

MICROWAVE SOLID STATE DEVICES

IMPATT DIODE

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Clasification of Microwave Solid State Devices

□ Based on Electrical Behavior

A. Non Linear Resistance

Ex. Varistor

B. Non Linear Reactance

Ex. Varactor

C. Negative Resistance Type

Ex. Tunnel Diode , IMPATT , Gun Diode

D. Controlled Impedance Type

Ex. PIN Diode

E. Based On construction

Ex

Point Contact Diode

Schottky Barrier Diode

Metal Oxide Semiconductor

Metal Insulation Type

Microwave Bipolar Transistor

- ❑ The Basic operation of Microwave Bipolar Transistor is the same as that of transistor at Low Frequency.
- ❑ Its operation depends on
 1. Thickness of the P-N junction
 2. The Transit Time

Features

Used as Amplifiers and Oscillators

Used in L and C band

Operated in Class C amplifier

FET-Field Effect Transistor

- The Operation of FET depends on the conductivity of the Semiconductor layer of Gallium arsenide

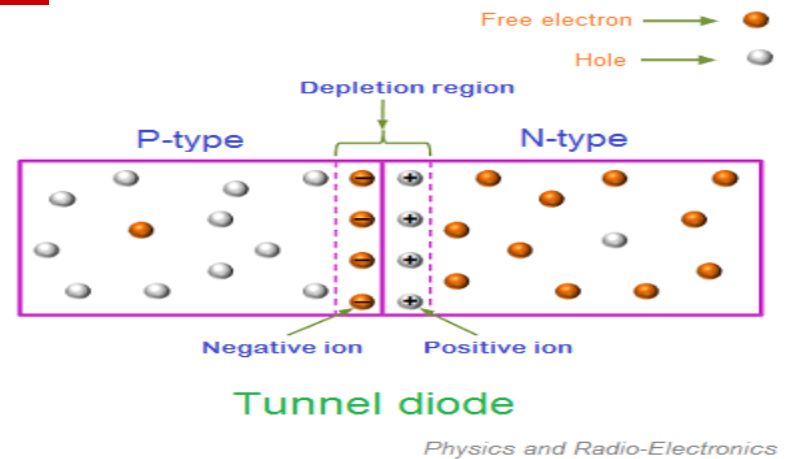
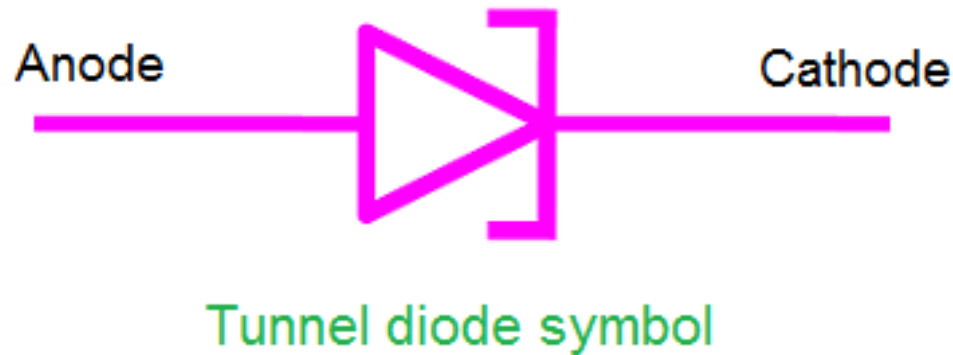
Features

1. They Can operate in X band
 2. Used as Amplifiers and Oscillators
 3. FET mostly used GaAs and Metal Semicon(MES) shotky junction for gate contact.
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Tunnel diode

- ❑ A Tunnel diode is a heavily doped p-n junction diode in which the electric current decreases as the voltage increases.
 - ❑ In tunnel diode, electric current is caused by “Tunneling”. The tunnel diode is used as a very fast switching device in computers. It is also used in high-frequency oscillators and amplifiers.
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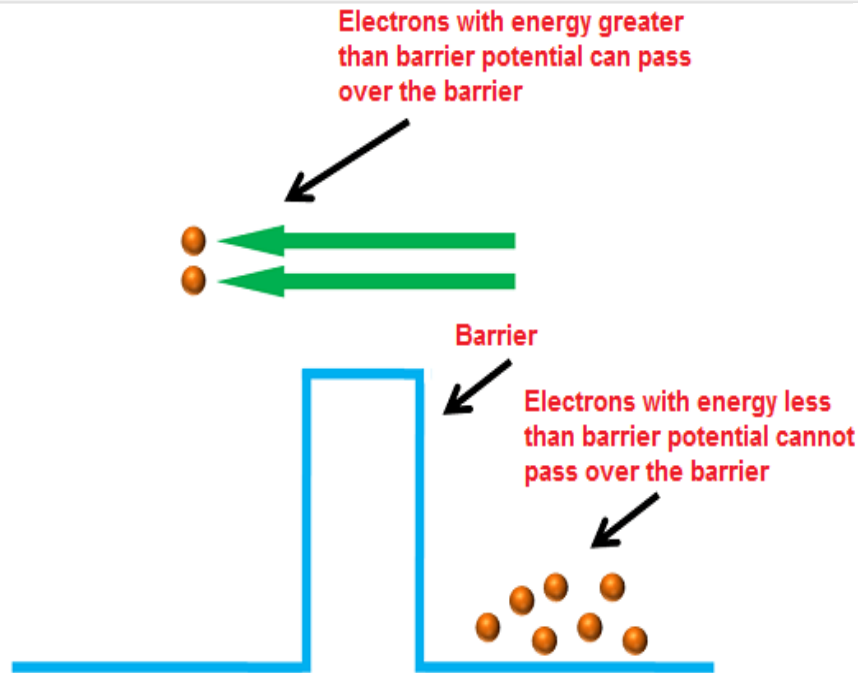
A tunnel diode is also known as Esaki diode which is named after Leo Esaki for his work on the tunneling effect. The operation of tunnel diode depends on the quantum mechanics principle known as “Tunneling”



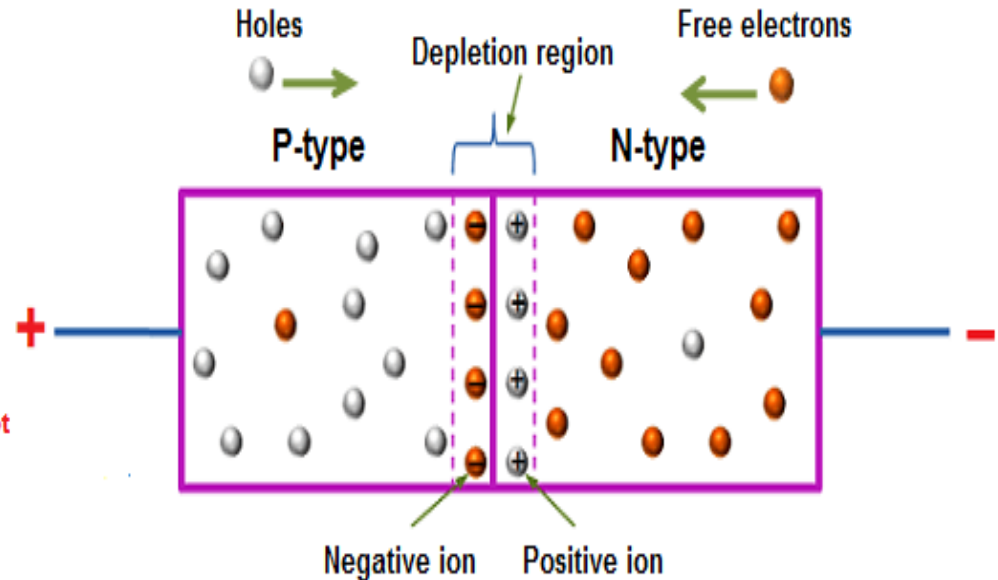
Concept of tunneling

The depletion region or depletion layer in a p-n junction diode is made up of positive ions and negative ions. Because of these positive and negative ions, there exists a built-in-potential of electric field in the depletion region. This electric field in the depletion region exerts electric force in a direction opposite to that of the external electric field (voltage).

In tunnel diode, the valence band and conduction band energy levels in the n-type semiconductor are lower than the valence band and conduction band energy levels in the p-type semiconductor. Unlike the ordinary p-n junction diode, the difference in energy levels is very high in tunnel diode. Because of this high difference in energy levels, the conduction band of the n-type material overlaps with the valence band of the p-type material.



Ordinary p-n junction diode

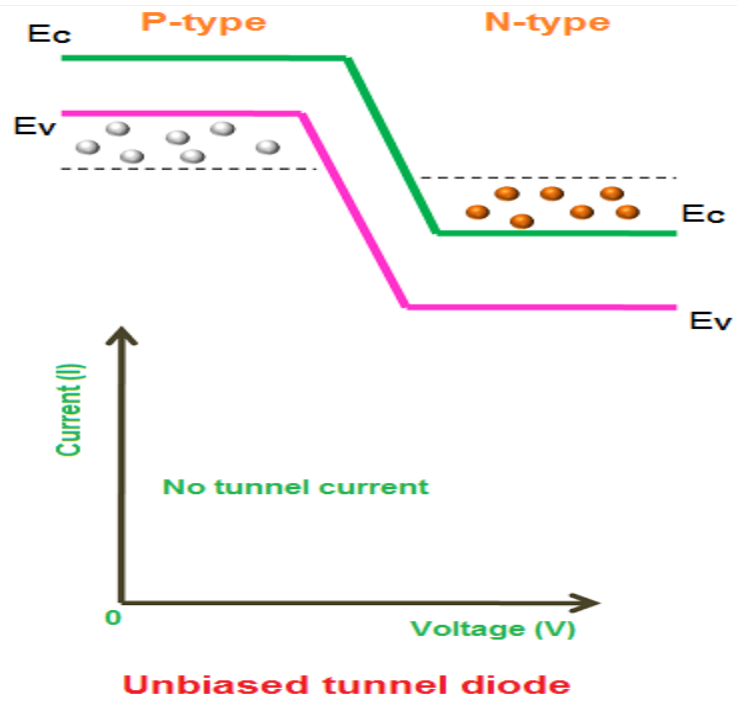


Forward bias tunnel diode

How tunnel diode works?

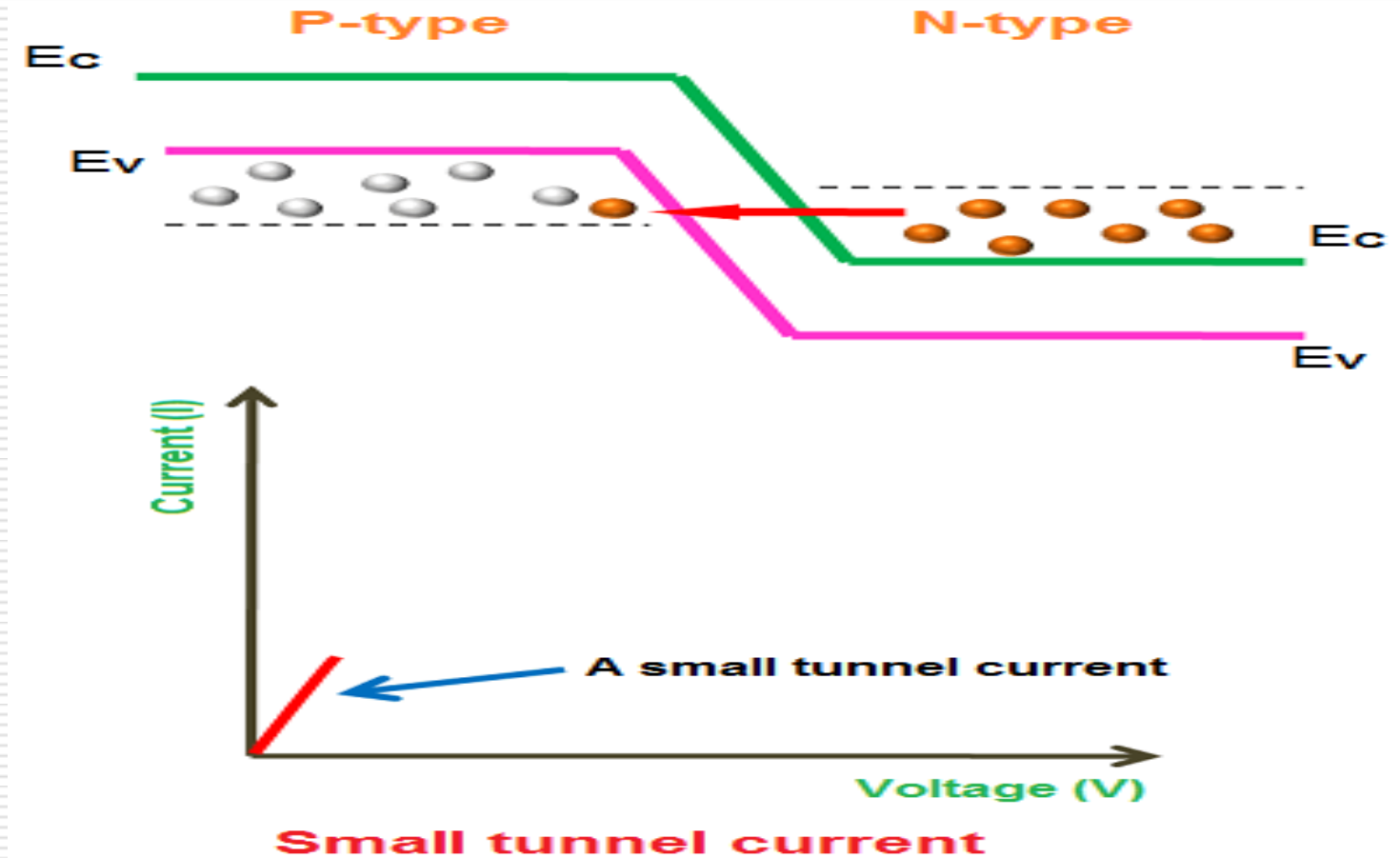
Step 1: Unbiased tunnel diode

When no voltage is applied to the tunnel diode, it is said to be an unbiased tunnel diode. In tunnel diode, the conduction band of the n-type material overlaps with the valence band of the p-type material because of the heavy doping.



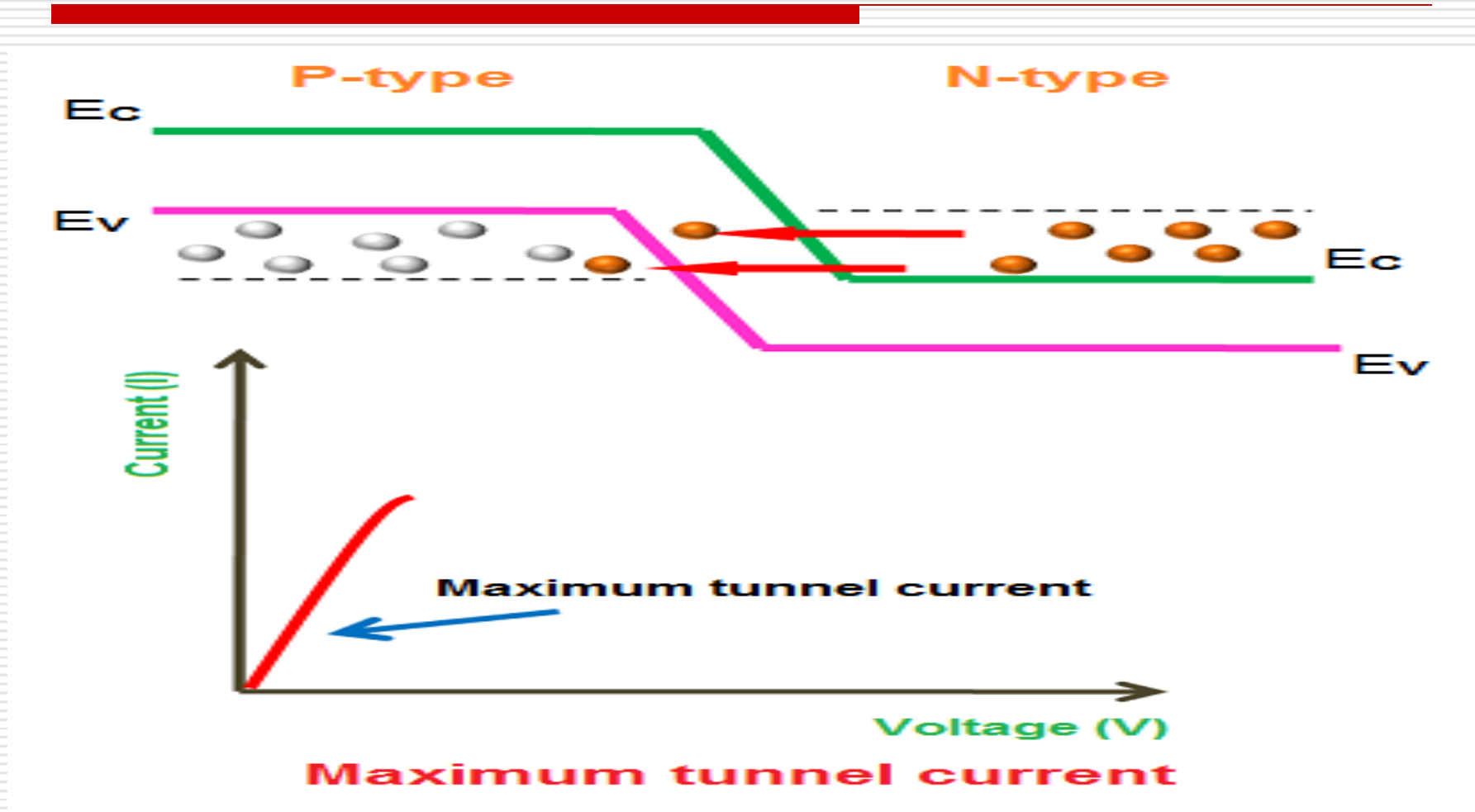
Step 2: Small voltage applied to the tunnel diode

When a small voltage is applied to the tunnel diode which is less than the built-in voltage of the depletion layer, no forward current flows through the junction.



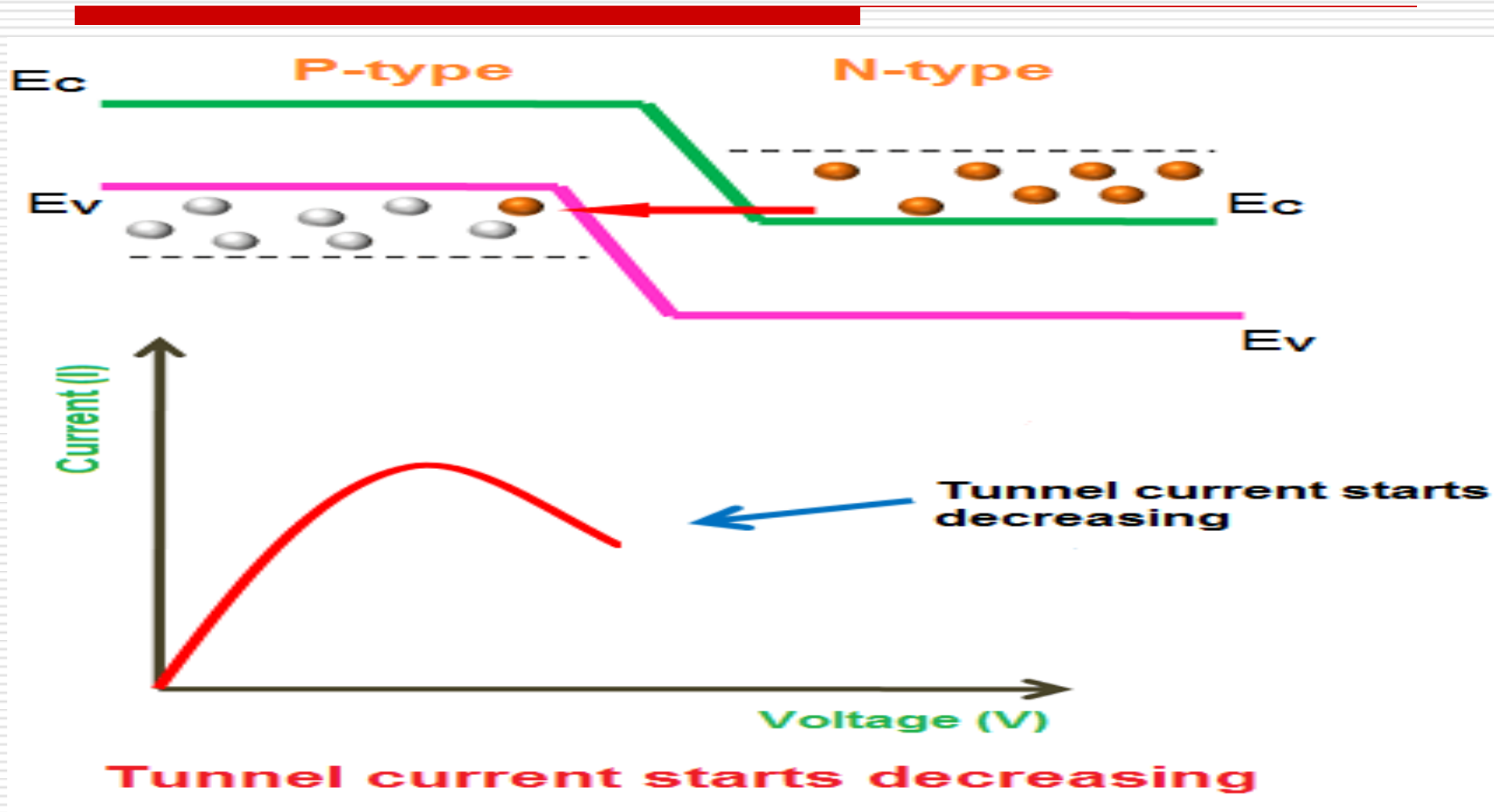
Step 3: Applied voltage is slightly increased

When the voltage applied to the tunnel diode is slightly increased, a large number of free electrons at n-side and holes at p-side are generated. Because of the increase in voltage, the overlapping of the conduction band and valence band is increased.



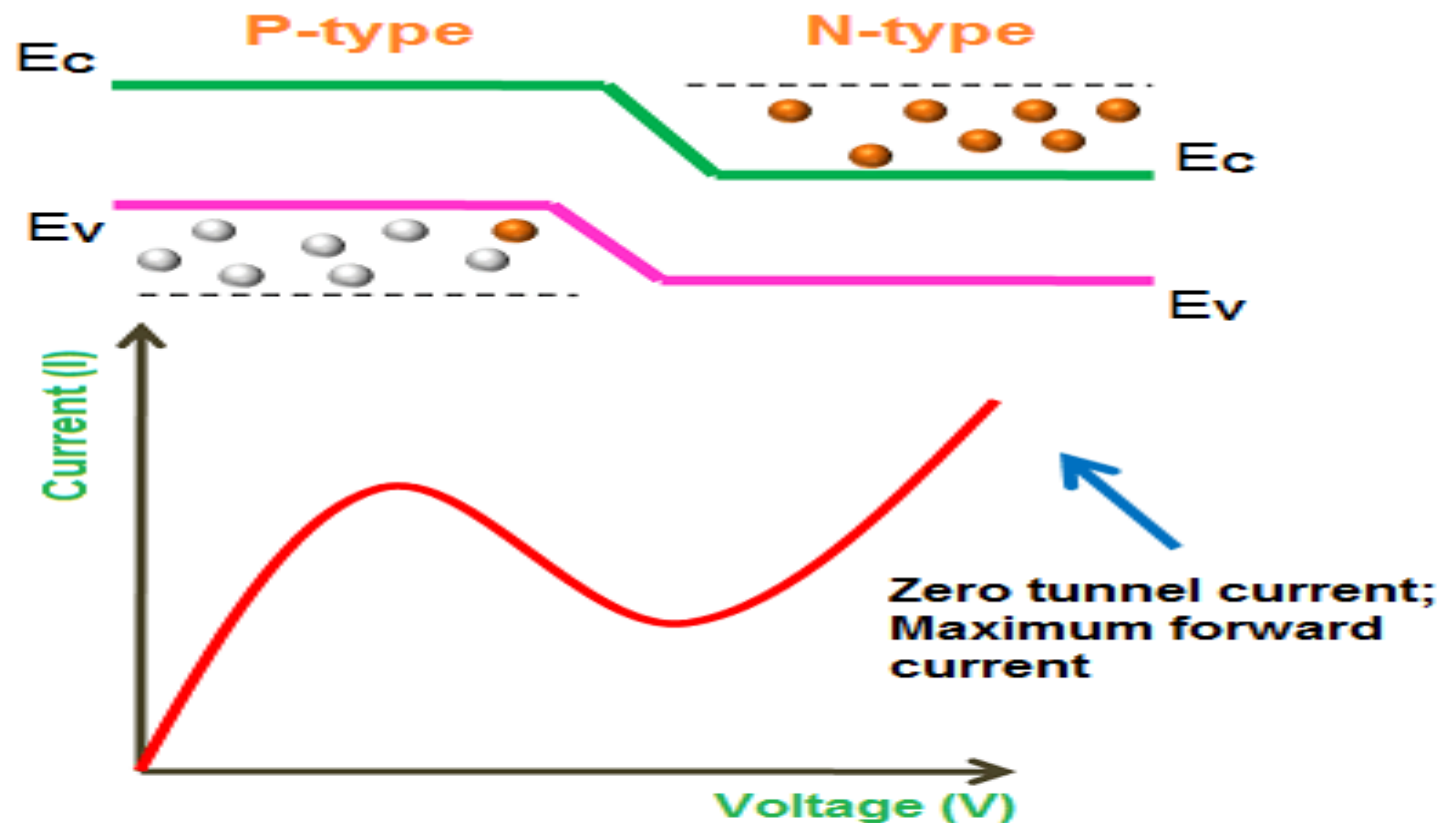
Step 4: Applied voltage is further increased

If the applied voltage is further increased, a slight misalign of the conduction band and valence band takes place



Step 5: Applied voltage is largely increased

If the applied voltage is largely increased, the tunneling current drops to zero. At this point, the conduction band and valence band no longer overlap and the tunnel diode operates in the same manner as a normal p-n junction diode.



Zero tunnel current; maximum forward current

Applications of tunnel diodes

Tunnel diodes are used as logic memory storage devices.

Tunnel diodes are used in relaxation oscillator circuits.

Tunnel diode is used as an ultra high-speed switch.

Tunnel diodes are used in FM receivers.

Advantages of tunnel diodes

Long life

High-speed operation

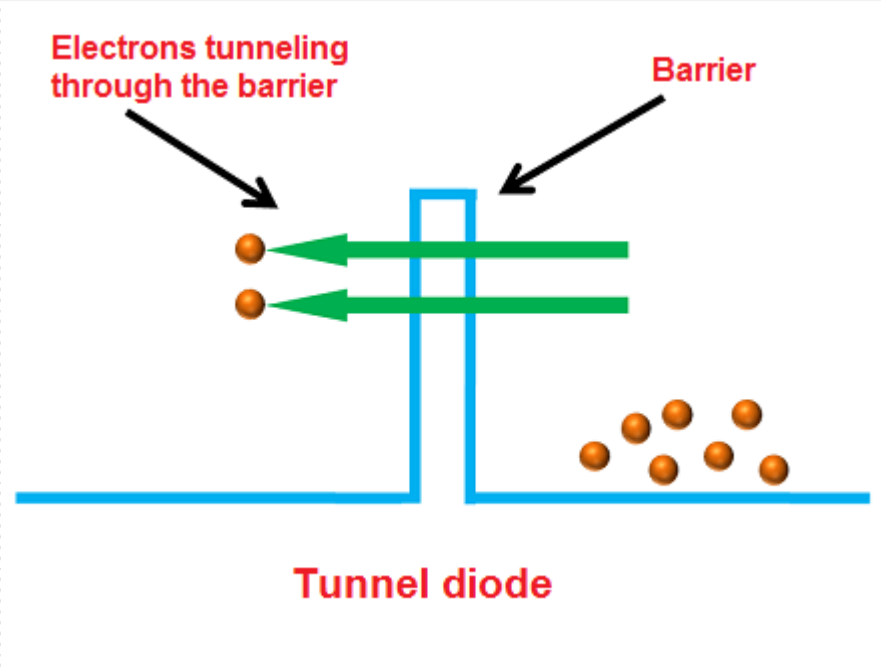
Low noise

Low power consumption

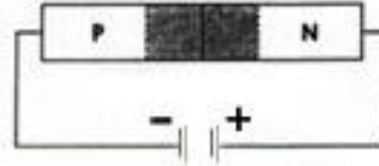
Disadvantages of tunnel diodes

Tunnel diodes cannot be fabricated in large numbers

Being a two terminal device, the input and output are not isolated from one another.



VARACTOR DIODE



- a microwave solid-state devices
- also called a parametric diode, tuning diodes or varicap diodes
- a nonlinear device
- provides a voltage-dependent variable capacitance and capacitance varies with reverse bias voltage . The variable capacitance makes it useful in designing tuning circuits.

Electrical equivalent circuit of varactor diode

$C_J(V)$ – variable

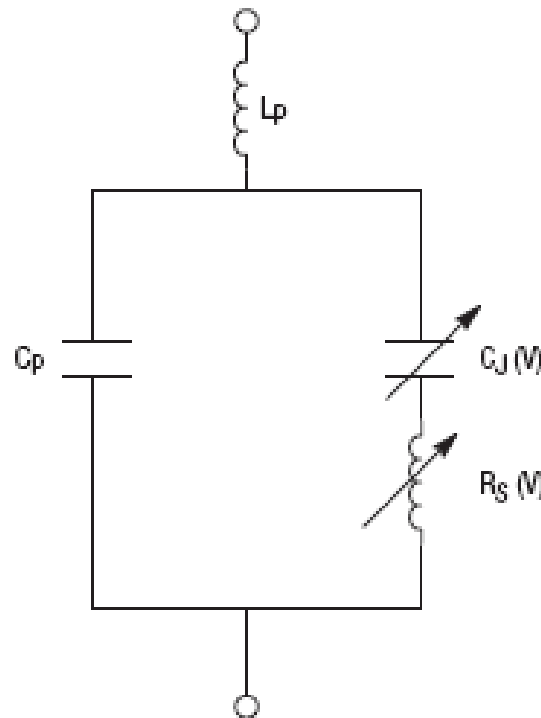
Junction Capacitance
of diode

$R_S(V)$ – variable Series
resistance of diode

C_P – parasitic

capacitance formed

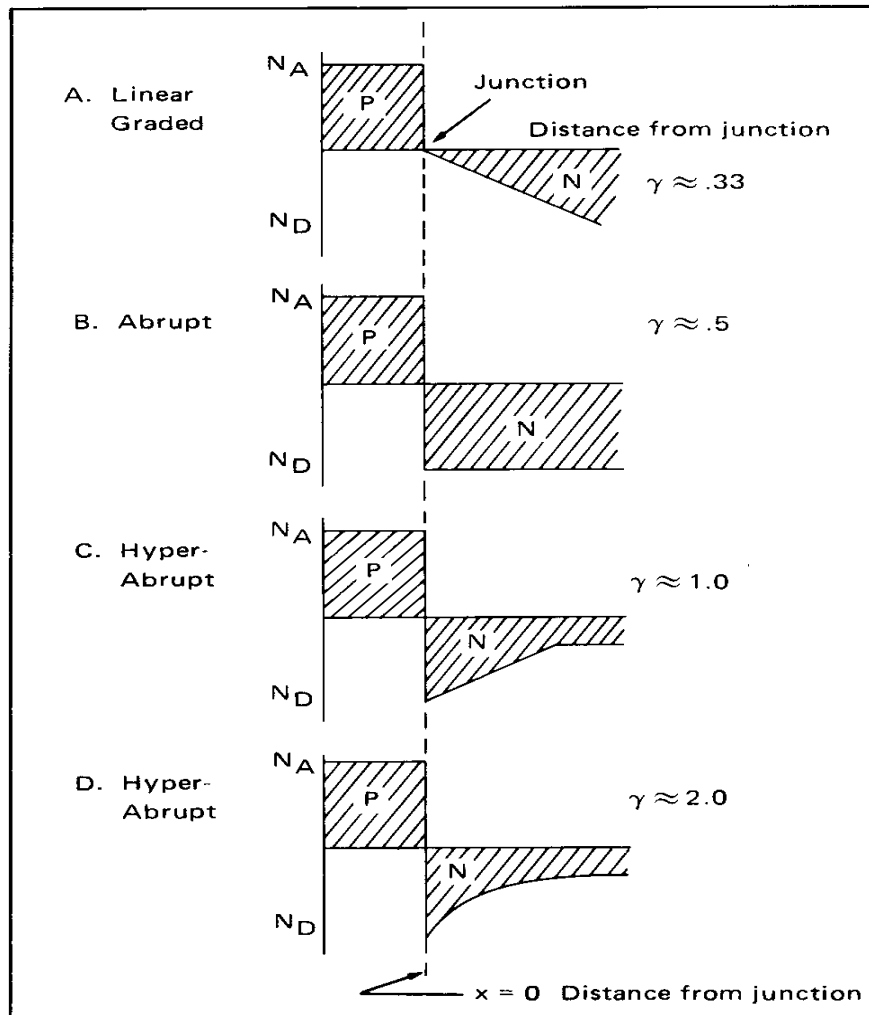
during fabrication



TYPES OF VARACTOR DIODES

- **1. Linearly graded junction:** in which carrier concentration varies linearly with distance away from the junction. It may be on both side or only one side. Generally one side junction are used.
- **2. Abrupt and Hyper abrupt p-n junction:** it employs very heavy doping on one side of the junction. In this case depletion region width on heavy doping side is negligible compared to lowly doped side .For an abrupt varactor diode the doping concentration is held constant, i.e constant doping level as far as reasonably possible.

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For a graded junction
(linear variation), $n = 0.33$.

For an abrupt junction
(constant doping density),
 $n = 0.5$.

If the density jumps
abruptly at the junction,
then decreases
(called hyperabrupt),
 n can be made as high
as $n = 2$.

The doping on one side of
the junction is heavy, and
the depletion layer is
predominately extends on
the other side only.

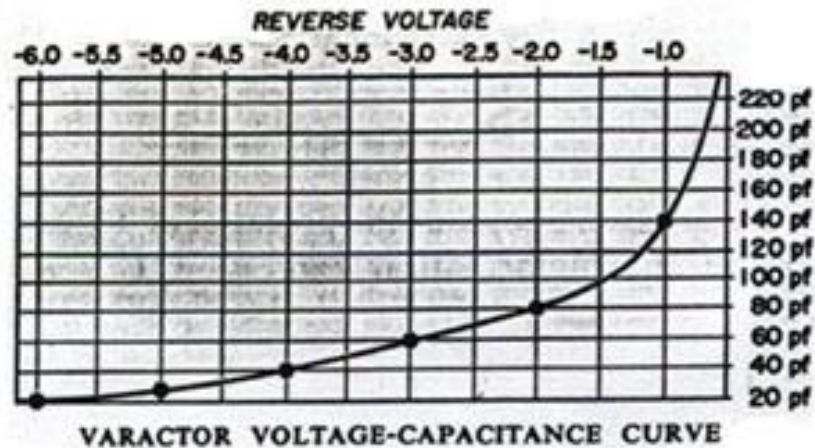
IMPORTANT CRITERIA

- **Capacitance** : Capacitance of the device. Capacitance from a few picoFarads to hundreds of picoFarads is provided.
- **Capacitance range** : Range of capacitance produced when voltage is varied.
- **Voltage range** : The minimum and maximum voltage that can be applied to the device.
- **Bias current** : The bias is always reverse. This means that the varactor diode does not conduct electricity. If the bias is turned positive then the device will start conducting.
- **Other criteria to be considered include** : reverse and breakdown voltage, leakage current, junction temperature.
- **Voltage and other transients must be avoided.** Transients can occur if the DC voltage is put off.

CHARACTERISTICS

- Low-noise characteristic : produce much less noise than most conventional amplifiers.
- Low cost
- High reliability
- Light weight
- Small size

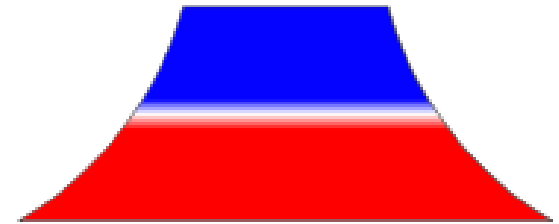
CHARACTERISTICS



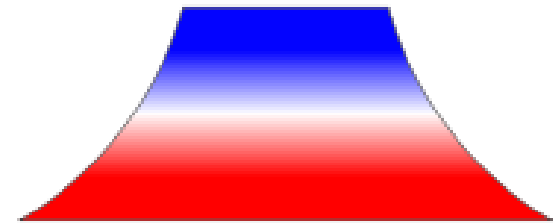
- Notice the nonlinear increase in capacitance as the reverse voltage is decreased.

OPERATION

- It has a p-n junction of semiconducting material and is always reverse biased.
- The depletion zone width depends on the applied voltage and this makes the capacitance vary with the applied voltage.



lower bias voltage,
narrower depletion zone,
higher capacitance



higher bias voltage,
wider depletion zone,
lower capacitance

APPLICATIONS

- **FREQUENCY MULTIPLIERS** - used in applications where it's difficult to generate microwave signals
- producing relatively high power outputs at frequencies up to 100GHz
- does not have gain ; in fact, it produces a signal power loss
- output can be as high as 80% of the input

APPLICATIONS

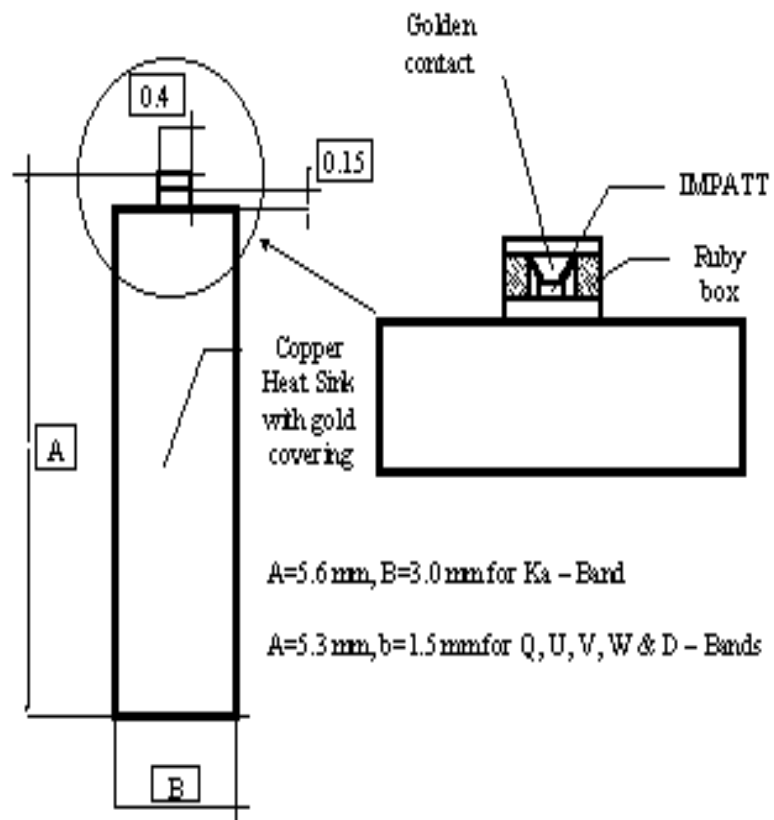
- **PARAMETRIC AMPLIFIERS.** - named for the time-varying parameter, or value of capacitance, associated with the operation.
- Since the underlying principle of operation is based on reactance, the parametric amplifier is sometimes called a **REACTANCE AMPLIFIER.**

APPLICATIONS

- **TUNING** - Since the frequency can be made to vary they are used as electronic tuning devices in tuners for television, mobiles.

- **Other Applications:**

They are used in PLL, voltage controlled oscillators, harmonic generation, electronic tuning devices in tuners for television, mobiles, parametric amplification, AM radios, voltage-variable tuning, frequency multipliers, etc.



IMPATT DIODE

A wide variety of **solid state diodes** and **transistor** have been developed for microwave use.

- **IMP**act ionization **Avalanche Transit-Time**
- Function as microwave **oscillator**.
- Used to produce **carrier signal** for microwave transmission system.
- IMPATT can operate from a **few GHz to a few hundred GHz**

IMPATT DIODE Operation

- The diode is **operated in reverse bias** near breakdown, and both the N and N- regions are **completely depleted**
- Because of the **difference** in doping between the "drift region" and "**avalanche region**", the **electric field** is **highly peaked** in the **avalanche region** and **nearly flat** in **drift region**.
- In operation, **avalanche breakdown** occurs at the point of **highest electric field**, and this generates a large number of hole-electron pairs by impact ionization.
- The **holes** are swept into the cathode, but the **electrons** travel across the drift region toward anode.

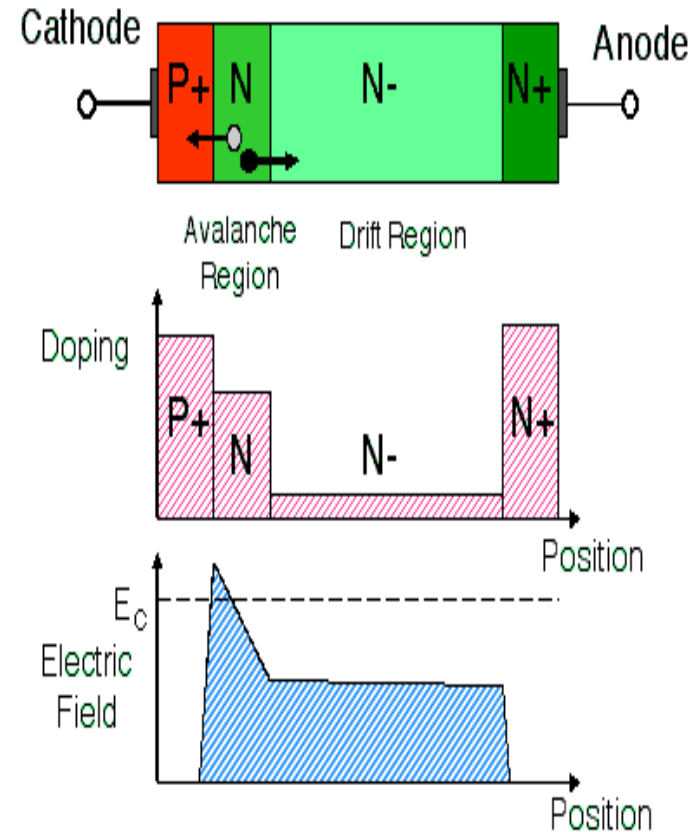


Figure 1: Impatt Diode Operation

IMPATT DIODE Operation

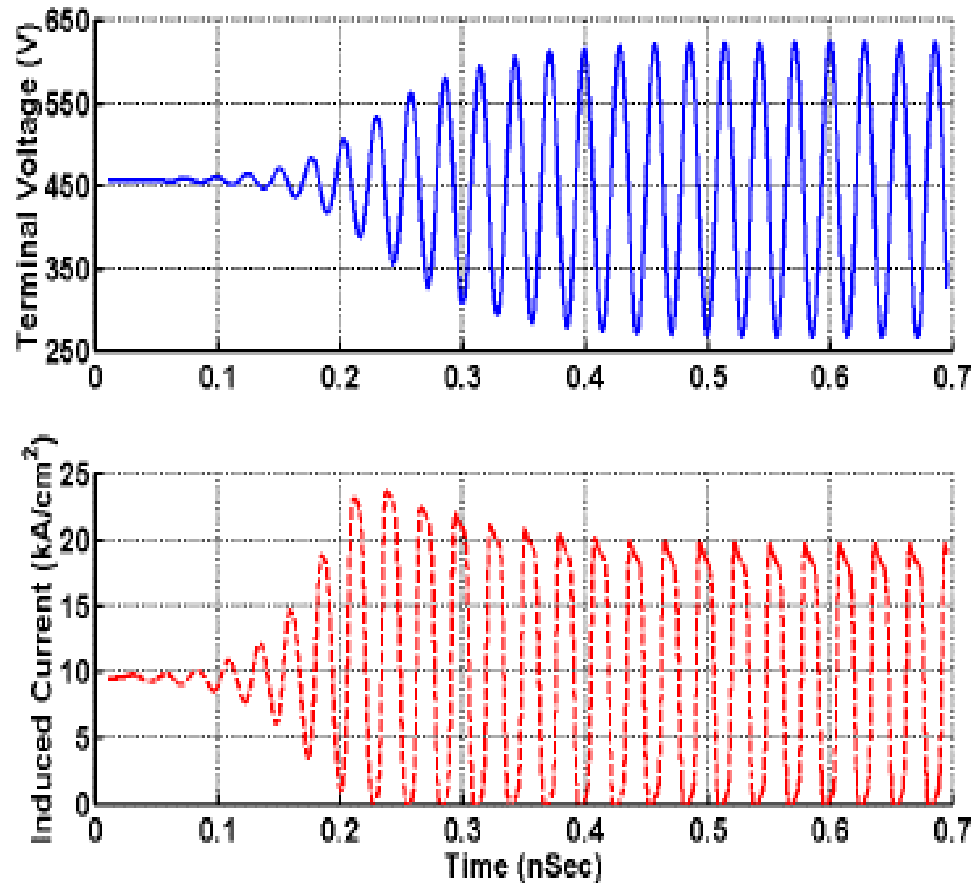


Figure 2: The Build Up Of Microwave Oscillation.

IMPATT DIODE Operation

- As they **drift**, they **induce image charges on the anode**, giving **rise** to a **displacement current** in the external circuit that is **180° out of phase** with the nearly sinusoidal voltage waveform
- **Figure 2** shows the buildup of microwave oscillations in the diode current and voltage when the **diode is embedded in a resonant cavity and biased at breakdown**

IMPATT DIODE Operation

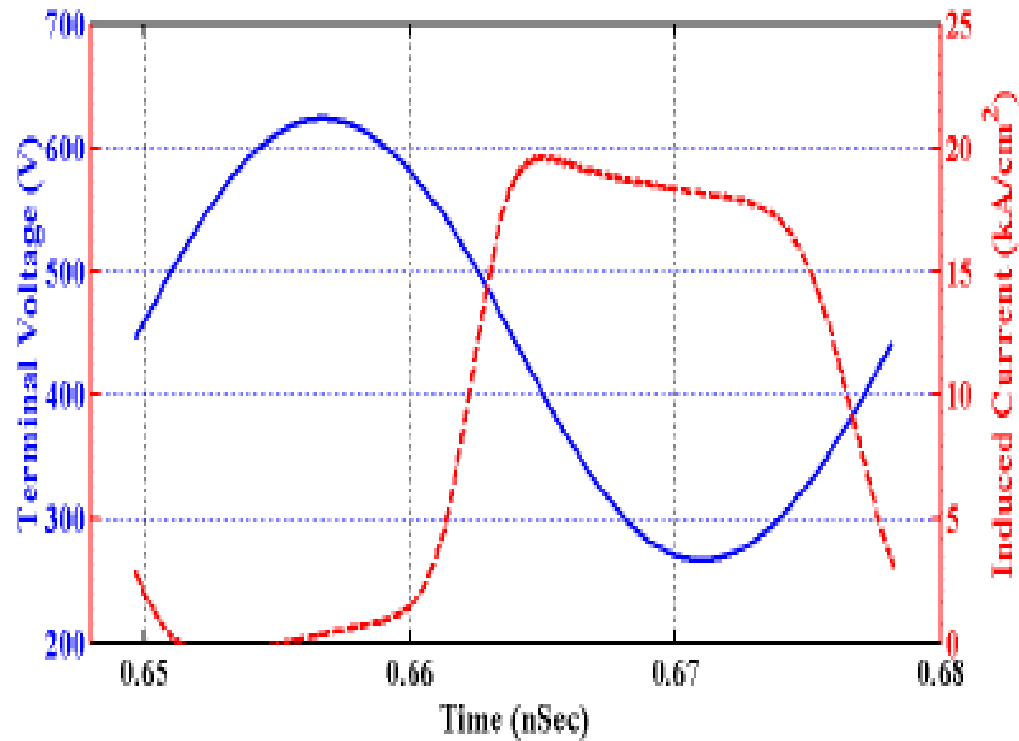


Figure 3: Close Up Current And Voltage.

IMPATT DIODE Operation

- **Figure 3** shows a close-up of the current and voltage waveforms **after oscillations have stabilized**. It is clear from Fig. 3 that the current is 180° out of phase with the voltage
- This represents a **NEGATIVE AC RESISTANCE**

Diode Mounting Procedure and Precautions

- The IMPATT diode has a **negative resistance from DC through microwave frequencies**. Consequently, it is prone to **oscillate at low frequencies**, with the lead inductance from bias circuit connections. The voltage due to bias circuit oscillations may be large enough to **burn** the device out if adequate precautions are not observed. It is prudent practice to suppress the bias circuit oscillation.

Diode Mounting Procedure and Precautions

- **Adequate heatsink must be provided for the diode to operate properly.** These IMPATT diodes have been designed to operate in the **precollection mode**. As the diode is tuned up from a low operating current from a constant current source, it will be noticed that at the onset of precollection mode, the diode voltage falls down..

Diode Mounting Procedure and Precautions

- The power output will increase by several dBs. with a slight shift in the operating frequency. When the circuit is detuned in such a fashion that the diode falls out of the precollection mode, the diode voltage will increase. The **power dissipation will increase as the power output falls down.** If the diode is **not adequately heatsink,** the **diode may burn out**

IMPATT DIODE Applications

- A **main advantage** is their **high power capability**. These diodes are used in a variety of applications from **low power radar systems to alarms**.
- Nevertheless these **diodes make excellent microwave generators** for many applications. An **alternating signal** is generated simply by **applying a DC supply** when a suitable **tuned circuit is applied**. The **output** is reliable and relatively **high** when **compared to other** forms of diode.

IMPATT DIODE Applications

- In view of its **high levels of phase noise** it is used in **transmitters** more frequently **than** as a **local oscillator** in receivers where the **phase noise performance** is generally more **important**.

IMPATT DIODE Applications

- The following **products are available as examples of IMPATT diodes application:**
 - 1) Cavity Stabilized IMPATT diode Oscillators CIDO series.
 - 2) Pulsed IMPATT Power Sources IPSP series.
 - 3) IMPATT Active Frequency Multipliers IAFM series.
 - 4) Pulsed and CW IMPATT Injection-Locked Amplifiers IILAP and IILA series.
 - 5) Voltage Controlled IMPATT Oscillators VCIO series.

- Frequency Oscillation

$$f = V_d / 2L$$

V_d = Drift Velocity

L = Length of Drift Region

- Transit Angle

$$\theta = 2\pi fL / V_d$$

- Avalanche Resonant Frequency

$$= \sqrt{2\alpha V_d I} / E_s A$$

A = Diode Current E_s = Semiconductor Permittivity

I = Current α = Ionization Coefficient

Example

- Find the Frequency of oscillation of IMPATT diode with carrier drift velocity $= 2.2 \times 10^5 \text{ m/s}$

Drift region length = $5 \text{ } \mu\text{m}$

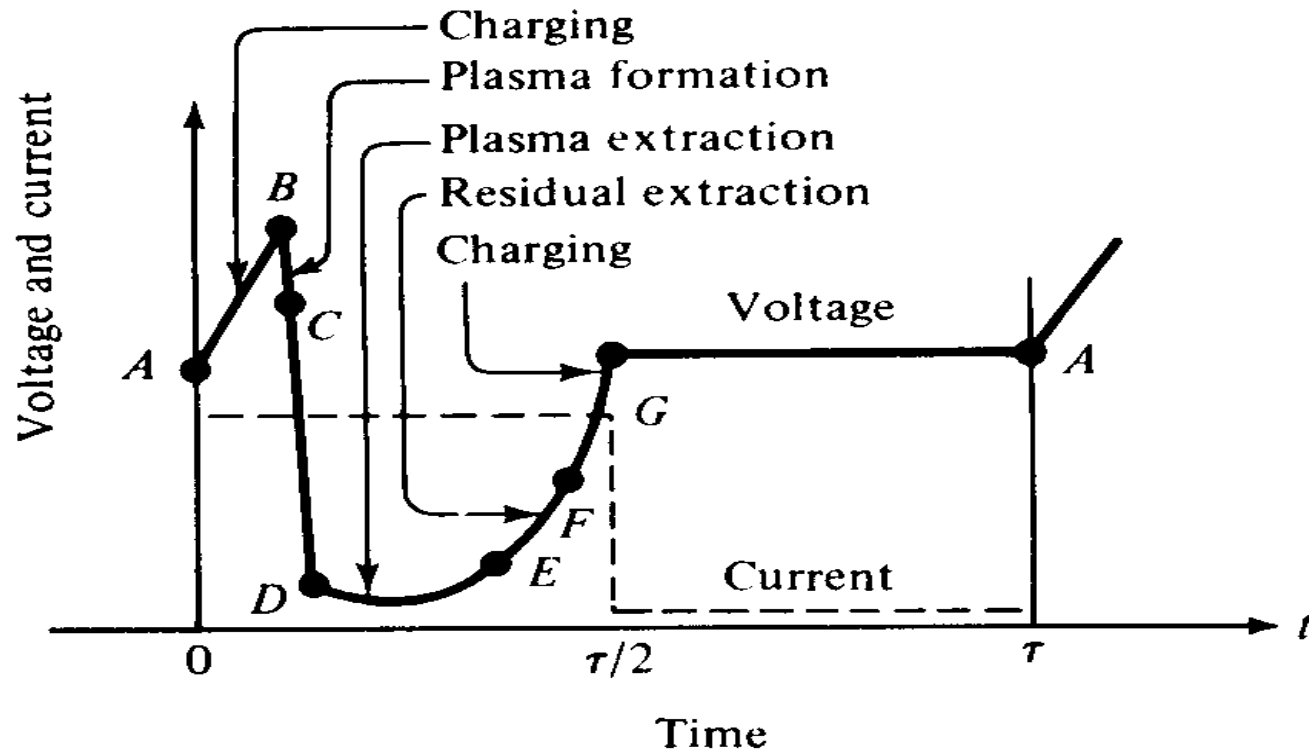
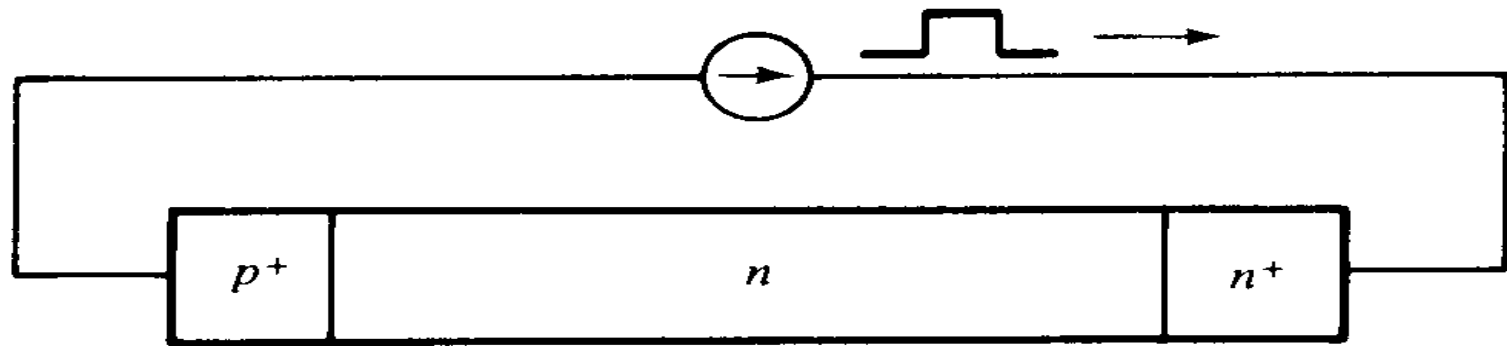
TRAPAT

- Trapped Plasma Avalanche Triggered Transit mode
- High efficiency microwave generator capable of operating from several hundred MHz to several GHz
- $n^+ - p - p^+$ or $(p^+ - n - n^+)$
- The doping of the depletion region is such that the diodes are well “punched through” at breakdown; i.e the dc electric field in the depletion region just prior to breakdown is well above saturated drift velocity level.

Principles of Operation

A high field avalanche zone propagates through the diode and fills the depletion layer with a dense plasma of electrons and holes that become trapped in the low field region behind the zone.

Voltage and Current waveforms



At point A the electric field is uniform throughout the sample and its magnitude is large but less than the value required for avalanche breakdown.

The current density is $J = \epsilon_s \frac{dE}{dt}$

where ϵ_s is the semiconductor dielectric permittivity of the diode.

At the instant of time at point A, the diode current is turned on.

The charge carriers present are those due to thermal generation,

hence the diode initially charges up like a linear capacitor, driving the magnitude of electric field above the breakdown voltage.

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

(B to C)

(B to C) During this time interval the electric field is sufficiently large for the avalanche to continue, and a dense plasma of electrons and holes are created.

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.

A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time in the external current.

At point E the plasma is removed, but a residual charge of electrons remains in one end of the depletion layer and a residual charge of holes in the other end.

As the residual charge is removed, the voltage increases (E to F).

At F, all the charge that was generated internally has been removed.

From point F to G, the diode charges up again like a fixed capacitor.

At G, the diode current goes to zero for half a period and the voltage remains constant at V_A until the current comes back on and the cycle repeats

The electric field expression

$$E(x, t) = E_m - \frac{qN_A}{\epsilon_s}x + \frac{Jt}{\epsilon_s}$$

where N_A is the doping concentration of the n region and x is the distance.

Thus the time t at which the electric field reaches E_m at a given distance x into the depletion region is

$$t = \frac{qN_A}{J}x$$

Differentiating w r t time t

$$v_z \equiv \frac{dx}{dt} = \frac{J}{qN_A}$$

where v_z is the avalanche-zone velocity.

$$\tau_s = \frac{L}{v_s}$$

where v_s is the saturated carrier drift velocity.

τ_s - nominal transit time of the diode in the high field.

Therefore the TRAPATT mode is still a transit-time mode

That is the time delay of carriers in transit (time between injection and collection) is utilized to obtain a current phase shift favorable for oscillation.

- Avalanche Zone Velocity

$V_{az} = J/qN_a$; J = Current Density q = Electron Charge 1.6×10^{-19} N_a = Doping Concentration

- Transit Time

$T = L/V_s$ L =Drift region length V_s =Saturated Carrier

- Frequency of Oscillation

$F = 1/2T$; Where $T = 2(\omega/v_f + (\omega/2)(1/v_p + 1/v_s))$

ω =Depletion Layer ; v_f =Front Velocity

v_p =Plasma Velocity v_s = Saturated Drift Velocity

Example

- What is the Avalance zone velocity of TRAPPAT diode if it characterized by doping concentration of $1.8 \times 10^{15} \text{ cm}^3$ and current density of 25 kA/cm^2

Formula = $V_{az} = J/qNa$

BARITT DIODES

Introduction

Barrier injected transit time diodes

Long drift regions

The carriers traversing the drift regions are generated by minority carrier injection from forward biased junctions instead of being extracted from the plasma of an avalanche region

P-n-p, p-n-v-p, p-n-metal and metal-n-metal

For a p-n-v-p baritt diode the forward biased p-n junction emits holes into the v region. These holes drift with saturation velocity through the v region and are collected at the p contact.

The diode exhibits a negative resistance for transit angles between π and 2π .

Characteristics

Much less noisy than IMPATT diodes.

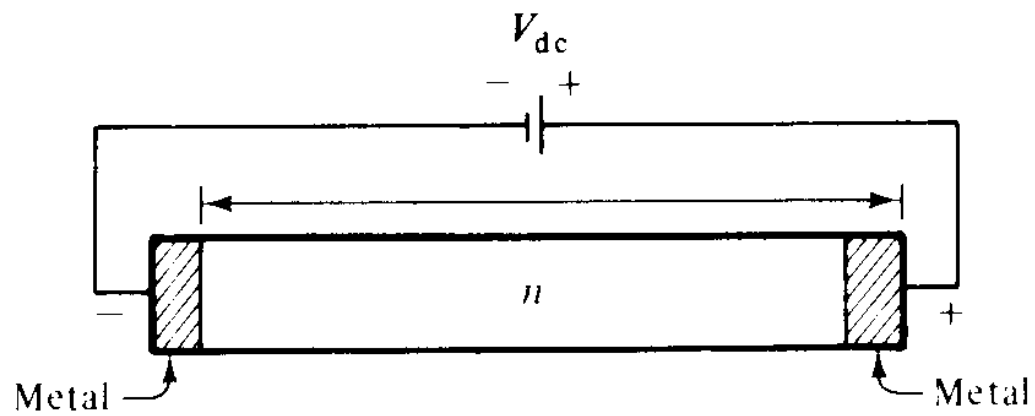
Noise figures are as low as 15 dB with Si BARITT amplifiers.

Narrow Bandwidth and power outputs limited to a few milliwatts.

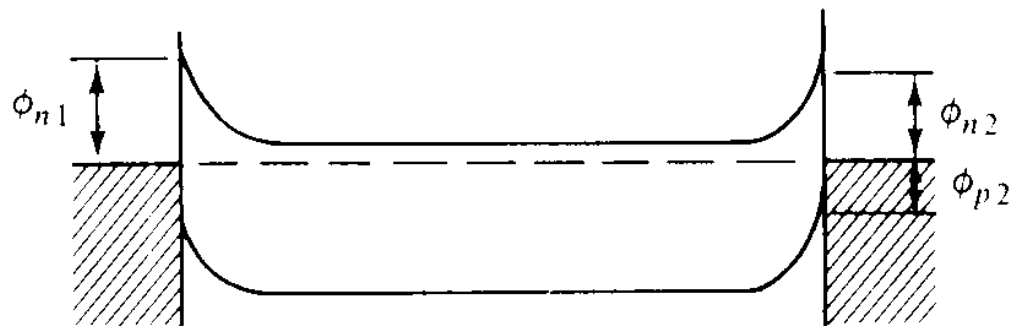
Principle of operation

A crystal n-type Si wafer with 11 Ω -cm resistivity and 4×10^{14} per cubic cm doping is made of a 10- μ m thin slice.

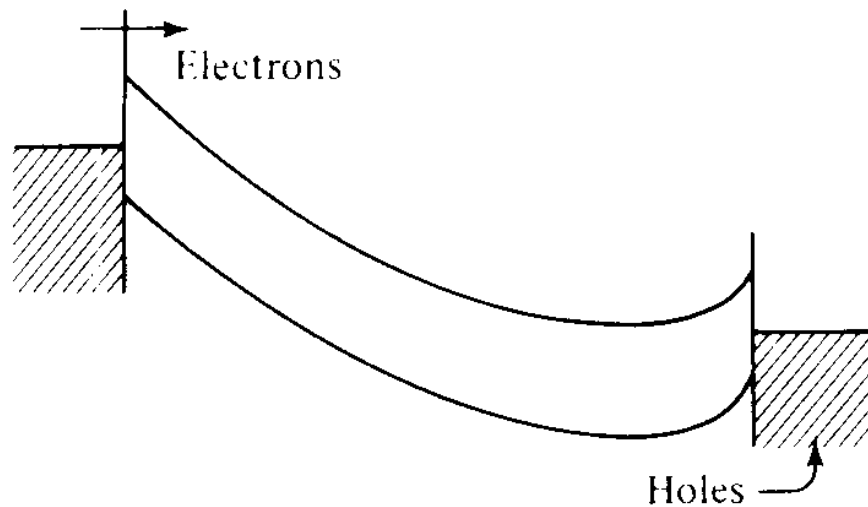
The wafer is sandwiched between two PtSi Schottky barrier contacts of about 0.1 μ m thickness.



(a) M-n-M diode



(b) Energy band diagram in thermal equilibrium



(c) Energy band under bias condition

The energy band diagram at thermal equilibrium is shown.

where ϕ_{n1} and ϕ_{n2} are the barrier heights for the metal-semiconductor contacts.

For the PtSi-Si-PtSi structure $\phi_{n1} = \phi_{n2} = 0.85$ eV.

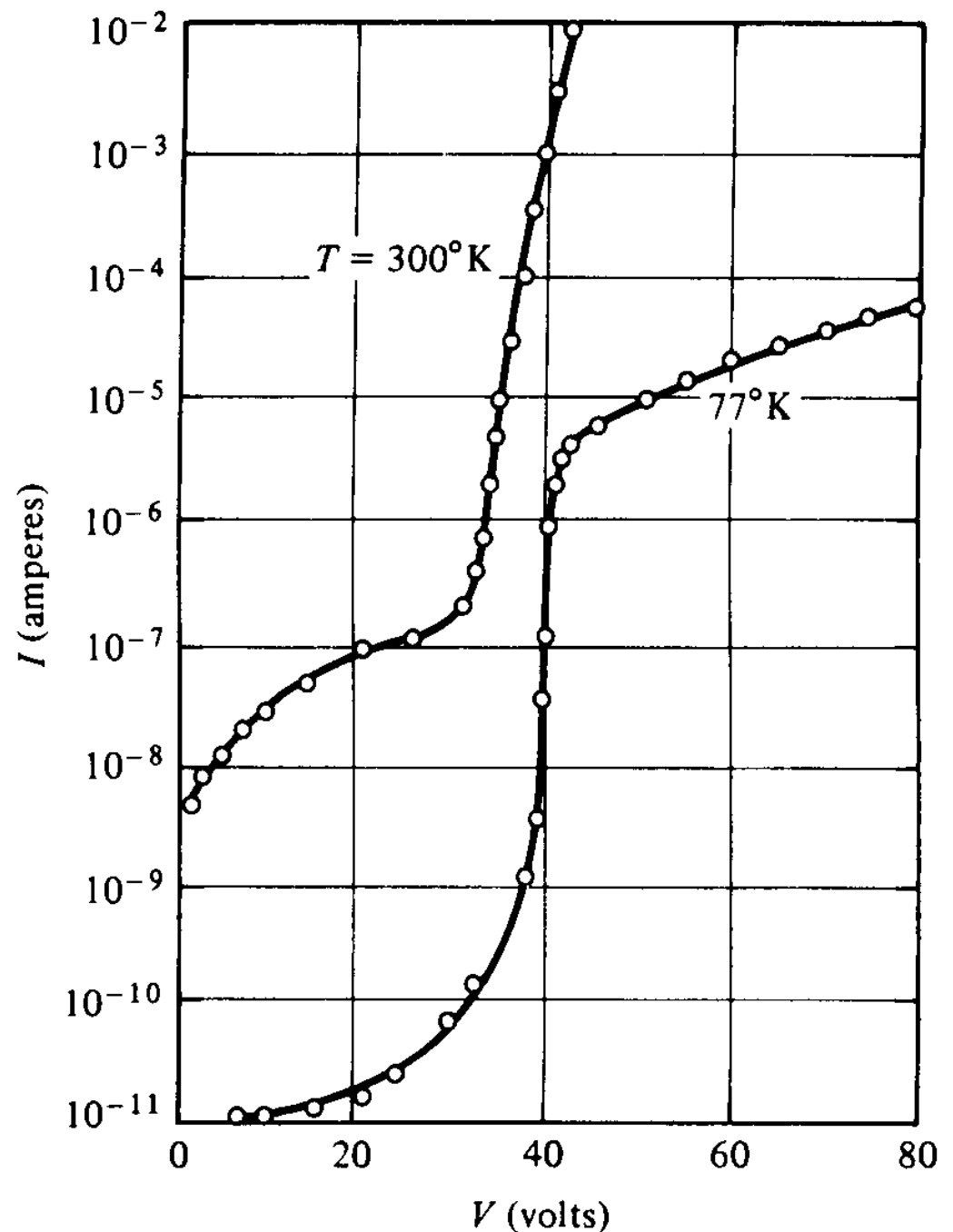
The hole barrier height ϕ_{p2} for the forward biased contact is about 0.15 eV

Fig c shows the energy band diagram when a voltage is applied.

The mechanisms responsible for oscillations are derived from:

1. The rapid increase of the carrier injection process caused by decreasing potential barrier of the forward biased metal semiconductor contact.
2. An apparent $3\pi/2$ transit angle of the injected carrier that traverses the semiconductor depletion region.

The rapid increase in terminal current with applied voltage (above 30 V) is caused by thermionic hole injection into the semiconductor as the depletion layer of the reverse-biased contact reaches through the entire device thickness.



The critical voltage is given by

$$V_c = \frac{qNL^2}{2\epsilon_s}$$

where N = doping concentration

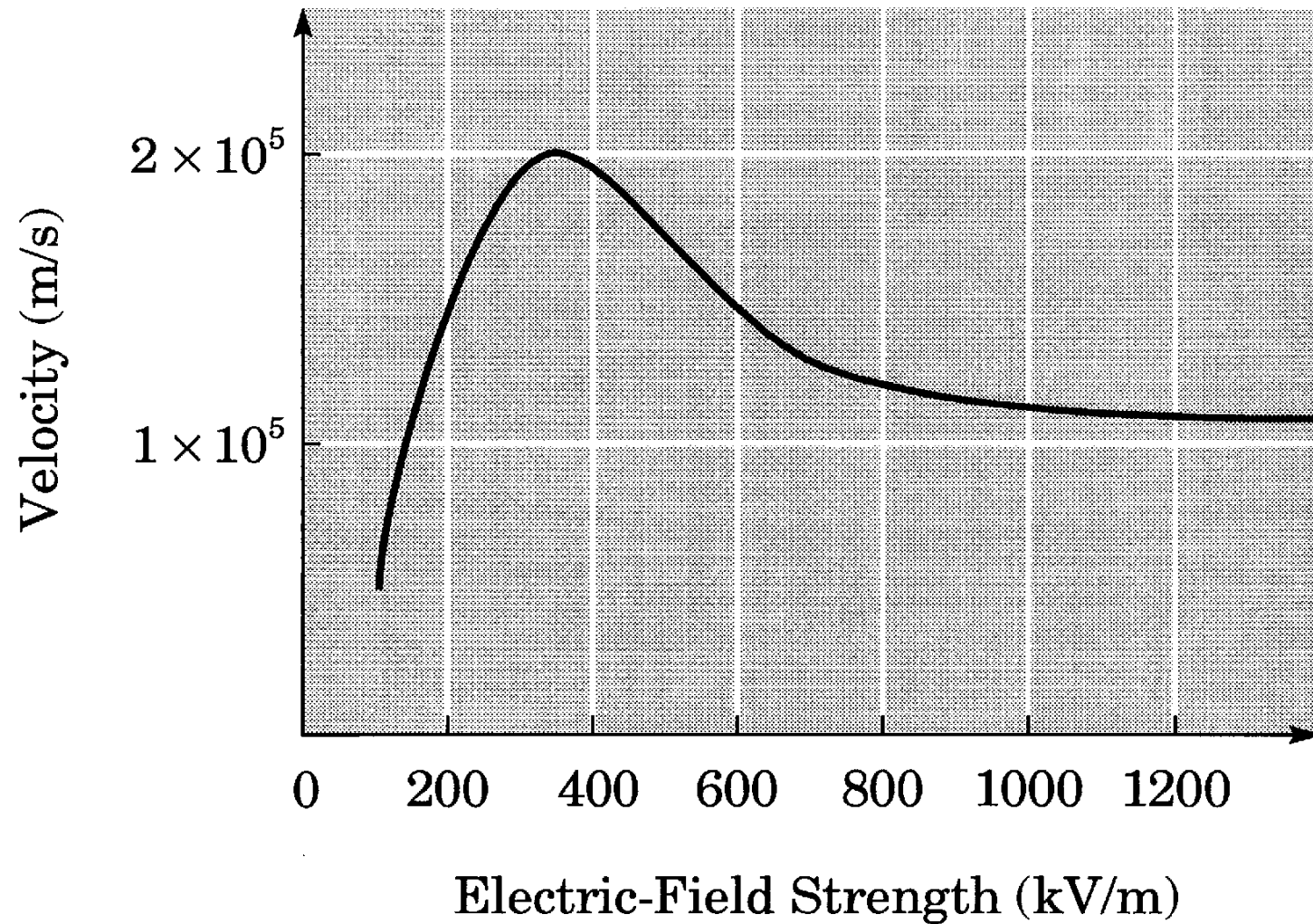
L = semiconductor thickness

ϵ_s = semiconductor dielectric permittivity

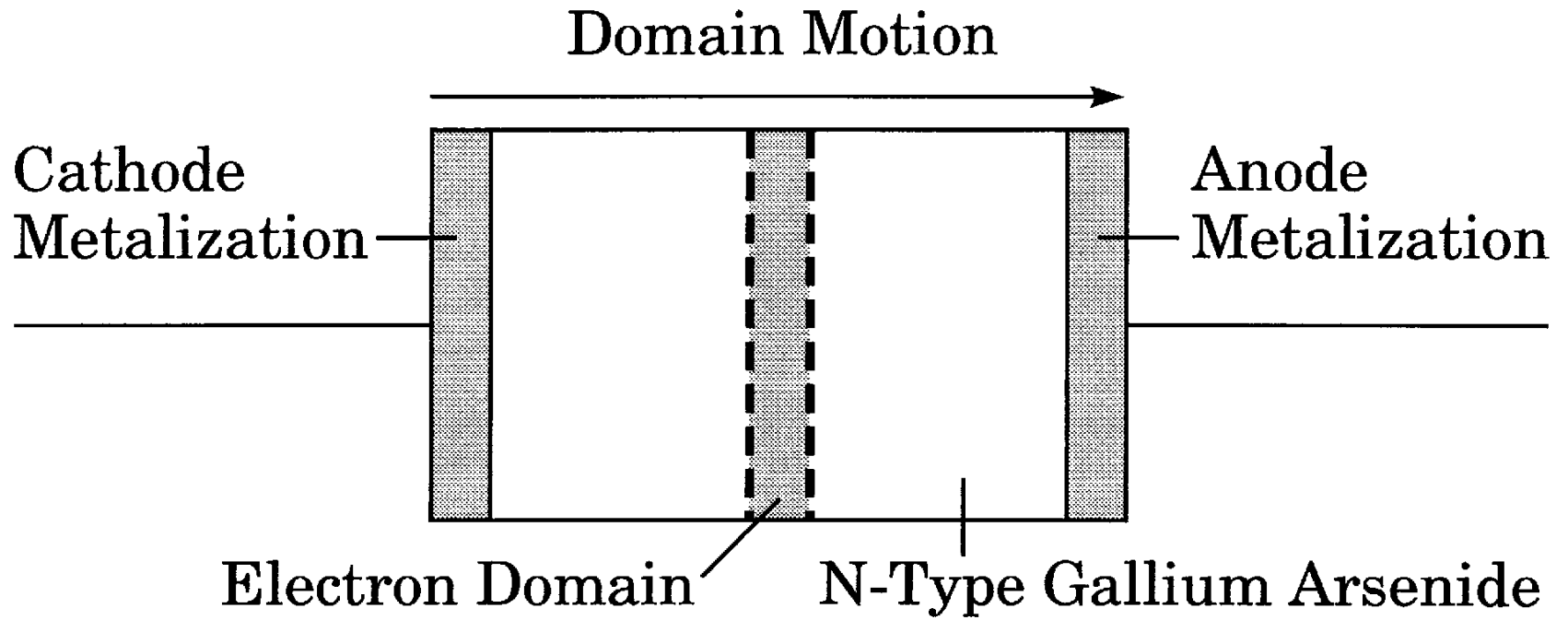
Gunn Device

- Slab of N-type GaAs (gallium arsenide)
- Sometimes called Gunn diode but has no junctions
- Has a negative-resistance region where drift velocity decreases with increased voltage
- This causes a concentration of free electrons called a domain

Drift Velocity in Gallium Arsenide



Gunn Device (Cross Section)



Gunn Oscillator Frequency

- $T = d/v$

T = period of oscillation

d = thickness of device

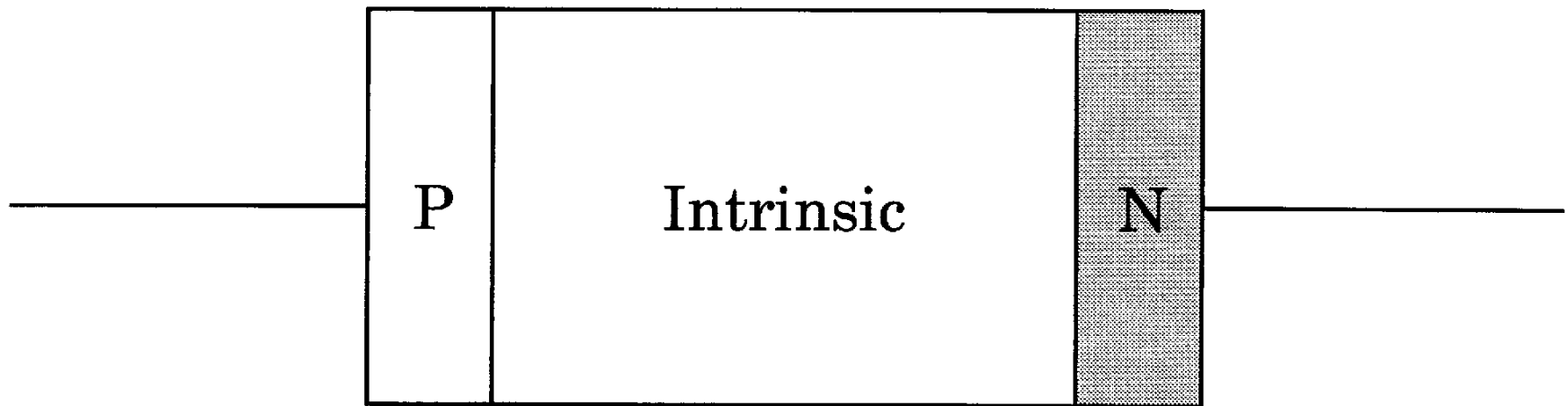
v = drift velocity, about 1×10^5 m/s

- $f = 1/T$

PIN Diode

- P-type --- Intrinsic --- N-type
- Used as switch and attenuator
- Reverse biased - off
- Forward biased - partly on to on depending on the bias

PIN Diode



Gallium Arsenide