Millimeter Wave Technology
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Module 6
Lecture No 27
Active Devices (Contd)

So next is Hetero junction bipolar transistor HBT, so in this case what we do, let us 1st discuss about the limitations of BJT high-frequency limitation. So, already we have seen that for high-frequency operations we have to decrease base width so that transit time decreases. Now, if we decrease base width then base resistance increases, then how to then compensate this problem? We can increase doping inside base, but if we increase doping than reverse saturation current will increase because from P type base we have holes which drift into emitter. Now, can we design a BJT which will provide different band gap of values to electrons and holes?

For example for an NPN transistor, emitter emits electrons and it is due to drift motion it will inject electron into base. Now, let us say the band gap for this electron it remains unchanged, but the gap increases for the holes. So in that case the number of holes, which will drift into emitter from base that will decrease, but it will not affect the normal operation of electrons, so that is how we get HBT. So why the name Hetero junction because for this type of device we have to use 2 different types of semiconductor materials having different band gap for the emitter and base to obtain this type of property.

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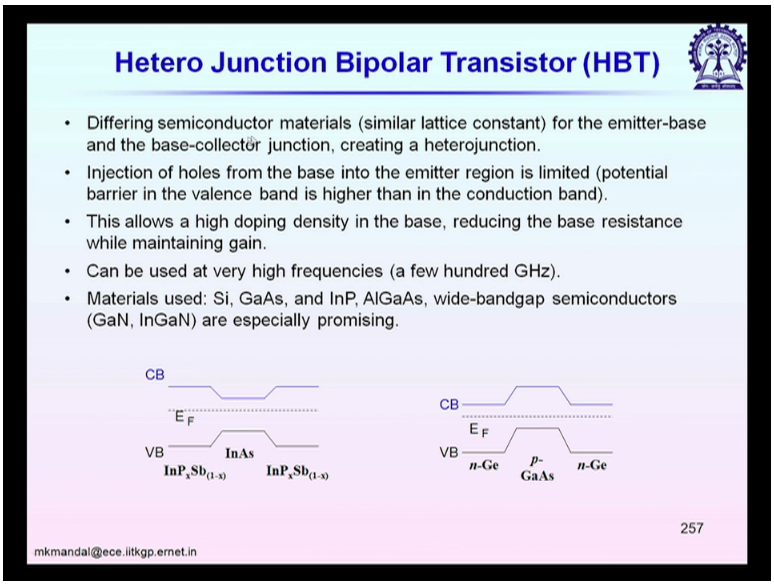

So let us see here, then in general different semiconductor materials, but obviously they should have similar lattice constant, otherwise he will not match to each other and it will be associated with some impedance so for the emitter-base and base-collector junction creating a Hetero junction. Then creation of holes from base into the emitter is limited, so potential barrier in the valence band is higher than in the conduction band. This allows a high doping density in the base, reducing the base resistance while maintaining gain and typically it can be used at very high frequencies even a few hundred gigahertz. You can see the band diagram, left hand side it shows for a PNP type transistor and right-hand side it shows for a germanium-based NPN type transistor, so for this NPN transistor, so emitter it is emitter and collector both are based on germanium, but the middle base layer it is P type gallium arsenide two different type of semiconductor.

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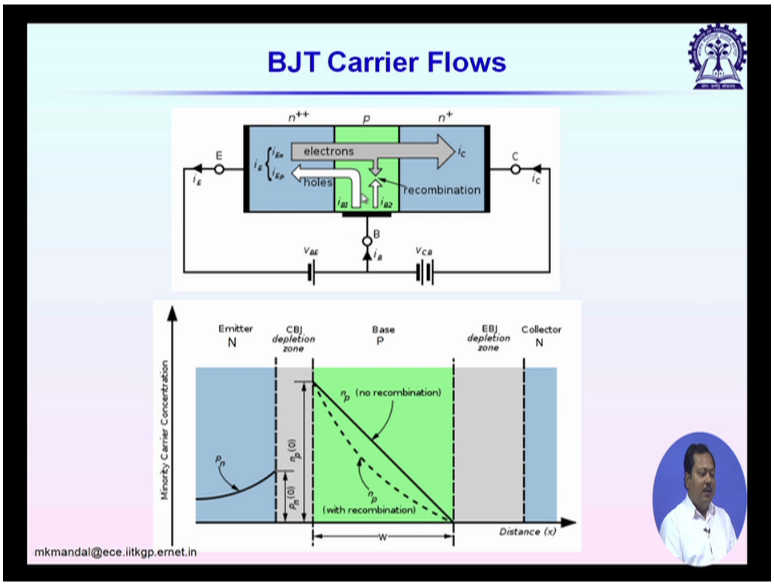

Now, at room temperature the Fermi level it will align itself throughout the structure, so accordingly we can draw then band diagram. So for N-type germanium, conduction band is close to Fermi level and for P-type gallium arsenide, valance band is close to Fermi level. Now if I go back to basic BJT operation of 1 NPN transistor, yousee emitter it injects electrons and from base we have a problem due to the holes. Now if I look at the band diagram, electrons which are in the conduction band that actually contribute to conduction current and the holes in the valence band that will contribute to current. So holes from the base region it has to traverse to N-side emitter region and the gap in the potential, we have the potential barrier here; it is shown by the difference of this valance band.

And similarly, for the electrons left-hand side to right-hand side, it has to overcome this potential barrier. Now, the potential barrier height it becomes different for electrons and for holes. For this particular example, this potential barrier is smaller under forward biased condition for electrons and it is higher for the holes. So under a given forward biased condition, then electrons it can easily move from emitter to base, but holes they have a problem here, so base to emitter movement becomes restricted that is how we can decrease reverse saturation current view to this hole movement from base to emitter so that is how one HBT operates. And the materials used for HBT; silicon, gallium arsenide, indium phosphide, aluminium gallium arsenide and different types of wide band gap semiconductors like gallium nitride, indium gallium nitride, they are being used for designing and fabricating HBT.

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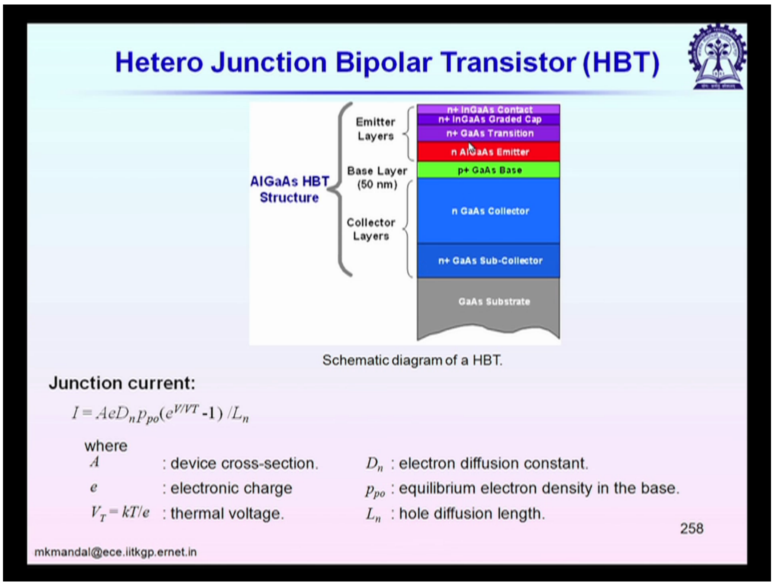

Here is one example of graded structure based on aluminium gallium arsenide HBT. The junction current, it can be given by A into e D n P po into this exponential function divided by L n, where A, this is the device cross-section, e is the electronic charge, V T this is the thermal voltage it depends on room temperature as well as electronic charge, D n this is the electron diffusion constant, P po this is equilibrium electron density in the base and L n this is hole diffusion length. So current increases with the device cross-section and decreasing hole diffusion length.

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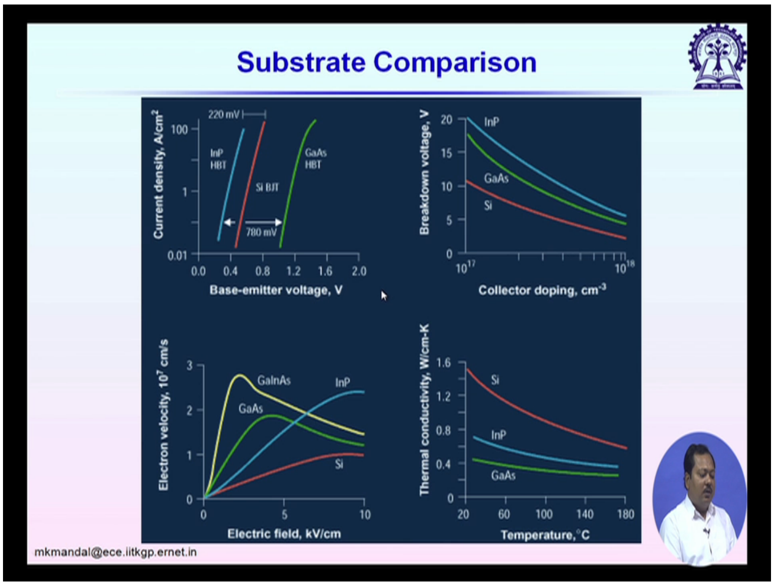

Now substrate comparison for different types of active devices, so you see current density is a function of base-emitter voltage, here we are showing different types of HBT based indium phosphide, on silicon and gallium arsenide. So current density rapidly increases with the increasing base emitter voltage and for gallium arsenide based HBT, you see we need more base-emitter voltage compared to let us say silicon device. Next one is the comparison of breakdown voltage for different substrates versus collector doping concentration. So silicon has the lowest breakdown voltage whereas, indium phosphide has the highest breakdown voltage. Now electron velocity versus electric field, so you can see here as I discussed before that electron velocity is a function of applied electric field.

For silicon or indium phosphide if we keep on increasing electric field initially electron velocity increases, but at some point it reaches its maximum value, we call that the saturation electron velocity. But for both group 3 group 5 materials like gallium arsenide gallium indium arsenide, we see that with the applied electric field initially electron velocity increases, it reaches the maximum value after that it decreases. So, electron velocity decreases after reaching V s, so that means the overall current it also will decrease. So with increasing voltage, current decreases that means we can obtain negative resistance, we will see later the applications of these types of devices in transferred electron device.

Next is thermal conductivity, thermal conductivity is important because it shows how fast we can remove the generated heat from the device. So, thermal conductivity it depends not only on substrate but also a function of temperature. You see, with increasing temperature thermal conductivity decreases. And silicon has highest thermal conductivity among these 3 and gallium arsenide thermal conductivity is lower.

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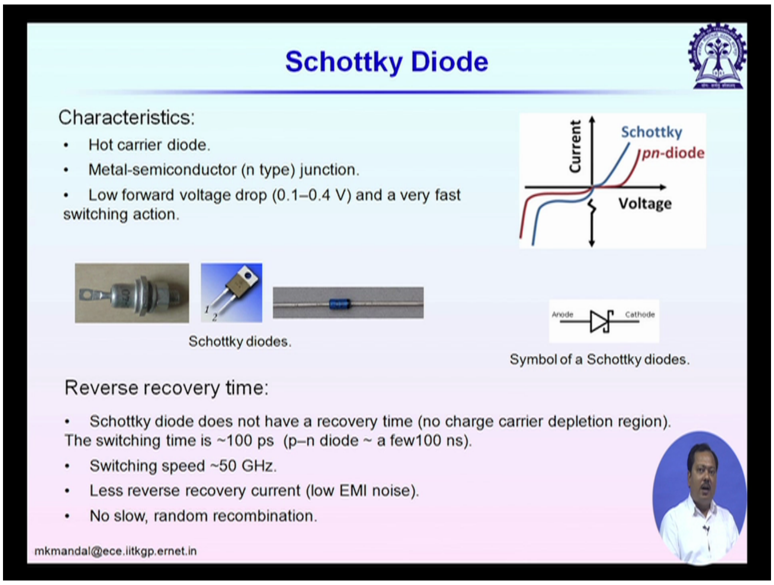

Next device Schottky Diode, although we are calling it a diode, but it does not involve any PN junction, this is basically a metal semiconductor junction and the metal with semiconductor, semiconductor usually it can be P type or N type, but most popular is N type typically doping concentration is higher, so we call it a metal N plus junction. Since we are not using any PN junction it is not associated with any space charge region, and the advantage is that we can avoid junction capacitance, which is usually seen for a given PN junction, so what is the advantage of that we can go for very high frequency operation. So reverse recovery time that is very less for Schottky diode.

So some basic characteristics than you can see here, these are hard carrier diode, so metal semiconductor junction physically N-type semiconductors are used and if you look at the current voltage plot characteristics DC characteristics, so for PN diode, PN junction diode in forward biased condition current increases exponentially after cut in voltage V gamma and reverse saturation current is usually very small, but if we keep on increasing the reverse voltage after some point where we have the breakdown voltage, current increases rapidly but till that point we can represent one reverse PN junction by very high resistance. But for Schottky diode, in forward biased condition almost similar to PN junction, current increases very rapidly, but in reverse biased condition we have very high saturation current component.

That means it will not behave like a reverse biased PN junction or the equivalent resistance in reverse biased condition is much smaller compared to a conventional reverse biased PN junction diode. Not only that, we see that the cut in voltage for Schottky diode in forward biased condition is much smaller compared to V gamma of PN diode. Similarly, in reverse biased condition breakdown voltage also much smaller compared to conventional PN junction diode. So this breakdown voltage in reverse biased condition, it depends on the type of semiconductor material we are using and it is also related to the cut in voltage of the Schottky diode in forward biased condition.

So Schottky diode with lower cut in voltage it will have higher reverse saturation current also, so that is why instead of using just 0.1 or 0.2 volt forward voltage drop typically 0.3-0.4 volt are preferred. Then in that case to some extent we can decrease the reverse saturation current and increase the reverse breakdown voltage, so why it is so popular at millimetre wave frequency, because of very low reverse recovery time. Since it does not have any space charge region for nothing there is nothing to recover from, so that is why the recovery it is almost instantaneous. Schottky diode does not have any recovery time theoretically, but due to the packaging effect and sometimes modification of the device, which are used to decrease the reverse saturation current or to increase the reverse breakdown voltage, it is associated with some capacitance.

Usually it is very small, typically less than 1 picofarad, so that is why the switching time of the order of 100 picoseconds, you can compare with the typical switching time for a PN junction diode, which is 100 nanosecond, so switching speed that can be achieved even 50 to 60 gigahertz is possible. And not only that, it has less reverse recovery current and no slow random recombination because it does not have any space charge region and it is only associated with let us say electron flow, so recombination of holes and electron can avoid here and it is why the EMI noise produced by recombination can be avoided.

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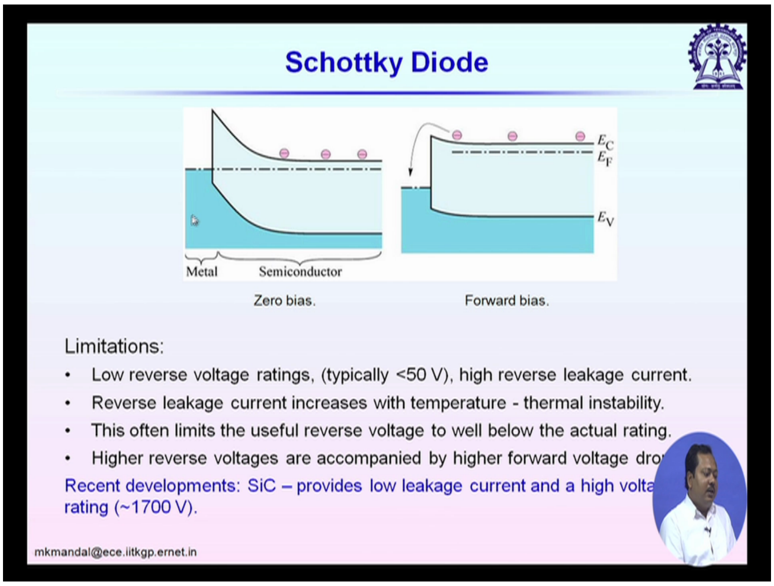

So it shows the man diagram for metal semiconductor Schottky diode, at room temperature you see the Fermi level, it aligns itself throughout the structure. Now for metal, Fermi level is inside conduction band so at room temperature already we have free electrons to move and inside N type material, you see there are just a few electrons at room temperature. Now under given biasing there will be a thin depletion region because in N type material electron density is smaller in metal we already have free electrons, so without biasing there will be a very thin depletion region like thing and the width of this depletion region decreases with the increasing doping concentration. But very high doping concentration in avoided otherwise, that semiconductor material it will behave like a metal and instead of semiconductor-metal junction it will behave like a metal-metal junction.

Now because of this high doping concentration, the thickness of so-called depression region is very narrow and there will be tunnelling effect through the depletion region, so details, operation and band diagram we are skipping here in this lecture. Due to this thin depletion we have one more problem, the problem is that the electric field due to the applied voltage it mainly appears across the depletion region and low reverse voltage rating, it is associated that is why it is associated with very low reverse voltage rating typically less than 50 volt and also it has high reverse leakage current, reverse leakage current increases with temperature that is one more problem and due to that we have instability because temperature variation.

Recent development; devices based in Silicon Carbide provides low leakage current and high voltage rating typically of the order of 1700 volt. In forward biased condition when we use this Schottky diode as a switch, in forward biased condition it will provide very low resistance and in reverse biased condition it will provide high resistance and the metal, we consider it as anode and the N type of semiconductor we will consider it as cathode.

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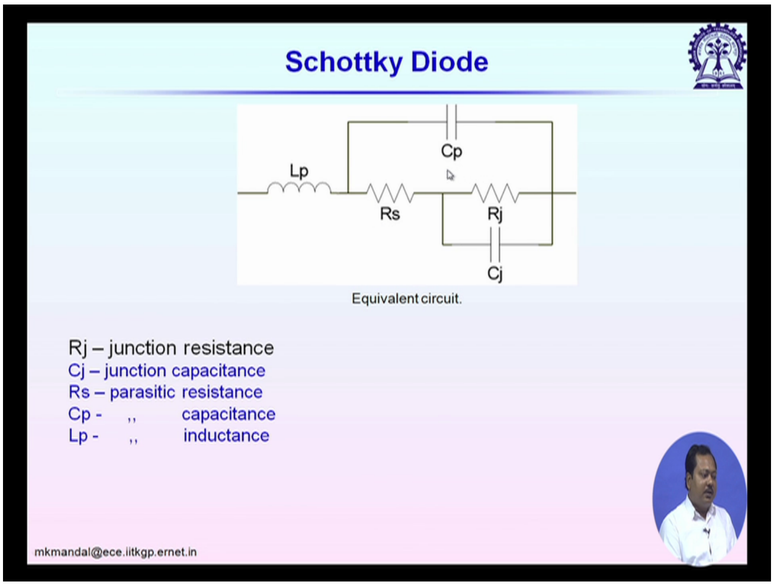

So this is the equivalent circuit, simplified equivalent circuit of a Schottky diode. Metal-semiconductor junction is represented by a resistor R j and capacitor C j, so R j it has different values in reverse and forward biased condition. In forward biased condition typically a few ohms and in reverse biased condition it is a few kilo ohms and then we have R s parasitic resistance and due to packaging and the external lids, we also have parasitic capacitance C p and parasitic inductance L p. So when we use as a display device, sometimes this L p value is so high, it can be even 1 narrow Henry, it can limit high-frequency operation, so you have to be very careful while choosing a Schottky diode for any given application.

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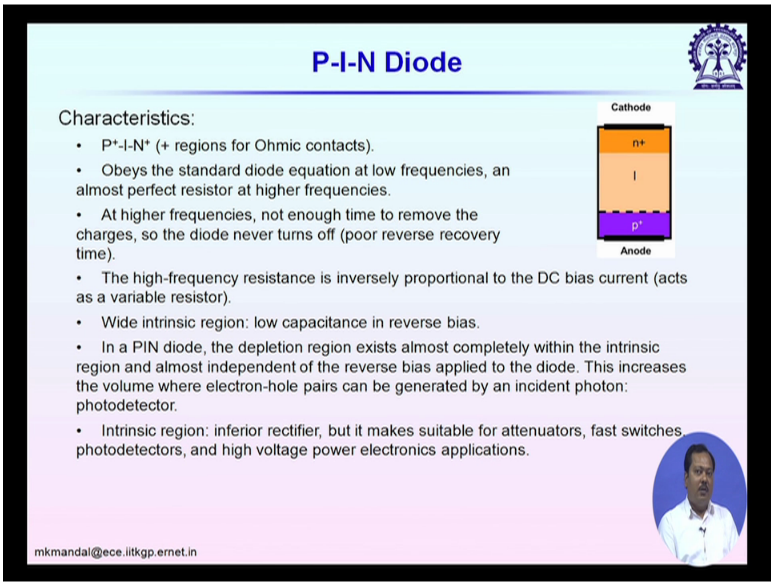

Next is P-I-N diode, so as this diagram shows it is a P + I N + structure, so I it represents intrinsic layer, usually its resistance is very high since we are not using any doping. Now since we have P + and N +, so the depletion region it extends deep inside the intrinsic region, whereas inside the P + region or N + region, the thickness of depletion region is very narrow. So what happen at lower frequencies it obeys standard diode equations, but if we keep on increasing the frequency, in that case the diode never turns off because its reverse recovery time is very high, so at very high frequency we can use it as a resistor and the resistance it becomes a function of the biasing current, so we can control the resistance by controlling the biasing current or we can use the PIN diode as the variable resistor at higher frequencies.

Another advantage due to the wide intrinsic layer is that since P + and N + region and their corresponding depletion layer, the separation is large it is associated with very low capacitance, so it is inferior as a rectifier but it make suitable for attenuators, fast switches, photo detectors and high-voltage power electronics applications.

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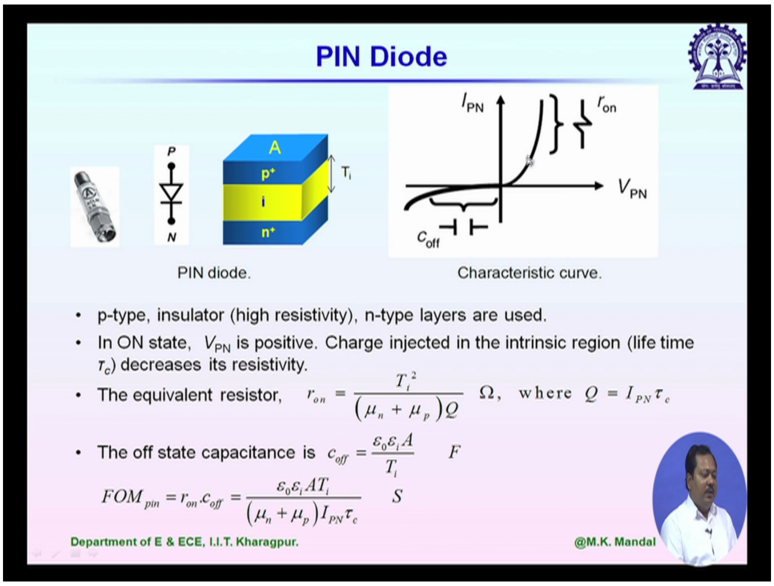

So it shows the V-I characteristics of a PIN diode, so this is the DC characteristics not the high frequency characteristics. So in forward biased condition it obeys the diode relationship also in reverse biased condition, but if we keep on increasing frequency, working principle it becomes different and in that case it does not obey this diode relationship. Now, in ON condition, when we are going to use it as a switch at lower frequencies then in ON condition it can be represented by a resistor and in OFF condition, that means in reverse biased condition it can be represented by a capacitor and r on roughly it can be given by T i square divided by Mu n + Mu p into Q.

So T I this is the thickness of the intrinsic layer and Mu n, Mu p, they are the electron and hole mobilities, Q is the stored charge inside intrinsic layer and it can be given by I pn multiplied by Tau c, Tau c in the carrier lifetime inside intrinsic region. And in the OFF state, the capacitance C 0 it is equal to Epsilon 0 Epsilon i into A by T i Farad. A is the cross-sectional area of the device, T i again thickness of the intrinsic layer and when we apply in switching application, we will see later that we can define figure of merit of any switch by R into C because in forward biased or in ON state it will give some resistance, in OFF state it will give some capacitance and the capacitance determining the insertion loss and isolation due to switch, so we have to decrease insertion loss and we have to increase isolation.

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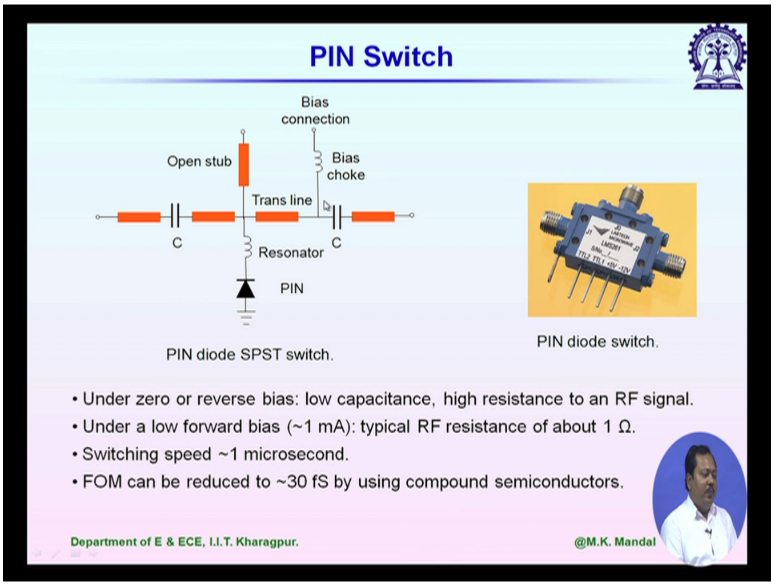

And we use a parameter we call it Figure of merit for switches, it is given by r on into C off, you can calculate it theoretically roughly from this given dimension. This example shows a PIN diode when being used as a switch, you can identify the PIN diode and with this diode we have some additional components like resistors and capacitors, so why they are used? So let us say we want to transmit one microwave or millimetre wave signal from left-hand side to right-hand side and this is the microstrip line and this PIN diode, it is being used in shunt configuration. So when this PIN diode is switched ON that means when it is in forward biased condition, in that case we can replace it by a small value of resistance typically a few ohms.

So that means the microstrip line will be grounded and there will not be any signal passing from left-hand side to right-hand side. Similarly, in OFF condition this PIN diode can replace by a very small value of capacitor, so due to this capacitor almost we can consider as if this path is broken and then will be power transmission from left-hand side to right-hand side. So in OFF condition then we have good isolation because this PIN diode and in ON condition this RF signal, it will pass through ground. Now, we have to provide this bias current to keep the diode in forward biased condition and reverse biased condition, that we can do by DC or RF source that is being connected by this bias connection. So this bias connection will provide the forward biased and reverse biased condition of the PIN diode.

Now, if we directly connect a DC source here to microstrip line, then whatever RF signal is coming from left-hand side it will also go to this bias connection, so we have to then somehow stop then RF signal to go to this biasing circuit, so we can use some inductor here r we call it biased choke that will provide very high resistance to RF signal and very low resistance to this biasing. Similarly, we have to somehow isolate this DC biasing source from RF input source or the RF load at the right-hand side. That is why we are using some blocking DC blocking capacitor C, so typically C value should be as high as possible so that it offers very small resistance or we can replace capacitor simply by a short-circuit for this millimetre wave signal, but we have to replace capacitor by open circuit for this biasing connection.

In addition to this, we have open stuff for matching purpose and typically sometimes we use a very small value of inductor that can improve isolation condition, we will see later when we will discuss electron switches. So in general than under 0 or reverse biased condition it will provide low capacitance and very high frequency, it will provide high resistance typical value at low forward biased current let us say 1 mili-ampere, resistance is 1 Ohms, switching speed typically 1 microseconds and figure of merit can be reduced to even 30 femtoseconds by using compounds semiconductors.

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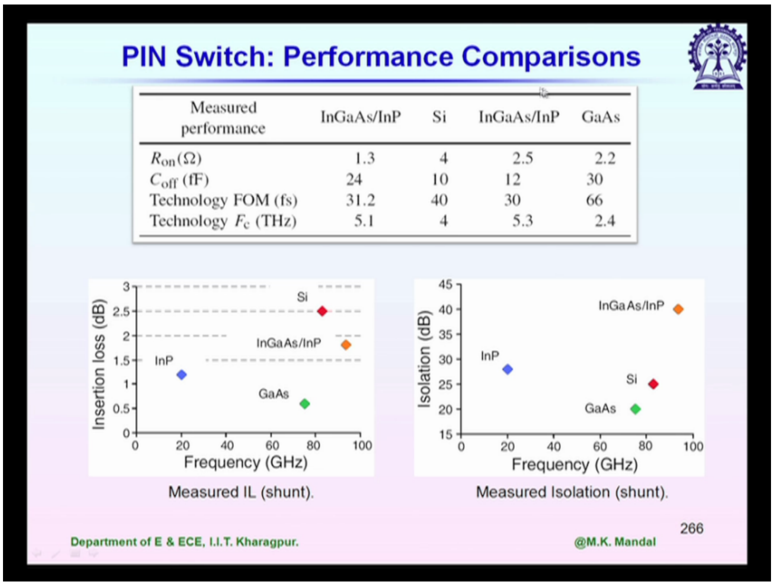

So PIN performance comparison in different technology. We have some available switches from market and here we are comparing the figure of merit values, we have Indian gallium arsenide or gallium phosphide-based devices, silicon based device and gallium arsenide-based device. If we look at the figure of merit, you see indium phosphide or Indian gallium arsenide, it will provide typical value is 31.2 or 30 it is having the smallest, among all these. For gallium arsenide-based device it is higher, so smaller is better, the figure of merit is smaller in that case we can achieve lower insertion loss and high isolation values. So we will take a break, then we will start Transferred Electron Devices.