Lecture-2

11 August 2023 15:28

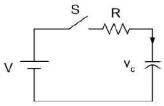
Step Response - RC Circuit

- Step response: DC voltage or current is suddenly applied to the RC circuit shown
- For a series R-C circuit

$$V_c = V_f + (V_{ci} - V_f)e^{-\frac{t}{\tau}}$$

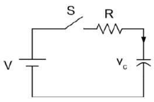
where, τ = time constant = RC,
V_{ci} is capacitor voltage at t = 0, (initial value)
V_f is the final value

- Circuit is assumed to attain steady state at t = 5τ



- **Steady state is achieved at 5t (Remember)**
- **5t assumption is based on experiments**

At $t = 0$, capacitor voltage, $v_c = 0$
Switch closed at $t = 0^+$
At $t = 0^+$, $v_c = 0$, $v_R = V$ and $i = \frac{V}{R}$
(voltage across C cannot change instantaneously)



With $V_f = V$, $V_{ci} = 0$,
$v_c = V\,(1 - \exp[-t/\tau])$

$i = (V/R) \exp[-t/\tau]$

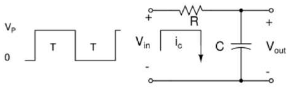
In steady state $v_c = V,\ i = 0, \therefore VR = 0$

Steady state attained at $t \approx 5\tau$

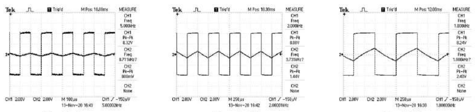
- After attaining steady state (i.e. v_c = V), if V = 0 and the switch is closed:
  - C will discharge through R
  - Steady state attained at $t \approx 5\tau$
  - For $t \geq 5\tau$, $v_c = 0$

RC Integrator Circuit

- Instead of a switch, here a square waveform is applied as V_{in}
- $V_{in} = V_P$ *(similar to switch closed with V = V)*
- $V_{in} = 0$ *((similar to switch closed with V = 0)*
- *C* will have both charge and discharge cycles through *R*
- Here $V_{out} = V_c$
- Depending on the relative values of *T* and $\tau = RC$, V_{out} will give different waveforms



RC Integrator Experimental Results



$T_s = 0.1\tau$
(τ is very large compared to T_s.)

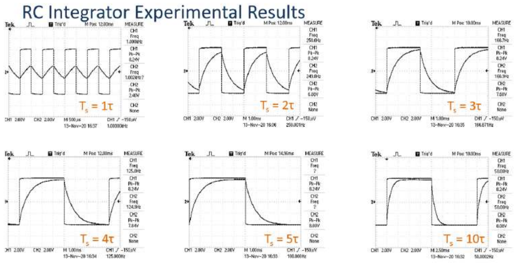
$T_s = 0.25\tau$

$T_s = 0.5\tau$

- For the RC circuit to work as an integrator, T << τ

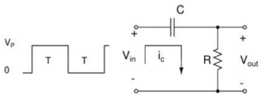
- When t >> T, the graph is almost linear i.e. integration of constant.
- That's why called integrator circuit
- For RC circuit to work as an integrator t>>T(vout = integration of vin)

RC Integrator Experimental Results



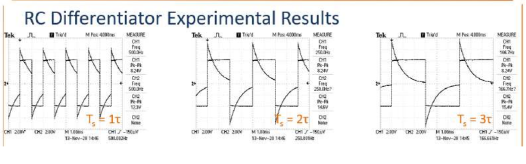
RC Differentiator Circuit

- Instead of a switch, here a square waveform is applied as V_{in}
- $V_{in} = V_P$ *(similar to switch closed with V = V)*
- $V_{in} = 0$ *((similar to switch closed with V = 0)*
- *C* will have both charge and discharge cycles through *R*
- Here $V_{out} = V_R$
- $(V_{out} = i_c \cdot R)$; $i_c = (V_P/R) \exp[-t/\tau]$
- Depending on the relative values of *T* and $\tau = RC$, V_{out} will give different waveforms



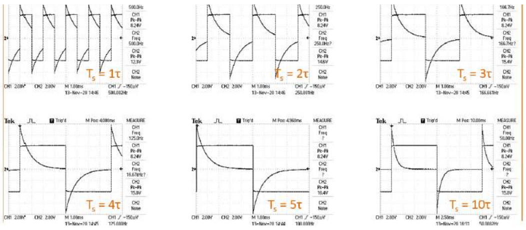
- For the RC circuit to work as a differentiator, *T* >> τ

RC Differentiator Experimental Results

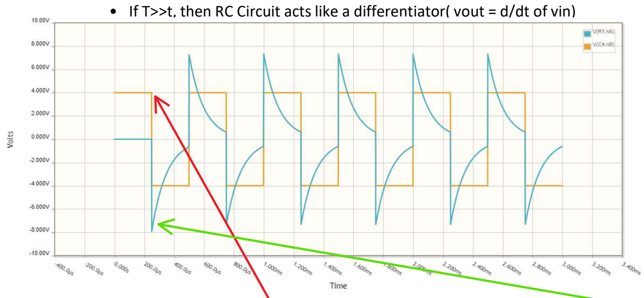


- **In the differentiator circuit the peak has doubled to 16v since direction of current has changed. So the 8v is the new zero.**

- If T>>t, then RC Circuit acts like a differentiator(vout = d/dt of vin)



- If T>>t, then RC Circuit acts like a differentiator(vout = d/dt of vin)



The capacitor is charged to +4
Then the voltage drops to -4 but voltage across capacitor can't change instantaneously so voltage across resistance is -8v

Frequency Response of RC Circuits

- Impedance : complex quantity
- Impedance found by giving a sinusoidal excitation (voltage) and finding the response (current) of R, L and C.
- Units of impedance: Ohms.
  - ω : angular frequency in radians/sec, and ω = 2πf
- Impedance of a resistor = R ohms (no dependence on ω)
- Capacitive impedance : 1/jωC
  - Inversely proportional to ω
- Inductive impedance : jωL
  - Directly proportional to ω

- Impedance is defined only for a sinusoidal waveform, and not pulse

Frequency Selective Circuits

- Offer different impedances at different frequencies
- Required in filters (used for passing a certain band of frequencies (pass band) and blocking or attenuating another band of frequencies – (stop band))
- Also required in the generation of sinusoidal waveform generators
- Passive Filters – made of R, L, and C
- Active filters – made using a combination of passive filters and amplifiers

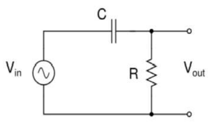
- Low pass, high pass filter. Used in radio, equalizer
- Higher the order of transfer function, more steeper will be the pass band

Transfer Function

- Transfer function: V_{out}/V_{in}
- Order of the transfer function:
  - Order of the polynomial
- First order – made using R and C
- Second order and higher – made using R, L and C (often cascaded)
- First order: the attenuation in the stop band is not very high

- Band pass filter (RLC Circuit with V_Out across Resistance)
- Band Stop filter(Inverse of band pass). Needed to remove the noise during experiment. Noise is generally 50hz since all appliances work on 50hz

RC High Pass Filter



- In the circuit, $V_{out}/V_{in} = R/[R + (1/j\omega C)]$
- The amplitude of (V_{out}/V_{in}) can be written as $| V_{out}/V_{in} | = 1/\text{sqrt}[1 + (f_c/f)^2]$, where $\omega = 2\pi f$, and $f_c = 1/(2\pi RC)$.
- f_c is called the cut-off frequency of the above RC filter.
- When $f = f_c$, $| V_{out}/V_{in} | = 1/\text{sqrt}(2) = 0.707$ V/V
- for $f < f_c$, $| V_{out}/V_{in} | < 0.707$
- $f > f_c$ and $| V_{out}/V_{in} |$ would reach unity asymptotically for $f >> f_c$

- Since the circuit passes frequencies above a certain cut-off frequency (f_c) and attenuate those below it, the circuit in is called a **high-pass filter**.

Doubts

- **Are Capacitors and Inductors linear elements? But their IV characteristics appear to be non-linear.**
- The definition of linearity: if $f(a+b) = f(a) + f(b)$ then the function f is linear. Its response to the sum of two stimuli is equal to the sum of the responses to those stimuli individually.
- The reason a capacitor is a linear component is: its voltage and current as functions of time depend in a linear way on each other.
- Differentiation is linear.
- Superposition of Current in a Capacitor:
  - $i_1 + i_2 = d/dt\,(v_1 + v_2) = d\,v_1/dt + dv_2/dt$

1. The *pn* Junction Diode

Semiconductors (Intrinsic Semiconductors)

- Semiconductors are materials whose conductivity lies between that of conductors, such as copper, and insulators, such as glass.
- There are two kinds of semiconductors:
  - **Single-element semiconductors**, such as germanium and silicon, which are in group IV in the periodic table; and
  - **Compound semiconductors**, such as gallium-arsenide, which are formed by combining elements from groups III and V or groups II and VI.
  - Compound semiconductors are useful in special electronic circuit applications as well as in applications that involve light, such as light-emitting diodes (LEDs).
- Two elemental semiconductors - Germanium (Ge) and Silicon (Si)
  - Ge was used in the fabrication of very early transistors (late 1940s, early 1950s).
  - Si became soon popular. Today's integrated-circuit technology is almost entirely

- Al-As-Ga , depending on the fraction of Al and Ga, we can get wavelength from 600-900nm
- In making pn diode, we take a p-type wafer and dope it with n type (or vice versa)
- Never use a diode directly, always put a resistance in series else diode will burn.
- IN4007(1A, PIV, 1000v) will be the diode used in lab.[Price is 55 paisa]

combining elements from groups III and V or groups II and VI.
    - Compound semiconductors are useful in special electronic circuit applications as well as in applications that involve light, such as light-emitting diodes (LEDs).
- Two elemental semiconductors - Germanium (Ge) and Silicon (Si)
    - Ge was used in the fabrication of very early transistors (late 1940s, early 1950s).
    - Si became soon popular. Today's integrated-circuit technology is almost entirely based on silicon.

- Silicon (Si) is the most commonly used material used in *pn* junction diodes.
- Si in its intrinsic (or pure) form is not useful for fabricating devices, instead it is doped with impurities.
- **Doping** involves introducing impurity atoms into the silicon crystal in sufficient numbers to substantially increase the concentration of either free electrons or holes but with little or no change in the crystal properties of silicon.
- To increase the concentration of free electrons, *n*, silicon is doped with an element with a valence of 5, such as phosphorus.
    - This results in an ***n* type** silicon.
- To increase the concentration of holes, *p*, silicon is doped with an element having a valence of 3, such as boron
    - This results in ***p* type** silicon.

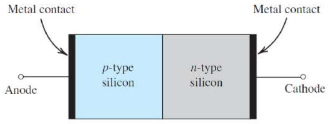


Fig. 1 Simplified physical structure of the *pn* junction.

Since the *pn* junction is used as a diode, the diode terminals are therefore labeled "anode" and "cathode" in keeping with diode terminology.

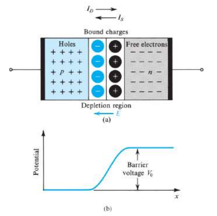


Fig 2 (a) The *pn* junction with no applied voltage (open-circuited terminals).

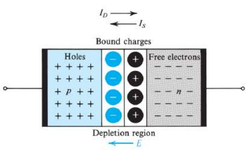
(b) The potential distribution along an axis perpendicular to the junction.

Source: Chap 3, Microelectronic Circuits, 7th ed., AS Sedra and KC Smith, Oxford University Press

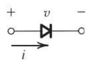
- Holes diffuse across the junction from the *p* side to the *n* side.
- Similarly, electrons diffuse across the junction from the *n* side to the *p* side.
- Recombination takes place close to the junction.
- There will be a region close to the junction that is *depleted of free electrons and holes*.
    - This region is called the **depletion region, or the space-charge region.**
- A potential difference results across the depletion region, with the *n* side at a positive voltage relative to the *p* side, as shown in (b).
- The resulting electric field acts as a **barrier** that has to be overcome for holes to diffuse into the *n* region and electrons to diffuse into the *p* region.
- Typically, for silicon at room temperature, the barrier voltage (or the **junction built-in potential**) V_0 is in the range of 0.6 V to 0.9 V.

The *pn* Junction with an Applied Bias

- Behaviour of the *pn* junction with an applied bias:
    - If the voltage is applied so that the *p* side is made more positive than the *n* side, it is referred to as a **forward-bias voltage.**
    - If our applied dc voltage is such that it makes the *n* side more positive than the *p* side, it is said to be a **reverse-bias voltage.**
- The *pn* junction exhibits vastly different conduction properties in its forward and reverse directions.



The *pn* junction Terminal Characteristic



- The terminal characteristic of a *pn* junction diode (i.e. *i* vs v) can be written as:

$$i = I_S\,[exp(v/V_T) - 1],$$

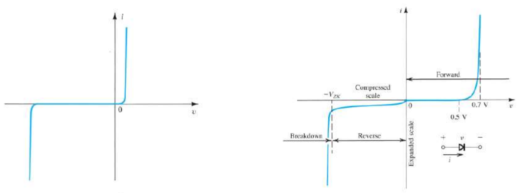
where I_S = reverse saturation current (typ of the order of 10^{-15} A)

$V_T = (kT/q)$ is the thermal voltage ($V_T \approx 25$ mV at 20 °C)

k = Boltzmann's constant = 8.62×10^{-5} eV/K = 1.38×10^{-23} joules/kelvin

T = the absolute temperature in kelvins = 273+temperature in °C

q = the magnitude of electronic charge = 1.60×10^{-19} coulomb

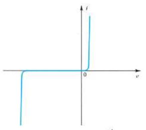


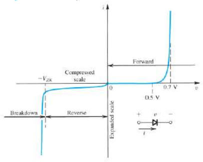
To scale

The *i*-*v* characteristic with expanded and compressed scales to reveal details

Fig. 3 The *i*-*v* characteristic of a silicon junction diode

- The forward-bias region, determined by $v > 0$
- The reverse-bias region, determined by $v < 0$
- The breakdown region, determined by $v < -V_{ZK}$
- **Forward region**





- The forward-bias region, determined by $v > 0$
- The reverse-bias region, determined by $v < 0$
- The breakdown region, determined by $v < -V_{ZK}$
- **Forward region**
  - Negligible current for $v < 0.5$ V (called *Cut-in voltage*)
  - Voltage drop for a "fully conducting" diode lies in a narrow range, approximately 0.6 V to 0.8 V.
- **Reverse region**
  - When v is made negative, current i will be negligible, and $I \approx I_S$
- **Breakdown region**
  - When v is large and negative, the reverse current increases rapidly
  - Diode breakdown is normally not destructive

Applications of Diodes

- The most important application is in rectifier circuits, for converting ac voltages to dc
  - Half-wave rectifier, full-wave rectifier and bridge rectifier circuits
- **Other Applications**
  - In general circuit applications to allow current flow only in one direction
  - As a protection device in relay circuits
  - In waveshaping circuits, such as diode clipper circuits
  - In switching and clamping circuits

2. Zener Diodes

- *pn* junction diodes have very steep *i–v* curve in the breakdown region, and have almost constant voltage drop in that region
- Zener diodes (or breakdown diodes) are diodes operating in the reverse breakdown region, and are manufactured to operate specifically in the breakdown region.
- Can be used in the design of voltage regulators
  - Voltage regulators are circuits that provide a constant dc output voltage for varying load currents and system power-supply voltages.
- In normal applications of Zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode.
  - Thus I_Z and V_Z in the figure have positive values.

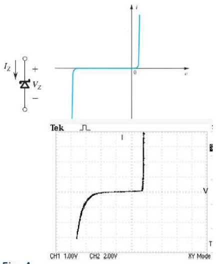


Fig. 4 Measured Zener characteristic

- R_zener=200ohms in the reverse breakdown, in spite of this all regulators use zener diode

Main Application of Zener diodes

- Zener regulator circuit
  - Output voltage V_{out} will be reasonably constant for
    - Variations in V_{in}, and
    - Variations in I_L

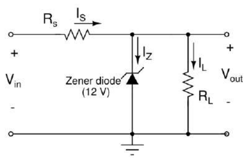


Fig. 5 Zener regulator circuit

3. Light Emitting Diodes

- LEDs are special diodes which convert the forward current through them into light (i.e. electrical-to-optical converter).
- Light is produced due to *radiative recombination* of injected minority carriers with the majority carriers.
- For radiative recombination, the *pn* junction should be made using a semiconductor of the type known as *direct-bandgap materials.*
- Examples of direct-bandgap material
  - Gallium arsenide (GaAs), AlGaAs, GaN, InP, ..
  - Wavelength of an LED's light depends on the electronic bandgap of the material used
- The light emitted by an LED is proportional to the number of recombinations that take, i.e. *proportional to the forward current* in the diode.

- Direct, Indirect band gap semiconductor.
- On drawing the conduction band and valence band of a direct semiconductor, the maxima of conduction band and minima of valence band match i.e. at the same value while in indirect they don't. In Led we need direct semiconductor.
- Non-radiated recombination: Heat
- Radiated recombination: Light

4. Photodiodes

- When a *pn* junction is reverse-biased, a depletion region is formed around the *pn* junction.
  - Only the reverse saturation current flows, which is very small and is primarily due to the minority carriers.
- If the reverse-biased *pn* junction is exposed to incident light
  - the photons impacting the junction cause covalent bonds to break, and thus electron-hole pairs are generated in the depletion layer.
  - The electric field in the depletion region then sweeps the liberated electrons to the *n* side and the holes to the *p* side, giving rise to a reverse current across the junction.
  - This current is known as **photocurrent**, and is proportional to the intensity of the incident light.
  - Such a diode is called a *photodiode*
  - It can be used to convert light signals into electrical signals.

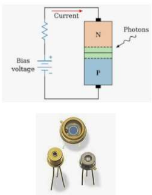
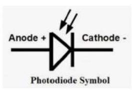


Fig. 11 Source: Electric Circuit Studio and OSI Optoelectronics

Applications of Photodiodes

- Electrical to optical conversion (EO conversion)
  - Remote control of electronic appliances
  - As a sensor for obstacle detection (eg. in a lift door)
  - Extensively used in optical fiber communications at the receiver side for detecting the optical signals sent.



- All the remotes use LED(In transmitter) and Photodiode(In Receiver)
- When we call a number from mobile, the communication between mobile and the nearest tower is radio based, but from the tower to other parts its optical fiber.
- A short circuited diode is in reverse bias i.e. if not in forward bias then in reverse bias.

appliances

- As a sensor for obstacle detection (eg. in a lift door)
- Extensively used in optical fiber communications at the receiver side for detecting the optical signals sent.
  - Optical fiber communications is employed for telecommunication and internet data applications.

Thorlabs, Inc.
Pigtailed Photodiodes

Fig. 12

but from the tower to other parts its optical fiber.

- A short circuited diode is in reverse bias i.e. if not in forward bias then in reverse bias.

Photodiodes vs Solar Cells

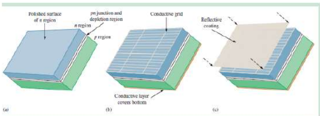
- Photodiodes can be used in two ways:
  - **Photodetector mode -** Reverse bias them and shine light on them; the resulting photo current is the electrical signal which can be used as it is or be converted into a voltage.
  - **Photovoltaic mode**: no reverse bias. Light made to fall on the device. The resulting current can be used as it is or can be converted into a voltage.
  - Both modes of operations are valid
  - If the light falling on the photo diode is time varying (and fast) then the photodetector mode would give better performance.

- Photovoltaic mode: Don't apply any voltage and shine light.
- Photodetector mode has a faster response
- The quantum efficiency of solar cell is not even 10%. Overall efficiency of solar cell is 10-20%

5. Solar Cells (used in the photovoltaic mode)

- Solar cells are illuminated photodiodes *without reverse bias* (uses **photovoltaic effect).**
- Fabricated from low-cost silicon.
- A solar cell converts sunlight into electricity.
- Photon energy creates electron-hole pairs in the *n* and *p* regions.
- Electrons accumulate in the *n*-region and holes accumulate in the *p* region, producing a potential difference (voltage) across the cell.
- When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.

Source: Chap 1, Electronic Devices, 9th ed., Thomas L Flyod, Prentice Hall, 2012.

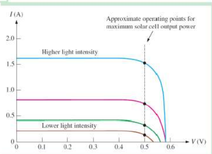


Basic construction of a photovoltaic (PV) solar cell.

Fig. 15

Source: Chap 1, Electronic Devices, 9th ed., Thomas L Flyod, Prentice Hall, 2012.

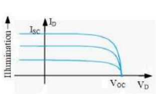
V-I characteristic for a typical single solar cell for increasing light intensities.



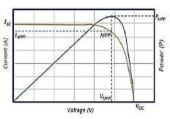
Photodiodes and Solar Cells

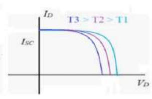
- Both are examples of current sources
- They can deliver fairly constant current up to a certain value of terminal voltage.
- Maximum current (I_{SC}) when terminal voltage is zero
- Maximum voltage (V_{OC}) when current is zero (open circuit voltage)
- Maximum power point is, at a point somewhere between $V_{term} = 0$ and $V_{term} = V_{OC}$.

Solar Cell Characteristic



Effect of illumination intensity on V-I characteristic





Effect of temperature on V-I characteristic

- Illumination intensity affects I_{SC}
- Temperature affects V_{OC}

Extra reading material:

- The breakdown of a diode is a non-destructive phenomenon given that the magnitude of reverse breakdown current is limited by external circuit to a safe value(i.e. power dissipated is not exceeding a safe allowable value)
- If breakdown voltage is <5v then it's usually zener; if it's >7v then it's usually avalanche; For junctions that breakdown between 5 and 7 it can be either zener or avalanche

3.6.1 Depletion or Junction Capacitance

When a *pn* junction is reverse biased with a voltage V_R, the charge stored on either side of the depletion region is given by Eq. (3.32),

$$Q_J = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}(V_0 + V_R)}$$

Thus, for a given *pn* junction,

Zener breakdown occurs when the electric field in the depletion layer increases to the point of breaking covalent bonds and generating electron–hole pairs. The electrons generated in this way will be swept by the electric field into the *n* side and the holes into the *p* side. Thus these electrons and holes constitute a reverse current across the junction. Once the zener effect starts, a large number of carriers can be generated, with a negligible increase in the junction voltage. Thus the reverse current in the breakdown region will be large and its value must be determined by the external circuit, while the reverse voltage appearing between the diode terminals will remain close to the specified breakdown voltage V_Z.

The other breakdown mechanism, avalanche breakdown, occurs when the minority carriers that cross the depletion region under the influence of the electric field gain sufficient kinetic energy to be able to break covalent bonds in atoms with which they collide. The carriers liberated by this process may have sufficiently high energy to be able to cause other carriers to be liberated in another ionizing collision. This process keeps repeating in the fashion of an avalanche, with the result that many carriers are created that are able to support any value of

reverse current, as determined by the external circuit, with a negligible change in the voltage drop across the junction.

As will be seen in Chapter 4, some *pn* junction diodes are fabricated to operate specifically depletion region is given by Eq. (3.32),

$$Q_J = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}(V_0 + V_R)}$$

Thus, for a given *pn* junction,

$$Q_J = \alpha\sqrt{V_0 + V_R} \tag{3.42}$$

where α is given by

$$\alpha = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}} \tag{3.43}$$

Thus Q_J is nonlinearly related to V_R, as shown in Fig. 3.15. This nonlinear relationship makes it difficult to define a capacitance that accounts for the need to change Q_J whenever V_R is

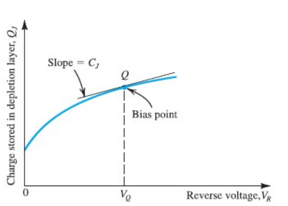


Figure 3.15 The charge stored on either side of the depletion layer as a function of the reverse voltage V_R.

changed. We can, however, assume that the junction is operating at a point such as Q, as indicated in Fig. 3.15, and define a capacitance C_j that relates the change in the charge Q_J to a change in the voltage V_R,

$$C_j = \left.\frac{dQ_J}{dV_R}\right|_{V_R = V_Q} \tag{3.44}$$

This incremental-capacitance approach turns out to be quite useful in electronic circuit design, as we shall see throughout this book.

Using Eq. (3.44) together with Eq. (3.42) yields

$$C_j = \frac{\alpha}{2\sqrt{V_0 + V_R}} \tag{3.45}$$

The value of C_j at zero reverse bias can be obtained from Eq. (3.45) as

$$C_{j0} = \frac{\alpha}{2\sqrt{V_0}} \tag{3.46}$$

which enables us to express C_j as

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} \tag{3.47}$$

where C_{j0} is given by Eq. (3.46) or alternatively if we substitute for α from Eq. (3.43) by

$$C_{j0} = A\sqrt{\left(\frac{\epsilon_s q}{2}\right)\left(\frac{N_A N_D}{N_A + N_D}\right)\left(\frac{1}{V_0}\right)} \tag{3.48}$$

Before leaving the subject of depletion-region or junction capacitance we point out that in the *pn* junction we have been studying, the doping concentration is made to change abruptly at the junction boundary. Such a junction is known as an **abrupt junction**. There is another type of *pn* junction in which the carrier concentration is made to change gradually from one side of the junction to the other. To allow for such a **graded junction**, the formula for the junction capacitance (Eq. 3.47) can be written in the more general form

$$C_j = \frac{C_{j0}}{\left(1 + \frac{V_R}{V_0}\right)^m} \tag{3.49}$$

where *m* is a constant called the **grading coefficient**, whose value ranges from 1/3 to 1/2 depending on the manner in which the concentration changes from the *p* to the *n* side.

to be liberated in another ionizing collision. This process keeps repeating in the fashion of an avalanche, with the result that many carriers are created that are able to support any value of

reverse current, as determined by the external circuit, with a negligible change in the voltage drop across the junction.

As will be seen in Chapter 4, some *pn* junction diodes are fabricated to operate specifically in the breakdown region, where use is made of the nearly constant voltage V_Z.

V_r : Reverse voltage
Q_j: Charge stored in depletion layer
A:
N_A: Amount of acceptor atom (P Type)
N_D: Amount of donor atom(N Type)
V_o:
ε_s: permitivity of the substance
q: Magnitude of charge on electron

Do read the other extra materials along with the lecture notes, they aren't mentioned here cause they are self-explanatory, only those which need explanation are written here.

Combining an LED with a photodiode in the same package results in a device known as an **optoisolator**. The LED converts an electrical signal applied to the optoisolator into light, which the photodiode detects and converts back to an electrical signal at the output of the optoisolator. Use of the optoisolator provides complete electrical isolation between the electrical circuit that is connected to the isolator's input and the circuit that is connected to its output. Such isolation can be useful in reducing the effect of electrical interference on signal transmission within a system, and thus optoisolators are frequently employed in the design of digital systems. They can also be used in the design of medical instruments to reduce the risk of electrical shock to patients.

Electronic equipment, such as microcontrollers, printed circuit boards and transformers are subject to voltage surges from radio frequency transmissions, lightning strikes and spikes in the power supply volts.
To prevent these changes to affect main circuit, we use optoisolator to transfer electric signal.