Introduction

• Special electronics effects encountered at microwave frequencies severely limit the usefulness of transistors in most circuit applications.
• Using vacuum tubes for low power applications become impractical
• Need for small-sized microwave devices has caused extensive research in this area
Introduction

• This research has produced solid-state devices with higher and higher frequency ranges.
• The new solid state microwave devices are predominantly active, two terminal diodes, such as tunnel diodes, varactors, transferred-electron devices, and avalanche transit-time diodes
Microwave Solid State Devices

- Tunnel diode devices
- Varactor devices
- IMPATT diode
- GUN diode
- PIN Diodes
- Microwave Transistors
Varactor Diode
Varactor Diode

- **VARiable reACTOR**
- Also referred as “Varicap (Variable Capacitor) diode”
- Referring to voltage-variable capacitance of reverse biased *pn* junction
- Designed to exploit the voltage-variable properties of the junction capacitance
- Junction capacitance depends on the applied voltage and the design of the junction
- Junction with fixed reverse bias may be used as a capacitance of fixed value
What is the difference between ordinary diodes and Varicap diodes?

• Although ordinary PN junction diodes exhibit the variable capacitance effect and these diodes can be used for this applications, special diodes optimized to give the required changes in capacitance. Varactor diodes or varicap diodes normally enable much higher ranges of capacitance change to be gained as a result of the way in which they are manufactured.
Varactor Diode - Applications

- Uses in many applications where electronically controlled tuning of resonant circuits is required, for items such as oscillators and filters, varactor diodes are an essential component within the portfolio of the electronics design engineer.
Varactor Diode - Applications

- Tuning stage of radio receiver to replace bulky variable plate capacitor
- Microwave frequency multiplication
- Active filters
- Voltage Controlled Oscillators
- RF Filters
Varactor Diodes used in VCOs

- Varactor diode is a key component within a VCO
- Oscillator within a phase locked loop
- VCOs are used in almost all radio, cellular and wireless receivers.
Varactor Diode used in RF Filters

- Used to tune filters
- Tracking filters may be needed in receiver front end circuits where they enable the filters to track the incoming received signal frequency
- Again this can be done using a control voltage
Varactor Diode - Operation

- The basis of operation of the varactor diode is quite simple. The diode is operated under reverse bias conditions and this gives rise to three regions.
- P region, N region, Depletion region
- P and N regions are the regions where current can be conducted
- Depletion region is the region where no current carriers are available
- P and N behave as conducting plates of a capacitor and Depletion region acts as an Insulator (dielectric in a capacitor)
Varactor Diode - Operation
Building an analogy ...

- The capacitance of a capacitor is dependent on a number of factors including the plate area, the dielectric constant of the insulator between the plates and the distance between the two plates. In the case of the varactor diode, it is possible to increase and decrease the width of the depletion region by changing the level of the reverse bias. This has the effect of changing the distance between the plates of the capacitor.
Transmission Capacitance

• It was established that there is a region of uncovered charge on either side of the junction that together the regions makes up the duplication region and define the depletion width $W_d$.

• The transmission capacitance ($C_t$) established by the isolated uncovered charges is determined by

$$C_t = \frac{A}{\varepsilon W_d}$$

Where $\varepsilon$ is the permittivity of the semiconductor materials, $A$ the $p-n$ junction area and $W_d$ the depletion width.
Relationship between Capacitance and Bias Voltage

- The ratio of varactor capacitance to reverse-bias voltage change may be as high as 10 to 1. Of course any decrease in applied bias voltage would cause a proportionate increase in capacitance, as the depletion region narrows.
Relationship between Capacitance and Bias Voltage

View A shows that a reverse bias of 3 volts produces a capacitance of 20 picofarads in the varactor. If the reverse bias is increased to 6 volts, as shown in view B, the depletion region widens and capacitance drops to 5 picofarads. Each 1-volt increase in bias voltage causes a 5-picofarad decrease in the capacitance of the varactor; the ratio of change is therefore 5 to 1.
Varactor Diode - Symbol
PIN Diode
Introduction

• A refinement of the ordinary PN diode
• Works as a variable resistor at microwave frequencies
• PIN diode includes a layer of intrinsic material between the P and N layers
• As a result of the intrinsic layer, PIN diodes have a high breakdown voltage and they also exhibit a low level of junction capacitance
Basics

- Intrinsic material sandwiched
- The PIN diode operates in exactly the same way as a normal diode
- The only real difference is that the depletion region, that normally exists between the P and N regions in an unbiased or reverse biased diode is larger.
Basics

• In any PN junction, the P region contains holes as it has been doped to ensure that it has a predominance of holes. Similarly the N region has been doped to contain excess electrons. The region between the P and N regions contains no charge carriers as any holes or electrons combine As the depletion region has no charge carriers it acts as an insulator.
Basics

• Within a PIN diode the depletion region exists, but if the diode is forward biased, the carriers enter the depletion region (including the intrinsic region) and as the two carrier types meet, current starts to flow.
Basics

• When the diode is forward biased, the carrier concentration, i.e. holes and electrons is very much higher than the intrinsic level carrier concentration. Due to this high level injection level, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from p to n region, which results in faster operation of the diode, making it a suitable device for high frequency operations.
Operation

• When a PIN diode is forward biased, holes and electrons are injected from the P and N regions into the I-region. These charges do not recombine immediately. Instead, a finite quantity of charge always remains stored and results in a lowering of the resistivity of the I-region.
Charge of the I material - Forward Biased Condition

- The quantity of stored charge, \( Q \), depends on the recombination time, \( \tau \) (the carrier lifetime), and the forward bias current, \( I_F \)
- \( Q = I_F \tau \) [Coulombs] .......................... Eq (1)
Resistance of the I region - Forward Biased Condition

- The resistance of the I-region under forward bias, $R_S$ is inversely proportional to $Q$ and may be expressed in equation 2 as:

$$R_S = \frac{W^2}{(\mu_N + \mu_p)Q} \quad [\text{Ohms}]$$

- Where:

  - $W$ = I-region width
  - $\mu_N$ = electron mobility
  - $\mu_p$ = hole mobility
Resistance of the I region - Forward Biased Condition

• Combining equations 1 and 2, the expression for $R_s$ as an inverse function of current is shown in equation 3:

\[ R_s = \frac{W^2}{(\mu_N + \mu_p) \tau I_F} \quad [\text{Ohms}] \]
$R_s$ vs $I_F$
$R_s$ vs $I_F$ - Explanation of the Graph

- Look at the range of resistance that you can obtain, from 0.1 ohm to 10,000 ohms... yes, the PIN diode pretty much covers the entire horizontal axis of the Smith chart! (Look at the chart above, and notice that 50 ohms occurs very close to the center of the response). This is what makes it such a versatile device, it can behave like an open circuit, a short circuit, or any reflection coefficient in between. You can use it to create switches, phase shifters and variable attenuators, and we'll show you how if you follow the links at the top of the page.
Practical Scenario

• The maximum forward resistance, $R_s(\text{max})$, of a PIN diode is generally specified at 100 mA forward bias current. For some PIN diodes, Microsemi specifies not only the $R_s(\text{max})$ but also the $R_s(\text{min})$ at a lower forward bias current (10mA). These specifications ensure a wide range of diode resistance which is particularly important in attenuator applications.
Lower Frequency Limitations

- A PIN diode only acts like a rectifier at low frequencies. At microwave frequencies, the IV curve undergoes a change, so that it behaves like a resistor, whose resistance value is determined by the level of DC current that is present in the I-region. Thus a PIN diode is essentially a DC-controlled high-frequency resistor. Just as important, if no DC current is present, the diode behaves like an open circuit.
Design

- A model of a *Microsemi* PIN diode chip is shown in Figure 1. The chip is prepared by starting with a wafer of almost intrinsically pure silicon, having high resistivity and long lifetime.
Design

• The resulting intrinsic or I region thickness ($W$) is a function of the thickness of the original silicon wafer, while the area of the chip ($A$) depends upon how many small sections are defined from the original wafer.

Figure 1 - PIN Diode Chip Outline
Performance

The performance of the PIN diode primarily depends on chip geometry and the nature of the semiconductor material in the finished diode, particularly in the I-region. Characteristics of PIN diodes are controlled thickness I regions having long carrier lifetimes and very high resistivity. These characteristics enhance the ability to control RF signals with a minimum of distortion while requiring low dc supply.
Application - PIN Diode as a Variable Resistor

- Resistance value of the PIN diode is determined by only the forward biased DC current
Application - PIN diode as a switch and attenuator

- In switch and attenuator applications, the PIN diode should ideally control the RF signal level without introducing distortion which might change the shape of the RF signal.
Symbol
GUNN Diode
Introduction

- Gunn diodes are also known as transferred electron devices, TED, are widely used in microwave RF applications for frequencies between 1 and 100 GHz.
- The Gunn diode is most commonly used for generating microwave RF signals - these circuits may also be called a transferred electron oscillator or TEO. The Gunn diode may also be used for an amplifier in what may be known as a transferred electron amplifier or TEA.
- As Gunn diodes are easy to use, they form a relatively low cost method for generating microwave RF signals.
Basics

- The Gunn diode is a unique component - even though it is called a diode, it does not contain a PN diode junction. The Gunn diode or transferred electron device can be termed a diode because it does have two electrodes.

- The Gunn diode operation depends on the fact that it has a voltage controlled negative resistance.
Design
Gunn diodes are fabricated from a single piece of n-type semiconductor. The most common materials are gallium Arsenide, GaAs and Indium Phosphide, InP. However other materials including Ge, CdTe, InAs, InSb, ZnSe and others have been used. The device is simply an n-type bar with n+ contacts. It is necessary to use n-type material because the transferred electron effect is only applicable to electrons and not holes found in a p-type material.
Operation

• When a voltage is placed across the device, most of the voltage appears across the inner active region. As this is particularly thin this means that the voltage gradient that exists in this region is exceedingly high.
Operation

- The device exhibits a negative resistance region on its V/I curve as seen below. This negative resistance area enables the Gunn diode to amplify signals. This can be used both in amplifiers and oscillators. However, Gunn diode oscillators are the most commonly found.
Operation

- This negative resistance region means that the current flow in diode increases in the negative resistance region when the voltage falls - the inverse of the normal effect in any other positive resistance element. This phase reversal enables the Gunn diode to act as an amplifier and oscillator.
Operation

- The electronic band structure of some semiconductor materials, including gallium arsenide (GaAs), have another energy band or sub-band in addition to the valence and conduction bands which are usually used in semiconductor devices. This third band is at a higher energy than the normal conduction band and is empty until energy is supplied to promote electrons to it. The energy stems from the kinetic energy of ballistic electrons. That is, electrons in the conduction band but moving with sufficient kinetic energy can reach the third band.
Applications

• **Sensors and measuring instruments**
  ▫ Gunn diode oscillators are used to generate microwave power for: airborne collision avoidance radar, anti-lock brakes, sensors for monitoring the flow of traffic, car radar detectors, pedestrian safety systems, "distance traveled" recorders, motion detectors, "slow-speed" sensors (to detect pedestrian and traffic movement up to 50 m.p.h), traffic signal controllers, automatic door openers, automatic traffic gates, process control equipment to monitor throughput, burglar alarms and equipment to detect trespassers, sensors to avoid derailment of trains, remote vibration detectors, rotational speed tachometers, moisture content monitors
Applications

- **Radio amateur use**
- By virtue of their low voltage operation, Gunn diodes can serve as microwave frequency generators for very low powered (few-milliwatt) microwave transmitters. In the late 1970s they were being used by some radio amateurs in Britain. Designs for transmitters were published in journals. They typically consisted simply of an approximately 3 inch waveguide into which the diode was mounted. A low voltage (less than 12 volt) direct current power supply that could be modulated appropriately was used to drive the diode. The waveguide was blocked at one end to form a resonant cavity and the other end ideally fed a parabolic dish.
IMPATT Diode

- Impact Avalanche and Transit-Time (IMPATT) Diode, also called Avalanche transit-time diodes
- Multilayer diodes of several different types used to generate microwave power
IMPATT Diode

- In contrast to other devices in this class (tunnel diodes, thyristors, and Gunn diodes), the negative resistance of avalanche-and-transit time diodes appears only at superhigh frequencies.
- Avalanche-and-transit time diodes are used to generate oscillations in the frequency range from 1 to 300 gigahertz.
- Avalanche-and-transit time diodes can be made from structures of the $p^+-n-i-n^+$ type (the Read diode) or the $p-i-n$, $p-n$, $p^+-n$, and $p-n^+$ types.
IMPATT Diode - Operation

- The IMPATT diode is operated under reverse bias conditions. These are set so that avalanche breakdown occurs. This occurs in the region very close to the P+ (i.e. heavily doped P region). The electric field at the p-n junction is very high because the voltage appears across a very narrow gap creating a high potential gradient. Under these circumstances any carriers are accelerated very quickly.
IMPATT Diode - Operation

- As a result they collide with the crystal lattice and free other carriers. These newly freed carriers are similarly accelerated and collide with the crystal lattice freeing more carriers. This process gives rise to what is termed avalanche breakdown as the number of carriers multiplies very quickly. For this type of breakdown only occurs when a certain voltage is applied to the junction. Below this the potential does not accelerate the carriers sufficiently.
IMPATT Diode - Operation

- Once the carriers have been generated the device relies on negative resistance to generate and sustain an oscillation. The effect does not occur in the device at DC, but instead, here it is an AC effect that is brought about by phase differences that are seen at the frequency of operation. When an AC signal is applied the current peaks are found to be 180 degrees out of phase with the voltage. This results from two delays which occur in the device: injection delay, and a transit time delay as the current carriers migrate or drift across the device.
IMPATT Diode - Operation

- The voltage applied to the IMPATT diode has a mean value that means the diode is on the verge of avalanche breakdown. The voltage varies as a sine wave, but the generation of carriers does not occur in unison with the voltage variations. It might be expected that it would occur at the peak voltage. This arises because the generation of carriers is not only a function of the electric field but also the number of carriers already in existence.
IMPATT Diode - Operation

- As the electric field increases so does the number of carriers. Then even after the field has reached its peak the number of carriers still continues to grow as a result of the number of carriers already in existence. This continues until the field falls to below a critical value when the number of carriers starts to fall. As a result of this effect there is a phase lag so that the current is about 90 degrees behind the voltage. This is known as the injection phase delay.
- When the electrons move across the N+ region an external current is seen, and this occurs in peaks, resulting in a repetitive waveform.
IMPATT Diodes - Applications

• To run an IMPATT diode, a relatively high voltage, often as high as 70 volts or higher may be required. This often limits their application as voltages of this order are not always easy to use in some pieces of equipment. Nevertheless IMPATT diodes are particularly attractive option for microwave diodes for many areas.