4.2 The Einstein Coefficients

We consider two levels of an atomic system as shown in Fig. 4.1 and let \( N_1 \) and \( N_2 \) be the number of atoms per unit volume present in the energy levels \( E_1 \) and \( E_2 \), respectively. The atomic system can interact with electromagnetic radiation in three distinct ways:

(a) An atom in the lower energy level \( E_1 \) can absorb the incident radiation at a frequency \( \omega = (E_2 - E_1) / \hbar \) and be excited to \( E_2 \); this excitation process requires the presence of radiation. The rate at which absorption takes place from level 1 to level 2 will be proportional to the number of atoms present in the level \( E_1 \) and also to the energy density of the radiation at the frequency \( \omega = (E_2 - E_1) / \hbar \). Thus if \( u(\omega)d\omega \) represents the radiation energy per unit volume between \( \omega \) and \( \omega + d\omega \) then we may write the number of atoms undergoing absorptions per unit time per unit volume from level 1 to level 2 as

\[
\Gamma_{12} = B_{12}u(\omega)N_1
\]

(4.1)

where \( B_{12} \) is a constant of proportionality and depends on the energy levels \( E_1 \) and \( E_2 \). Notice here that \( u(\omega) \) has the units of energy density per frequency interval.
(b) For the reverse process, namely the deexcitation of the atom from $E_2$ to $E_1$, Einstein postulated that an atom can make a transition from $E_2$ to $E_1$ through two distinct processes, namely stimulated emission and spontaneous emission. In the case of stimulated emission, the radiation which is incident on the atom stimulates it to emit radiation and the rate of transition to the lower energy level is proportional to the energy density of radiation at the frequency $\omega$. Thus, the number of stimulated emissions per unit time per unit volume will be

$$\Gamma_{21} = B_{21}u(\omega)N_2$$

where $B_{21}$ is the coefficient of proportionality and depends on the energy levels.

(c) An atom which is in the upper energy level $E_2$ can also make a spontaneous emission; this rate will be proportional to $N_2$ only and thus we have for the number atoms making spontaneous emissions per unit time per unit volume

$$U_{21} = A_{21}N_2$$

At thermal equilibrium between the atomic system and the radiation field, the number of upward transitions must be equal to the number of downward transitions. Hence, at thermal equilibrium

$$N_1B_{12}u(\omega) = N_2A_{21} + N_2B_{21}u(\omega)$$

or

$$u(\omega) = \frac{A_{21}}{(N_1/N_2)B_{12} - B_{21}}$$

Using Boltzmann’s law, the ratio of the equilibrium populations of levels 1 and 2 at temperature $T$ is

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/k_B T} = e^{\hbar \omega/k_B T}$$

where $k_B (= 1.38 \times 10^{-23} \text{J}/\text{K})$ is the Boltzmann’s constant. Hence

$$u(\omega) = \frac{A_{21}}{B_{12}e^{\hbar \omega/k_B T} - B_{21}}$$
\[ \sigma_a = \frac{\pi^2 c^2}{\omega^2 \hbar^2 t_{sp}} g(\omega) \]  

(4.22)

Similarly we can define the emission cross section \( \sigma_e \) through the rate \( \Gamma_{21} \). Since \( \Gamma_{12} \) and \( \Gamma_{21} \) are equal, the absorption and emission cross sections are equal.

Note that the absorption and emission cross sections are functions of frequency and are related to the line broadening function \( g(\omega) \) and the lifetime \( t_{sp} \).

The peak emission cross sections for some of the important laser transitions are given in Table 4.1.

<table>
<thead>
<tr>
<th>Laser transition</th>
<th>Wavelength (nm)</th>
<th>Cross section (m(^2))</th>
<th>Lifetime ((\mu)s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He–Ne laser</td>
<td>632.8</td>
<td>(5.8 \times 10^{-17})</td>
<td>(30 \times 10^{-3})</td>
</tr>
<tr>
<td>Argon ion</td>
<td>514.5</td>
<td>(2.5 \times 10^{-17})</td>
<td>(6 \times 10^{-3})</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1064</td>
<td>(2.8 \times 10^{-23})</td>
<td>230</td>
</tr>
</tbody>
</table>

Example 4.3 Consider the transition in neon atom at the wavelength of 1150 nm. This transition is Doppler broadened with a linewidth of 900 MHz and the upper state spontaneous lifetime is 100 ns. Using Eq. (4.22) we can calculate the peak absorption cross section. If we assume \( g(\omega_0) \sim 1/\Delta \omega \), we obtain \( \sigma_a \sim 5.8 \times 10^{-16} \text{ m}^2 \).

4.3 Light Amplification

We next consider a collection of atoms and let a near-monochromatic radiation of energy density \( u \) at frequency \( \omega' \) pass through it. We shall now obtain the rate of change of intensity of the radiation as it passes through the medium.

Let us consider two planes \( P_1 \) and \( P_2 \) of area \( S \) situated at \( z \) and \( z + d z \), \( z \) being the direction of propagation of the radiation (see Fig. 4.4). If \( I(z) \) and \( I(z+dz) \) represent the intensity of the radiation at \( z \) and \( z + dz \), respectively, then the net amount of energy entering the volume \( Sdz \) between \( P_1 \) and \( P_2 \) will be

\[
[I(z) - I(z + dz)]S = [I(z) - I(z) - \frac{dI}{dz}dz]S
= -\frac{dI}{dz}Sdz
\]

(4.23)

Fig. 4.4 Propagation of radiation at frequency \( \omega' \) through a medium leading to a change of intensity with propagation.
4.4 The Threshold Condition

In the last section we saw that in order that a medium be capable of amplifying incident radiation, one must create a state of population inversion in the medium. Such a medium will behave as an amplifier for those frequencies which fall within its linewidth. In order to generate radiation, this amplifying medium is placed in an optical resonator which consists of a pair of mirrors facing each other much like in a Fabry–Perot etalon (see Fig. 4.6). Radiation which bounces back and forth between the mirrors is amplified by the amplifying medium and also suffers losses due to the finite reflectivity of the mirrors and other scattering and diffraction losses. If the oscillations have to be sustained in the cavity then the losses must be exactly compensated by the gain. Thus a minimum population inversion density is required to overcome the losses and this is called the threshold population inversion.

\[ I_0 R_1 R_2 e^{2(\gamma - \alpha)d} \geq 1 \]  

(4.29)

In order to obtain an expression for the threshold population inversion, let \( d \) represent the length of the resonator and let \( R_1 \) and \( R_2 \) represent the reflectivities of the mirrors (see Fig. 4.6). Let \( \alpha_1 \) represent the average loss per unit length due to all loss mechanisms (other than the finite reflectivity) such as scattering loss and diffraction loss due to finite mirror sizes. Let us consider a radiation with intensity \( I_0 \) leaving mirror \( M_1 \). As it propagates through the medium and reaches the second mirror, it is amplified by \( e^{\gamma d} \) and also suffers a loss of \( e^{-\alpha d} \); for an amplifying medium \( \gamma \) is positive and \( e^{\gamma d} > 1 \). The intensity of the reflected beam at the second mirror will be \( I_0 R_2 e^{(\gamma - \alpha_1)d} \). A second passage through the resonator and a reflection at the first mirror leads to an intensity for the radiation after one complete round trip of \( I_0 R_1 R_2 e^{2(\gamma - \alpha_1)d} \). Hence for laser oscillation to begin

the equality sign giving the threshold value for \( \alpha \) (i.e., for population inversion). Indeed, when the laser is oscillating in a steady state with a continuous wave oscillation, then the equality sign in Eq. (4.29) must be satisfied. If the inversion is increased then the LHS becomes greater than unity; this implies that the round trip gain is greater than the round trip loss. This would result in an increasing intensity inside the laser till saturation effects take over, which would result in a decrease
5.2 The Two-Level System

We first consider a two-level system consisting of energy levels $E_1$ and $E_2$ with $N_1$ and $N_2$ atoms per unit volume, respectively [see (Fig. 5.1)]. Let radiation at frequency $\omega$ with energy density $u$ be incident on the system. The number of atoms per unit volume which absorbs the radiation and is excited to the upper level will be [see Eq. (4.18)]

$$\Gamma_{12} = \frac{\pi^2c^3}{\hbar\omega^3t_{sp}n_0}ug(\omega)N_1 = W_{12}N_1$$  \hspace{1cm} (5.1)

where

$$W_{12} = \frac{\pi^2c^3}{\hbar\omega^3t_{sp}n_0}ug(\omega)$$  \hspace{1cm} (5.2)

The number of atoms undergoing stimulated emissions from $E_2$ to $E_1$ per unit volume per unit time will be [see Eqs. (4.16) and (4.18)]

$$\Gamma_{21} = W_{21}N_2 = W_{12}N_2$$  \hspace{1cm} (5.3)

where we have used the fact that the absorption probability is the same as the stimulated emission probability. In addition to the above two transitions, atoms in the level $E_2$ would also undergo spontaneous transitions from $E_2$ to $E_1$. If $A_{21}$ and $S_{21}$ represent the radiative and non-radiative transition rates from $E_2$ to $E_1$, then the number of atoms undergoing spontaneous transitions per unit time per unit volume from $E_2$ to $E_1$ will be $T_{21}N_2$ where

$$T_{21} = A_{21} + S_{21}$$  \hspace{1cm} (5.4)

Thus we may write the rate of change of population of energy levels $E_2$ and $E_1$ as

$$\frac{dN_2}{dt} = W_{12}(N_1 - N_2) - T_{21}N_2$$  \hspace{1cm} (5.5)

![Fig. 5.1](image.png) A two-level system

---

1In a non-radiative transitions when the atom de-excites, the energy is transferred to the translational, vibrational or rotational energies of the surrounding atoms or molecules.
5.3 The Three-Level Laser System

In the last section we saw that one cannot create a steady-state population inversion between two levels just by using pumping between these levels. Thus in order to produce a steady-state population inversion, one makes use of either a three-level or a four-level system. In this section we shall discuss a three-level system.

We consider a three-level system consisting of energy levels $E_1$, $E_2$, and $E_3$ all of which are assumed to be nondegenerate. Let $N_1$, $N_2$, and $N_3$ represent the population densities of the three levels [see (Fig. 5.2)]. The pump is assumed to lift atoms from level 1 to level 3 from which they decay rapidly to level 2 through some nonradiative process. Thus the pump effectively transfers atoms from the ground level 1 to the excited level 2 which is now the upper laser level; the lower laser level being the ground state 1. If the relaxation from level 3 to level 2 is very fast, then the atoms will relax down to level 2 rather than to level 1. Since the upper level 3 is not a laser level, it can be a broad level (or a group of broad levels) so that a broadband light source may be efficiently used as a pump source (see, e.g., the ruby laser discussed in Chapter 11).

![Fig. 5.2](image)

If we assume that transitions take place only between these three levels then we may write

$$N = N_1 + N_2 + N_3$$

(5.17)

where $N$ represents the total number of atoms per unit volume.

We may now write the rate equations describing the rate of change of $N_1$, $N_2$ and $N_3$. For example, the rate of change of $N_3$ may be written as

$$\frac{dN_3}{dt} = W_p(N_1 - N_3) - T_{32}N_3$$

(5.18)

where $W_p$ is the rate of pumping per atom from level 1 to level 3 which depends on the pump intensity. The first term in Eq. (5.18) represents stimulated transitions.
marked $M$ which is the upper laser level. The level $M$ is a metastable level with a lifetime of $\sim 3 \text{ ms}$. Laser emission occurs between level $M$ and the ground state $G$ at an output wavelength of $\lambda_0 = 6943 \text{ Å}$.

The flashlamp operation of the laser leads to a pulsed output of the laser. As soon as the flashlamp stops operating the population of the upper level is depleted very rapidly and lasing action stops till the arrival of the next flash. Even during the short period of a few tens of microseconds in which the laser is oscillating, the output is a highly irregular function of time with the intensity having random amplitude fluctuations of varying duration as shown in Fig. 11.2. This is called laser spiking, the formation of which can be understood as follows: when the pump is turned on, the intensity of light at the laser transition is small and hence the pump builds up the inversion rapidly. Although under steady-state conditions the inversion cannot exceed the threshold inversion, on a transient basis it can go beyond the threshold value due to the absence of sufficient laser radiation in the cavity which causes stimulated emission. Thus the inversion goes beyond threshold when the radiation density in the cavity builds up rapidly. Since the inversion is greater than threshold, the radiation density goes beyond the steady-state value which in turn depletes the upper level population and reduces the inversion below threshold. This leads to an interruption of laser oscillation till the pump can again create an inversion beyond threshold. This cycle repeats itself to produce the characteristic spiking in lasers.

Figure 11.3 shows a typical setup of a flashlamp pumped pulsed ruby laser. The helical flashlamp is surrounded by a cylindrical reflector to direct the pump light onto the ruby rod efficiently. The ruby rod length is typically 2–20 cm with diameters of 0.1–2 cm. As we have seen in Section 5.3, typical input electrical energies required are in the range of 10–20 kJ. In addition to the helical flashlamp pumping scheme shown in Fig. 11.3, one may use other pumping schemes such as that shown in Fig. 11.4 in which the pump lamp and the laser rod are placed along the foci of
A device which converts a physical quantity into the proportional electrical signal is called a transducer. The electrical signal produced may be a voltage, current or frequency. A transducer uses many effects to produce such conversion. The process of transforming signal from one form to other is called transduction. A transducer is also called pick up. The transduction element transforms the output of the sensor to an electrical output, as shown in the Fig.

A transducer will have basically two main components. They are

1. **Sensing Element**
The physical quantity or its rate of change is sensed and responded to by this part of the transistor.

2. **Transduction Element**
The output of the sensing element is passed on to the transduction element. This element is responsible for converting the non-electrical signal into its proportional electrical signal.

There may be cases when the transduction element performs the action of both transduction and sensing. The best example of such a transducer is a thermocouple. A thermocouple is used to generate a voltage corresponding to the heat that is generated at the junction of two dissimilar metals.

**Classification of Transducers**

The Classification of Transducers is done in many ways. Some of the criteria for the classification are based on their area of application, Method of energy conversion, Nature of output signal, According to Electrical principles involved, Electrical parameter used, principle of operation, & Typical applications.

The transducers can be classified broadly

i. On the basis of transduction form used
ii. As primary and secondary transducers
iii. As active and passive transducers
iv. As transducers and inverse transducers.

Broadly one such generalization is concerned with energy considerations wherein they are classified as active & Passive transducers. A component whose output energy is supplied entirely by its input signal (physical quantity under measurement) is commonly called a ‘passive transducer’. In other words the passive transducers derive the power required for transduction from an auxiliary source. Active transducers are those which do not require an auxiliary power source to produce their output.
also known as self generating type since they produce their own voltage or current output. Some of the passive transducers (electrical transducers), their electrical parameter (resistance, capacitance, etc), principle of operation and applications are listed below.

Resistive Transducers
1. Resistance Strain Gauge – The change in value of resistance of metal semi-conductor due to elongation or compression is known by the measurement of torque, displacement or force.
2. Resistance Thermometer – The change in resistance of metal wire due to the change in temperature known by the measurement of temperature.
3. Resistance Hygrometer – The change in the resistance of conductive strip due to the change of moisture content is known by the value of its corresponding humidity.
4. Hot Wire Meter – The change in resistance of a heating element due to convection cooling of a flow of gas is known by its corresponding gas flow or pressure.
5. Photoconductive Cell – The change in resistance of a cell due to a corresponding change in light flux is known by its corresponding light intensity.
6. Thermistor – The change in resistance of a semi-conductor that has a negative co-efficient of resistance is known by its corresponding measure of temperature.
7. Potentiometer Type – The change in resistance of a potentiometer reading due to the movement of the slider as a part of an external force applied is known by its corresponding pressure or displacement.

Capacitance Transducers
1. Variable capacitance pressure gage -
   Principle of operation: Distance between two parallel plates is varied by an externally applied force Applications: Measurement of Displacement, pressure
2. Capacitor microphone
   Principle of operation: Sound pressure varies the capacitance between a fixed plate and a movable diaphragm. Applications: Speech, music, noise
3. Dielectric gauge
   Principle of operation: Variation in capacitance by changes in the dielectric. Applications: Liquid level, thickness

Inductance Transducers
1. Magnetic circuit transducer
   Principle of operation: Self inductance or mutual inductance of ac-excited coil is varied by changes in the magnetic circuit. Applications: Pressure, displacement
2. Reluctance pickup
   Principle of operation: Reluctance of the magnetic circuit is varied by changing the position of the iron core of a coil. Applications: Pressure, displacement, vibration, position
3. Differential transformer
   Principle of operation: The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force. Applications: Pressure, force, displacement, position
4. Eddy current gage
   Principle of operation: Inductance of a coil is varied by the proximity of an eddy current plate. Applications: Displacement, thickness
5. Magnetostriction gauge
   Principle of operation: Magnetic properties are varied by pressure and stress. Applications: Force, pressure, sound

Voltage and current Transducers

1. Hall effect pickup
   Principle of operation: A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current. Applications: Magnetic flux, current
2. Ionization chamber
   Principle of operation: Electron flow induced by ionization of gas due to radioactive radiation. Applications: Particle counting, radiation
3. Photoemissive cell
   Principle of operation: Electron emission due to incident radiation on photoemissive surface. Applications: Light and radiation
4. Photomultiplier tube
   Principle of operation: Secondary electron emission due to incident radiation on photosensitive cathode. Applications: Light and radiation, photo-sensitive relays

Self-Generating Transducers (No External Power) – Active Transducers

They do not require an external power, and produce an analog voltage or current when stimulated by some physical form of energy.

1. Thermocouple and thermopile
   Principle of operation: An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated. Applications: Temperature, heat flow, radiation.
2. Moving-coil generator
   Principle of operation: Motion of a coil in a magnetic field generates a voltage. Applications: Velocity, Vibration
3. Piezoelectric pickup
   An emf is generated when an external force is applied to certain crystalline materials, such as quartz. Sound, vibration, acceleration, pressure changes
4. Photovoltaic cell
   Principle of operation: A voltage is generated in a semi-conductor junction device when radiant energy stimulates the cell. Applications: Light meter, solar cell

Primary Transducers and Secondary Transducers- Bourdon tube acting as a primary detector senses the pressure and converts the pressure into a displacement of its free end. The displacement of the free end moves the core of a linear variable differential transformer (LVDT) which produces an output voltage.

Analog Transducers-These transducers convert the input quantity into an analog output which is a continuous function of time. ◦ Strain Gauge ◦ LVDT ◦ Thermocouple ◦ Thermistor

Digital Transducers-These transducers convert the input quantity into an electrical output which is in the form of pulses. ◦ Glass Scale can be read optically by means of a light source, an optical system and photocells
Transducers and Inverse Transducers - A Transducer can be broadly defined as a device which converts a non-electrical quantity into an electrical quantity. Ex: Resistive, inductive and capacitive transducers - An inverse transducer is defined as a device which converts an electrical quantity into a non-electrical quantity. Ex: Piezoelectric crystals

Advantages of Electrical transducers
Mostly quantities to be measured are non-electrical such as temperature, pressure, displacement, humidity, fluid flow, speed etc., but these quantities cannot be measured directly. Hence such quantities are required to be sensed and changed into some other form for easy measurement. Electrical quantities such as current, voltage, resistance, inductance and capacitance etc. can be conveniently measured, transferred and stored, and, therefore, for measurement of the non-electrical quantities these are to be converted into electrical quantities first and then measured. The function of converting non-electrical quantity into electrical one is accomplished by a device called the electrical transducer.

Basically an electrical transducer is a sensing device by which a physical, mechanical or optical quantity to be measured is transformed directly, with a suitable mechanism, into an electrical signal (current, voltage and frequency). The production of these signals is based upon electrical effects which may be resistive, inductive, capacitive etc. in nature. The input versus output energy relationship takes a definite reproducible function. The output to input and the output to time behavior is predictable to a known degree of accuracy, sensitivity and response, within the specified environmental conditions. Electrical transducers have numerous advantages. Modern digital computers have made use of electrical transducers absolutely essential.

Electrical transducers suffer due to some drawbacks too, such as low reliability in comparison to that of mechanical transducers due to the ageing and drift of the active components and comparative high cost of electrical transducers and associated signal conditioners. In some cases the accuracy and resolution attainable are not as high as in mechanical transducers. Some of the advantages are:

1. Electrical amplification and attenuation can be done easily and that to with a static device.
2. The effect of friction is minimized.
3. The electric or electronic system can be controlled with a very small electric power.
4. The electric power can be easily used, transmitted and processed for the purpose of measurement.

Factor to be considered while selecting transducer:

It should have high input impedance and low output impedance, to avoid loading effect.
It should have good resolution over is entire selected range.
It must be highly sensitive to desired signal and insensitive to unwanted signal.
Preferably small in size.
It should be able to work in corrosive environment.
It should be able to withstand pressure, shocks, vibrations etc.
It must have high degree of accuracy and repeatability.
Selected transducer must be free from errors.
The transducer circuit should have overload protection so that it will withstand overloads.

Requirements of a good transducers

- Smaller in size and weight.
- High sensitivity.
- Ability to withstand environmental conditions.
- Low cost.

**RESISTIVE TRANSDUCERS**

Resistance of an electrical conductor is given by,

\[ R = \rho \frac{l}{A} \]

Where,

- \( R \) = Resistance in ‘\( \Omega \)’
- \( \rho \) = Resistivity of the conductor (\( \Omega \cdot \text{cm} \))
- \( l \) = Length of the conductor in cm.
- \( A \) = Cross-sectional area of the metal conductor in cm\(^2\)

It is clear from the equation that, the electrical resistance can be varied by varying,

(i) Length

(ii) Cross-sectional area and

(iii) Resistivity or combination of these.

**Principle:**
A change in resistance of a circuit due to the displacement of an object is the measure of displacement of that object, method of changing the resistance and the resulting devices are summarized in the following

Method of changing resistance-
Length - Resistance can be changed varying the length of the conductor, (linear and rotary).

Dimensions - When a metal conductor is subjected to mechanical strain, change in dimensions of the conductor occurs, that changes the resistance of the conductor.

Resistivity -
When a metal conductor is subjected to a change in temperature and change in resistivity occurs which changes resistance of the conductor.

Resulting device:-
Resistance potentiometers or sliding contact devices displacements, Electrical resistance strain gauges, Thermistor and RTD

Use:-
the resistive transducer used for the measurement of linear and angular, and used for the temperature mechanical strain measurement.
Linear variable differential transformer (LVDT)

When an externally applied force moves the core to the left-hand position, more magnetic flux links the left-hand coil than the right-hand coil. The emf induced in the left-hand coil, $E_S$, is therefore larger than the induced emf of the right-hand coil, $E_s^2$. The magnitude of the output voltage is then equal to the difference between the two secondary voltages and it is in phase with the voltage of the left-hand coil.

Output voltage of LVDT at different core positions

Construction of LVDT
Main Features of Construction are as,

- The transformer consists of a primary winding $P$ and two secondary winding $S_1$ and $S_2$ wound on a cylindrical former (which is hollow in nature and will contain core).
• Both the secondary windings have equal number of turns and are identically placed on the either side of primary winding.
• The primary winding is connected to an AC source which produces a flux in the air gap and voltages are induced in secondary windings.
• A movable soft iron core is placed inside the former and displacement to be measured is connected to the iron core.
• The iron core is generally of high permeability which helps in reducing harmonics and high sensitivity of LVDT.
• The LVDT is placed inside a stainless steel housing because it will provide electrostatic and electromagnetic shielding.
• The both the secondary windings are connected in such a way that resulted output is the difference of the voltages of two windings.

Principle of Operation and Working
As the primary is connected to an AC source so alternating current and voltages are produced in the secondary of the LVDT. The output in secondary $S_1$ is $e_1$ and in the secondary $S_2$ is $e_2$. So the differential output is, $e_{out} = e_1 - e_2$. This equation explains the principle of Operation of LVDT.

Now three cases arise according to the locations of core which explains the working of LVDT are discussed below as,

• **CASE I** When the core is at null position (for no displacement) When the core is at null position then the flux linking with both the secondary windings is equal so the induced emf is equal in both the windings. So for no displacement the value of output $e_{out}$ is zero as $e_1$ and $e_2$ both are equal. So it shows that no displacement took place.
• **CASE II** When the core is moved to upward of null position (For displacement to the upward of reference point) In the this case the flux linking with secondary winding $S_1$ is more as compared to flux linking with $S_2$. Due to this $e_1$ will be more as that of $e_2$. Due to this output voltage $e_{out}$ is positive.
**Photovoltaic cell:**
Fig shows structure of photovoltaic cell. It shows that cell is actually a PN-junction diode with appropriately doped semiconductors. When photons strike on the thin p-doped upper layer, they are absorbed by the electrons in the n-layer; which causes formation of conduction electrons and holes. These conduction electrons and holes are separated by depletion region potential of the pn junction. When load is connected across the cell, the depletion region potential causes the photocurrent to flow through the load N.

**Phototransistor:**
The phototransistor has a light sensitive collector to base junction. A lens is used in a transistor package to expose base to an incident light. When no light is incident, a small leakage current flows from collector to emitter called IeEO, due to small thermal generation. This is very small current, of the order of nA. This is called a dark current. When the base is exposed to the light, the base current is produced which is proportional to the light intensity. Such photoinduced base current is denoted as I...The resulting collector current is given by, The structure of a phototransistor is shown in the Fig. (a) while the symbol is shown in the Fig.

\[ I_C \approx h_{fe} I_{\lambda} \]

To generate more base current proportional to the light, larger physical area of the base is exposed to the light. The fig. shows the graph of base current against the radiation flux density measured in mW/cm². The Fig. (b) shows the collector characteristics of a phototransistor. As light intensity increases, the base current increases exponentially. Similarly the collector current also increases corresponding to the increase in the light intensity. A phototransistor can be either a two lead or a three lead device. In a three lead device, the base lead is brought out so that it can be used as a conventional BJT with or without the light sensitivity feature. In a two lead device, the base is not electrically available and the device use is
Figure 5.6 The principle of the moving iron (variable reluctance) microphone.

The linearity of the conversion can be reasonable for small amplitudes of movement of the armature, but is very poor for large amplitudes. The linearity can be considerably improved by appropriate shaping of the armature and careful attention to its path of vibration. These features depend on the maintenance of close tolerances in the course of manufacturing the microphones, so that there will inevitably be differences in linearity between samples of microphones of this type from the same production line.

The maximum useable output level from a moving iron microphone can be high, of the order of 50 mV, and the output impedance is also high, typically several hundred ohms. Because the flux path in the transducer is almost closed, external changes in the magnetic field will be very efficiently picked up, and the result is that the magnetic component of mains hum is superimposed on the output. This can be reduced by shielding the magnetic circuit, using mu-metal or similar alloys. The magnetic circuit that is the predominant feature of this type of microphone also makes the instrument heavier than some other types.

MOVING COIL MICROPHONE

The moving coil microphone uses a constant-flux magnetic circuit in which the electrical output is generated by moving a small coil of wire in the magnetic circuit (Figure 5.7). The coil is attached to a diaphragm, and the whole arrangement is usually in capsule form, making this pressure-operated rather than velocity-operated. As before, the maximum output occurs as the coil reaches maximum velocity between the peaks of the sound wave so that the electrical output is at 90° phase angle to the sound wave.

The coil is usually small, and its range of movement very small, so that linearity is excellent for this type of microphone. The coil has a low impedance, and the output is correspondingly low, but not so low that it has to compete with the noise level of an amplifier. The low inductance of
**Figure 5.7** The moving coil type of microphone has a coil wound on a former attached to the diaphragm and moving in an annular gap of a magnet.

the coil makes it much less susceptible to hum pick-up from the magnetic field of the mains wiring, and it is possible to use hum-compensating (non-moving) coils, known as *humbuckers*, in the structure of the microphone to reduce hum further by adding an antiphase hum signal to the output of the main coil.