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A Survey On Small Size Diodes For Microwave And Millimeter Wave Frequency Region

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Abstract*— *This paper attempts to present a collection of microwave and millimetre wave semiconductor diodes. These semiconductor diodes are operates at microwave frequencies and millimetre frequencies. The invention of these semiconductor diodes led to almost complete replacement of vacuum devices which are bulky and large in size. Because of small size a large number of diodes can integrate on a single chip and this arrangement forms very large-scale integrated circuits which led to solid-state replacement on computer switching circuits. This paper surveys characteristics, applications, advantages and disadvantages of microwave and millimetre wave semiconductor devices.

Keywords— **Microwave, millimetre wave, solid state devices, vacuum tube, compound material, Microsemi**

I. INTRODUCTION

Microwave cover the wavelength range 10-1 cm, and millimetre waves cover the wavelength 1 cm-1 mm, corresponding to high frequency electromagnetic oscillation ranging from 3 GHz-300 GHz. These frequencies ranges have significant application in communication. Devices which can generate microwaves and millimetre waves are essential for satellite and line of sight communication for audio and video signals as also for digital data communication. Microwaves are also very useful for radar communication since they can penetrate through cloud and fog [1].

The early generation of microwaves during the II world war was vacuum devices, i.e. Magnetrons, Klystrons and travelling wave tubes. These vacuum devices are depends on the motion of electrons in vacuum for various configurations of electric and magnetic fields. These tubes were heavy and required high voltage for their operation and occupied large space. These solid state microwaves and millimetre wave devices are replaced by semiconductor diodes which are small in size and lighted weighted. Among these devices, pin diode, Gunn diodes, IMPATT diode, TRAPTT diode, Varactor diode and tunnel diodes are most commonly used because of their several advantages. This paper we present characteristics, applications, advantages and disadvantages of these microwave and millimetre wave semiconductor devices [1].

II. TYPES OF DIODE

(A) PIN DIODE:

A PIN diode (p-intrinsic-n) is a semiconductor device that operates as a variable resistor at RF and microwave frequencies. It is used as a microwave power switching, limiting and modulation, in which silicon is widely used because of its power handling capacity and high resistivity in the intrinsic region and easy fabrication .The PIN diode acts a low frequency rectifier that could rectify more power than ordinary p-n junction diode, up to about 100MHz, the operation is similar to an ordinary p-n junction diode. Rectification ceases at higher frequencies due to carrier storage junction and the transit time across the large intrinsic region [2].

A PIN diode is a current controlled device. It can be used for attenuating, leveling, and amplitude demodulating an RF signal when the forward bias control current of the PIN diode is varied continuously. The microwave PIN diode's small physical size compared to a wavelength, low package parasitic reactance and high switching speed, make it an ideal component for use in miniature, broadband RF signal control circuits. Microsemi PIN diodes offer a unique highly reliable package due to void less construction, metallurgical bonded pin structure. Microsemi PIN diodes offer significant electrical and thermal advantages compared to PIN diodes manufactured by other suppliers. The Microsemi has a thicker I-region, longer carrier lifetime and larger cross sectional area for the same basic electrical characteristics of series resistance (R_S), and capacitance (C) [3].

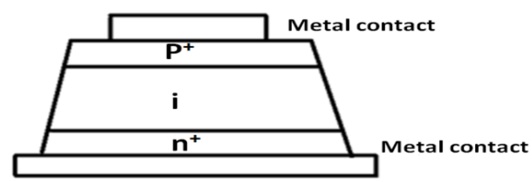


Figure 1: Pin diode

WHY YOU SHOULD USE A PIN DIODE [2-3]:

1. Rugged, High Reliability
2. High Voltage Capability > 2000 Volts
3. High Current Capability > 25 Amperes continuous
4. High surge Current Capability > 500 Amperes
5. Low Distortion < -60dBc @ 455 KHz
6. High Power Gain > 10,000: 1
7. Fast Switching speed < 100 ns
8. Small Physical Size
9. Various Thermal Packaging Available
10. RF Relay Replacement etc.

APPLICATION [2-3]:

1. PIN diode acts as a switch.
2. PIN diode acts as an Amplitude modulator.
3. PIN diode acts as a phase shifter.
4. PIN diode acts as a limiter

(B) VARACTOR DIODE:

Varactor diode simply means “variable reactor diode”. It is also define as voltage variable capacitances of a reversed bias p-n junction. Varactor diode is semiconductor diode that is design to maximize the capacitance variation with applied reverse bias. The capacitance of Varactor diode which is form at junction depends on the applied voltage and the design of the junction. The Varactor diode is designed to exploit the voltage variables properties of the junction capacitances [2].

OPERATIONS:

All the semiconductor junction diodes exhibit a junction capacitance in reverse bias condition. Application of reverse bias increases the width of charge free depletion region of p-n junction in a semiconductor. The surfaces of charge free depletion region represent effective plates of the capacitance of the junction.

If the magnitude of reverse bias voltage is increased, the depletion layer width (w) will increase and the junction capacitance (C_j) will decrease in accordance with

$$C_j \propto \frac{1}{W}$$

A varactor diode is so designed to maximize the capacitance variation with applied reverse bias. In varactor diode, the capacitance is maximum for zero bias and varies inversely with applied reverse bias voltage. The useful reverse voltage swing is between the reverse saturation point (maximum capacitance) and the point just above avalanche (minimum capacitance). Conduction and avalanche are two conditions which limit the voltage swing and hence the capacitance variation operation of varactor diode depends on the types of the junction. The relation between junction capacitance (C_r) and reverse bias voltage (v_r) is given by:

$$C_r \propto v_r^{-n}$$

Where n is a parameter that decides the type of junction. If the junction is abrupt then the capacitance varies a square root of the reverse bias ($C_r \propto v_r^{-1/2}$) i.e. n=1/2, if the junction is linear graded, then n is 1/3 i.e. voltage sensitivity of junction capacitance (C_j) is greater for an abrupt junction than for a liner graded junction, for hyper abrupt junction n>1/2 [2].

In general

$$C_r \propto v_r^{(-1/(m+2))}$$

Where,

For abrupt junction m=0.

For linear graded junction m=1.

For hyper abrupt junction $m=-3/2$

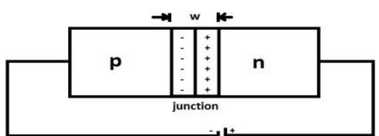


Figure 2 (a): Biasing of Varactor diode

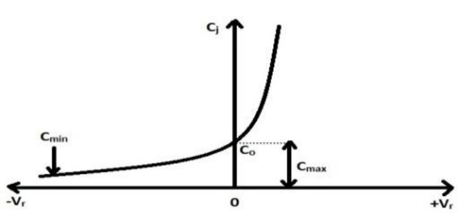


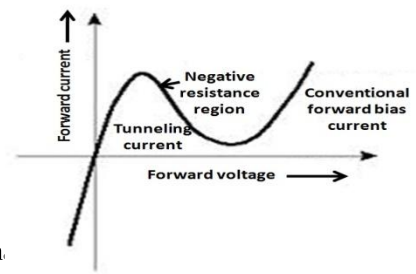
Figure 2 (b): Capacitance variation in Varactor diode with bias

APPLICATION [2]:

1. Frequency multiplication.
2. Parametric Amplifier.
3. Voltage controlled oscillators.
4. Cellular and wireless receivers.
5. In radio and TV.
6. In electronic tuning

(C) TUNNEL DIODE:

Tunnel diode was discovered in 1958. Tunnel diode is also called Esaki Diode because it was discovered by Japnese scientist Esaki. The tunnel diode is a p-n junction which is heavily doped on both sides of junction and there is an abrupt transition from to p-side to n-side. Heavy doping makes width of depletion region becomes very thin and an overlap occurs between the conduction band level on the n-side and the valance band level on the p-side [2].



It is clear th rse direction, the diode responds with a huge current for a very small applied voltage. In forward direction, the current reaches a maximum value equal to I_p (peak current) at a voltage V_p (peak voltage). At this point di/dv is zero, after this, current starts increasing with increase in voltage, at the peak point, the slope of characteristics changes from positive to negative while at the valley point, it changes from negative to positive again. Between these two points the device exhibits negative resistance.

Although Tunnel diode can be made from any semiconductor material, but gallium arsenide and gallium antimonide are mainly prefer because they provide high ion mobalities and high speed operations [2].

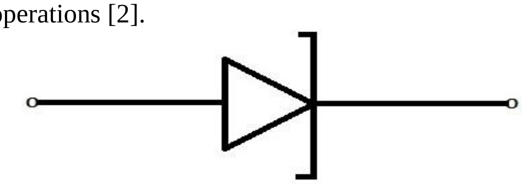


Figure 4: Symbol of Tunnel Diode

OPERATIONS:

Tunnel diode is a negative resistance semiconductor p-n junction diode. In tunnel diode negative resistance is created by the tunnel effect of electron in the p-n junction. The tunnel effect is majority carrier effect. Due to heavy doping of both the p and n regions in Tunnel diode, the depletion-barrier at the junction is very thin (on the order of 100 A^0). But according to Quantum-mechanical theory, if barrier is less than $3A^0$ there is an appreciable probability that particles will tunnel through the potential barrier even though they do not have enough kinetic energy to pass over the same barrier. In addition to the barrier thickness, there must also be filled energy states on the side from which particles will tunnel and allow empty states on the other side into which particles penetrate through at the same energy level [2].

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APPLICATION [1,4]:

1. Tunnel diode oscillators
2. Tunnel-diode Amplifiers
3. Tunnel-diode frequency converters and mixers.
4. Tunnel-diode switch.

ADVANTAGES [2,4]:

1. Tunnel-diode has less weight, high speed, low noise and low cost.
2. Require very simple DC power supply.
3. Low noise figures less than (5dB at 10GHz) due to low current levels.
4. Broadband operation is possible.
5. Immune to the natural radiation in the solar system and suitable for space communication.

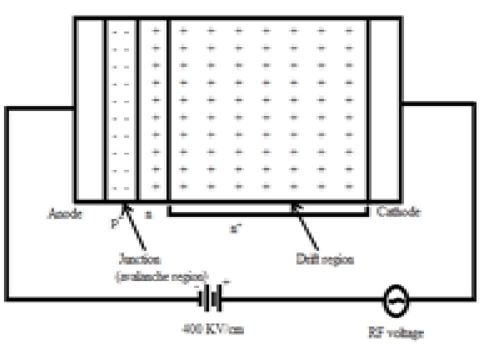
DISADVANTAGES [2]:

1. Tunnel diode has low tunneling current and this means that they are low power device.
2. When tunnel diodes are used in oscillators as further amplification is needed and this can only be undertaken by devices that have a high power capability.
3. Higher production cost.

(D) IMPATT DIODE:

IMPATT diode is an RF semiconductor device that is used for generating microwave radio frequency signal. The reported frequency range of IMPATT oscillators extend from below X-band (6GHz) to the sub-millimeter wave region. The CW (continuous wave) power output from a single device is 12W at 6 GHz [5], 1W at 94 GHz, and 2.2mW at 412 GHz [6]. IMPATT diode is highly suitable device to meet the ever-increasing communication needs of the world due to vast frequency range and high power output [1].

IMPATT is the acronym for Impact Avalanche transit time, which reflects the mechanism of its operation. IMPATT is a p-n junction diode reverse biased to breakdown, in which an avalanche of electron-hole pairs is produced in the high field region of the device depletion layer by impact ionization.



IMPATT DIODE

Microwave oscillations from a simple p^+-n-n^+ silicon diode reverse-biased to break down were first reported in 1965 by Johnston ,deloach and cohen [7] from Bell Laboratories, but the same was earlier predicted by read [8] for a special doping profile (p^+-n-n^+). It was later found that p-n junction of various doping profile based on any semiconductor would give rise to IMPATT oscillations. So far IMPATT oscillation has been observed from Ge, Si, GaAs and InP diodes [1].

Basic Principle of Generation of Microwaves in IMPATT DIODES: Any device which exhibits negative resistance for dc will also exhibit negative resistance for ac, if an alternating voltage is applied current rise when voltage falls, at an ac rate. We may now redefine negative resistance as that property of a device which causes the current through it to be 180^0 out of phase with voltage across it. The point is important here, because this is the only kind of negative resistance exhibited by the IMPATT diode. If we show voltage and current have 180^0 phase difference, then the negative resistance in IMPATT diode is proved. An externally high voltage gradient is applied in reverse bias to the IMPATT diode, of the order of $400KV/cm$, eventually resulting in very high current. A normal diode would very quickly breakdown under these conditions but IMPATT diode is constructed so as to able to withstand such condition repeatedly [1].

Electron and hole velocity has now become so high that these carriers from additional holes and electrons by knocking them out of the crystal structure, by so called “impact ionization”. At the junction the process is continue due to additional carriers, and in now snowballs into an avalanche. If the original dc field was just at the threshold of allowing this situation to develop, and avalanche current multiplication will be take place during entire time. This process takes a time such that the current pulse maximum, at the junction, it occurs at that instant when the RF voltage across the diode is zero and going negative. A 90^0 phase difference between voltage and current has been obtained. The resonant frequency (f) of IMPATT diode is given by [1]

$$f= v_d/2l$$

Where,
v_d=drift velocity.
l=length of drift space

ADVANTAGES [1-2]:

1. High operating range (up to 100 GHz)
2. Above about 20 GHz, the IMPATT diode produces a high CW power output per unit than any other semiconductor device.
3. High efficiency.

DISADVANTAGES [1-2]:

1. IMPATT diode is very noisy because avalanche is noisy process. Noise figure for IMPATT diode being 30 dB are not good as klystron/Gunn diode/TWT amplifier.
2. Tuning range is not good as Gunn diode.

PERFORMANCE CHARACTERISTICS [1-2]:

1. Efficiency=30% (<30% practice) and, 15% for Si and 23% for GaAs.
2. Frequency=1 to 300 GHz.
3. Maximum output power for single diode is 5W in X band 0.5W at 30 GHz.
4. Several diodes combined = 40 W at X band.
5. Pulse power= 4 KW.

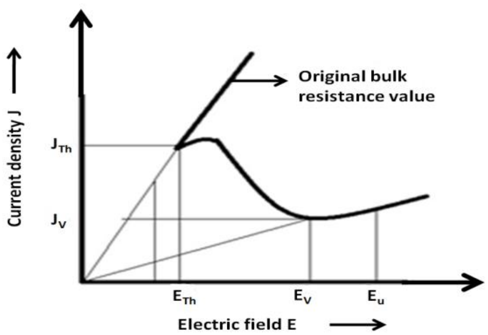
APPLICATION [1-2]:

1. IMPATT diodes are used as microwave generator.
2. Modulated output oscillators.
3. Receiver local oscillator.
4. High Q IMPATTS are used in instruction alarm network, low power microwave transmitter and police radar where as low Q IMPATTS are useful in FM (frequency modulated) telecommunication transmitters CW (continuous wave) Doppler radar transmitter.

(E) GUNN DIODE:

In 1961-62, Ridely, Watkins and Hilsum [9-10] showed a negative differential mobility of electrons some compound semiconductor materials like GaAs, and InP. This phenomenon is caused by the field-induced transfer of conduction band electrons from a low energy, high mobility valley to high energy, and low mobility satellite valley. This phenomenon is known as “Transferred electron effect” or “Ridely-Watkins-Hilsum effect”. The devices based on this effect are called “transferred electron devices” [1].

The first experimental microwave oscillation based on this effect was observed by Gunn [11] in 1963 from an n-type GaAs and so the transferred electron device were named as Gunn devices after his name Later on devices based on InP, GaAsP, CdTe and ZnSe have also exhibited this effect [1].



DOMAIN FORMATION:

A small applied voltage across the Gunn diode creates a uniform electric field, which results in uniform current density throughout the diode. At low voltage the GaAs is ohmic, since the drift velocity of electron is proportional to the electric field. When the applied voltage is more than the threshold voltage the charge densities and the electric field within the samples become non-uniform creating domains, i.e. electrons in some region of the sample will be first to experience the field during inter valley transfer. A high field domain is formed near the cathode that reduces the electric field in rest of the material and causes the current to drop to about two third of its maximum value [1].

MODES OF OPERATION OF GUNN DIODE:

Most of the Gunn diodes have the product of doping (n_0) and drift lengths (L) greater than $10^{12}/cm^2$. But depending on the material parameters are operating conditions, a gunn diode can be made to oscillate in any of the following four frequency modes [1]:

(a) Domain mode or transit time mode
(b) Delayed or inhibited domain mode
(c) Quenched domain mode
(d) Limited space-charge accumulator (LSA) mode

(i) Transit time domain mode ($fL=10^7 cm/sec$):

In this mode the oscillation period is equal to transit time; i.e., $\tau_0 = \tau_t$ and efficiency is below 10. It is a low power, low efficiency mode and does not need any external circuits for its operation.

(ii) Delayed domain mode (10^6 cm/s $<fL< 10^7$ cm/s): In this case the oscillation period is greater than the transit time, i.e., $\tau_0 > \tau_t$. The efficiency of this mode is about 20%. This mode is also called inhibited mode.

(iii) Quenched domain mode ($fL = 10^7$ cm/s): In this mode, instead of transit time frequency, the device oscillates at resonant frequency of the circuit, which is several times the transit time frequency. The threshold efficiency of the oscillation this mode is up to maximum of 13%.

(iv)Limited space-charge accumulation (LSA) mode ($fL> 2 \times 10^7$ cm/s): The device operates in LSA mode with an efficiency of 20%. Here the oscillation period (τ_0) is very few time of the dielectric relaxation time (τ_d).

TYPICAL CHARACTERISTICS [1]:

A typical biased voltage of 10-12 V with a bias current 300mA gives the power output of 100 mW in the X-band.

Typical frequency range: 4 to 94 GHz
Efficiency : 10-20%
CW Power output : 250 mW at 15 GHz
Pulsed power : 5W at 12 GHz

APPLICATION OF GUNN DIODE [1-2]:

1. High power Gunn diodes are used in CW Doppler radar.
2. Used as low and medium power oscillator in microwave receivers.
3. Broad band linear amplifiers.
4. Fast combinational and sequential and logical circuits.
5. It can be used as a pump source for most of the parametric amplifiers because of its low noise figure.

DISADVANTAGES OF GUNN DIODE [1-2]:

1. Gunn diode is very much temperature dependent i.e., a frequency shift of 0.5 to 3 MHz per degree centigrade.
2. Power output is limited by the difficulty of heat dissipation from small chip.

(F) TRAPATT DIODE:

It is derived from IMPATT diode and is closely related to it. It is also a high efficiency microwave generator its operating frequency range is several hundred MHz to several GHz [2].

The TRAPATT (Trapped Plasma Avalanche Triggered Transit) diodes are manufactured from Si or GaAs, and have p^{+}-n-n^{+} (or n^{+}-p-p^{+}) configuration. The p-n junction is reverse biased beyond the breakdown region, so that the current density is higher. This causes electric field in the space charge region to be decreased and the current transit time is increased. Consequently the frequency of operation becomes lower and is limited to below 10 GHz, although efficiency of diode increased due to low power dissipation [1].

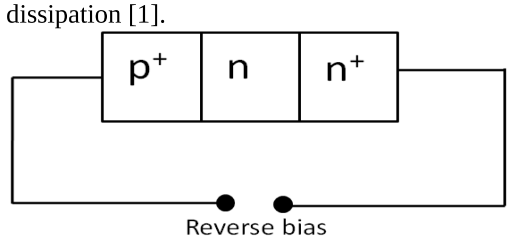


Figure 6: Structure of TRAPATT diode

APPLICATIONS [2]:

1. TRAPATT diodes are mainly used in low power Doppler radars, as oscillators for radars, radio altimeter and phase array radars etc.

SPECIFICATION [1-2]:

1. CW powers: 1-3 W between 8GHz to 0.5GHz.
2. Pulse power: 1.2kW at 1.1GHz.

3. Operating voltage: 60 to 150V.
4. Efficiency: 15 to 40% (8 GHz-0.5 GHz).
5. Noise figure: > 30dB.
6. Frequency: 3 to 50 GHz.

ADVANTAGES [1-2]:

1. Low power dissipation.
2. Capable of operating at much large pulse powers.

DISADVANTAGES [1-2]:

1. High noise figure (60dB).
2. Operating frequency is limited (below 10 GHz).
3. Due to the short duration current pulse, it generates strong harmonics.

III. CONCLUSION

In this paper we summaries various types of diodes which are used at microwave and millimetre wave frequencies. PIN diode is most commonly used for the detection of microwave and millimetre wave frequency over p-n diode because of its various advantages. Varactor diode is very useful for frequency multiplication. Tunnel diode is also very famous because of its tunneling effect. Gunn diode is most commonly used in CW radar. IMPATT and TRAPATT diode are used because of their higher efficiency. In this paper we do a comparative study of all diodes and we understand that these diodes are very useful for communication at higher frequency.

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