UNIT-VII

MICROWAVE SOLID STATE DEVICES

Introduction

Even though in the earlier stages of development of microwave technology, it was the tubes that played a key role, in later stages it is the semiconductor or solid state source that took the lead. The development of semiconductor technology in general helped in fabricating low voltage operated and miniaturized solid state sources at a low cost. With the advent of microwave solid state devices, the microwave applications in the area of consumer electronics rapidly expanded.

The solid state sources are claimed of the advantages of longer life, requiring low voltages, easy control of amplitude of the transmitted wave form, wider bandwidths, low production costs and air cooling.

In this chapter, the basic principles of functioning of Gunn diodes are first explained. Different modes of operation and theories explaining their behavior are then discussed. IMPATT and TRAPATT diodes are used to design microwave amplifiers and oscillators. Their function and design aspects are then explained. Tunnel diodes, varactor diodes are introduced and the theory of their functioning is illustrated parametric amplifies and tunnel diode amplifiers are then discussed. The chapter is concluded with a discussion on detector diodes.

GUNN DIODES

Gunn oscillators and amplifiers are most important microwave devices that have been extensively used as a local oscillators and power amplifiers covering the frequency range of 1 to 100 GHz in which Gunn diode is a critical part. Gunn diode is an n-type semi-conductor slab of one of the compounds, namely Ga As (Figure 7.1), InP, InAs, InSb and CdTd. This diode exhibits dynamic negative resistances when it is biased to a potential gradient more than a certain value known as threshold field Eth due to the phenomenon known as Gunn Effect or Transferred Electron Effect (TEE).

The importance of the Gunn diode lies in its dynamic negative resistance characteristic [Figure 7.2]. In any n-type semiconductor, the following relations govern current, field and drift velocity.

$v_d = \mu E$ $\qquad\qquad$ $d\,v_d / dE = \mu$

and $J = nq\,\mu E$ $\qquad\qquad$ $\therefore\ d\,J / dE = nq\mu$

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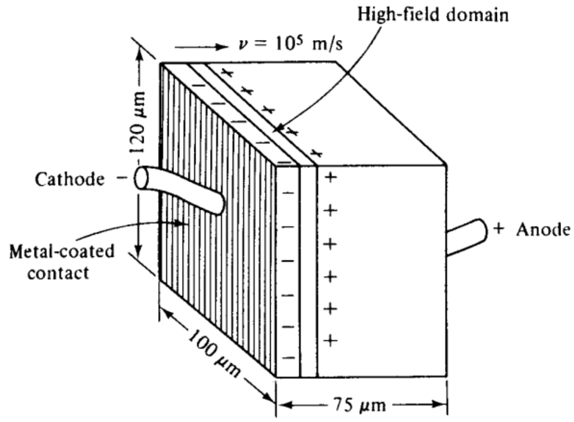

Fig 7.1: Structure of Ga As Gunn diode

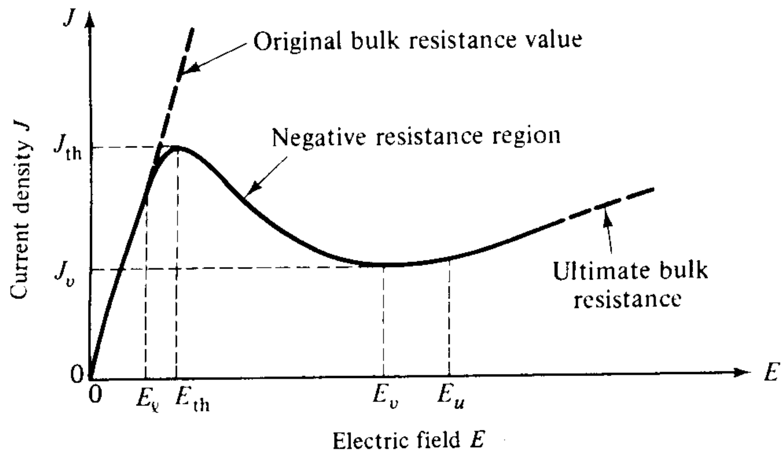

Fig 7.2: Variation of current density with electric field

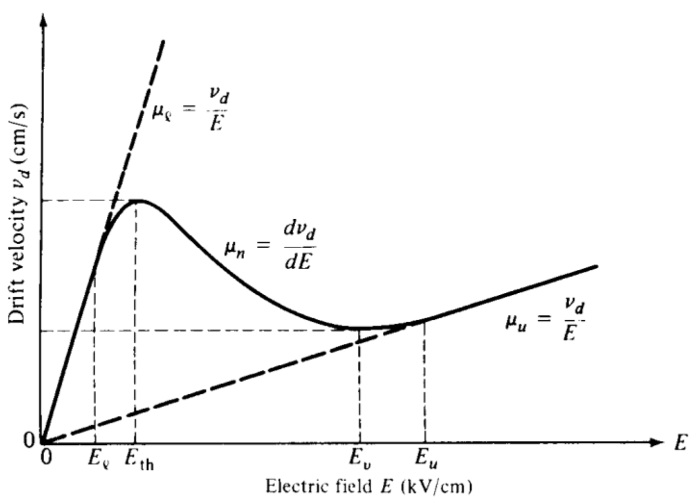

Fig 7.3: Variation of drift velocity with electric field

In Gunn diodes, which are also n-type semiconductors,

- When the field is less than the certain value, called threshold value E_{th}, increase in the field intensity E causes the v_d to increase resulting in the positive mobility μ. Hence, an increase in the E causes I to increase resulting in positive resistance.

- When the field is in between threshold value E_{th} and valley value E_v increase in the field E causes the v_d to decrease due to the onset of TEE resulting the negative mobility μ. Hence an increase in the field the E causes J to decrease resulting in the manifestation of differential negative resistance. When the field is more than E_v increase in field E causes v_d to increase resulting in the positive mobility μ due to the disappearance of the TEE. Hence, an increase in the E causes I to increase resulting in positive resistance.

- The threshold field values are **GaAs-3.3 kV/cm**, InP-10.53 kV/cm, InAs-1.63 kV/cm, lnSb-0.63 kV/cm, CdTd-13.03 kV/cm.

The TEE is actually 'a field induced transfer of conduction band electrons from a high mobility lower energy satellite valley to low mobility higher energy satellite valley'. The salient features of this phenomenon are as follows:

- It is a bulk material property, i.e. it takes place at each and every point in the body of the material.
- Due to this effect the mobility of the electrons in the diode exhibits negative resistance property.

Certain important points pertaining to Gunn diodes worth noting are mentioned below.

- The electrons drift through the diode with velocities depending upon the field intensity and it is maximum when the diode is biased to threshold value [Figure 7.3].
- Peak drift velocities in various diodes are GaAs-2.2, InP-2.5, InAs-3.6, InSb-5.0 and CdTd-1.5 times 10^7 cm/s.
- Noise in these diodes is of two types, one is AM noise normally small, due to amplitude variations and the other one FM noise which is due to frequency deviations.
- The upper frequency of the transferred electron devices (TEDs) is limited to 150 GHz mainly due to the 'finite response time'.

The output power is inversely proportional to the square of the frequency, i.e.

$$p_{out} \propto \frac{1}{f^2} \qquad (7.1)$$

- Gunn oscillators and amplifiers are being widely used as local oscillators and power amplifiers covering 1 to 100 GHz range.

Gunn Domains

The transfer to lower mobility valley starts with the electrons located in a small region, where the field intensity is more due to lower carrier concentration. These regions are called *high field domains.* The domains travel to anode shifting all the electrons in their path to lower mobility valley. The velocity of domains is slightly more than the drift velocity of electrons.

Salient features of gunn domains are:

- Domains start to form whenever the electric field in a region of the sample increases above the threshold value and after formation they drift with the stream through the device.

- If additional voltage is applied to the diode with a domain, the domain will increase in size and absorb more voltage than was added and the current will decrease.

- The domain disappears after reaching the anode or in the mid- way if the field drops to a value less than sustain field value E_x.

- Decreasing the field slightly lower than the threshold value can prevent the formation of new domain.

- The domain modulates the current through the device as the domain passes the regions of different doping and cross sectional areas.

- The domain length is inversely proportional to the doping concentration.

Two Valley Model Theory

Two valley model theory is one of the several theories put forth to explain the manifestation of negative resistance in Gunn diodes. The salient features of this theory are as follows:

- It has been proposed by Kroemer to explain the manifestation of negative resistance in certain types of bulk semiconductor materials.
- In the conduction band of n-type GaAs, a high mobility lower valley is separated from a low mobility upper valley by an energy difference of 0.36 eV.
- The effective mass and mobility of the electrons in lower valley are 0.068 and 8000 cm^2/V s whereas these quantities are 1.2 and 180 cm^2/V s in the upper valley of n-type GaAs (Table 7.1).
- Under equilibrium conditions the electron densities in both the valleys remain same.
- When the applied field is lower than the field corresponding to the energies of the electrons in the lower valley, then no transfer of electrons takes place from one to other valley. The mobility of the carriers is positive.
- When the applied field is higher than the field corresponding to the energies of the electrons in the lower valley and lower than the field corresponding to the energies of the electrons in the upper valley, then transfer of electrons takes place from high mobility lower to low mobility upper valley. The mobility of the carriers becomes negative (Figure 7.4).
- When the applied field is higher than the field corresponding to the energies of the electrons in the higher valley, then no transfer of electrons takes place because by that time all the electrons of the lower valley must have been transferred to the upper valley. The mobility of the carriers is positive.

TABLE 7.1 Data for two valley semiconductors

Semiconductor	Gap energy (at 300 K) E_z(eV)	Separation energy between two valleys ΔE(eV)	Threshold field E_{th}(kV/cm)	Peak velocity v_p(10^7 cm/s)
Ge	0.80	**0.18**	2.3	1.4
GaAs	1.43	**0.36**	5.2	2.2
InP	1.33	**0.60, 0.80**	10.5	2.5
CdTe	1.44	**0.51**	13.0	1.5
InAs	0.33	**1.28**	1.60	5.6

InSb	0.16	**0.41**	0.6	5.0

Note: InP is a three valley semiconductor 0.60 eV is the separation energy between the middle and lower valleys. 0.8 eV that between the upper and lower valleys

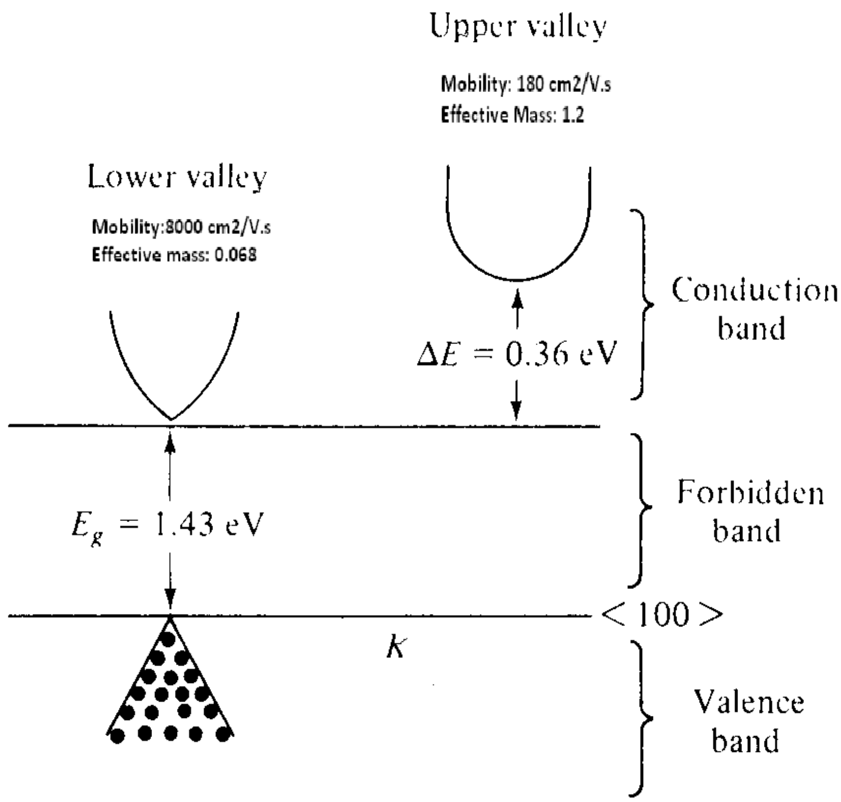

Fig7.4: Two valley model of n-type Ga As

8.1.3 RWH Theory

Ridley, Watkins and Hilsum (RWH) proposed this theory to explain the phenomenon of Negative Differential Resistance (NDR) in certain bulk materials. Its salient features are as follows:

- Bulk NDR devices are classified into two groups. One voltage controlled NDRs and second current controlled NDRs.
- The characteristic relation between electric field *E* and the current density *J* of voltage controlled NDRs is *N* shaped and that of the current controlled NDRs is *S* shaped (Figure 7.5).

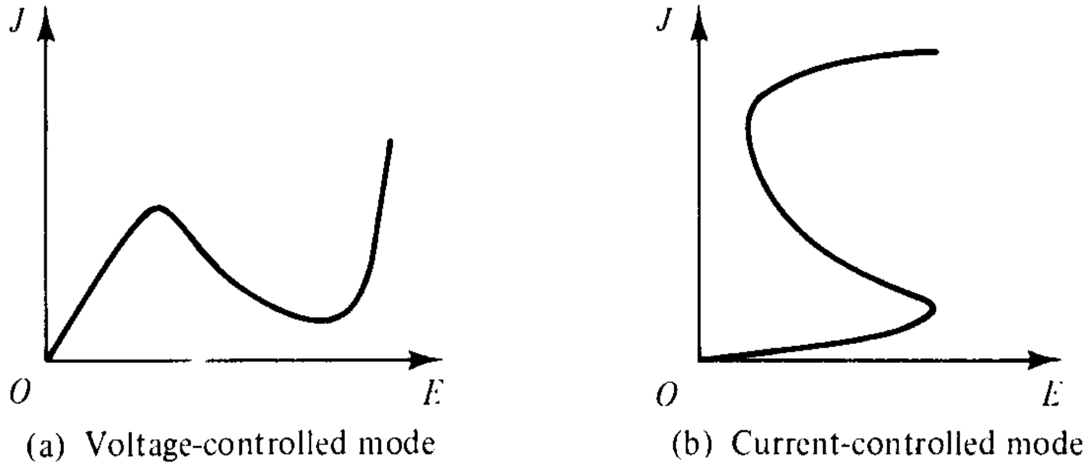

Fig 7.5:Diagram of negative resistance

- The electric field is multi-valued in the case of voltage controlled NDRs and it is electric current that is multi-valued in case of current controlled NDRs.
- The differential resistivity increases with field in case of voltage controlled NDRs and decreases in case of current controlled NDRs.
- A semiconductor exhibiting bulk NDR is inherently unstable because a momentary space charge, which might have been created due to random fluctuation in the carrier density, grows exponentially with time because the relaxation time is negative.
- Because of NDR, the initially homogeneous semiconductor becomes heterogeneous to achieve stability. It results in 'High field domains' in voltage controlled NDRs and 'High current filaments' in current controlled NDRs (Figure 7.6).

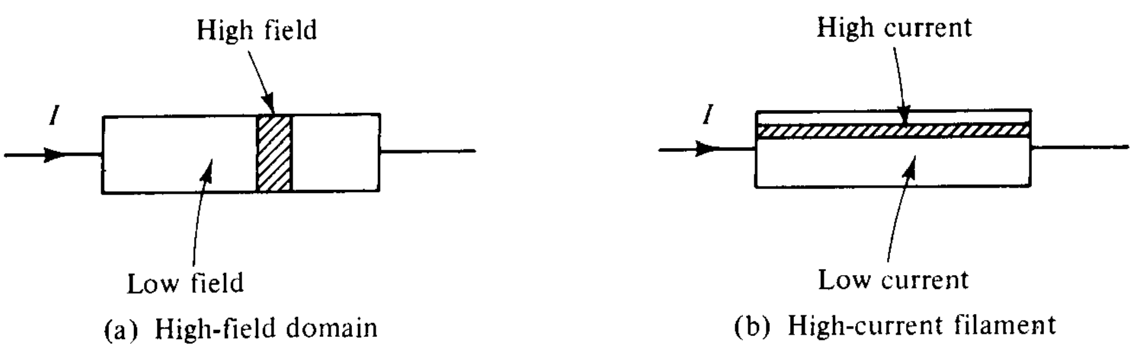

Fig 7.6: Diagrams of high field domain and high current filament

- The high field domain starts forming at a region, where the field intensity is higher extending further perpendicular to the direction of current flow separating two low field regions.

- The high current filament starts forming at a region where the field intensity is higher extending further along the direction of the current flow separating two low current regions.

- The RWH theory explained the phenomenon of negative resistance and gave the necessary conditions to be satisfied by the semiconductors with the help of energy band theory. It said, for any semiconductor to exhibit negative resistance

- The conduction electrons must exist in semiconductors at different energy levels or valleys.

- The separation energy between the lower valley and the upper valley must be several times larger than the thermal energy (about 0.026 eV) of the electrons at room temperatures.

- The separation energy between the valleys must be smaller than forbidden energy gap between the conduction band and valence band.

- Electrons in the lower valley must have high mobility, small effective mass and low density of state whereas those in the upper valley must have low mobility, large effective mass and high density of state.

- The semiconductors Si and Ge do not meet these criteria and hence they cannot exhibit dynamic negative resistance.

Gunn modes of operation

Major factors that determine the modes of operation are the following:

1. Concentration and uniformity of the doping
2. Length of the active region
3. Operating bias voltage
4. Cathode contact property
5. Type of the external circuit used.

- The important criterion for classifying the modes of operation for the gunn effect diodes is

$$nL > \frac{\varepsilon \ v}{e \, | \, \mu_n \, |}$$

For *n*-type GaAs $\varepsilon v / e|\mu_n|$ **≈ 10^{12} cm^{-2}**.

Where

V = electron drift velocity

μ_n = Negative electron mobility

$\epsilon = \epsilon_o \, \epsilon_r$

Hence an important boundary separating the various modes of operation is

$\boldsymbol{nL = 10^{12}\ cm^{-2}}$.

- The TEDs with nL products less than 10^{12} cm^{-2} exhibit a stable field distribution.(n= electron density, L = drift region length)

Ever since Gunn announced his observations of microwave oscillations in the n-type GaAs and n-type InP diodes in 1963, various modes of operation have been developed depending on the material parameters and operating conditions.

Copeland proposed four basic modes of operation in uniformly doped bulk diodes with low resistance contacts, namely,

1. **Gunn oscillation mode,**
2. **Limited space charge accumulation mode,**
3. **Stable amplification mode**
4. **Bias circuit oscillation mode.**

1. Gunn oscillation mode:

$$\left(\frac{nL > 10^{12} cm^{-2}}{fL \cong 2\times 10^{7} cm/s} \right)$$

This mode is operated with the field more than the threshold value, i.e. $E > E_{th}$.

- The high field domain drifts along the specimen until it reaches anode or low field value drops to below the sustaining field value, i.e. $E < E_{sus}$.

- The frequency of oscillation is given by $f = v_{dom}/L_{eff}$, where v_{dom} is the velocity of the domain and L_{eff} is the effective length the domain travels before a new domain gets nucleated.

The gunn oscillation mode has three sub-modes namely.

a) Transit time domain mode,
b) Delayed domain mode and
c) Quenched domain mode.

The salient features of these modes are explained below.

(a) Transit-time domain mode: [$fL = 10^7$ cm/s]

- The high field domains are stable in the sense that they propagate with a particular velocity but do not change in any way with time.
- When the high field domain reaches the anode, the current in the external circuit increases.

The frequency of the current oscillations depends on among other things, the velocity of the domain across the sample. If the velocity increases, the frequency increases and vice versa. It also depends upon the bias voltage. The shape of the domains in GaAs and InP TEDs is triangular. In this mode the oscillation period is transit time. The efficiency is below 10%. It is illustrated in Figure 7.7.

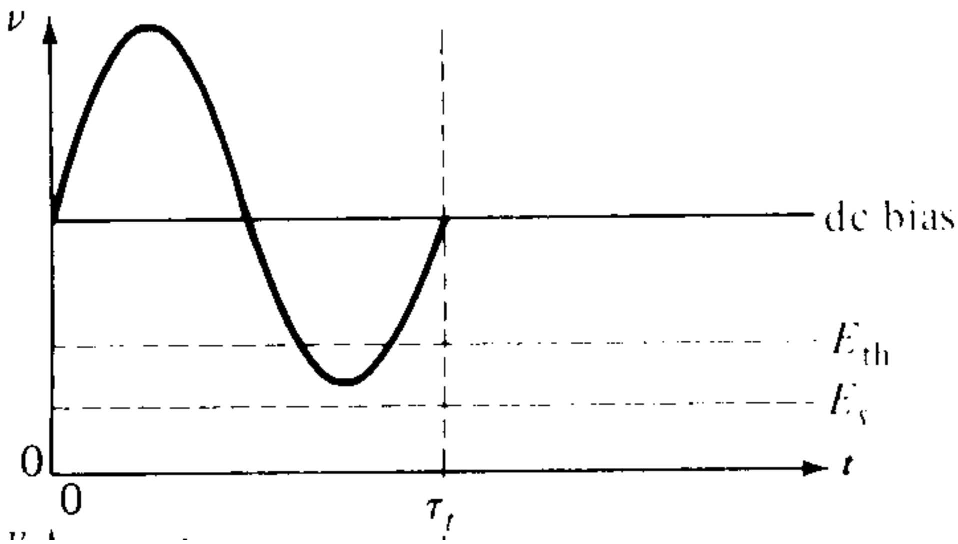

Fig 7.7: Transit Time domain mode

(b) **Delayed domain mode:** [10^6 cm/s < *fL* < 10^7 cm/s]

In this mode the domain is collected by the anode when $E < E_{th}$ and the new domain formation gets delayed until the rise of the field to above threshold.

- The oscillation period is greater than the transit time as shown in Figure 7.8.

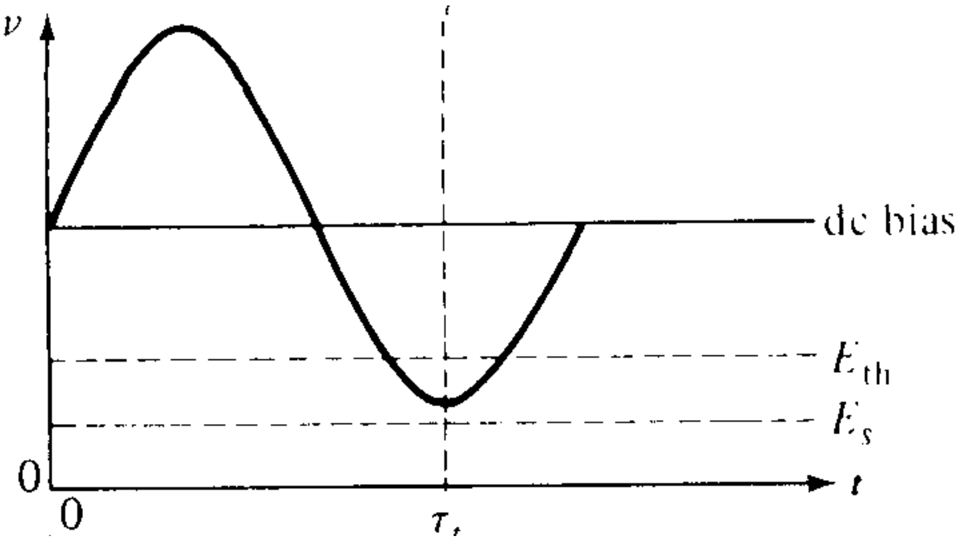

Fig 7.8: Delayed domain mode

- The oscillations occur at the frequency of the resonant circuit which is tuned to a value below that of the gunn mode. The dipole domain will arrive at the anode will in time but the formation of a new dipole domain will be delayed until the oscillation voltage increases above the threshold value.
- The efficiency of this mode is about 20%.

(c) **Quenched domain mode:** **[**$fL > 2 \times 10^7$ cm/s]

- While the domain is travelling, the bias field drops to a value less than E_s. E_{sus} during negative half cycle quenching the domain. A new one cannot form until the field again rises above the E_{th}.
- Oscillations occur at the frequency of the resonant circuit rather than the transit time frequency. The resonant circuit is tuned to a value slightly above that of the TT mode, the dipole domain will be quenched before it arrives at the above by the negative swing of the oscillation voltage but the Gunn diode will operate mostly like Gunn mode.
- The operating frequencies are higher than the transit time frequency as shown in Figure 7.9.
- Formation of multiple high field layers takes place.
- The upper frequency limit for this mode is determined by the speed of quenching.

  In this mode the efficiency is about 13%.
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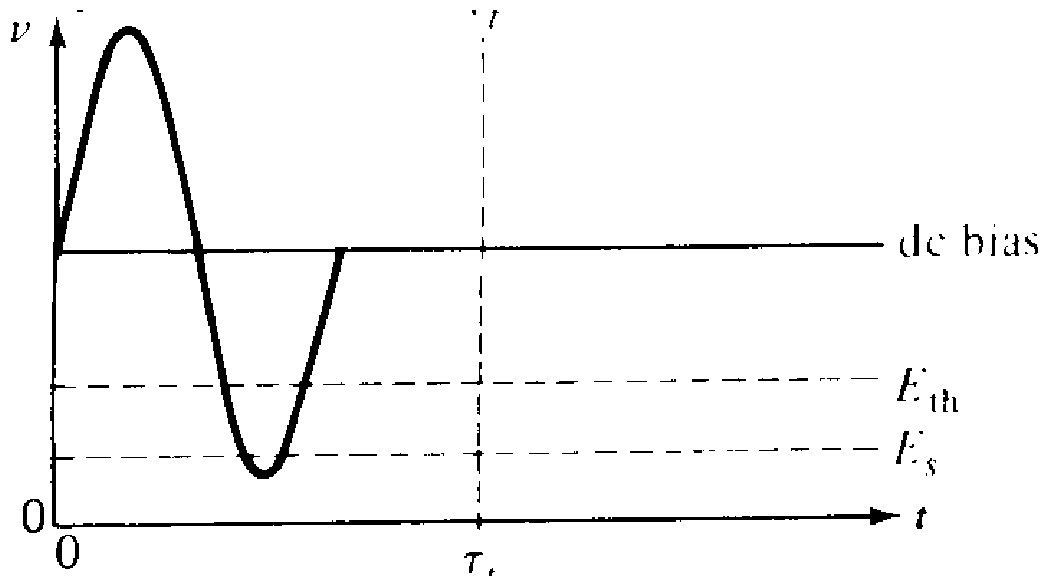

Fig 7.9: Quenched mode

2. Limited Space charge Accumulation LSA) $\left(\dfrac{nL \cong 10^{12} cm^{-2}}{fL > 2 \times 10^{7} cm/s} \right)$ **mode:**

- The coefficient of doping divided by frequency *(n / f)* should be in between 2×10^4 and 2×10^5.
- This is the simplest mode of operation and it consists of uniformly doped semiconductor without any internal space charge.
- As the frequency is high the domains do not get sufficient time to form as shown in Figure 7.10.
- Most of the domains find themselves in the negative conduction state during a large fraction of voltage cycle.
- A large portion of the device exhibits a uniform field resulting in efficient power generation at the circuit controlled frequency.
- This mode is suitable to generate short pulses of high peak power. LSA mode of operation can produced several watts of power with minimum efficiencies of 20%. The power output decreases with frequency, viz 1 W at 10 GHz and several mW at 100 GHz.
- Its maximum operating frequency is much lower than that of the TT devices.
- Its limitations are sensitivity to load conditions, temperature and doping fluctuations.

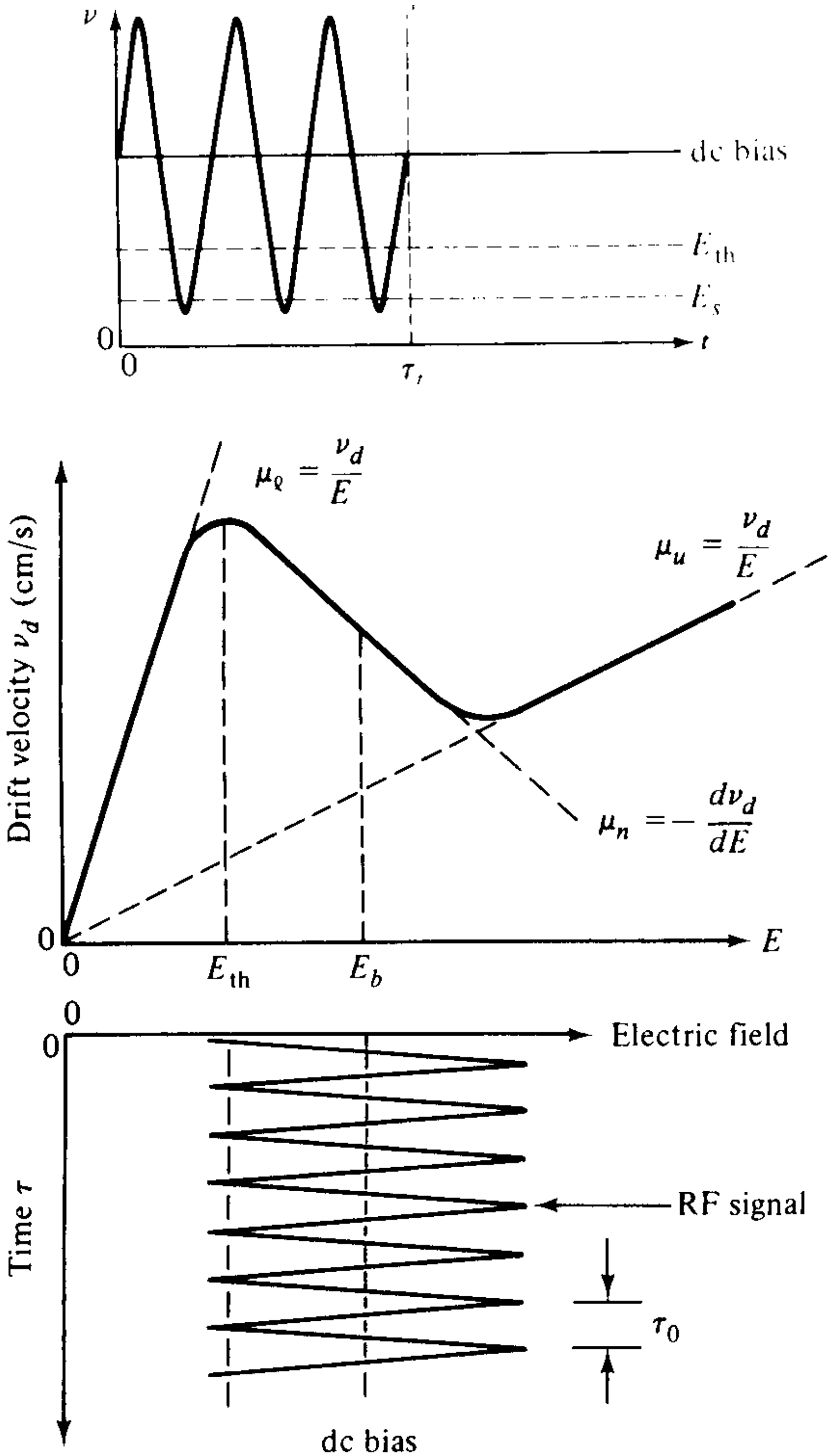

Fig 7.10: LSA mode

3. Stable amplification $\left(\dfrac{nL = 10^{11}\ to\ 10^{12} cm^{-2}}{fL = 10^{7} cm/s}\right)$ **mode:**

- In this mode the devices exhibit stable amplification at the transit time frequency.
- Negative conductance is utilized to prevent the formation of the domains.
- There exists three regions of amplification depending on the product *fL* range from 10^7 to 0.5 x 10^8.

4. Bias circuit oscillation $\left(\dfrac{nL \geq 10^{12} cm^{-2}}{fLsmall}\right)$ **mode:**

- This mode occurs when there is either Gunn or LSA oscillation and *fL* is small or less that about 10-12/cm2. The device exhibits amplification at the transit time frequency rather than spontaneous oscillation. This situation occurs because the negative conductance is utilized without domain formation. Therefore amplification of signals near the transit time frequency can be accomplished.
- When the diode is biased to threshold Gunn oscillation begin leading to sudden decrease in the average current of the circuit driving it to oscillations.

Table 7.2

Mode	nL	fL
1. Gunn oscillation mode:	$nL > 10^{12} cm^{-2}$	$fL \cong 2 \times 10^{7} cm/s$
(a) Transit-time domain mode:		[*fL* = 10^7 cm/s]
(b) Delayed domain mode:		[10^6 cm/s < *fL* < 10^7 cm/s]
(c) Quenched domain mode:		**[***fL* > *2* x 10^7 cm/s]
2. Limited Space charge Accumulation (LSA) **mode:**	$nL \cong 10^{12} cm^{-2}$	$fL > 2 \times 10^{7} cm/s$
3. Stable amplification mode:	$nL = 10^{11}\ to\ 10^{12} cm^{-2}$	$fL = 10^{7} cm/s$
4. Bias circuit oscillation mode:	$nL \geq 10^{12} cm^{-2}$	$fLsmall$

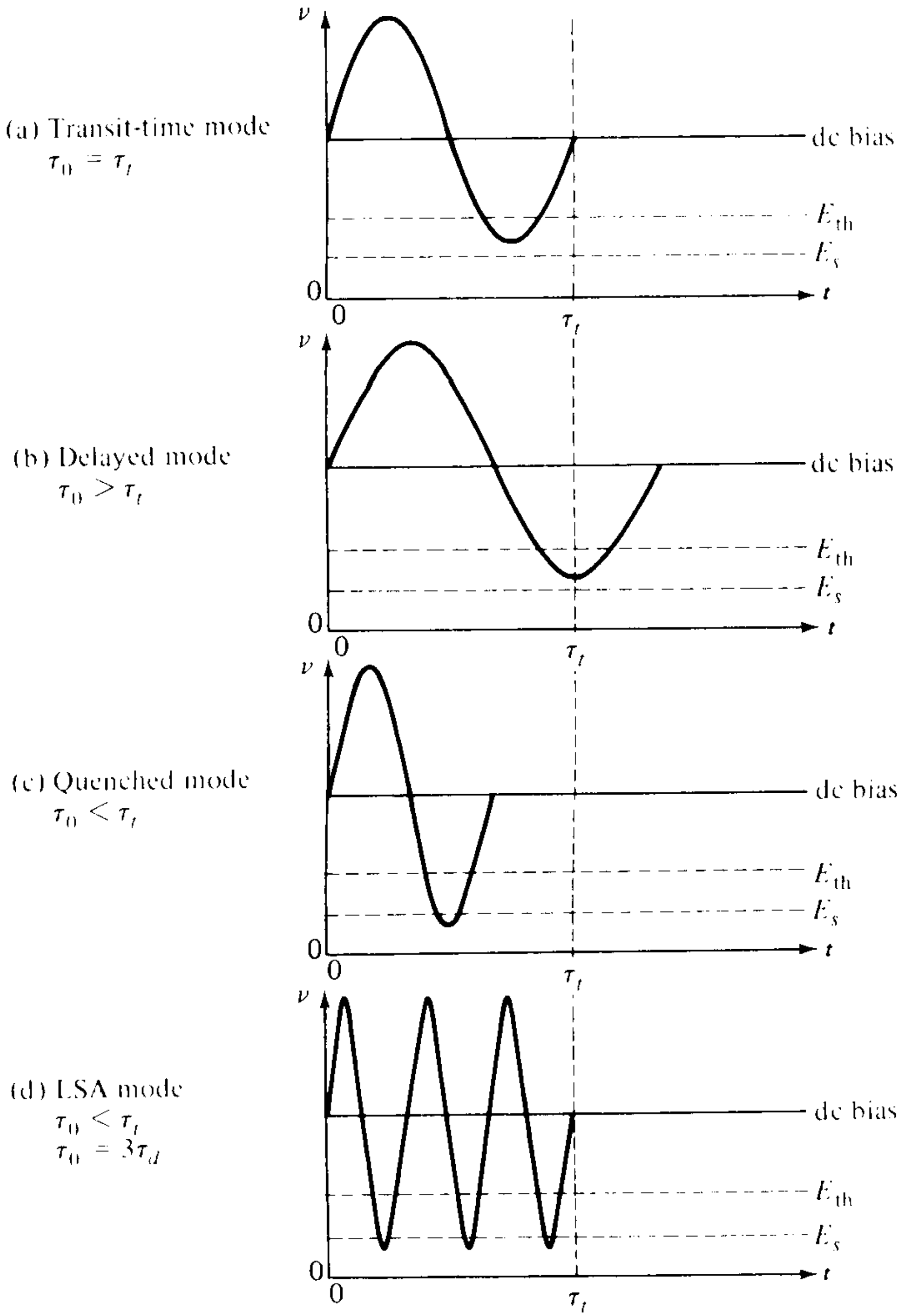

Fig 7.11: Comparision of waveforms in differenct gunn modes

Gunn Amplifiers

Two types of Gunn amplifiers are possible, one is stable amplifier and the other one is travelling domain amplifier.

It has been observed when an RF signal is applied to a Gunn oscillator, amplification of the signal takes place provided the signal frequency is low enough, where the sample impedance has negative real part that can be utilized for amplification. A diode with the product n_0L is smaller than $10^{l2}/cm^2$ can exhibit non uniform stable field distribution with respect to time and space and it can amplify signals in which are near to the transit time frequency or its harmonics. It is called *stable amplifier* and the power output of the stable amplifier is quite low.

Another type of amplifier called *travelling domain amplifier* is also possible with Gunn diodes. In this mode of operation, n_0L is larger than $10^{12}/cm^2$ and amplification takes place at a frequency other than transit time frequency.

The basic configuration of almost all the amplifiers consists of a broadband circuit at the signal frequency and a short circuit at Gunn oscillation frequency. For the sake of stability at signal frequency, the Gunn diode must see source admittance whose real part is larger than the negative conductance of the diode. A typical amplifier circuit is shown in Figure 7.12 which exhibits an average gain of 3 dB between 5.5 and 6.5 GHz.

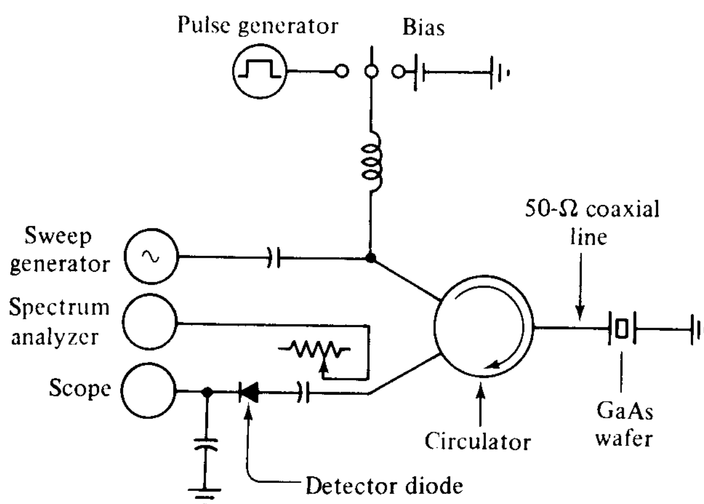

Fig 7.12: Gunn diode amplifier circuit

AVALANCHE TANSIT TIME DEVICES

Avalanche transit time devices are p-n junction diodes with the highly doped p and n regions. They could produced a negative resistance at microwave frequencies by using a carrier impact ionization avalanche breakdown and carriers drift in the high filed intensity region under reverse biased conditions. There are three types of these devices

1. Impact Ionization Avalanche Transit Time effect (IMPATT)
2. Trapped Plasma Avalanche Triggered Transit effect (TRAPATT)
3. Barrier Injected transit Time effect (BARITT)

IMPATT DIODE

The IMPATT diode is now one of the most powerful solid state sources for the generation of microwaves. It can generate higher CW power outputs in millimetre wave frequencies, i.e. above 30 GHz of all solid state devices. These are compact, inexpensive, moderately efficient and with improved device fabrication technology these diodes also have become reliable under high temperature operation. The salient features of this diode are as follows:

- IMPATT stands for TMPact ionization Avalanche Transit Time'.
- IMPATT diodes employ 'Impact ionization' and 'Transit time' properties of semi-conductor structures to get negative resistance at microwave frequencies.
- **Impact ionization or Avalanche multiplication:** It is a process related to semiconductors in which the generation and multiplication of hole-electron pair takes place due to knocking off the valence electrons into conduction band by the highly energetic carriers when the electric field is increased above certain value'. The rate of pair production is a sensitive non-linear function of field.
- The negative resistance occurs from the delay, which cause the current to lag behind the voltage by half cycle time, have two components:
    - One is *avalanche time delay* caused by 'finite buildup time of the avalanche current.'
    - Other is *transit time delay* by the finite time for the carriers to cross the drift region.
- These diodes are made from GaAs, Ge, Si.
- Extremely high voltage gradient 400 kV/cm back biasing the diode is required for its operation.
- In all the structures there exists two regions (Figure 7.13)
    - *Avalanche region:* In this region avalanche multiplication takes, doping

concentration and field intensity are high.

- *Drift region:* In this region avalanche multiplication does not take place, doping concentration and field levels are low.

Depletion region is Avalanche Region plus Drift Region.

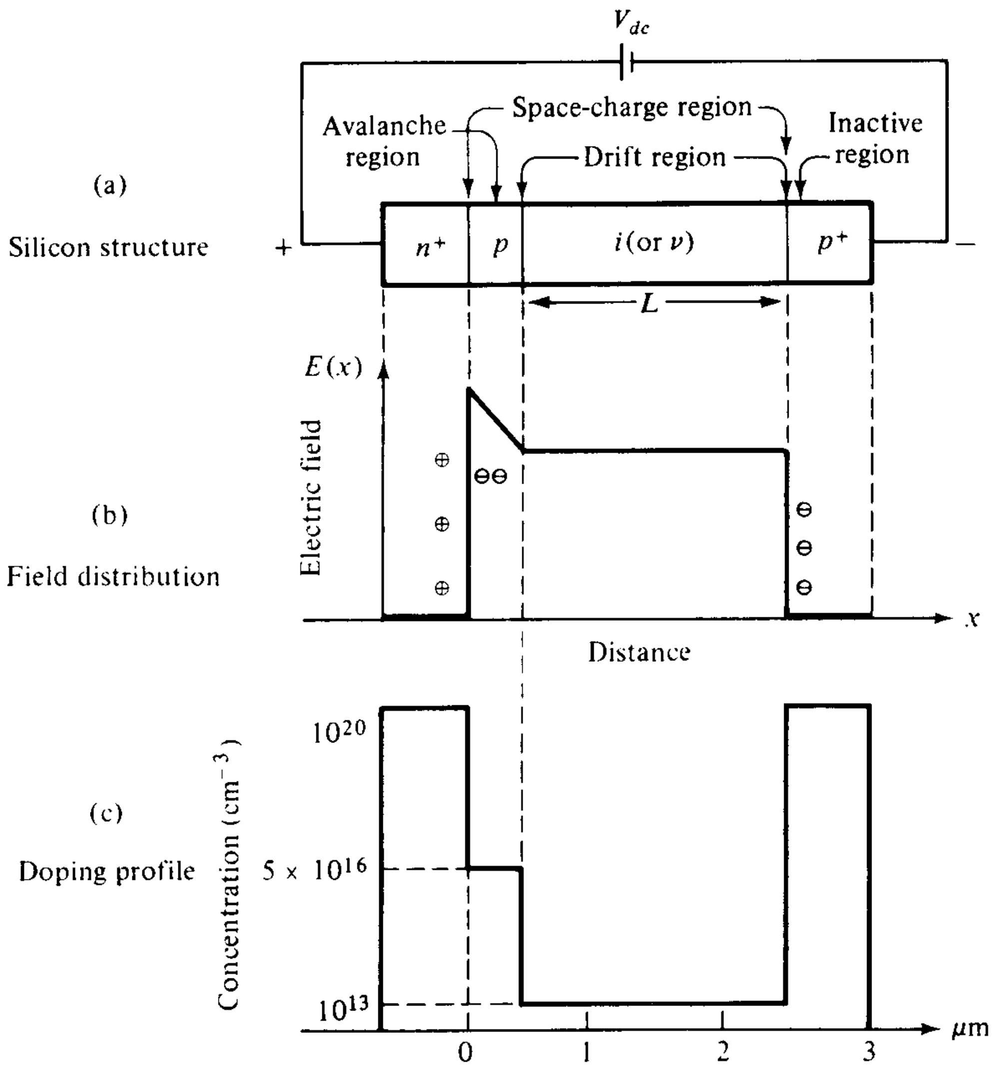

Fig 7.13: Read diode

It can be shown that the maximum negative resistance occurs when the transit angle $\theta = \pi$ at which the operating frequency becomes $f = v_d / 2L$. where v_d is drift velocity of the carriers and L length of the drift region. Its operation is illustrated in Figure 7.14.

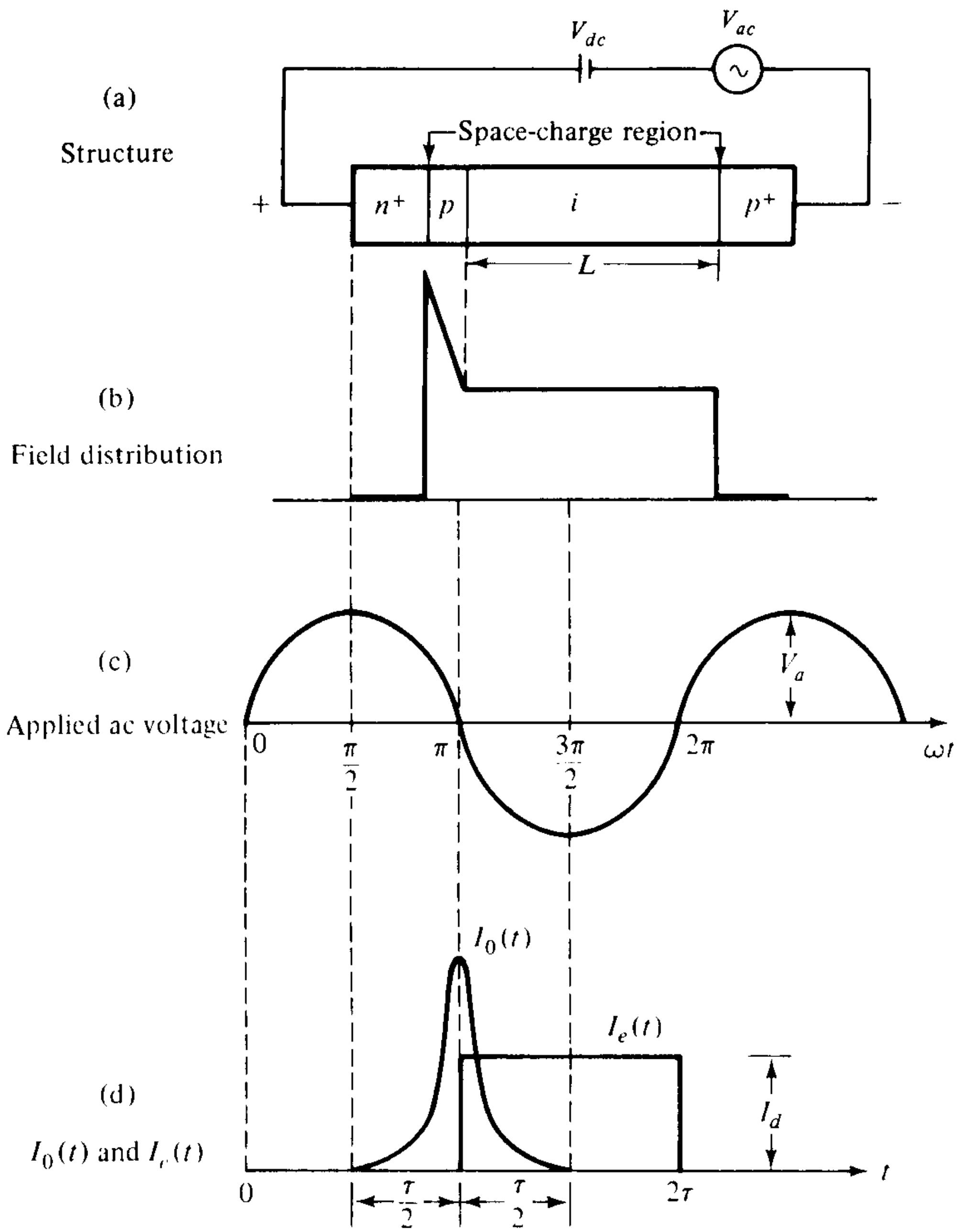

Fig 7.14: Field, voltage and currents in read diode.

IMPATT is the name of a diode family. Its basic members are

- Read diode $p^+ - n - i - n^+$ or its dual $n^+ - p - i - p^+$.
- Single drift diode $p^+ - n - p^+$.
- Double drift diode or RIMPATT diode $p^+ - p - n - n^+$.
- PiN diode $p^+ - i - n^+$.

The noise measure in GaAs is low when compared to Si and for Ge it is in between GaAs and Si. The main reason for the low noise behavior of GaAs is that for a given field the electron and hole ionization rates are essentially same, whereas in Si these are quite different.

The highest powers, frequency and efficiency are obtained from double drift diodes that are also known as RIMPATTs. The power-frequency product is highest for these diodes. The improved performance results mainly from the fact that holes and electrons produced by the avalanche are allowed to give energy to RF signal while traversing the drift region. In the case of single drift diodes only one type of carriers is so utilized.

Comparison:

- When compared to Gunn diode these diodes have more efficiency around 30%, more powerful around 15 W CW and their frequency can reach up to 200 GHz whereas in the case of Gunn it is only 100 GHz.
- But when compared to Gunn diodes these are noisier.
- Below 40 GHz GaAs IMPATTs have higher powers and efficiency than do Si IMPATTs.
- Between 40-60 GHz GaAs IMPATTs show higher power and efficiency whereas Si IMPATTs give high reliability and yield.

Above 60 GHz Si IMPATTs outperform the GaAs IMPATTs. Around the frequency 10 GHz, the efficiency is close to 40%.

Power output:

- At lower frequencies the power output is thermal-limited and is inversely proportional to the frequency, i.e. varies as f^{-1}.
- At higher frequencies (>50 MHz) the power is electronic limited and varies as f^{2}

Drawbacks:

- The noise is high mainly because of the statistical nature of the generation rates of electron hole pairs in the avalanche region.
- Highly sensitive to operational conditions.
- Large electronic-reactance, which can cause detuning or even burnout of the device unless proper care is taken.

Applications:

IMPATT diodes are at present the most powerful CW solid state microwave power sources. The diodes have been fabricated from germanium, silicon, and Ga As and can probably be constructed from other semiconductors as well. IMPATT diodes provide potentially reliable, compact, inexpensive and moderately efficient microwave power sources. They are generally used in

- microwave links, In CW radars
- In electronic counter measures

TRAPATT

TRAPATT is another diode used in the generation of microwave signals which has a very complicated design methodology and functioning. It is a high efficiency microwave generator capable of operating up to several GHz. The basic operation of the oscillator is a semiconductor p-n junction diode reverse biased to current densities well in excess of those encountered in normal avalanche operation. High peak power diodes are structures with n-type depletion region width varying from 2.5 to 12.5 μ m. The doping of the depletion region is generally such that the diodes are well punched though at breakdown. The device's p+ region is kept as thin as possible at 2.5 to 7.5 μ m. The TRAPATT diode's diameter ranges from as small as 50 μ m for CW operation to 750 μ m at lower frequency for high peak-power devices. Some important points worth noting about this diode are mentioned below:

- TRAPATT stands for 'TRApped Plasma Avalanche Triggered Transit'
- TRAPATT diode is a high power, high efficiency device.
- The design and performance of the device are highly complicated because of strong device circuit interaction that dictates most of the device performance.
- Silicon p^+ - n – n+ or n^+ - p - p^+ structures are used to get high powers [Figure 7.14]. The doping of the depletion region is generally such that the diodes are well punched through at break down, i.e. depletion region extends from p^+ - n junction to n - n^+ junction.

Operation (Refer Fig 7.15):

At point A: The diode current is turned on. Since the only charge carriers present are those caused by the thermal generation, the diode initially charges up like a linear capacitor, driving the magnitude of electric field above the breakdown voltage.

B to C: When sufficient number of carriers is generated, the particle current exceeds the external current and the electric field is depressed throughout the depletion region causing the voltage to decrease.

C to D: During this time interval the electric field is sufficiently large for the avalanche to continue, and a dense plasma of electrons and holes is created. As some of the electrons and holes drift out of the ends of the depletion layer, the field is further depressed and traps the remaining plasma. The voltage decreases to point D.

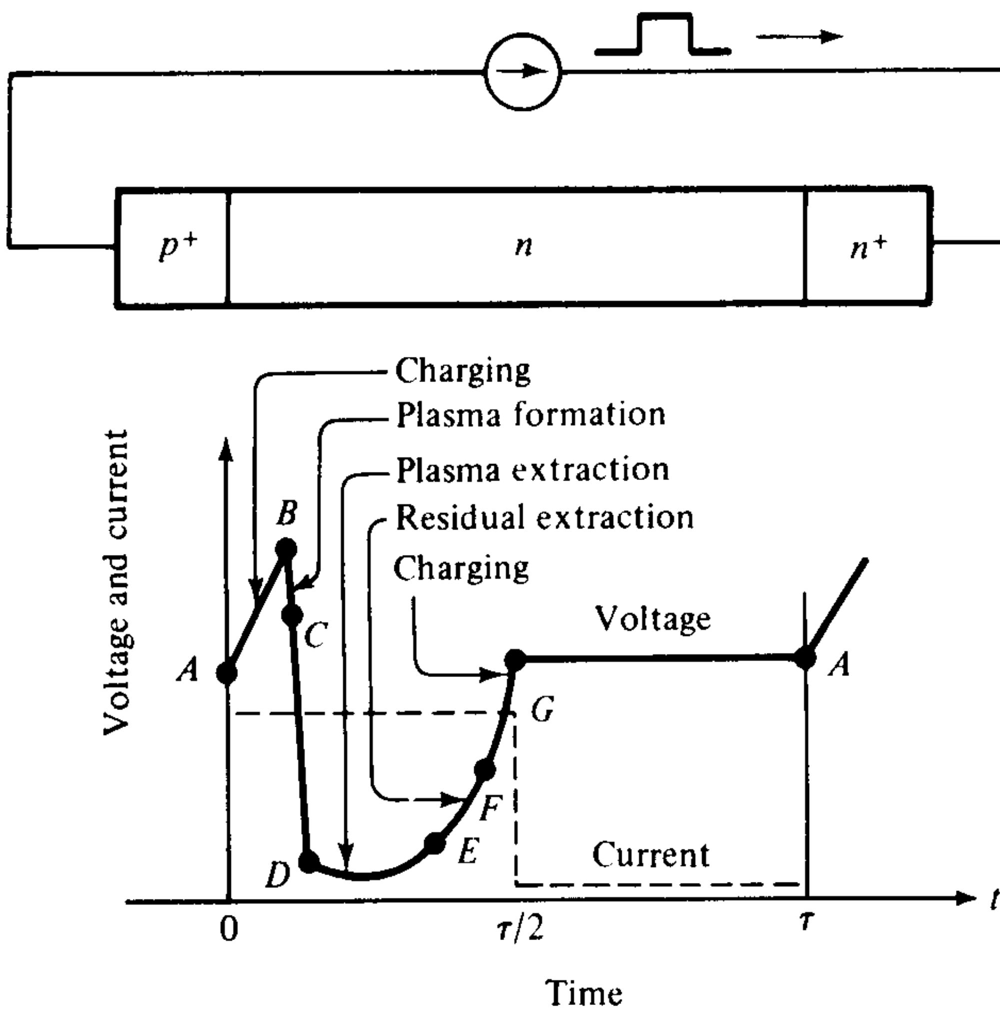

Fig 7.15: Voltage and current waveforms for TRAPATT diode

D to E: A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time. At point E plasma is removed, but a residual charge of holes in the other end.

E to F: As the residual charge is removed, the voltage increases from point E to F. At point F all the charge that was generated internally has been removed This charge must be greater than at point A.

F to G: The diode charge up again like a fixed capacitor. At point G the diode current goes to zero for half a period and the voltage remain constant at VA until the current comes back on and the cycle repeats.

This diode requires a circuit that can support harmonics of fundamental frequency of high voltage amplitudes. The rich harmonic content is necessary to get the required phase delay in the current at such low frequencies.

The avalanche zone velocity or the velocity of the shock front is given by $v_z = J/eN_A$.

Drawbacks:

- It has higher noise figure when compared to IMPATT diodes.
- Its operation is quite complicated and requires good control over the device and circuit.
- The upper operating frequencies are practically limited to below millimeter wave range, i.e. 10 GHz.

It is highly sensitive even to small changes in circuit or operating conditions or temperature

Performance:

- The output power of a series connection of five diodes under pulse condition reaches 1.2 kW with a efficiency of 25%.
- The upper frequency limit is close to 10 GHz and highest obtained efficiency is 75%
- Its high pulse power output is much larger than most other microwave semiconductor devices.

BARITT DIODES

BARITT stands for Barrier Injected transit time diodes, are the latest addition to the family of active microwave diodes. They have long drift regions similar to those of IMPATT diodes. They are formed by forward biased p-n junction with p-n-p or p-n-i-p or p-n-metal or metal-n-metal configurations. **The carriers traversing the drift regions of BARITT diodes however, are generated by minority carrier injection from forward-biased junction instead of being extracted from the plasma of an avalanche region.**

BARITT diodes are much less noisy than IMPATT diodes, Noise figures are as low as 15 dB at C-band frequencies with silicon BARITT amplifiers. The major disadvantage of BARITT diodes are relatively narrow bandwidth and power outputs limited to a few mill watts.

Principle of operation

Minority carriers are injected into the drift region. The transit time though the drift region provides the required phase shift between the current and voltage to give a negative resistance. When the diode is mounted in a resonator a noise spike generates microwave voltage across the diode. During the positive half cycle the total voltage produces sharp pulse of minority carrier current in the drift region. During the drift time, a constant external current delivers energy to the resonator from the dc bias source to maintain a continuous oscillation.

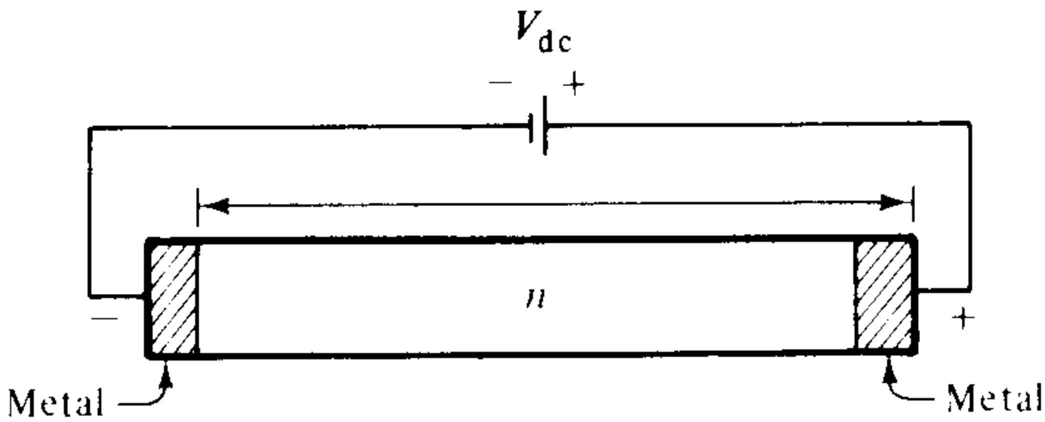

Fig7.16(a): Metal-n-Metal BARITT diode

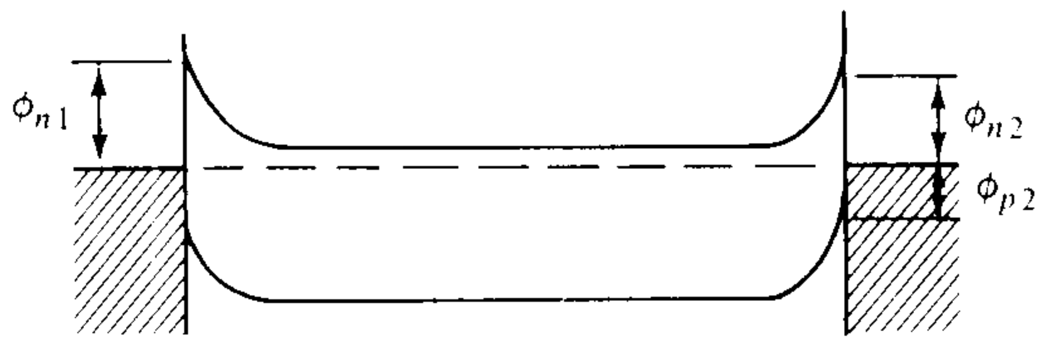

Fig7.16(b): BARITT diode: energy band diagram in thermal equilibrium

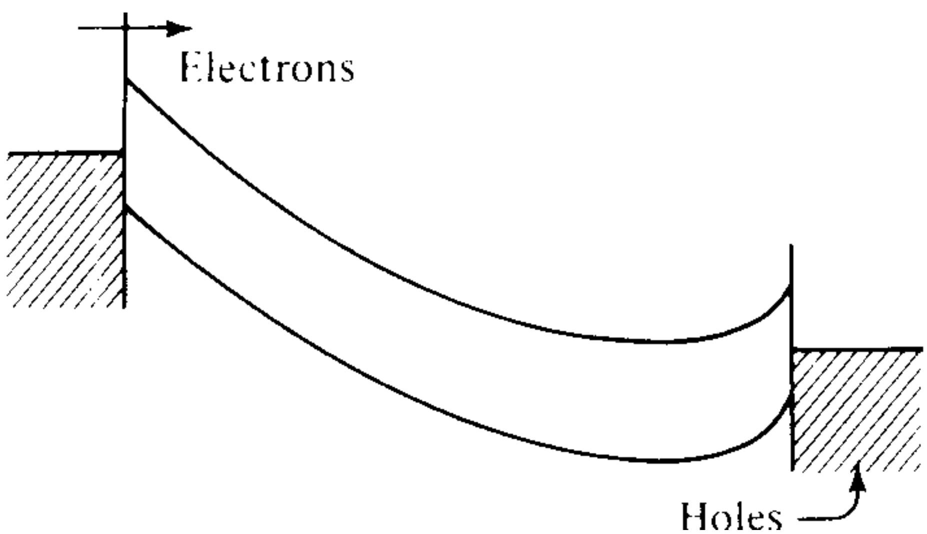

Fig7.16©: BARITT diode: Energy band under bias condition

Applications

BARITT diodes are low power low efficiency and less noisy devices. They are used as local oscillator at microwave frequencies.

Table7.1 Comparison between Gunn, IMPATT, TRAPATT and BARITT devices

Parameter	**Gunn**	**IMPATT**	**TRAPATT**	**BARITT**
Operating Frequency	1-100 GHz	0.5-100 GHz	1-10 GHZ	4-8 GHz
Bandwidth	2% of centre frequency	10% of centre frequency	---	Narrow
Power Output	A Few watts CW mode, 100-200 W (pulsed)	1 W CW mode, 400 W Pulsed mode	Several 100 W Pulsed mode	Low (mW)
Efficiency	--	3% CW, 60% Pulsed	20-60% Pulsed	Low (2%)
Noise Figure	--	High, 30 dB	High, 60 dB	Low, <15 dB
Application	Oscillator	Oscillator	Oscillator	Local Oscillator
Basic semi conductors	GaAs, InP	Si, Ge, GaAs or InP	Si	Si/metal
Harmonics	----	Less	Strong	Less
Size	Small	Small	Small	Small
Ruggedness	Yes	Yes	Yes	Yes

Solved examples

Eg 7.1 *Determine the conductivity of GaAs Gunn diode if electron density is $n=10^8$ cm^{-3}, electron density at lower valley $n_l = 10^{10}$ cm^{-3}, electron density at upper valley $n_u = 10^8$ cm^{-3}, and temperature is T = 300 K. Consider the mobilities in lower and upper valleys as $\mu_l = 8000 \times 10^{-4}$ m^2/V s and $\mu_u = 180 \times 10^{-4}$ m^2/V s.*

Solution: Conductivity of the Gunn diode is

$$\sigma = e(\mu_1 n_1 - \mu_u n_u)$$

$$= 1.6 \times 10^{-19} (8000 \times 10^{-4} \times 10^{16} + 180 \times 10^{-4} \times 10^{14})$$
$$= 1.6 \times 10^{-19} \times 8000 \times 10^{12} = 12.8 \times 10^{-4}\ \Omega$$

Eg 7.2 *Determine the criterion for classifying the modes of operation of Gunn diode, given that electron drift velocity is $v_d = 2.5 \times 10^5$ m/s, negative electron mobility $|\mu_n| = 0.015 \times 10^5$ m^2/V s and $\varepsilon_r = 13.1$.*

Solution: The value of $\varepsilon v/e\,|\mu_n|$ relative to nL is the criterion for classifying the modes of operation of Gunn diode. Given that

Permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$ - $8.854 \times 10^{-12} \times 13.1$
Drift velocity $v_d = 2.5 \times 10^5$ m/s
Mobility $|\mu_n| = 0.015 \times 10^5$ m^2/Vs

For the given values it is

$$\frac{\varepsilon v}{e|\mu_n|} = \frac{13.1 \times 8.854 \times 10^{-12} \times 2.5 \times 10^5}{1.6 \times 10^{-19} \times 0.015 \times 10^5}$$

$$= \frac{13.1 \times 8.854 \times 10^7 \times 2.5}{1.6 \times 0.015} = 12.1 \times 10^{10} m^{-2}$$

Eg 7.3 *In a GaAs Gunn diode, working at a frequency of 8 GHz, the threshold field is 3 kV/m, applied field is 3.5 kV/m, device length is 10 x 10^{-6} m and the doping constant is 10^{16} electrons/cm^3. Calculate the current density and negative electron mobility in the device, explaining the relations used.*

Solution: The electron drift velocity is

$$vd = fL = 8 \times 10^9 \times 10 \times 10^{-6} = 8 \times 10^4 m/s$$

The current density is

$$J = env_d = 1.6 \times 10^{-19} \times 10^{22} \times 8 \times 10^4 = 12.8 \times 10^7 A/m^2$$

The negative electron mobility is

$$\mu_n = -\frac{v_d}{E} = -\frac{8 \times 10^4}{3.5 \times 10^3} = -22.8\ m^2/Vs$$

Eg *7.4: An IMPATT diode has the following parameters: carrier drift velocity $v_d = 3 \times 10^7$ cm/s, drift region length L =1 x 10-^{6} m, maximum operating voltage Vo.max = 150 V, maximum operating current $I_{0\,max}$ = 200 mA, an efficiency of η = 20%. Find the maximum CW output power in watts and resonant frequency.*

Solution: The continuous wave output power is

$$P = \eta P_{dc} = \eta V_{0.max} I_{0.max}$$
$$= 0.20 \times 150 \times 200 \times 10^{-3} = 6\ W$$

The resonant frequency is

$$f = \frac{v_d}{2L} = \frac{3\times10^5}{2\times7\times10^{-6}} = 21.4\ GHz$$

***Eg** 7.5 A Ku band IMPATT diode has a pulse operating voltage of 100 V and pulse operating current of 0.9 A. If the efficiency is about 10%, calculate the output power, the duty cycle if the pulse width is 0.01 ns and frequency is f = 16 GHz.*

Solution: The continuous wave output power is

$$P = \eta P_{dc} = \eta V_{0.max} I_{0.max}$$

$$= 0.10 \times 100 \times 0.9 = 9\ W$$

The duration of cycle is

$$T = \frac{1}{f} = \frac{1}{16\times10^9} = 0.0625\ ns$$

The duty cycle is the ratio of on time to period. In the present case

Duty cycle= $= \dfrac{0.01}{0.0625} = 0.16$

Eg 7.6: *Calculate the avalanche zone velocity of a TRAPATT diode with doping concentration $N_A = 2 \times 10^{15}\ cm^{-3}$ and current density $J = 20\ kA/cm^2$.*

Solution: The avalanche zone velocity is given by

$$v_z = \frac{J}{eN_A} = \frac{20\times10^3}{1.6\times10^{-19}\times2\times10^{15}} = 6.25\times10^7\ cm/s$$