UNIT-4

Microwave Engineering

Microwave Solid State Devices

- Two problems with conventional transistors at higher frequencies are:

  1. Stray capacitance and inductance.

     - remedy is interdigital design.

  2. Transit time.

     - free electrons move quicker than holes therefore change from silicon to Gallium Arsenide

Microwave Transistors

- Conventional bipolar transistors are not suitable for microwave frequencies.
- Electrons move faster than holes.
- Component leads introduce elevated reactance.
- XL increases and XC decreases therefore collector feedback becomes worse as frequency increases.
- Transit time and mobility of carriers. As transit time approaches signal period phase shifts occur.

Microwave Transistors

- REMEDIES:
- Interdigital design of emitter and base minimizes capacitances.
- Gallium arsenide. Faster than silicon.
- N type GaAsFET. Why N type?
- Flat component leads.

Microwave Transistors

- REMEDIES contd.:

➢ Low noise design considerations:

* Planar and epitaxial methods of construction use diffusion and surface passivation to protect surfaces from contamination as opposed to diffusion method of mesa structure implementing acid etching.

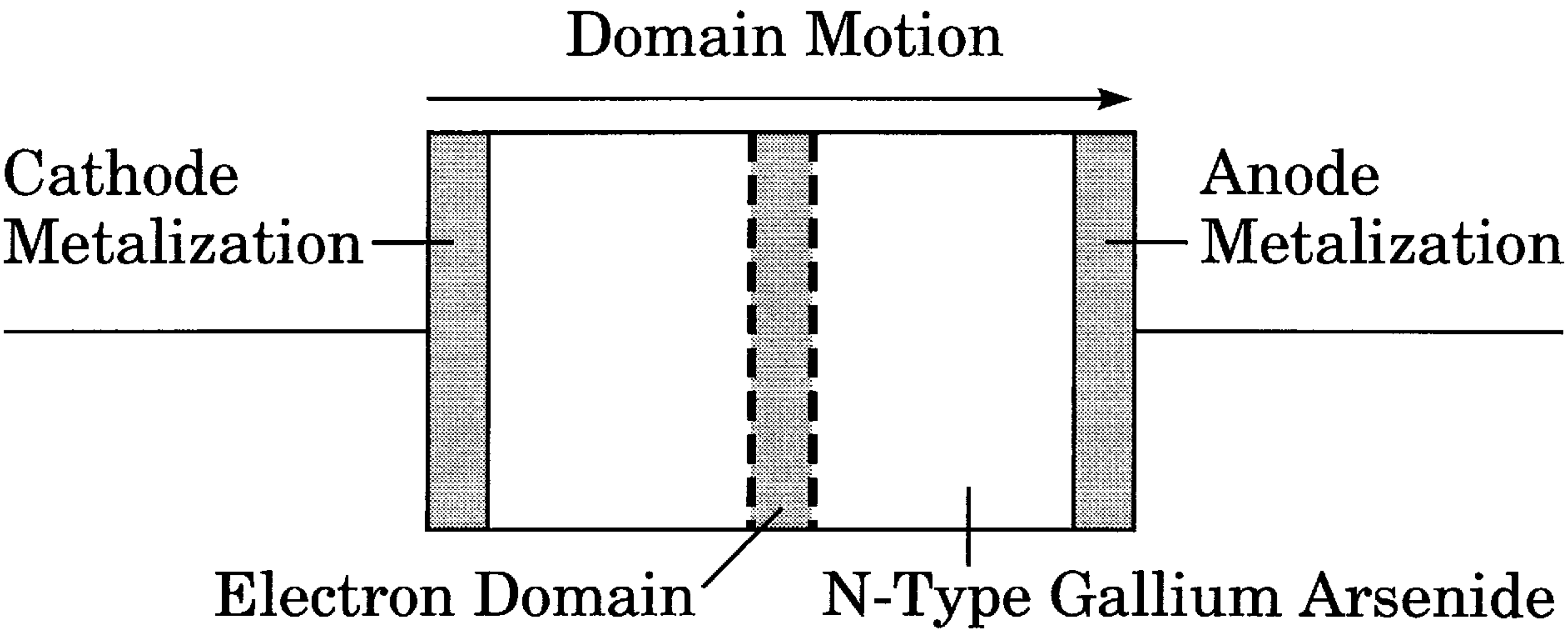
* Shot noise is proportional to the square of current therefore operate at moderate Ic.

* Thermal noise is reduced at lower power levels. With interdigital base design Rb is low therefore lower voltage drop and less power.

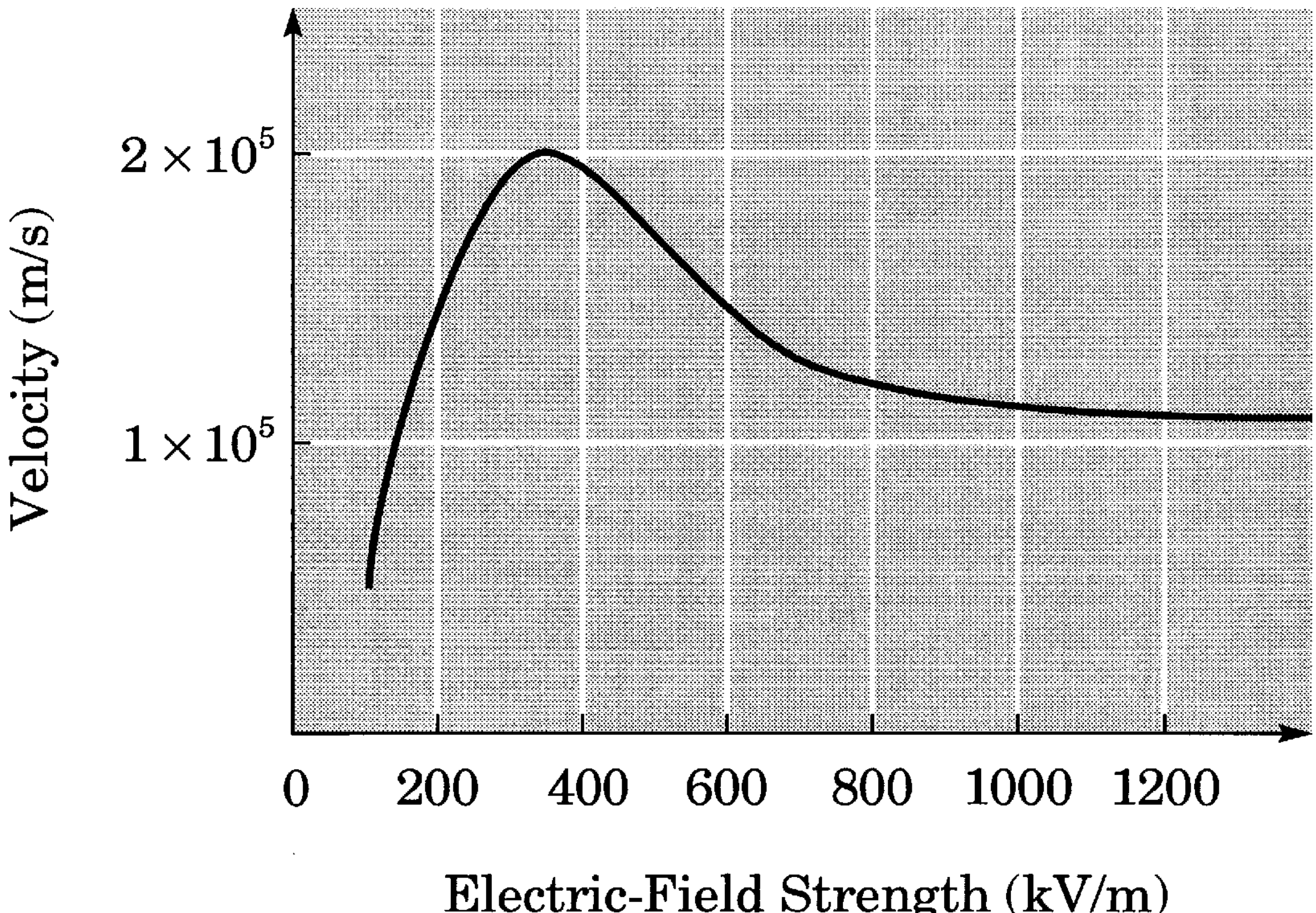
Gunn Devices

- Uses phase shift to minimize transmit time.
- Transferred-electron device (TED).
- N type GaAs – electron mobility decreases as electric field strength increases.
- Characterized by a negative resistance region.
- A domain is developed that sustains oscillations as a voltage is applied to the substrate of GaAS.
- A pulse current develops as domain of charge travels to the positive terminal.

Gunn Device (Cross Section)



Drift Velocity in Gallium Arsenide



Transparency 267 (Figure 19.33)

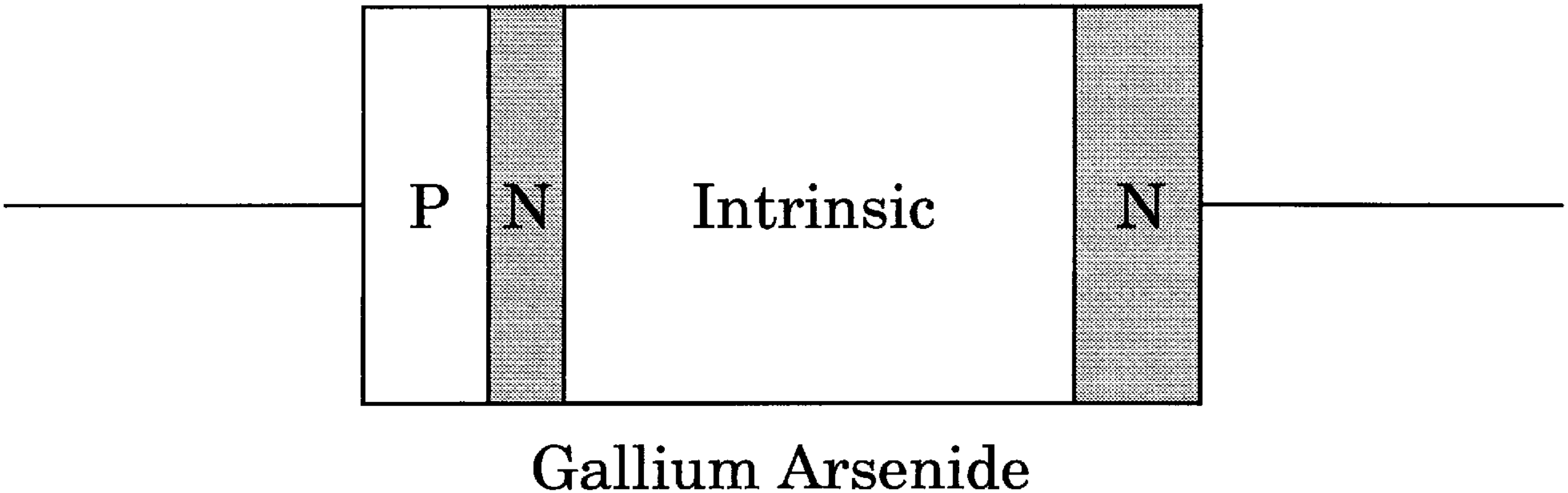
Other Devices

- Pin Diodes - R.B.(R II C) F.B. (variable R)
- Varactor Diodes – R.B. (variable junction capacitance)
- YIG Yitrium-Iron-Garnet Devices
- Dielectric Resonators
- MMICs – monolithic microwave integrated circuits

HEMT

- High Electron Mobility Transistor
- Similar to GaAsFET construction.
- Difference is that motion of charge carriers is confined to a thin sheet within a GaAs buffer layer.
- GaAs/AlGaAs heterostructure epitaxy.
- The thickness of the channel remains constant while the number of carriers is modulated by the gate bias as opposed to a MESFET that modulates the channel thickness.
- PHEMT- pseudomorphic HEMT used above 20 GHz (mm wave)

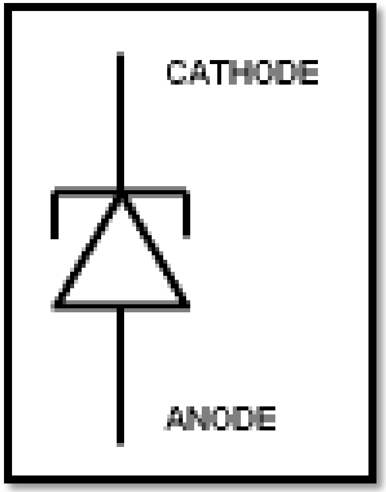
IMPATT Diode

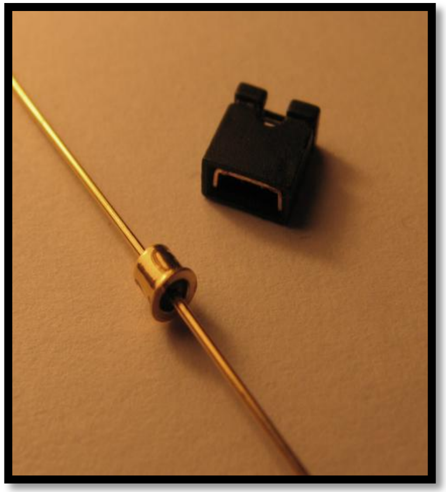


Transparency 268 (Figure 19.36)

Introduction

- Invented by Dr. Leo Esaki in 1958.
- Also called Esaki diode.
- Basically, it is heavily doped PN- junction.
- These diodes are fabricated from germanium, gallium arsenide (GaAs), and Gallium Antimonide.
- Symbol:





Description

- Tunnel diode is a semi-conductor with a special characteristic of negative resistance.

- By negative resistance, we mean that when voltage is increased, the current through it decreases.

- Highly doped PN- junction. Doping density of about 1000 times greater than ordinary junction diode.

Construction

- Heavy Doping Effects:

i. Reduces the width of depletion layer to about 0.00001 mm.
ii. Produces negative resistance section in characteristics graph of diode.
iii. Reduces the reverse breakdown voltage to a small value approaches to zero.
iv. Small forbidden gaps in tunnel diode.
v. Allows conduction for all reverse voltages.

Basic principle of operation:

- The operation depends upon quantum mechanics principle known as “tunneling”.
- The movement of valence electrons from valence energy band to conduction band with no applied forward voltage is called “tunneling”.
- Intrinsic voltage barrier (0.3V for Ge) is reduced which enhanced tunneling.
- Enhanced tunneling causes effective conductivity.

Working:

- In a conventional diode, forward conduction occurs only if the forward bias is sufficient to give charge carriers the energy necessary to overcome the potential barrier.
- When the tunnel diode is slightly forward biased, many carriers are able to tunnel through narrow depletion region without acquiring that energy.
- The carriers are able to tunnel or easily pass because the voltage barrier is reduced due to high doping.

Working(contd.)

- Forward Bias operation:

At first voltage begin to increase,

1. Electrons tunnel through pn junction.
2. Electron and holes states become aligned.

Voltage increases further:

1. States become misaligned.
2. Current drops.
3. Shows negative resistance (V increase, I decrease).

As voltage increase yet further:

1. The diode behave as normal diode.
2. The electrons no longer tunnel through barrier.

Working(contd.)

- Reverse Bias Operation:

When used in reverse direction, they are called as Back Diodes.

In this,

i. The electrons in valence band of p-side tunnel directly towards the empty states present in the conduction band of n-side.
ii. Thus, creating large tunneling current which increases with application of reverse voltage.

I/V Characteristics

As forward bias is applied, significant I is produced.

After continuous increase of V, the current achieves its minimum value called as Valley Current. After further increase in V, current start increasing as ordinary diode.

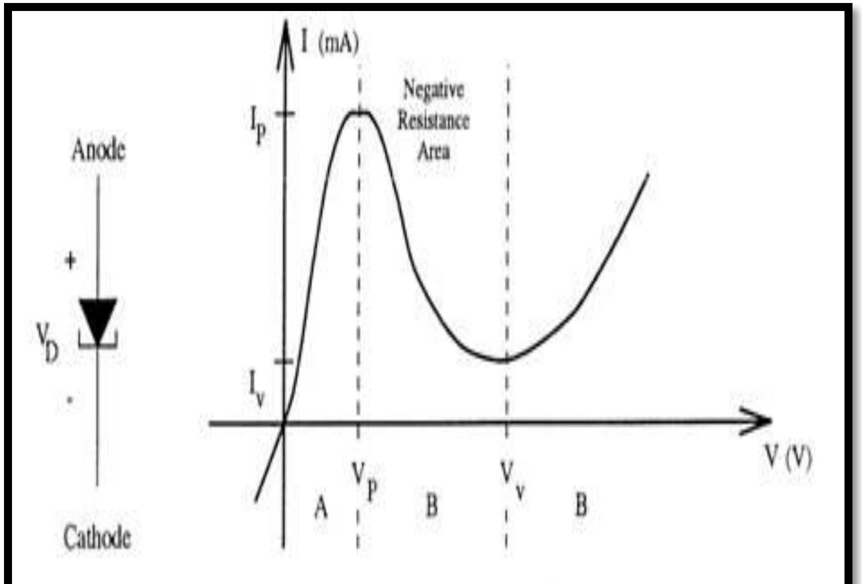
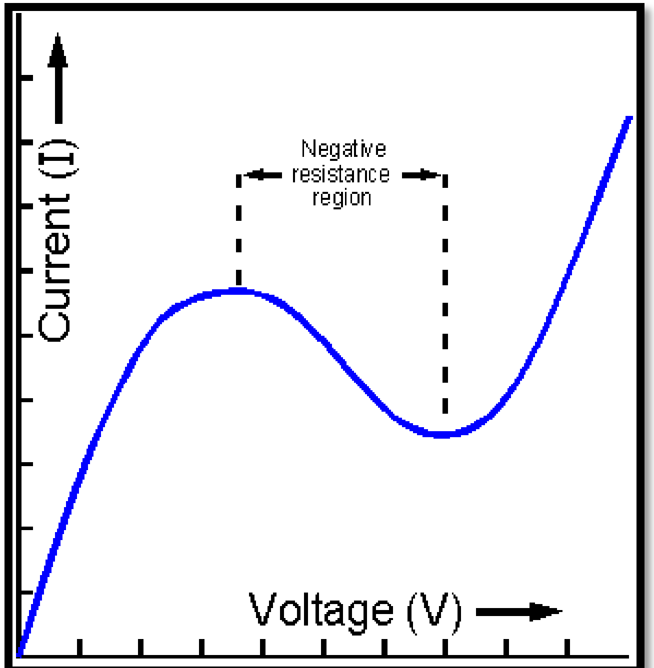
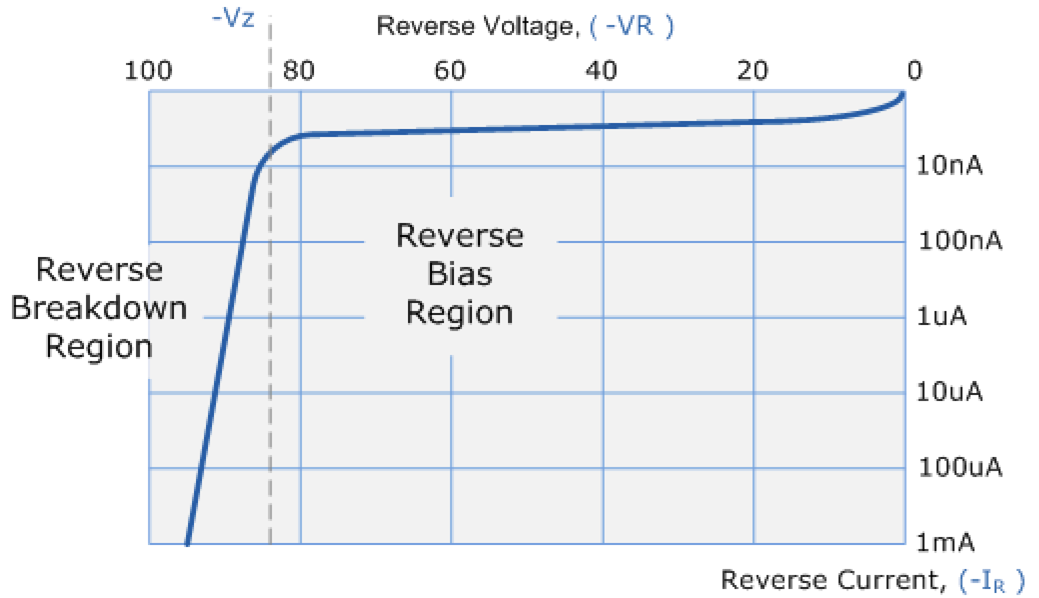


Figure 6.3: Tunnel Diode



I/V Characteristic(contd.)

- The Tunnel diode reverse I-V is similar to the Zener diode.
- The Zener diode has a region in its reverse bias characteristics of almost a constant voltage regardless of the current flowing through the diode.



Applications:

- It is used as an ultra- high speed switch due to tunneling (which essentially takes place at speed of light). It has switching time of nanoseconds or picoseconds.
- Used as logic memory storage device.
- In satellite communication equipment, they are widely used.
- Due to its feature of –ive resistance, it is used in relaxation oscillator circuits.

Applications(contd.):

- Tunnel diodes are resistant to the effects of magnetic fields, high temperature and radioactivity. That's why these can be used in modern military equipments -

  NMR machines.

- Due to low power requirement, they are used in FM receivers.

Avalanche transit time devices

Principle of operation

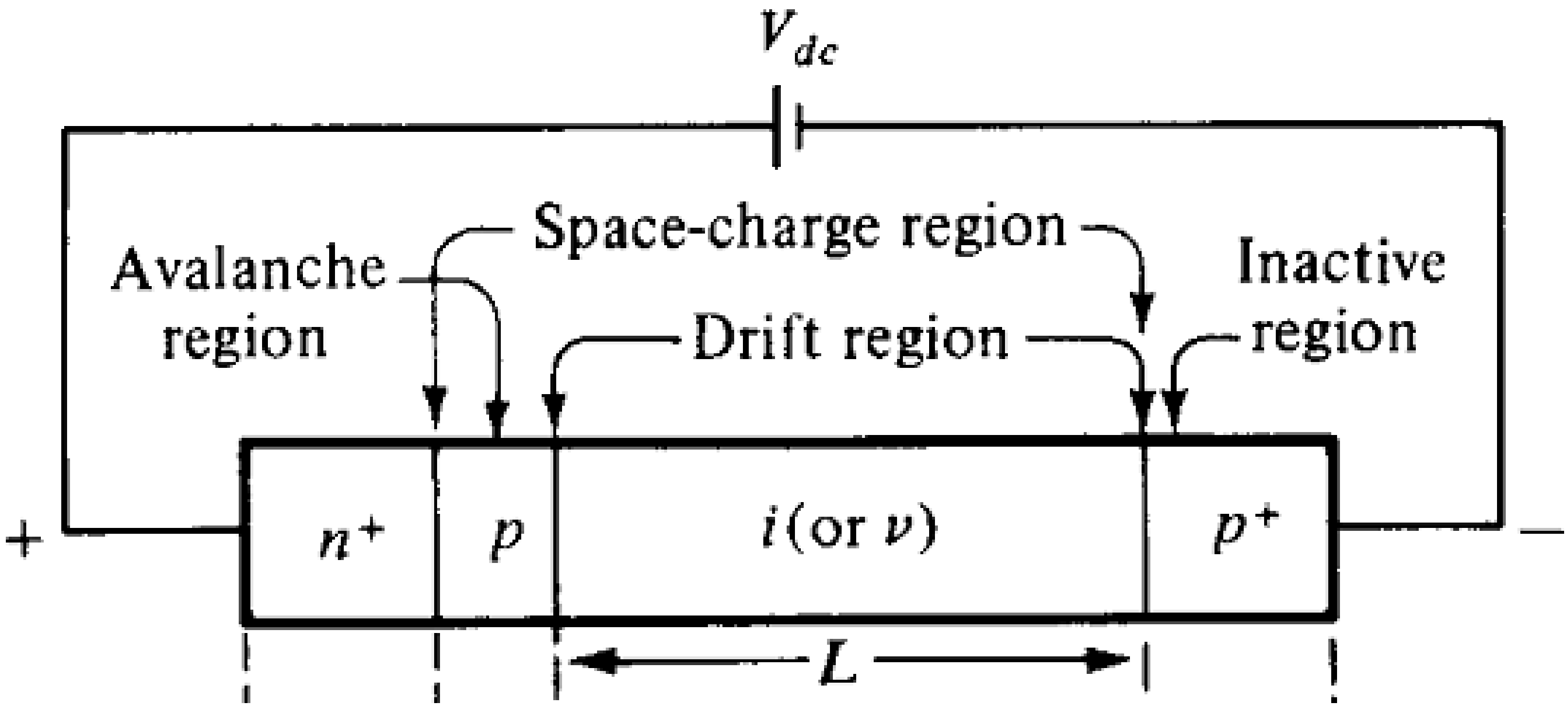
- Negative resistance is achieved by creating a delay (180^0 Phase shift) between the voltage and current.
- Delay is achieved by,
  - Delay in generating the **avalanche** current multiplication
  - Delay due to transit time through the material
- So called **Avalanche transit time (ATT) devices**
- Avalanche is generated by Carrier impact ionization
- TT is due to the drift in the high field domain

Features

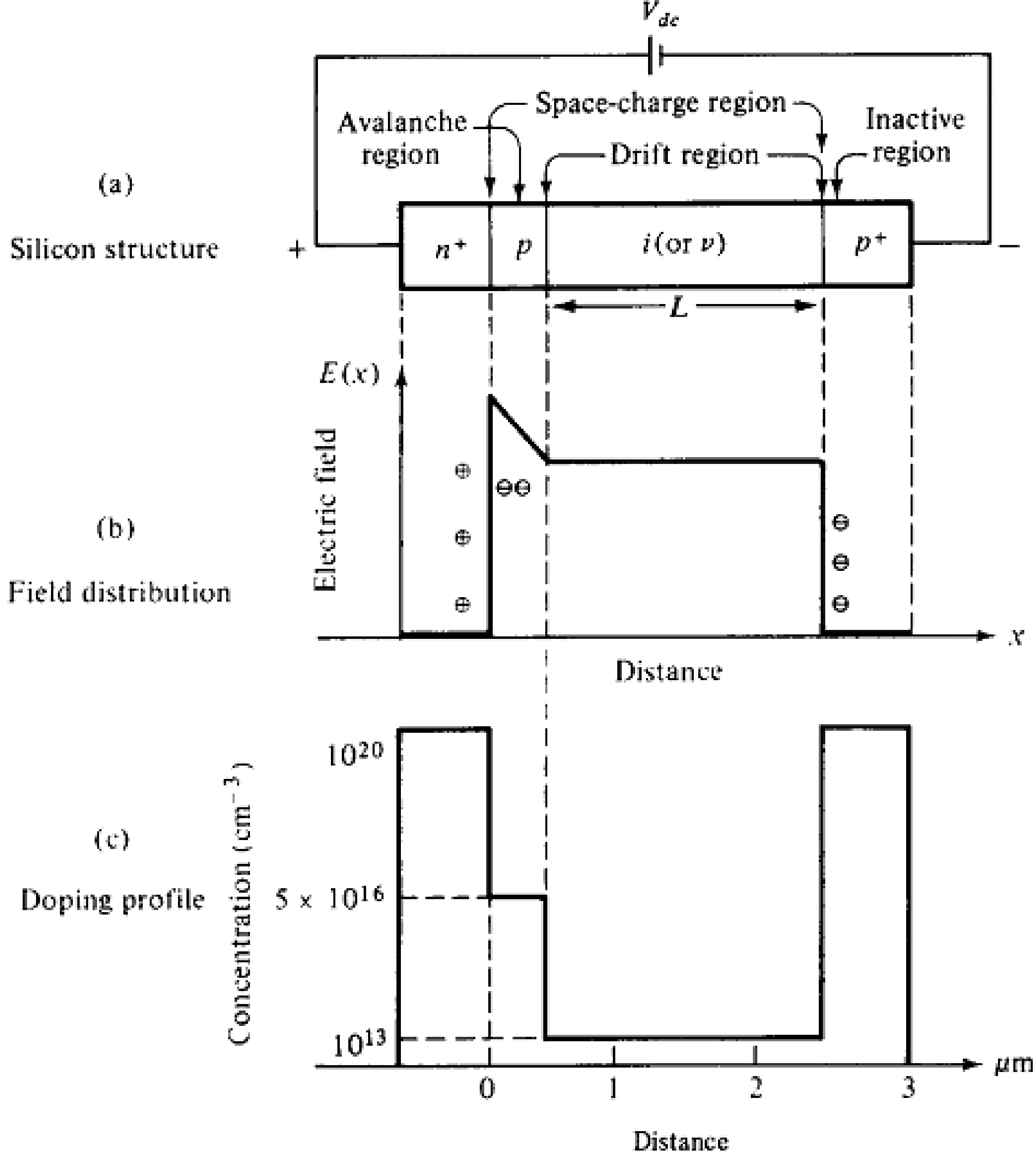
- Presence of P-N junctions
- Diode is reverse biased
- High field (potential gradient) is applied of the order 400 KV/cm

- Two modes of ATT
  - IMPATT- Impact ionization ATT (Efficiency 5-10%)
  - TRAPATT- Trapped plasma ATT (Efficiency 20-60%)

Read diode(IMPATT)



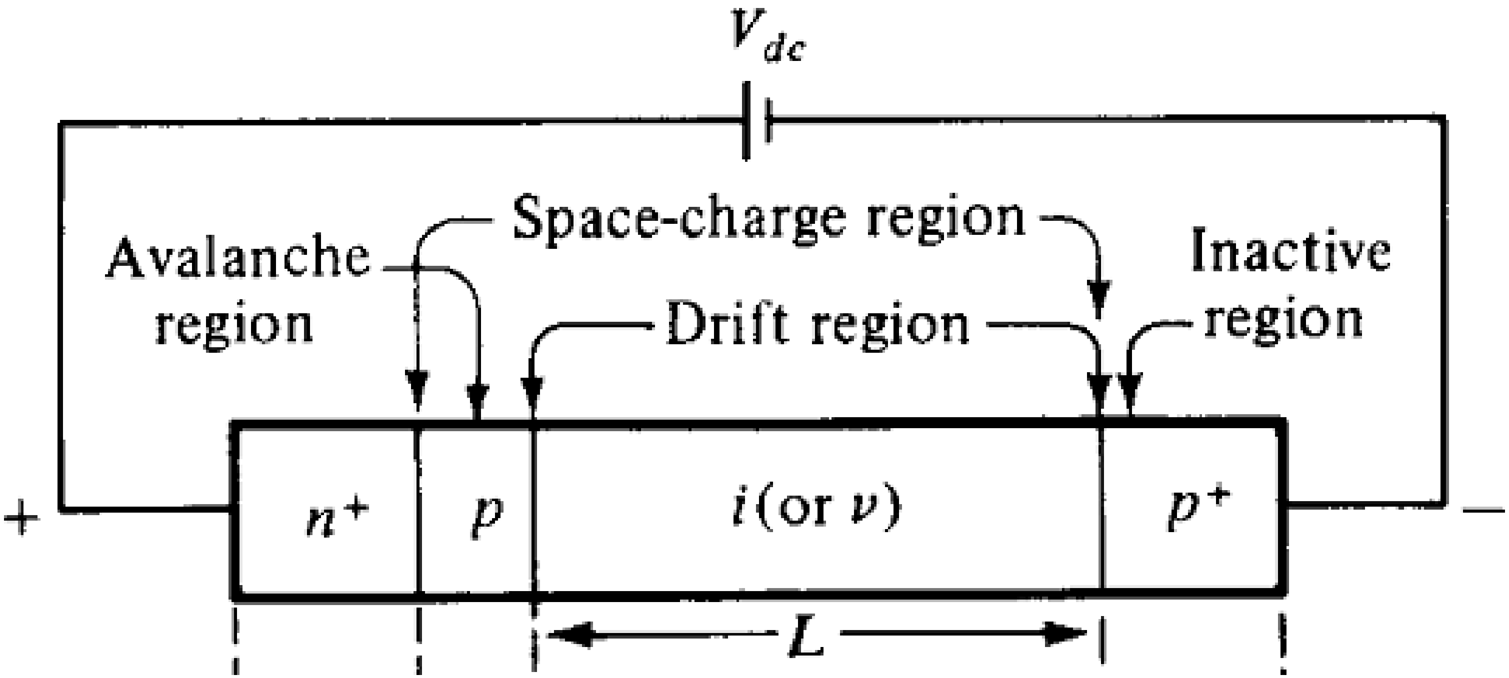
Read diode (IMPATT)



- Read diode is $n^+ p\ i\ p^+$ diode
- Avalanche multiplication at p region
- Intrinsic region acts as the drift space where the generated holes must drift toward p+
- Space between $n^+ p$ junction and $i\ p^+$ junction is called the space charge region
- The device operation delivers power from the dc bias to the oscillation

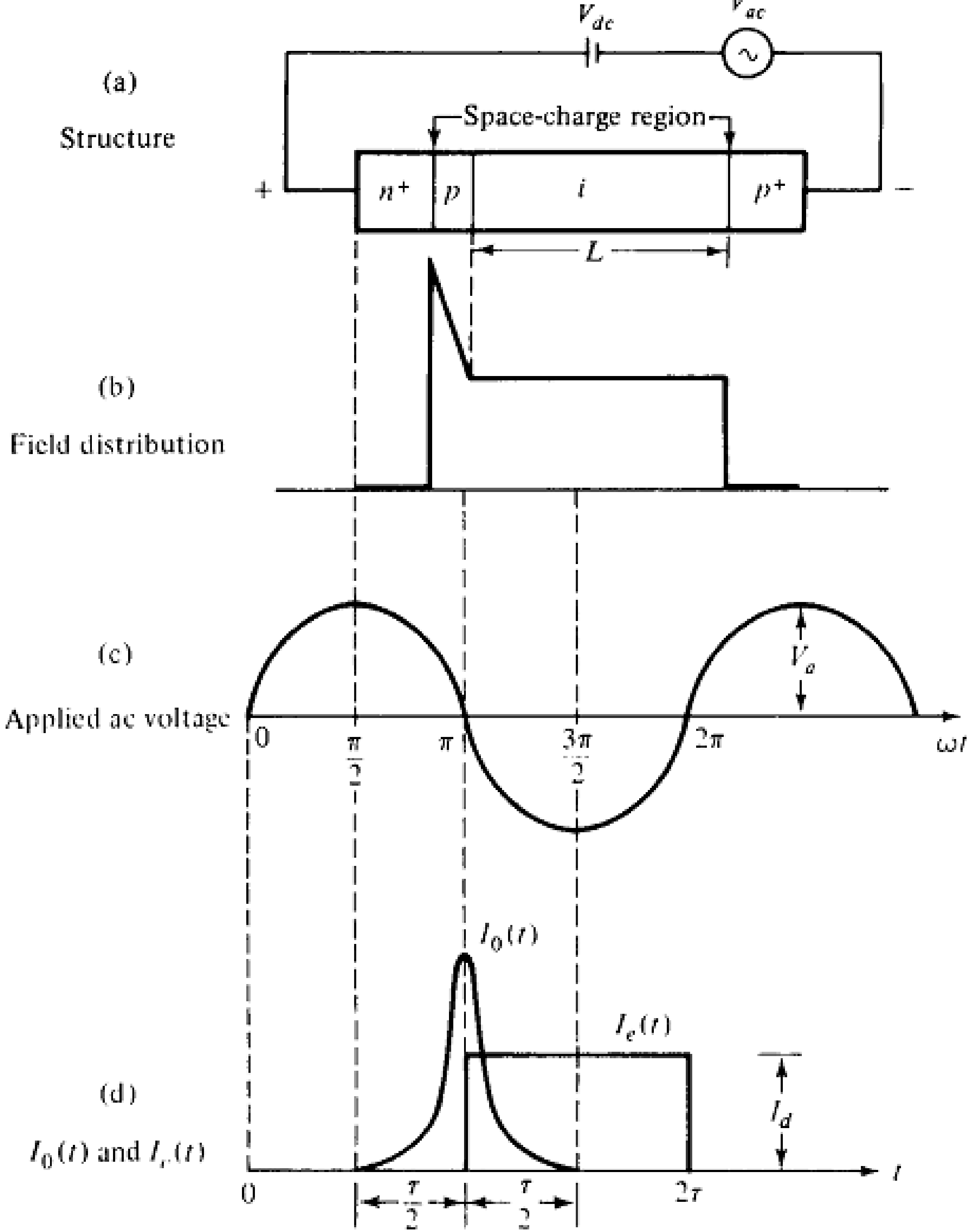
- Operation:

  – Avalanche multiplication and drift of the



$$\tau = \frac{L}{v_d}$$

$$M = \frac{1}{1 - (V/V_b)^n}$$



– Carrier current $I_0(t)$ and External current $I_e(t)$

$$2\pi f = \frac{\pi}{\tau}$$

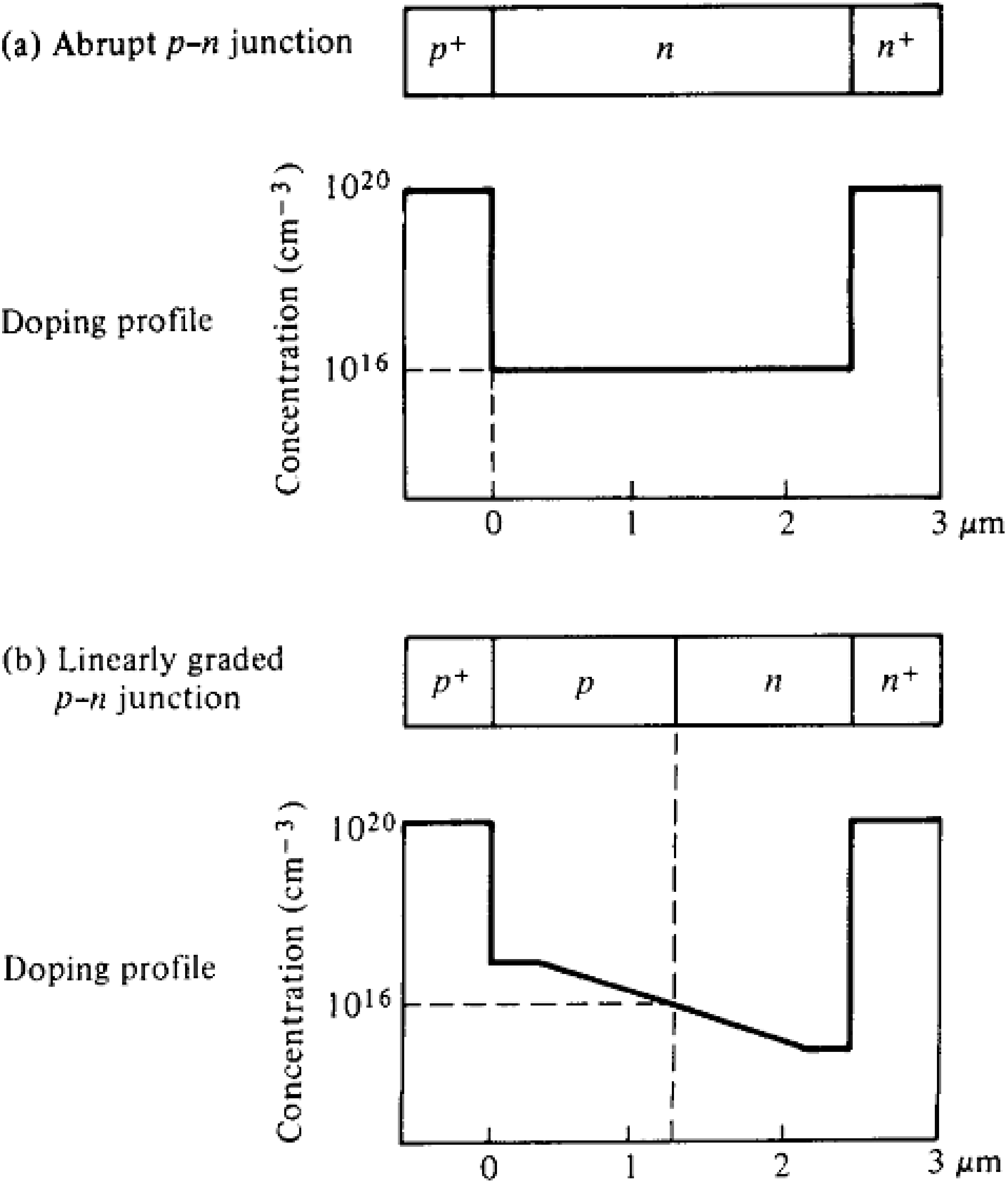
$$f = \frac{1}{2\tau} = \frac{v_d}{2L}$$

IMPATT DIode

- The physical mechanism is the interaction of impact ionization avalanche and the transit time of charge carriers.
- So Read-type diodes are also called IMPATT diode.

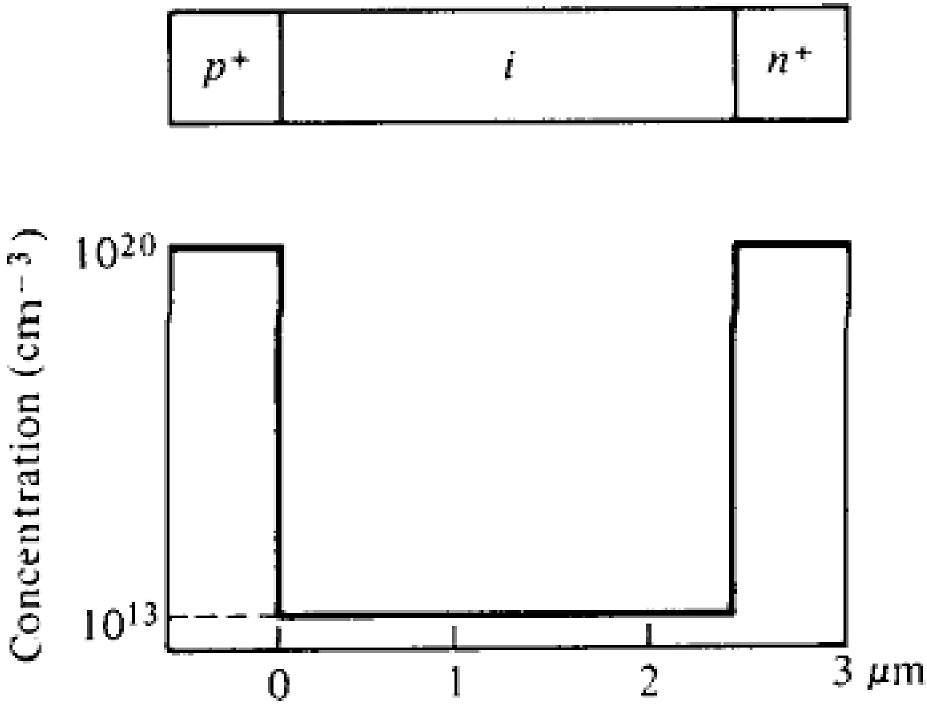
$n^+\text{-}p\text{-}i\text{-}p^+$ or $p^+\text{-}n\text{-}i\text{-}n^+$

- Most simplest IMPATT diodes are the basic Read diodes
- Three typical *Si* IMPATT diodes are shown below. Operations are similar to Read diode


(a) Abrupt p–n junction
p+
n
n+
Doping profile
Concentration (cm−3)
10^20
10^16
0
1
2
3 μm
(b) Linearly graded p–n junction
p+
p
n
n+
Doping profile
Concentration (cm−3)
10^20
10^16
0
1
2
3 μm

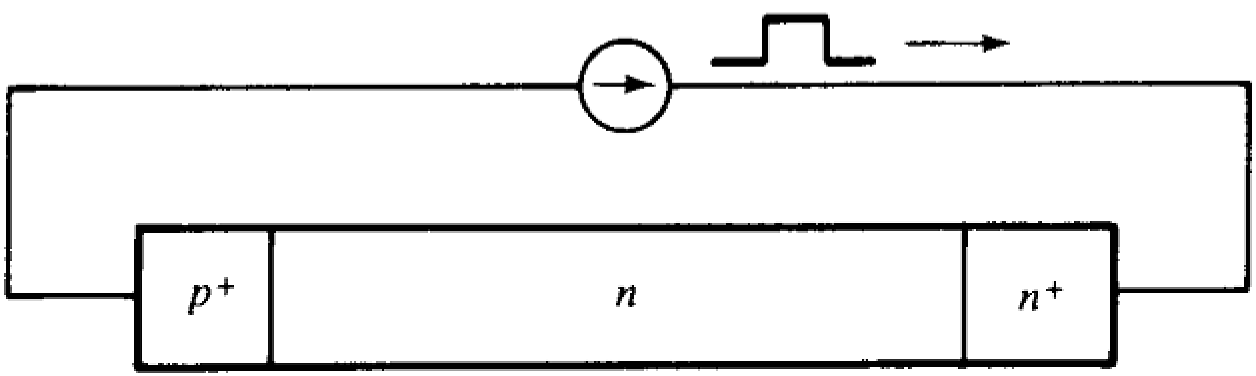
(c) *p–i–n* diode

Doping profile

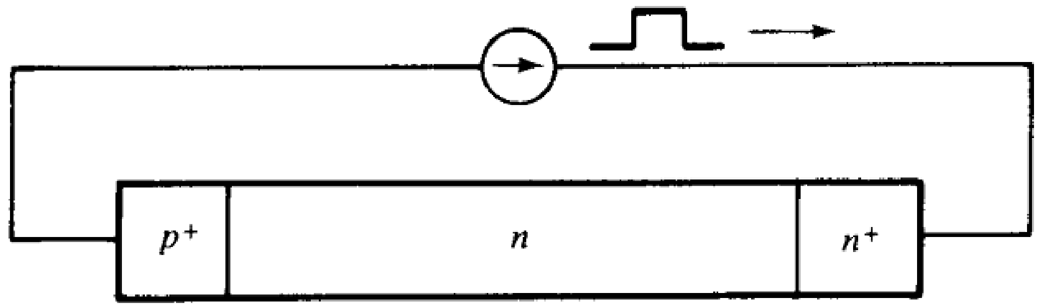


TRAPATT DIOde

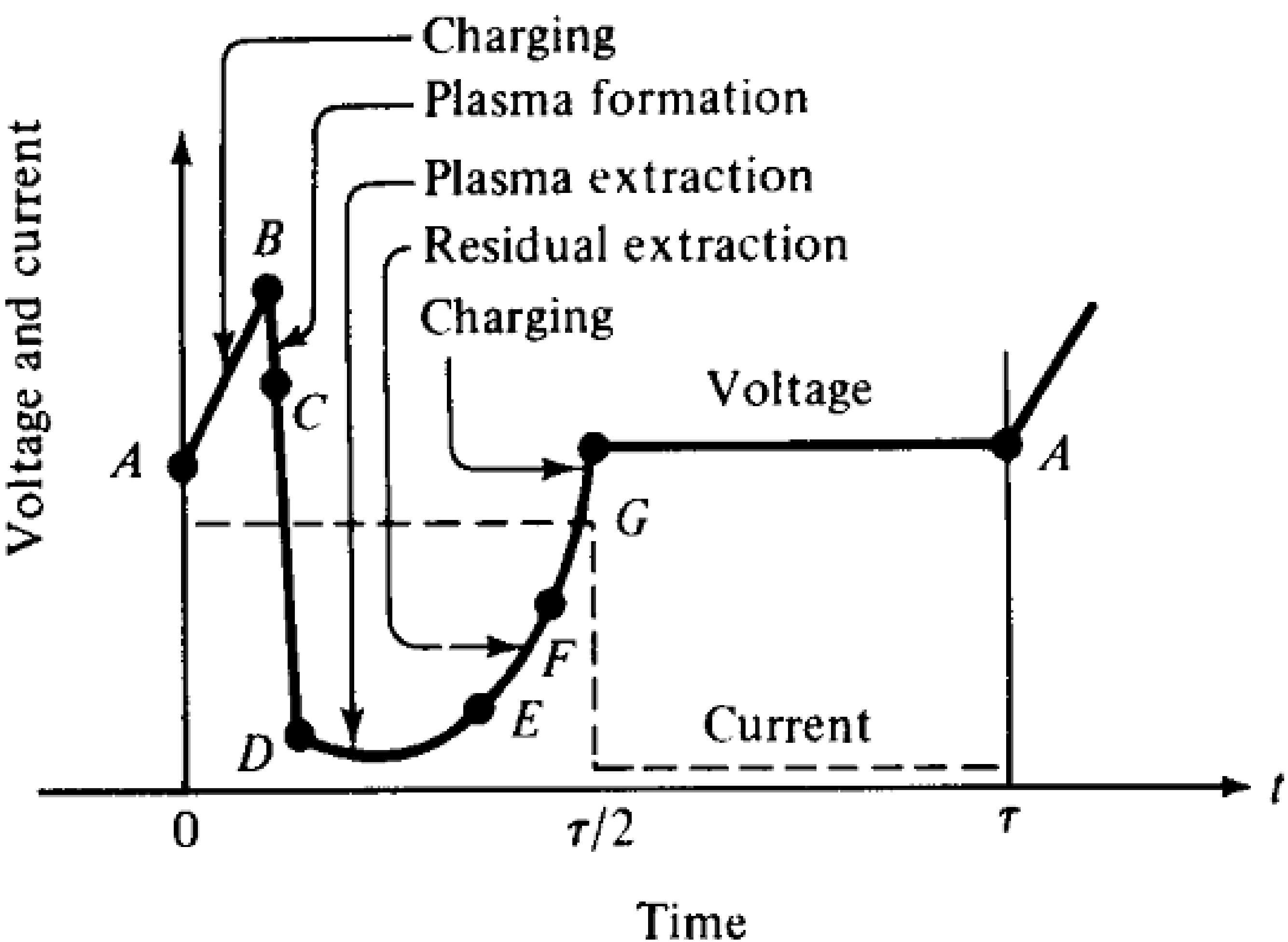
- Derived from IMPATT diode
- Presence of P-N junctions
- Diode is reverse biased
- High current densities than normal ava n^+-p-p^+ (or p^+-n-n^+)
- It



- Operation:

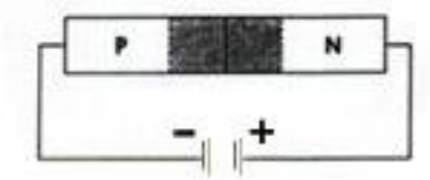


p^+
n
n^+



Charging
Plasma formation
Plasma extraction
Residual extraction
Charging
Voltage
Current
Voltage and current
A
B
C
D
E
F
G
A
0
τ/2
τ
t
Time

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

TYPES OF VARACTOR DIODES

- **Abrupt and hyper abrupt type** : When the changeover p-n junction is abrupt then it is called abrupt type. When change is very abrupt, they are called hyper abrupt type. They are used in oscillators to sweep for different frequencies.

- **Gallium-arsenide varactor diodes** : The semiconductor material used is gallium arsenide. They are used for frequencies from 18 GHz up to and beyond 600 GHz.

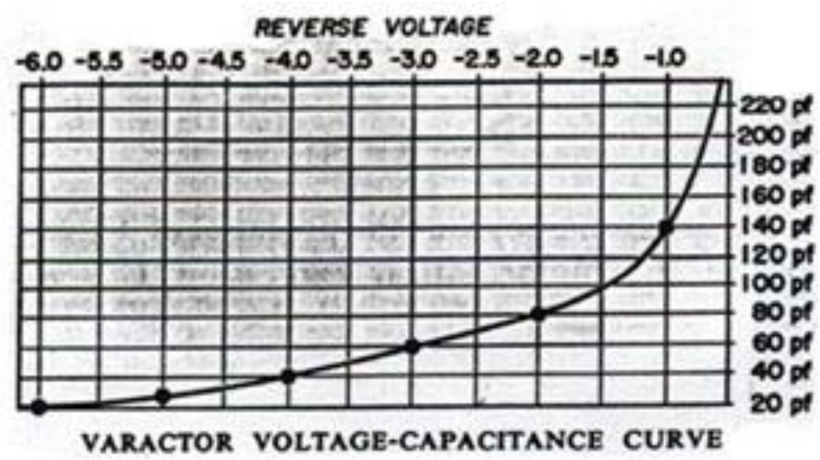
IMPORTANT CRITERIA

- **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

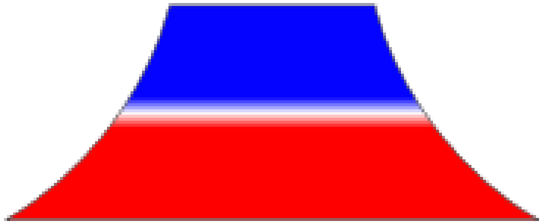


- Notice the nonlinear increase in capacitance as the reverse voltage is decreased.

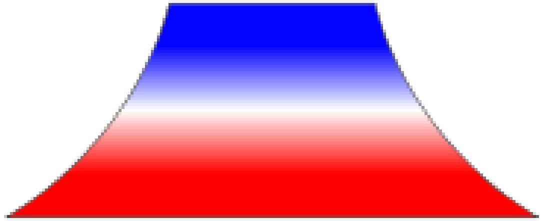
OPERATION

- 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

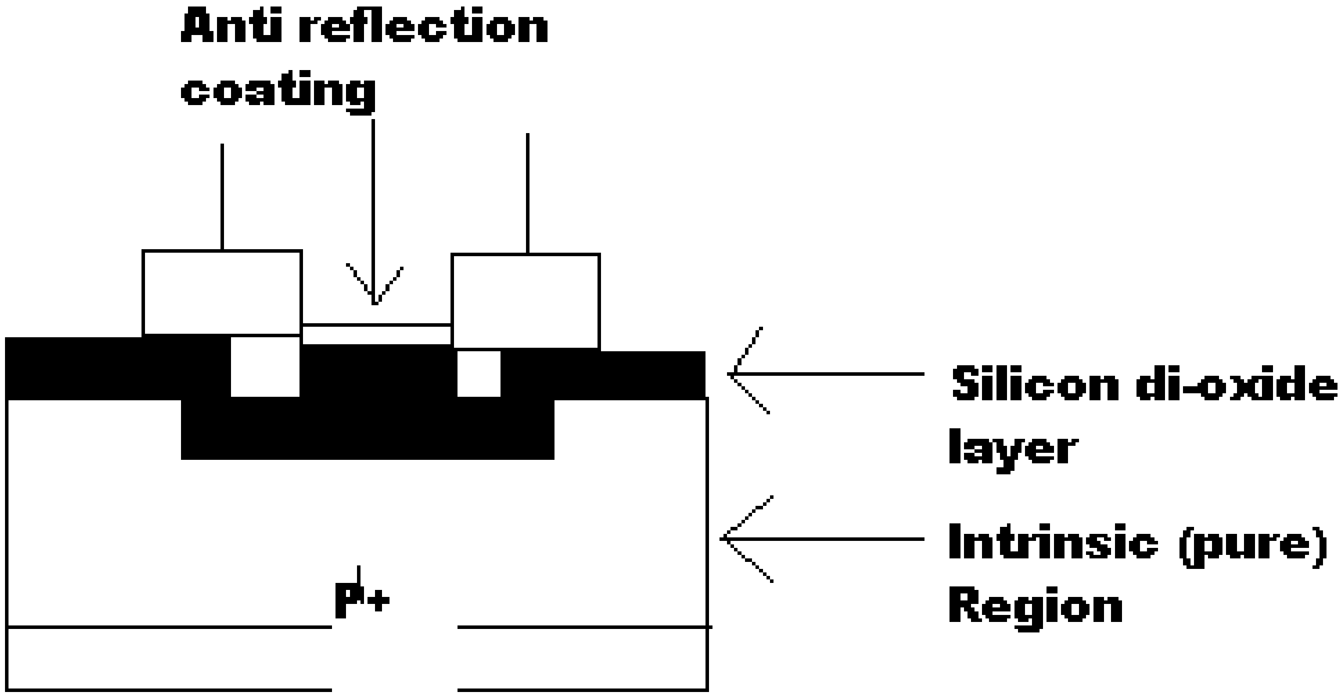
- **TUNING** - Since the frequency can be made to vary they are used as electronic tuning devices in tuners for television, mobiles.

- **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.

PIN DIODE

Construction



- PIN diode constructed by sandwiching an intrinsic (pure) semiconductor between heavily doped p+ and n+ semiconductor
- An anti-reflecting coating is applied at the top face of the pin diode to received light radiation and ovoid secondary emission
- By concentrating absorption at the intrinsic region, it reduce the noise and slow switching response when it radiates to light as in the case of conventional photo diodes
- The reduce noise and increased speed can also be achieved due to the fact that it has higher resistivity than other devices of this family
- The speed of the PIN diode is limited by variation in the time it takes electrons to pass through the device. This time spread can be spread in two ways:
    - ➢ By increasing the bias-voltage
    - ➢ By reducing the thickness of intrinsic layer

Types

- Metal – semiconductor PIN diode
- Heterojunction PIN diode

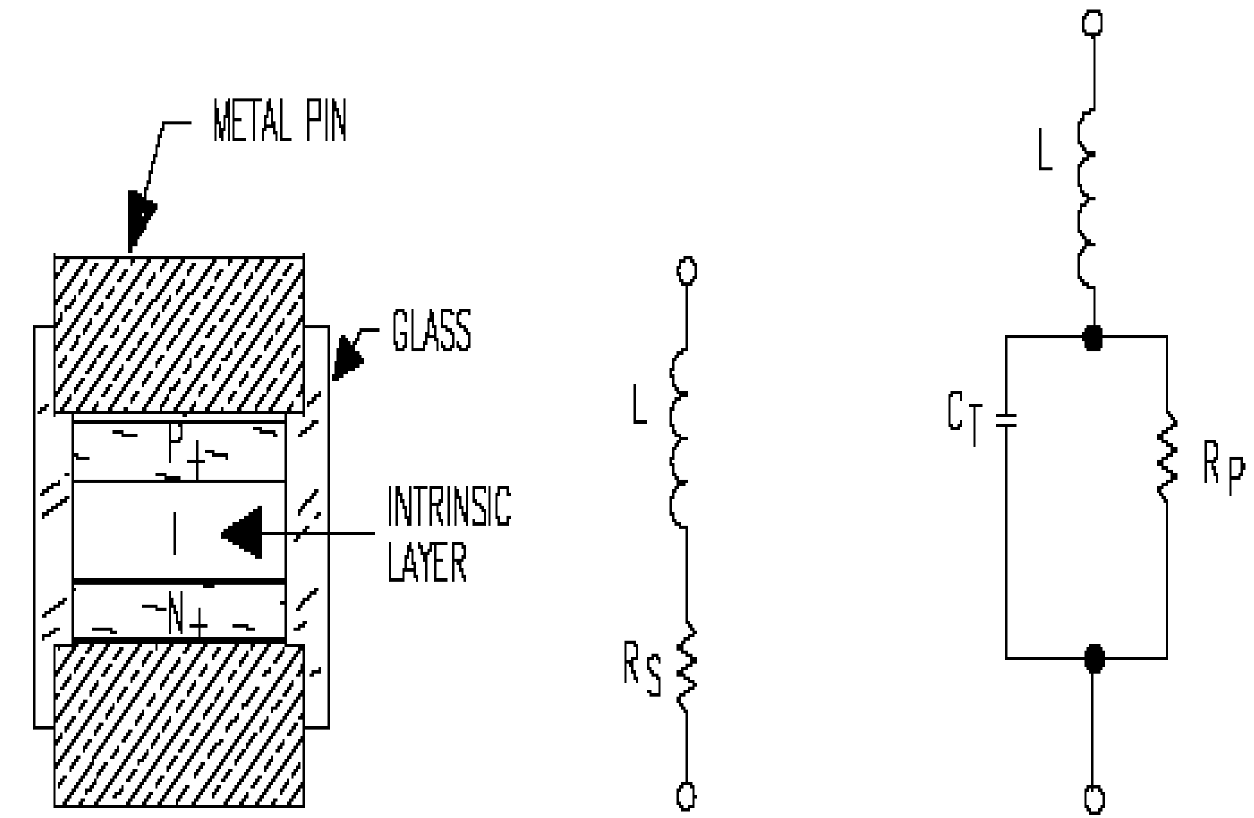
Operation

- A microwave PIN diode is a semiconductor device that operates as a variable resistor at RF and Microwave frequencies.
- A PIN diode is a current controlled device in contrast to a varactor diode which is a voltage controlled device.

- When the forward bias control current of the PIN diode is varied continuously, it can be used for attenuating, leveling, and amplitude modulating an RF signal.

- When the control current is switched on and off, or in discrete steps, the device can be used for switching, pulse modulating, and phase shifting an RF signal.

- A drawing of a PIN diode chip is shown in Figure 1.1 (a). The performance characteristics of the PIN diode depend mainly on the chip geometry and the processed semiconductor material in the intrinsic or I - region, of the finished diode.



(a) Cross Section of Basic PIN Diode

(b) Forward Bias Equivalent Circuit

(c) Reverse Bias Equivalent Circuit

Figure 1.1 PIN Diode and the Corresponding Equivalent Circuits

- When the diode is forward biased, holes and electrons are injected into the I-region. This charge does not recombine instantaneously, but has a finite lifetime (t) in the I-region.

- If the PIN diode is reverse biased , there is no stored charge in the I-region and the device behaves like a Capacitance (CT) shunted by a parallel resistance (RP).

Forward Bias Condition:

- The PIN diode must be forward biased (Low Loss or ON State) so that the stored charge, Qs, is much larger than the RF induced charge that is added or removed from the I-region cyclically by the RF current. This relationship is shown by the inequality: $Q_s \gg I_{rf} / 2\pi f$.

Reverse Bias Condition:

- If large values of RF current are being switched, the reverse bias voltage must be large enough that the RF voltage during its forward excursion does not induce the flow of RF current through the PIN diode.
- If the PIN diode becomes warm when operating as a high power switch, the reverse bias voltage should be increased to minimize this effect.

- PIN diodes are used to control RF power in circuits such as switches, attenuators, modulators and phase shifters.
- The process of controlling RF power naturally results in some of the RF power being dissipated in the controlling device.

- As a PIN diode dissipates power, its junction temperature begins to rise.
- The diode's junction temperature depends on the amount of power dissipated, Pd, the ambient temperature T_{amb}, and the thermal impedance, (qJ), between the diode junction and the diode's ambient temperature.

- The RF System Requirement that usually determines the choice of the particular PIN Diode to be used is the RF power that the switch must handle.
- The PIN Diode characteristically has relatively wide I-region and can therefore withstand larger RF Voltages than Varactors or microwave Schottky diodes.

- An ideal PIN diode acts as a variable resistor controlled by dc current.
- In attenuation applications, the performance is independent of carrier
- power level or frequency.

Frequency Effect

- Attenuation as a function of power level at 2 GHz is shown for three types of diodes in Figures 1, 2, and 3.
- Corresponding data at 10 GHz is shown in Figures 4, 5, and 6. At the lower frequency, the longer period allows the charges to be influenced by the RF voltage.

Table I. Attenuation Change at 1 Watt Power Level

Frequency (GHz)	2	10
Diode	Attenuation Above 3dB (dB)	
5082-3170	4.4	2.2
5082-3140	5.7	2.6
5082-3141	15.8	7.2

Bias Current Effect

- A glance at Figure 3 will confirm that attenuation setting or bias level has a significant effect on high power behavior.

- The high power effects are most serious at intermediate bias current levels. At high bias currents, a large electric field is necessary in order to have a significant effect on the large number of charge carriers present in the intrinsic layer of the diode.

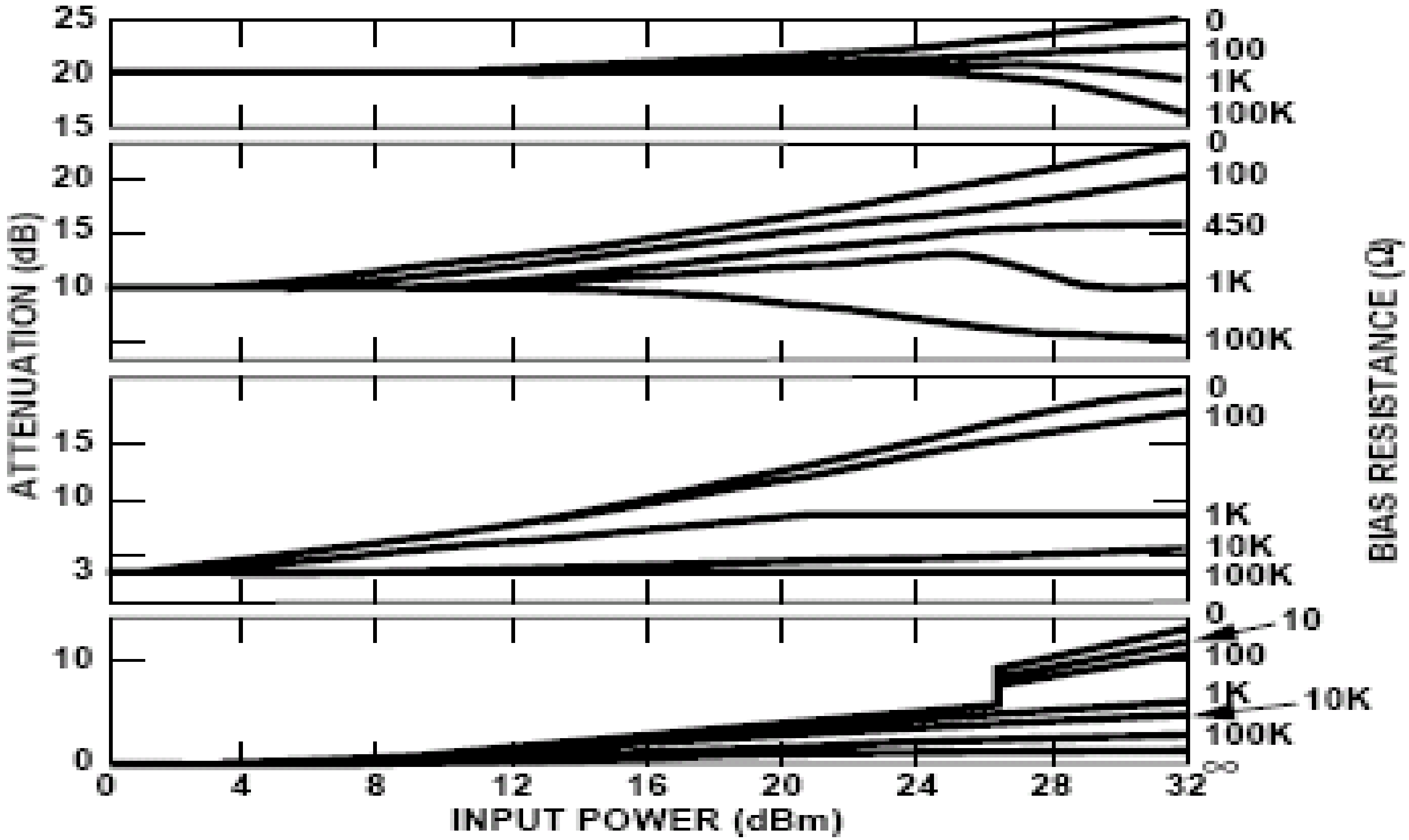


Figure 3. Attenuation at 2 GHz vs. Input Power with Bias Resistance as a Parameter. 5082-3141 at 0 dB, 3 dB, 10 dB and 20 dB.

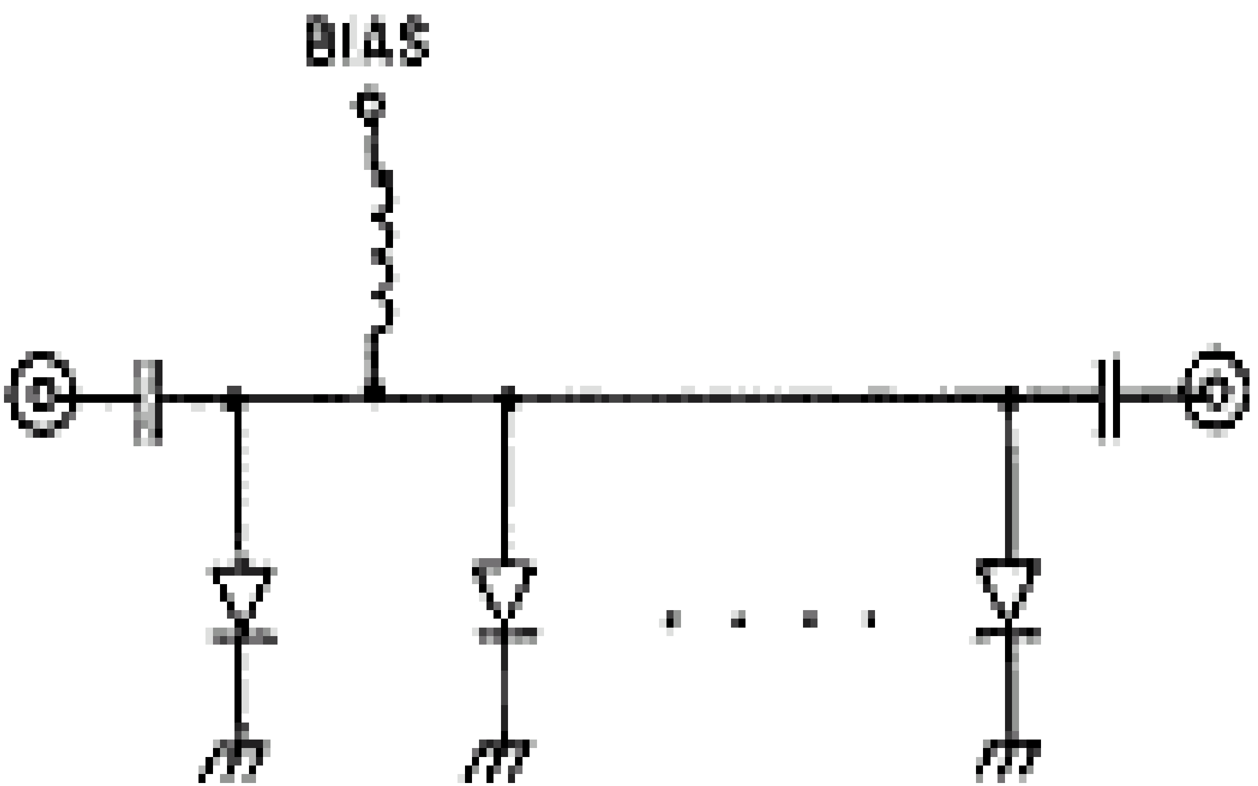
Load Resistance and Temperature Effects

- The temperature effects are related to the increases in the bias resistor value.
- Current, and therefore attenuation, rises with temperature with a voltage source, corresponding to the low values of bias resistance.

Treatment

- The simplest version of a PIN diode attenuator treatment is consists of one or more PIN diodes in shunt with a transmission line.
- This design provides a broadband reflective attenuator that can reach very high levels of attenuation, depending upon the number and electrical spacing of the diodes.

Shunt reflective attenuator

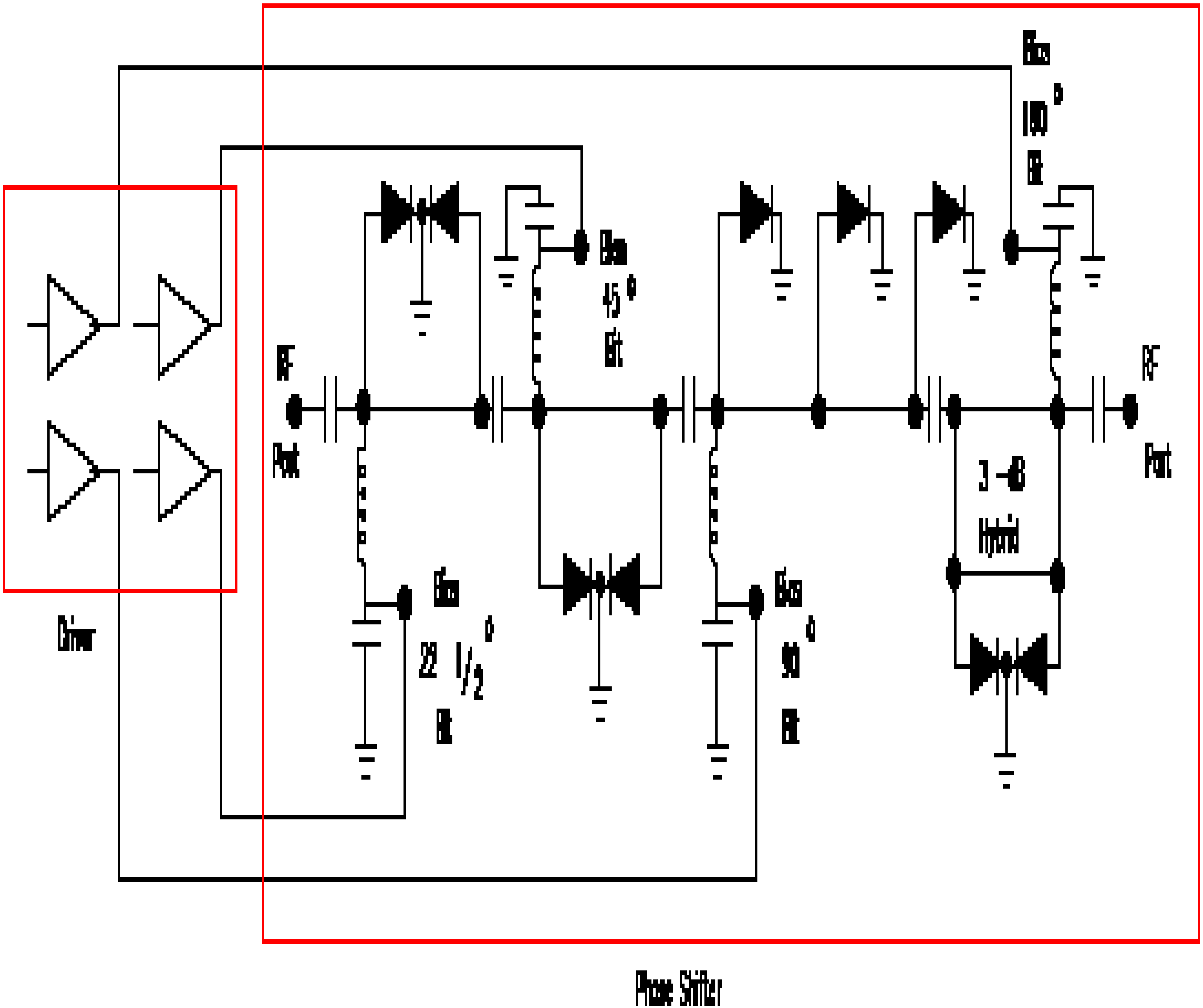


- The performance of a real PIN diode, however, is limited by both carrier level and frequency because of rectification effects.
- The effects are more serious at low frequencies because the period is closer to the lifetime of the charge carriers in the diode intrinsic layer.
- General Microwave PIN diode attenuators cover the frequency range from 200 MHz to 40 GHz and are available in numerous configurations to permit the user to optimize system performance.

Applications

- It is used as a Photo Detector for most fiber optic application
- They are Used in electronic pre-amplifier to boost sensitivity
- They are Used as a variable resistor in at RF and microwave frequency

- Widely used in RF modulator circuit to control RF intermodulation distortion
- In a phase shifter circuit considered as a lumped variable-impedance microwave circuit element.
- PIN diodes are utilized as series or shunt connected switches in phase shifter designs. The switched elements are either lengths of transmission line or reactive elements



Bias
180°
Bit
Bias
45°
Bit
RF
Port
RF
Port
Bias
22 1/2°
Bit
Bias
90°
Bit
3 -dB
Hybrid
Driver
Phase Shifter

- When the forward bias control current of the PIN diode is varied continuously, it can be used for attenuating, leveling, and amplitude modulating an RF signal.
- When the control current is switched on and off, or in discrete steps, the device can be used for switching, pulse modulating, and phase shifting an RF signal

- The microwave PIN diode's small physical size compared to a wavelength, high switching speed, and low package parasitic reactance, make it an ideal component for use in miniature, broadband RF signal control circuits

- PIN diode has the ability to control large RF signal power while using much smaller levels of control power.
- In modulator circuit, PIN diode’s minority carrier provide a low level of RF Intermodulation Distortion. (switching speed)

PIN DIODE ATTENUATOR CIRCUIT APPLICATIONS

- PIN diode attenuator circuits are used in automatic gain control (AGC) circuits and power leveling applications.
- The PIN diode attenuator may be a simple reflective attenuator, such as a series or shunt diode mounted across the transmission line.
- Some AGC attenuators are more complex networks that maintain impedance match to the input power and load as the attenuation is varied across its dynamic range.

- Other methods are used to implement the AGC function, such as varying the gain of an RF transistor stage. The PIN diode AGC circuit results in lower frequency pulling and lower signal distortion.

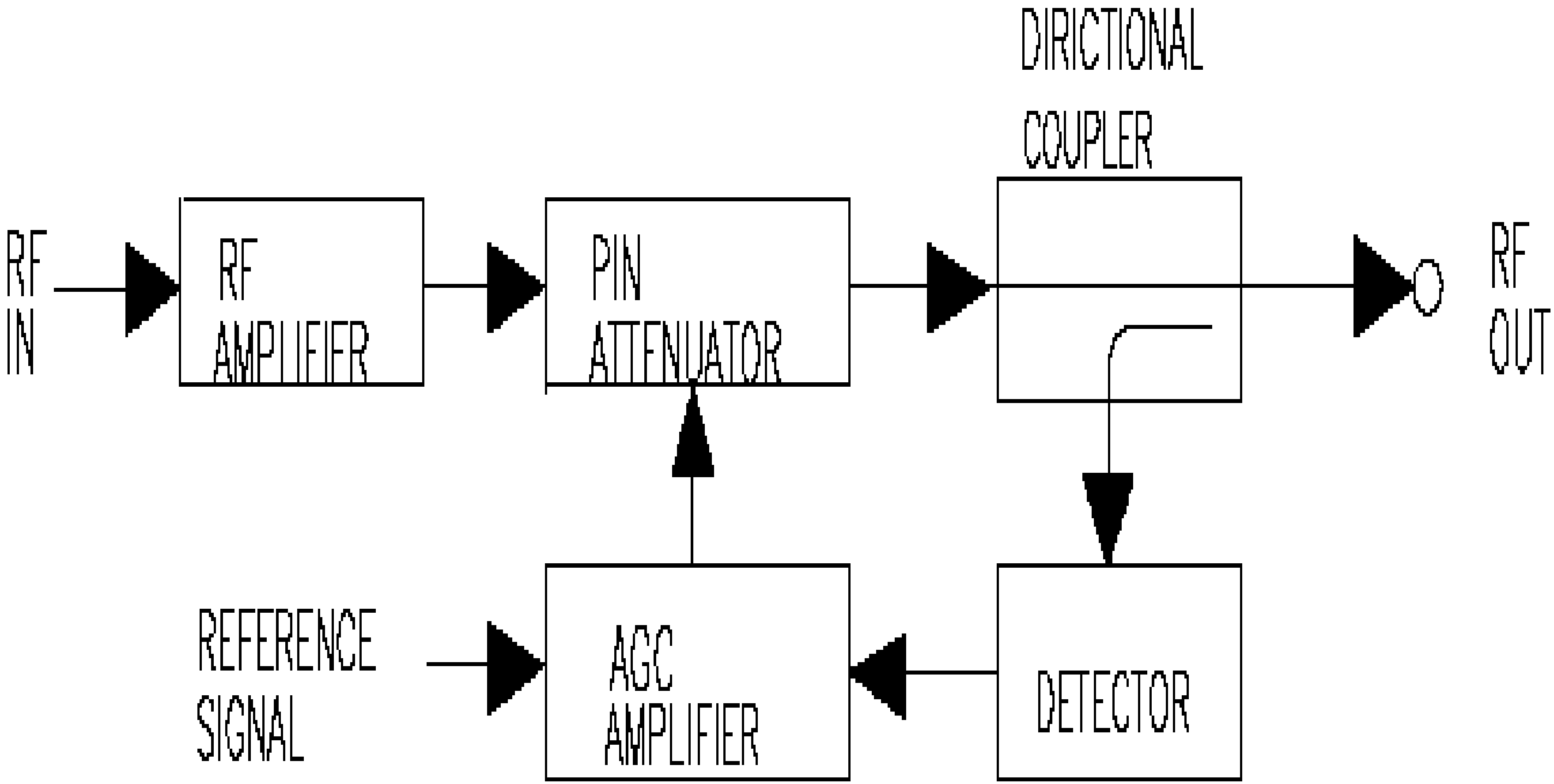


Figure 3.5 RF AGC / Leveler Circuit