EEE118: Electronic Devices and Circuits

Lecture III

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Last Lecture: Review

- Considered perfect and imperfect voltage and current sources
- Showed that perfect current sources have infinite parallel resistance and that voltage sources have zero series resistance.
- Introduced the Thévanin and Norton theorems of source transformation. And gave a simple example of each.
- Introduced the Superposition theorem and gave a simple example.
- Considered the conditions required for maximum power transfer from a Thévanin source ($\mathrm{R}_L = R_T$). Could you derive for Norton on your own?
- Described what happens to the current and voltage in a simple RC network excited by a *unit step* in the time domain.
- Showed some analysis of the differential equation from which the exponential relationship is derived (not examinable)

Outline

Signal

A voltage, current or other measurable quantity which carries useful information.

Bias

A constant voltage or current which is used to set up favourable quiescent conditions in a circuit containing active components.

Passive Component

One which requires no external energy (other than the signal) to operate.

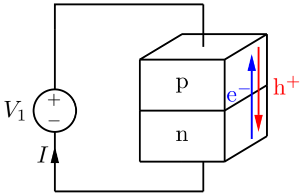
Active Component

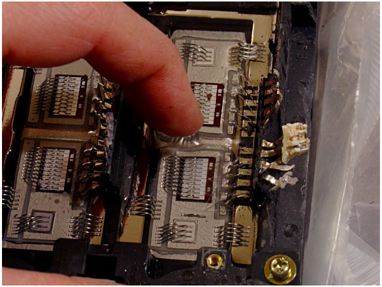
One which requires external energy (bias) to set the quiescent conditions so that the circuit containing the active component(s) will perform some useful function.

Diodes

- A diode is a two terminal electronic device that allows current flow in one direction only.
- Diodes are non-linear circuit elements. The current through a diode is not *linearly* proportional to the voltage across it.
- Diodes are active components.
- Diodes can be produced using several technologies, including thermionic valves, semiconductor-metal junctions and semiconductor-semiconductor junctions.

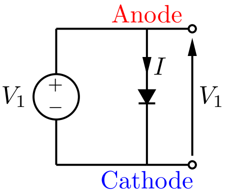
By far the most common is the silicon p-n junction diode. It is formed by two pieces of semiconductor, one doped n-type and another p-type in close metallurgical contact. The n-type material is doped with impurities to add additional electrons and the p-type doped to add additional holes. An alloy of metals are deposited on the surfaces of the n and p-type semiconductors. Fine gold or aluminium wires are bonded to the contacts and to the package body. The package is hermetically sealed.

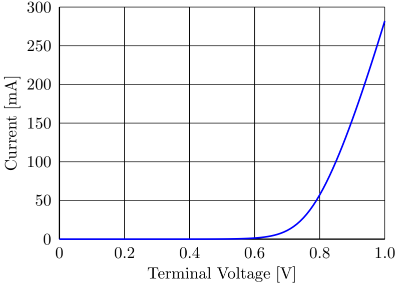




Forward Bias Characteristics

Under forward bias the diode obeys the Shockley - or diode equation - $I = I_0 \left(\exp\left(\frac{q\,V}{k\,T}\right) - 1 \right)$, where I is the total current, I_0 is the saturation current, q is the electron charge, V is the terminal voltage, k is Boltzmann's constant and T is the absolute temperature. Diodes can be tested for polarity using a "multimeter" and can be fully investigated using a curve tracer which produces a plot of the diode's characteristic.



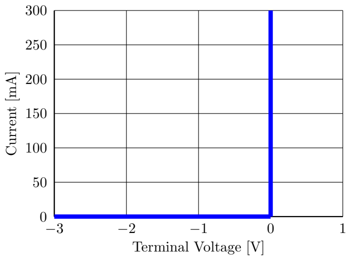


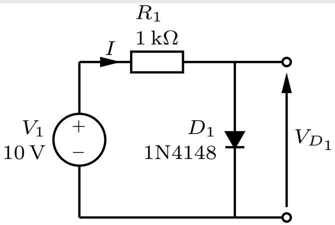
- When a positive voltage, V_1, is applied to the p region (anode) with respect to the n region (cathode), the device is forward biased and a current, I, flows through the device.
- A certain value of applied bias voltage is necessary before an observable current flows, but once this value is reached, very small increases in applied voltage lead to very large increases in current.
- For a silicon diode the current begins to increase when the applied voltage is 0.7 V.
- The voltage at which the current begins to rise is the turn on voltage. It is also called the forward voltage drop. It's an approximation, but a good one for most purposes.
- Turn on voltage is a function of band-gap. In other materials (specialist diodes, LEDs etc.) it could be higher or lower e.g. for a GaN "blue" LED it is ~ 3 V.

The diode equation is difficult to use in circuit analysis. A piecewise linear model is preferable. The simplest practical model of a diode only addresses the direction of current flow.

First Linear Model

Assume that the diode conducts perfectly in the forward direction without any voltage drop. If the diode is forward biased the current flowing is limited only by the circuit elements surrounding it.



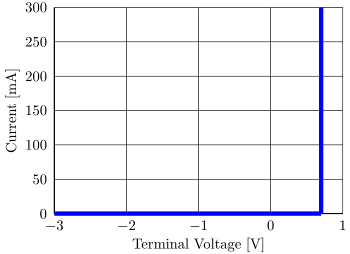


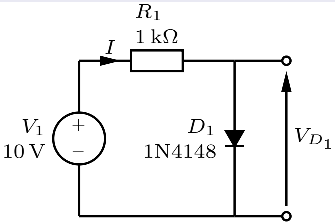
In this diode resistor circuit the resistor limits the current to 10 mA. In this model, the diode is incapable of dissipating power!

The simple model can be improved easily by the addition of a 0.7 V source to model the turn on voltage of the diode.

Improved Linear Model

Assume that the diode conducts perfectly in the forward direction with a constant 0.7 V drop. If the diode is forward biased the current flowing is limited only by the circuit elements surrounding it.

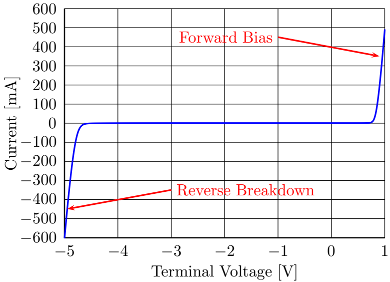




In this simple series diode resistor circuit the diode will limit the current to 9.3 mA. This improved model is often used.

Reverse Bias Characteristics

When the cathode voltage is greater than the anode the diode is reverse biased. The diode can be approximated by an open circuit. The current flowing is I_s - the saturation current. If the reverse bias voltage is sufficiently large *impact ionisation* occurs and the diode conducts a reverse current. This effect is used to produce Zenner diodes. The maximum reverse voltage that can be sustained by a diode is the repetitive reverse maximum or peak inverse voltage.



Conduction State Definitions

A diode in conduction

A diode is conducting if the magnitude of the current flowing in the diode is greater than zero. A diode ceases to be in a conducting state when the current falls to zero.

A diode on the point of conduction

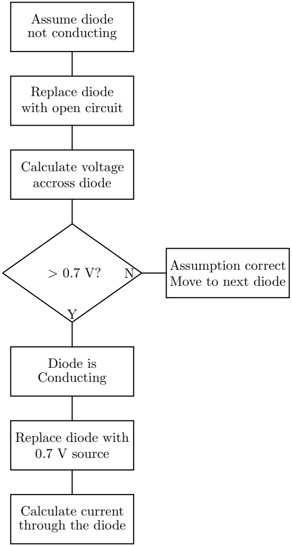
A diode is on the point of conduction if the anode voltage is 0.7 V greater than the cathode. No current flows on the point of conduction.

The beginning of conduction

Conduction begins when the anode voltage is *more* than 0.7 V greater than the cathode.

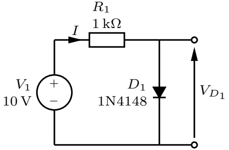
A general method for deciding if a diode is conducting in any circuit is desirable.

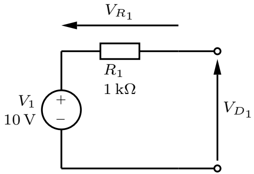
General Method for Conduction State Problems

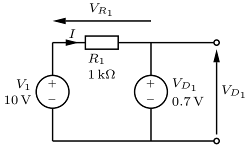


This flow diagram assumes the diode is not conducting. It is equally acceptable to assume that the diode is conducting and construct a slightly different flow diagram. In circuits containing more than one diode, the order in which they are analysed may be important. It is necessary to check that each prior diode every time one is found to change state.

Simple Conduction State Example



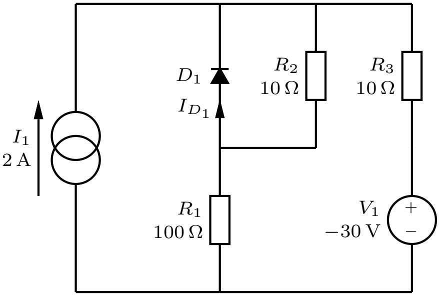




1. Assume the diode is not conducting.
2. Replace it with an open circuit. No current flows in R_1 and so no voltage is dropped across R_1. Therefore all of V_1 appears across the diode (V_{D_1}). The diode will enter conduction $V_{a-c} = 10$ V, (> 0.7).
3. Replace the open circuit with a 0.7 V perfect voltage source. $V_{R_1} = 10 - 0.7 = 9.3$ V. By Ohm's law $I = 9.3$ mA.

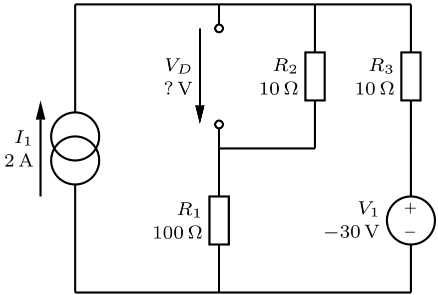
Example Question, Part A.

In the circuit below determine if the diode, D_1, is conducting. If D_1 is conducting find the current, I_{D_1} flowing through it. If D_1 is not conducting find the magnitude of the reverse bias voltage across it.



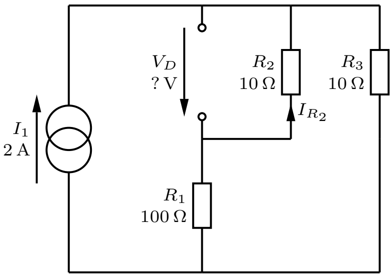
The node voltage and loop current methods and superposition theorem can be used. In this example Ohm's law and superposition will be used.

Follow the flow diagram in an earlier slide. Assume the diode is not conducting and is therefore replaced by an open circuit.



Use the superposition theorem to find the voltage across this open circuit. If the voltage is greater than 0.7 V then the non-conducting assumption is invalid. If the voltage is less than 0.7 V the non-conducting assumption is valid and we can state the reverse bias voltage. If the voltage is exactly 0.7 V the diode will be on the point of conduction and *no current will flow*.

Since superposition is being used, each of the sources must be considered individually and then their effects are combined. Choose to consider the current source, I_1, and switch off the voltage source, V_1. Replace it with a short circuit.



$$I_{R_2} = -I \cdot \frac{R_3}{R_1 + R_2 + R_3} \quad (1)$$

$$I_{R_2} = -2 \cdot \frac{10}{100 + 10 + 10} \quad (2)$$

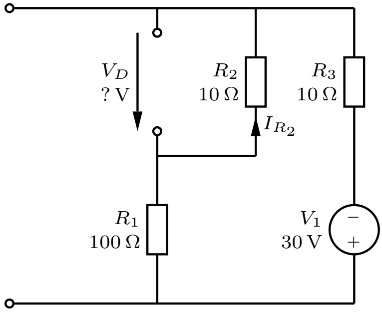
$$I_{R_2} = -0.166\dot{6} \text{ A} \quad (3)$$

$$V_{R_2} = I_{R_2} \cdot R_2 \quad (4)$$

$$V_{R_2} = -1.66\dot{6} \text{ V} \quad (5)$$

Note that R_2 is in parallel with the open circuit. Note also that this is a current divider circuit and is analogous to a potential divider.

The voltage source, V_1, which was previously replaced with a short circuit (its internal impedance) is now considered alone. The current source is replaced by an open circuit (its internal impedance).



$$I_{R_2} = \frac{V_1}{R_1 + R_2 + R_3} \quad (6)$$

$$I_{R_2} = \frac{30}{100 + 10 + 10} \quad (7)$$

$$= 0.25 \text{ A} \quad (8)$$

$$V_{R_2} = I_{R_2} \cdot R_2 \quad (9)$$

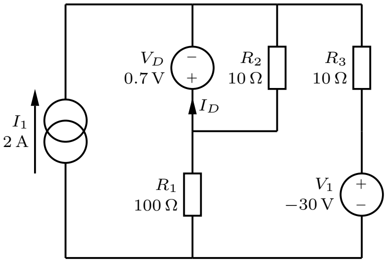
$$V_{R_2} = 0.25 \cdot 10 = 2.5 \text{ V} \quad (10)$$

This is a potential divider circuit containing three resistors. The voltage is shared according to the magnitude of the resistances.

Summing the voltage across the open circuit due to both the current and voltage sources (I_1 & V_1) we have

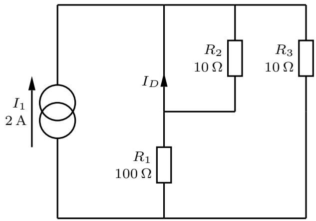
$$V_D = 2.5 + (-1.66\dot{6}) = 0.83\dot{3}\ \mathrm{V}.$$

The assumption that the diode is not conducting is invalid!



The open circuit must be replaced with a 0.7 V perfect voltage source. Each of the three sources (I_1, V_1 and V_D) must be considered individually and superposition used to find the current, I_D, flowing in the forward biased diode.

Since superposition is being used, each of the sources must be considered individually and then their effects are combined. As before, choose to consider the current source, I_1, and switch off the voltage sources, V_1 and V_D. Replace both with short circuits.



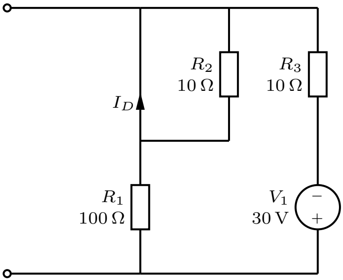
$$I_D = -I_1 \cdot \frac{R_3}{R_1 + R_3} \tag{11}$$

$$I_D = -2 \cdot \frac{10}{100 + 10} \tag{12}$$

$$I_D = -0.1\dot{8}\dot{1} \text{ A} \tag{13}$$

This is a slightly easier current divider problem than before. In potential dividers, larger resistances = larger share of the voltage. Potential dividers are series circuits driven by voltage sources. In current dividers, smaller resistors = larger share of the current. Current dividers are parallel circuits driven by current sources.

The voltage source, V_1, which was previously replaced with a short circuit (its internal impedance) is now considered alone. I_1 and V_D are replaced by there internal resistances (open and short circuit, respectively).



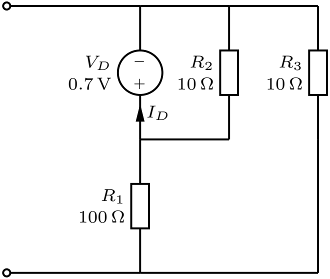
$$I_D = \frac{V_1}{R_1 + R_3} \tag{14}$$

$$I_D = \frac{30}{100 + 10} \tag{15}$$

$$I_D = 0.2\dot{7}\dot{2}\ \mathrm{A} \tag{16}$$

This is a potential divider circuit containing two resistors. The voltage is shared according to the magnitude of the resistances. R_2 *is shorted, no current flows in it.*

The voltage source, V_D, which was previously replaced with a short circuit (its internal impedance) is now considered alone. I_1 and V_1 are replaced by there internal resistances (open and short circuit, respectively).



$$-I_D = \frac{V_D}{R_2} + \frac{V_D}{R_1 + R_3} \quad (17)$$

$$-I_D = \frac{0.7}{10} + \frac{0.7}{110} \quad (18)$$

$$-I_D = 70 + 6.36\dot{3}\dot{6} \text{ mA} \quad (19)$$

If R_1 and R_3 are combined (summed because they are in series), this problem reduces to two cases of Ohm's law.

The contribution to current flow in the diode can be summed from the three circuit problems (one from each source I_1, V_1 & V_D) to yield the total current, I_D.

$$I_D = 0.2\dot{7}\dot{2}\dot{7} + (-0.1\dot{8}\dot{1}\dot{8}) + (-76.3\dot{6}\dot{3}\dot{6} \times 10^{-3}) \tag{20}$$

$$I_D = 14.5\dot{4}5\dot{4} \text{ mA} \tag{21}$$

The negative signs are due to the direction of current as drawn on the diagrams. Remember that in power sources current flows in the same direction that the voltage faces but in other elements the direction of voltage and current oppose each other.

Part B.

What magnitude would V_1 have to be changed to in order that the diode would be on the point of conduction (0.7 V across but no current flowing)?

Review

1. Defined some terminology (Bias, Signals, Passive and Active components)
2. Introduced Diodes as active components having a non linear relationship between voltage and current.
3. Briefly considered how a diode is constructed from semiconducting materials
4. Considered the effect of "forward" and "reverse" biasing a diode.
5. Constructed two linear models of the diode action under forward bias.
6. Defined three distinct states of conduction and non-conduction for a diode
7. Provided a general method for solving conduction state problems in diode circuits.
8. Worked through an example of a conduction state problem.