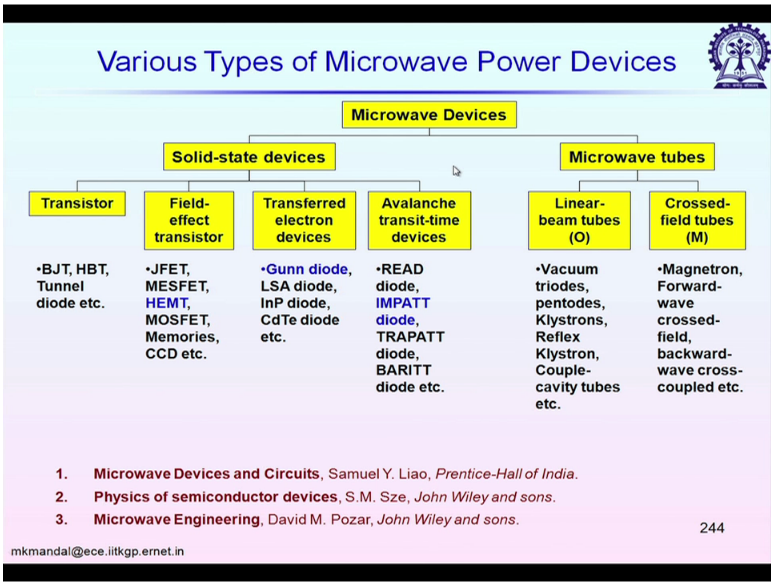
Millimeter Wave Technology
Professor Mrinal Kanti Mandal
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology Kharagpur
Module 6
Lecture No 26
Active Devices

Good morning, so today we will start millimetre wave activity devices. Now, different applications they need different types of requirements. For example, one satellite let us say geo-stationary satellite is 36,000 kilometres above earth surface, so obviously it will need very high-power to communicate. Now mobile phone, it needs maybe milliwatts that should be sufficient, but for mobile base stations it is a few watts, so different applications have different types of requirements. Now, for any millimetre wave system we need millimetre wave sources and for any amplifier design we also need different types of amplifiers, power amplifiers, low noise amplifiers, oscillators, switches, so all involved active devices. So, we will see different types of popular active devices, how they operate, what are their characteristics, so let us start with the basic chart.

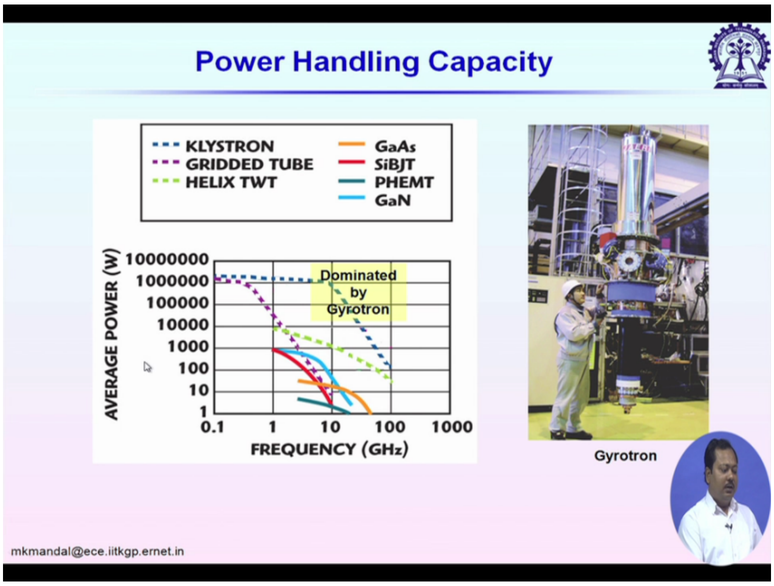
(Refer Slide Time: 1:32)



So in general microwave devices they can be divided into 2 parts; solid state devices and microwave tube-based devices. Again, solid-state devices they can be categorised according to their working principles into 4 major categories; transistor, field effect transistor, transferred electron devices and avalanche transit time devices. So under transistor we have bipolar junction transistor, HBT, tunnel diode, et cetera. Under field effect transistor we have JFET, MOSFET, MESFET, HEMT and different types of memories and CCDs. Under transferred electron devices we have gunned diode, LSA diode, Indium Phosphide diode then different other types of drives and under avalanche transit time devices we have READ diodes, IMPATT diode, TRAPATT diode, BARITT diode, so they are categorised according to their working principles.

So among all different types of active devices popular are HEMT (High Electron Mobility Transistor), Gunn diode and the IMPATT diode. So in today's discussion we are going to discuss about these popular active devices and under now microwave tubes we have 2 different types of tube linear beam tubes or sometimes we call simply O type tubes and Crossed field tube or sometimes also called M type tube. So we are not going to discuss about the tubes, so mainly we will concentrate on active devices solid-state devices.

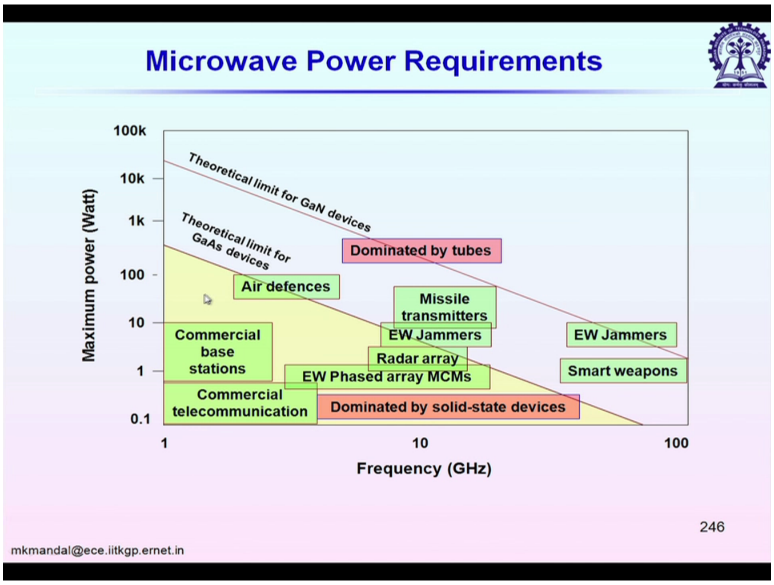
(Refer Slide Time: 3:29)



So here is one chart, which relates the average power versus frequency, so if we look at this chart where this comparison we are doing among different types of tubes and different types of solid state devices are being considered here. So, if we look at this chart for any given device, if we increase frequency maximum available power it decreases. And not only that, the high-frequency parts and high-power together these are mainly dominated by tubes, but the problem with tubes is that they are expensive and bulky, so we try to avoid them in low-cost applications. And now looking at the different solid-state devices we have again solid state devices based in gallium arsenide technology, gallium nitride technology and also different examples are HEMT, BJT, so again for these solid state devices also power handling capacity it decreases with increasing frequency.

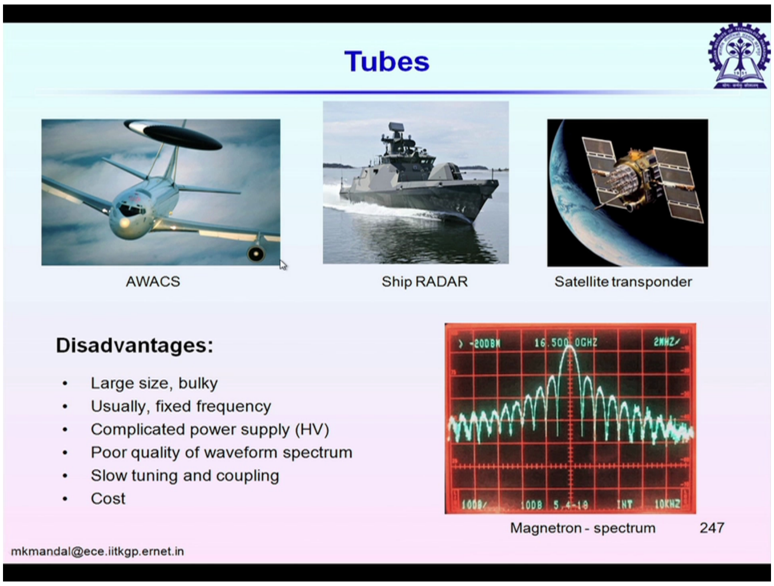
And if you look at this plot, not only that so gallium nitride usually it provides high-power and gallium arsenide based devices, they are used at much higher frequencies. So the stop curve, it belongs to Gyrotron, but the problem with Gyrotron is its size and cost. For example, Gyrotron is shown here it occupies almost one building so you can compare the size with human being.

(Refer Slide Time: 5:30)



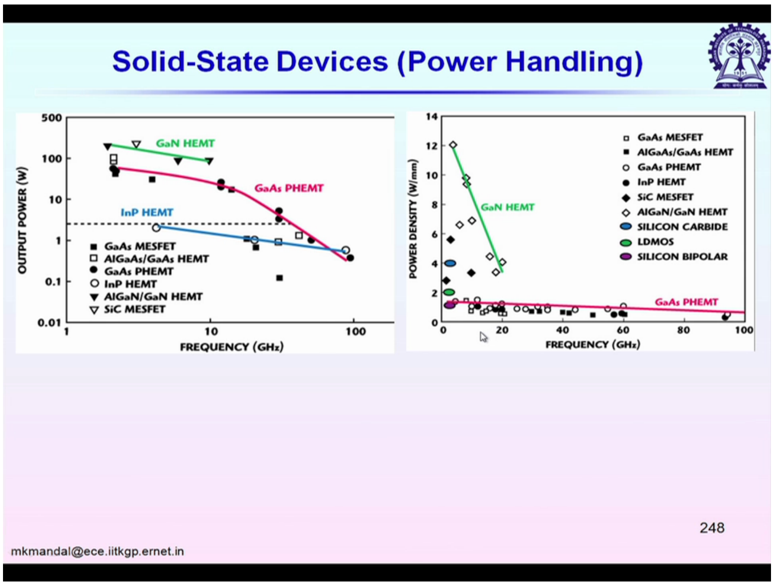
Now Microwave power requirements, so in this chart we see that different applications they have different types of power requirement and they correspond to different frequency bands. So right now, at millimetre wave frequencies mainly we have defence and space locations, so consumer applications is very much limited, but with the incoming 5G Wireless application it might be at millimetre wave frequencies may be at 60 gigahertz, so it is expected that millimetre wave activity devices will be used for this type of communication. Now for solid-state devices, gallium nitride-based device it can provide more power compared to other solid-state devices and this is the theoretical limit for gallium nitride devices and the 2nd line, it shows the theoretical limit for gallium arsenide devices. So we will see which parameter determines high-frequency operation and its maximum power capacity.

(Refer Slide Time: 6:44)



Now, here are some more examples of microwave and millimetre wave power sources. So in most of these applications till now, we have many different types of tubes they are being continuously used, but the disadvantage of these tubes they are of large size they are bulky, usually they operate at fixed frequency, so frequency tune-ability it becomes a problem with them. And not only that, they are usually narrowband and it has also spurious spectrum with that, so for example, in our today use we use microwave oven, usually it uses a magnetron to generate microwave power at frequency 2.45 gigahertz. Now in this plot I am showing you microwave spectrum of 1 magnetron, so you can see the pic, it is here around 16.5 gigahertz, but it is associated with many sidebands. So we have many spurious bands, so the quality of wave form spectrum it is very poor and another disadvantage is its high cost.

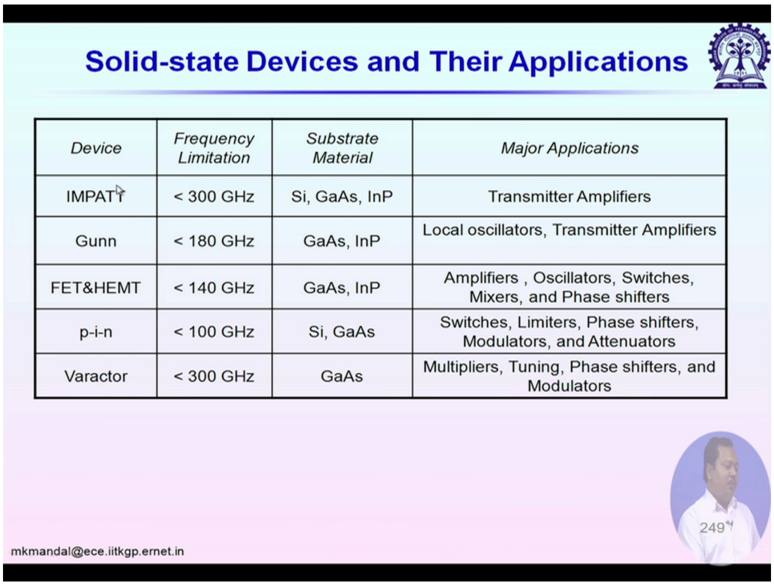
(Refer Slide Time: 8:11)



So then going back to solid-state device, so 2 points become very important, one is power handling and another one is high-frequency operation. Now, if we compare different types of solid-state devices which are already available in market, so here is the chart. So in the 1st figure we are showing the output power versus frequency, so if we increase frequency maximum output power from the device it decreases and again we can see that gallium nitride based HEMPT provides maximum power whereas, gallium arsenide-based PHEMPT provides high-frequency operation. We also have indium phosphide HEMPT; it also goes beyond 100 gigahertz. Now another important parameter is power density considering component miniaturisation, so how much power is available per square millimetre versus frequency?

Again gallium nitride based devices are the winner, but their frequencies are much limited to let us say 30 to 40 gigahertz. So if we want to use them at higher millimetre wave frequencies then again we have to go for gallium arsenide-based devices, but gallium arsenide-based devices it has again one problem compared to silicon-based devices that it consumes much power, so we will discuss this point later in detail.

(Refer Slide Time: 9:52)



Device	Frequency Limitation	Substrate Material	Major Applications
IMPATT	< 300 GHz	Si, GaAs, InP	Transmitter Amplifiers
Gunn	< 180 GHz	GaAs, InP	Local oscillators, Transmitter Amplifiers
FET&HEMT	< 140 GHz	GaAs, InP	Amplifiers , Oscillators, Switches, Mixers, and Phase shifters
p-i-n	< 100 GHz	Si, GaAs	Switches, Limiters, Phase shifters, Modulators, and Attenuators
Varactor	< 300 GHz	GaAs	Multipliers, Tuning, Phase shifters, and Modulators

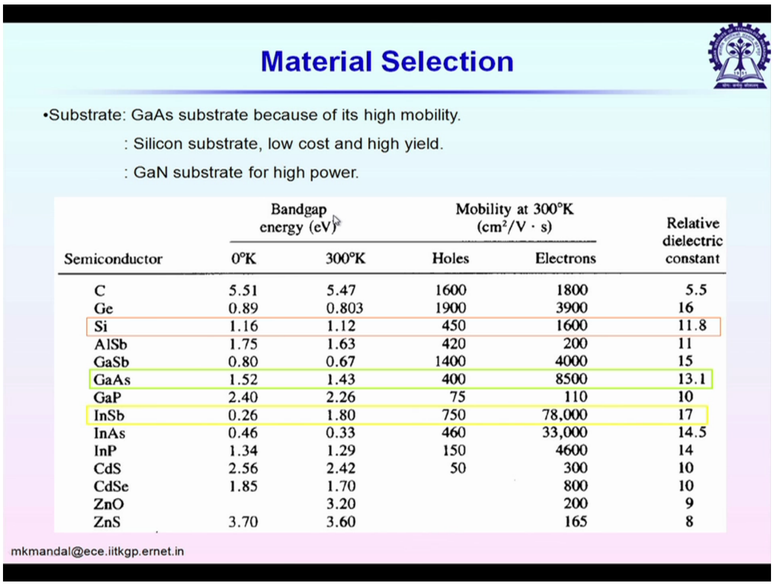
So some of the popular devices, their applications and frequency limitations so for example, IMPATT device, they are typically used below 300 gigahertz, so it can cover the whole millimetre wave spectrum starting from 30 to 300 gigahertz. This so this frequency, whatever is mentioned here it is it represents the popular applications, so but there are examples where IMPATT diode has been used above 300 gigahertz and physical substrate used for IMPATT diode fabrication are silicon, gallium arsenide, indium phosphide and they are popular for transmitter amplifiers. So in high-power amplifiers where we need power amplifier, we can use IMPATT diode but they are not much popular as a source, millimetre wave source because they are associated with phase noise we will see later.

Next is Gunn diode typically used below 180 gigahertz, substrate; gallium arsenide and indium phosphide. It is a very popular millimetre wave source which we use in laboratory experiments in the universities, so it is popular in local oscillators, and also it can be used it transmitter amplifiers. Next FET and HEMT typically used below 140 gigahertz again based on gallium arsenide and indium phosphide and they are widely used in different types of amplifiers, oscillators, switches, mixers, mixers, phase shifters, so different types of applications.

Next is p-i-n diode, typical frequency below 100 gigahertz and the materials used for fabrication, silicon, gallium arsenide, p-i-n diode is mainly popular in switching applications and at millimetre wave frequencies sometime they are also used as variable resistor. Next Varacter and it can give variable capacitor, so where we need any tunable component, we can use varactor and we can electronically tune the capacitance of a varactor diode. Typical applications, multipliers, tuning, phase shifters and different types of modulators.

Now, how to choose the material for any given solid-state devices? There are several parameters, when we go for millimetre wave frequency applications; the frequency is so high that the signal is changing very fast. So device should be narrow enough so that carriers from left side to right side, it takes minimum time typically less than the time period of the given signal so we characterise it by transit time. So then the 1st conclusion is the device size should be small, whatever carriers we are using here so carrier velocity should be very high. Now carrier velocity inside the substrate material, it depends on many parameters, it depends on electric field, it depends on mobility, electron mobility and hole mobility, so electron mobility and hole utility it is a it depends on the type of substrate. So depending upon our application requirement we can choose a proper substrate for fabricating the solid-state devices.

(Refer Slide Time: 13:45)

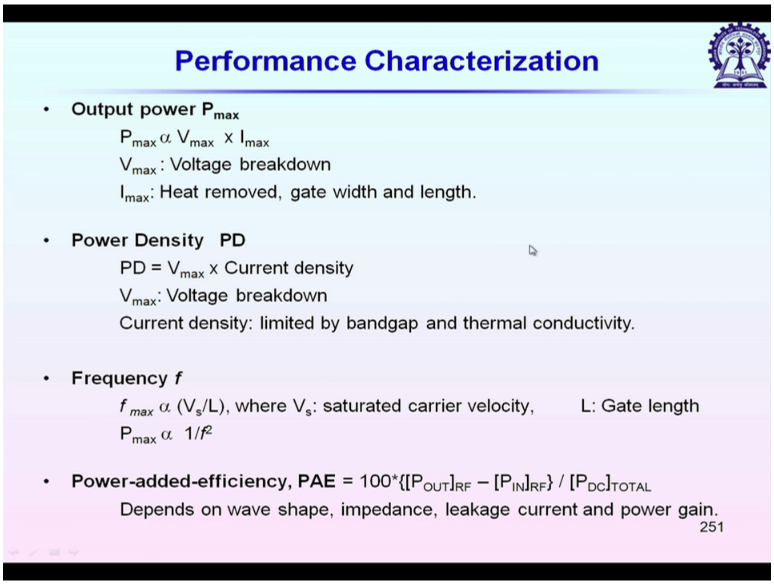


Semiconductor	Bandgap energy (eV) 0°K	Bandgap energy (eV) 300°K	Mobility at 300°K ($cm^2/V \cdot s$) Holes	Mobility at 300°K ($cm^2/V \cdot s$) Electrons	Relative dielectric constant
C	5.51	5.47	1600	1800	5.5
Ge	0.89	0.803	1900	3900	16
Si	1.16	1.12	450	1600	11.8
AlSb	1.75	1.63	420	200	11
GaSb	0.80	0.67	1400	4000	15
GaAs	1.52	1.43	400	8500	13.1
GaP	2.40	2.26	75	110	10
InSb	0.26	1.80	750	78,000	17
InAs	0.46	0.33	460	33,000	14.5
InP	1.34	1.29	150	4600	14
CdS	2.56	2.42	50	300	10
CdSe	1.85	1.70		800	10
ZnO		3.20		200	9
ZnS	3.70	3.60		165	8

So here are some examples, gallium arsenide substrates they are used because of its high mobility. Silicon substrate, the fabrication procedure it is very low-cost and also high yield, so for consumer market silicon substrate is very popular. Gallium nitride substrate, it is mainly used for high-power applications, but their high-frequency application is limited, typically they are used below 30 or 40 gigahertz. Now we see the characteristics of some popular semiconductor materials, so we are comparing the band gap energy and mobility at room temperature 300 Kelvin.

So if we look at the silicon, it has a band gap of 1.12 electron volt at room temperature, whereas for gallium arsenide it is 1.43, so the band gap value is higher than means its power handling capacity will be higher. Now look at the mobility values, so if I look at the electron mobility, silicon electron mobility is 1600 centimetres square per Volt second, whereas for gallium arsenide 8500. So obviously for gallium arsenide-based devices, electron mobility will be much higher under a given electric field and we can increase (())(15:24) of the device, we can go for high frequency operations with gallium arsenide-based devices.

(Refer Slide Time: 15:38)



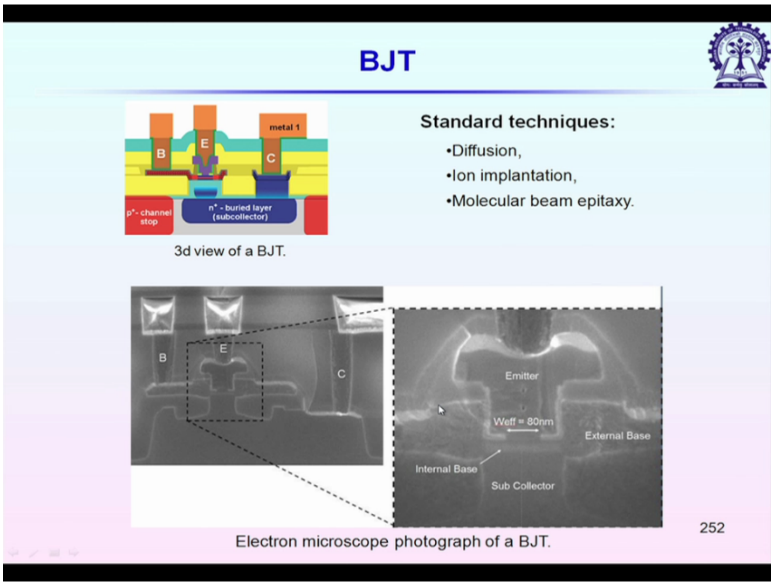
So some important parameters how we characterise any solid-state device, so for example, output power or what is the maximum power available from the device, power density, what is the maximum frequency of operation, then Power added efficiency, so these are the mostly well used parameters. So output power P max it is proportional to V max multiplied by I max, where V max represents the breakdown voltage and I max depends on how fast we can remove heat from the device, also gate width and length because the resistance depends on it. Next is Power density, power density is equal to V max current density, so V max is the breakdown voltage and current density is limited by the band gap and thermal conductivity.

Next high-frequency operation F max, it is proportional to V s by L, where V s, it is the saturated carriers velocity and L is the gate length for a given let us say gate and P max it is proportional to 1 by F square, so if we increase the frequency, it is expected that the power will decrease very fast so what we seen in the previous plot. Next is Power added efficiency, so here what we do let us say any given solid-state device we are using in amplifier applications so we will be having RF good power and then the amplified RF output power.

And to amplify the signal we have to apply some energy to the device and this is being done by DC source.

Now, how much power it will absorb from the DC source and what would be the efficiency of the device we call it the power added efficiency and it is defined as 100 multiplied by output RF power - input RF power divided by P DC total, total DC power what it consumes. So it depends on many parameters such as wave shape, what is the impedance of the device, then what is the leakage current and power gain of the device

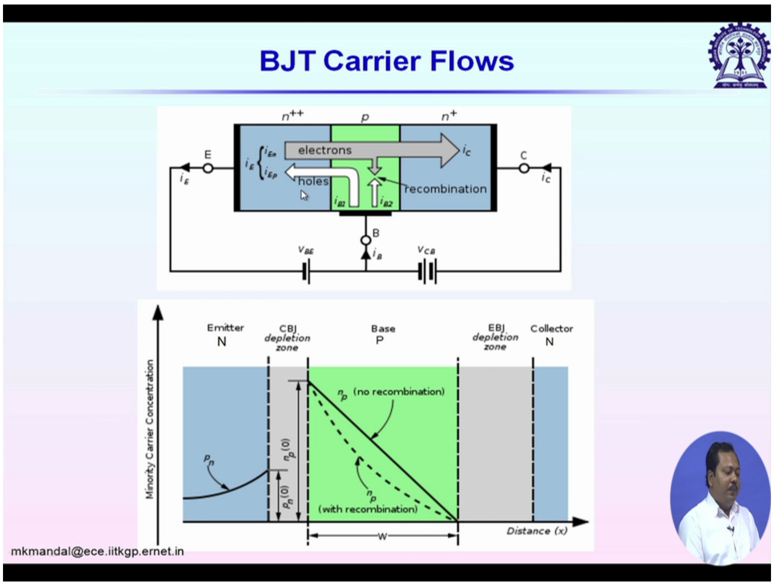
(Refer Slide Time: 18:15)



Now, let us start with the 1st device Bipolar Junction Transistor, so bipolar junction transistor also we used in basic electronics lab. It has very similar principle and only thing is that whenever we use for low-frequency applications let us say at megahertz frequency, we do not use different capacitances offered by PN junctions. We have two PN junctions in BJP but for high-frequency applications we have to consider all these capacitances and the device also is associated with some inductance because of its leads, we have to also consider the effect of inductance so high-frequency model, it will be little different than what we use at lower frequencies.

So let us look at one BJT, so this is a typical BJT used at lower millimetre wave frequencies, so you can see the base, emitter and collector, so the bottom most portion it is called the sub-collector and actual collector, it sits over the sub-collector and on top of this collector we have a thin layer of base. Gain of the transistor, it depends on base width, thinner is the base we will have higher gain, so look at this plot then this base lead, it is connected to this thin layer and over it we have emitter and collector connection is coming from right-hand side. So for high frequency operation we have to decrease the transit time and if we need to decrease the transit time, we have to reduce the base width.

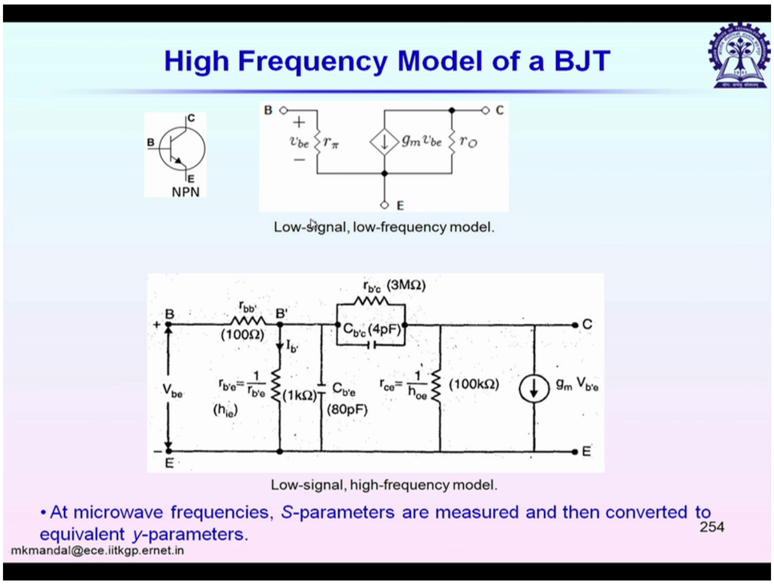
(Refer Slide Time: 20:14)



Now looking back to basic operation of BJT, I will skip the very basic things, only I am going to discuss the limitations which arise at higher frequencies, so let us consider one NPN type BJT. Usually an NPN type BJT is popular at higher frequencies since it involves mostly electron, and electron mobility is higher compared to whole mobility, so emitter it will eject electron and for normal operation we will forward bias the base emitter PN junction and we will keep the base collector junction in reverse bias condition. So, due to the applied electric field then electrons drifts into base, where we have recombination with the holes available in base and then rest of the part we have 1st diffusion and then drift inside the collector. Now for high-frequency operation we have to decrease the transit time so that means we have to decrease the base width.

But if we will decrease base width, the problem we will be facing that based resistance will become very high so we have to avoid this problem, so how we can avoid this high resistance problem? One solution is that we can increase doping inside base, but if we increase doping inside base than the hole which drifts into electron from base that part will increase, so the reverse situation current will increase, so then we just cannot keep on increasing doping concentration inside the base, so that is why conventional BJP it is not used at millimetre wave frequencies. We have some other version, which can take care of this diverse saturation current and this modification is called Hetero junction bipolar transistor or HBT that comes just after this.

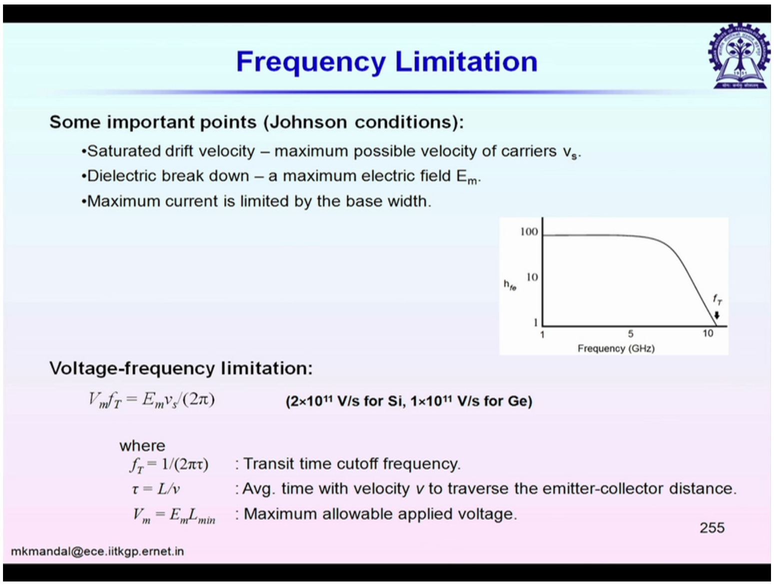
(Refer Slide Time: 22:33)



So HBT modelling, the 1st model this is, it shows low signal low-frequency model, you can see here we are just considering r Pi, the current roles g m V be and output resistance R 0 and we are not considering any capacitor, this is the low-frequency model. Now if I go back to device, we have a forward biased PN junction for this base emitter junction, so forward biased PN junction it is associated with some capacitance, we also have reverse biased base collector junction, it is again associated with some capacitor and usually reverse biased capacitance is smaller than the forward biased capacitor, so we have to consider all these capacitors, their typical values of the order of Pico farad at low-frequency that is why we avoid this, but at millimetre wave or at microwave frequencies we cannot avoid their effect.

So then the modified circuit how it looks here shown here. In addition to the previous one, we have introduced two more capacitors, C be, it represents the base emitter forward biased PN junction capacitor and C bc, it represents the base collector reverse biased PN junction capacitor and this is the internal model of BJP. In addition to this we have packaging effect, we have external leads, so we have to add more resisters, capacitors and inductors, for that will take into account the effect of packaging effect of the leads.

(Refer Slide Time: 24:24)

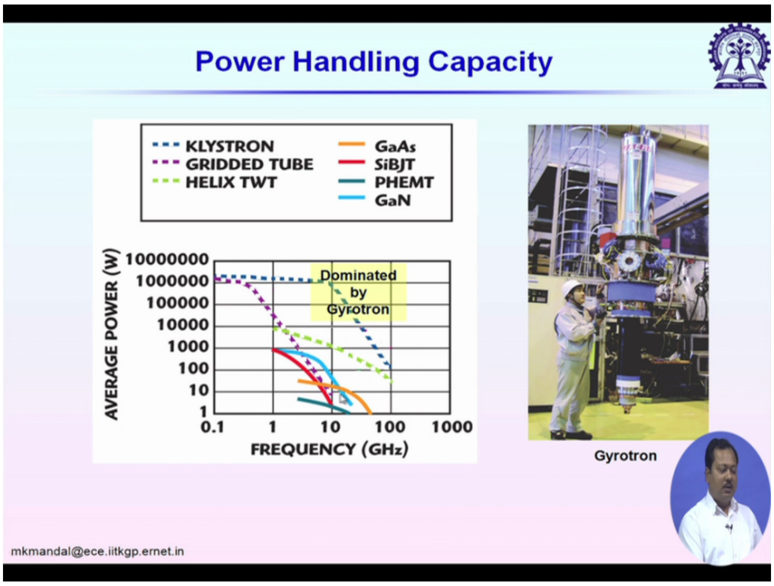


Next high-frequency limitations, so high-frequency limitations depends on many parameters and the condition sometimes we call it junction condition, so it depends on the following parameters, saturated grip velocity. So carriers inside the substrate, it has some velocity under given electric field, if we keep on increasing electric field value then this carrier velocity will increase, but finally it will reach a saturation which after which it cannot increase for silicon or germanium or this type of semiconductor materials. We call that velocity as the saturated velocity V s, but there are another categories of material usually, group 3 group 5 semiconductor conductor materials like gallium arsenide. So for this type of materials, after a half highest velocity V s, if we keep on increasing electric field then V s decreases.

So we will consider the maximum velocity of carriers V s and then next is the dielectric breakdown, dielectric breakdown depends on applied electric field and it is the property of that given dielectric, so let us called the break down electric field is E m, then maximum current it is also limited by the base width. So considering all that effect, if we plot current gain for a BJT, it becomes a function of frequency. So here in this graph we are showing the plot of HBT for current gain or sometimes we call it Beta. So typically you see, at lower frequencies it is fairly constant but at higher frequency decreases and at a frequency current gain it becomes one or unity, we call that frequency f T of the device, so it mainly depends on the capacitance value.

Now let us see some parameters, which determine its maximum frequency of operation, so the 1st one is voltage frequency limitation. So here V m is the maximum allowable applied voltage device, it is given by E m multiplied by L minimum, so L minimum is distance between emitter and collector and V m multiplied by f T, where f T, this is 1 by twice Pi Tau transit time cut-off frequency, it is equal to E m V s by twice Pi. So E m, that is the maximum allowable electric field and V s that is this saturated trip velocity. E m V s by twice Pi, then we see that it is related to the maximum allowable applied voltage multiplied by f T, so if we increase frequency, then maximum allowable applied voltage it decreases. We can also express this quantity E m V s by twice Pi in terms of current frequency in terms of power frequency, so simply we have to replace the voltage by the corresponding expression of current and corresponding operation for power, so it is shown in next slide.

(Refer Slide Time: 3:31)



So current frequency limitation here I m into X c multiplied by f T equal to E m V s by twice Pi, where I m is the maximum current of the device and X c, this is the reactive impedance of the device, so it depends on f T and mainly based to collector junction capacitance, then the power frequency limitation, so of P m into X c multiplied by f T equal to E m V s by twice Pi. We also can define power gain frequency limitation, so G m V th V m whole square root multiplied by f T, this is equal to E m V s by twice Pi, where G m this is the maximum available power gain and V th this is the thermal voltage, so it depends on room temperature, so what we see then gain of any BJT it becomes a function of frequency. At higher frequencies we will aspect lower gain and not only that, it is also a function of temperature, so we will take a break and then we will move to next topic HBT thank you.