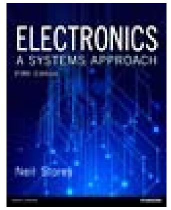
Last time: Operational Amplifiers
Key points

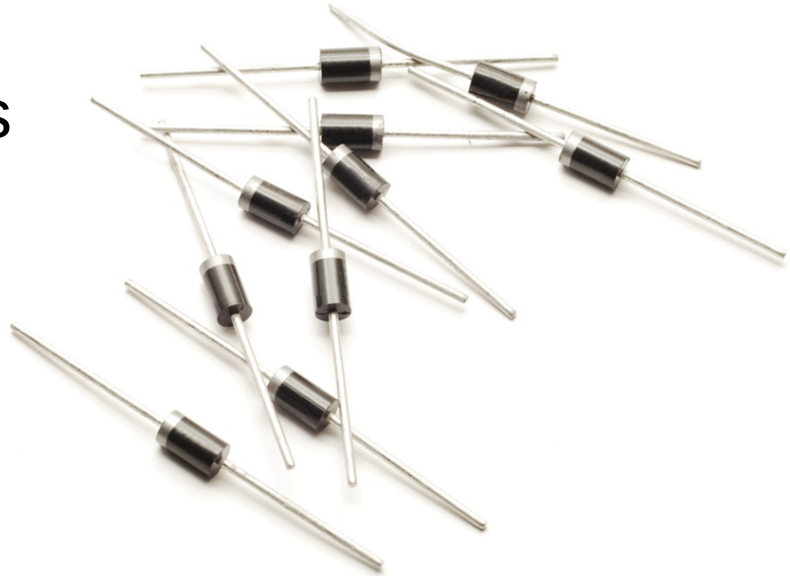
- Operational amplifiers are among the most widely used building blocks in electronic circuits
- An *ideal* operational amplifier would have infinite voltage gain, infinite input resistance and zero output resistance
- Designers often make use of cookbook circuits
- Real op-amps have several non-ideal characteristics However, if we choose components appropriately this should not affect the operation of our circuits
- Feedback allows us to increase bandwidth by trading gain against bandwidth
- Feedback also allows us to alter other circuit characteristics



Last time: Semiconductors and diodes

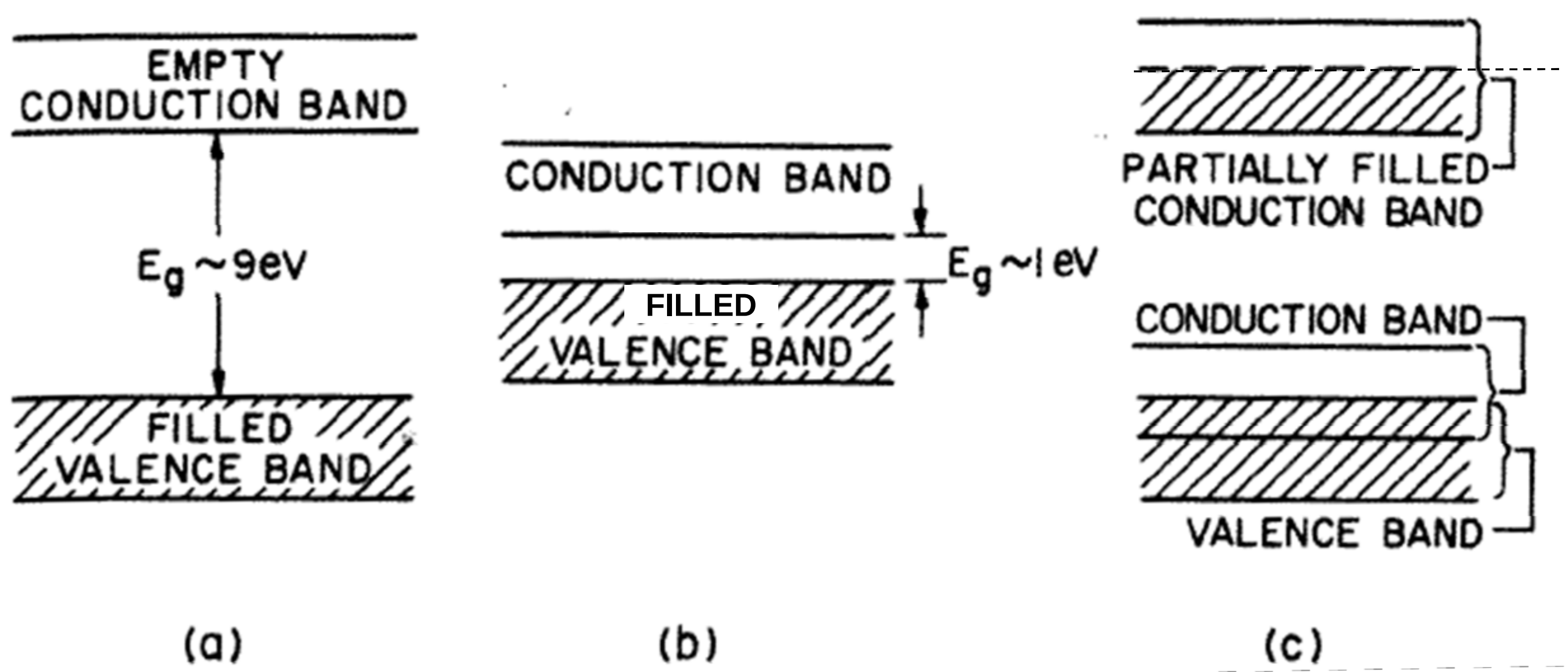
Chapter 17

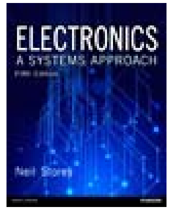
- Introduction
- Electrical properties of solids
- Semiconductors
- *pn* Junctions
- Diodes
- Semiconductor diodes
- Special-purpose diodes
- Diode circuits.
- Field effect transistors



Band separation and electronic properties

Insulators | **Undoped Semiconductors** | **Metals**





Semiconductors

17.3

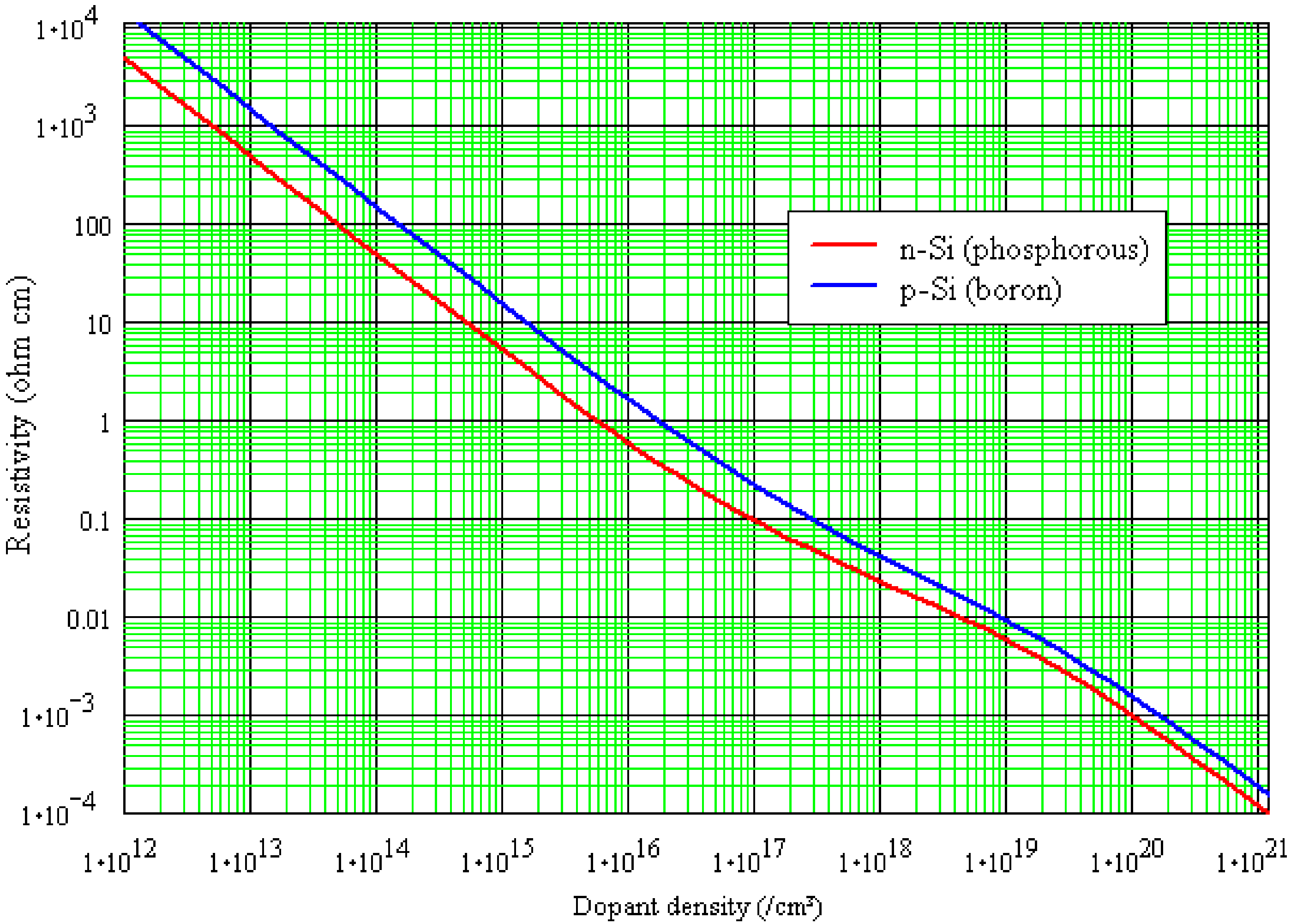
- **Pure semiconductors**
  - thermal vibration results in some bonds being broken, generating **free electrons** which move about
  - these leave behind **holes** which accept electrons from adjacent atoms and therefore, also move about
  - electrons are **negative charge carriers**
  - holes are **positive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

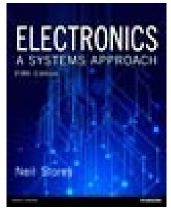
Doping of semiconductors

- **Doping**
  - the addition of small amounts of impurities drastically affects its properties
  - some doping materials form an excess of *electrons* and produce an ***n*-type semiconductor**
  - some doping 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
  - this is **extrinsic conduction**

Effect of doping on resistivity of Si

$3.2 \times 10^5\ \Omega \cdot cm$ for intrinsic Si (no doping)





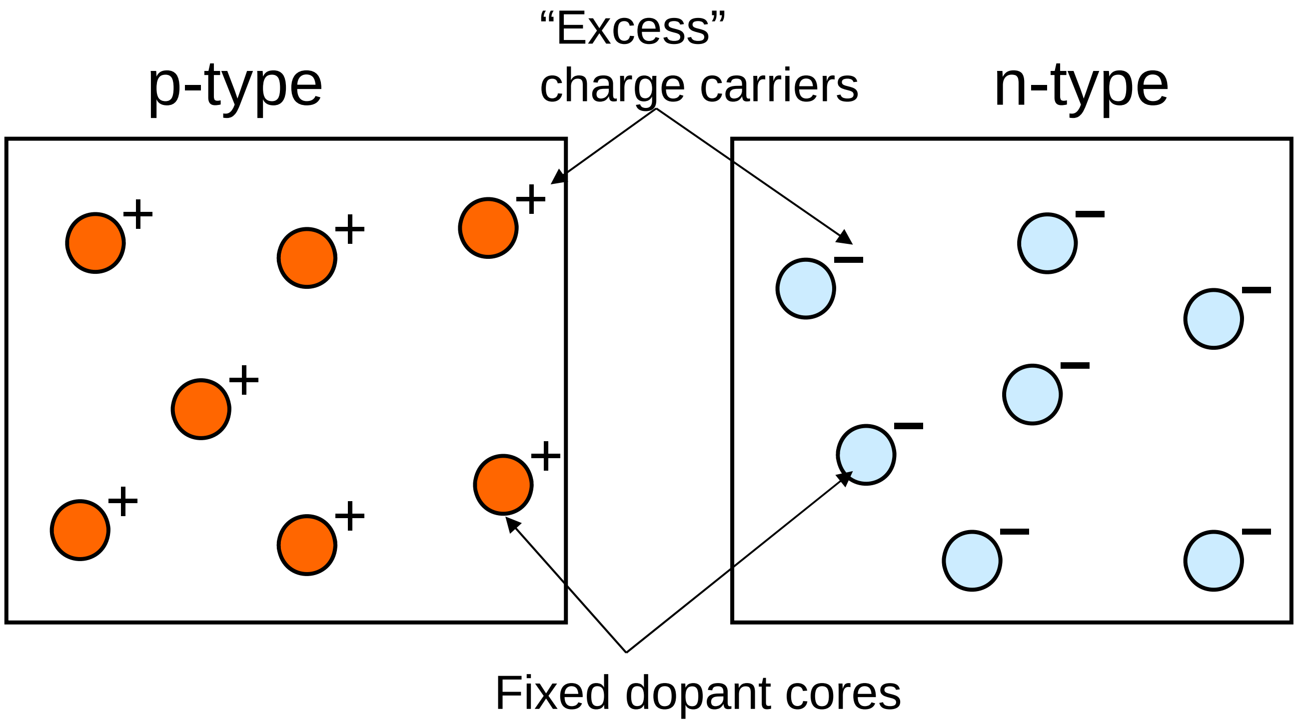
pn Junctions

17.4

- 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**)

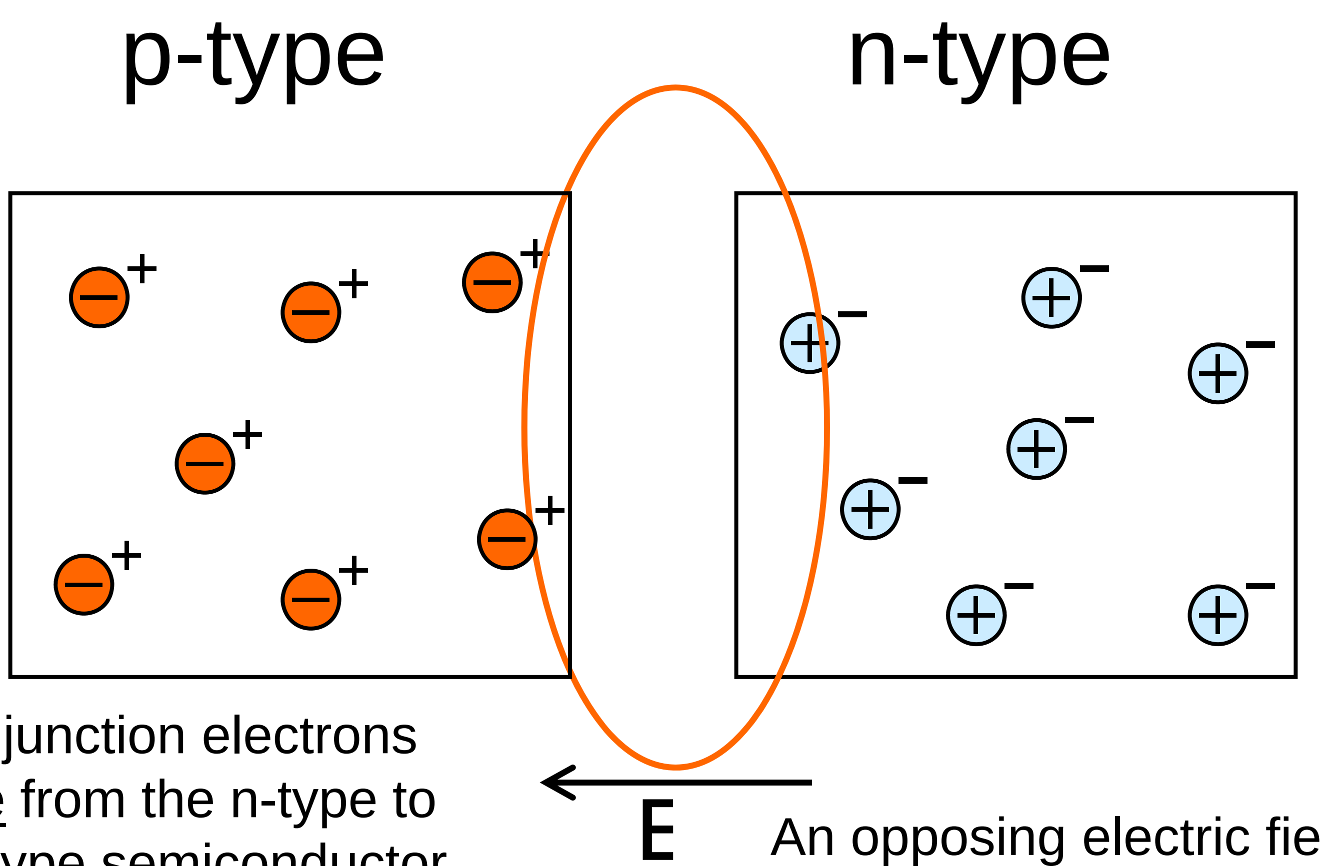
pn-junction

To create an built-in electric field : join a p-type and an n-type semiconductor, to create a pn-junction.



Here shown before ionization of the dopants; In the ionization process the free carriers will be (thermally) released to the surrounding semiconductor.

What happens when the p- and n-type materials are brought together?

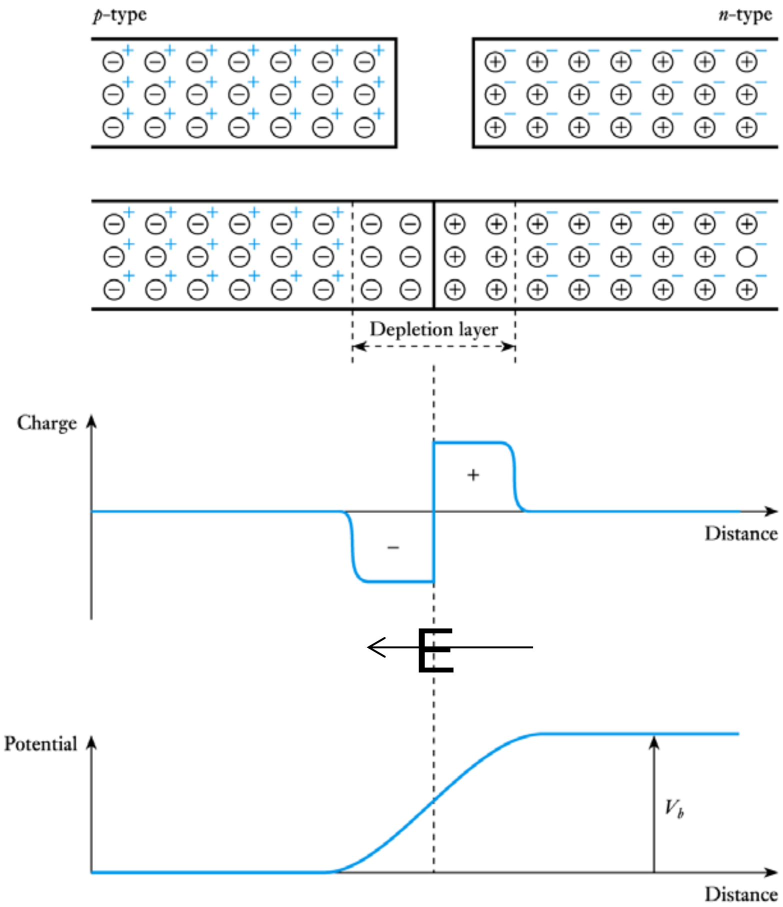


At the junction electrons diffuse from the n-type to the p-type semiconductor, where they recombine with available holes. This creates a region with a depletion of free charges

An opposing electric field builds up due to the charge associated with the ionized donor and acceptor atoms.

This electric field stops the diffusion. But any thermal electrons generated more towards n-type

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



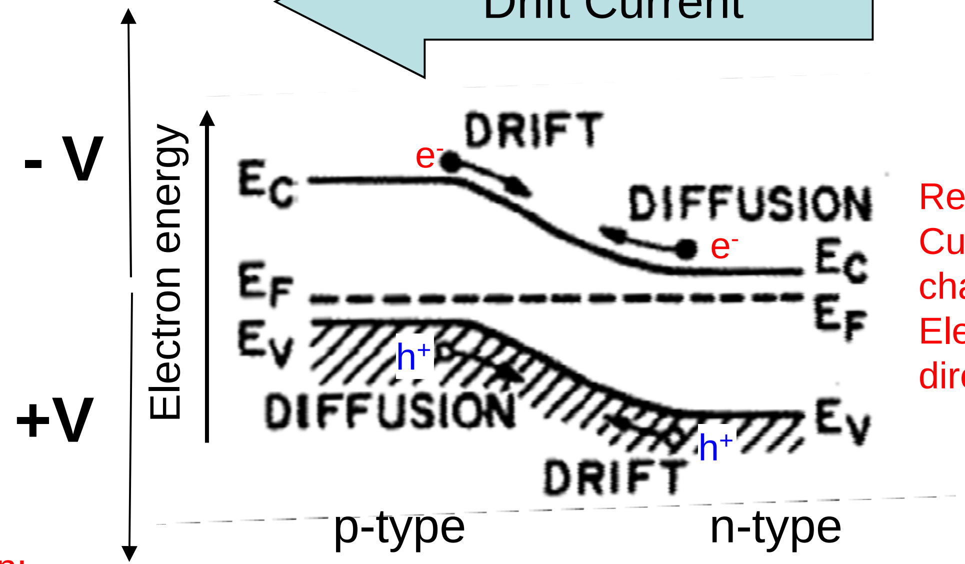
- **Potential barrier**
  - Barrier *opposes the flow of majority charge carriers* and only a small number have enough energy to cross it
    - This generates a *small* **diffusion current**
  - Barrier *encourages the flow of minority carriers* and any that come close to it or *are thermally generated within the depletion region* will be swept across
    - This generates a *small* **drift current**
  - for an isolated junction these two currents must balance each other and *the net current is zero*

Currents at Equilibrium

- The Drift and Diffusion currents are = and opposite: $J_t = J_{drift} - J_{diffusion} = 0$

Drift Current

Due to E field



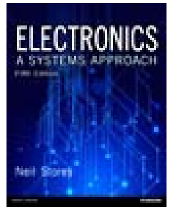
Remember:
Current is defined as motion of + charge carriers,
Electrons move in opposite direction

Constant charge motion:
- Thermal events generate e^-/h^+ pairs
They drift in E-field and weaken it
- Weakened E-field allows n-e^- and p-h^+ to diffuse and re-build E-field
- Diffusion cancels drift: no net current

Diffusion Current

Due to n/p
Concentration gradients

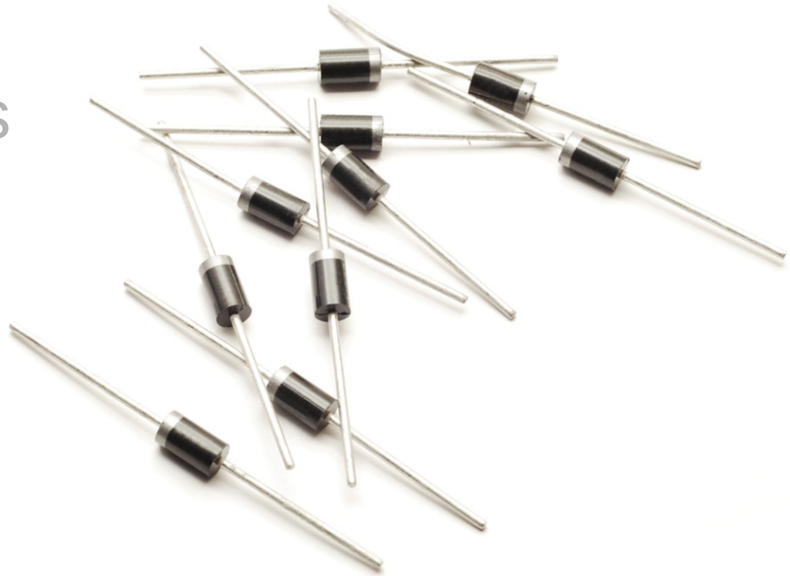
- Questions?



Today: Semiconductors and diodes

Chapter 17

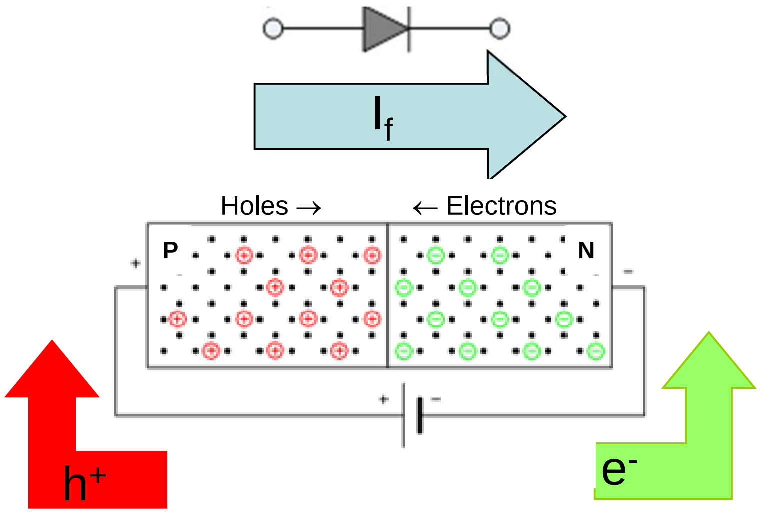
- Introduction
- Electrical properties of solids
- Semiconductors
- *pn* Junctions
- Diodes
- Semiconductor diodes
- Special-purpose diodes
- Diode circuits.
- Field effect transistors

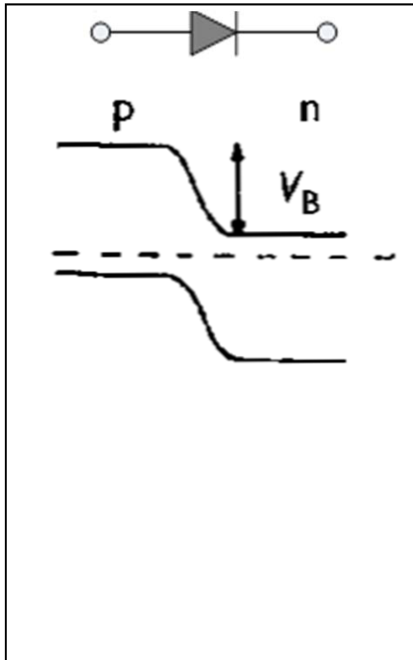


Biasing the *pn* Junction ⇒ the diode

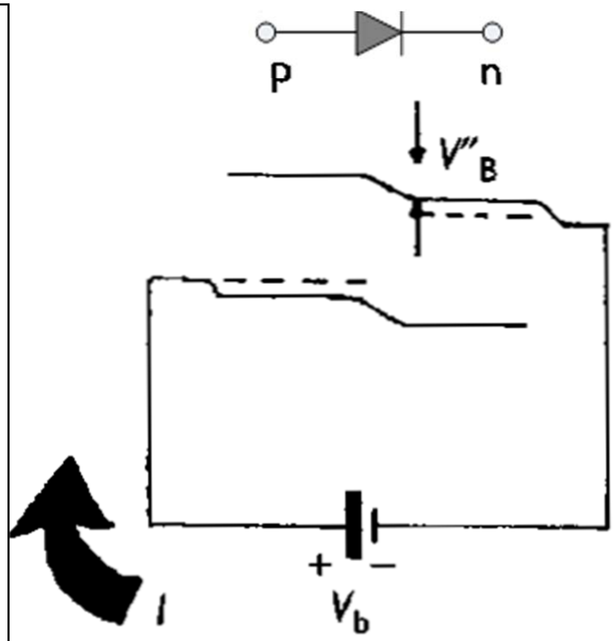
- **Forward bias**
  - if the *p*-type side is made *positive* with respect to the *n*-type side the height of the barrier is *reduced*
  - more majority charge carriers have enough energy to cross
  - the diffusion current therefore increases while the drift current remains the same
  - there is thus a net current flow across the junction which *increases with the applied voltage*
  - *Threshold* for conduction is ~0.7 V. That is, the forward potential has to be 0.7 V for the diode to pass current.

Biasing of the p-n junction





Isolated junction
Zero bias



Forward bias

$V''_B < V_b$

Forward Bias-reduce V_B

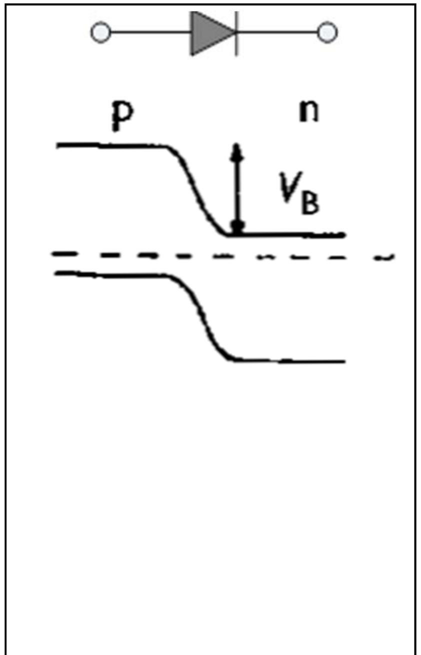
$$V''_B = V_B - |V_b|$$

Forward battery bias:

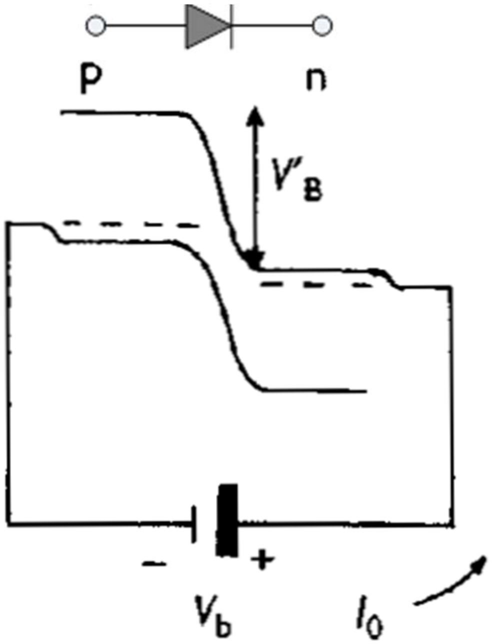
- *pushes h^+ into p side, e^- into n side*
- *this repels other majority carriers toward junction,*
- *recombination there results in battery current I_f=diffusion current enhanced by forward bias .*

- **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 enough energy to cross 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)

Biasing of the p-n junction



Isolated junction
Zero bias

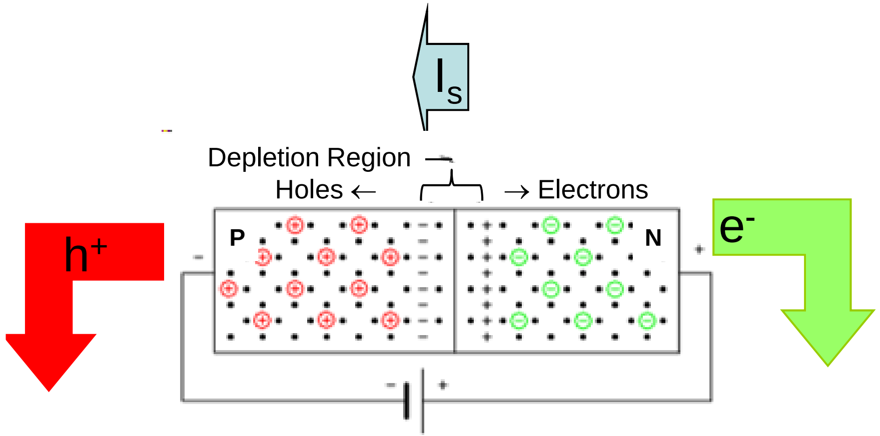


Reverse bias

$V'_B > V_b$

Reverse Bias-increase V_B

$$V'_B = V_B + |V_b|$$



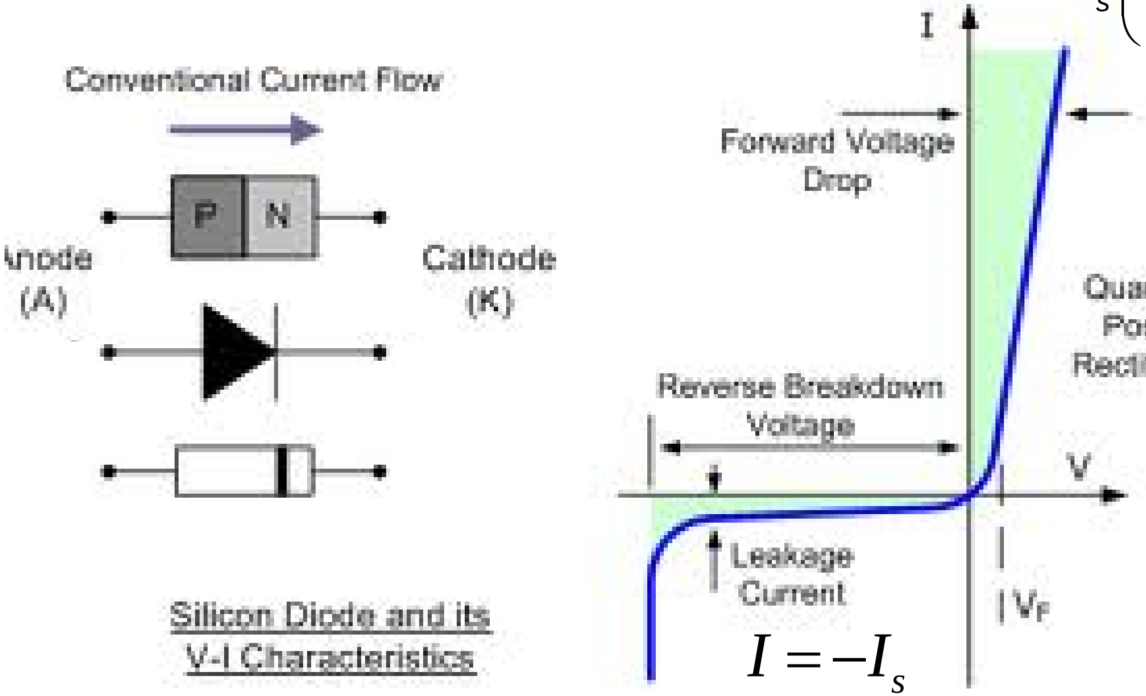
Reverse battery bias:

- *attract majority carriers to battery terminal away from junction.*
- *Depletion region thickness increases.*
- *No sustained battery current flows*
- *Only random thermal events supply I_s=drift cuttent*

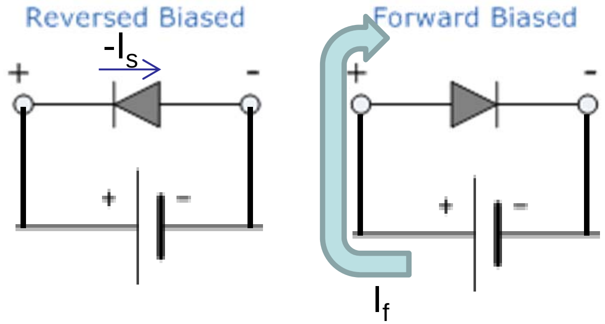
External currents across a pn-junction

- The diode passes current in <u>one</u> direction.

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



$$I = -I_s$$



There is a voltage drop across a forward biased diode of ~0.7 V (threshold for conduction)

- Questions?

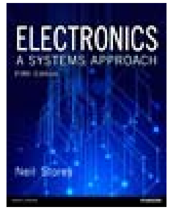
Today: Reverse breakdown

- 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

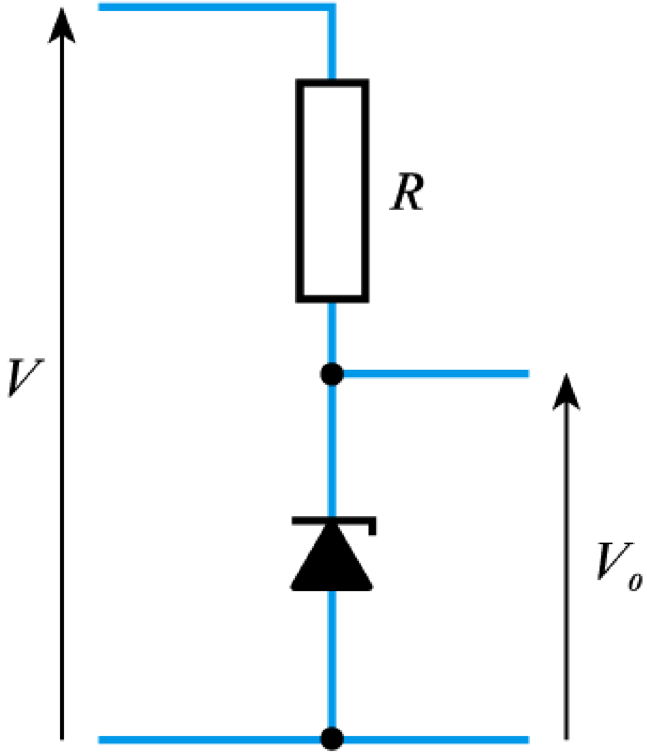
- **Avalanche breakdown**
  - occurs in diodes with more lightly doped materials
  - field strength across junction is insufficient to pull electrons from their atoms, but is sufficient to accelerate the electrons within the depletion layer
  - they loose energy by colliding with atoms
  - if they have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

Special-purpose diodes

Too much current will
kill diode



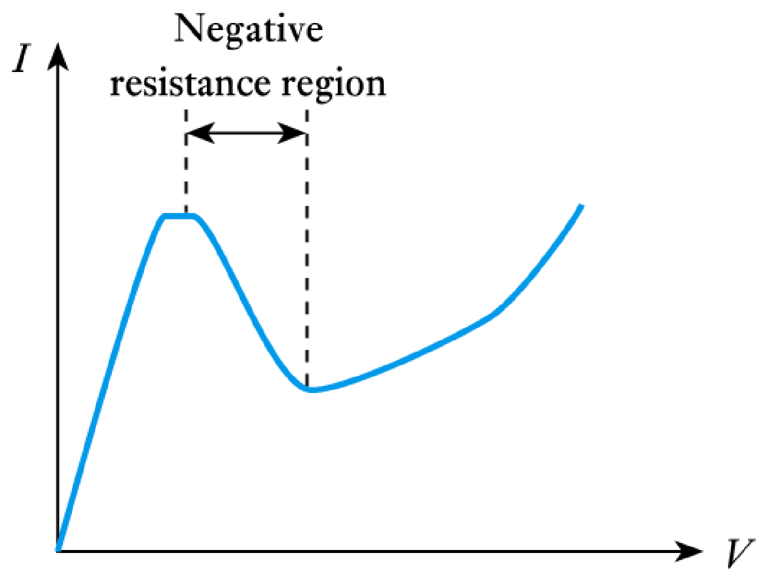
- **Zener diodes**
  - uses the relatively constant reverse breakdown voltage to produce a voltage reference
  - breakdown voltage is called the **Zener voltage**, V_Z
  - output voltage of circuit shown is equal to V_Z despite variations in input voltage V
  - a resistor is used to limit the current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



Schottky diodes

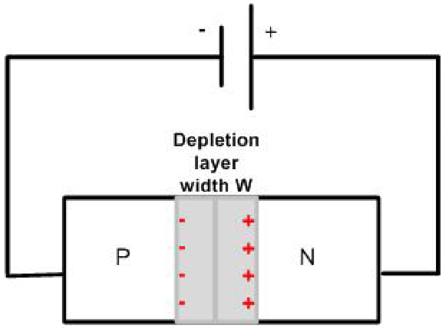
- formed by the junction between a layer of metal (e.g. aluminium) and a semiconductor
- action relies only on majority charge carriers
- much faster in operation than a *pn* junction diode
  - Don’t have to wait for recombination of minority carriers
- has a low forward voltage drop of about 0.25 V
- used in the design of high-speed logic gates

- **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

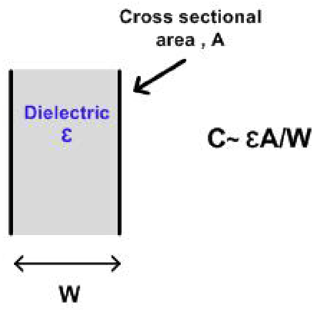


  - used in high-frequency oscillators, where they can be used to ‘cancel out’ resistance in passive components

Extra Large depletion region

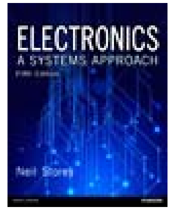


PN junction - reverse biased



PN junction- effective parallel plate capacitor

- **Varactor diodes**
  - a reversed-biased diode looks like two conducting regions separated by a large 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**

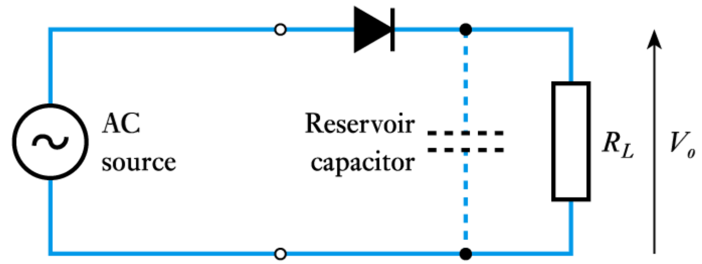


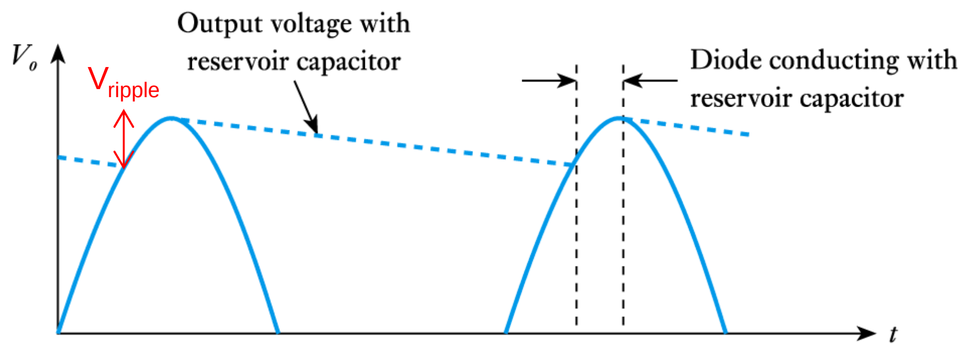
Diode circuits

Video 17A

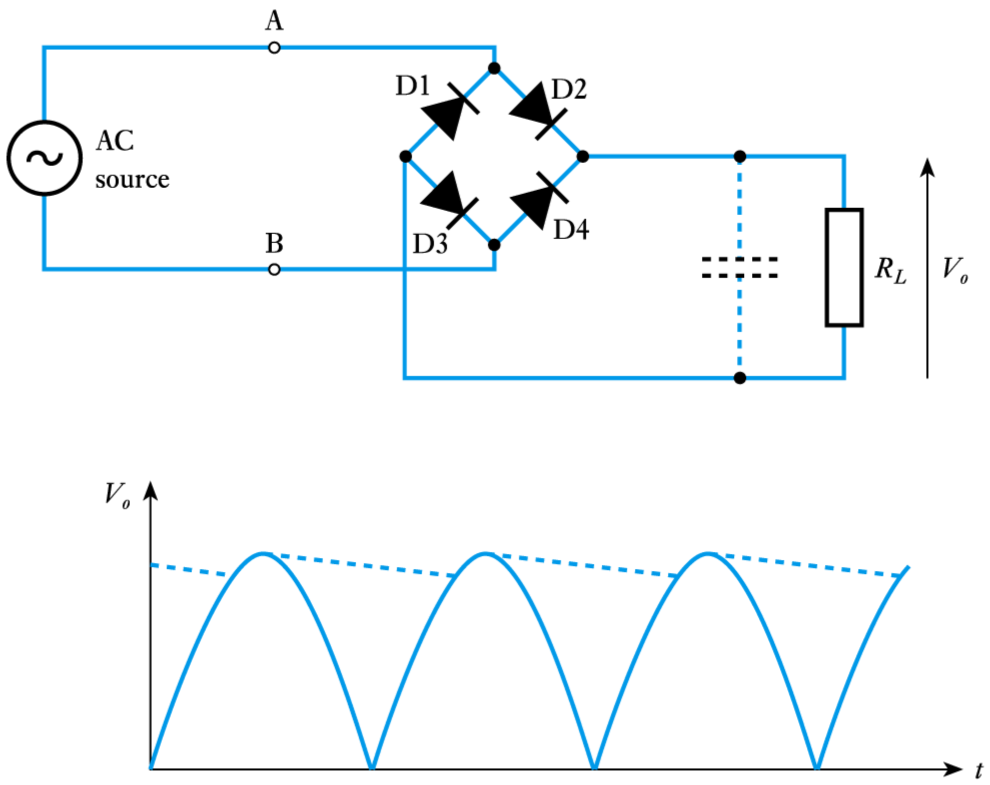
17.8

- **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

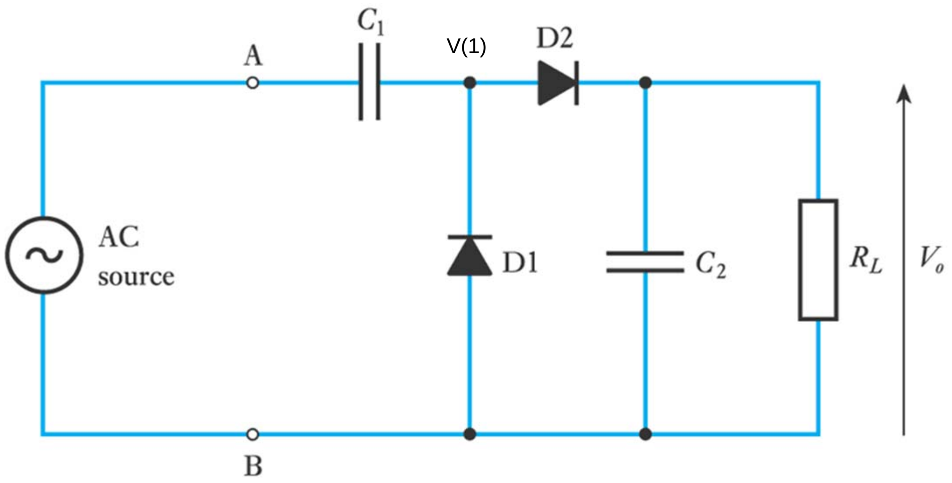


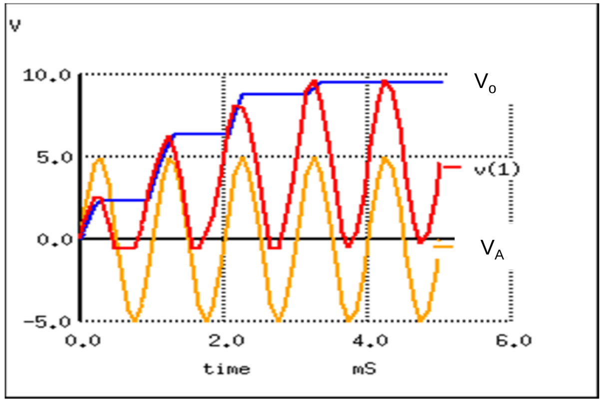


- **Full-wave rectifier**
  – use of a diode bridge reduces the time for which the capacitor has to maintain the output voltage and thus reduce the ripple voltage



- **Voltage doubler**
  - charges C_2 to nearly twice the peak input voltage
  - several stages can be cascaded to produce very high voltages
  - ideal in applications requiring high voltages at low currents



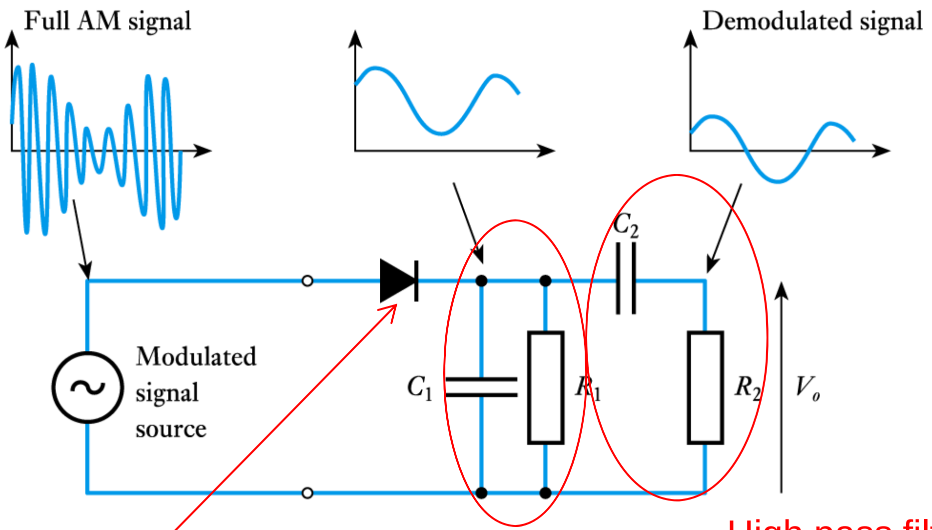


Video 17B

- **Signal rectifier**

Signal is the low frequency part
Carrier is the high frequency part

  - 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



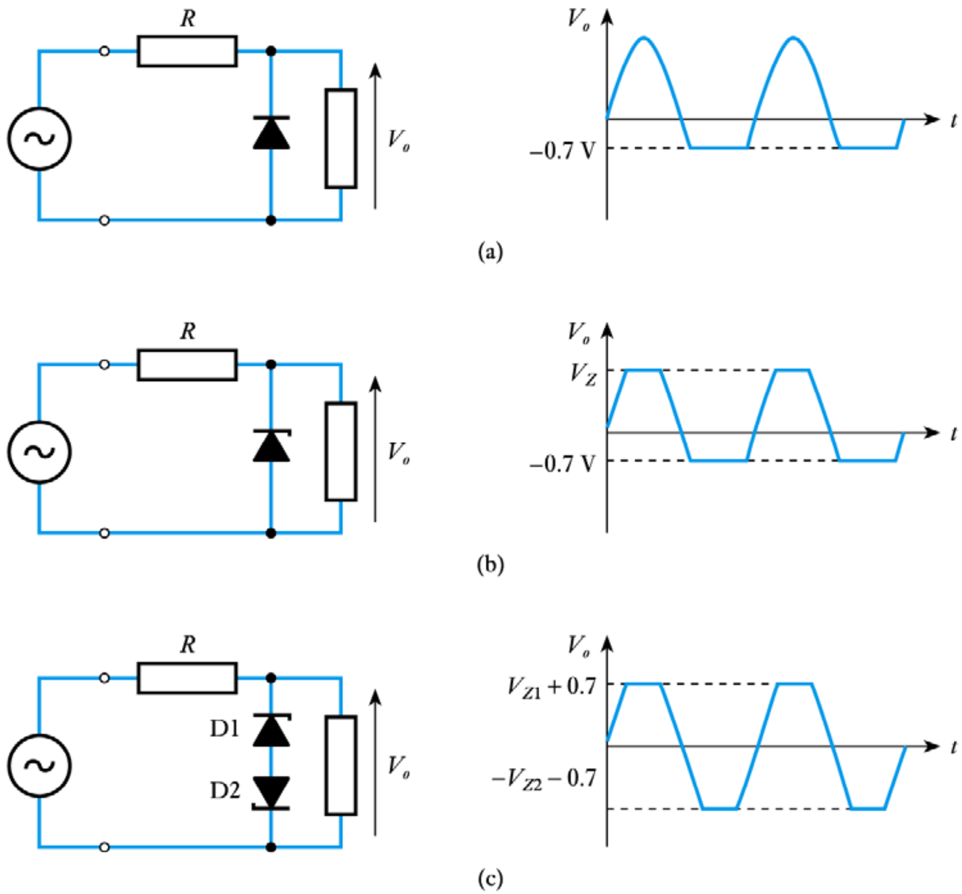
Diode half-wave rectifies the signal (no negative voltages)

Low pass filter
$\omega_c = R_1 \cdot C_1 > \omega_s$ but less than carrier frequency
Removes carrier frequency

High pass filter removes DC

Signal clamping

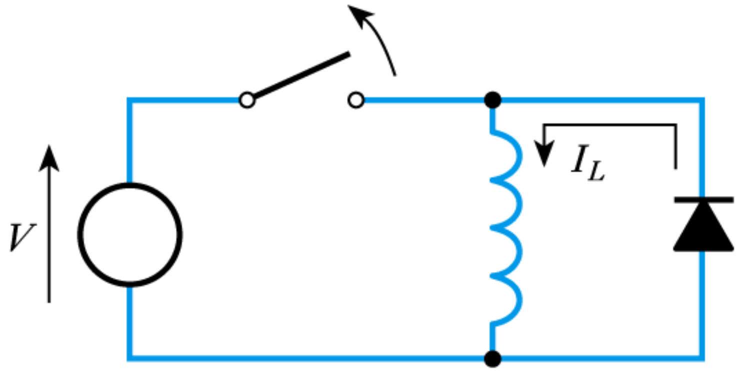
- a simple form of **signal conditioning**
- circuits limit the excursion of the voltage waveform
- can use a combination of signal and Zener diodes



Input to a device where input voltage must be < V_Z

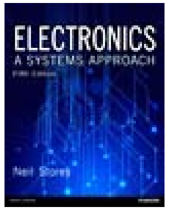
Catch diode

- used when switching inductive loads
- the large back e.m.f. can cause problems such as arcing in switches
- **catch diodes** provide a low impedance path across the inductor to dissipate the stored energy
- the applied supply voltage reverse-biases the diode, which therefore has no effect
- when the supply voltage is removed the back e.m.f. forward biases the diode which then conducts



Further Study

Video 17C



Further Study

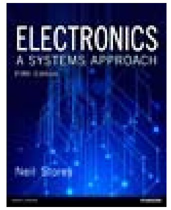
- The Further Study section at the end of Chapter 17 is concerned with the design of a mains power supply.
- The supply is to drive an appliance that requires a fairly constant input of 12V and takes a current that varies from 100 to 200 mA.

- Design such a unit and then look at the video.

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

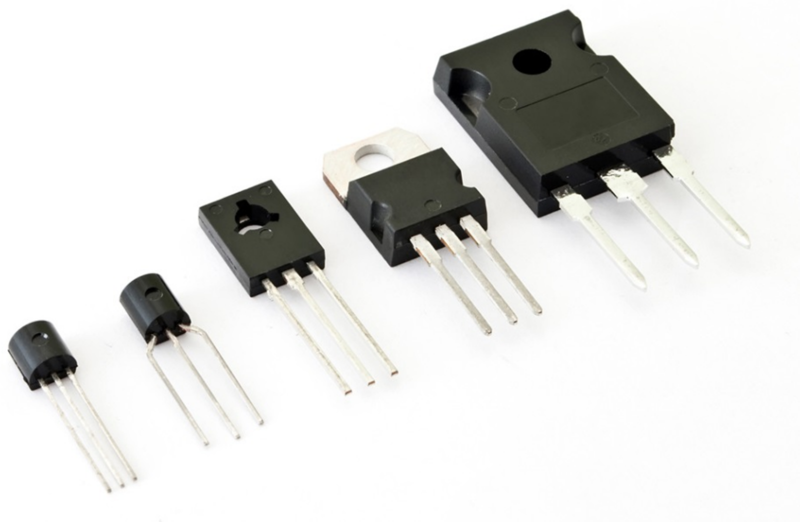
- Questions?

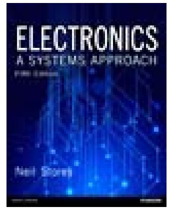


Chapter 18

Today: Field-effect transistors

- Introduction
- An overview of field-effect transistors
- Insulated-gate field-effect transistors
- Junction-gate field-effect transistors
- FET characteristics
- FET amplifiers
- Other FET applications
- FET circuit examples

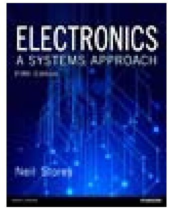




18.1

Introduction

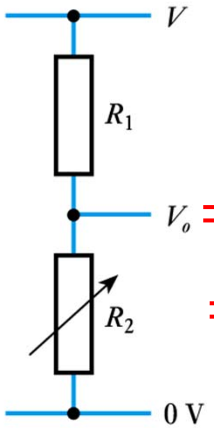
- **Field-effect transistors** (**FETs**) are probably the simplest form of transistor
  - widely used in both analogue and digital applications
  - they are characterized by a very high input resistance and small physical size, and they can be used to form circuits with a low power consumption
  - they are widely used in **very large-scale integration**
  - two basic forms:
    - **junction gate FETs**
    - **insulated gate FETs**



14.9

Simple amplifiers

- Amplifiers can also be formed using a ‘control device’
  - circuit is a potential divider with one resistor replaced with a variable resistor that controls I flowing through the resistors
  - If we could control (adjust) R_2 or the current from V to ground with the input voltage, then we have $V_o \propto V_i$ which is an amplifier



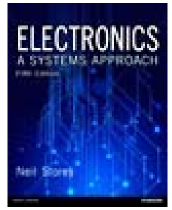
A potential divider

$= V\,R_2 / (R_1+R_2)$

$= V - I{\cdot}R_1$

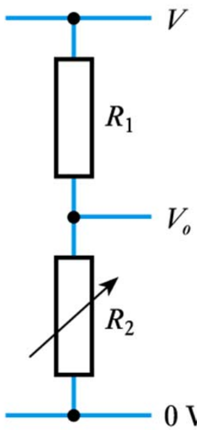
As R_2 decreases, V_o decreases
(or I through the system increases)
As $R_2 \rightarrow 0$, (I increases) and $V_o \rightarrow 0$

As R_2 increases, V_o increases
(or I through the system decreases)
When R_2 is >> R_1, $R_2/(R_1+R_2) \rightarrow R_2/R_2 = 1$
And $V_o \rightarrow V$



Simple amplifiers

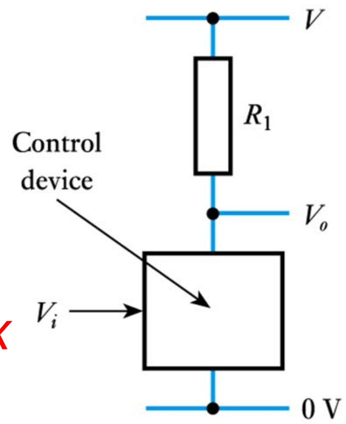
- Amplifiers can also be formed using a ‘control device’
  - circuit is similar to a potential divider with one resistor replaced with a variable resistor that controls I flowing through the resistors
  - ‘control device’ typically a **transistor**
  - $V_o = V\text{-}I{\cdot}R_1$ so that if the device controls I, it controls V_o



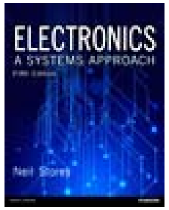
$= V\,R_2\,/\,(R_1+R_2)$

A potential divider

V_i controls R of box
(or I thorough box)

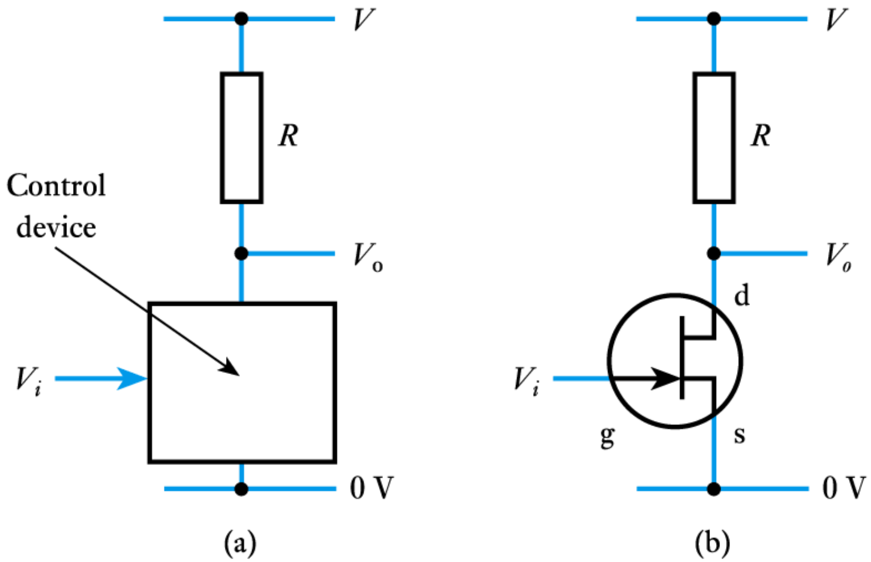


A simple amplifier

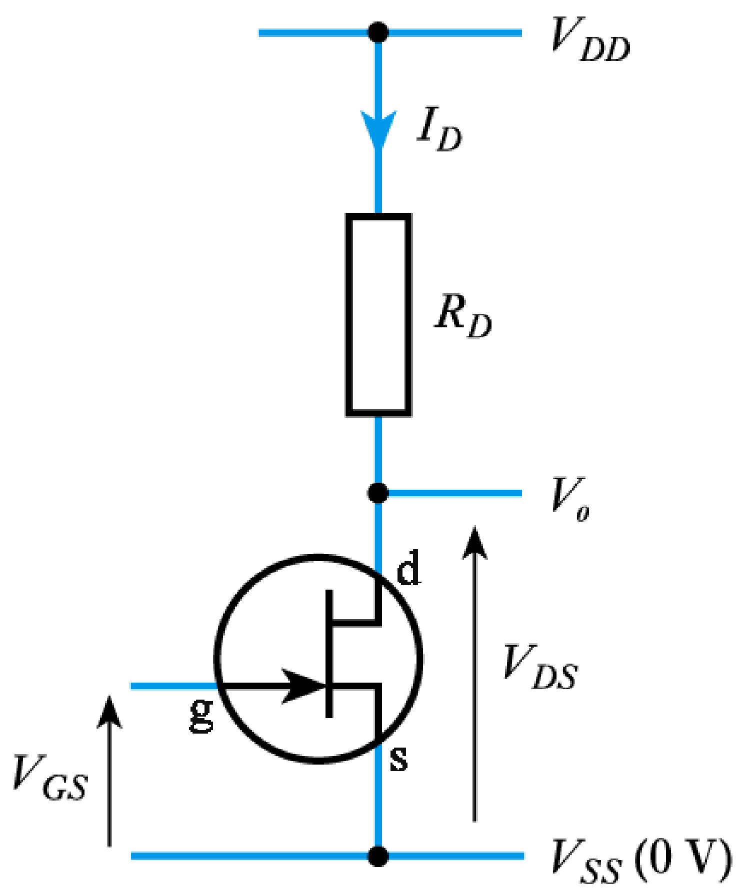


An overview of field-effect transistors

- Many forms, but basic operation is the same
  - a voltage on a control input produces an electric field that affects the current between two other terminals
  - when considering amplifiers we looked at a circuit using a 'control device'
  - a FET is a suitable control device

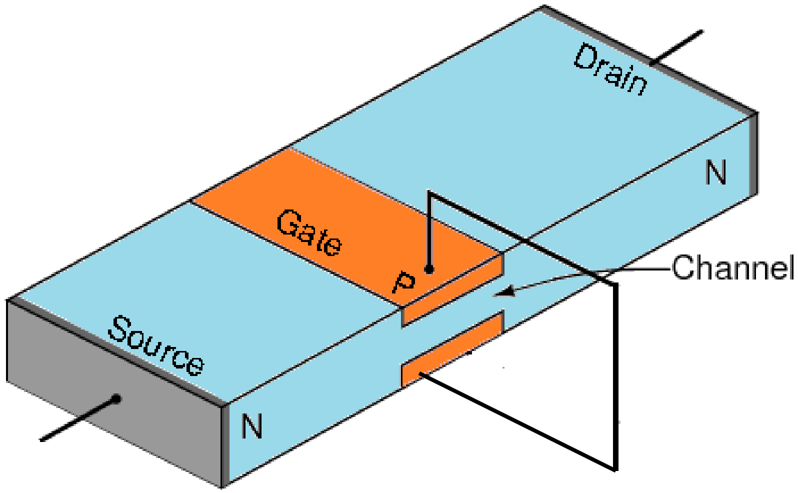


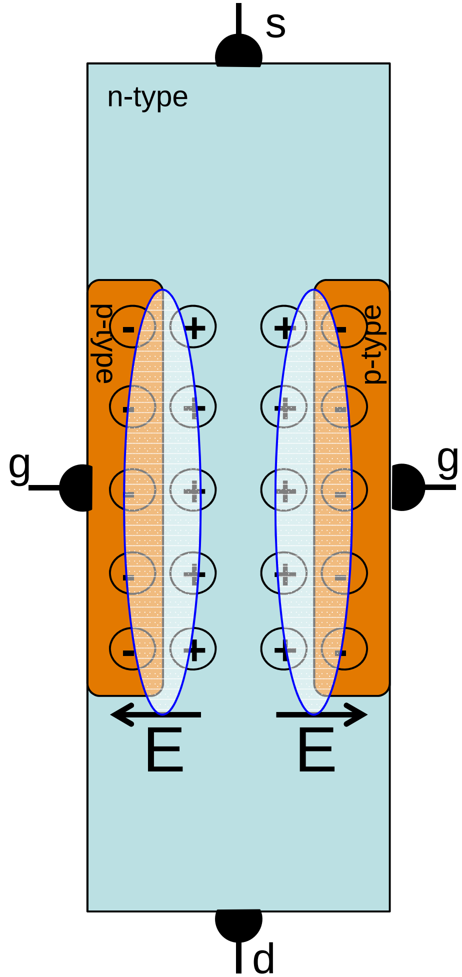
- **Notation**
  - FETs are 3 terminal devices
    - drain (d)
    - source (s)
    - gate (g)
  - the gate is the control input
  - diagram illustrates the notation used for labelling voltages and currents



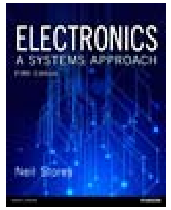
Why does this work? What's in the box?

A diode—pn-junctions!
An n-type bar with 1 or 2 p-type inserts
Will get majority carriers diffusing across the junction that leave ionized dopants
Creates electric fields and depletion regions





- Questions?



Chapter 18

Next time: Field-effect transistors

- Introduction
- An overview of field-effect transistors
- Insulated-gate field-effect transistors
- Junction-gate field-effect transistors
- FET characteristics
- FET amplifiers
- Other FET applications
- FET circuit examples