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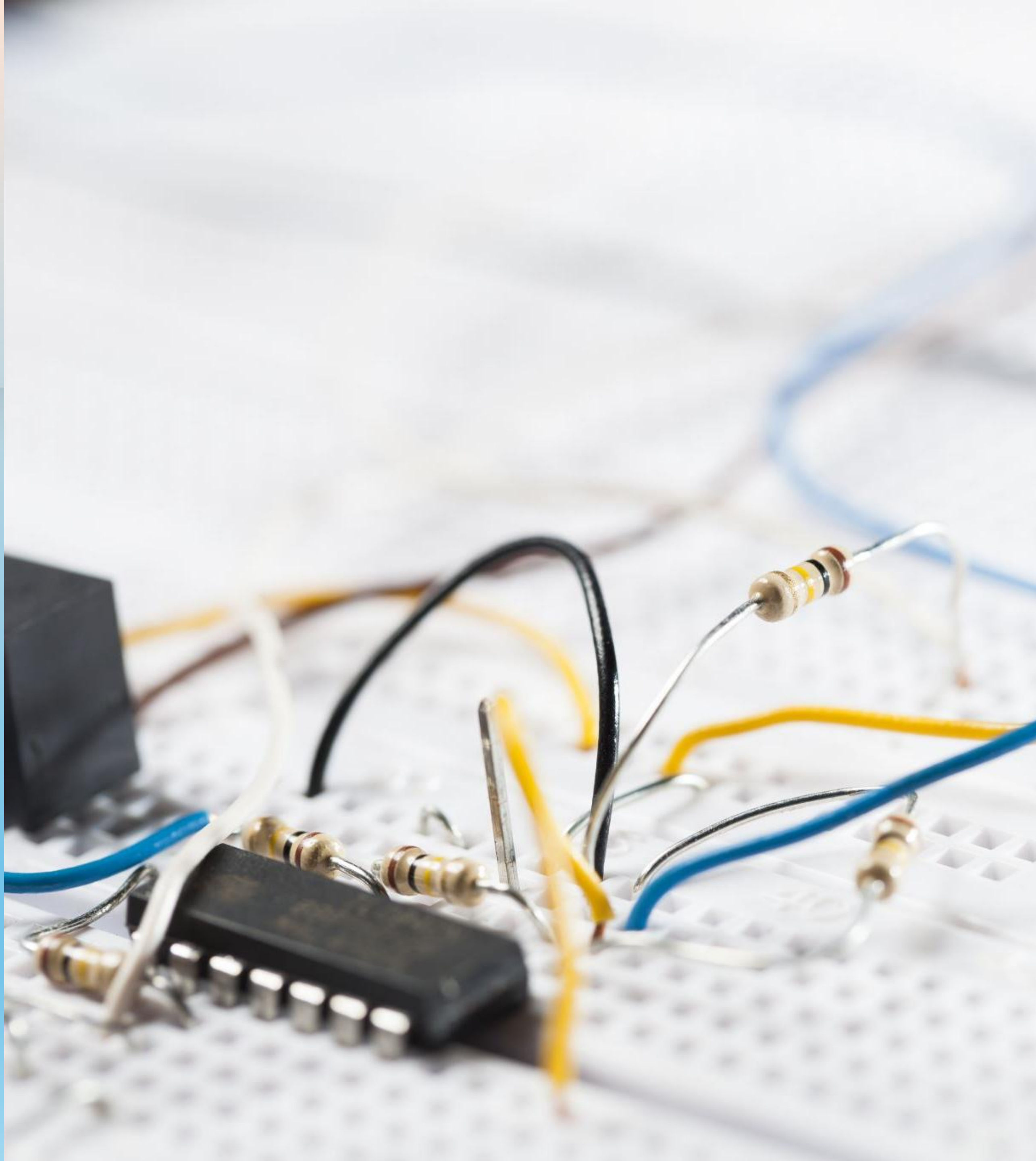
Contents:

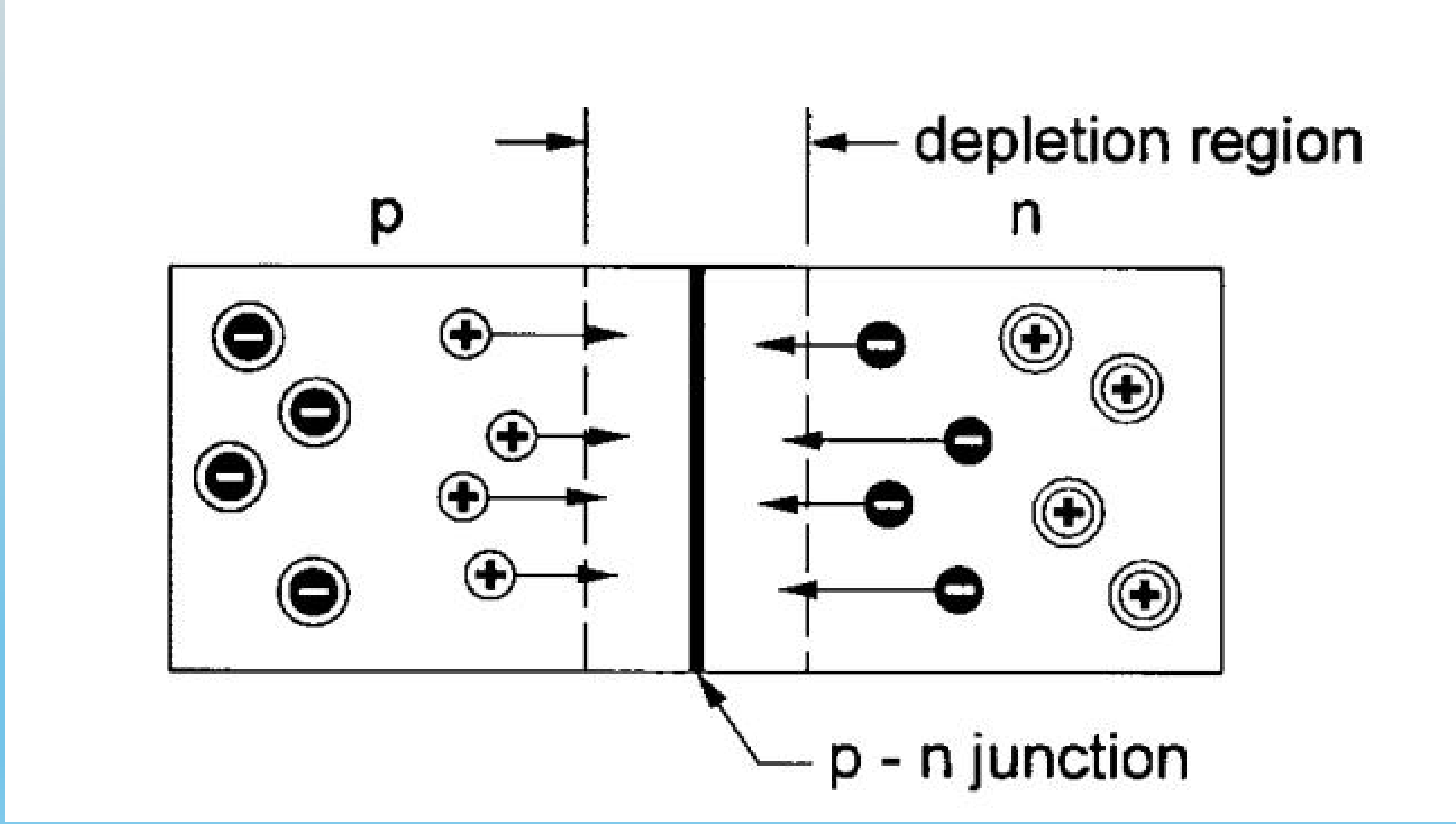
- P-N junction.
- Current flow through a biased p-n junction
- Examples



The p-n junction

Apiece of semiconductor in which a section of p-type material is joined toone of n-type material is called a p-n junction. It is on the properties of this junction that the semiconductor (diode and the transistor) depend. Such a junction is notusually made by joining two separate pieces of material, but by taking as ingle crystal of silicon and introducing donor and acceptor impurities, perhaps by diffusion, into the appropriate parts of the solid. We shall now consider the electrical properties of such a junction Let us imagine what happens to the electrons and holes in two pieces of semiconductor, one p-type and n-type, as the yare placed together.The initial distribution of hole sand electronsis shownin Fig.1.

Fig.1: P-type/n-type semiconductor junction with depletion region.



On one side of the junction is a material containing electrons moving freely and randomly at high velocities through the lattice, while on the other side is a material with free holes moving at similar velocities. It is natural that the excess carriers on either side will be able to cross the junction into the foreign material, just two gases will diffuse into one another. But, unlike gasser, the free electrons and holes can combine self-destructively with one another; far from the junction on either side the normal, undistributed carrier densities must persist.

This means that the concentration gradients of free electrons and holes across the junction persist in spite of the diffusion. Moreover, the diffusion rate, which is proportional to the concentration gradient is high at this point, and the carrier density close to the junction is thereby depleted. This depletion is so marked that there is a thin layer on either side of the e junction which is virtually empty of free carriers the densities are several orders of magnitude lower than in the rest of the crystal.

To calculate the voltage difference across the junction we shall make use of the fact that the two halves of the crystal are in thermal equilibrium. The condition for thermal equilibrium between two bodies, is that the probability that quantum states of a given energy are occupied is the same in both bodies.

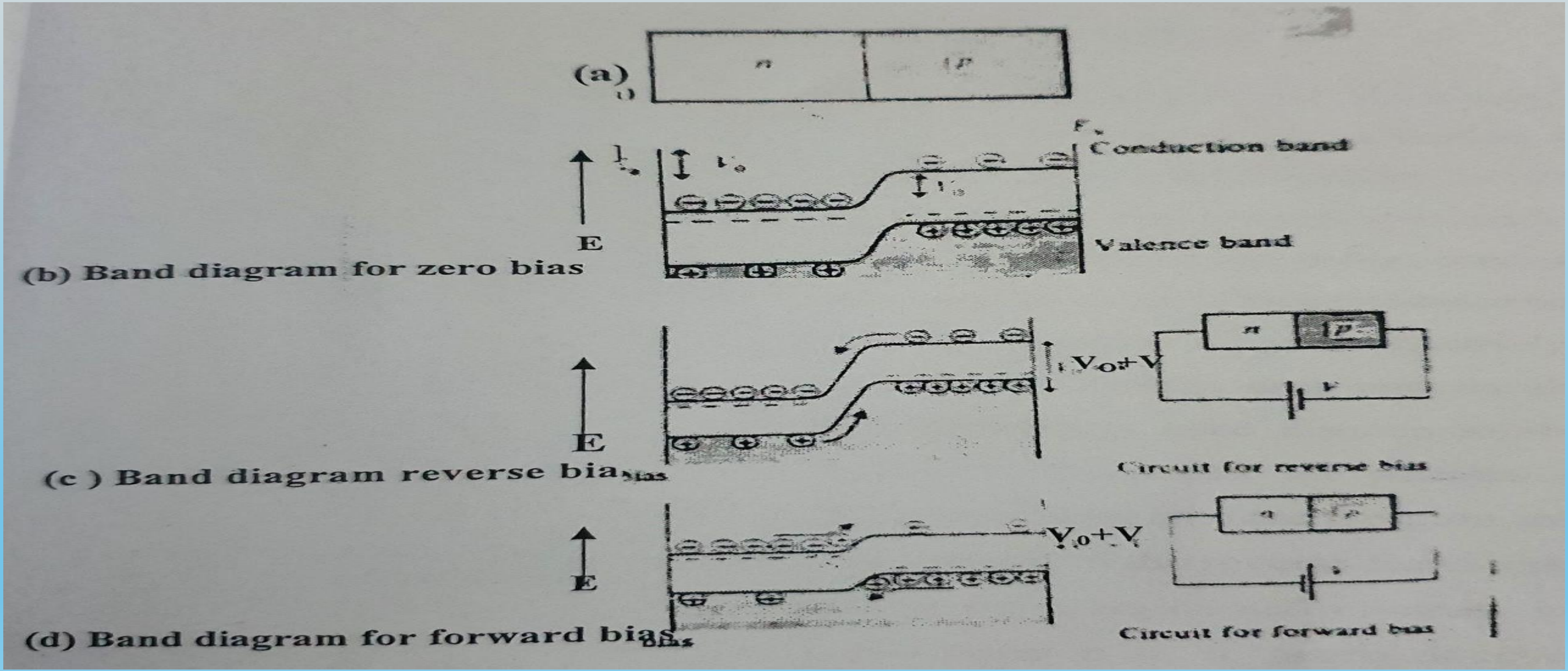
$$N_P = N_N \exp\left(\frac{eV^0}{K\,T}\right)$$

$$V° \approx 1\,V$$

Current flow through a biased p-n junction

- The dynamic equilibrium set up by the interdiffusion of holes and electrons is upset when a voltage is applied across the ends of the crystal. To understand the new situation we must first decide what form the energy band diagram takes when the voltage is applied. Let us take the case where the n-type region is made electrically positive with respect to the p-type region. The first think to note is that, compared to
- the bulk of the crystal, the depletion layer has a high resistance because of the absence of free carriers. Thus, remembering that the depletion layer is effectively in series with the rest of crystal, we see that the applied voltage drop appears almost entirely across the depletion layer. This gives a new energy band diagram as shown in Fig.2(c).

Fig.2 : the energy band diagram for a biased p-n junction



The effect of the applied voltage is to increase the potential difference across the junction. This reduces the flows of holes into the n region and of electrons into the p region, while making little difference to the reverse flows since the latter are limited mainly by the scarcity of holes in the n region and electrons in the p region. The result is a small net current flow from p to n, nearly independent of applied voltage.

On the other hand, reversing the sign of the bias voltage V reduces the height of the potential drop across the junction Fig.2(d). Once again the flow of holes and electrons from n and p regions is scarcely affected remember that these flows are limited by the total numbers of minority carriers in the crystal and not by the rate at which they cross the depletion layers. But the flow in the other direction -up the potential hill-is increased, because the hill now causes less hindrance to the motion of the large number of majority carriers. This current can increase continuously as the applied voltage increases, so that the junction responds differently to voltages applied in opposite senses.

- Just how the current depends upon voltage can be determined by equcation:

$$N_P = N_N \exp\left(\frac{e\,V_\circ}{KT}\right) \ldots\ldots\ldots (1)$$

- That equation expresses the fact that the two halves of the crystal are in thermal equilibrium and the passage of a current through it dose not upset this equilibrium.
- However, the potential energy difference between electrons on either side of the junction is no longer $eV_\circ$, but $e(V_\circ \pm V)$ or just $e(V_\circ - V)$, if we give the voltage V a positive sign when the n region is made electrically positive and a negative sign when it is negative with respect to the p region.

This change in the potential energy difference means that equcation:

$$N_P = N_p \exp\left(-\frac{e\,V_\circ}{KT}\right)\ldots\ldots(1)$$

must be modified, giving:

$$N_P^- = N_N^- \exp[\frac{-e(V_\circ - V)}{KT}]\ldots\ldots\ldots\ldots(2)$$

where the concentration N_P, and N_N, have been primed to indicate that they are different from the normal values given by equcation a similar equation holds for holes

$$P_N^- = P_N^- \exp[\frac{-e(V_\circ - V)}{KT}]\ldots\ldots\ldots\ldots(3)$$

Since the crystal is electrically neutral outside the depletion layers any change in N_P, must be associated with an equal change in N_P.

- But since P_N, is very much greater than the percentage change in N_P. Hence the interception of eq. (2) is that the dominant change occurring is securring is that n, the concentration of electrons in the p region, is dramatically altered. Eq.(3) similarly tells us that pois also changed. In forward bias (V positive) the value of np, is increased. The extra electrons have come from the n region, because the potential barrier has been lowered by the applied voltage. But these extra electrons can travel only a short distance (about 0.1 mm on average) before recombining with holes so that, far from the junction, the electron concentration is back to its normal value. The concentration gradient is illustrated in Fig.2(d), and it is this gradient which gives rise to the flow of current, by diffusion, at the edge of depletion layer where the voltage gradient is very small.

According to Fick's law F-B (dn/dx), (F: flux of atoms or molecules, B: diffusion coefficient, dn/dx: concentration gradient), the magnitude of the current is proportional to the concentration gradient. Which in turn is proportional to the excess concentration of carriers, (n,p).

Using eq.(2) and (3) and remembering, we find that:

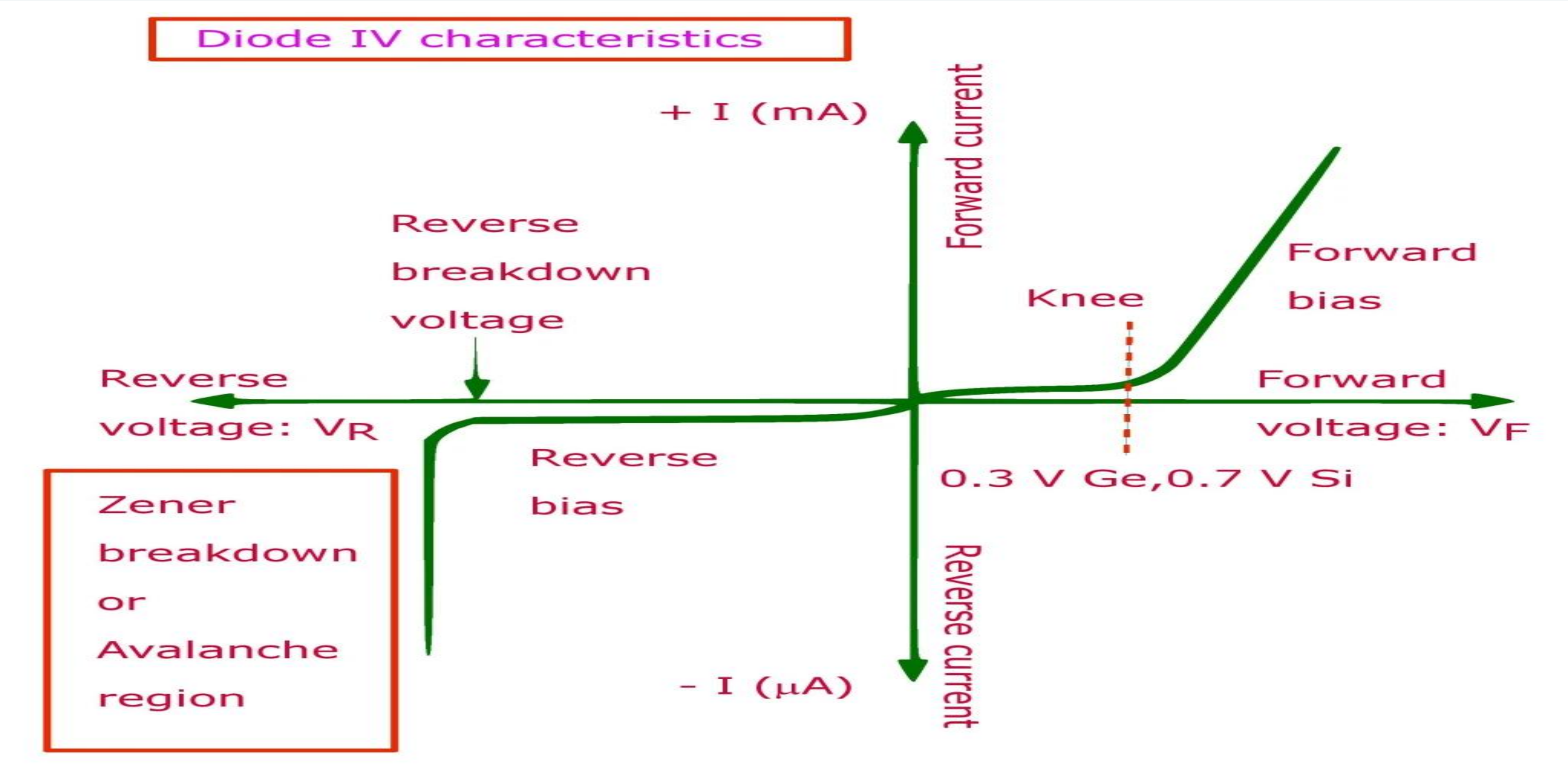
$$N_P^- - N_P = N_P[\exp\left(\frac{eV}{KT}\right) - 1]$$

So that the current can be written:

$$\mathrm{I} = \mathrm{I_S}[\exp\left(\frac{eV}{KT}\right) - 1]$$

Where $\mathrm{I_S}$ a constant, independent of the applied voltage. Fig.3 shows that the I,V characteristic for a real junction does indeed have this form-at least for low values of applied voltage. The reverse current is so small that for practical purposes the junction behaves very nearly as a one-way conductor, that is, as a rectifier.

Fig.3 : The voltage current relationship for a silicon p-n junction



Problems

1. A small rod of pure Ga 1Cm long, 2mm wide, and 1mm thick has an electrical resistance of 2160**Ω** at 20°C , $\boldsymbol{\mu}\ \boldsymbol{n}$ and $\boldsymbol{\mu}\ \boldsymbol{P}$ are 0.39 and 0.19 $m^2v^{-1}sec^{-1}$respectively. How many electrons are in the conduction bond?

2. Silicon contains 5×10^{28} atoms per cubic meter. If its drops with 2ppm of As. Find the current density (approximately)?

3. A pure semiconductor has $\boldsymbol{E}\ \boldsymbol{g}$ = 0.7 ev, $\boldsymbol{N}\ \boldsymbol{C}$ =$\mathbf{2\ .5\ \times 1\ 0\ 2\ 5}\ \boldsymbol{m}\mathbf{-3}$, $\boldsymbol{\mu}\ \boldsymbol{n}$ =$\mathbf{2\ .3}$ $m^2v^{-1}sec^{-1}$, $\boldsymbol{\mu}\ \boldsymbol{p}$ =$\mathbf{0\ .0\ 1}$ $m^2v^{-1}sec^{-1}$. Give its conductivity of 300K?

4. The energy gap in pure Germanium is 0.74 eV. Compare the number conduction electrons at 25°C and 50°C?

5. A germanium crystal is doped with boron atoms to achieve a p-type semiconductor. If the concentration of boron atoms is 2 x 1015 cm^{-3}, calculate the conductivity of the semiconductor at room temperature (300K). Assume that the hole mobility in germanium at 300 K is 500 $cm^2V^{-1}S^{-1}$.

6. A silicon wafer is doped with arsenic atoms to achieve an n-type semiconductor with a conductivity of 0.2 (Ω-cm)-1. Calculate the concentration of arsenic atoms required to achieve this conductivity. Assume that the electron mobility in silicon is 1500 $cm^2V^{-1}S^{-1}$.

Thank you