Millimeter Wave Technology
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Module 6
Lecture No 29
Passive Components (Contd)

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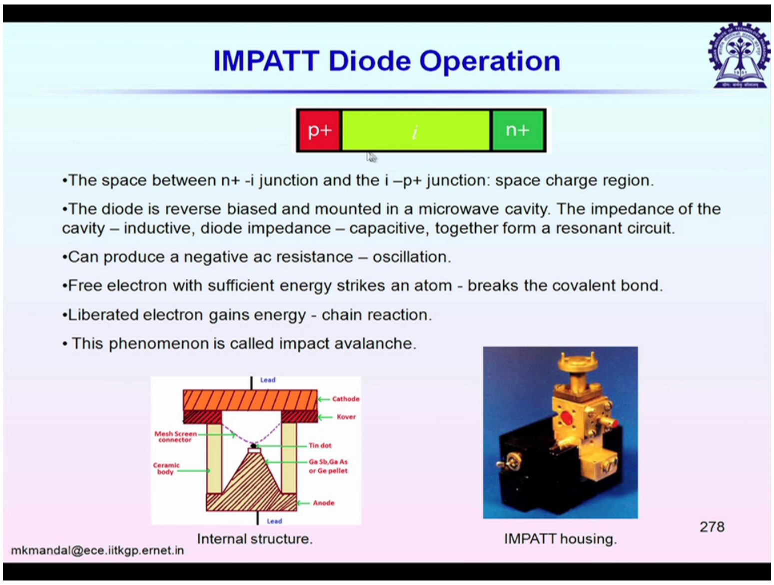

IMPATT Diode Operation

p+	i	n+

- The space between n+ -i junction and the i –p+ junction: space charge region.
- The diode is reverse biased and mounted in a microwave cavity. The impedance of the cavity – inductive, diode impedance – capacitive, together form a resonant circuit.
- Can produce a negative ac resistance – oscillation.
- Free electron with sufficient energy strikes an atom - breaks the covalent bond.
- Liberated electron gains energy - chain reaction.
- This phenomenon is called impact avalanche.

Internal structure.

IMPATT housing.

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Generate negative resistance for AC signal, so in IMPATT diode for a typical let us say P + I N +, it is kept under reverse biased condition first of all, so positive side will be connected to N + region and electrons they will be accelerated and move towards the N + region and this N + region for this typical P + I N + device, it is used for electron-holes pair generation or for that avalanche impact effect. So once electron-holes pair is generated, and then holes will drift to I region and they will be collected by the P + region. Now there is a typical transit time to collect these holes since these holes it takes finite time to travel this I region. So this transit times depends on the length of I region. Now this picture it shows a typical housing of IMPATT diode, usually IMPATT diode itself it would provide capacitive reactance and to nullify that we need some inductive reactance.

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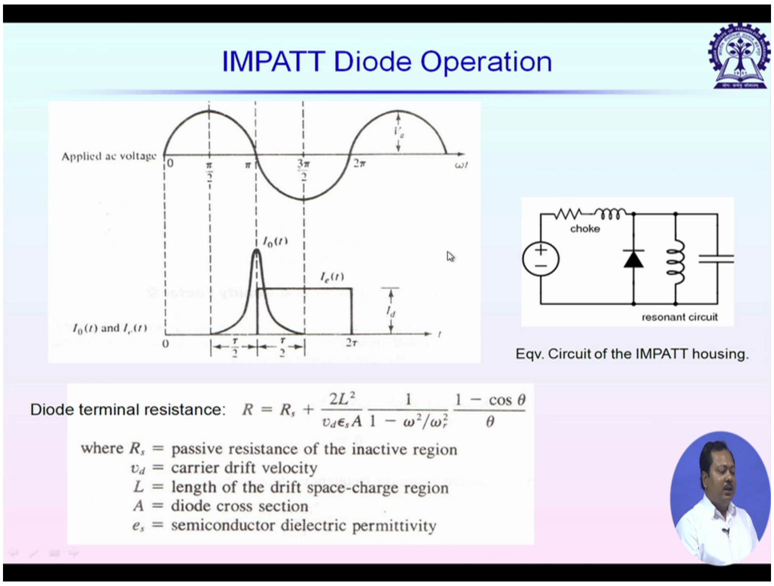

IMPATT Diode Operation

Eqv. Circuit of the IMPATT housing.

Diode terminal resistance: $R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta}$

where R_s = passive resistance of the inactive region
v_d = carrier drift velocity
L = length of the drift space-charge region
A = diode cross section
e_s = semiconductor dielectric permittivity

It is usually obtained by using a bonding wire as shown by this magenta line here and altogether they sit inside a cavity. So you can see in right-hand side picture how it looks from outside, we have arrangement for external biasing and we have the RF output from this end, now how this chain reaction it continues, let us consider we have biased the IMPATT diode by using a DC source and it is just near to the breakdown voltage. Now we are sending some RF signal through the IMPATT diode. So in positive half of this RF signal, it process that V th required for the breakdown, so in the positive half cycle of this super imposed AC breakdown will start but it is delayed by a finite time. So if I look at this picture, it shows the applied AC voltage versus Omega t and in the 2nd picture it shows the electron-hole pairs generation and the current due to that.

So when the AC voltage it crosses this 0 point, it is positive and the diode it is in breakdown mode, so slowly electron-hole pair generation it starts and it continues. And when the applied AC voltage it crosses the point Pie just after this it is this total superimposed AC + DC, it is just below the voltage that required for the breakdown. So then the electrons-hole pair generation it continues throughout this positive half cycle and it reaches a maximum point when this applied AC voltage it crosses this high point. And now, after that it does not instantaneously stop, it even after that it continues to some extent and due to that we have some more electron-holes pair generation.

So at the negative most point of this AC, it stops completely. And now once these electron-holes pairs are generated, these holes they drift through this I region and it will take finite time to reach this P + region. So if I look at the external current component, it would be exactly in opposite phase, and usually the length of the I region is so made that it will provide us another Pie by 2 phase shift or the current generated due to this avalanche break down, it is exactly in opposite phase to the applied RF signal. So the RF signal then it can absorb energy from the avalanche breakdown and that is how we can use IMPATT diode as an amplifier. So this right-hand side picture it shows the equivalent circuit of that IMPATT diode in addition to the housing, so we have the capacitive diode effect and the inductive wire bonding and also the effect of packaging, it is modelled by a parasitic resistor and inductor.

So diode terminal resistance, it depends on the series resistance passive series resistance of the in active region or I region we can say, V d the carrier drift velocity through I, L length of the drift space charge region, so I region it plays an important role, its length, its resistance and the carrier drift velocity through it. Next A this is the diode cross-section, e s this semiconductor dielectric permittivity and Theta is the transit angle. So transit angle it has one important relationship with R, R depends on transit angle.

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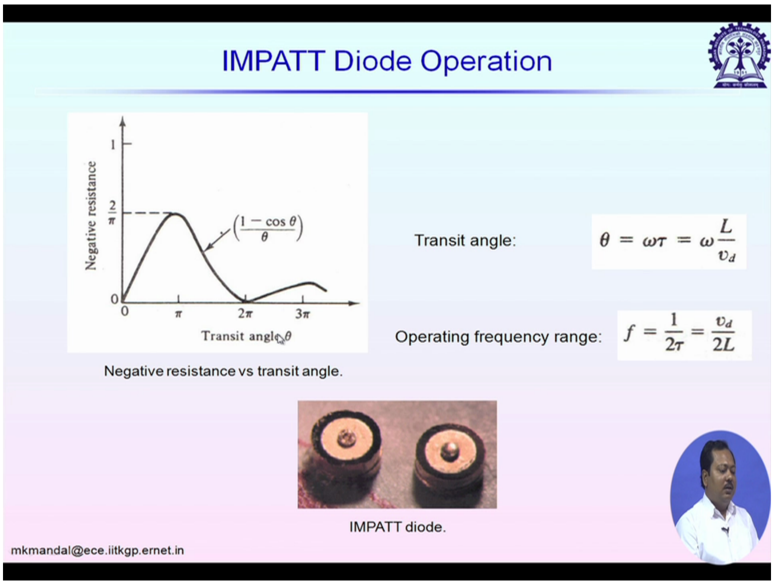

IMPATT Diode Operation

Negative resistance vs transit angle.

Transit angle: $\theta = \omega\tau = \omega\frac{L}{v_d}$

Operating frequency range: $f = \frac{1}{2\tau} = \frac{v_d}{2L}$

IMPATT diode.

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So here we have a plot of negative resistance versus transit angle, transit angle is simply Omega t where t can be given by L by V d, L is the length of the intrinsic region. So we see that negative resistance it is a function of transit angle and it is maximum when transit angle is equal to Pie, so it has almost periodic nature with decreasing amplitude, at transit angle equal to 0 and twice Pie it has minimum value. These are photographs of IMPATT diode typically used at 90 GHz band.

Next is field effect transistor MOSFET typically, so in low-frequency applications we already know the equivalent circuit of MOSFET, it is a unipolar device and the device characteristics is controlled by the applied electric field. But the problem is due to the capacitance high capacitance value used as the oxide layer for the gate. So we have to consider this capacitance effect at the high frequency and the high frequency operation is mainly limited due to the capacitor and not only that, inside MOSFET we have N type material and P type material, so it is associated with P-N junction.

Now, carrier mobility is highest in intrinsic material. Now if we introduce some doping so that means this foreign atoms they behave as a scattered, while carriers like electrons and holes they move through this doped material, they will be scattered by this foreign agent. So if we increase doping concentration, obviously carrier velocity will decrease. So that is why inside P type or N type material carrier velocity will be lower than that inside intrinsic layer. So we will see there is another modification of conventional MOSFET where we avoid this P type or N type material and we use simply intrinsic material for realisation of the channel and that is called the high electron mobility transistor or HEMT. Let us 1st discuss the basic operation of MOSFET and why its high-frequency operation is very much limited.

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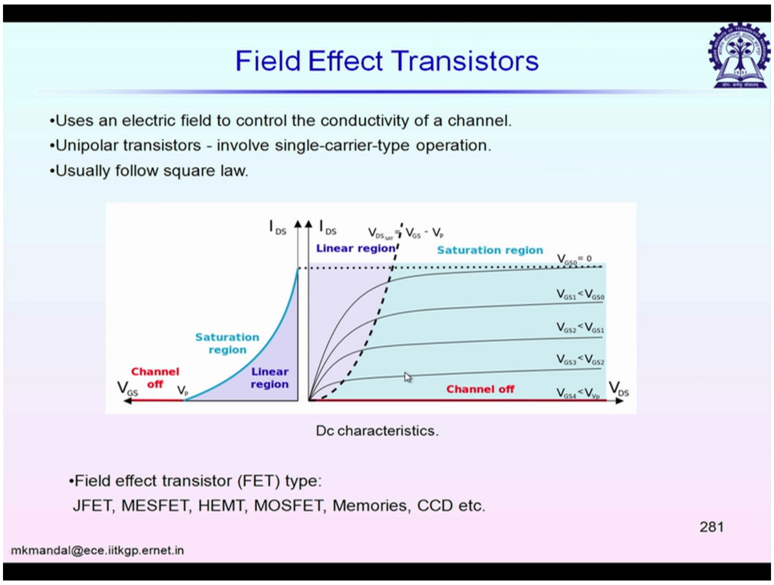

Field Effect Transistors

- Uses an electric field to control the conductivity of a channel.
- Unipolar transistors - involve single-carrier-type operation.
- Usually follow square law.

Dc characteristics.

- Field effect transistor (FET) type:
JFET, MESFET, HEMT, MOSFET, Memories, CCD etc.

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So if I look at the characteristics, transfer characteristics and output characteristics, you will see D s drain to source current it is a function of gate to source voltage, so we can control the drain current by controlling gate to source voltage and if we look at the output characteristics, V ds it is if I increase V ds there is almost no change in I ds, so after this pinch off effect or in saturation region we can represent MOSFET by a current source and this current value, it can be controlled by gate to source voltage. And below this region it behaves as a linear device or we can replace the drain to source by a resistance.

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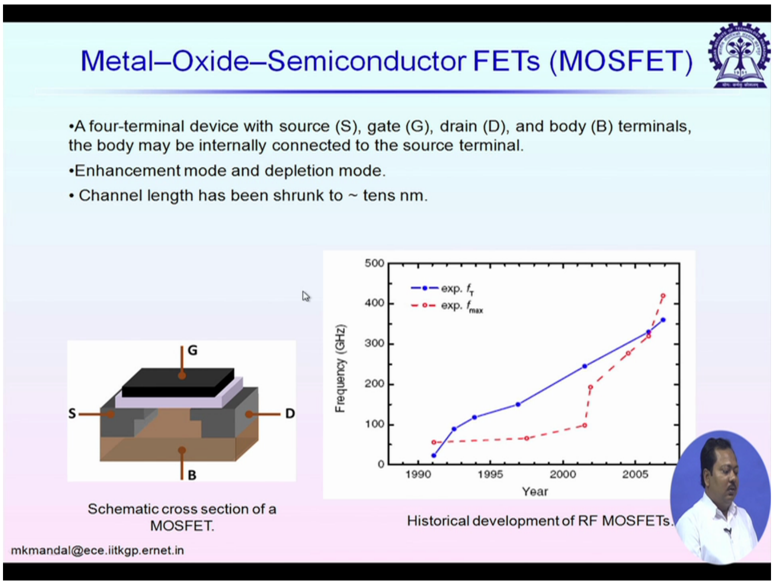

Metal–Oxide–Semiconductor FETs (MOSFET)

- A four-terminal device with source (S), gate (G), drain (D), and body (B) terminals, the body may be internally connected to the source terminal.
- Enhancement mode and depletion mode.
- Channel length has been shrunk to ~ tens nm.

Schematic cross section of a MOSFET.

Historical development of RF MOSFETs.

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So this is a typical MOSFET device, you can see below is the body and we have source, drain, over that we have a thin oxide layer and on top of this oxide layer we have gate layer made of metal or poly silicon and if I now look at the frequency versus the F t and F max realised F t and F max with years, so in recent years there are conventional MOSFETs, they have been developed for which the F t value is as high as 500 or 600 gigahertz. So for that what we have to do, to increase F t we have to decrease the transit time just like BJT, so we have to reduce the gate length, now even 10 nanometre technology is possible and we have to increase the carrier mobility so that transit time it decreases.

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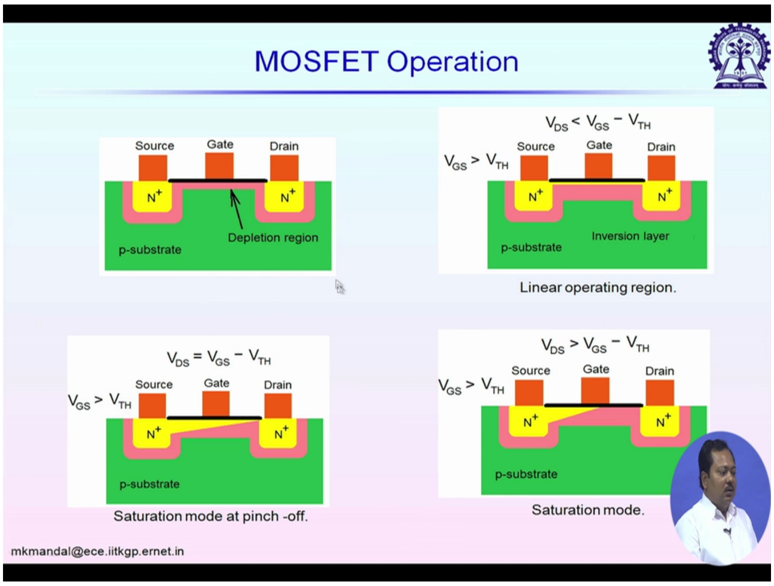

MOSFET Operation

$V_{DS} < V_{GS} - V_{TH}$

$V_{GS} > V_{TH}$

Linear operating region.

$V_{DS} = V_{GS} - V_{TH}$

$V_{GS} > V_{TH}$

Saturation mode at pinch -off.

$V_{DS} > V_{GS} - V_{TH}$

$V_{GS} > V_{TH}$

Saturation mode.

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So for normal operation, so I will just a few basic points so that we can go to HEMT and we can discuss the problems of basic MOSFET. So when we do not apply any external biasing in that case if we consider a N MOS, it starts with P type substrate and we have N + source region and N + drain region and since it involves PN, 2 back to back PN junctions at normal condition we do not have any current flow from source to drain. Now let us consider a situation, we have applied some drain to source voltage but it is less than V gs minus V th. V th is the threshold voltage that needed to realise the channel in between source and drain. So in this case one small inversion layer is created and we have a thin contacting layer here and we can represent the device by a resistance or we have this linear region of this curve.

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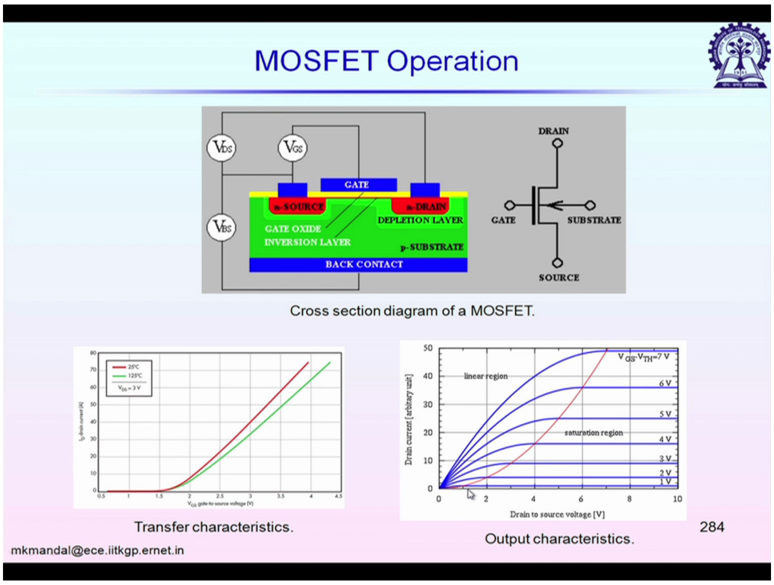

MOSFET Operation

Cross section diagram of a MOSFET.

Transfer characteristics.

Output characteristics.

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Now if I keep on increasing the drain to source voltage for a given gate to source voltage, then what will happen we have this pinch off condition, so we have this pinch off condition. So once this pinch off condition is achieved when V ds is equal to V gs minus V th, this device it behaves like a current source. So after that if we keep on increasing the drain to source voltage, the device current I d it becomes almost constant.

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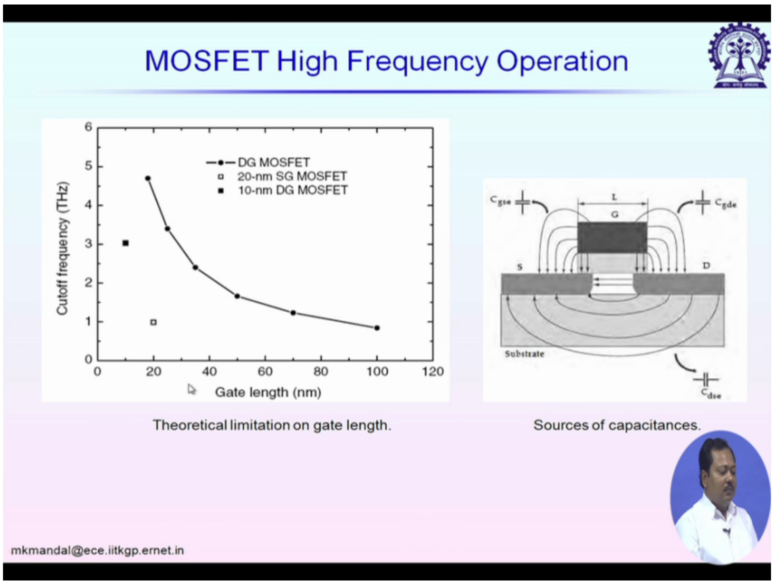

MOSFET High Frequency Operation

Theoretical limitation on gate length.

Sources of capacitances.

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So, this figure shows the cut-off frequency in terahertz versus Gate length, this is the theoretical plot for double gate MOSFET and single gate MOSFET in different technology. So in 10 nanometre double gate or dual gate MOSFET technology you see the typical value is 3 terahertz cut-off frequency, whereas in 20 nanometre single gate MOSFET technology gate length is 20 nanometre, so typical cut-off frequency it is 1 terahertz using conventional MOSFET. Now when we go for amplifier application, in that case the thumb rule is if Ft is given, we can easily use the device to Ft by 10 frequency points. Now you look at the electric field plot between the gate source and through oxide layer, this electric field it is associated with capacitance.

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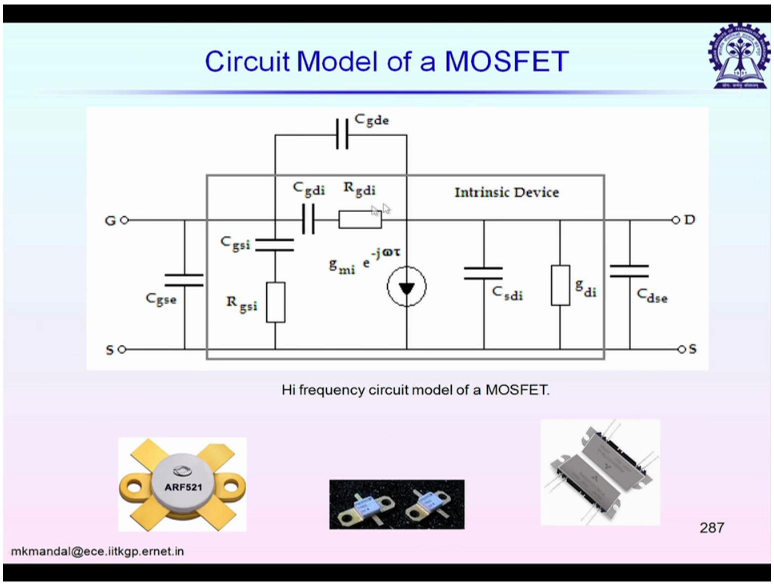

Circuit Model of a MOSFET

Hi frequency circuit model of a MOSFET.

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So we have a capacitor between gate and source, which can be represented by C gs and we have another capacitor between gate and drain, which is represented by C gd and in addition to that we have body effect. So in the equivalent circuit then for high frequency operation, we have to add all these capacitors one between gate and source, one between gate and drain, so this capacitors, resistors inside the rectangular box it shows the intrinsic device property. In addition to that, due to packaging and some other effects we have some additional capacitors and that is sometimes called the extrinsic model of the device. So because of these capacitors, the gain of the device it becomes a function of frequency. And the frequency at which this gain becomes unity, current gain typically we call Ft of the device.

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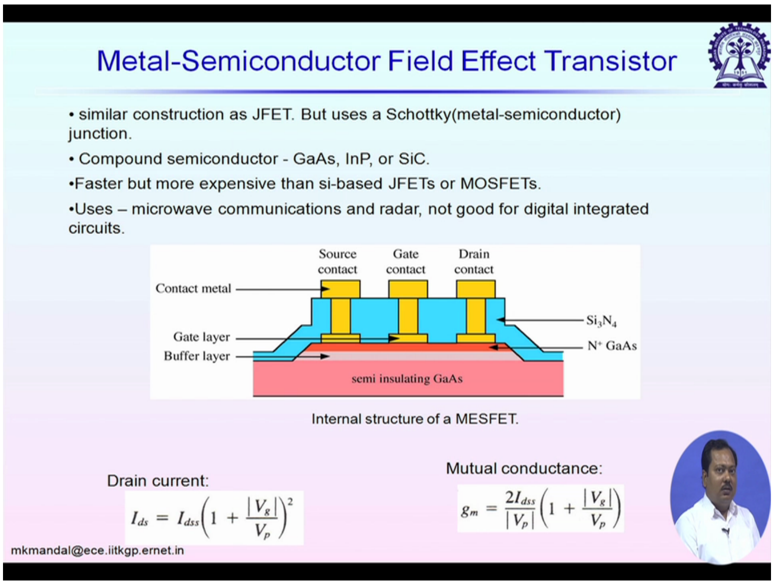

Metal-Semiconductor Field Effect Transistor

- similar construction as JFET. But uses a Schottky(metal-semiconductor) junction.
- Compound semiconductor - GaAs, InP, or SiC.
- Faster but more expensive than si-based JFETs or MOSFETs.
- Uses – microwave communications and radar, not good for digital integrated circuits.

Internal structure of a MESFET.

Drain current:

$$I_{ds} = I_{dss}\left(1 + \frac{|V_g|}{V_p}\right)^2$$

Mutual conductance:

$$g_m = \frac{2I_{dss}}{|V_p|}\left(1 + \frac{|V_g|}{V_p}\right)$$

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Now for high-frequency operation one thing can be done that we can decrease the treat capacitance. So instead of oxide layer there is one type of MOSFET where Schottky junction is used, simply metal semiconductor, we call it MESFET. So you can see the picture here, so just below gate we have N + gallium arsenide layer, so there is no oxide layer and it will give lower capacitance and we can increase F t of the device, but it is not very popular it has some other problems. So next we will move to a modified version of MOSFET, we call it high electron mobility transistor. So as I discussed that if we keep on increasing the doping concentration, then the carrier velocity it will decrease due to the scattering effect of this region which are being used for doping. So in a HEMT device typically it is a hetero junction device, two different types of semiconductors are used to realise this type of device.

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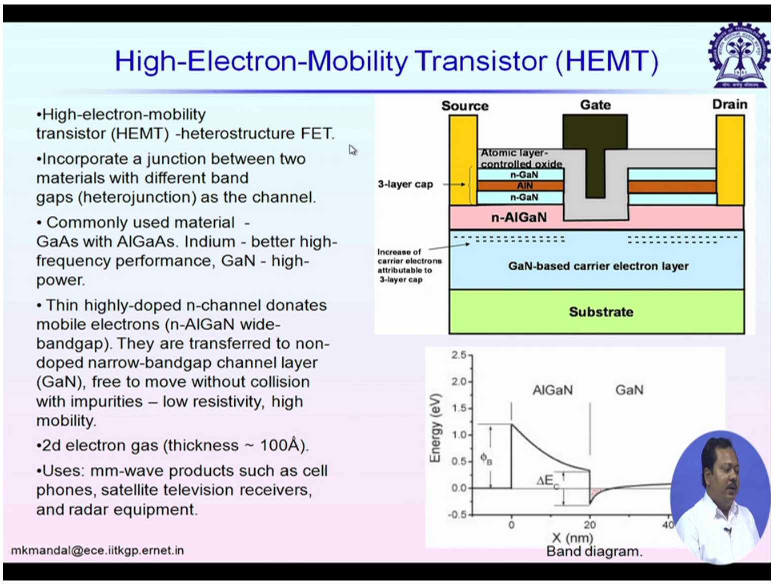

High-Electron-Mobility Transistor (HEMT)

- High-electron-mobility transistor (HEMT) -heterostructure FET.
- Incorporate a junction between two materials with different band gaps (heterojunction) as the channel.
- Commonly used material - GaAs with AlGaAs. Indium - better high-frequency performance, GaN - high-power.
- Thin highly-doped n-channel donates mobile electrons (n-AlGaN wide-bandgap). They are transferred to non-doped narrow-bandgap channel layer (GaN), free to move without collision with impurities – low resistivity, high mobility.
- 2d electron gas (thickness ~ 100Å).
- Uses: mm-wave products such as cell phones, satellite television receivers, and radar equipment.

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Band diagram.

Here we use one intrinsic layer and where channel it will be completely inside the intrinsic layer so that the carriers typically electrons since electrons mobility is higher will be will prefer electrons as the carrier, it is much higher inside intrinsic layer compared to that doping layer and that is how we can improve the mobility of the carriers and that is why the name is high electron mobility transistor. So some characteristics, this is a hetero structure field effect transistor, it incorporates a junction between 2 materials with different band gaps so that is why it is called a hetero junction as the channel. Commonly used materials are gallium arsenide with aluminium gallium arsenide, indium it can give high better high-frequency performance and gallium nitride it can give high power performance.

So in the right-hand side picture you can see a schematic diagram of a HEMT. So below gate we have thin oxide layer and below that we have N type aluminium gallium nitride and below that we have simply gallium nitride-based carrier layer gallium nitride-based carrier electron layer. So now how it operates, the electron concentration inside N type aluminium gallium nitride is much higher compared to the second layer gallium nitride, so because of that we have bending effect and electronic accumulation effect in the second layer. So look at this band diagram, aluminium gallium nitride it is a wide band gap semiconductor whereas gallium nitride, its band gap is lower. At room temperature the Fermi lever, it aligns itself and now at this transition point this band conduction band it bends itself for continuity and it bends deep inside the Fermi level.

So I am plotting the energy of conduction band versus X, so X it started from the top layer and as X increases, we are going inside gallium nitride so just at this transition inside gallium nitride the conduction band bends below Fermi level and electrons in the conduction band of aluminium gallium nitride it sees a lower energy state unoccupied inside gallium nitride. So it will move to gallium nitride and it will be occupied by electrons. So you can see inside the device then we have electrons diffusion initially from this N type material to gallium nitride and because of that we have a very thin layer of electrons and it will form a small depletion region here and this will stop any further electron depletion due to the built-in field of this depletion region. The thickness of this electron layer is typically very small, just maybe 10 of Armstrong and sometimes because of that we call it is a 2-dimensional electron gas.

Now, when some electric field is applied so we have electric field between source and drain, then mostly carrier movement it is inside the gallium nitride layer not inside the N type layer, so that is how we can increase the velocity because of the increased carrier mobility inside undope gallium nitride and that is why it is called high electron mobility transistor or HEMT. So it is being widely used at for different millimetre wave products, for satellite television receivers, radar equipments, et cetera. Now, when we use two different types of materials, they simply cannot be placed one after another one, there is some problem due to their different lattice structure. When we use 2 different weighted semiconductor materials, their lattice constant should be very close to each other otherwise, it will provide some loading effect and because of that electron mobility again it will decrease.

So there are 2 techniques to avoid that, usually a very thin layer of 1 semiconductor material is used on another semiconductor material so that that thin layer of semiconductor material it close it stretches itself and closely follow the lattice formation of the second material that is how we can obtain lattice matching and the HEMT due to that we call pseudo-morphic

HEMT or PHEMT. There is another technique where another material is used a third material is used as a buffer layer between this N type material and the intrinsic material. This buffer layer is used to match the lattice constant between these 2 layers and this is called metamorphic HEMT or MHEMT, so we have two different types of HEMT devices, PHEMT and MHEMT.

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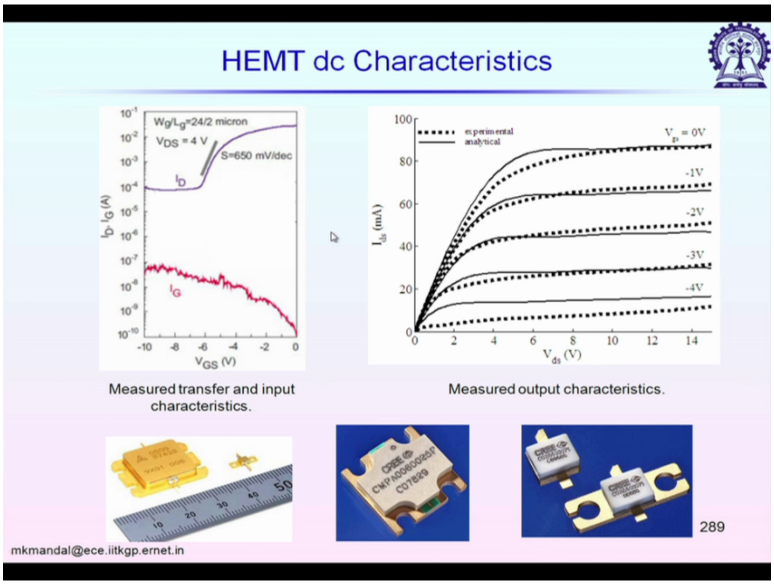

HEMT dc Characteristics

Measured transfer and input characteristics.

Measured output characteristics.

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So this picture it shows HEMT DC characteristics, gate current we still have some leakage current gate current, but typically it is very small but with the increasing gate to source voltage it increases and of the order of fraction of some micro ampere and look at the variation of I d versus gate to source voltage, you can compare with the conventional MOSFET. At very high gate to source voltage it is almost constant, this is the measured characteristics and after that it follows nearly what we see for conventional MOSFET. And looking at the output characteristics, it almost looks like a conventional MOSFET device, it has the linear region and the saturation region, so in saturation region we can replace the device as the current source.

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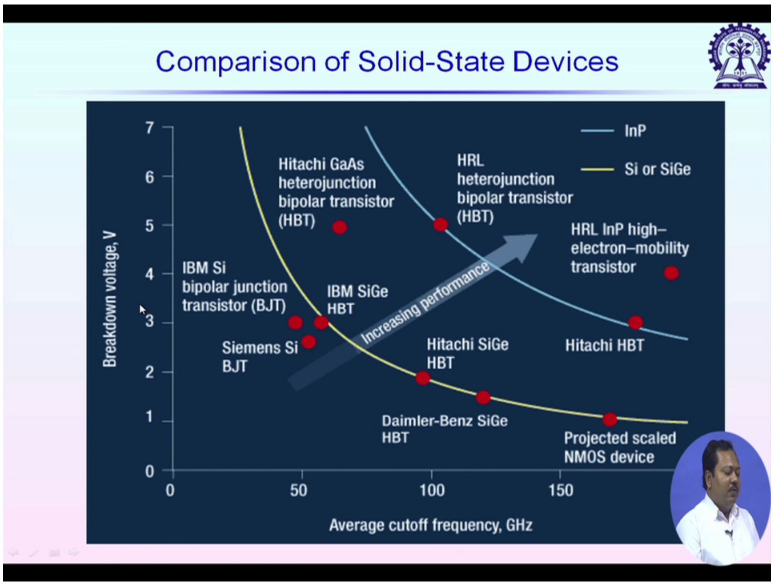

Comparison of Solid-State Devices

Comparison of different solid-state devices available in market, we are comparing breakdown voltage versus average cut-off frequency in gigahertz, so they are available commercially and this yellow curve, it shows devices based on silicon and silicon germanium technology and this blue one, it shows based on indium phosphide, so if I look at the different types of, this is showing high-frequency and high-power high breakdown voltage mean. So in most of the cases, HBT is the winner, Indium phosphide based HBT is the winner. So after this we will see one application of active devices that is electronic switch, but before that we will take a short break thank you.