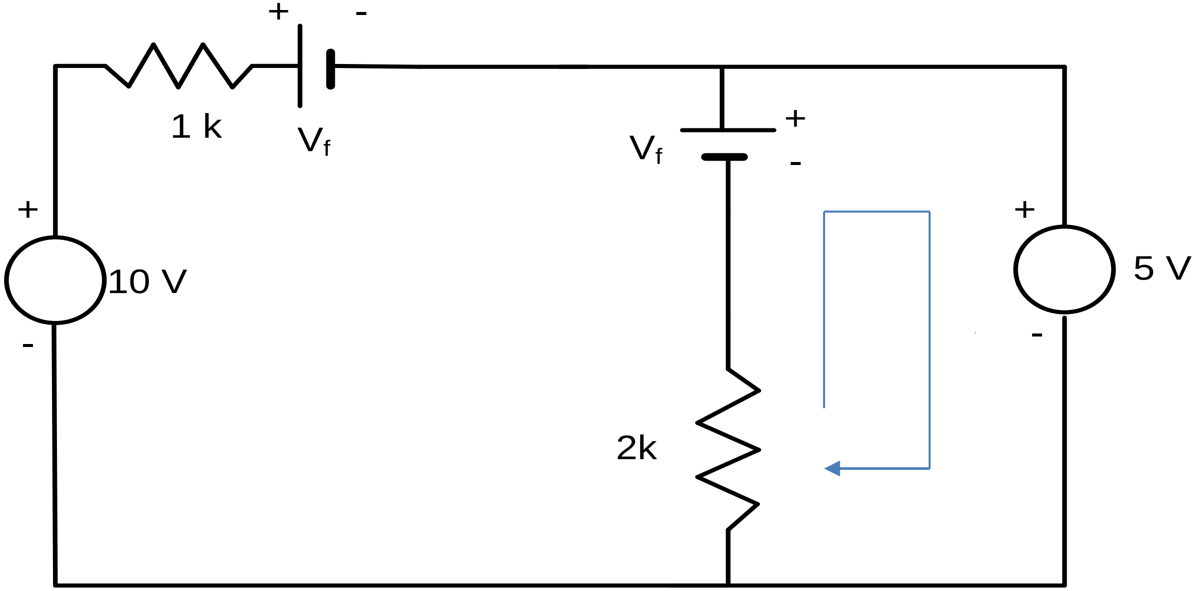
4. Refining the Ideal Diode Model (cont..)

- Writing a KVL around the right-hand-loop:

$$5 - V_f - I_{D_2} R_2 = 0$$

- And

$$I_{D_2} = (5 - V_f)/2000$$



4. Refining the Ideal Diode Model (cont..)

- This will produce positive values for the current as long as V_f < 5 V which is to be expected.
- Diode D_2 can then again assumed to be on.
- A diode current I_{D_2} = 2.15 mA will flow for a voltage drop of V_f = 0.7 V over the diode.
- We can also calculate the voltage drop over both the resistors as 4.3 V.

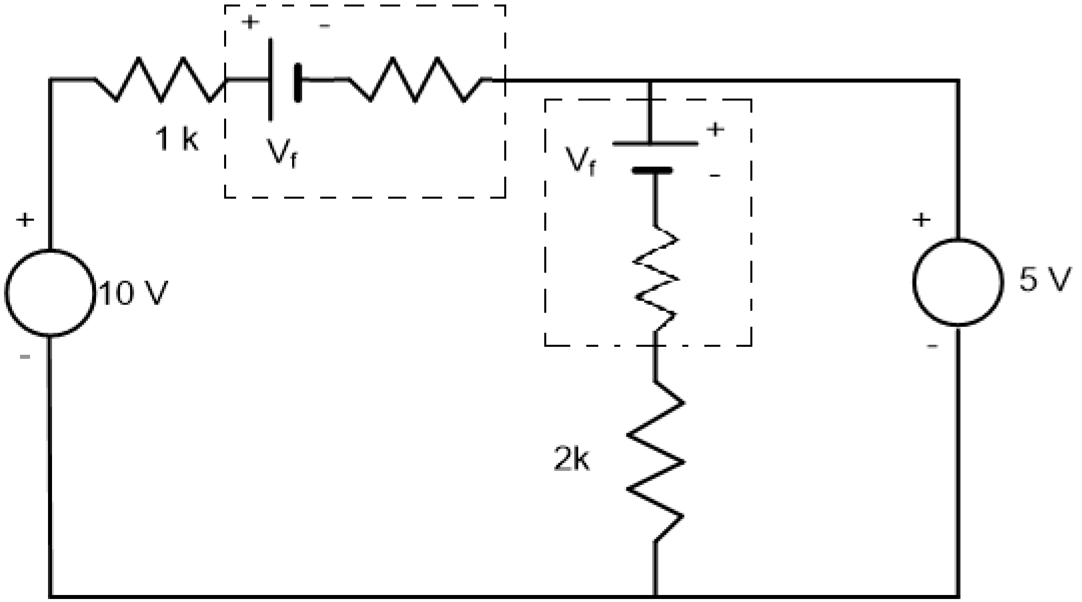
Ideal Model vs. Refinement Model

How do results from the two models compare?

	Ideal Diode	**Ideal Diode + Voltage Drop**
I_{D_1}	5 mA	4.3 mA
I_{D_2}	2.5 mA	2.15 mA
V_{R_1}	5 V	4.3 V
V_{R_2}	5 V	4. 3 V
V_{D_1}	0 V	0.7 V
V_{D_2}	0 V	0.7 V

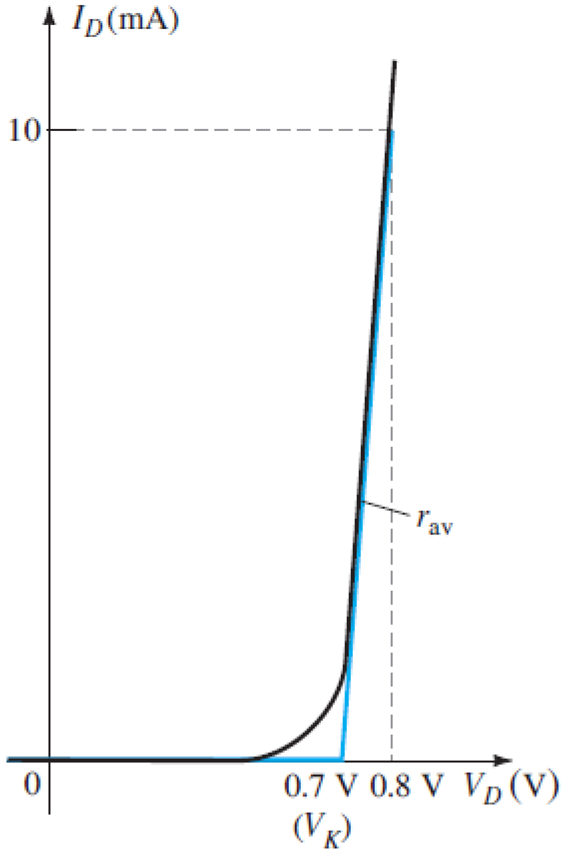
5. More Sophisticated Models

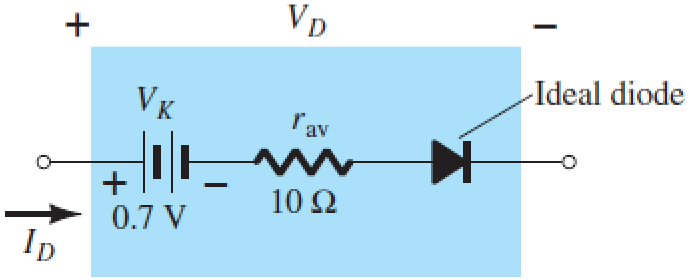
- We can further refine our diode models, for example by taking into account that a diode that is ON has a small resistance and thus introducing a further resistor in the model.



5. More Sophisticated Models

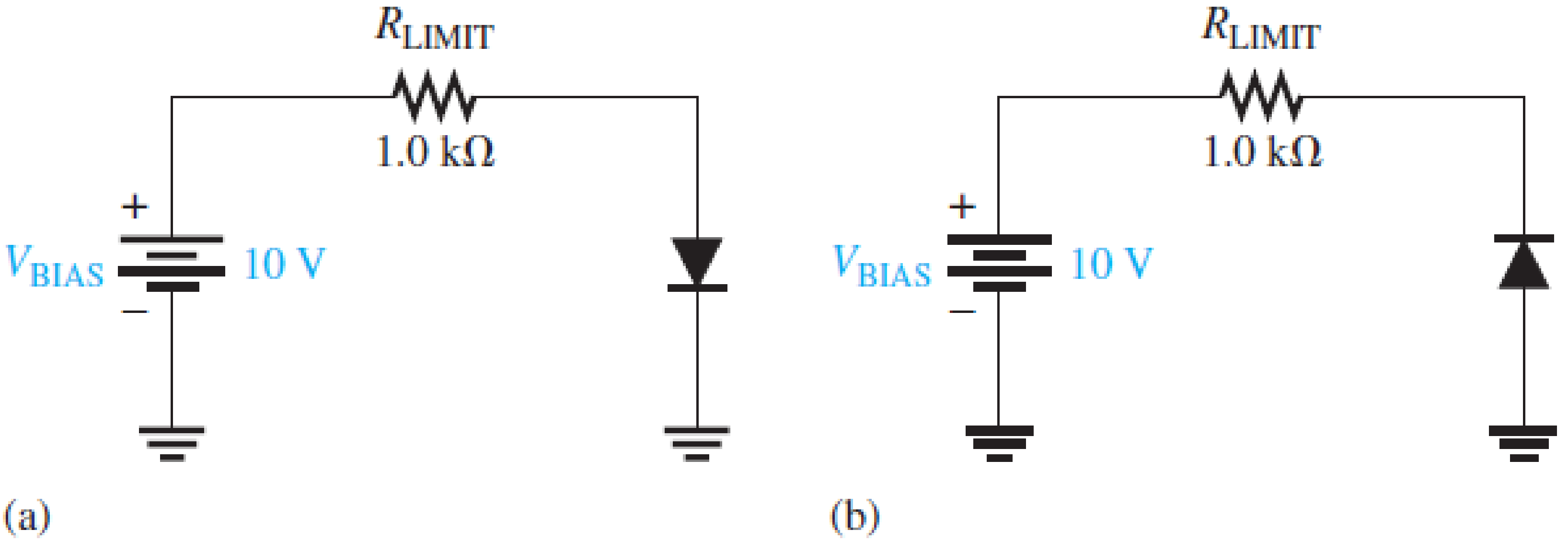
- Such a piece wise linear model will further improve the accuracy with which circuits can be simulated.
- However, the gains are relatively small and the ideal diode + voltage source model is normally accurate enough for most applications.
- Practical diode has resistance and the slope of the curve is the diode resistance.





Example for Tutorial 2 – Diode Circuits

Given two diode circuits in the figure below, for each of the diode models e.g. ideal, voltage source, and voltage source + resistance models, answer the following questions.



a. Determine the forward voltage and forward current for the diode in part (a) of the figure below for each of the diode models. Also, find the voltage across the limiting resistor in each case. Assume $r'_d = 10\ \Omega$ at the determined value of forward current. [9 marks]

b. Determine the reverse voltage and reverse current for the diode in part (b) of the figure below for each of the diode models. Also, find the voltage across the limiting resistor in each case. Assume I_R = 1 μA. [9 marks]

a. The analysis for the first circuit is given below.

For ideal diode model:

- Forward biased voltage of the diode is:

$$V_F = 0 \text{ V}$$

- Forward biased current of the diode is:

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}}$$

$$= \frac{10 \text{ V}}{1.0 \text{ k}\Omega} = 10 \text{ mA}$$

- The voltage across the limiting resistor is:

$$V_{R_{LIMIT}} = I_F R_{LIMIT}$$

$$= (10 \text{ mA})\ (1.0 \text{ k}\Omega) \ = \ 10 \text{ V}$$

For voltage source model:

- Forward biased voltage of the diode is:

$$V_F = 0.7\ \mathrm{V}$$

- Forward biased current of the diode is:

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

$$= \frac{10\ \mathrm{V} - 0.7\ \mathrm{V}}{1.0\mathrm{k}\Omega} = 9.3\ \mathrm{mA}$$

- The voltage across the limiting resistor is:

$$V_{R\,LIMIT} = I_F R_{LIMIT}$$

$$= (9.3\ \mathrm{mA})\ (1.0\ \mathrm{k}\Omega) = 9.3\ \mathrm{V}$$

For voltage source + resistance model:

- Forward biased current of the diode is:

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT} + r'_d}$$

$$= \frac{10\ \mathrm{V} – \ 0.7\ \mathrm{V}}{1.0\mathrm{k}\Omega + 10\Omega} = 9.21\ \mathrm{mA}$$

- Forward biased voltage of the diode is:

$$V_F = 0.7\ \mathrm{V} + I_F r'_d$$

$$= \ 0.7\ \mathrm{V} + (9.21\ \mathrm{mA})\ (10\ \mathrm{A}) = 792\ \mathrm{mV}$$

- The voltage across the limiting resistor is:

$$V_{R\,LIMIT} = I_F R_{LIMIT}$$

$$= (9.21\ \mathrm{mA})\ (1.0\ \mathrm{k}\Omega) = 9.21\ \mathrm{V}$$

b. The analysis for the second circuit is given below.

For ideal diode model:

- Reverse biased current of the diode is:

$$I_R = 0\ \mathrm{A}$$

- Reverse biased voltage of the diode is:

$$V_R = V_{BIAS} = 10\ \mathrm{V}$$

- The voltage across the limiting resistor is:

$$V_{R_{LIMIT}} = 0\ \mathrm{V}$$

For voltage source model:

- Reverse biased current of the diode is:

$$I_R = 0\ \mathrm{A}$$

- Reverse biased voltage of the diode is:

$$V_R = V_{BIAS} = 10\ \mathrm{V}$$

- The voltage across the limiting resistor is:

$$V_{R_{LIMIT}} = 0\ \mathrm{V}$$

For voltage source + resistance model:

- Reverse biased current of the diode is:

$$I_R = 1\ \mu\text{A}$$

- Reverse biased voltage of the diode is:

$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu\text{A})(1.0\ \text{k}\Omega) = 1\ \text{mV}$$

- The voltage across the limiting resistor is:

$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 10\ \text{V} - 1\ \text{mV} = 9.999\ \text{V}$$

Example for Tutorial 3 – V-I Characteristics of Diode

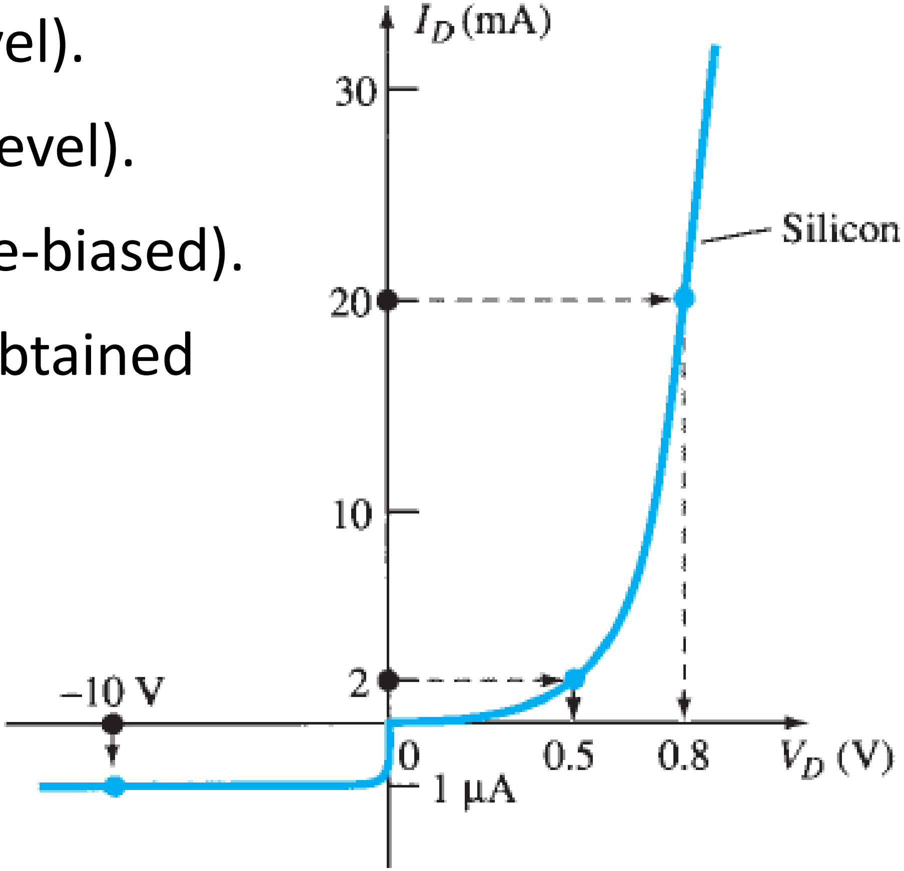
Determine the dc resistance levels for the diode of the figure given below at: [8 marks]

a. Current I_D = 2 mA (low level).

b. Current I_D = 20 mA (high level).

c. Voltage V_D = -10 V (reverse-biased).

d. Comment on the results obtained in parts (a)-(c).



a. At I_D = 2 mA, V_D = 0.5 V (from the curve) and diode resistance is:

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = 250\ \Omega$$

b. At I_D = 20 mA, V_D = 0.8 V (from the curve) and diode resistance is:

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = 40\ \Omega$$

c. At V_D = -10 V, I_D = $-I_s$ = -1 uA (from the curve) and diode resistance is:

$$R_D = \frac{V_D}{I_D} = \frac{10\ \mathrm{V}}{1\ \mu\mathrm{A}} = 10\ \mathrm{M\Omega}$$

d. The results clearly are supporting some of the earlier comments regarding the dc resistance levels of a diode.