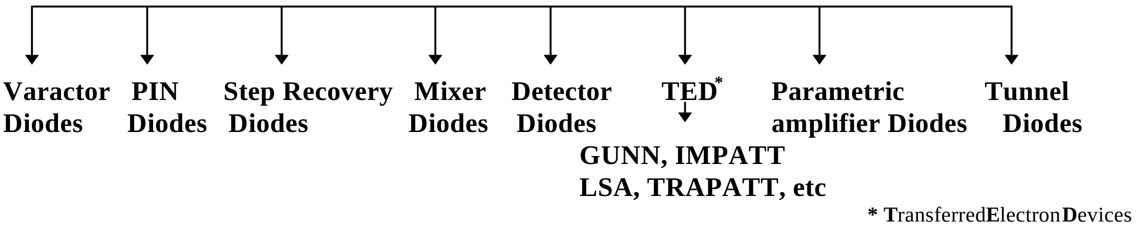
R F and Microwave Diodes

Diodes which finds application in R F and Microwave circuits are classified under this category. At lower frequencies these diodes behave like ordinary junction diodes. But at R F and microwave frequencies , their characteristics can be made use to process signals in that frequency range. The classification chart is shown below.

R F and Microwave Diodes



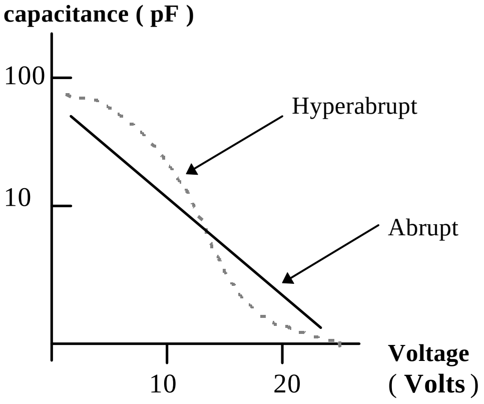
(1). Varactor Diodes

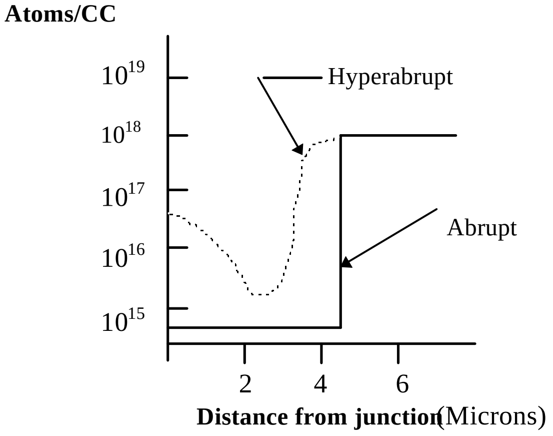
In P-N junction as the junction is formed holes and electrons at the junction diffuses to either sides leaving behind immobile charged ions. So as the equilibrium is reached at the junction only ions will be left out. This region is called the depletion region. This layer is the cause of contact potential of the diode. On either sides of the layer there are electrons and holes. So this layer behaves like an insulator separating charged particles. This analogues to a parallel plate capacitor.

When the diode is forward biased the electrons and holes gets energy to cross the junction and they recombine with the opposite charge at the other side of the junction. This results in a storage of charges on either sides of the junction. This in turn is equivalent to a capacitance called Diffusion capacitance. The value of this is negligibly small.

When the diode is reverse biased more electrons and holes move away from the junction, and effectively the depletion layer width increases. As in the case of a parallel plate capacitor (where the capacitance is inversely proportional to the distance between the plates), the capacitance decreases. This capacitance is called transition capacitance. Comparatively this is more than the diffusion capacitance.

This property of varying the diode capacitance with the reverse voltage is useful in tuning circuits, Automatic Frequency Control (AFC) circuits, etc. Hence Varactor diodes finds application in these areas. The variation of capacitance with frequency is dependent on the semiconductor doping, because the concentration of electrons affects the capacitance. Depending on the doping, varactor diodes are classified as Abrupt Junction and Hyperabrupt Junction varactors. The variation of the capacitance with voltage in these two cases are illustrated below.





In the case of Abrupt junction diodes, the capacitance variation is roughly inversely proportional to the reverse voltage. The variation is represented by the following equation.

$$C = K.A.(V + V)^{-n} \qquad ....(1)$$

where:

C = capacitance of the diode at voltage, V.
K = Constant.
A = Area of cross-section of the diode.
V = Built in potential of the diode.
n = Slope exponent.

In the case of Hyperabrupt junction diodes, the capacitance variation is represented by the following equation.

$$C = \mathbf{C_0} .(1 + V/V)^{-\gamma} \qquad ....(2)$$

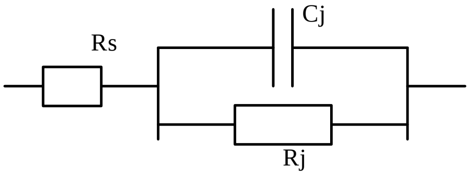
where:

C = capacitance of the diode at voltage, V.
C_0 = capacitance of the diode at voltage, V= 0.
V = Built in potential of the diode.
γ = Slope exponent.

The only difference between the above two equations are that in the case of Hyperabrupt diodes, the slope exponent (γ) is a function of the voltage. This varies in the range of 0.5 to 2, whereas slope exponent in the case of Abrupt diodes is approximately equal to 0.5. The slope exponent is generally called “Gamma”.

Quality Factor of a varactor(Q - Factor)

A tuning varactor can be represented by the following electrical equivalent circuit.



Cj = Junction Capacitance.
Rs = Series Resistance.
Rj = Junction resistance.

The resistor ‘Rs’ represents the resistance of the diode material. This causes unwanted power dissipation in the diode. This dissipation should be as low as possible. To measure this a parameter called Quality factor is introduced. It is defined as,

$$Q = 2.\pi \text{ . Energy stored / Energy dissipated per cycle.}$$
$$= 1 / (2.\pi.f.Cj.\ Rs).$$

Where: f = Frequency.

From the above equation it is clear that Q factor varies inversely as the frequency. High Q factor is preferred for a varactor to give better performance. If the Q factor at one frequency is known, the value at another frequency can be calculated as,

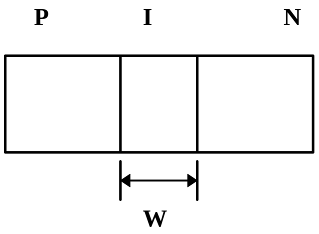
$$Q \text{ at } f_1 = Q \text{ at } f_2 .(f_2 / f_1)$$

Usually manufacturers measures the Q factor at a higher frequency and extrapolate to lower frequency (usually 50 MHz), using the above relationship.

Another important parameter of the varactor diodes is the capacitance ratio. This is the ratio of the diode capacitance at a lower voltage to the value at a higher voltage. This gives the range in which we can operate the diode. A higher value of capacitance ratio (also called ‘tuning ratio’), is preferred.

(2). PIN Diodes (Positive Intrinsic Negative)

PIN diode is a semiconductor device that operates as a variable resistor at RF and Microwave frequencies. It can also be used as a switch and Limiter. The variable resistor property makes it usable as an Attenuator.



The figure shows the construction of PIN diode. A P -type material and N -type are separated by an intrinsic region. The thickness of the intrinsic region has a major role in the characteristics of the diode.

When forward biased, holes and electrons are injected from P and N regions to the Intrinsic region. These charges do not immediately recombine, instead a finite quantity of charge always remain stored and effectively results in lowering the resistivity of the I - region. The quantity of the stored charge depends on the carrier life time (τ), and the forward current I_F.

Charge Stored $Q = I_F \,.\, \tau$ .... (1)

The resistance of the intrinsic region under forward bias is given by

Resistance $R_S = W^2 / (\mu N + \mu P).\, Q$ ....(2)

Where :

W = I - region width
μN = electron mobility
μP = hole mobility

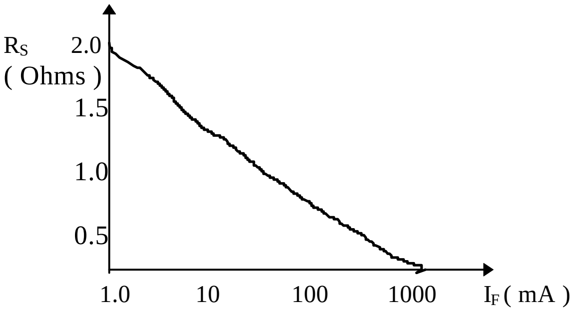
[***Note***: The velocity of electrons under an applied electric field is directly proportional to the electric field. If '**E**' is the electric field intensity and '**v**' is the electron velocity, then

$\mathbf{v} \propto \mathbf{E}$ or, $\mathbf{v} = \mu \mathbf{E}$ where μ = Mobility of electrons**]**

Combining both equations we get :

$$R_S = W^2 / (\mu N + \mu P).\, I_F \,.\, \tau$$

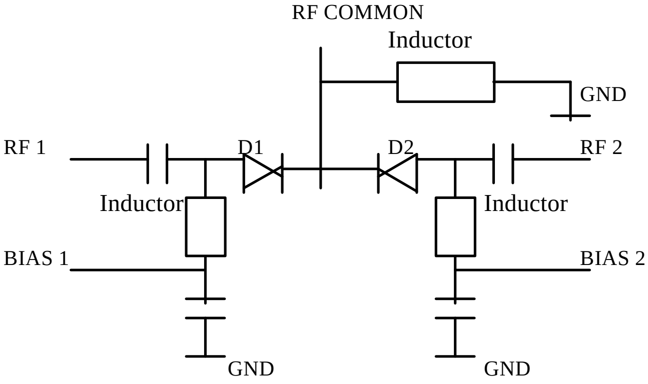
So as the forward current increases the resistance decreases. This explains the use as a Current Controlled Resistor. The graph shown below gives the resistance variation characteristics.



Applications

As the PIN diode resistance is controlled by the forward current, the diode can be used as a switch at RF and Microwave frequencies. If the forward current is sufficient to reduce the resistance to a very low value, it behaves like a short circuit. If reverse biased the diode is an open circuit and the signal is not allowed to pass through.

A typical PIN diode switching circuit is shown below. In this case diode combination behaves as an SPDT switch.



If the BIAS 1 is to forward bias D1, then the input RF signal will be available at RF1 output. Similarly if the diode D2 is biased in the forward direction by the voltage BIAS 2, then RF input is directed to output, RF2. In this manner the diode combination acts as an SPDT switch.

PIN diode can be used as an attenuator similar to a resistive attenuator. Here the resistance of the I- region is controlled by the current and thus the attenuation ratio can be controlled.

PIN diodes with thin I- region width are best suited for Limiter applications. But for high power limiter applications thick I- region is preferred. PIN diodes protects the Mixer or Detector circuits from the high power input signals by providing a bypass path to the ground. If the input current is very high, the diode resistance decreases to a very low value so that current will be bypassed through the diode, to the ground.

(3). Step Recovery Diodes

Step recovery diodes (also called Snap off varactors) are used for frequency multiplication, Harmonic frequency generation etc.
When a diode is forward biased, it stores charge and as the diode is reverse biased, the diode ceases to conduct.
If the turning off of the diode is so fast then the diode can be used to generate an impulse of current. If this is done cyclically, then a train of impulses can be generated. A periodic series of impulses is equivalent to a series of frequencies (all multiples of the exciting signal frequency). If this pulses are applied to a resonant circuit with the desired frequency as the resonant frequency of the circuit, then the output power will be maximum at the resonant frequency. Thus the input power at one frequency can be converted into output power at higher frequency.

Efficiency of the step recovery diode is measured as:

$$\eta = P_O / (P_O + P_D) . 100 \%$$

Where:

P_O = output power
P_D = power dissipation.

Applications

1. Frequency multiplication

Step recovery diodes can be used as frequency multipliers. In this case, signal frequency which is to be multiplied is given as input to the diode. The multiplied frequency signal power is a function of the multiplication ratio. Higher the multiplication ratio, lower the power output. This in turn results in the decrease in the efficiency. So most of the manufacturers will be giving the efficiency for a particular output power and multiplication order.

Let us see how the signal frequency gets multiplied. The application of an AC voltage to a non-linear resistor (or reactance) results in a current which is proportional to the higher order components of the voltage. i.e

$$\text{Current } i = A.\, v + B.\, v^2 + C.\, v^3 + \ldots \quad \text{where A, B, C .. are constants.}$$

If we neglect the components of power more than 2, then

$$i = A.\ v + B.\ v^2$$

if $v = V.\mathrm{Cos}\,\omega t$, then

$$i = A.\ V.\mathrm{Cos}\,\omega t + B.(\ V.\mathrm{Cos}\,\omega t\ )^2$$

$$= A.\ V.\mathrm{Cos}\,\omega t + B.\ V^2.(\ \mathrm{Cos}\,\omega t\ )^2 \ =\ A.\ V.\mathrm{Cos}\,\omega t + B.\ V^2.(\ 1+ \mathrm{Cos}\,2\omega t\ ) / 2$$

From the above equation, it is clear that output contains the second harmonic of the input frequency. As the Step recovery diode acts as a voltage variable capacitor, it is behaving as a non-linear reactance, and the generated current will have higher harmonics of the input signal frequency.

2. Harmonic generation

When a step voltage is applied to the diode, it generates series of current pulses, which can be applied to a tuned circuit to get the desired frequency. Depending on the resonant frequency of the tuned circuit, any harmonic component of the input frequency can be generated.

3. Comb generation

Comb generator gives very sharp and narrow pulses, which can be used in measurement equipments like Spectrum analysers to produce locking signals. Step recovery signals can be used to generate comb signals by applying a step voltage input to the diode. In this case tuned circuit is not required, as the required signal should be rich with harmonic components.

(4). Mixer diodes

Mixer is an important part of a communication receiver. If the RF signal coming from the transmitter is directly fed to a demodulator and amplifiers, the received signal will not be an exact replica of the transmitted signal. As the circuit components are not linear operation at RF frequencies, this results in introduction of unwanted noise, unstable operation of amplifiers due to the feedback caused by capacitors (i.e, at RF frequencies, capacitive reactance is very less, causing in a short circuiting effect.). These problems can be avoided if the translation of frequency to a lower value is done without affecting the message. In mixers, the RF signal is mixed with a Local oscillator frequency and the difference frequency is generated (called Intermediate Frequency - **IF**) and applied to the rest of the circuits. Mixer circuit makes use of the non-linear properties of a mixer diode, to produce the Intermediate Frequency. This can be done with a single diode or with multiple diodes in ‘ balanced ‘ or ‘ double balanced ‘ circuit configurations.

Schottky barrier, point contact barrier, planar doped barrier, etc. are the most common diode technologies preferred for the mixer application. Let us see how the signal frequency and Local oscillator frequency gets Mixed (or subtracted and giving the Intermediate frequency).

The application of an AC voltage to a non-linear resistor (or reactance) results in a current which is proportional to the higher order components of the voltage. i.e

$$\text{Current } i = A.\ v + B.\ v^2 + C.\ v^3 + \ldots \qquad \text{where } A, B, C \text{ .. are constants.}$$

If we neglect the components of power more than 2, then

$$i = A.\ v + B.\ v^2$$

If we apply two AC signals to the device, then

$$i = A.(\ v_1 + v_2\ ) + B.(\ v_1 + v_2\ )^2$$

if $v_1 = V_1.\mathrm{Sin}\,\omega_1 t$, and $v_2 = V_2.\mathrm{Sin}\,\omega_2 t$ then

$$i = A.(\ V_1.\mathrm{Sin}\,\omega_1 t + V_2.\mathrm{Sin}\,\omega_2 t\ ) + B.(\ V_1.\mathrm{Sin}\,\omega_1 t + V_2.\mathrm{Sin}\,\omega_2 t\ )^2$$

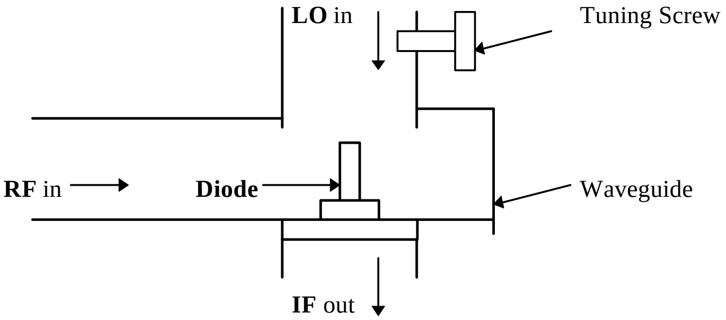
$$= A.\ V_1.\mathrm{Sin}\,\omega_1 t + A.\ V_2.\mathrm{Sin}\,\omega_2 t + B.\ V_1^2.(\ \mathrm{Sin}\,\omega_1 t\ )^2 + B.\ V_2^2.(\ \mathrm{Sin}\,\omega_2 t\ )^2 + 2B\ V_1\ V_2\ \mathrm{Sin}\,\omega_1 t\ \mathrm{Sin}\,\omega_2 t$$

$$= A.\ V_1.\mathrm{Sin}\,\omega_1 t + A.\ V_2.\mathrm{Sin}\,\omega_2 t + B.\ V_1^2.(\ 1- \mathrm{Cos}\,2\omega_1 t\ ) / 2 + B.\ V_2^2.(\ 1- \mathrm{Cos}\,2\omega_2 t\ ) / 2$$

$$+ B\ V_1\ V_2 [\ \mathrm{Cos}\,(\omega_1 - \omega_2) - \mathrm{Cos}\,(\omega_1 + \omega_2)\ ] \quad \text{...... as} \quad \mathrm{Sin}.x\ \mathrm{Sin}.y\ = [\ \mathrm{Cos}\,(x - y) - \mathrm{Cos}\,(x + y)\ ]/ 2$$

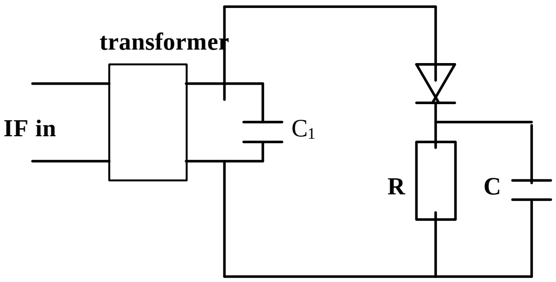
It is clear from the above derivation that the current has the Sum and Difference frequencies, along with the second harmonic components and the input signal frequency.

In the case of a diode used as a mixer, the RF and Local Oscillator inputs are given as shown in the figure. The IF output is taken from the other end as indicated in the figure.



(5). Detector Diodes

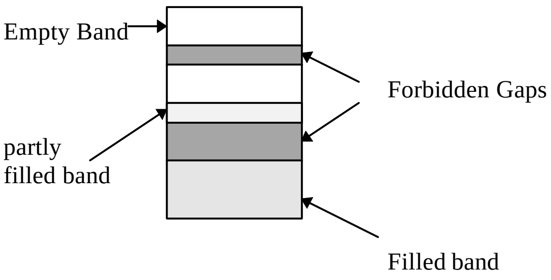
Detector is an important part of a receiver. This circuit is used for recovering the transmitted signal from the modulated signal. Schottky, Point contact, Pressure contact, Planar doped barrier, etc. are the common diode technologies used for detector diode construction. A typical diode detector circuit is shown in figure.



Impedance matching and tuning is done by the transformer. The output of the transformer (IF) is fed to the detector diode, which rectifies the signal, giving out the positive half cycles. This is applied to the R-C circuit. At each positive cycle of the IF input, C charges to the value almost equal to the input voltage. Between the peaks of the input voltage, capacitor discharges through R, similar to the case of a rectifier filter arrangement. So across the diode we get the modulating signal.

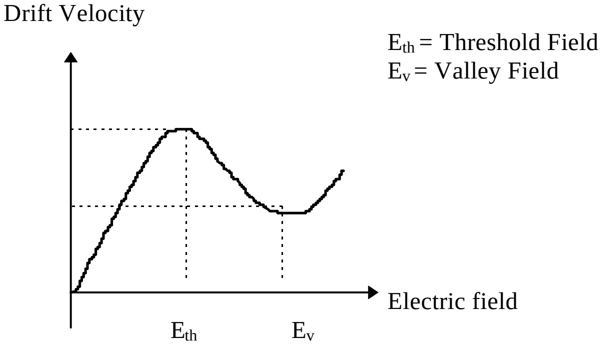
(6). Gunn Diodes

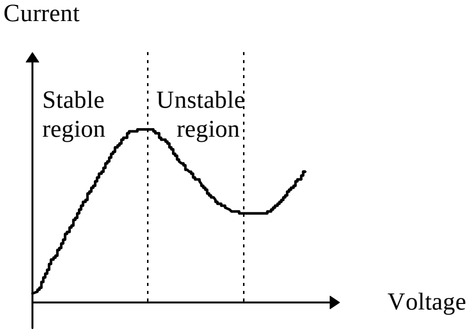
Gunn diodes works under the principle of " transferred electron effect ". This was invented by the scientist Gunn. He had found this in compound semiconductors like GaAs, InP, etc. As these are compound semiconductors, these has a complex energy band structure. this is shown in the figure below.



The upper forbidden gap is very narrow. If voltage is applied across GaAs slice, electrons flow towards the positive end. But the applied field makes the electrons able to get transferred to the upper energy band, as the electrons require very less energy to jump to this level (because of the complex energy band structure). Thus instead of moving faster under the applied field, these electrons slows down. This is because, as they acquire more energy, they become less mobile. This is called '**transferred electron effect**'. So in effect, the current is reduced even though there is an increase in voltage. This results in the '**negative resistance**' property.

In a semiconductor slice, the doping of impurity will not be uniform throughout the slice. So there is a chance that number of electrons in an area (possibly nearer to the negative end), is less compared to the other areas of the slices. So this region becomes less conductive than the other regions. So the potential across this region will be greater than the average potential across the slice. As the applied potential is increased, this region will be the first to have a voltage large enough to introduce transfer of electrons to the higher energy band. these electrons form a bunch in which the electrons in the front level moves faster while the ones behind buch up. So in effect, the bunch of electrons travel towards the positive end of the slice. As the bunch of electrons reach the positive end, it generates a current pulse there. This pulse is rich in harmonics and if it is applied to a tank circuit (LC tuned circuit), it results in oscillations at the resonant frequency of the tank circuit. Thus GUNN diodes can be used as oscillators.





The figures given above shows the variation of the drift velocity with electric field, and variation of current with voltage. If the applied field is less than the Threshold value (E_{th}), the specimen is stable. In this region, the Gunn diode can be used to amplify the input signal. If the diode is to be used as an oscillator, then the applied field should be more than the threshold value. At the initial formation of the domain, as explained earlier, the field behind the domain decreases and the field in front increases. As the layer approaches the anode, the field behind it begins to increase again. When the high field domain disappears at the anode, a new dipole field starts at the cathode and start moving towards the anode. So a series of pulses are obtained at the anode. The oscillation frequency is given by

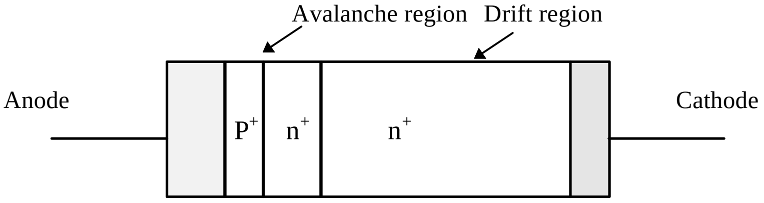
$$\text{frequency (f)} = v_d / L_{eff}$$

Where: v_d = Velocity of the domain, (approximately equal to the drift velocity of electrons)
L_{eff} = Effective length that the domain travels

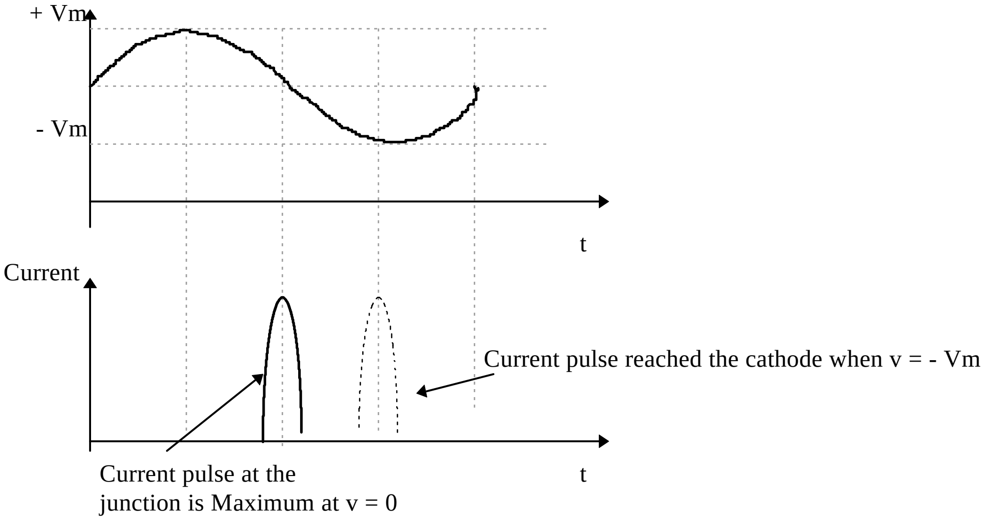
(7). IMPATT diodes (IMPact Avalanche Transit Time diodes)

When sufficient reverse voltage is given to a diode, electrons acquire energy to move faster hitting the bonded electrons and imparting energy to them. Thus the electrons are made free. These free electrons move faster the applied electric field and the process is continued. This goes on resulting in avalanche multiplication of electrons. After application of the field, there will be a time delay for generation of the multiplication. Similarly electron velocity will not be sufficient to cop up with the variation of voltage (transit time effect). These two factors results in a delay in the generation of the current. If it sufficiently high to make a 180^0 phase difference between the voltage and the current, it results in the ' negative resistance effect ' (current decreases as voltage increases).

IMPATT diode works under this principle. This includes impact ionisation of atoms, avalanche multiplication of electrons, and the transit time effect. The structure of the diode is shown below.



<u>Operation:</u> A d.c biasing voltage is applied just enough to start avalanche multiplication. When an AC voltage is applied over the DC, during the negative half cycle, the diode gets more reverse biased, and avalanche multiplication starts. For the entire half cycle, it develops. When the AC voltage decreases to zero, (i.e, voltage across the diode equals DC reverse voltage) avalanche current becomes maximum (at the junction). Because of the positive voltage at the cathode, electrons are attracted towards cathode. During this time applied AC voltage decreases to zero. While constructing the diode, the length and area of the semiconductor is selected such that, the electrons reaches the cathode when the applied voltage is reaching the negative peak. This is indicated in the figure.



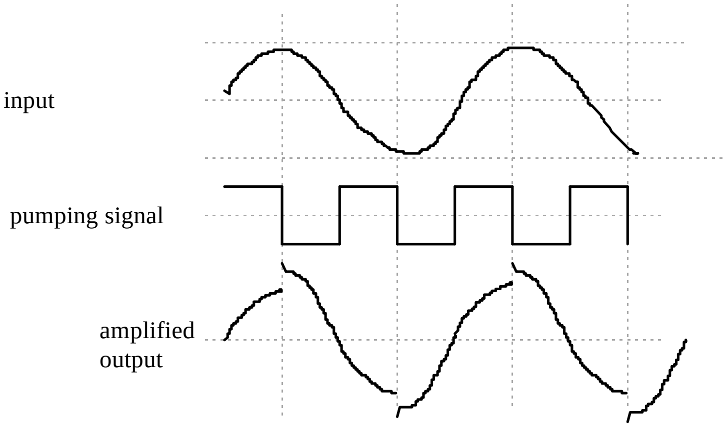
<u>Applications</u>

The negative resistance property can be made use of in the application as an oscillator, similar to a Gunn diode. The stable region of operation can be used to amplify the RF signals. Compared to Gunn diodes, IMPATT diodes give more output power. But the noise immunity of IMPATT diodes is very less than Gunn diodes. Moreover it requires higher supply voltage for the operation. But IMPATT diodes are more efficient and powerful than Gunn diodes.

<u>(8).Parametric Amplifier</u>

Parametric amplifier diodes are similar to varactor diodes. Here, the parametric variation (reactance variation with the voltage) is made use of to amplify RF signals. A rectangular wave called ‘ pumping signal ‘ is applied to the diode to vary the reactance. This signal frequency is selected such that it is twice the frequency of the signal to be amplified.

Consider an LC circuit oscillating at its resonant frequency. If the capacitance plates are pulled apart at the instant when the voltage reaches the positive peak, the capacitance decreases. The charge stored remains the same and the voltage across the capacitor increases (to satisfy the relation **Charge = Voltage X Capacitance**). Similar to this case, if we apply a reverse biasing voltage across a varactor diode(which is used as a part of an LC circuit), when the reverse bias is maximum at the positive peak, the voltage across the diode gets increased.



(9).Tunnel Diode

Before discussing the operation of tunnel diode, let us see the energy band structure of semiconductors. Electrons in a semiconductor bar may have different energies. So in the energy band diagram, electrons lie in different positions. The probability of finding an electron in a particular energy band can be calculated using ‘ Fermi - Dirac probability function’. It is given by,

Probability of finding an electron in energy band E , $f(E) = 1/(1 + e^{(E - E_F)/kT})$

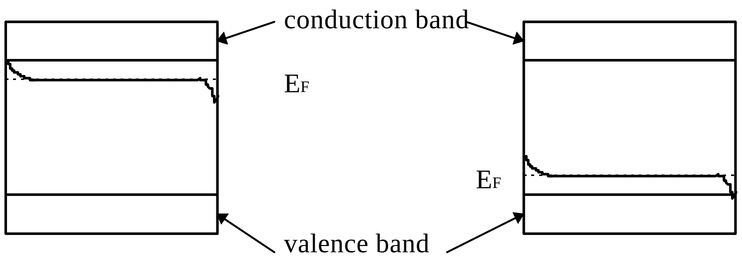
where:

E_F = Fermi energy, in eV
k = Boltzmann’s constant = 8.62×10^{-5} eV/ ^{0}K
T = Temperature , in ^{0}K

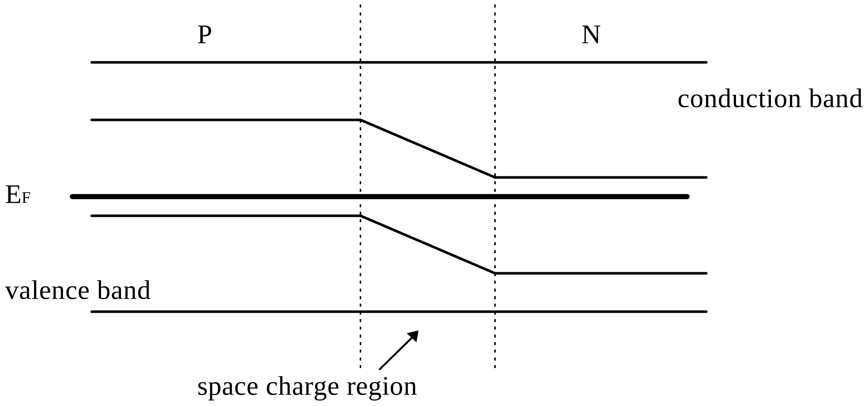
In the above equation, if $E = E_F$ is substituted, then we get $f(E) = 1/2 = 50\%$.

So Fermi level can be defined as the energy level at which there is 50 % probability of finding an electron.

In a semiconductor having impurities, the energy band diagram will be as shown in the figure.



Energy band diagram of a P-N junction is shown below.



In the case of tunnel diode, the doping is very high that the tunneling occurs. If reverse bias is applied, the minority carriers of P - region (electrons) gains energy and move to the upper energy level. So the percentage of finding electrons in the higher energy level increases. In turn the Fermi level rises. So the electrons finds the conduction band of N-region to be in the same level as them and they tunnel through the depletion region. Thus the reverse current increases unlike other P-N junctions. In the case of forward biasing, the holes manages to tunnel across the junction (electrons tunnel to P region). As the higher energy band electrons tunnel to the other side, the Fermi level goes down. So the current reaches a maximum value and then starts decreasing. This results in the formation of the‘ negative resistance region‘ in the characteristics curve. As the tunneling of electrons are over, the diode starts behaving similar to an ordinary junction diode and current increases.

The negative resistance property of tunnel diodes can be made use of in oscillators, amplifiers , etc. as explained in the case of Gunn and IMPATT diodes.

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