Microwave Engineering

Professor Ratnajit Bhattacharjee
Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati

Lecture No 24

We discuss three devices Gunn and IMPATT diode and also the Varactor diode. It may be noted that a Gunn diode is not a diode in the true sense. That it does not have any PN-junction. It is essentially an n-type gallium arsenide sample, and we have metallic contacts at the two ends.

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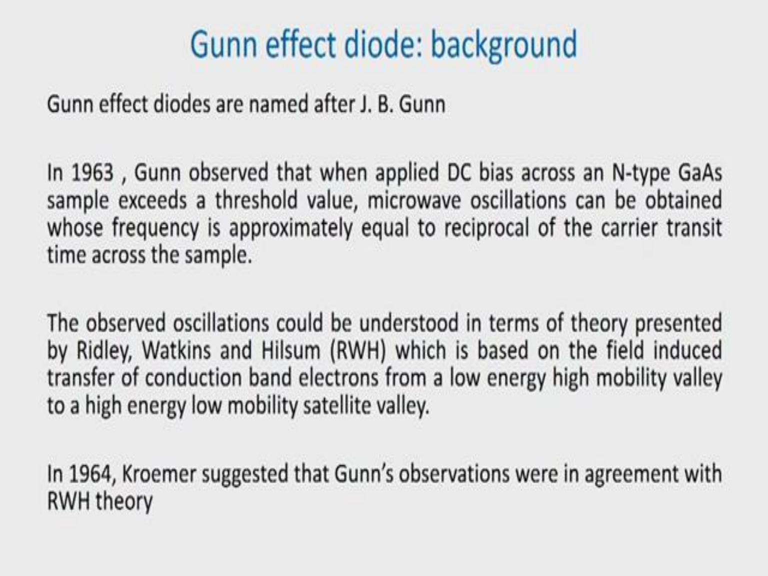

Gunn effect diode: background

Gunn effect diodes are named after J. B. Gunn

In 1963 , Gunn observed that when applied DC bias across an N-type GaAs sample exceeds a threshold value, microwave oscillations can be obtained whose frequency is approximately equal to reciprocal of the carrier transit time across the sample.

The observed oscillations could be understood in terms of theory presented by Ridley, Watkins and Hilsum (RWH) which is based on the field induced transfer of conduction band electrons from a low energy high mobility valley to a high energy low mobility satellite valley.

In 1964, Kroemer suggested that Gunn's observations were in agreement with RWH theory

So, Gunn effect diodes are named after J. B. Gunn, who actually experimentally observed some oscillations in a sample of gallium arsenide biased above some threshold voltage. In 1963, Gunn observed that when applied DC bias across an N-type gallium arsenide sample exceeds a threshold value, microwave oscillations can be obtained whose frequency is approximately equal to the reciprocal of the carrier transit time across the sample. So, this was the experimental observation.

Now, the observed oscillations could be understood in terms of the theory presented by Ridley, Watkins, and Hilsum, popularly known as RWH theory, which is based on the field-induced transfer of conduction band electrons from a low energy high mobility valley to a high energy low mobility satellite valley.

So, whatever was observed by Gunn, experimentally, this could be explained in terms of the theory presented by Ridley, Watkins, and Hilsum. In 1964, Kroemer suggested that Gunn's observations were in agreement with RWH theory.

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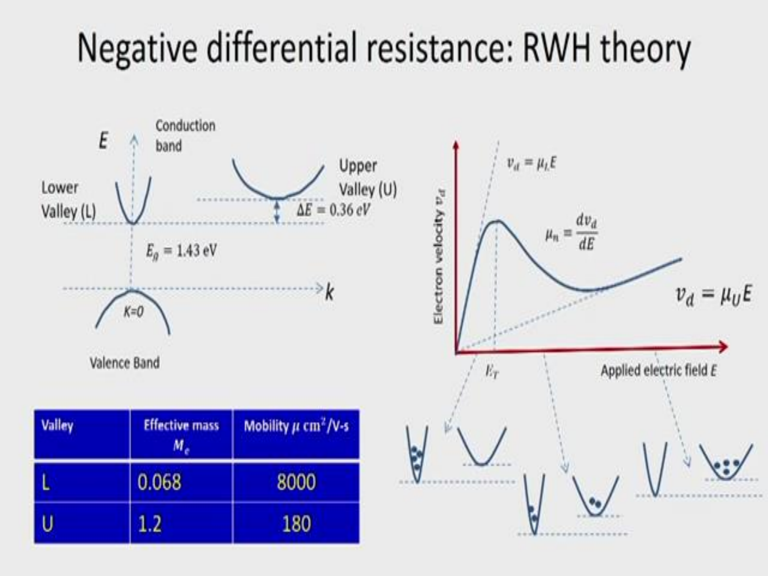

Negative differential resistance: RWH theory

Valley	Effective mass M_e	Mobility μ $cm^2/V\text{-}s$
L	0.068	8000
U	1.2	180

So, let us now consider the negative differential resistance based on the RWH theory. So, we have gallium arsenide, which is a direct bandgap material with E_g equal to 1.43 electron volt, and we can see that the maximum of the valence band and minimum of the conduction band are aligned in the EK diagram. Now, this valley in the conduction band is called the lower valley L., And in gallium arsenide, another upper valley U exists. It is slightly higher energy Delta E is equal to 0.36 electron volt.

So, to have negative differential resistance, we should have at least two such valleys. In these valleys, the electron effective mass and mobility are different. In the lower valley of the conduction band, effective mass of the electron is 0.068, and mobility is 8000 centimeter square per volt second.

So, these are typical values for a given semiconductor, whereas in the upper valley, effective mass is 1.2, and the mobility is only 180. So, we see that when the electrons stay in this lower value of

the conduction band they are much much mobile as compared to the electrons in the upper valley U.
Now, when a bias field is applied in this type of material, the electrons move to the lower valley, and the upper valley U does not have any electron. So, this is shown here. Now, in this region we can see that as the applied electric field increases, the electron velocity increases. This is the average electron velocity or the drift velocity, and V_d is equal to mu L E.

Now, as the applied bias field is increased and we have the field greater than a threshold voltage ET, the field is greater than a threshold voltage ET as we have said that because of this field-induced transfer of electrons, we have some electrons migrating to the upper valley.

As we keep on increasing the applied electric field this migration of electrons from lower valley to upper valley continues. And finally, at a very large applied electric field all the electrons move to the upper valley. Please note that initially the drift velocity increases linearly with the applied electric field, and the slope of VD EE curve it is very high because mobility is very large in this lower valley.

Here once again, beyond certain applied field when all the electrons have migrated to the upper valley, we once again get the drift velocity increases linearly with the applied field. But this time, the rate of increase is much lower because the mobility of the electrons has much much lower value in this upper valley.

In the intermediate region, we find that the drift velocity changes from a high value to a low value. And this rate of change of drift velocity with respect to the applied electric field, this gives negative differential mobility. Here we can see that this slope, the mobility of the electrons decreases.

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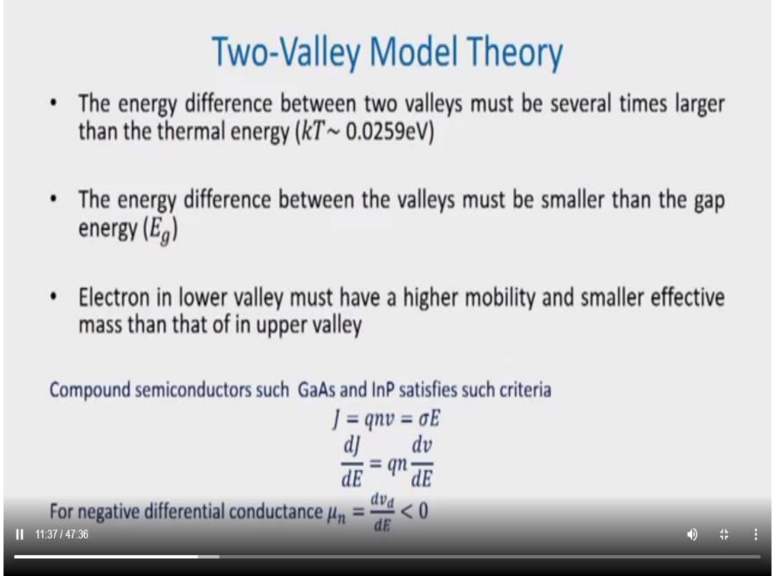
Compound semiconductors such GaAs and InP satisfies such criteria

$$J = qnv = \sigma E$$

$$\frac{dJ}{dE} = qn\frac{dv}{dE}$$

For negative differential conductance $\mu_n = \frac{dv_d}{dE} < 0$



Two-Valley Model Theory

- The energy difference between two valleys must be several times larger than the thermal energy (kT~ 0.0259eV)
- The energy difference between the valleys must be smaller than the gap energy (E_g)
- Electron in lower valley must have a higher mobility and smaller effective mass than that of in upper valley

Compound semiconductors such GaAs and InP satisfies such criteria

$$J = qnv = \sigma E$$

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For negative differential conductance $\mu_n = \frac{dv_d}{dE} < 0$

So, in our two valley model, the energy difference between the two valleys must be several times larger than the thermal energy, which is kT and approximately equal to 0.0259 electron volt. Secondly, the energy difference between the valleys must be smaller than the gap energy, E_g. We have seen that in gallium arsenide, we have E_g approximately equal to 1.43 electron volt and the energy difference between the valleys is 0.36 electron volt.

Electron in the lower valley must have higher mobility and smaller effective mass than that of in upper valley. Now, compound semiconductors, such as gallium arsenide and indium phosphide they satisfy such criteria. We have current density J is equal to q n v, and that is equal to Sigma E. Therefore, d J, d E, that means rate of change of current density with respect to electric field can be written as q n d v d E.

Now, for negative differential conductance, we must have mu n is equal to d v d d E, and that should be less than 0. We will see how this negative differential mobility essentially contributes to the operation of a Gunn device.

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In a medium with +ve differential mobility, any space charge inhomogeneity , $\boldsymbol{Q}$ decays exponentially.

$$\boldsymbol{\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \Rightarrow \nabla.\left(\nabla \times \vec{H}\right) = \frac{\partial\, \nabla.\vec{D}}{\partial t} + \nabla.\vec{J}}$$

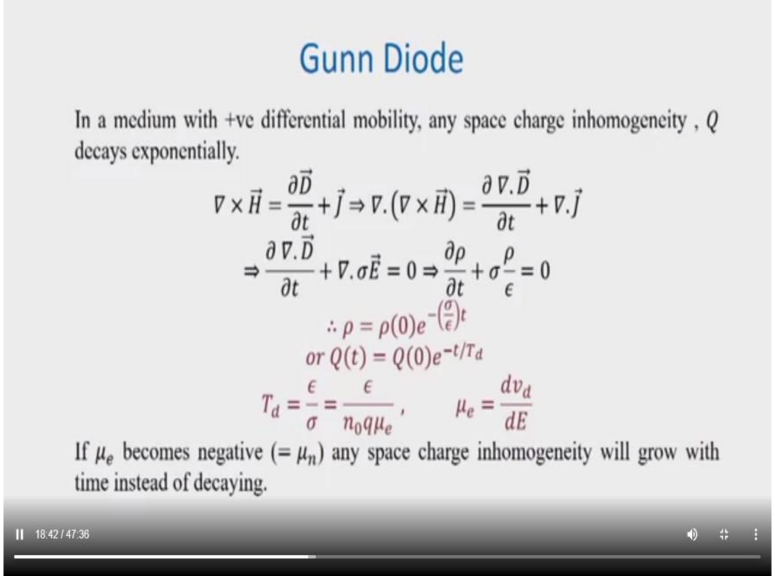
$$\boldsymbol{\Rightarrow \frac{\partial\, \nabla.\vec{D}}{\partial t} + \nabla.\sigma\vec{E} = 0 \Rightarrow \frac{\partial \rho}{\partial t} + \sigma\frac{\rho}{\epsilon} = 0}$$

$$\boldsymbol{\therefore \rho = \rho(0)e^{-\left(\frac{\sigma}{\epsilon}\right)t}}$$

$$\boldsymbol{or\ Q(t) = Q(0)e^{-t/T_d}}$$

$$\boldsymbol{T_d = \frac{\epsilon}{\sigma} = \frac{\epsilon}{n_0 q \mu_e} \quad \mu_e = \frac{dv_d}{dE}}$$

If $\boldsymbol{\mu_e}$ becomes negative ($\boldsymbol{= \mu_n}$) any space charge inhomogeneity will grow with time instead of decaying.



Gunn Diode

In a medium with +ve differential mobility, any space charge inhomogeneity , Q decays exponentially.

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If μ_e becomes negative ($= \mu_n$) any space charge inhomogeneity will grow with time instead of decaying.

When we have a medium with positive differential mobility if we have any space charge inhomogeneity caused due to some reason. Then this space charge inhomogeneity Q will decay exponentially. So, we have curl of H is equal to Del D Del t plus J from Maxwell's equation, and if you take divergence on both sides, we can write divergence of the curl of H is equal to Del Del t of divergence of D plus divergence of J.

Now, the divergence of curl of H equal to 0 and therefore we can write Del Del t of divergence of D plus in place of J we can write Sigma E, so Del Del t of divergence of D plus divergence of sigma E equal to 0. And therefore, we can write divergence of D we can write rho the charge density. So, we have Del rho Del t plus sigma rho by epsilon is equal to 0. So, we have Del rho Del t plus sigma rho by epsilon equal to 0.

Now, a solution to this equation can be written as rho equal to rho equal to 0 e to the power minus sigma by epsilon t. In terms of charge Q, we can write Q of t equal to Q at t equal to 0, e to the power minus t by T d. So, T d is equal to epsilon by sigma, which is equal to epsilon divided by n naught q mu e. We substitute the expression for sigma here n naught is the carrier density, q is the electronic charge and mu is the mobility and mu e is given by d v d d E.

Now, we have seen that if mu e becomes negative equal to mu n, then T d will become negative, and Q t instead of decaying exponentially with time will start growing exponentially with time. That is, any space charge inhomogeneity will grow with time instead of decaying. And this is very important in the context of operation of the Gunn device because when the sample is biased in the negative resistance region. We have mu n the mobility to be negative, and hence any space charge inhomogeneity present in the sample will grow giving rise to what is known as high field domains.

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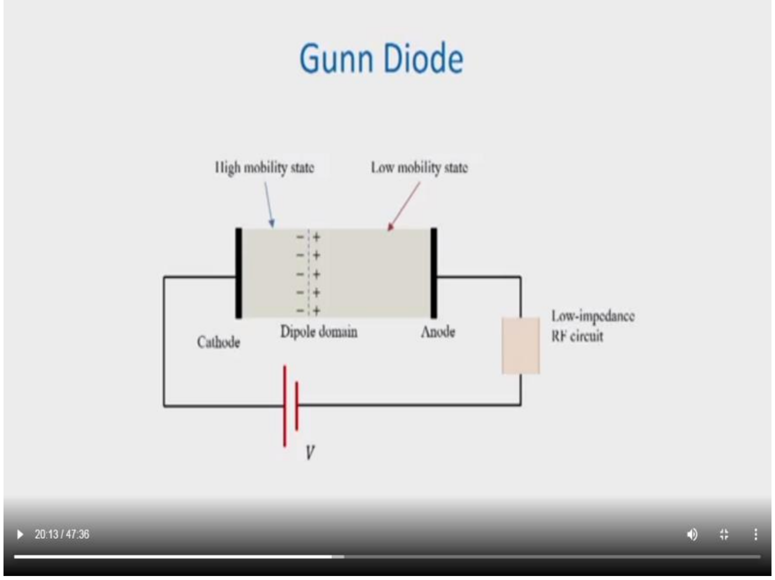

Gunn Diode

So, we have seen that when we have negative differential mobility, then and the device operates in the negative resistance region, a space charge inhomogeneity if it is present, it grows instead of decaying, and this forms the basis of the operation of a Gunn diode.

So a Gunn device is biased in such a way that the field inside the device exceeds the threshold voltage. Now, when the device goes into this negative resistance mode, the operation of the device is described in terms of formation of a dipole domain. A dipole domain is essentially a region of electron concentration and depletion. So, such dipole domains are formed near cathode.

Now, as the accumulation of changes takes place it also causes a localized enhancement of the electric field. Now, around this dipole domain, we have a high field domain formed, and that happens with the reduction of field in the remaining part of the sample. Now, this dipole domain formation is shown here, and we have high mobility states on one side of it and low mobility state at the other.

This dipole domain actually sweeps across the device, and a new domain can only be formed when this dipole domain is collected at the anode. This is because the formation of a dipole domain is accompanied with a high field domain around it.

And when this since the applied bias is constant when the concentration of the field takes place near this domain, the field in the rest of the sample goes below the threshold value. And therefore it prevents formation of another dipole domain in other locations.

So, this mechanism of formation of dipole domain, its movement to the anode, and this are self-repeating. So, once the dipole domain is collected at the anode, we have now another domain formed, and this is self-repeating and we have an oscillation with the period same as that of the transit time through the device.

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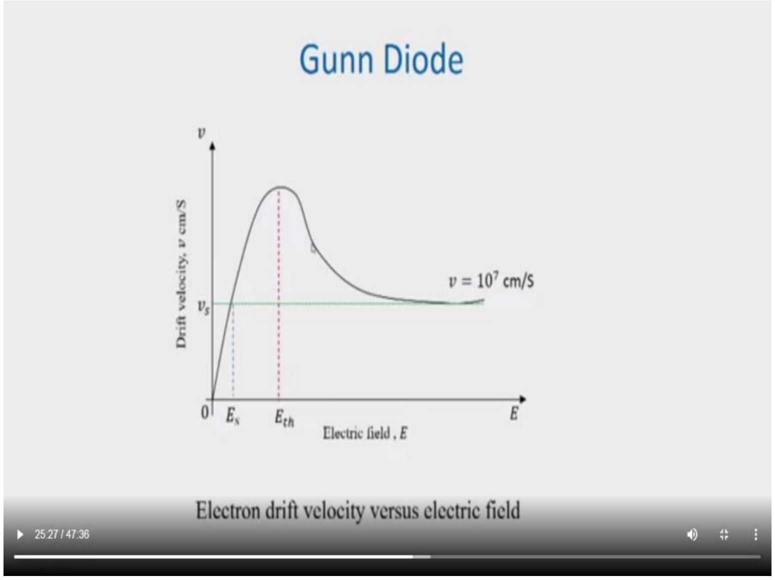

Gunn Diode

Electron drift velocity versus electric field

Here we can see that if you draw a line, we essentially have drift velocity at two points, but the difference is that here it is in the higher mobility region, here it is in the lower mobility region. Eth is the threshold electric field above which the negative differential mobility comes into the picture.

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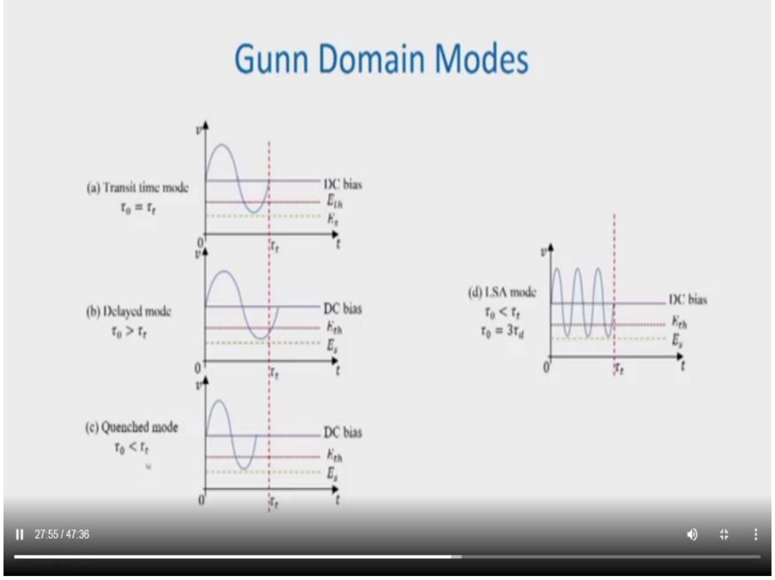

Gunn Domain Modes

Now, this type of Gunn devices are often used as a part of a resonator circuit, and we assume an AC signal is present. Now, depending upon the period of this AC signal, here tau t is the transit time, and tau naught is the period of oscillation. So, if the period of oscillation of the AC signal and the transit time they are same and during the positive half cycle, we have the device biased above the threshold voltage then domain formation will take place.

And as long as the voltage across the device does not fall below some sustaining field and as long as the electric field inside the device is above some sustaining field Es, the domain will transit through the device and the formation of the next domain will start after the end of this tau naught. But, by choosing the frequency tau naught either greater than tau t or less than tau t.

We can have two modes of operation. One is delayed mode. Here you can see that even after the domain has reached the anode, the formation of the next domain is delayed till this AC voltage goes above E^{th}. So and the opposite case is the quenched mode when tau naught is less than tau t. So, by choosing a proper resonant circuit for a delayed or a quenched mode a transfer electron oscillator it can be made to operate above or below the intrinsic transit time-frequency.

In one particular mode where the device is operated for most of the time within the negative resistance region here, we can see that the oscillation frequency is much much higher that is tau naught is very less compared to tau t. And several oscillations occur within the same transit time and therefore a domain will collapse before it is fully formed and travels to the anode. And by this process the device is maintained in the negative resistance region for a large portion of time.

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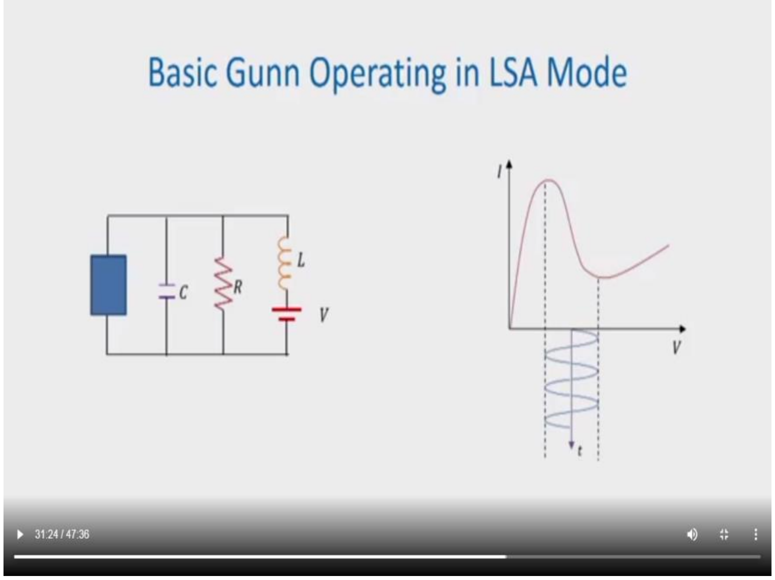

Basic Gunn Operating in LSA Mode

A basic Gunn type device operating in LSA mode is shown. Here we have this device as a part of a resonant circuit whose resonant frequency is much higher as compared to the intrinsic transit time-frequency.

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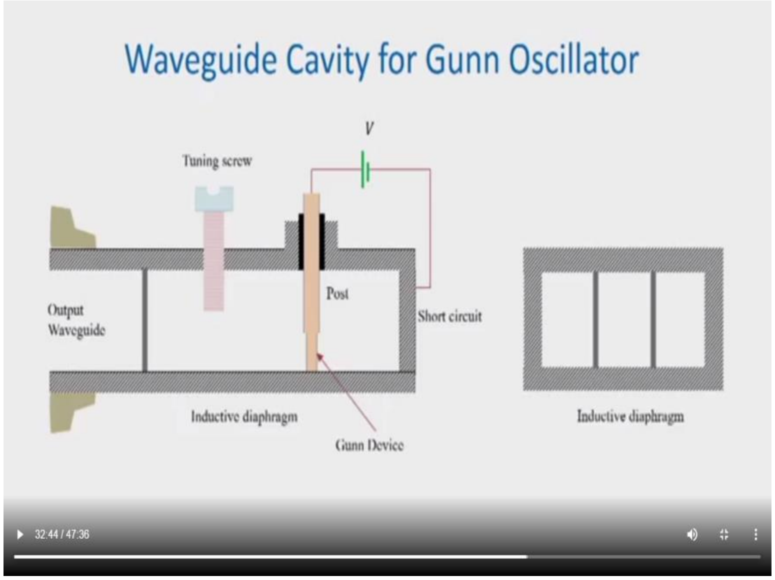

Waveguide Cavity for Gunn Oscillator

Gunn diodes are used as microwave sources, and this is the configuration of a Gunn, which is used configuration of a Gunn oscillator which is often used as a laboratory power source. So, here we have the Gunn device mounted on a metallic post, and it is enclosed in a cavity. We have a short circuit end which can be made movable for changing the tuning, and also we have an inductive iris present here which couples power to the output waveguide. So, this type of Gunn oscillators are very popular and extensively used in laboratories.

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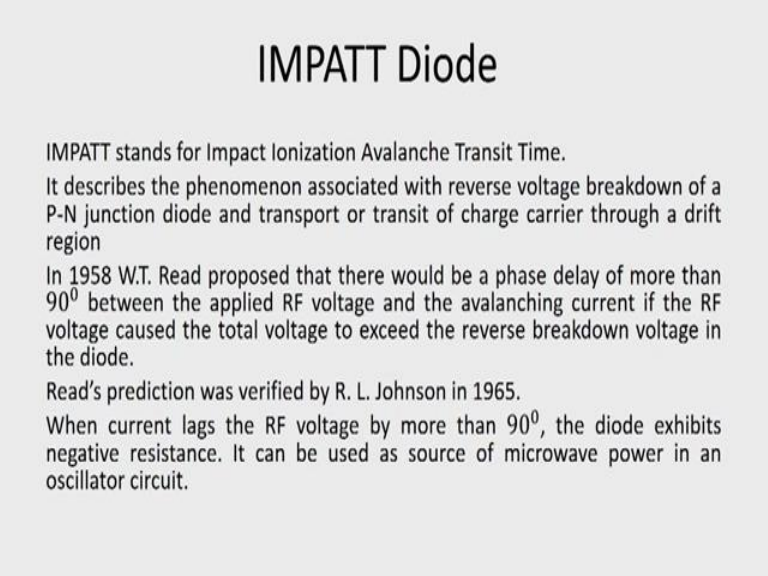

IMPATT Diode

IMPATT stands for Impact Ionization Avalanche Transit Time.

It describes the phenomenon associated with reverse voltage breakdown of a P-N junction diode and transport or transit of charge carrier through a drift region

In 1958 W.T. Read proposed that there would be a phase delay of more than 90^0 between the applied RF voltage and the avalanching current if the RF voltage caused the total voltage to exceed the reverse breakdown voltage in the diode.

Read's prediction was verified by R. L. Johnson in 1965.

When current lags the RF voltage by more than 90^0, the diode exhibits negative resistance. It can be used as source of microwave power in an oscillator circuit.

Next, we move on to another device, and we briefly discuss the operation of this device. It is an IMPATT diode. IMPATT stands for Impact ionization Avalanche Transit Time. So, it involves two mechanisms. One is the avalanche and also the transit time. We know that if a PN Junction is operated in the reverse bias condition and the reverse bias becomes very high then the junction breaks down an avalanche breakdown is the mechanism of carrier multiplication when the device goes into back down.

So, it describes the phenomena associated with the reverse voltage background of a PN Junction diode and transport or transit of charge carrier through a drift region. In 1958 W.T. Read, he proposed that there would be a phase delay of more than 90 degrees between the applied RF voltage and avalanching current if the RF voltage causes the total voltage to exceed the reverse breakdown voltage in the diode. And Read's prediction was verified later by R L Johnson in 1965.

So, essentially when the current lags the RF voltage by more than 90 degrees, the diode will exhibit negative resistance, and this negative resistance can be used as a source of microwave power if this device operates a part of the oscillator circuit. We have already discussed that positive resistance means it dissipates power and negative resistance essentially will deliver power.

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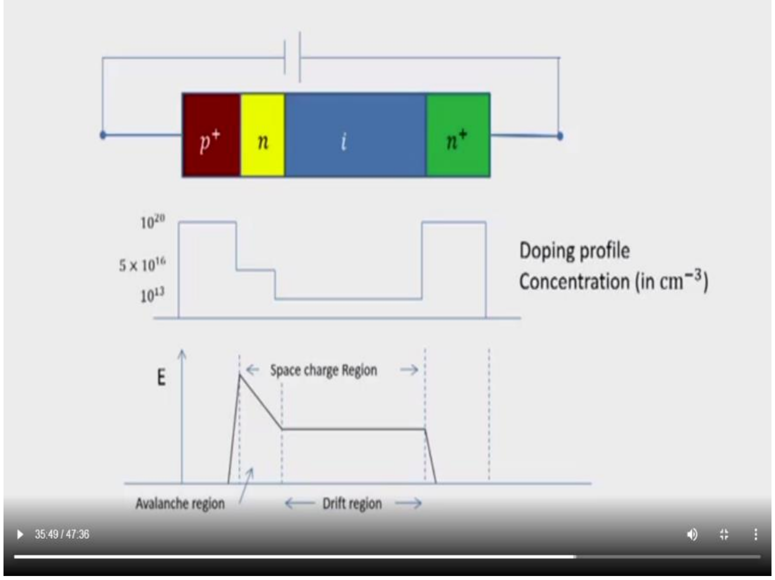

An IMPATT diode contains a heavily doped p region followed by a moderately doped n region and then an intrinsic region and again another heavily doped n region. And we can see that the bias applied here is a reverse bias. The doping profile the concentration typical values are 10 to the power 20. This is the normal concentration of a PN junction 10 to the power 16, and the intrinsic region has a concentration of around 10 to the power 13.

Now, because of this heavy doping in p region, the depletion region will be mostly in the n region, and the electric field distribution is shown here. Now, this is the space charge region, i region is the region through which the carriers generated during break down they will drift, and this region is the avalanche region.

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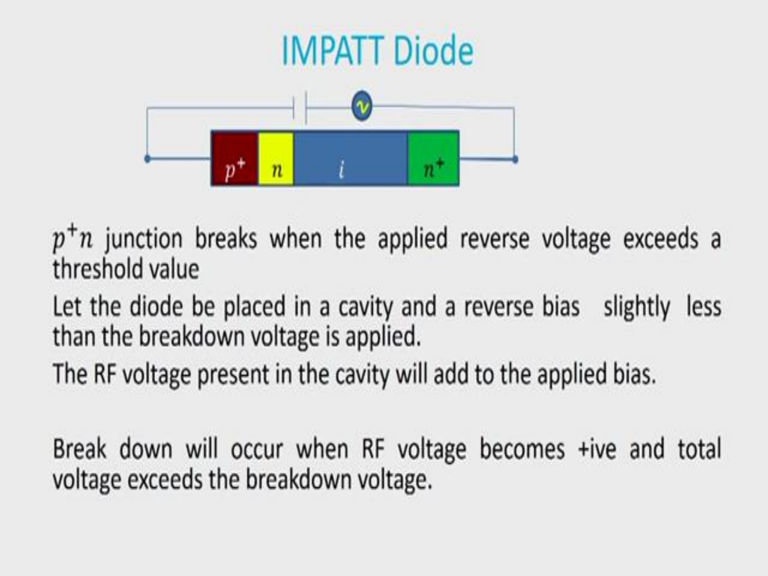

IMPATT Diode

p^+n junction breaks when the applied reverse voltage exceeds a threshold value

Let the diode be placed in a cavity and a reverse bias slightly less than the breakdown voltage is applied.

The RF voltage present in the cavity will add to the applied bias.

Break down will occur when RF voltage becomes +ive and total voltage exceeds the breakdown voltage.

Now here, we now consider, we consider an IMPATT diode where we have an AC signal present along with the applied DC bias. Now, this total voltage AC plus DC will appear across the device and let it be biased in such a way that p plus n Junction breaks when the applied reverse voltage exceeds some threshold value. So, this DC voltage is chosen in such a way that it is slightly below the threshold.

And this AC voltage comes from a cavity where the diode is placed, and the DC reverse bias is slightly less than the breakdown voltage. As we have said that the RF voltage present in the cavity will add to the applied bias, breakdown will occur when the RF voltage becomes positive and total applied voltage it exceeds the breakdown voltage.

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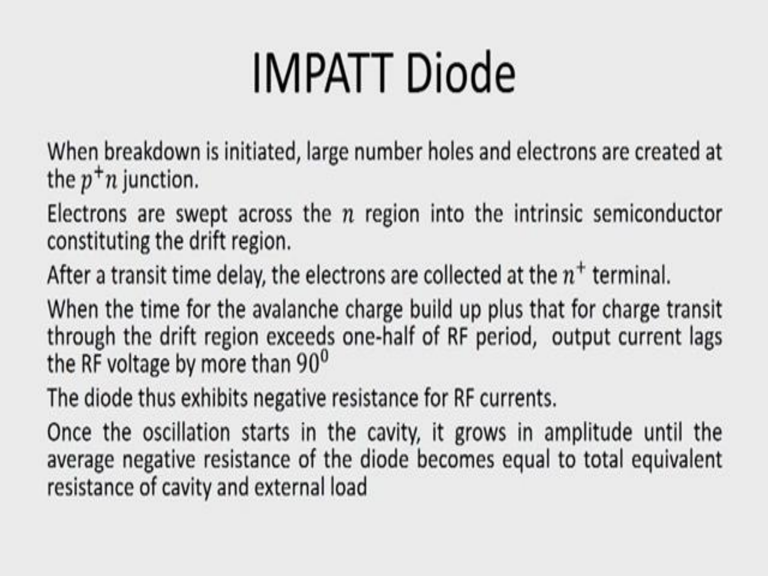


IMPATT Diode

When breakdown is initiated, large number holes and electrons are created at the p^+n junction.

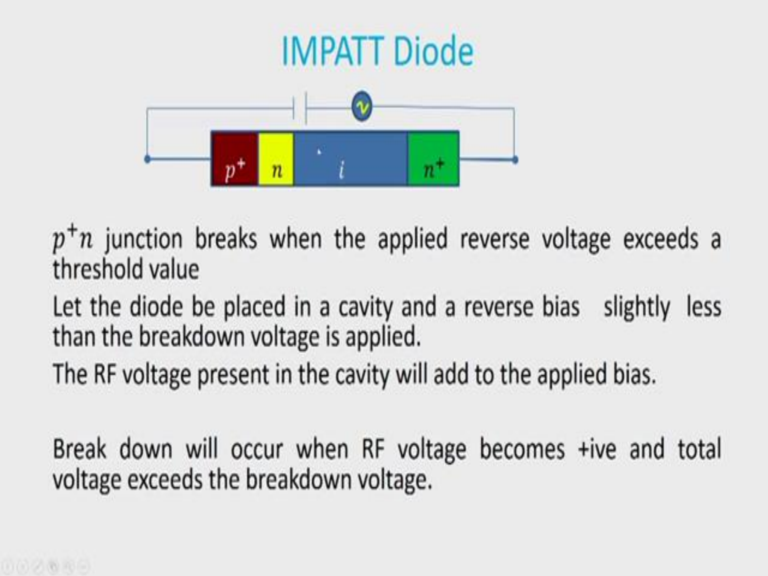
Electrons are swept across the n region into the intrinsic semiconductor constituting the drift region.

After a transit time delay, the electrons are collected at the n^+ terminal.

When the time for the avalanche charge build up plus that for charge transit through the drift region exceeds one-half of RF period, output current lags the RF voltage by more than 90^0

The diode thus exhibits negative resistance for RF currents.

Once the oscillation starts in the cavity, it grows in amplitude until the average negative resistance of the diode becomes equal to total equivalent resistance of cavity and external load



IMPATT Diode

p^+n junction breaks when the applied reverse voltage exceeds a threshold value

Let the diode be placed in a cavity and a reverse bias slightly less than the breakdown voltage is applied.

The RF voltage present in the cavity will add to the applied bias.

Break down will occur when RF voltage becomes +ive and total voltage exceeds the breakdown voltage.

When the breakdown is initiated, a large number of holes and electrons are created at the p plus n junction. Because of the field, we can see that the DC field is acting in this direction and this field will sweep the electrons across the n region into the intrinsic semiconductor, which constitutes the drift region.

So, after a transit time delay, the electrons are collected at n plus terminal. When the time for the avalanche charge buildup, the avalanche process is an exponential process, it is exponential growth, plus that for the charge transmit through the drift region exceeds one half of RF period, the output current lags the RF voltage by more than 90 degrees.

And the diode thus exhibits negative resistance for RF currents. Once the oscillation starts in the cavity, it grows in amplitude until the average negative resistance of the diode becomes equal to the total equivalent resistance of the cavity and external load. So, at that time a steady state is reached, and the oscillator oscillates in producing a steady output. The next device we consider is a varactor diode

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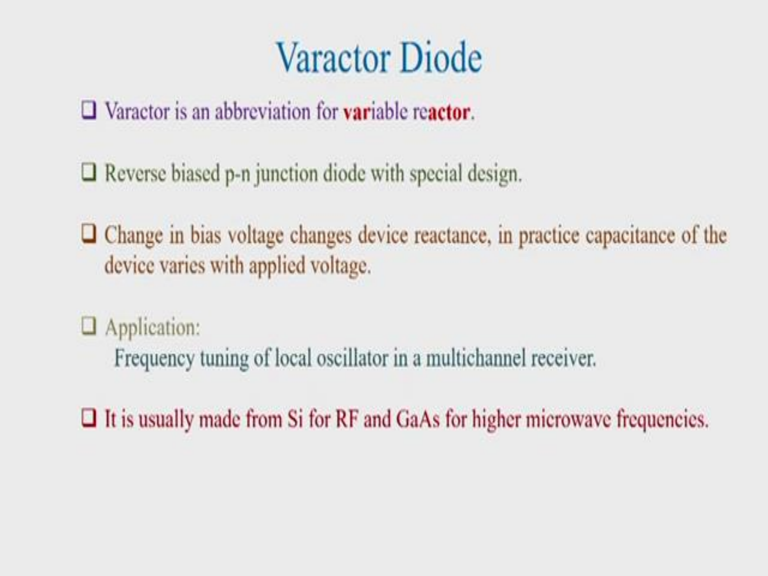

Varactor Diode

- Varactor is an abbreviation for **var**iable re**actor**.
- Reverse biased p-n junction diode with special design.
- Change in bias voltage changes device reactance, in practice capacitance of the device varies with applied voltage.
- Application:
  Frequency tuning of local oscillator in a multichannel receiver.
- It is usually made from Si for RF and GaAs for higher microwave frequencies.

We now turn our attention to another device, which is called a Varactor diode. A varactor is essentially a variable reactor. It is a reverse-biased p-n junction diode with some special design. Now, when the bias voltage is changed, it changes the device reactants, and in practice, the capacitance of the device varies with applied voltage.

Now, varactor diodes are specifically used for the frequency tuning of local oscillators. Such diodes are usually made from Silicon for RF frequencies and from gallium arsenide for higher microwave frequencies.

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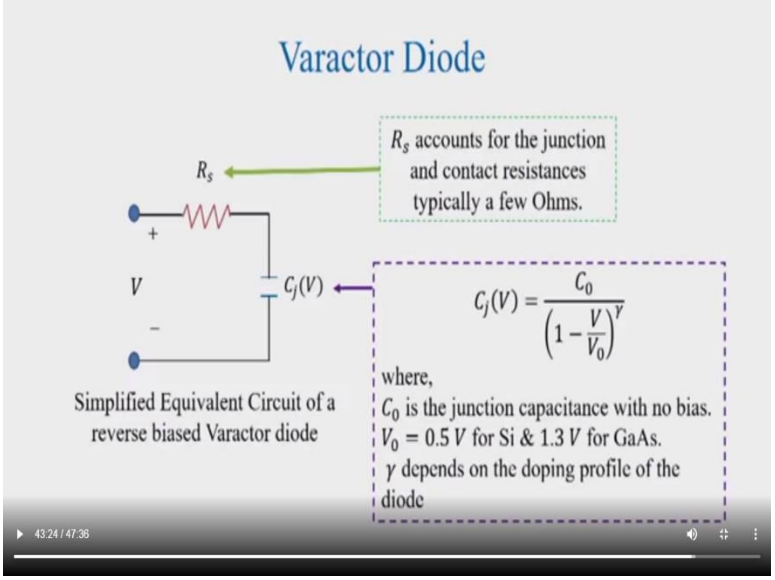
$$C_j(V) = \frac{C_0}{\left(1 - \frac{V}{V_0}\right)^{\gamma}}$$

where,

C_0 is the junction capacitance with no bias.

$V_0 = 0.5\ V$ for Si & $1.3\ V$ for GaAs.

γ depends on the doping profile of the diode



Varactor Diode

R_s accounts for the junction and contact resistances typically a few Ohms.

Simplified Equivalent Circuit of a reverse biased Varactor diode

$$C_j(V) = \frac{C_0}{\left(1 - \frac{V}{V_0}\right)^{\gamma}}$$

where,

C_0 is the junction capacitance with no bias.

$V_0 = 0.5\ V$ for Si & $1.3\ V$ for GaAs.

γ depends on the doping profile of the diode

The simplified equivalent circuit of a varactor diode consists of a series resistance RS with a variable capacitance C_J. So, it is essentially the capacitance of the reverse bias junction. RS accounts for the junction and contact resistances and typically a few ohms. C_j, the junction capacitance is given by C naught divided by 1 minus V by V naught raise to the power gamma, where C naught is the junction capacitance with no bias.

So, when we do not apply any reverse bias, the capacitance that is offered by the diode is denoted by C naught and V naught. It is 0.5 volt for silicon and 1.5 volts for gallium arsenide. The value of gamma depends on the doping profile of the diode. We know that a junction maybe steps junction; it may be a graded junction.

So, as we have said, the varactor diode is used for tuning in oscillator circuits, and this can be a part of an oscillator circuit where we can apply a voltage to slightly vary the capacitance and thereby tune the frequency of the oscillator circuit.

So, in this module we have seen the basics of some of the solid-state devices which are used at microwave frequencies for signal amplification or signal generation. We have seen microwave transistors, different types of diodes, pin diodes as a control element, Gunn or impaired diode, which can be used as a part of an oscillator to generate microwave signals.

We have also seen short key barrier diode, which can be used as a detector. So, in the next module we will discuss the design of microwave amplifiers and oscillators. In fact, we will represent the active devices, the transistors by their s parameters and we will see the two-port power gains, stability, design of single-stage amplifier, how we can design it for maximum gain, for the specified gain and briefly discuss low noise amplifier and RF oscillators.