UNIT IV MICROWAVE SEMICONDUCTOR DEVICES AND INTEGRATED CIRCUITS

Avalanche Transit Time Devices- principle of operation and characteristics of IMPATT and TRAPATT diodes, Point Contact Diodes, Schottky Barrier Diodes, Parametric Devices, Detectors and Mixers.Monolithic Microwave Integrated Circuits (MMIC), MIC materials- substrate, conductors and dielectric materials. Types of MICs, hybrid MICs (HMIC).

1.1 Avalanche Transit Time Devices

Semiconductor Microwave Devices

Like conventional ordinary vacuum tubes cannot be used at high frequency, because some parameters generate complicated situations and these parameters are

1. The interelectrode capacitance effect 2. The Lead inductance effect 3.Transit time

To overcome the above problems one should use either a high frequency transistor or some other special type of semiconductor devices. Like negative resistance and non-linearity in the operation make these special devices (i.e. like Varactor diode, PIN diode, IMPATT diode, TRAPATT diode, Tunnel diode and Gunn diode along with the high frequency transistors) suitable for their operations in the microwave region. Some observations we conclude that

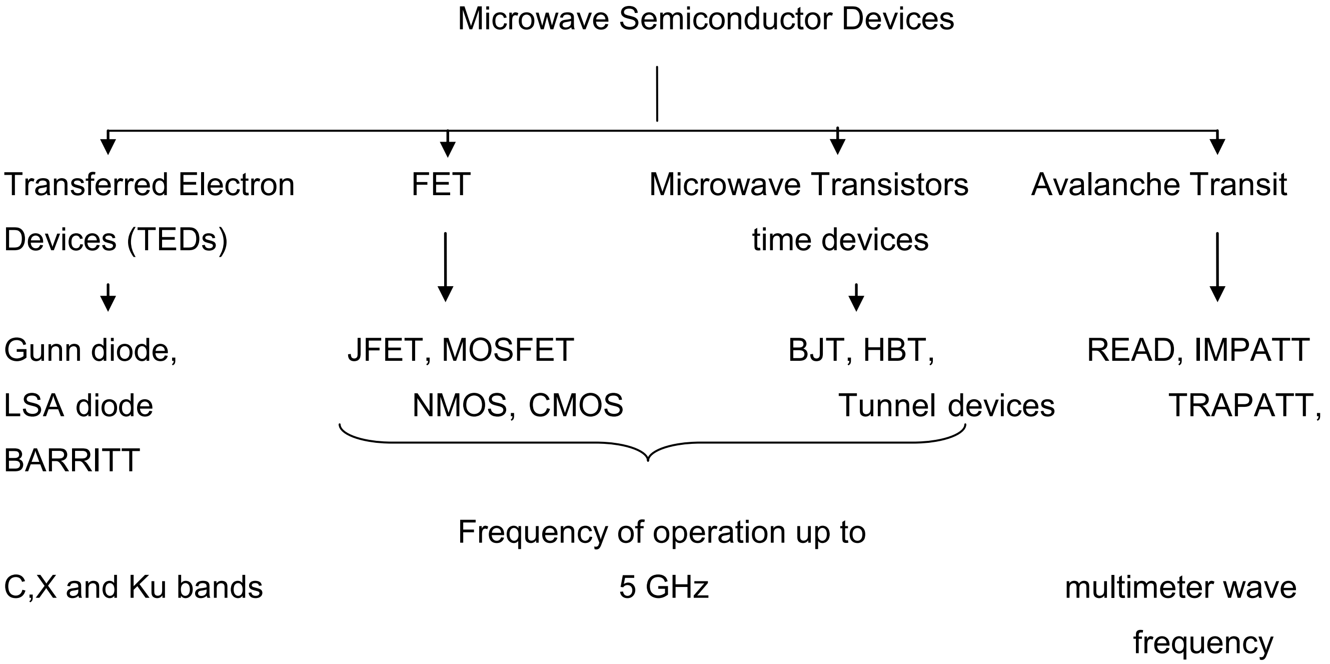
Bulk semiconductor device- Gunn diode

Ordinary p-n junction diodes- Varactor and Tunnel diodes

Modified p-n junction diodes- IMPATT, TRAPATT, PIN diodes such as p^+-n or p-i-n type

Microwave semiconductor devices have been developed for various applications like, detection, mixing, frequency multiplications, attenuation, switching, limiting, amplification or oscillation etc. Advantages of these devices are low cost, small size, less weight, low noise, greater bandwidth, lesser switching time, also employed in microwave integrated circuit and other improvements in performance characteristics for achieving the above functions.

Classification:-



LSA- Limited Space Charge Accumulation

IMPATT- Impact Ionization Avalanche Transit Time Device

TRAPATT- Trapped Plasma Avalanche Triggered Transit Device

BARITT- Barrier Injected Triggered Transit Device

Avalanche Transit Time Devices

It is proposed by the W.T.Read in 1958, that the delay between voltage and current in an avalanche together with transit time through the material. By which it is possible to make a microwave diode which exhibits negative resistance. These types of devices are known as Avalanche transit time devices.

Types of Avalanche Transit Time Devices:-

There are three types-

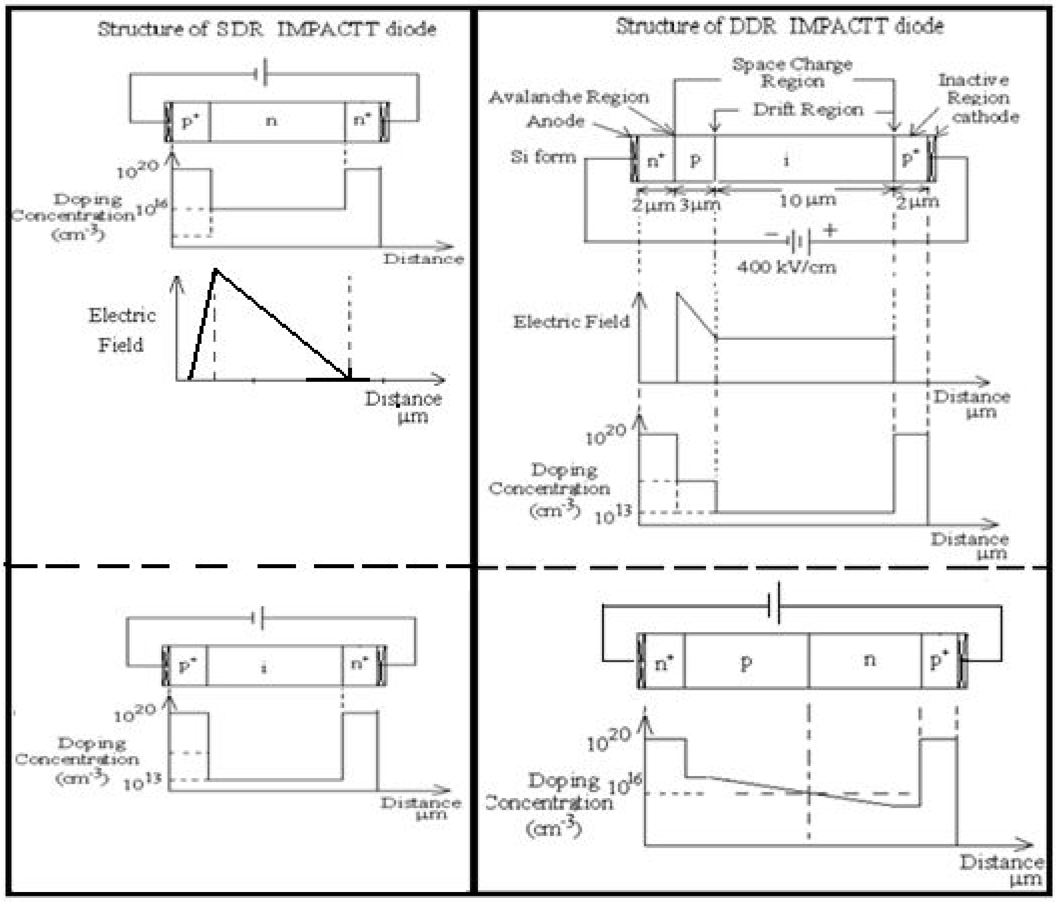
1. IMPATT (Impact Ionization Avalanche Transit Time) device
2. TRAPATT (Trapped Plasma Avalanche Triggered Transit Time) device
3. BARITT (Barrier Injected Transit time) device

1.2 IMPATT (Impact Ionization Avalanche Transit Time) device

An **IMPATT diode** (**I**mpact ionization **A**valanche **T**ransit-**T**ime) is a form of high-power diode used in high-frequency electronics and microwave devices. They operate at frequencies between about 3 and 100 GHz or more.

- It has many forms like $n^{+}pip^{+}$, $p^{+}nin^{+}$ read device, $p^{+}nn^{+}$ abrupt junction and $p^{+}in^{+}$ diode. Here positive (+) sign indicates a high level of doping and i stands for intrinsic or pure silicon.

Types IMPATT diodes and Doping Profile

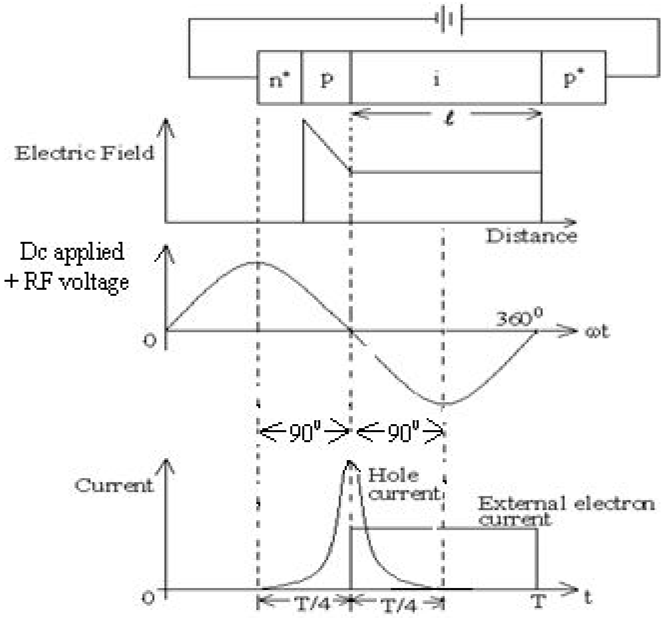


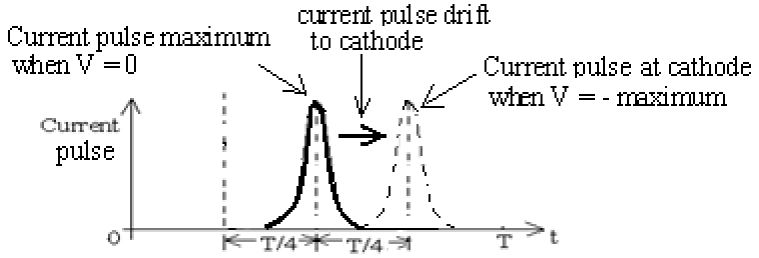
The two common types of IMPATT structures are SDR (Single Drift Region) and DDR (Double Drift Region). The doping and field profile of both SDR and

DDR are shown in above figure.

- IMPATT diodes can be manufactured from Ga, Si, GaAs or InP. However GaAs provides the highest priority, because of its high efficiency, the highest operating frequency and least noise figure. But the fabrication process is more difficult and costly than Si.
- A main advantage is high-power capability. These diodes are used in a variety of applications from low-power radar systems to alarms.
- A major drawback of using IMPATT diodes is the generation of phase noise which result from the statistical nature of the avalanche process. Nevertheless these diodes make excellent microwave generators for many applications.

Operation:- A very high voltage 400 kV/cm is applied to the IMPATT diode, resulting in a very high current. A normal diode would easily break down under this condition, but IMPATT diode is constructed such that it will withstand these conditions repeatedly. Such a high potential gradient back biasing the diode causes a flow of minority carriers across the junction.





If it is now assumed that oscillations exist, we may consider the effect of a positive swing of the RF voltage superimposed on top of the high dc voltage. Electron and hole velocity has now become so high that these carriers form additional holes and electrons by knocking them out of the crystal structure, by so called ***impact ionization***. We have two steps to understand the operation-

Step I-These additional carriers continue the process at the junction and the voltage will be exceeded during the whole of the +ve RF cycle. The avalanche current multiplication will be taking place during this entire time. Since avalanche is a multiplication process, it is not instantaneous or we can say it is a cumulative process. This process takes time such that the current pulse maximum, at the junction, occurs at the 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.

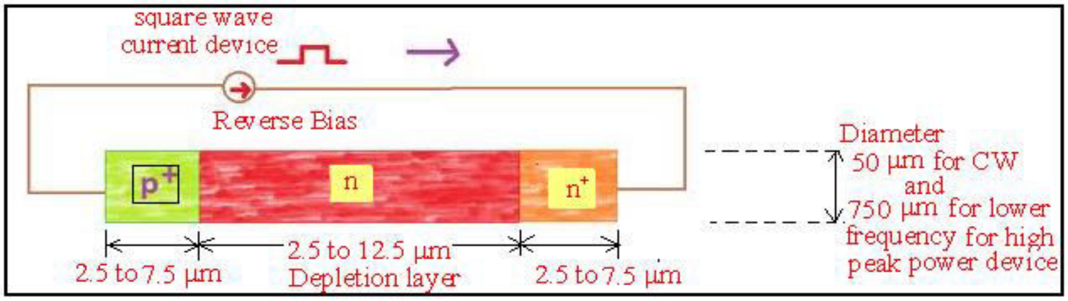
Step II- The current pulse in the IMPATT diode is situated at the junction. However it does not stay there because of the reverse bias, the current pulse flows to the cathode, at a drift velocity depending on the presence of the high dc field. The time taken by the pulse to reach the cathode depends on this velocity and on the thickness of the highly doped n^+ layer. The thickness of the drift space is adjusted such that time taken for current pulse to arrive at the cathode corresponds to further 90^0 phase difference.

Thus voltage and current are 180^0 out of phase and a dynamic RF negative resistance has been proved to exist. In summary, negative resistance phenomenon is taken into account by using

1) The impact multiplication avalanche effect, which causes the minority current to lag the microwave output voltage by $90^{0.}$ phase shift
2) The effect of transit time through the drift region, this results in the external current lagging the microwave voltage by a further 90^0 phase shift.

1.3 TRAPATT Diode

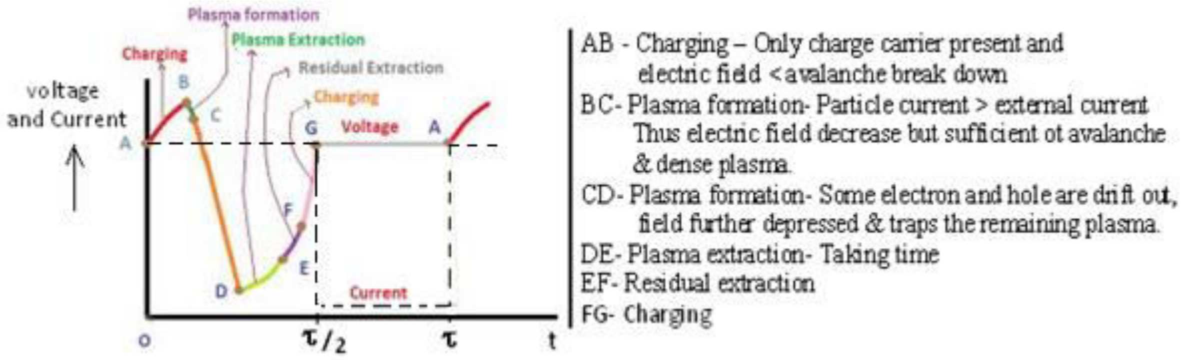
An **TRAPATT diode** (**T**rapped **P**lasma **A**valanche Triggered Transit-**T**ime), is a very high efficiency microwave generator, capable of operating from several hundred MHz to several GHz. It is derived from the IMPATT diode and is closely related to it.The basic operation of the TRAPATT oscillator is a semiconductor p-n junction diode reverse biased to current densities well in excess of these encountered in normal avalanche operation.



- High peak power diodes are typically silicon **n^{+}-p-p^{+}** or **p^{+}-n-n^{+}** structures with the n type depletion region varying from 2.5 to 12.5 µm.
- The doping of depletion region is generally such that the diodes are well punched through at breakdown.
- The device P+ region is kept as thin as possible at 2.5 to 7.5 µm.
- The Trapatt diodes diameter ranges from as small as 50 µm for µw operation to 750 µm at
  lower frequency for high peak power device.
- Good result from TRAPATT diodes below 10 GHz.

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

Operation:-



AB - Charging – Only charge carrier present and electric field < avalanche break down

BC- Plasma formation- Particle current > external current Thus electric field decrease but sufficient ot avalanche & dense plasma.

CD- Plasma formation- Some electron and hole are drift out, field further depressed & traps the remaining plasma.

DE- Plasma extraction- Taking time

EF- Residual extraction

FG- Charging

To know the operation, we follow some given steps

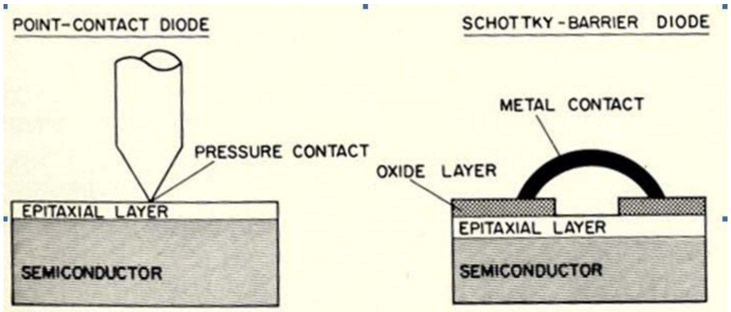
1. **Curve from A to B:-** At the instant of time at point A, the diode current is turned ON. Since only the charge carriers present, are those caused by the thermal generation, the diode initially charges up like a linear capacitor. Curve AB shows the magnitude of the electric field above the break down voltage.
2. **Curve from B to C**:- When a 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 from point B to C. A dense plasma formation is started.
3. **Curve from C to D:-** During the time instant the electric field is sufficiently large for the avalanche to continue and the dense plasma of electrons and holes is increased. In this plasma of electrons and holes, some of the electrons and holes drift out of the ends of the depletion layer. Thus the field is further depressed and traps the remaining plasma.
4. **Curve from 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 in the external current. At point E the plasma is removed then voltage increases from point D to E.
5. **Curve from E to F:-** A residual charge of electrons remains in one end of the depletion region and a residual charge of holes in the other end. As the residual charge is removed, the voltage increased from point E to point F. at point F all the charge that was generated initially has been removed.

6. **Curve from F to G:-** The diode charges 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 voltage V_A until the current comes back on the cycle repeats.

1.4 Point-contact diodes

These work the same as the junction semiconductor diodes, but their construction is simpler. A block of n-type semiconductor is built, and a conducting sharp-point contact made with some group-3 metal is placed in contact with the semiconductor. Some metal migrates into the semiconductor to make a small region of p-type semiconductor near the contact. The long-popular 1N34 germanium version is still used in radio receivers as a detector and occasionally in specialized analog electronics

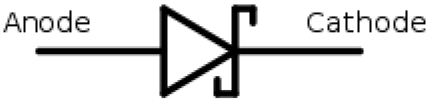
Both the point-contact and Schottky diodes consist of a die of semiconductor material on which an epitaxial layer is deposited. The point-contact diode uses a metal whisker to make pressure contact against the epitaxial layer, forming the rectifying junction. The Schottky diode has an additional oxide layer deposited over the epitaxial layer. A "window" is photo-etched through the oxide layer to the epitaxial layer through which a metal contact is then deposited. Thus, the main difference between these devices is the pressure contact used in the point-contact diode compared with the deposited contact in the Schottky diode. The pressure contact in the point-contact diode can damage the junction, depending on the amount of pressure exerted on the contact, while the Schottky diode lends itself to better control and more repeatable fabrication.

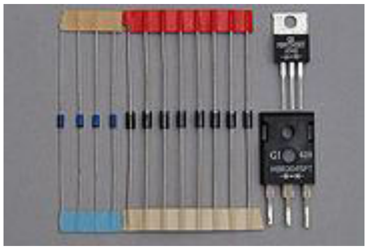


1.5 Schottky diodes

Schottky diodes are constructed from *a metal to semiconductor contact*. *They have a lower forward voltage drop than p-n junction diodes.* Their forward voltage drop at forward currents of about 1 mA is in the range 0.15 V to 0.45 V, which makes them useful in voltage clamping applications and prevention of transistor saturation. They can also be used as *low loss rectifiers* although their reverse leakage current is generally higher than that of other diodes. Schottky diodes are majority carrier devices and so do not suffer from minority carrier storage problems that slow down many other diodes so *they have a faster "reverse recovery" than p-n junction diodes*. They also tend to have much lower junction capacitance than p-n diodes which provides for high switching speeds and their use *in high-speed circuitry and RF devices* such as switched-mode power supply, mixers and detectors.

The **Schottky diode** (named after German physicist Walter H. Schottky; also known as **hot carrier diode**) is a semiconductor diode with a low forward voltage drop and a very fast switching action. The cat's-whisker detectors used in the early days of wireless can be considered as primitive Schottky diodes.





Schottky diode schematic symbol

Various Schottky barrier diodes: Small signal rf devices (left), medium and high power Schottky rectifying diodes (middle and right).

A Schottky diode is a special type of diode with a very low forward-voltage drop. When current flows through a diode there is a small voltage drop across the diode terminals. A normal diode has between 0.7-1.7 volt drops, while a Schottky diode voltage drop is between approximately 0.15-0.45 – this lower voltage drop translates into higher system efficiency.

A Schottky diode uses a metal-semiconductor junction as a Schottky barrier (instead of a semiconductor-semiconductor junction as in conventional diodes). This Schottky barrier results in both *very fast switching times* and *low forward voltage drop*.

Reverse recovery time

The most important difference between p-n and Schottky diode is reverse recovery time, when the diode switches from non-conducting to conducting state and vice versa. Where in a p-n diode the reverse recovery time can be in the order of hundreds of nanoseconds and less than 100 ns for fast diodes, Schottky diodes do not have a recovery time, as there is nothing to recover from. The switching time is ~100 ps for the small signal diodes, and up to tens of nanoseconds for special high-capacity power diodes. With p-n junction switching, there is also a reverse recovery current, which in high-power semiconductors brings increased EMI noise. With Schottky diodes switching instantly with only slight capacitive loading, this is much less of a concern.

It is often said that the Schottky diode is a "majority carrier" semiconductor device. This means that if the semiconductor body is doped n-type, only the n-type carriers (mobile electrons) play a significant role in normal operation of the device. The majority carriers are quickly injected into the conduction band of the metal contact on the other side of the diode to become free moving electrons. Therefore no slow, random recombination of n- and p- type carriers is involved, so that this diode can cease conduction faster than an ordinary p-n rectifier diode. This property in turn allows a smaller device area, which also makes for a faster transition. This is another reason why Schottky diodes are useful in switch-mode power converters; the high speed of the diode means that the circuit can operate at frequencies in the range 200 kHz to 2 MHz, allowing the use of small inductors and capacitors with greater efficiency than would be possible with other diode types. Small-area Schottky diodes are the heart of RF detectors and mixers, which often operate up to 50 GHz.

Limitations

The most evident limitations of Schottky diodes are the relatively *low reverse voltage* rating for silicon-metal Schottky diodes, *50 V and below*, and a *relatively high reverse leakage current*. The reverse leakage current, increasing with temperature, leads to *a thermal instability issue*. This often limits the useful reverse voltage to well below the actual rating, but the diodes are improving. The voltage ratings are now at 200 V.

Shottky Diode Applications (Voltage clamping)

While standard silicon diodes have a forward voltage drop of about 0.7 volts and germanium diodes 0.3 volts, Schottky diodes' voltage drop at forward biases of around 1 mA is in the range 0.15 V to 0.46 V, which makes them useful in voltage clamping applications and prevention of transistor saturation. This is due to the higher current density in the Schottky diode.

A typical application of power Schottky diodes is discharge-protection for solar cells connected to lead-acid batteries.

They are also used as rectifiers in switched-mode power supplies; the low forward voltage and fast recovery time leads to increased efficiency.

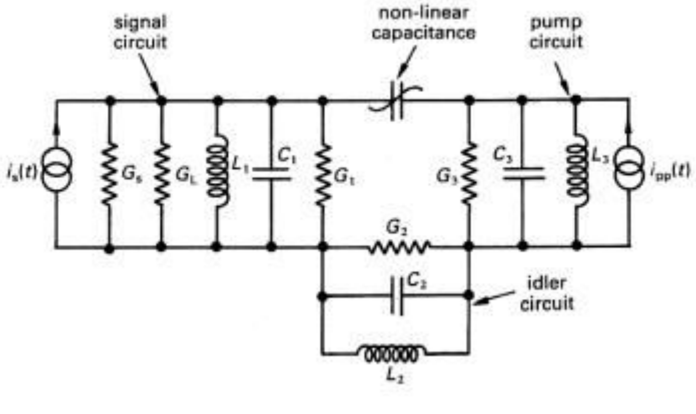
Schottky diodes can be used in power supply "OR"ing circuits in products that have both an internal battery and a mains adapter input, or similar. However, the high reverse leakage current presents a problem in this case, as any high-impedance voltage sensing circuit (e.g. monitoring the battery voltage or detecting whether a mains adaptor is present) will see the voltage from the other power source through the diode leakage.

Commonly encountered Schottky diodes include the 1N5817 series 1 A rectifiers. Schottky metal-semiconductor junctions are featured in the successors to the 7400 TTL family of logic devices, the 74S, 74LS and 74ALS series, where *they are employed as* *clamps in parallel with the collector-base junctions of the bipolar transistors to prevent their saturation*, thereby greatly reducing their turn-off delays.

Small signal Schottky diodes like the 1N5711, 1N6263, 1SS106, 1SS108 or the BAT41-43, 45-49 series are widely used in high frequency applications as detectors, mixers and nonlinear elements, and have replaced germanium diodes, rendering them obsolete. They are also suitable for ESD protection of ESD sensitive devices like III-V-semiconductor devices, LASER diodes and, to a lesser extent, exposed lines of CMOS circuitry.

1.6 Parametric Devices, Detector and Mixer

A nonlinear capacitor is surrounded by three parallel LCR circuits, which represent the signal, idler and pump circuits, respectively. In reverse-biased PN junction has the non-linear charge-voltage characteristic due to the voltage-dependent capacitance. The mixing occurs between the three frequency components of signal, idler and pump waves in such a nonlinear element and the energy flows from a strong pump wave to weak signal and idler waves. This flow of the power from the pump to the signal introduces the negative conductance into the signal circuit. In optical spectral domain, the atomic dipole moment, driven by an intense pump laser, features a similar non-linearity and is capable of amplifying weak signal and idler waves.



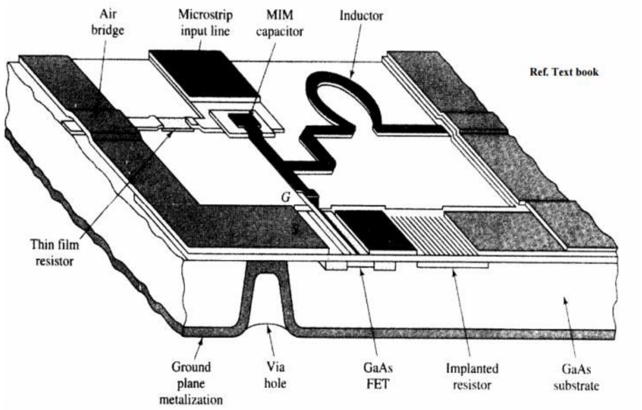
1.7 Monolithic Microwave Integrated Circuits (MMICs)

It is a type of circuit in which all active and passive elements as well as transmission lines are formed into the bulk or onto the surface of a substance by some deposition scheme as epitaxy, ion implantation, sputtering, evaporation, and diffusion.

RF/MW MMIC circuits are important as

- The trend in advanced microwave electronic systems is toward increasing integration, reliability, and volume of production with lower costs.
- The new millimeter-wave circuit applications demand the effects of bond-wire parasitics to be minimized and use of discrete elements to be avoided.
- New developments in military, commercial and consumer markets demand a new approach for mass production and for multi-octave bandwidth response in circuits

A typical Monolithic MIC. One example of a MMIC is 2-40 GHz distributed amplifier with a gain of 4 dB.



Hybrid versus Monolithic Microwave Integrated Circuits: Important areas that MMIC has advantage over HMIC are, Cost, Size and weight, Design flexibility, Circuit tweaking, Broadband performance, Reproducibility, Reliability.

- Substrate material: features for an ideal substrate are,

(1) Justifiably low cost, suitable dielectric thickness and permittivity to allow useful frequency range and achievable impedance values

(2) Negligible dielectric loss which means to a low ‘tan δ’

(3) Good substrate surface finish (0.05-0.1 μm) free of voids to keep conductor

(4) Loss low with good metal-film adhesion

(5) Good mechanical strength and thermal conductivity

Conductor Materials: features for ideal conductor are,

(1) High conductivity

(2) High coefficient of thermal expansion

(3) Low resistance at RF/microwaves

(4) Good adhesion to the substrate

(5) Good etch ability and solder ability

(6) Easy to deposit or electroplate

- **Dielectric Materials:** features for ideal dielectric are,

(1) Reproducibility and High breakdown voltage

(2) Low loss tangent and Process ability

- **Resistive Films**: features for ideal resistive film are,

(1) Good stability

(2) Low Temperature Coefficient of Resistance (TCR)

(3) Sheet resistivity in the range of 10-2000 Ohm/square