Microwave Theory and Techniques

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Module - 06
Lecture – 26
Microwave Diodes: PN Junction, Varactor, Schottky, PIN, Tunnel, and GUNN. Diodes

Hello, I am Rinky Chopra. I am a Phd student at Electrical Engineering Department IIT Bombay. Also, I am a Teaching Assistant for this course. I am working in the area of RF and Microwave. So, today I will be taking a lecture on Microwave Diodes.

So, let us start the lecture. Firstly, I will give you the brief outline of this lecture, we will be starting with semiconductor materials. Then, we will talk about n type and p type of semiconductor materials. After, that we will discuss about PN Junction Diode, then Varactor diode, Schottky diode, PIN diode, Tunnel diode, and finally, GUNN Diode.

So, let us start with semiconductor material, we know in any atom electrons can occupy only discrete energy levels. Now, if 2 or more such type of atoms are brought in close vicinity, then the electrons at the similar level should shift to the higher energy level. Now, many of such atoms are if brought in the close vicinity, they form an energy regions, these regions are called S bands; 2 of the bands are the conduction band and the valence band.

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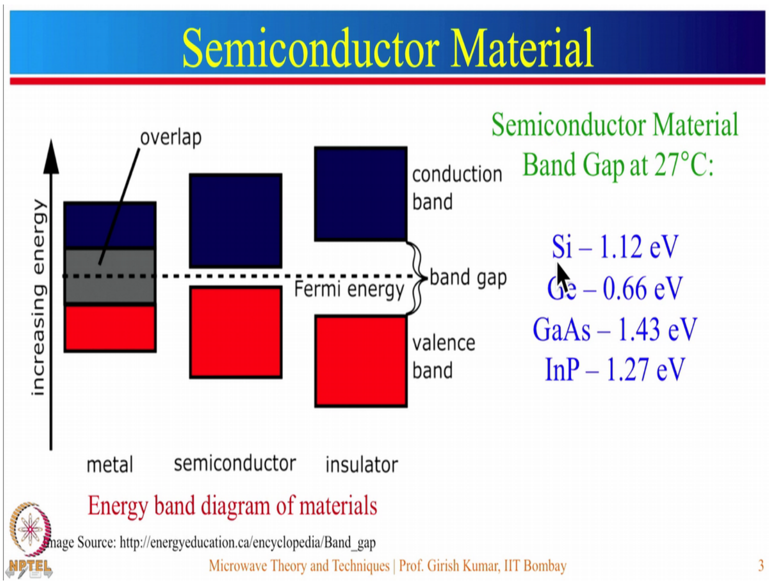

And they are separated by a forbidden region. This forbidden region is also known as the energy band gap or forbidden gap.

The band gap defines a significant role in defining the conductivity of the material. Now, the materials are divided into 3 types. First one is metal, then semiconductor and insulators. So, in case of metals the conduction band and the valence band, overlap with each other. So, an electron can move from the valence band to the conduction band at 0 Kelvin. In this case electrons play may role in the conduction.

So, the only type of carriers is the electrons. So, this is a material which has only one type of charge carriers that are electrons the next type of material is insulator. In case of insulator the band gap between the conduction band and the valence band is relatively high it is of the order of 4 to 9 electron volt. So, electron cannot move easily from valence band to the conduction band. It requires a sufficient amount of energy to move an electron from the valence band to the conduction band. So, they are not a conducting material.

The next type of material is the semiconductor material, in the band gap in the semiconductor material is between the insulators and the metals; it is of the order of 1 electron volt. Now, at room temperature the electrons gains sufficient energy from the thermal energy. So, that they can move from the valence band to the conduction band,

and when an electron moves from the valence band to the conduction band it leaves behind a hole.

Now, if you supply some energy in this particular case this vacancy is filled by another electron. So, it looks like that they movement is also taking place because of holes. So, in the semiconductors there are 2 types of charge carriers holes and electrons. Now, the concentration of holes in any band is defined by the Fermi energy level. So, Fermi level is an energy level, which would have 50 percent of probability of occupying at any instant of time.

Now, I will talk about the semiconductor materials, which are used by the industry. So, the most commonly used semiconductor material is silicon the band gap for silicon is 1.12 electron volt, for germanium the band gap is 0.66 electron volt, for gallium arsenide it is 1.43 electron volt for indium phosphide, it is 1.2 7 electron volt.

Now, among these semiconductor materials silicon is the most widely used semiconductor materials. And, most of the electronic devices are made using silicon materials. And, few of the active devices are also made using the semiconductor material , but they are not suitable candidates for the microwave frequency series, because they suffers with the a problem of minority charge carriers storage, which will not provide the desirable performance at the microwave frequency region.

Now, if I see these 2 types of materials. They are the compound semiconductor materials. Now, if you see the energy gap for these materials are relatively high, but they offers the significant advantages over these 2 materials like they provide low noise figure, high power handling capability and they can operate up to very high frequency range maybe up to terahertz.

Now, if I want to increase the conductivity of the semiconductor material. So, the semiconductor material conductivity can be increased by adding the small amount of impurity in the semiconductor materials. So, there are 2 types of impurities, which can be added to semiconductor materials. The one of the impurity is the n type of impurity which belongs to valence 5 groups.

So, let us take an example of an atom from valence 5 groups. So, phosphorus is the example from valence 5 groups.

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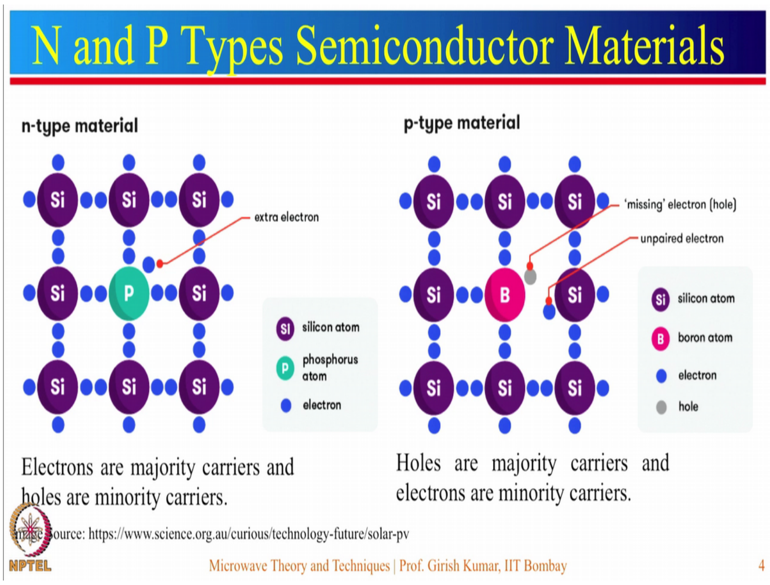

If, we add the impurity of phosphorus in silicon lattice, now we know in case of phosphorus, it contains the 5 electrons in it is outermost shell. So, these electrons form the covalent bond with the silicon lattice that can be seen from this particular figure. And, the 5th is loosely coupled to this lattice.

Now, at the room temperature this electron gains the sufficient energy. So, that it can move from the valence band to the conduction band. And, it is negatively ionized. Similar case happen in case of other impurity atoms. Now, when the impurity atoms are added the amount of impurity atoms are generally lies between 10 to the power 10 to 10 to the power 18s atoms in per centimeter cube region.

So, if you see in these n-type of materials the impurity atom have a tendency to donate the electrons. So, that is why this impurity atom is called as donor. So, in this n-type of materials electrons are the majority carriers and holes are the minority carriers. Now, the Fermi level in these types of materials is shifted towards the conduction band, I will show you Fermi level in the next slide. The next type of material is the p-type of material.

When you add the impurity from valence 3 group; for example, if we add a boron atom which belongs to valance 3 groups; now, we know in case of boron in it is outermost shell 3 electrons are there. So, they form a covalent bond with the silicon lattice, you can see here and at the fourth position. It has a tendency to accept the electrons from the adjacent covalent bond of the silicon.

Now, at room temperature it again gains sufficient energy. So, that it accept the electrons from the adjacent silicon lattice and becomes positively ionized. Now, the vacancy is created at this particular place. This vacancy is again filled by another electron and the hole will be created at that particular location. So, it looks like that the movement of hole is taking place. In these types of materials holes are the majority carriers and electrons are the minority carriers.

Now, these types of impurity atoms have a tendency to accept the electrons. So, they are called as acceptors. In these types of materials the Fermi energy level lies near the valence band, that I will show you in the next slide. Now, if the n type of material and p-type of material are brought together, then they form a junction that junction is called as the PN Junction Diode.

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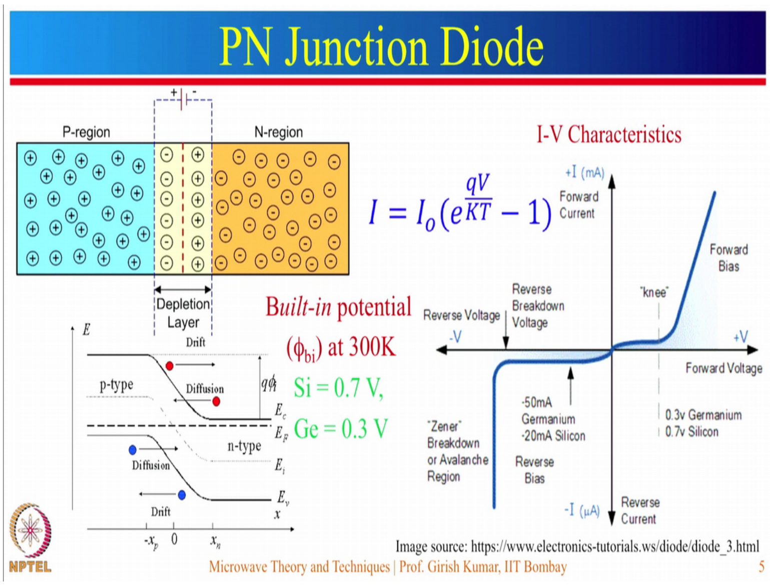

Here you can see that in case of P-region the Fermi energy level is near the valence band, in case of n region the Fermi energy level is near the conduction band.

Now, when these materials are brought close to each other they have a tendency to make a equilibrium. So, we know in case of P-regions holes are the majority carriers, and in case of N-region the electrons are the majority carriers. Then these carriers will try to make the equilibrium. So, whole from the P-region will try to diffuse into the N-region and electrons from the N-region will try to diffuse into the P-region. And, they will leave behind the positive ions in case of N-region and the negative ions in case of P-region.

Near the junction the space charge region takes place. So, and so, the nearest junction they forms a space charge region, which based the electrostatic potential. And, this electrostatic potential further refuses the diffusion of electrons from the N side to the P side and it also refuses the diffusion of holes from the P side to the N side.

Therefore, in equilibrium there is no flow of current due to the built in potential. The built in potential is defined by the impurity atoms or the doping profile and the type of material which is used.

So, the built in potential for silicon lattice is 0.7 volt and for germanium it is 0.3 volt. Now, I will talk about the operation of this PN junction diode, before going into the operation mode just see the I-V Characteristics of this diode. Now, I will talk about the operation of this diode using the I-V Characteristics of this diode well.

So, when the PN Junction is connected in forward bias mode; that means, if the positive terminal is connected to the P side, and the negative terminal is connected to the N side. Then it will repel the holes away from the terminal and it will again repel the electrons away from the negative terminal.

So, they will try to reduce the depletion region. So, that can be seen from this particular curve. So, when the forward biased voltage is greater than the built in potential or the knee voltage. So, up to this points only the reverse saturation current will flow which comes into the picture due to the electron hole thermal, electron hole pair generation.

So, when the forward bias voltage is greater than the built in potential. The current flows in this particular circuit, when the forward bias voltage is much greater than the thermal voltage, which is defined by the KT by q and that is 26 millivolt at room temperature.

So, when the forward bias voltage is much larger than the thermal voltage, then the currents increases exponentially. This can be seen from this particular curve and the current of this particular curve is represented by this expression, this is known as

Shockley's current equation. So, here you can see if VT is less it if V is much greater than the KT by q, then it will increase exponentially.

Now, if I bias this PN Junction diode in reverse mole, that is if the P-region is connected to the negative terminal and the N side is connected to the positive terminal. Now, the terminal will attract the holes toward the P-region and the positive terminal will attract the electrons towards the negative terminal. So, the depletion layer with will increase and it will restrict a flow of current.

So, you can see in reverse mode there is a very less of current which is equivalent to the reverse saturation current. Now, if we increase the reverse bias voltage to a sufficient large value, then the current increases suddenly. Why does this happen? Because for this particular voltage the electrons gains sufficient energy so, that they knock out the electrons from the outer orbit of the atom and the current increases.

The reverse bias voltage can also be increased further, there is no harm in using the PN junction diode above this reverse bias voltage , but make sure that there should be a connection with the resistor. So, that it should not damage the diode. One more thing one should keep in mind while using this diode in this particular region that it should not exceed the maximum current because, if it is to be brought in below breakdown voltage, then it should be operated in the normal region. So, that is the thing that one should keep in mind when one is exceeding the 'Zener' Breakdown Voltage.

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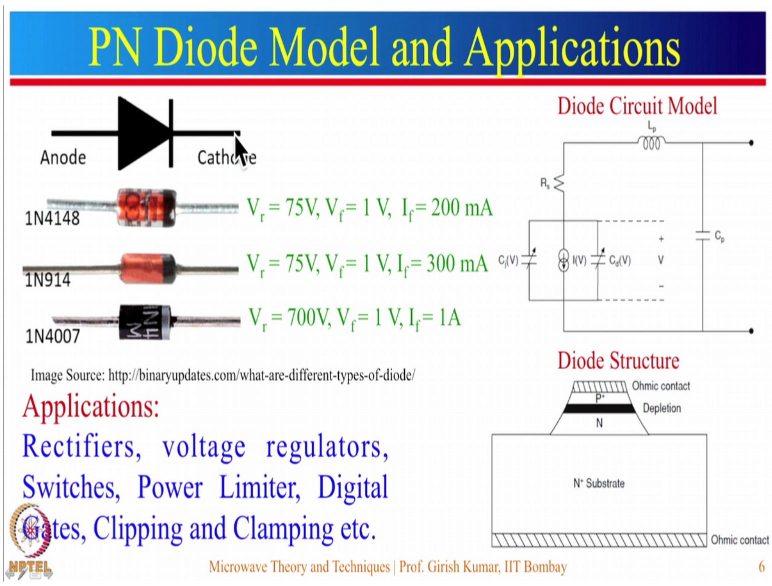

Next, I will talk about this diode circuit model. So, the diode will be represented by a non-linear current source in parallel with 2 type of capacitance. The one capacitance is the junction capacitant capacitance and another one is the diffusion capacitance. Then this should be connected in series with the series resistor, which accounts for the losses in the depletion region. Now this diode is to be packaged. So, the packaging losses should also be considered. So, the C p capacitor is included to account for the packaging capacitance. And, this L p is considered here to account for the bonding wire inductance.

Now, how to make this particular diode? To make the diode the lightly doped n type of layer should be deposited on heavily doped, n type of substrate then the p type of layer should be deposited on the n type of layer. Now, to make the electrical connection with the circuit the metallic contacts are provided at both the ends these are the metallic [con/contacts] contacts you can see. These metallic contacts could be of tungsten aluminum gold etcetera.

The next is where this type of diode should be used. So, they are various applications, in which these diodes can be use the diode can be used as a rectifier voltage regulators, switches, power limiter, digital gates, clipping, clamping, etcetera. Now, depending upon the application one should choose the diodes. Now, before going into the practical diodes, I will talk about the representation of this diode. So, this diode is represented by this particular symbol. Here, this terminal represents the anode and this terminal represents the cathode.

Now, the power current will flow in this particular direction. So, it supports the movement in 1 direction and this is called as the unipolar device. In ideal case it will only support the current flow in this direction and it will not allow any current to flow in the reverse direction. Now, the diodes can be defined into 2 types depending upon their current rating and the power rating.

So, the diodes are divided into 2 categories small signal diode and the large signal diodes. So, the true examples have been taken for the small signal diode. So, in 4 1 4 8 and in 9 1 4 are the diodes for the small signal diode these specifications of these diodes are given here. You can see from the current rating their current is relatively this these diodes are a good candidate for switching applications or flop clamping.

The third type of diode that is I N 4 double 0 7 is a power diode, that you can see from the specification of this diode the current rating is relatively high. So, it is more suitable for the applications like it can be used as a power diode or rectifier. So, one should choose the diode according to the application.

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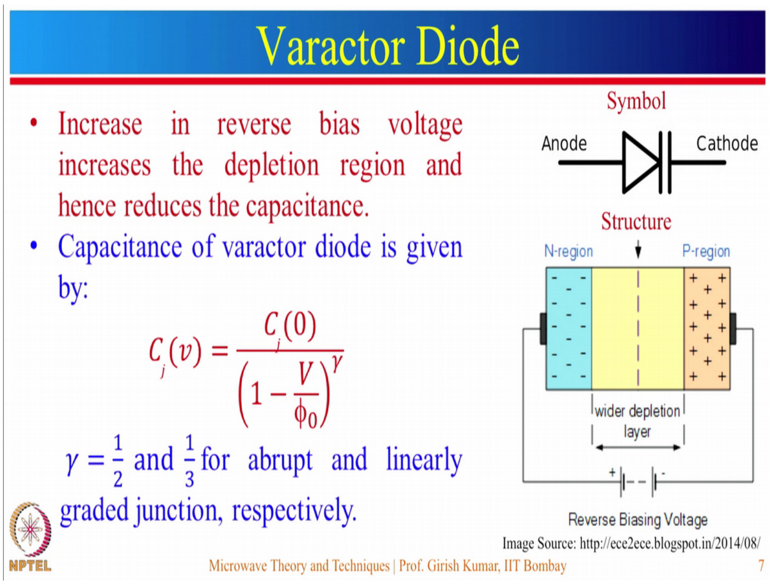

The next diode that we will talk about is the varactor diode. Now, if we see the PN Junction diode and if we try to see the reverse bias behavior of this diode, it shows a very interesting property just to explore that particular behavior just connect the PN junction diode in a reverse polarity. So, that the positive terminal is connected to the N-region and the negative terminal should be connected to the P-region.

Now, if you increase the reverse bias voltage this depletion layer width will increase. So, you can try to relate this geometry with the capacitor. These 2 regions and N and P regions will be analogous to the parallel plate capacitors. And, this will be analogous to the parallel plates of the capacitor whereas, the depletion region is analogous to the insulating material between the capacitor plates. So, now, we know in case of parallel plate capacitor, the capacitance is given by epsilon a by d. Where d is the width of the insulating material.

So, if we increase the reverse bias voltage the width of the depletion layer will increase. So, the capacitance will decrease. So, therefore, with increase in reverse bias voltage the depletion region increases and the capacitance reduces. Now, the capacitance of the varactor diode is given by this expression. Here V is the reverse bias voltage phi naught is the del tel potential and gamma depends on the doping profile. So, gamma is equals to 1 by 2 or 1 by 3 for abrupt or the linearly graded junction.

Here C j 0 is the capacitance corresponding to 0 bias conditions. And, it will be mixing. Now, this particular diode is represented by this particular symbol, here you can see this is similar to the pn junction and in series the 1 capacitor is added. So, this represents the symbol of the varactor diode.

Now, there is a very important characteristic of varactor diode and that is the q vector. So, suppose if a varactor diode is used for any application like oscillator. So, if it has higher q, it will provide relatively low phase noise. Similarly, in case of tunable band pass filter if the q vector is high. So, the tunable filter will be more selective or their response will be steeper.

So, depending upon the application q vector should be chosen. Now, we know the q is inversely proportional to the c value and the series resistance. So, there is a tradeoff between the capacitor value and the quality factor. So, one should choose this the capacitor according to the application.

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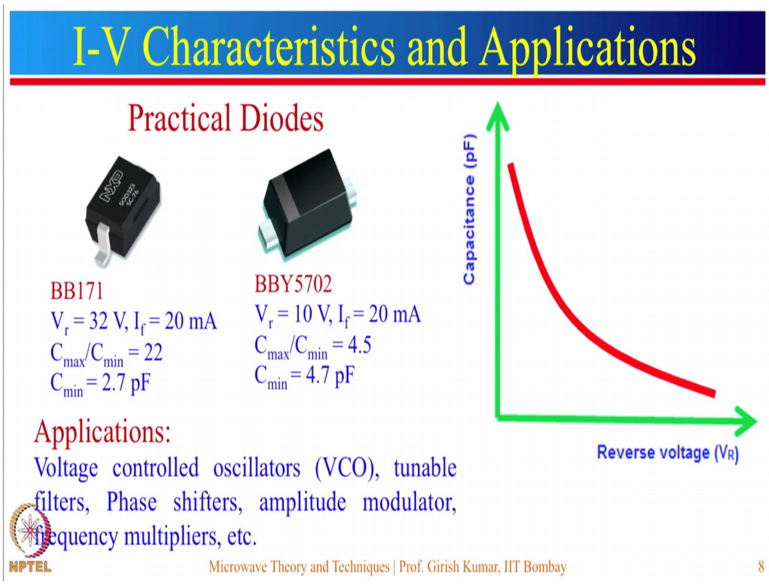

Next, I will talk about the IV characteristics of this diode as I mentioned earlier capacitance decreases with increase in reverse bias voltage. So, this shows the characteristics of the varactor diodes.

Now, these I V characteristics of the diode can be altered by changing the doping profile. So, there are 2 types of doping profile abrupt and the hyper abrupt. In case of hyper abrupt doping profile, the capacitance variation range is relatively high, but it comes at the cost and low q vector.

Now, if I talk about the applications these varactor diodes can be used in various applications like Voltage Controlled Oscillators, tunable filters, phase shifters, amplitude modulator, frequency multipliers etcetera. Now, again similar to the PN Junction diode one should choose the diode depending upon the applications.

So, here I have taken the 2 examples of practical diode 1 is BBY 5 7 0 2 these specifications for this diode is given here, the quality factor of this diode is very high. So, it is more suitable for the selective filter and another example I have taken where the tunability range is relatively more. You can see in this case the C max to C min ratio is relatively more? And, it defines the tunability range. So, it is more suitable for the wide band tuning range; like if you want to use it in vector network analyzer or a spectrum area network analyzer, then the diode will be more suitable. So, one should choose the diode and n again depending upon the application.

The next type of diode is the Schottky Diode. So, the schottky diode is similar to the PN Junction diode.

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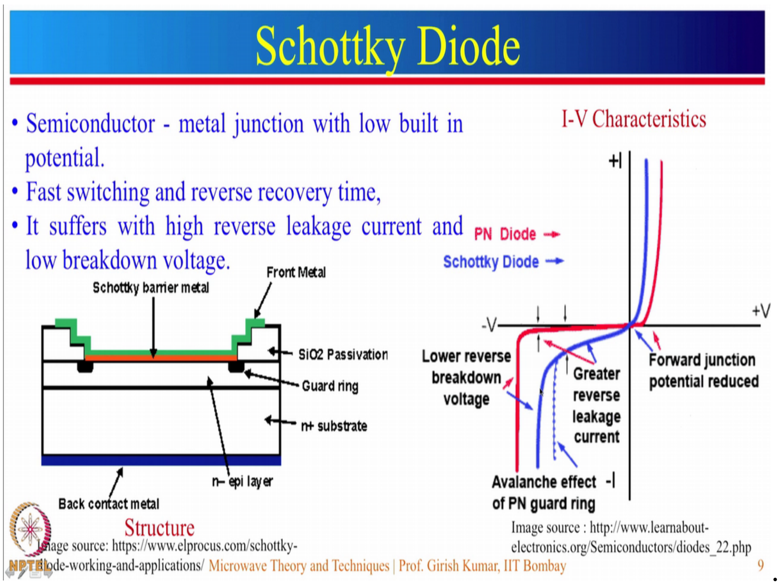

But in this case the junction should be made using the n type of material and the metal. So, in this case the n type of epitaxial layer is deposited on the highly doped n type of substrate and then metal is deposited on the n type of epitaxial layer.

Now, to make the electrical connection with the circuit, they metal contacts have been made. And, this is how the structure of schottky diode is made. Now, we know this is the junction of metal and the n type of semiconductors. So, the depletion region will be less in this case. So, this is provides relatively low built in potential or low turn on voltage, and due to the less depletion region, it provides relatively faster switching and less reverse recovery time.

So, what is reverse recovery time? So, reverse recovery time is the time taken for a diode to switch from on to the off a state or vice versa. So, in case of PN Junction diode this time is around 5 to 200 nanoseconds; however, in case of schottky diode this time is of the order of 1 Nano second , but there is a disadvantage of this diode, it suffers with the high reverse leakage current and low breakdown voltage, due to the low depletion region.

Now, if I compare the I V characteristics of this diode with the PN Junction diode from these I V characteristics you can see it provides low turn on voltage, and it is of the order of around 0.3 to 0.4 volt. And, you can see here the reverse leakage current in this case is very high, it is of the order of micro ampere. However, in case of PN Junction it is of the order of Nano ampere and the breakdown voltage for this diode is relatively less. So, this is the drawback of this diode.

Now, if this diode is to be designed for the varactor applications the doping profile should be altered accordingly. Now, if I talk about this circuit model, this circuit model of the schottky diode is similar to the PN Junction diode.

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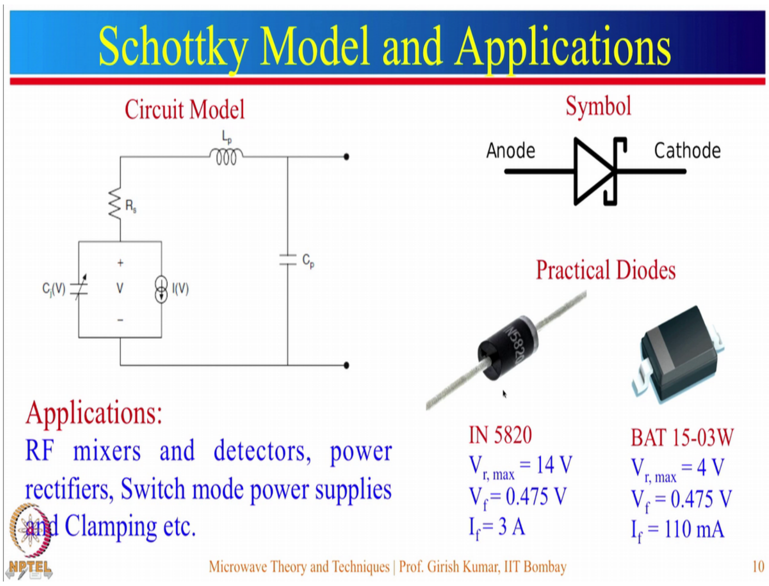

Only thing is there will not be any diffusion capacitance. So, that is not included in the circuit model. And, the schottky diode is represented by this symbol this corresponds to the anode and this represents the cathode.

If I talk about the applications so, the applications of the schottkey diode are similar to the pn junction diode they are used in RF mixers and detectors, power rectifier SMPS and clamping etcetera. Now, again here I have taken the example of 2 practical diodes, this one belongs to the power diode you can see from the current and the voltage rating. And, this one is more suitable for the switching applications. So, once you choose again the diode according to the application.

The, next type of the diode is the pin diode as the name says that; here the intrinsic layer is inserted between the highly doped P and N Junction.

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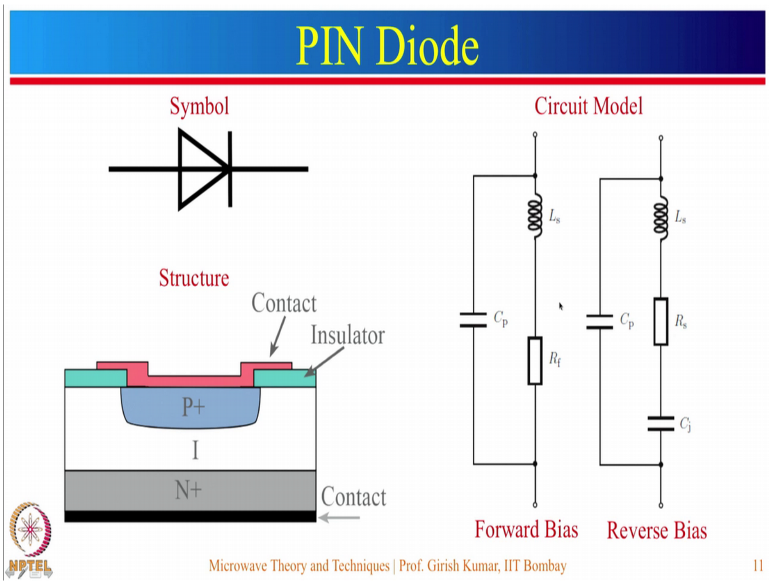

So, the high layer is deposited only on highly doped substrate. And then highly doped P type of subs layer is deposited on the intrinsic region. So, this is how the geometry of this structure is made? Then again the contacts are made to make the connection with the electrical circuit.

So, in this case the depletion region is relatively wider due to the insertion of this intrinsic region. So, in this case if I talk about the reverse bias case, it will provide very wide depletion region. So, the capacitance for this diode will be very less and it will be almost constant, because the depletion layer length is relatively wide.

So, in this case it provides the lower capacitance. And, if I connect this diode any forward bias then with increase in forward bias voltage, first the recombination of electrons and holes will take place in the intrinsic region, after that the recombination will take place in the P and N region.

So, the in resistance of the diode will vary. So, in the forward bias it will act like a variable resistor. Now, the symbol of the pin diode is represented here this denotes the diode and this represents the cathode. Now, if I want to make a circuit model of this it can be divided into 2 cases the forward bias and the reverse bias, in the forward bias it acts like a variable resistor and in the reverse bias it is x like capacitor whose value will be much less as compared to the PN junction diode, and then a series resistor is added to account for the losses in the depletion region. And these L s and C p are accounted for the losses due to the packaging.

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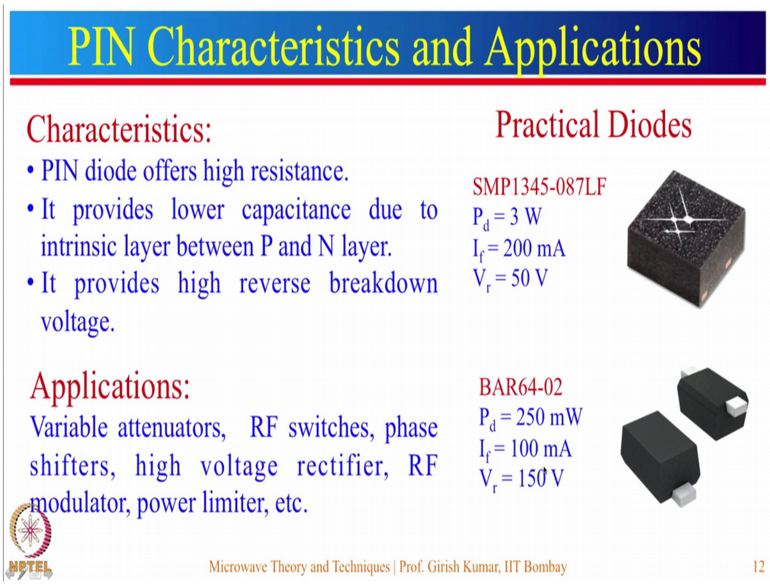

Now, if I talk about the characteristics as I told you earlier the pin diodes offers high resistance. It provides lower capacitance due to the insertion of the intrinsic layer between the highly doped P and N layer, it provides high breakdown region due to the intrinsic region. So, if I talk about the applications these diodes are mainly used for the applications like in variable attenuators RF switches phase shifters high voltage rectifiers, RF modulators power limiters etcetera.

Now, just to show again the applications I have taken the 2 practical diodes the first one is corresponding to the power diode and the second one is more suitable for the high voltage variable resistor. So, one should again choose the diode according to the application. The next type of diode is the tunnel diode. So, the tunnel diode is a diode where the P and N junctions are highly doped.

Now, we know in case of conventional PN junction diode, the conduction and the valence band are separated by a large forbidden gap. When they are heavily doped the Fermi level shifts in the conduction band in case of N type of material and it is shift in the valence band in case of P type of material. So, there is a mechanical phenomenon which takes place this quantum mechanical [is phenomena is called as the tunneling.

So, in the thermal equilibrium the Fermi level of the conduction band and the valence band will line up. So, there will not be any flow of the electrons from the conduction band to the valence band.

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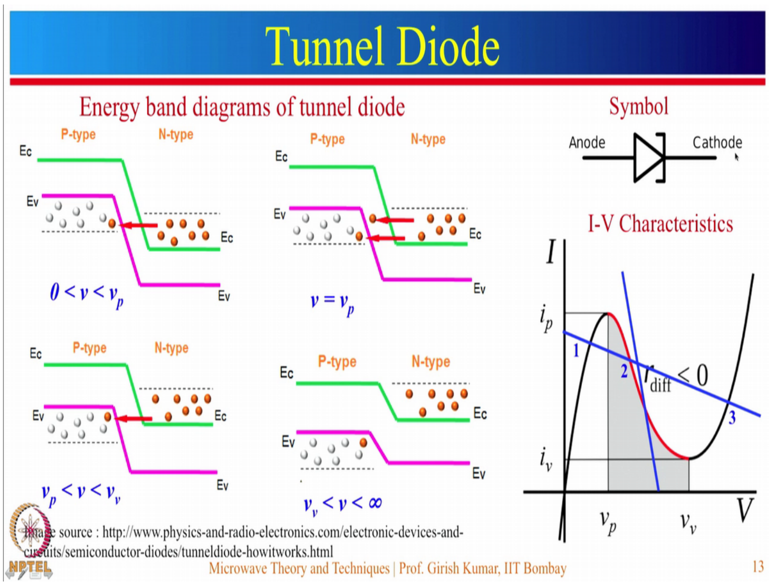

Now, if we increase the voltage from 0 to the voltage corresponding to the peak current, then the barrier potential will decrease and the level will shift up. So, there is a possibility that the electrons from the filled state in the conduction band can tunnel into the empty states in the valence band.

So, this can be seen from this particular figure; so, as the electrons tunnel from the valence band to the conduction band, the current increases. Now when the voltage is equivalent to the peak voltage, in that case the maximum tunneling of electrons can take place from the conduction band to the valence band. So, it represents a maximum peak current.

Now, if the voltage is increased further in that case the tunneling of charge carriers will decrease. So, the current will decrease with increase in voltage. Now, when the voltage is increased more than the valley voltage, in that case there will not be any overlap of this band. So, the current will come to a minimum value or it may be 0. Now, if voltage is increased further this tunnel diode will behave like a conventional PN junction diode and the injection current will start flowing which increases exponentially. So, that is represented by this I V curve.

Now, if you try to make a load line, if you make us shallow a load line whose resistance is relatively higher, then it will cut these I V characteristics at these 3 points 1 2 and 3. Now, this 0.2 is the unstable point. Now, if there is a little deviation in the voltage then either it will come to 0.1 or 0.3. So, depending upon the previous stage, in this mode this tunnel diode are used as a memory device or they storage device, but this is of little less interest to the microwave circuit designers the another type of load line can be drawn when the r is relatively less.

So, it will show you the steeper line and it will cut here in the negative resistance region. So, this particular region represents a negative resistance region and if you connect like this circuit now with an external L c component it will act like a oscillator. So, here you can see that the negative resistance region is less. So, it will provide low current. And the power provided by the tunnel diode will also be low.

So, it can provide the low output power oscillators. Now, if you see here in this region the current increases linearly with voltage. However, in this region it acts like a conventional diode. So, the region 2 is a transition between the linear region and the PN junction region. And, in this region it behaves like a negative differential resistance. Now, this diode represented by this symbol this represents the anode and this represents the cathode.

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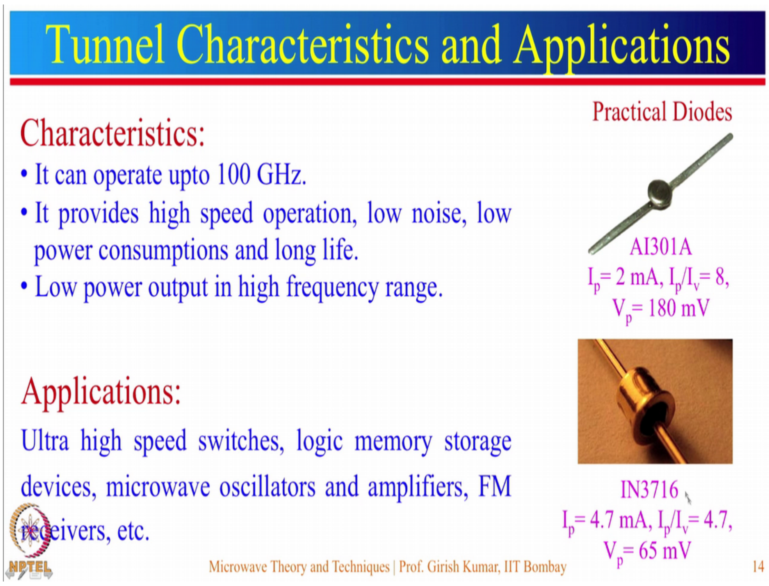

So, the characteristics of these diode is that it can operate up to very high frequency range maybe up to a very meter wave frequency range, and it can operate up to 100 gigahertz it provides very high speed operations. And, it provides low noise low power consumption, but it suffers with a drawback of low output power.

So, nowadays this is replaced by transistors. Now, if I talk about the applications tunnel diodes are used as ultra-high speed switches, they can be used logic memory storage devices microwave oscillators and amplifier, they can also be used in FM receivers. So, here I have included the 2 examples of practical diode. And, this first one is used by the Russian military for switching applications. And, the second one that is I N 3 7 1 6 is used to make the oscillators or the transmitters.

So, depending upon the application again one can choose the diode. The next type of the diode is the GUNN diode.

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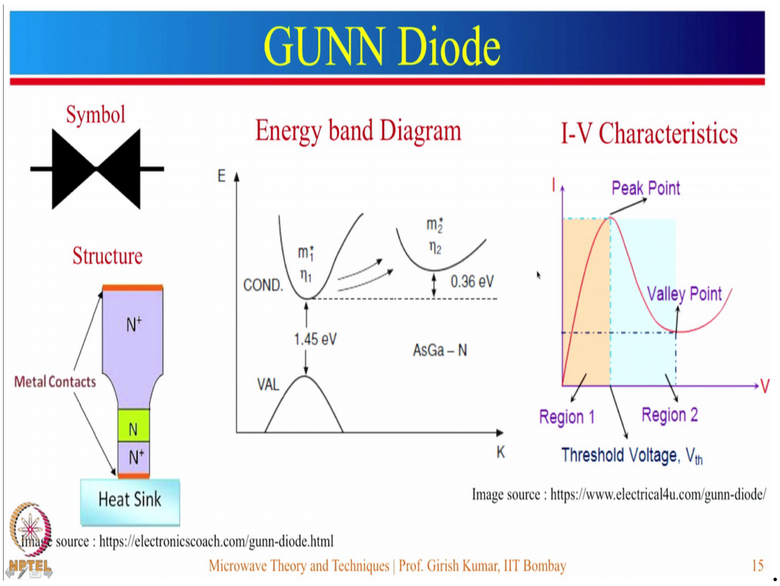

So, this is a special kind of diode it uses only one type of semiconductor material here, the lightly doped N type of material is inserted between the 2 heavily doped, N type of semiconductor material. And the metallic contacts are made to make the electrical connection with the circuit. And, the heat sink is provided to account for the heat losses.

So, we know in case of few materials like gallium arsenide and indium phosphide. They have local minima’s in the conduction band. See one of the local minima contains the higher mobility and low effective mass. However, the another minima which is at relatively higher energy is level, it contains lower mobility and higher effective mass. So, in general all the electrons occupy the lower energy is states.

Now, if you provide the energy to this material the electron gains the energy and they try to shift from the lower energy state to the higher energy state where the mobility is less. So, as long as the concentration of electrons is more in this band the current increases. However, if you again increase the electric field there will be a situation, when the concentration of electrons will be more in this case which corresponds to lower mobility. So, the mobility decreases with increase in voltage; that means, the current decreases with increase in voltage that represents the region 2.

Now, there will be a situation when you again increase the voltage, then all the electrons will shift to this van. And, it will have the lowest mobility in this case the current will be minimum. So, if you again increase the electric field diode will behave like a normal PN junction diode and it is current will increase exponentially. So, this is the I V characteristics of these GUNN diodes.

Now, if you see here this looks similar to the tunnel diode, but the if you look into the operation principle of these diodes they are quite different and that is the region that GUNN diode provides relatively high out of rf output power.

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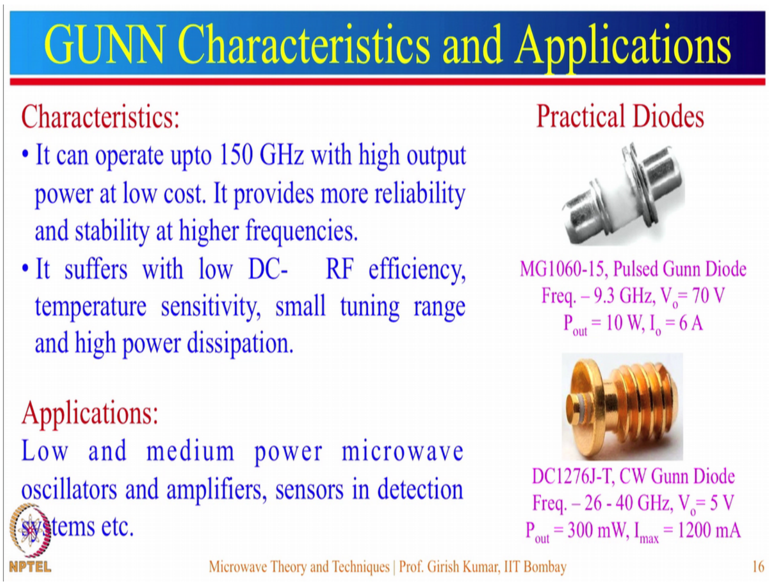

So, this diode is represented by the symbol the next I will talk about the GUNN diode characteristics, this GUNN diode can operate up to very high frequency range maybe up to 150 gigahertz with relatively high output power at low cost.

So, nowadays many of the GUNN diodes are replacing the microwave tubes. They are more reliable and stable at higher frequency range, but this suffers with the low dc to RF efficiency, they are also sensitive to the temperature variations. And, they provide relatively small tuning range and the power dissipation in these diodes are relatively high.

Now, if I talk about the applications these diodes can be used in as a low and medium power microwave oscillators and amplifiers, they can also be used as sensors in detection systems. Now, here I have included the 2 practical diodes. This one is the pulse diode and provides relatively high output power. And this is design in the x band the output power for these cases of 10 watt. And, in this particular diode this is a continuous wave diode, and it is designed for the carbon the output power for this diode is 300 milli watt which is considered as a medium power GUNN diode.

Now, just to conclude, in this lecture we started with semiconductor material. Then we saw how the conductivity of the material can be increased by adding the impurity in the material? Then, we combined the N type of and P type of materials and the combination of N type and P type of material forms a PN junction, which provides a very interesting feature like; rectification, switching, then we talked about the varactor diode. And, we saw that how this diode can provide the high tuning range of capacitance, which will be used in various applications like in oscillators, tunable filters, etcetera, after that we talked about the schottky diode, which is the junction of metal and the semiconductor and due to this particular junction it provides very high switching.

So, it is more suitable for the mixing and the detection, then we talked about the PIN diode, due to the insertion of intrinsic region between the 2 highly doped P and N layer. It provides a variable resistance. So, it is highly used in case of variable attenuators and other applications, then we talked about the tunnel diode which is highly doped PN junction diode. And, it provides a special feature of negative differential resistance, but this suffers with the low output power. So, using the tunnel diodes low output power oscillators or the amplifiers can be designed, then we talked about the GUNN diode and then we saw that the GUNN diode provides relatively high output power. And, nowadays they are replacing many of the microwave tubes and cavities. So, with this I would like to conclude.

Thank you very much.