UNIT-3

Microwave Solid State Devices and Application

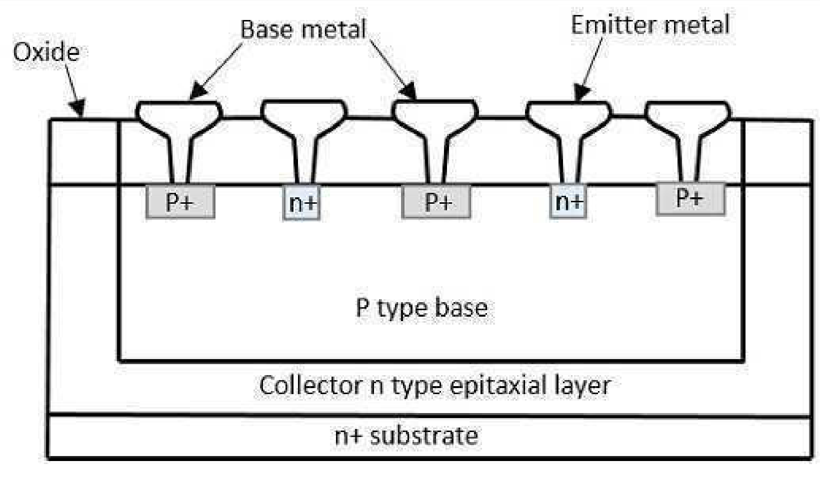
PIN diodes, Properties and applications, Microwave detector diodes, detection characteristics, Varactor diodes, parametric amplifier fundamentals, Manley-Rowe power relation MASER, LASER , Amplifiers, Frequency converters and harmonic generators using varactor diodes, Transferred electron devices, Gunn effect, Various modes of operation of Gunn oscillator, IMPATT, TRAPATT and BARITT.

Microwave Engineering - Components

In this chapter, we shall discuss about the microwave components such as microwave transistors and different types of diodes.

Microwave Transistors

There is a need to develop special transistors to tolerate the microwave frequencies. Hence for microwave applications, silicon n-p-n transistors that can provide adequate powers at microwave frequencies have been developed. They are with typically 5 watts at a frequency of 3GHz with a gain of 5dB. A cross-sectional view of such a transistor is shown in the following figure.

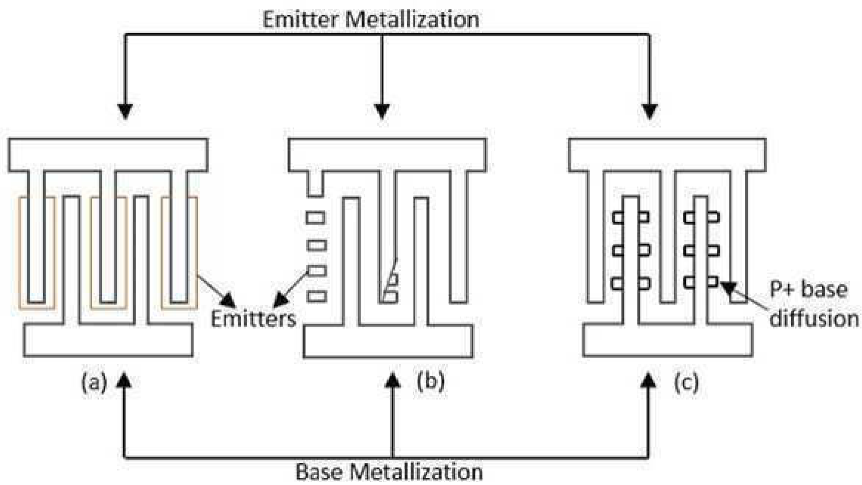


n-p-n silicon double diffused epitaxial transistor

Construction of Microwave Transistors

An n type epitaxial layer is grown on n+ substrate that constitutes the collector. On this n region, a SiO_2 layer is grown thermally. A p-base and heavily doped n-emitters are diffused into the base. Openings are made in Oxide for Ohmic contacts. Connections are made in parallel.

Such transistors have a surface geometry categorized as either interdigitated, overlay, or matrix. These forms are shown in the following figure.



Surface geometry of n-p-n microwave transistor
(a) Inter-digitated (b) Overlay (c) Matrix

Power transistors employ all the three surface geometries.

Small signal transistors employ interdigitated surface geometry. Interdigitated structure is suitable for small signal applications in the L, S, and C bands.

The matrix geometry is sometimes called mesh or emitter grid. Overlay and Matrix structures are useful as power devices in the UHF and VHF regions.

Operation of Microwave Transistors

In a microwave transistor, initially the emitter-base and collector-base junctions are reverse biased. On the application of a microwave signal, the emitter-base junction becomes forward biased. If a p-n-p transistor is considered, the application of positive peak of signal, forward biases the emitter-base junction, making the holes to drift to the thin negative base. The holes further accelerate to the negative terminal of the bias voltage between the collector and the base terminals. A load connected at the collector, receives a current pulse.

Solid State Devices

The classification of solid state Microwave devices can be done −

Depending upon their electrical behavior

- Non-linear resistance type.

Example − Varistors (variable resistances)

- Non-Linear reactance type.

Example − Varactors (variable reactors)

- Negative resistance type.

Example − Tunnel diode, Impatt diode, Gunn diode

- Controllable impedance type.

Example − PIN diode

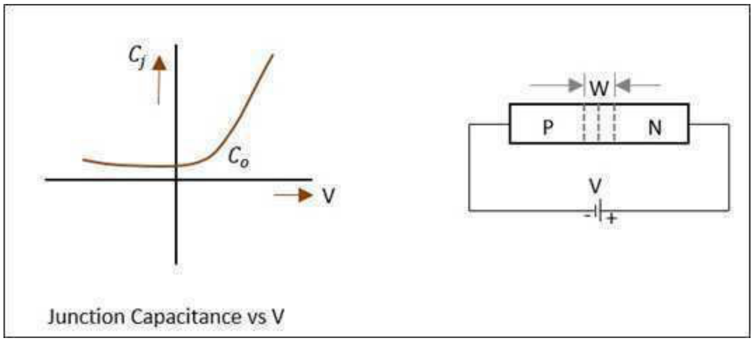
Depending upon their construction

- Point contact diodes
- Schottky barrier diodes
- Metal Oxide Semiconductor devices (MOS)
- Metal insulation devices

The types of diodes which we have mentioned here have many uses such as amplification, detection, power generation, phase shifting, down conversion, up conversion, limiting modulation, switching, etc.

Varactor Diode

A voltage variable capacitance of a reverse biased junction can be termed as a Varactor diode. Varactor diode is a semi-conductor device in which the junction capacitance can be varied as a function of the reverse bias of the diode. The CV characteristics of a typical Varactor diode and its symbols are shown in the following figure.



Varactor Diode

The junction capacitance depends on the applied voltage and junction design. We know that,

$C_j \alpha V_r^{-n}$

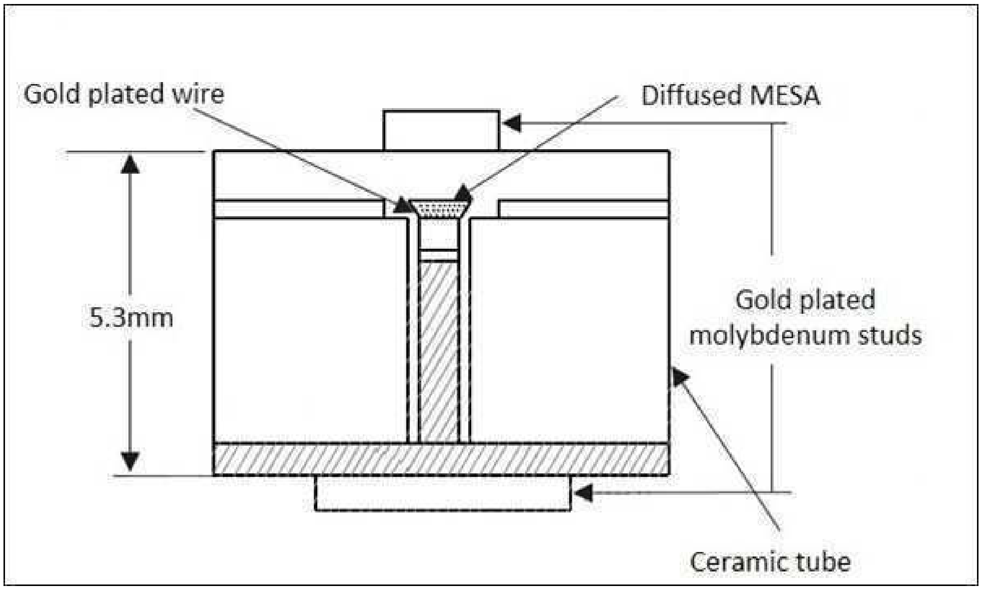
Where C_j = Junction capacitance

V_r = Reverse bias voltage

n = A parameter that decides the type of junction

If the junction is reverse biased, the mobile carriers deplete the junction, resulting in some capacitance, where the diode behaves as a capacitor, with the junction acting as a dielectric. The capacitance decreases with the increase in reverse bias.

The encapsulation of diode contains electrical leads which are attached to the semiconductor wafer and a lead attached to the ceramic case. The following figure shows how a microwave Varactor diode looks.



Microwave Varactor Diode

These are capable of handling large powers and large reverse breakdown voltages. These have low noise. Although variation in junction capacitance is an important factor in this diode, parasitic resistances, capacitances, and conductances are associated with every practical diode, which should be kept low.

Applications of Varactor Diode

Varactor diodes are used in the following applications −

- Up conversion
- Parametric amplifier
- Pulse generation
- Pulse shaping
- Switching circuits
- Modulation of microwave signals

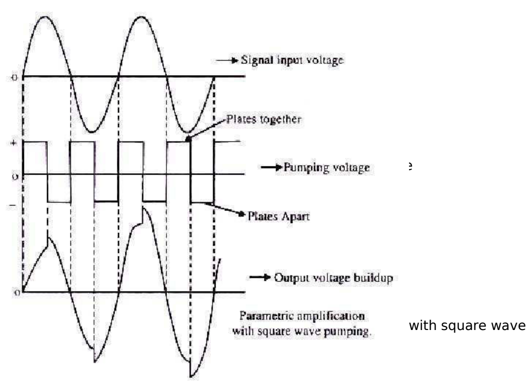
PARAMETRIC AMPLIFIERS

The parametric amplifier is an amplifier using a device whose reactance is varied to produce amplification. Varactor diode is the most widely used active element in a parametric amplifier. It is a low noise amplifier because no resistance is involved in the amplifying process. There will be no thermal noise, as the active element used involved is reactive (capacitive). Amplification is obtained if the reactance is varied electronically in some predetermined fashion.

Due to the advantage of low noise amplification, parametric amplifiers are extensively used in systems such as long range radars, satellite ground stations, radio telescopes, artificial satellites, microwave ground communication stations, radio astronomy etc.

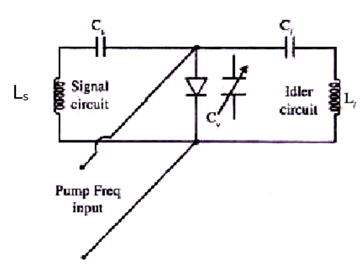
Basic Parametric Amplifier

A conventional amplifier uses a variable resistance and a dc power supply. For a parametric amplifier, a variable reactance and an ac power supply are needed. Pumping signal at frequency fp and a small amplitude signal at frequency fs are applied simultaneously to the device (varactor). The pump source supplies energy to the signal (at the signal frequency) resulting in amplification. This occurs at the active device where the capacitive reactance varies at the pump frequency.



The voltage across the varactor is increased by the pumping signal at each signal voltage peak as shown above i.e., energy is taken from the pump source and added to the signal at the signal frequency. With an input circuit and load connected, amplification results. One port non-degenerate amplifier is the most commonly used parametric amplifier. Only three frequencies are involved - the pump, the signal and the idler frequencies. If pump frequency is fp' the signal frequency is fs' then idler frequency is $f_j = f_p - f_s'$

If $f_i = f_s'$ then it is called Degenerate amplifier and if f_i is not equal to f_s' then it is non-degenerate amplifier.



L_s C_s ~ tuned circuit at signal frequency f_s

$L_j\ C_j$ ~ tuned circuit at idler frequency f_j (pump frequency tuned circuit is not shown),

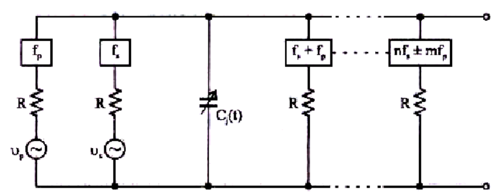
The output can be taken at idler frequency f_r Gain is possible with this type of amplifier. Because the pump source gives more energy

$$\text{Gain}=f_j/f_s=(f_p-f_s)/f_s$$

In non-degenerate type, usually $f_j > f_s$ resulting in gain. The idler circuit permits energy to be taken from the pump source. This energy is converted into signal frequency and idler frequency energy and amplified output can be obtained at either frequency.

MANLEY – ROWE RELATIONS:

For the determination of maximum gain of the parametric amplifier, a set of power conservation relations known as "Manley-Rowe" relations are quite useful.



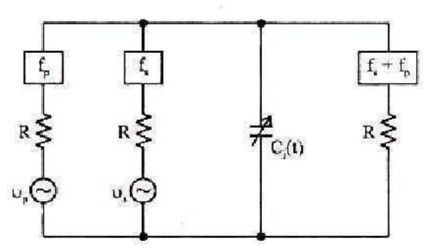
Two sinusoidal signals f_p and f_s applied across a lossless time varying non-linear capacitance C_j (t). At the output of this varying capacitance, harmonics of the two frequencies fp and fs are generated. These harmonics are separated using band-pass filters having very narrow bandwidth. The power at these harmonic frequencies is dissipated in the respective resistive loads.

From the law of conservation of energy, we have

$$\sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty}\frac{nP_{mn}}{nf_s+mf_p}=0$$

$$\sum_{m=0}^{\infty}\sum_{n=-\infty}^{\infty}\frac{mP_{mn}}{nf_s+mf_p}=0$$

The above relations are called "Manley-Rowe" power conservation equations. When The power is supplied by the two generators, then Pmn is positive. In this case, power will flow into the non-linear capacitance. If it is the other way, then Pmn is negative.



As an example, let us consider the case when the power output flow is allowed at the sum frequency $f_p + f_s$ only, with all the remaining harmonics being open circuited. With the above rest ructions, the quantities 'm' and 'n' can take on values -1, 0 and respectively.

$$P_{01}/f_s+P_{11}/(f_s+f_p)=0$$

$$\text{And } P_{10}/f_p+P_{11}/(f_s+f_p)=0$$

The powers $P_{01}$and P_{10} are considered positive, whereas P_{11} is considered negative. The power gain defined as the power output from the non-linear capacitor delivered to the load at a frequency to that power received at a frequency f_s is given by

$$G_p=P_{11}/P_{01}=(f_s+f_p)/f_s \text{ (For Modulator)}$$

Thus the power gain is the ratio of output to input frequency. This type of parametric device is called "Sum-frequency parametric amplifier" or "up-converter". On the other hand, if the signal frequency is fp+fs and output frequency is fs' then

$$G_p= f_s / (f_s+f_p) \text{ (For Demodulator)}$$

This type of parametric device will now be called "parametric down-converter" and the power gain becomes power attenuation.

Parametric Amplifier Advantages:

- Noise Figure: Because of minimum resistive elements, thermal noise in parametric amplifier is very less in comparison to transistor amplifier. Hence noise figure is less and will be in the range 1-2 dB.
- Frequency Range: The upper frequency limit (about 40 to 200GHz) is set by the difficulty of obtaining a source power at pump frequency and also by the frequency at which the varactor capacitance can be pumped. The lower frequency limit is set by the cut-off frequency of the microwave components used in circuit
- Because of its low noise, parametric amplifiers are used in space communications systems, tropo-receivers and radio telescopes.

Parametric Amplifier Disadvantages

- Bandwidth: Parametric amplifier bandwidth is small due to the presence of tuned circuits. Bandwidth can be increased by stagger tuning.
- Gain: It is limited by the stabilities of pump source and the time varying capacitance. It is usually in the range of 20 to 80 dB.

MASER

A maser is a device that produces coherent electromagnetic waves through amplification by stimulated emission. The word MASER stands for Microwave Amplification by Stimulated Emission of Radiation.

When the electrons are emitted from the lower energy band towards the higher energy band by pump input, the population inversion takes place at the higher energy band. Now the electrons fall back towards the lower energy band. At this time they emit the photon's which generates the microwave frequency. The generation of frequency produced by the photons depends upon the gape between the energy bands. In case of maser this gape is created by different methods for example the magnetic flux in case of Ruby Maser.

Uses of MASER

- Maser is used in satellite communication.
- It is also used in air to air communication.
- We use the maser in radio telescope.
- Maser is also used in radar technology.
- Maser is used as an amplifier and oscillator in microwave in those components or equipment where low noise factor is of the most importance.

Types of MASER

There are different types of MASER designed for amplification and oscillation at microwave frequencies in which the following types are widely used.

1. Ruby MASER

2. Travelling Wave MASER (TWM)

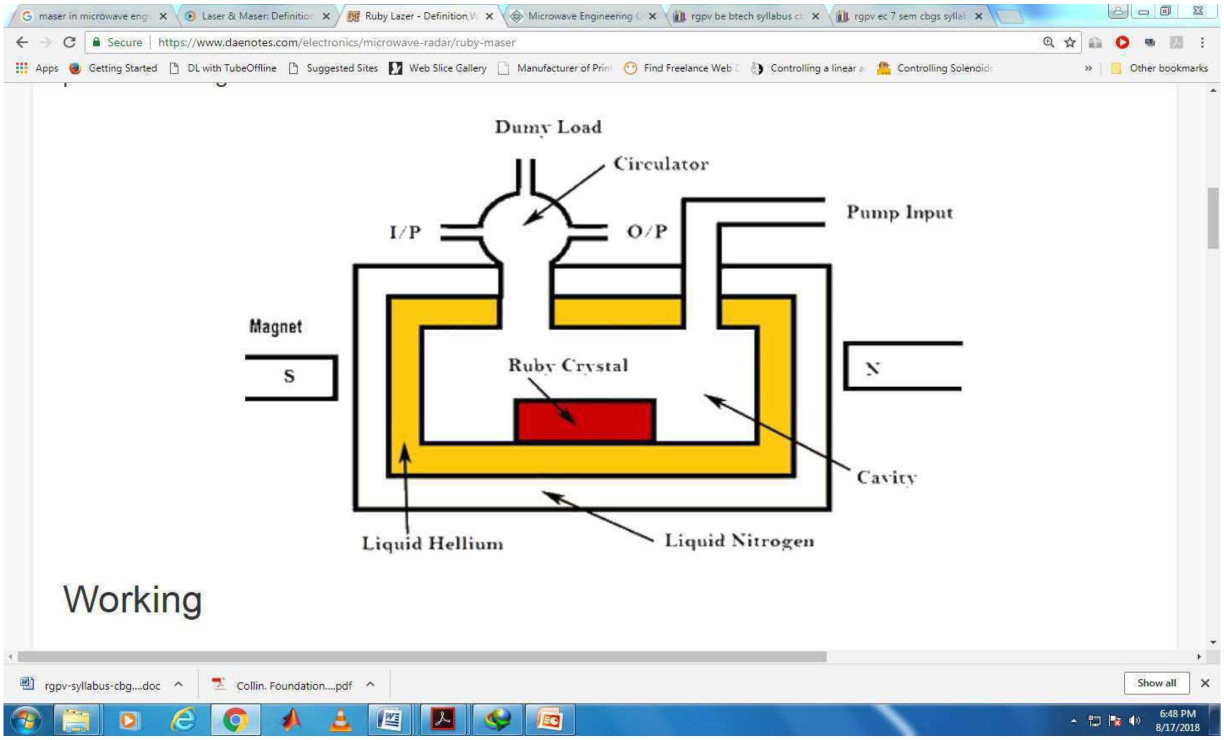
Ruby Maser

Construction

The RUBY MASER consist of a ruby crystal kept in the cavity. The cavity is enclosed by a jacket of liquid helium in order to observe the heat generated by the ruby crystal during operation.

For further cooling the jacket of liquid nitrogen is used at the outermost surface of the ruby maser. A pump input is provided to the cavity in order to excite the ruby crystal.

The input and output of microwave frequencies is given through the divice known as circulator. A permanent magnet is also used across the maser.



Working

When the pump input is provided to the cavity the electron in the ruby maser moves from lower energy band to the higher energy band. The population inversion takes place which results to fall back of the electrons from high energy band to the lower energy band. During this time the electrons emits the photons which produces the microwave frequency. The field of this frequency excites the cavity. As a result the oscillation takes place inside the cavity at the microwave length of frequency.

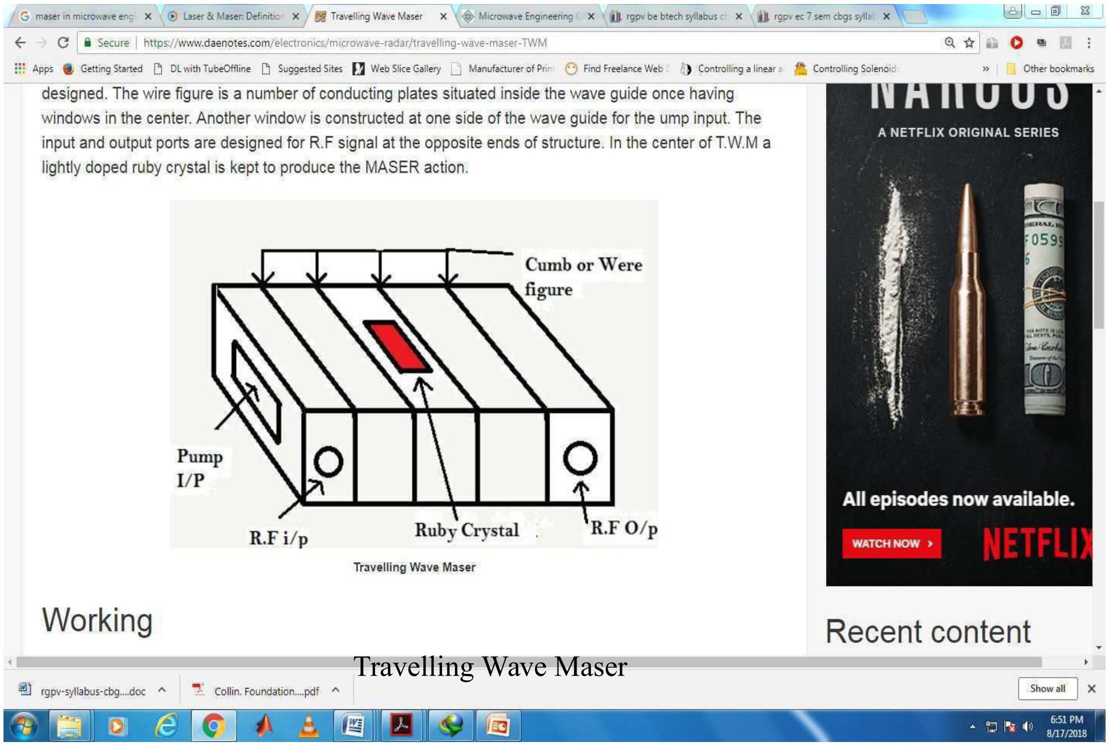
When the high range R.F ainput signal is applied to the cavity through circulator, It finds itself in the high level of signal at the same frequency inside the cavity so the output of this signal is taken from the output port of the circulator in amplified form.

The input and output port between the circulator and cavity is the same. It is possible due to the reason that when the input is maximum at the input port. It is minimum at the cavity port, because the distance between these two ports is λ/4. The same is the case for the output signal.

Travelling Wave Maser

Construction

The travelling wave MASER (T.W.M) consists of a wave guide structure in which the wire figure or comb is designed. The wire figure is a number of conducting plates situated inside the wave guide once having windows in the center. Another window is constructed at one side of the wave guide for the ump input. The input and output ports are designed for R.F signal at the opposite ends of structure. In the center of T.W.M a lightly doped ruby crystal is kept to produce the MASER action.



Travelling Wave Maser

Working

When the pump input is provided to the travelling wave maser (T.W.M). The electrons move from lower band of energy level towards the high band of energy level at the higher energy band population inversion take place and the electrons fall back to the lower energy band. During this time they emit the photons, which generate the microwave frequency.

This action causes to excite the (T.W.M) cavities. As shown in the diagram. That we have a number of cavities inside the wave guide structure from input port to the output ports. This structure results to increase the band width of the maser. The structure is known as slow wave structure, which produces or generates when the R.F signal moves from input to the output through the wire figure. This structure causes to increase the band width of the maser and makes the (T.W.M) useful for different purposes in the radar system.

LASER

The word LASER is actually an acronym for Light Amplification by Stimulated Emission of Radiation. In 1960, the first fully functional laser was completed, but the technology of the laser goes back to Einstein's study of blackbody radiation in 1917. Blackbody radiation refers to a cavity that absorbs all the radiation that falls upon it and re-emits part of this radiation in a proportion of quantized energy. Max Planck made this discovery. It was one of the founding discoveries in quantum physics (the physics of the subatomic world). This study of blackbody radiation led Einstein to discover the phenomenon of stimulated emission.

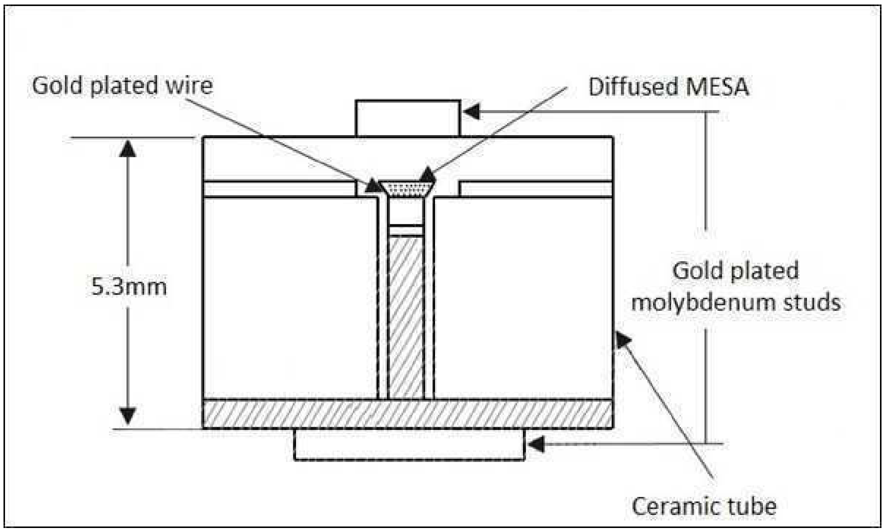
Stimulated emission is when electrons absorb energy from an electric current or other source of electromagnetic waves and become 'excited,' meaning they jump from a lower energy level to a higher energy level. When the electrons return to their original energy state they give off a photon (electromagnetic radiation). This light is different from the normal light spectrum that we can see because the photons emitted are all the same wavelength, focused, and directional. This stimulated emission of photons from excited electrons is the main principle of how lasers work.

Schottky Barrier Diode

This is a simple diode that exhibits non-linear impedance. These diodes are mostly used for microwave detection and mixing.

Construction of Schottky Barrier Diode

A semi-conductor pellet is mounted on a metal base. A spring loaded wire is connected with a sharp point to this silicon pellet. This can be easily mounted into coaxial or waveguide lines. The following figure gives a clear picture of the construction.



Schottky Barrier Diode

Operation of Schottky Barrier Diode

With the contact between the semi-conductor and the metal, a depletion region is formed. The metal region has smaller depletion width, comparatively. When contact is made, electron flow occurs from the semi-conductor to the metal. This depletion builds up a positive space charge in the semi-conductor and the electric field opposes further flow, which leads to the creation of a barrier at the interface.

During forward bias, the barrier height is reduced and the electrons get injected into the metal, whereas during reverse bias, the barrier height increases and the electron injection almost stops.

Advantages of Schottky Barrier Diode

- Low cost
- Simplicity
- Reliable
- Noise figures 4 to 5dB

Applications of Schottky Barrier Diode

- Low noise mixer
- Balanced mixer in continuous wave radar
- Microwave detector

Gunn Effect Devices

J B Gunn discovered periodic fluctuations of current passing through the n-type GaAs specimen when the applied voltage exceeded a certain critical value. In these diodes, there are two valleys, L & U valleys in conduction band and the electron transfer occurs between them, depending upon the applied electric field. This effect of population inversion from lower L-valley to upper U-valley is called Transfer Electron Effect and hence these are called as Transfer Electron Devices (TEDs).

Applications of Gunn Diodes

- Radar transmitters
- Transponders in air traffic control
- Industrial telemetry systems
- Power oscillators
- Logic circuits
- Broadband linear amplifier

Avalanche Transit Time Devices

The process of having a delay between voltage and current, in avalanche together with transit time, through the material is said to be Negative resistance. The devices that helps to make a diode exhibit this property are called as Avalanche transit time devices.

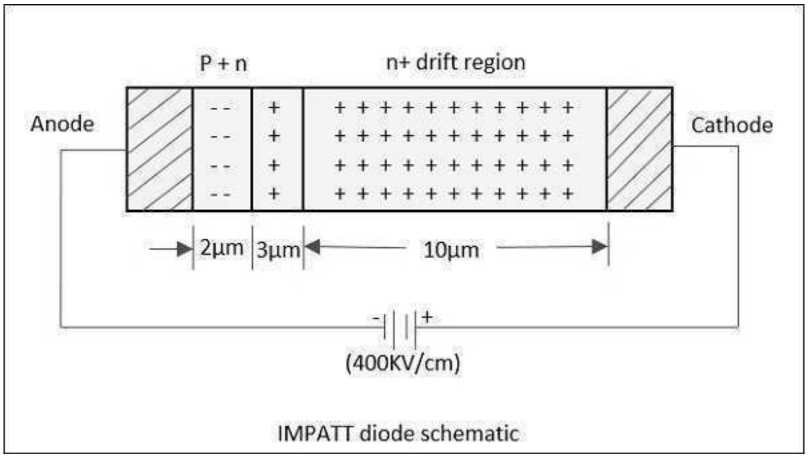
The examples of the devices that come under this category are IMPATT, TRAPATT and BARITT diodes. Let us take a look at each of them, in detail.

IMPATT Diode

This is a high-power semiconductor diode, used in high frequency microwave applications. The full form IMPATT is IMPact ionization Avalanche Transit Time diode.

A voltage gradient when applied to the IMPATT diode, results in a high current. A normal diode will eventually breakdown by this. However, IMPATT diode is developed to withstand all this. A high potential gradient is applied to back bias the diode and hence minority carriers flow across the junction.

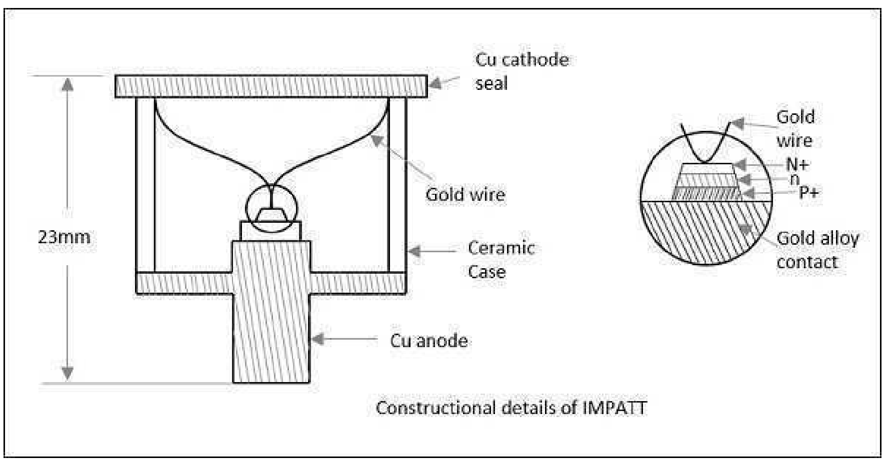
Application of a RF AC voltage if superimposed on a high DC voltage, the increased velocity of holes and electrons results in additional holes and electrons by thrashing them out of the crystal structure by Impact ionization. If the original DC field applied was at the threshold of developing this situation, then it leads to the avalanche current multiplication and this process continues. This can be understood by the following figure.



Impatt Diode Schematic

Due to this effect, the current pulse takes a phase shift of 90°. However, instead of being there, it moves towards cathode due to the reverse bias applied. The time taken for the pulse to reach cathode depends upon the thickness of n+ layer, which is adjusted to make it 90° phase shift. Now, a dynamic RF negative resistance is proved to exist. Hence, IMPATT diode acts both as an oscillator and an amplifier.

The following figure shows the constructional details of an IMPATT diode.



IMPATT

The efficiency of IMPATT diode is represented as

$$\eta=[P_{ac}/P_{dc}]=V_a/V_d[I_a/I_d]$$

Where,

P_{ac} = AC power

P_{dc} = DC power

V_a&I_a = AC voltage & current

V_d&I_d = DC voltage & current

Disadvantages

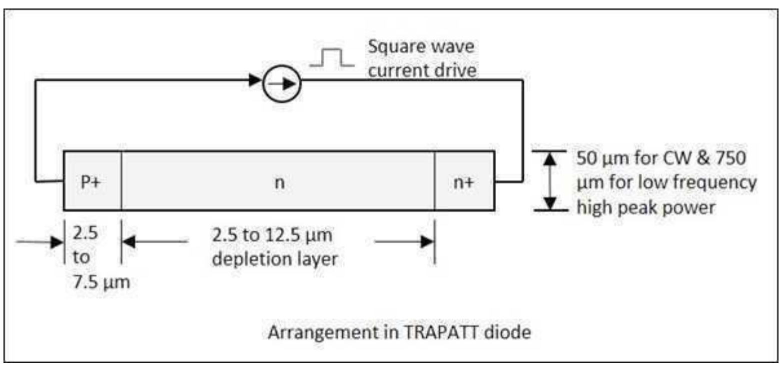
- It is noisy as avalanche is a noisy process
- Tuning range is not as good as in Gunn diodes

Applications

- Microwave oscillator
- Microwave generators
- Modulated output oscillator
- Receiver local oscillator
- Negative resistance amplifications
- Intrusion alarm networks (high Q IMPATT)
- Police radar (high Q IMPATT)
- Low power microwave transmitter (high Q IMPATT)
- FM telecom transmitter (low Q IMPATT)
- CW Doppler radar transmitter (low Q IMPATT)

TRAPATT Diode

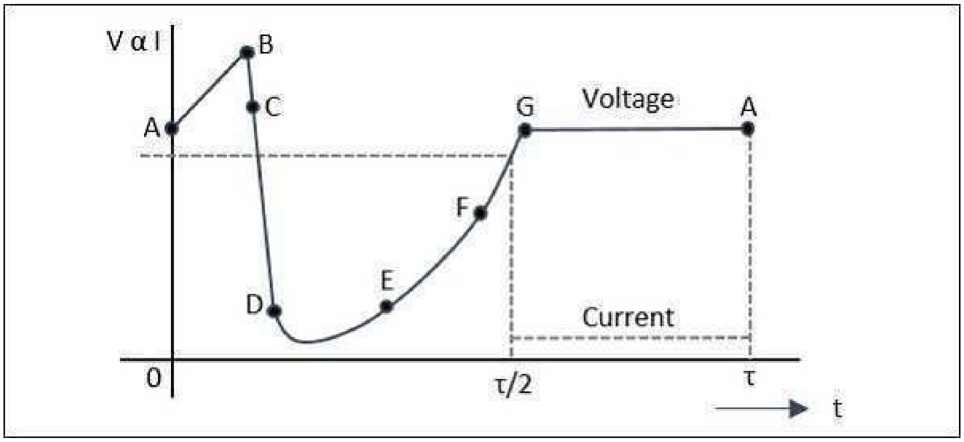
The full form of TRAPATT diode is TRApped Plasma Avalanche Triggered Transit diode. A microwave generator which operates between hundreds of MHz to GHz. These are high peak power diodes usually n+- p-p+ or p+-n-n+ structures with n-type depletion region, width varying from 2.5 to 1.25 Âµm. The following figure depicts this.



TRAPATT Diode

The electrons and holes trapped in low field region behind the zone, are made to fill the depletion region in the diode. This is done by a high field avalanche region which propagates through the diode.

The following figure shows a graph in which AB shows charging, BC shows plasma formation, DE shows plasma extraction, EF shows residual extraction, and FG shows charging.



Depletion Region

Let us see what happens at each of the points.

A: The voltage at point A is not sufficient for the avalanche breakdown to occur. At A, charge carriers due to thermal generation results in charging of the diode like a linear capacitance.

A-B: At this point, the magnitude of the electric field increases. When a sufficient number of carriers are generated, the electric field is depressed throughout the depletion region causing the voltage to decrease from B to C.

C: This charge helps the avalanche to continue and a dense plasma of electrons and holes is created. The field is further depressed so as not to let the electrons or holes out of the depletion layer, and traps the remaining plasma.

D: The voltage decreases at point D. A long time is required to clear the plasma as the total plasma charge is large compared to the charge per unit time in the external current.

E: At point E, the plasma is removed. Residual charges of holes and electrons remain each at one end of the deflection layer.

E to F: The voltage increases as the residual charge is removed.

F: At point F, all the charge generated internally is removed.

F to G: The diode charges like a capacitor.

G: At point G, the diode current comes to zero for half a period. The voltage remains constant as shown in the graph above. This state continues until the current comes back on and the cycle repeats.

The avalanche zone velocity Vs is represented as

$$V_s = dx/dt = J/qN_A$$

Where

J = Current density

q = Electron charge 1.6 x 10-19

N_A = Doping concentration

The avalanche zone will quickly sweep across most of the diode and the transit time of the carriers is represented as

$$\tau_s=LV_s$$

Where

V_s = Saturated carrier drift velocity

L = Length of the specimen

The transit time calculated here is the time between the injection and the collection. The repeated action increases the output to make it an amplifier, whereas a microwave low pass filter connected in shunt with the circuit can make it work as an oscillator.

Applications

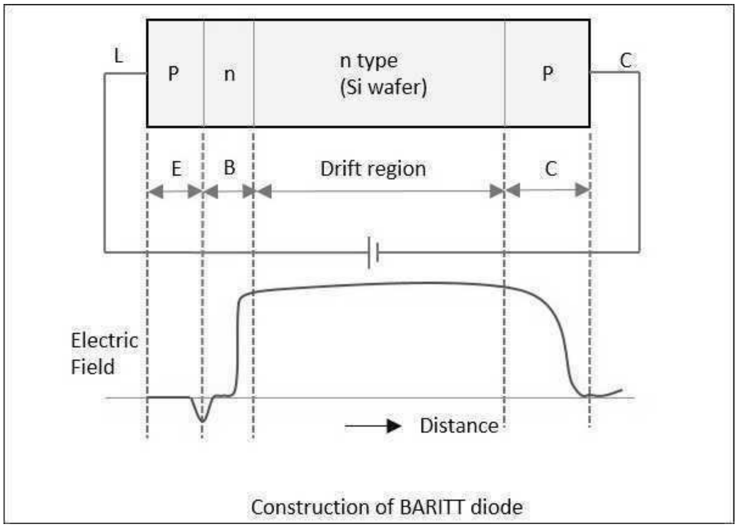
- Low power Doppler radars
- Local oscillator for radars
- Microwave beacon landing system
- Radio altimeter
- Phased array radar, etc.

BARITT Diode

The full form of BARITT Diode is BARrier Injection Transit Time diode. These are the latest invention in this family. Though these diodes have long drift regions like IMPATT diodes, the carrier injection in BARITT diodes is caused by forward biased junctions, but not from the plasma of an avalanche region as in them.

In IMPATT diodes, the carrier injection is quite noisy due to the impact ionization. In BARITT diodes, to avoid the noise, carrier injection is provided by punch through of the depletion region. The negative resistance in a BARITT diode is obtained on account of the drift of the injected holes to the collector end of the diode, made of p-type material.

The following figure shows the constructional details of a BARITT diode.



BARITT Diode

For a m-n-m BARITT diode, Ps-Si Schottky barrier contacts metals with n-type Si wafer in between. A rapid increase in current with applied voltage (above 30v) is due to the thermionic hole injection into the semiconductor.

The critical voltage (V_c) depends on the doping constant (N), length of the semiconductor (L) and the semiconductor dielectric permittivity (ϵ_S) represented as

$$V_c=qN_L^2/2\epsilon_S$$