Electronic Circuits

Prof. Nizamettin AYDIN

naydin@yildiz.edu.tr

http://www.yildiz.edu.tr/~naydin

1

Semiconductors and diodes

- Introduction
- Electrical properties of solids
- Semiconductors
- *pn* Junctions
- diodes
- Semiconductor diodes
- Special-purpose diodes
- Diode circuits.

2

Electrical properties of solids

- **Conductors**
  - e.g. copper or aluminium
  - have a cloud of free electrons (at all temperatures above absolute zero). If an electric field is applied electrons will flow causing an electric current.
- **Insulators**
  - e.g. polythene
  - electrons are tightly bound to atoms, so, only a few can break free to conduct electricity.

3

Properties of solids (contd.)

- **Semiconductors**
  - e.g. silicon or germanium
  - at very low temperatures these have the properties of insulators
  - as the material warms up some electrons break free and can move about, and it takes on the properties of a conductor – albeit a poor one
  - however, semiconductors have several properties that make them distinct from conductors and insulators.

4

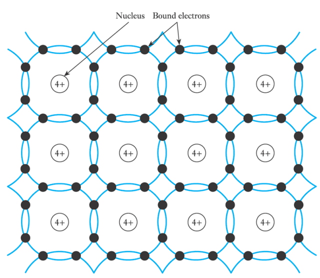
Semiconductors

- **Pure semiconductors**
  - thermal vibration results in some bonds being broken, generating **free electrons** which move about
  - these leave behind **holes** which accept electrons from adjacent atoms and therefore, also move about
  - electrons are **negative charge carriers**
  - holes are **positive charge carriers.**
- At room temperatures there are few charge carriers
  - *pure* semiconductors are poor conductors
  - this is **intrinsic conduction.**

5

Structure of a semiconductor

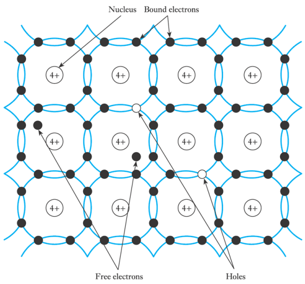
- The atomic structure of silicon



6

Structure of a semiconductor (contd.)

- The effect of thermal vibration on the structure of silicon

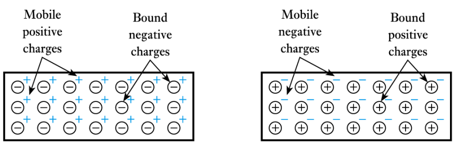


Doping of semiconductors

- **Doping**
  - the addition of small amounts of impurities drastically affects its properties
  - some materials form an excess of *electrons* and produce an ***n*-type semiconductor**
  - some materials form an excess of *holes* and produce a ***p*-type semiconductor**
  - both *n*-type and *p*-type materials have much greater conductivity than pure semiconductors

Doping of semiconductors (contd.)

- The dominant charge carriers in a doped semiconductor (e.g. electrons in *n*-type material) are called **majority charge carriers**. The other type are **minority charge carriers.**
- The overall doped material is electrically neutral.



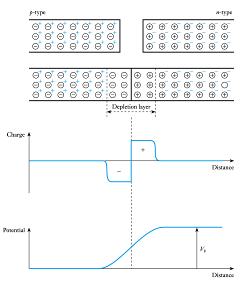
(a) *p*-type semiconductor (b) *n*-type semiconductor

pn Junctions

- When *p*-type and *n*-type materials are joined, this forms a ***pn* junction**
  - the majority charge carriers on each side diffuse across the junction where they combine with (and remove) the charge carriers of the opposite polarity.
  - hence, around the junction there are few free charge carriers and we have a **depletion layer** (also called a **space-charge layer**).

pn Junctions (contd.)

- The diffusion of positive charge in one direction and negative charge in the other produces a charge imbalance
  - this results in a **potential barrier** across the junction.



pn Junctions (contd.)

- **Potential barrier**
  - the barrier opposes the flow of *majority* charge carriers and only a small number have enough energy to surmount it.
    - This generates a small **diffusion current.**
  - the barrier encourages the flow of *minority* carriers and any that come close to it will be swept over
    - This generates a small **drift current.**
  - for an isolated junction these two currents must balance each other and the net current is zero.

pn Junctions (contd.)

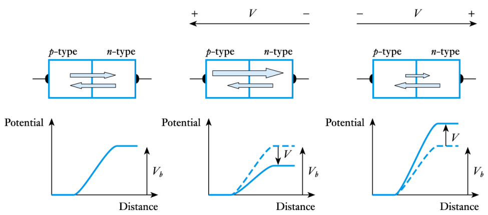
- **Forward bias**
  - if the *p*-type side is made *positive* with respect to the *n*-type side the height of the barrier is reduced
  - more majority charge carriers have sufficient energy to surmount it
  - the diffusion current therefore increases while the drift current remains the same
  - there is thus a net current flow across the junction which increases with the applied voltage.

pn Junctions (contd.)

- **Reverse bias**
  - if the *p*-type side is made *negative* with respect to the *n*-type side the height of the barrier is increased
  - the number of majority charge carriers that have sufficient energy to surmount it rapidly decreases
  - the diffusion current therefore vanishes while the drift current remains the same
  - thus the only current is a small leakage current caused by the (approximately constant) drift current
  - the leakage current is usually negligible (a few nA).

pn Junctions (contd.)

- **Currents in a *pn* junction**



(a) An isolated junction (b) Forward bias (c) Reverse bias

pn Junctions (contd.)

- **Forward and reverse currents**
  - *pn* junction current is given approximately by

$$I = I_S\left(\exp\frac{eV}{\eta kT} - 1\right)$$

  - where
    - I is the current,
    - I_S is the reverse saturation current,
    - e is the electronic charge,
    - V is the applied voltage,
    - k is Boltzmann's constant,
    - T is the absolute temperature and
    - η (Greek letter *eta*) is a constant in the range 1 to 2 determined by the junction material
      - for most purposes we can assume $\eta = 1$.

pn Junctions (contd.)

- Thus,

$$I \approx I_S\left(\exp\frac{eV}{kT} - 1\right)$$

at room temperature $e/kT \sim 40\ \mathrm{V}^{-1}$

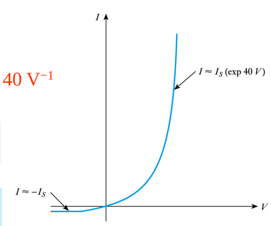
- If $V > +0.1$ V,

$$I \approx I_S\left(\exp\frac{eV}{kT}\right) = I_S(\exp 40V)$$

- If $V < -0.1$ V,

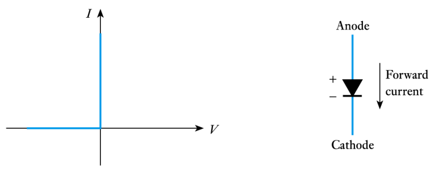
$$I \approx I_S(0-1) = -I_S$$

  - I_S is the **reverse saturation current.**



Diodes

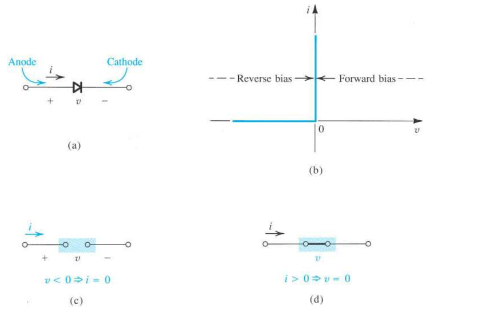
- An **ideal diode** passes electricity in one direction but not in the other.



(a) I–V characteristic (b) Diode circuit symbol

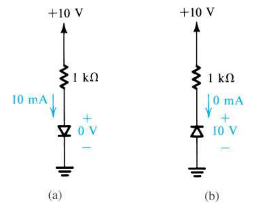
Ideal Diode

- **(a)** diode circuit symbol; **(b)** i–v characteristic; **(c)** equivalent circuit in the reverse direction; **(d)** equivalent circuit in the forward direction.



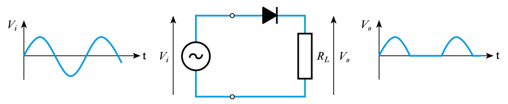
Ideal Diode

- The two modes of operation of ideal diodes and the use of an external circuit to limit the forward current **(a)** and the reverse voltage **(b)**.



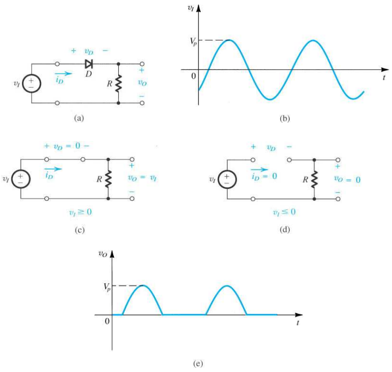
half-wave rectifier

- One application of diodes is in **rectification**
  - the example below shows a **half-wave rectifier.**

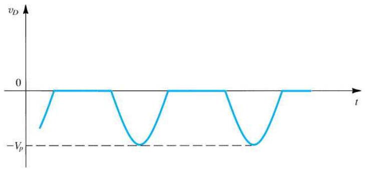


- In practice, no real diode has ideal characteristics but semiconductor ***pn* junctions** make good diodes.

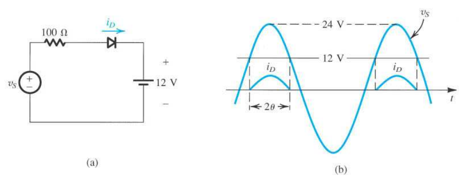
(a) Rectifier circuit. (b) Input waveform. (c) Equivalent circuit when $v_I \geq 0$. (d) Equivalent circuit when v_I ✧ 0. (e) Output waveform.

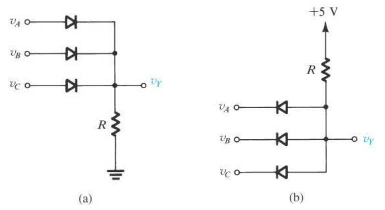


Example



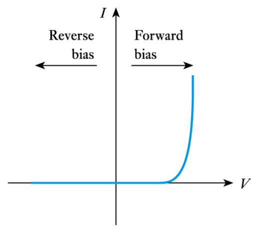
Example





Semiconductor diodes

- **Forward and reverse currents**

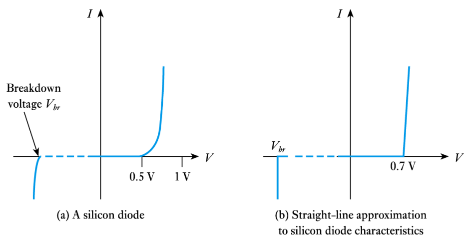


Silicon diodes (contd.)

- **Silicon diodes**
  - generally have a turn-on voltage of about 0.5 V
  - generally have a conduction voltage of about 0.7 V
  - have a breakdown voltage that depends on their construction
    - perhaps 75 V for a **small-signal diode**
    - perhaps 400 V for a **power device**
  - have a maximum current that depends on their construction
    - perhaps 100 mA for a **small-signal diode**
    - perhaps many amps for a **power device.**

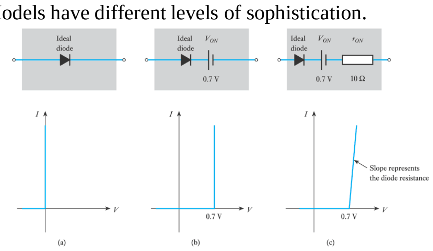
Silicon diodes (contd.)

- **Turn-on** and **breakdown voltages** for a silicon device



Diode equivalent circuits

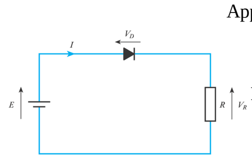
- Sometimes we represent a diode by an equivalent circuit. Models have different levels of sophistication.



Diode circuit analysis

- The non-linear behaviour of diodes makes analysis difficult – consider this simple circuit.

Applying Kirchoff's voltage law



$$E = V_D + V_R$$
$$= V_D + IR$$

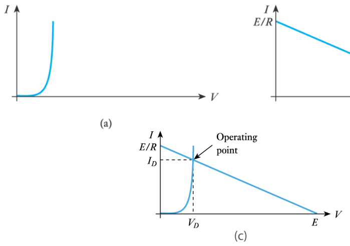
From the diode equation

$$I = I_S(\exp 40V_D)$$

To find *I* we need to solve these two simultaneous equations.

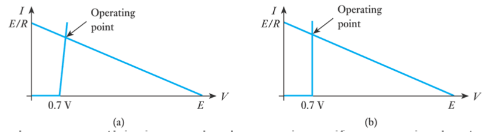
Diode circuit analysis (contd.)

- One approach is through the use of a **load line.**



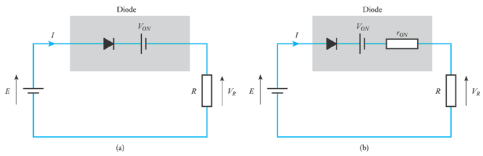
Diode circuit analysis (contd.)

– Load lines can also be used with equivalent circuits…



…however, this is rarely done, since if an equivalent circuit is used, the circuit can normally be analysed directly, without resorting to a graphical method.

Diode circuit analysis (contd.)



$$I = \frac{E - V_{ON}}{R}$$

$$I = \frac{E - V_{ON}}{R + r_{ON}}$$

Effects of temperature

- Earlier we noted that

$$I \approx I_S\left(\exp\frac{eV}{kT} - 1\right)$$

  – for a given *I*, the voltage is inversely proportional to *T*
  – for a silicon diode, *V* decreases by about 2 mV per °C

  – the diode current is also affected by the reverse saturation current, which increases with temperature
  – I_S increases by about 7% per °C.

Reverse breakdown

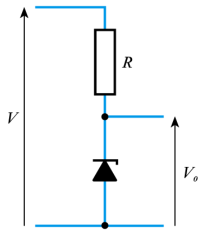
- Can be caused by two mechanisms:
- **Zener breakdown**
  – in devices with heavily doped *p*- and *n*-type regions the transition from one to the other is very abrupt.
  – this produces a very high field strength across the junction that can pull electrons from their covalent bonds.
  – produces a large reverse current.
  – breakdown voltage is largely constant.
  – Zener breakdown normally occurs below 5 V.

Reverse breakdown (contd.)

- **Avalanche breakdown**
  – occurs in diodes with more lightly doped materials
  – field strength across junction is insufficient to pull electrons from their atoms, but is sufficient to accelerate the electrons within the depletion layer
  – they loose energy by colliding with atoms
  – if they have sufficient energy they can liberate other electrons, leading to an avalanche effect
  – usually occurs at voltages above 5 V.

Special-purpose diodes

- **Zener diodes**
  - uses the relatively constant reverse breakdown voltage to produce a voltage reference
  - breakdown voltage is called the **Zener voltage**, V_Z
  - output voltage of circuit shown is equal to V_Z despite variations in input voltage V
  - a resistor is used to limit the current in the diode.

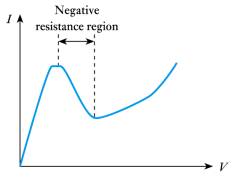


Special-purpose diodes (contd.)

- **Schottky diodes**
  - formed by the junction between a layer of metal (e.g. aluminium) and a semiconductor
  - action relies only on majority charge carriers
  - much faster in operation than a *pn* junction diode
  - has a low forward voltage drop of about 0.25 V
  - used in the design of high-speed logic gates.

Special-purpose diodes (contd.)

- **Tunnel diodes**
  - high doping levels produce a very thin depletion layer which permits 'tunnelling' of charge carriers
  - results in a characteristic with a **negative resistance** region
  - used in high-frequency oscillators, where they can be used to 'cancel out' resistance in passive components.

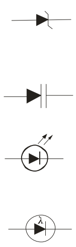


Special-purpose diodes (contd.)

- **Varactor diodes**
  - a reversed-biased diode has two conducting regions separated by an insulating depletion region
  - this structure resembles a capacitor
  - variations in the reverse-bias voltage change the width of the depletion layer and hence the capacitance
  - this produces a **voltage-dependent capacitor**
  - these are used in applications such as **automatic tuning circuits.**

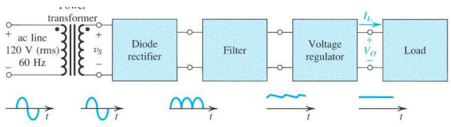
Special-purpose diodes

- Zener diodes
  - used for establishing a reference voltage
- Varactor diodes
  - used as variable capacitors
- Light-emitting diodes
  - used in displays
- Photodiodes
  - used as light sensors

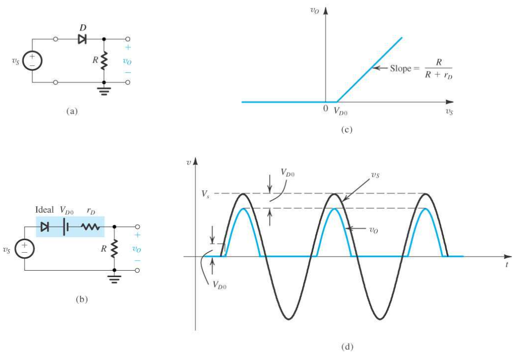


Diode circuits

- Block diagram of a dc power supply

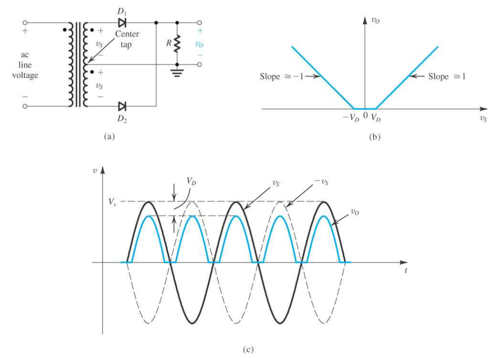


Half-wave rectifier

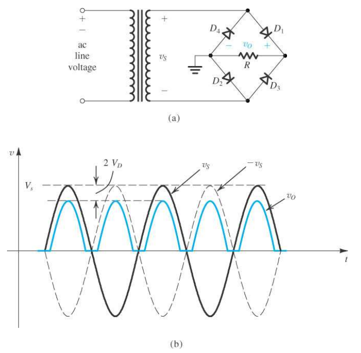


43

Full-wave rectifier

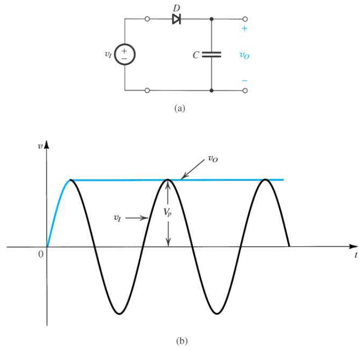


44



45

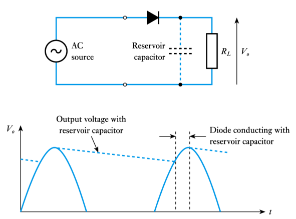
(a) A simple circuit used to illustrate the effect of a filter capacitor. (b) Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a peak rectifier or a peak detector.



46

Diode circuits

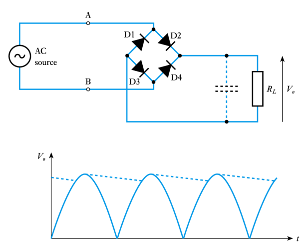
- **Half-wave rectifier**
  - peak output voltage is equal to the peak input voltage minus the conduction voltage of the diode
  - reservoir capacitor used to produce a steadier output.



47

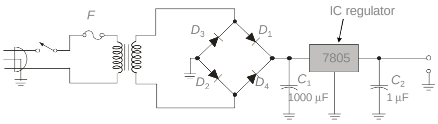
Diode circuits (contd.)

- **Full-wave rectifier**
  - use of a diode bridge reduces the time for which the capacitor has to maintain the output voltage and thus reduce the ripple voltage.



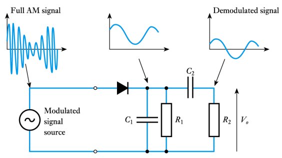
48

A typical regulated power supply



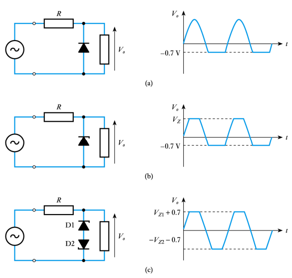
Diode circuits (contd.)

- **Signal rectifier**
  - used to demodulate full amplitude modulated signals (**full-AM**)
  - also known as an **envelope detector**
  - found in a wide range of radio receivers from crystal sets to superheterodynes.

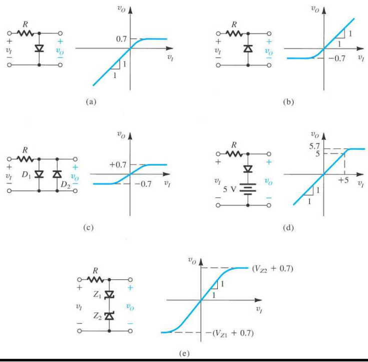


Diode circuits (contd.)

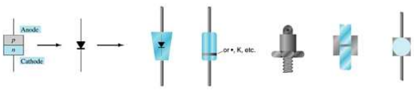
- **Signal clamping**
  - a simple form of **signal conditioning**
  - circuits limit the excursion of the voltage waveform
  - can use a combination of signal and Zener diodes.



A variety of basic limiting circuits.



Diode Symbol and Packaging



The anode is abbreviated A
The cathode is abbreviated K

Diode Testing

Diode checker
Ohmmeter
Curve tracer

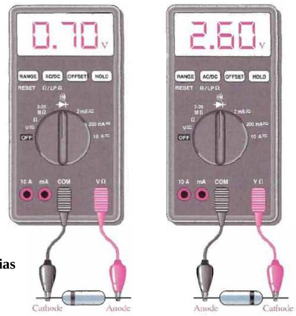
Diode Checker

Many digital multimeters have a diode checking function.
The diode should be tested out of circuit.

A normal diode exhibits its forward voltage:

- **Gallium arsenide ≅ 1.2 V**
- **Silicon diode ≅ 0.7 V**
- **Germanium diode ≅ 0.3 V**

DMM diode test on a properly functioning diode

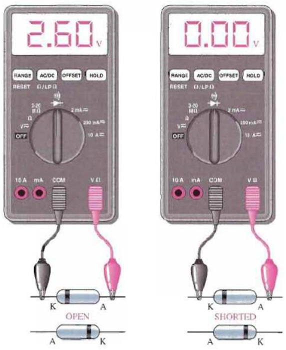


forward –bias check

reverse –bias check

Testing a defective diode

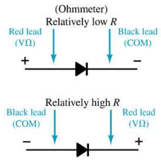
Forward- and reverse–bias tests for an open diode give the same indication. Some meters display "OL".



Forward- and reverse–bias test for a shorted diode give the same 0 V reading. If the diode is resistive, the reading is less than 2.6 V.

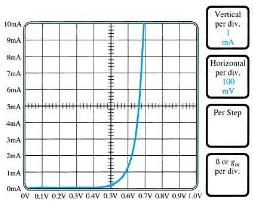
Ohmmeter

An ohmmeter set on a low Ohms scale can be used to test a diode. The diode should be tested out of circuit.



Curve Tracer

A curve tracer displays the characteristic curve of a diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



Key points

- Diodes allow current to flow in only one direction.
- At low temperatures semiconductors act like insulators.
- At higher temperatures they begin to conduct.
- Doping of semiconductors leads to the production of *p*-type and *n*-type materials.
- A junction between *p*-type and *n*-type semiconductors has the properties of a diode.
- Silicon semiconductor diodes approximate the behaviour of ideal diodes but have a conduction voltage of about 0.7 V.
- There are also a wide range of special purpose diodes.
- Diodes are used in a range of applications.