Millimeter Wave Technology
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Module 6
Lecture No 28
Active Devices (Contd)

Okay so next we will start Transferred Electron Devices. So in this type of devices we do not use any PN junctions, typically one type of semiconductor material either N type or P type are used. N type is preferred since in N type mainly it is associated with electrons mobility and we have seen that electron mobility is higher than the hole mobility, then how it can generate millimetre wave signal we will see. This type of devices associated with 2 conduction bands and because of this 2 conduction bands, they are associated with 2 different types of effective mass and which gives two different types of mobility, so electron velocity become different and due to which given device or given structure will give you differential resistance and this differential resistance can give you millimetre wave signal, so how we will see later.

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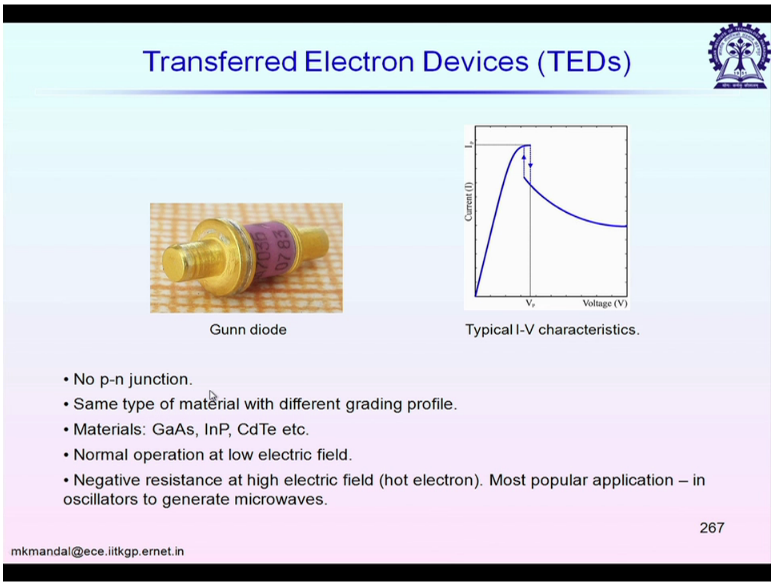

Transferred Electron Devices (TEDs)

Gunn diode

Typical I-V characteristics.

- No p-n junction.
- Same type of material with different grading profile.
- Materials: GaAs, InP, CdTe etc.
- Normal operation at low electric field.
- Negative resistance at high electric field (hot electron). Most popular application – in oscillators to generate microwaves.

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So let us see some basic characteristics of this transferred electron devices. So we do not use any PN junction here as I said, so some types of material sorry same type of material with different getting profile and typical materials are gallium arsenide, indium phosphide, CdTe, silicon, germanium, these conventional materials are not used, why I am going to discuss later. Normal operation at low electric field and it will provide negative resistance at high electric field we call it electron effect, most popular application in oscillators to generate microwave and millimetre wave signals. So we if we keep on increasing the applied bias voltage for this type of devices initially current increases, after a saturation value then it decreases.

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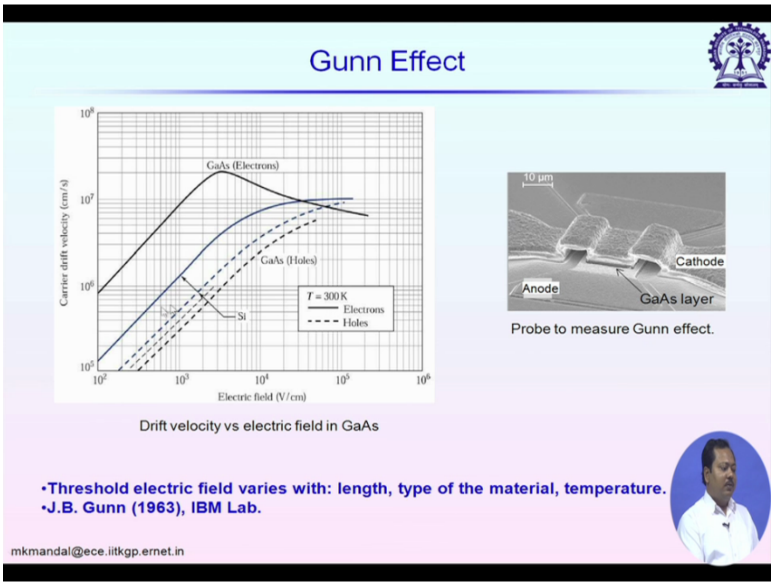

Gunn Effect

Drift velocity vs electric field in GaAs

Probe to measure Gunn effect.

- **Threshold electric field varies with: length, type of the material, temperature.**
- **J.B. Gunn (1963), IBM Lab.**

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And if we further increase the applied voltage after that it follows the conventional resistance property, then current again increases. It happens due to this type of variation of velocity, carrier drift velocity with the applied electric field. In this chart, we are comparing the carrier drift velocities for different types of materials and for electrons and holes. So if I see that for silicon both for electrons and holes carrier drift velocity increases with the applied electric field and at some point it reaches the saturation value. But for gallium arsenide electrons, the carrier drift velocity first increases, reaches a maximum value and then it decreases, so since carrier drift velocity decreases then current will decrease with the increasing voltage in this region and it will give negative resistance.

So right hand side picture shows a typical Gunn diode using gallium arsenide layer, so it is using a chunk gallium arsenide between 2 metals, these metals are simply used for connections, one is used as cathode and another one is used as anode. Then the threshold fold where the velocity changes its slope, it depends on length of the material, type of the material and also temperature. JB Gunn was doing an experiment using this group 3 group 5 materials in IBM lab and he discovered characteristics of these transferred electron devices and that is why sometimes it is called Gunn diode, so let me discuss his experiment what he was doing.

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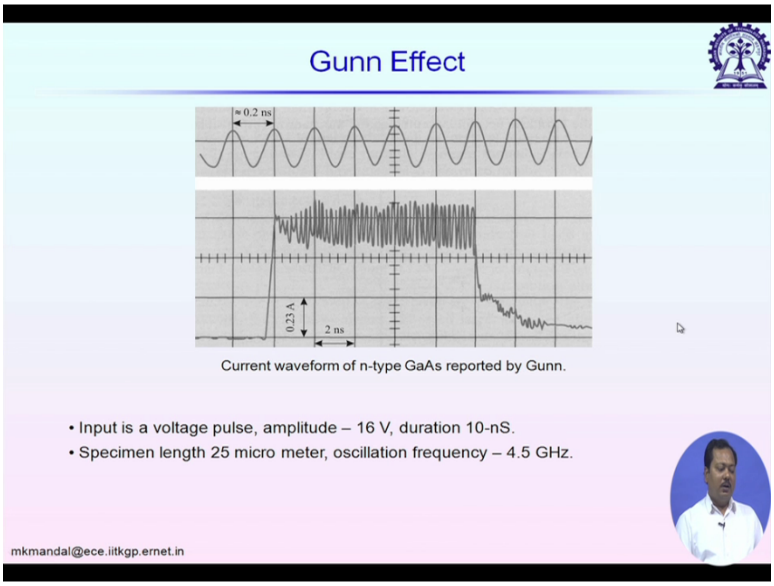

Gunn Effect

Current waveform of n-type GaAs reported by Gunn.

- Input is a voltage pulse, amplitude – 16 V, duration 10-nS.
- Specimen length 25 micro meter, oscillation frequency – 4.5 GHz.

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That time it was well-known that gallium arsenide device is noisy, whenever we send some RF signal through any gallium arsenide device, then it provides noise. So what was JB Gunn’s intention, he investigated the source of noise and what he found out is shown here in this plot. He sent one square wave through a gallium arsenide sample of amplitude 16 volt and ON time is given by 10 nanoseconds, so 10 nanoseconds that means it belongs to megahertz. And what he received at the output, you can see some noise like signal, it is superimposed on the given signal. Now if we zoom in this noise part, it looks like a very good sinusoidal signal with a time period of 0.2 nanoseconds that belongs to microwave frequencies.

So the input is a RF signal whereas, the output contains both the RF input and microwave frequencies. And also he observed the frequency this high-frequency component generated by the device; it depends on the length of the sample. He used for this particular example typical specimen length was 25 micrometres. Now, how are gallium arsenide device can generate microwave or millimetre wave signal, so to understand that we have to understand our RWH theory or popularly known as Ridley Watkins Hilsum theory.

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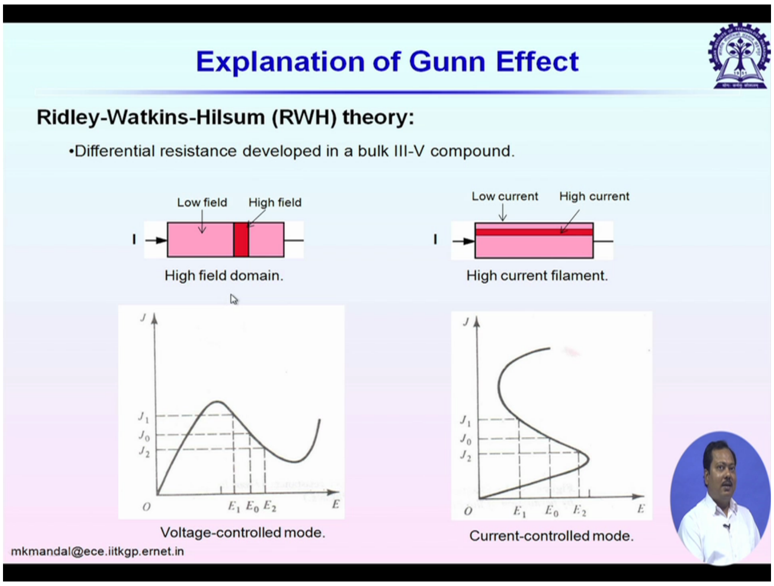

Explanation of Gunn Effect

Ridley-Watkins-Hilsum (RWH) theory:

- Differential resistance developed in a bulk III-V compound.

High field domain.

High current filament.

Voltage-controlled mode.

Current-controlled mode.

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So it deals with differential resistance, so let us say we have a simple here shown by this rectangular block. Now, some voltage is applied between the left-hand side and right-hand side cathode and anode and somehow on a given filament let us say resistance increases, then most of the applied electric field will appear across that high resistant regions is shown hear bear by this red block here. So outside this red block, the electric field value will be much smaller compared to that across this red block since this red block has higher resistivity compared to other regions. Now this filament having high electric field moves from cathode to anode, we will see how later and how this high field region is generated.

And once it reaches the anode terminal, then suddenly we have high current. At the same time we have another high electric region high electric field region generated at the cathode terminal, so it keeps on generating and that is how microbial or millimetre wave signal and the frequency depends on the specific specimen length. Similarly, we may have also high current filament so where the controlling signal is current, now why it happens?

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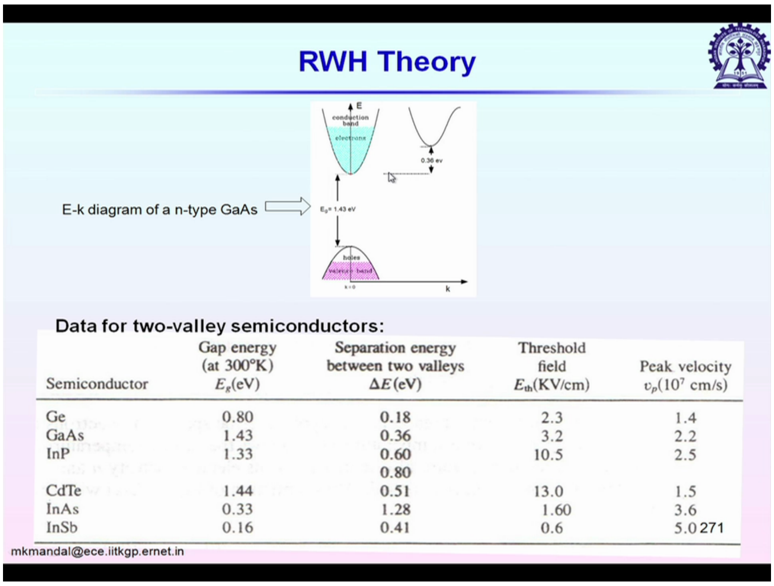

RWH Theory

E-k diagram of a n-type GaAs

Data for two-valley semiconductors:

Semiconductor	Gap energy (at 300°K) E_g(eV)	Separation energy between two valleys ΔE(eV)	Threshold field E_{th}(KV/cm)	Peak velocity v_p(10^7 cm/s)
Ge	0.80	0.18	2.3	1.4
GaAs	1.43	0.36	3.2	2.2
InP	1.33	0.60 0.80	10.5	2.5
CdTe	1.44	0.51	13.0	1.5
InAs	0.33	1.28	1.60	3.6
InSb	0.16	0.41	0.6	5.0

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This picture shows the E-K diagram for N-type gallium arsenide. So this bottom part shows the valence band and this top one is showing the conduction band. Now in addition to this primary conduction band we have one more valley, the bottom of this valley is little high compared to the previous one. The band gap at 300 Kelvin for gallium arsenide from this balance band to the 1st conduction band is 1.43 electron volt whereas, the gap between the 1st and 2nd conduction band it is 0.36 electron volt. Now, when we apply some voltage between left-hand side and right-hand side what will happen, so electrons will transit to conduction band? Now if we keep on increasing the voltage, so electron momentum will increase or electrons will go higher region of this E-K diagram inside the conduction band.

Same thing happens for the hole, but this is in the valence band. Now, if the electron kinetic energy is sufficiently high, in that case if it is more than let us say the bottom of the 2nd band, then it will say that there is one empty band available, which has lower energy so it will jump into the 2nd band but for that we need to provide sufficient energy to electron. Now what will happen, the electrons we have some inside the 1st band and some inside the 2nd band, let me show you the next plot.

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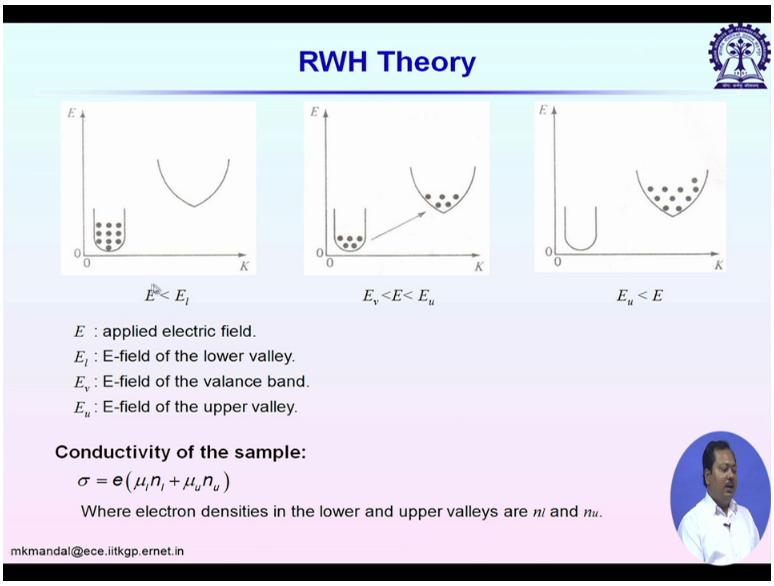

RWH Theory

$E < E_l$ $E_v < E < E_u$ $E_u < E$

E : applied electric field.
E_l : E-field of the lower valley.
E_v : E-field of the valance band.
E_u : E-field of the upper valley.

Conductivity of the sample:

$$\sigma = e(\mu_l n_l + \mu_u n_u)$$

Where electron densities in the lower and upper valleys are n_l and n_u.

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So you see the when the electric field is less than this E l, where E l we are calling the electric field of the Lower Valley and in that case mostly electrons it is in the 1st conduction band. Now, if we keep on increasing the electric field value so X axis it shows the kinetic energy or else it shows the momentum K, so the kinetic energy and momentum it will increase and let us say E v this is the E-field of the valance band and E u it represents the E-field of the upper valley the 2nd band. Now if we keep on increasing the applied electric field, in that case its momentum will increase and some of the electrons, it will transit to this 2nd band second valley.

So what happens here, in this case if I calculate total conductivity of this material that can be given by Sigma is equal to e into Mu l n l, so it corresponds to the electrons which are inside the Lower Valley and plus we have some electrons in upper valley also, then we have a contribution Mu u multiplied by n u give to the electrons inside upper valley. Now, one interesting thing is that if I compare the effective masses at these 2 different valleys, this Lower Valley is associated with lower effective mass and is higher valley is associated with higher effective mass, so since effective mass of the electron is high, then electron mobility is low. So that means the electrons in this 2nd conduction band in upper valley they have lower velocity. So if we keep on increasing the electric field, more and more electrons will transit to this upper valley and as a whole overall current will decrease due to the reduced velocity in the 2nd band.

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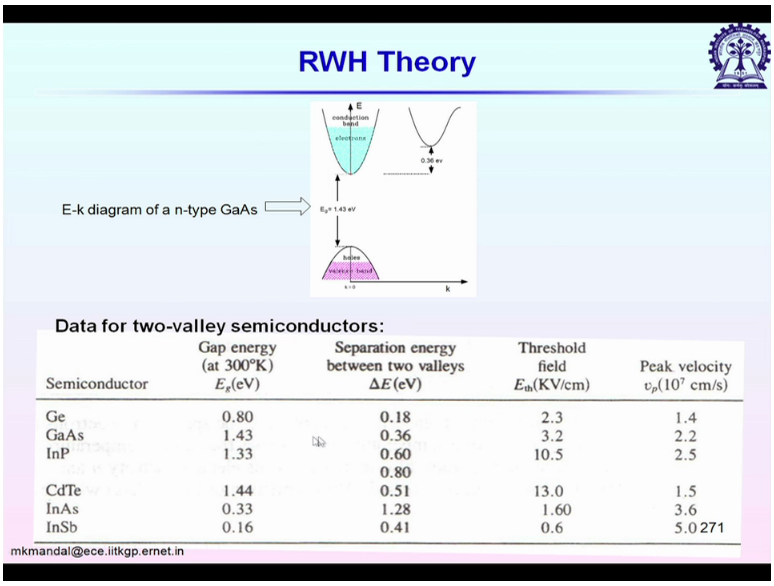

RWH Theory

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Now, a condition third condition, when the electric field is sufficiently high so that it is more than the E-field of the upper valley E you, so 1st band is almost empty and almost all electrons now in the 2nd valley. So, in this case we do not have any contribution or N l = 0 and it will behave like a normal semiconductor material. So again if I keep on increasing electric field beyond this value, this velocity will increase due to increment in K. So we see, so then it can happen if only 2nd or this upper valley is present, so these are some typical popular materials for which the gap energy is given here. For germanium E g is 0.8 and separation energy between 2 valleys is 0.18, typical threshold field is 2.3 kilovolt per centimetre and peak velocity is given 1.4 into 10 to the power 7 centimetres per second, for gallium arsenide these values are 1.43 and 0.36.

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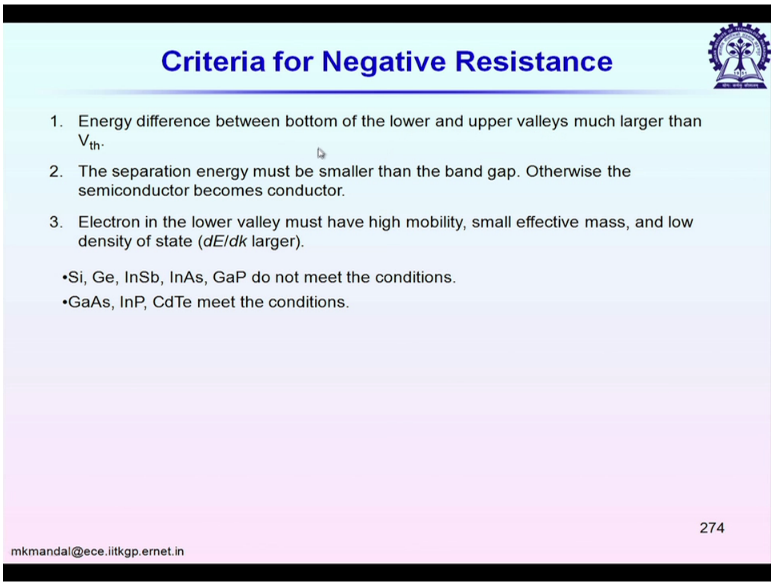

Criteria for Negative Resistance

1. Energy difference between bottom of the lower and upper valleys much larger than V_{th}.
2. The separation energy must be smaller than the band gap. Otherwise the semiconductor becomes conductor.
3. Electron in the lower valley must have high mobility, small effective mass, and low density of state (*dE*/*dk* larger).

- Si, Ge, InSb, InAs, GaP do not meet the conditions.
- GaAs, InP, CdTe meet the conditions.

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So looking at the working principle than we see that it should have 2 valleys not only that, the separation between the 1st valley and valence band and 1st valley and 2nd valley it should be different, and for the 2nd case it should be smaller than the difference between valence band and the 1st valley otherwise, it will not happen and not only that, there should be a difference of effective mass so that we will have different velocities for these 2 different valleys. So criteria for negative resistance then we can generalise, energy difference between bottom of the lower and upper valleys be much larger than V th threshold value. The separation energy must be smaller than the band, otherwise the semiconductor becomes conductor and electrons in the Lower Valley must have high mobility, small effective mass and low density of state.

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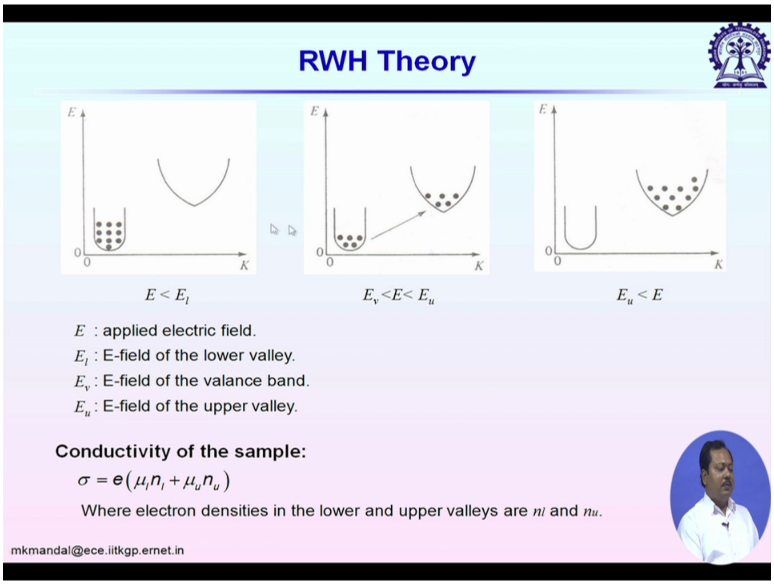

RWH Theory

$E < E_l$ $\quad$ $E_v < E < E_u$ $\quad$ $E_u < E$

E : applied electric field.
E_l : E-field of the lower valley.
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Conductivity of the sample:

$$\sigma = e(\mu_l n_l + \mu_u n_u)$$

Where electron densities in the lower and upper valleys are n_l and n_u.

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Low density of state that means low rate of change of E with respect to K should be larger as shown in this figure. So if I look at the edges for the 2nd band 2nd conduction band you see it is more flat. So looking at this criteria, silicon, germanium, indium antimony, indium arsenide, gallium phosphide do not meet the conditions, but gallium arsenide, indium phosphide, cadmium Telluride, they meet the condition, so we can use these materials to fabricate any Gunn diode or negative resistance device due to transferred electronic effect. Now let me discuss then how we can generate microwave or millimetre wave signals from these types of devices, so let us go back to very basic things.

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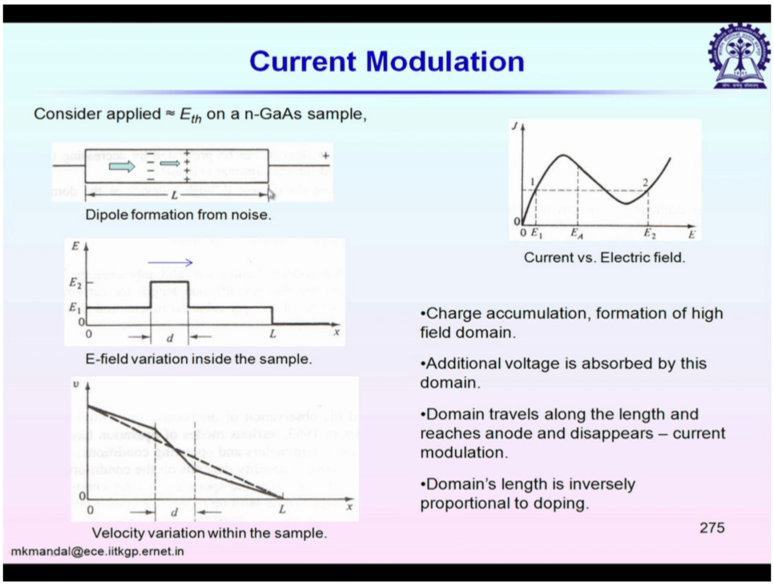

Current Modulation

Consider applied ≈ E_{th} on a n-GaAs sample,

Dipole formation from noise.

E-field variation inside the sample.

Velocity variation within the sample.

Current vs. Electric field.

- Charge accumulation, formation of high field domain.
- Additional voltage is absorbed by this domain.
- Domain travels along the length and reaches anode and disappears – current modulation.
- Domain's length is inversely proportional to doping.

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So let us say we have this rectangular block that shows this schematic n type gallium arsenide sample. And consider the applied voltage is E th we have the threshold, so in that case let us say somehow usually due to noise there is accumulation of electrons here in some region. Now, because of that the velocity of this electron it decreases or the resistance it increases. So once the resistance increases, in that case we have high electric field so we are applying some biasing voltage between left and right hand side cathode and anode and because of that we have electric field inside the Sample. Initially it is uniform throughout the material, but somehow if there is a accumulation of electrons here, so the resistance it will increase and as a result then electric field across this filament it will suddenly increase and it will keep on increasing because the electron it will start moving to the 2nd band 2nd conduction band.

And now we have a dipole formation somewhat like this and then because of the applied electric field, it also drifts from left-hand side to right-hand side. Once it reaches this anode terminal then suddenly we have high current, at the same time to keep the voltage at same level we have a generation of another filament at the cathode terminal and it keeps on generating so as a result we have a series of current maxima, which the separation of these 2 current maxima it depends on the type of material and the length of the material and we have microwave or millimetre wave signal or that. So domain length, it is inversely proportional to doping concentration.

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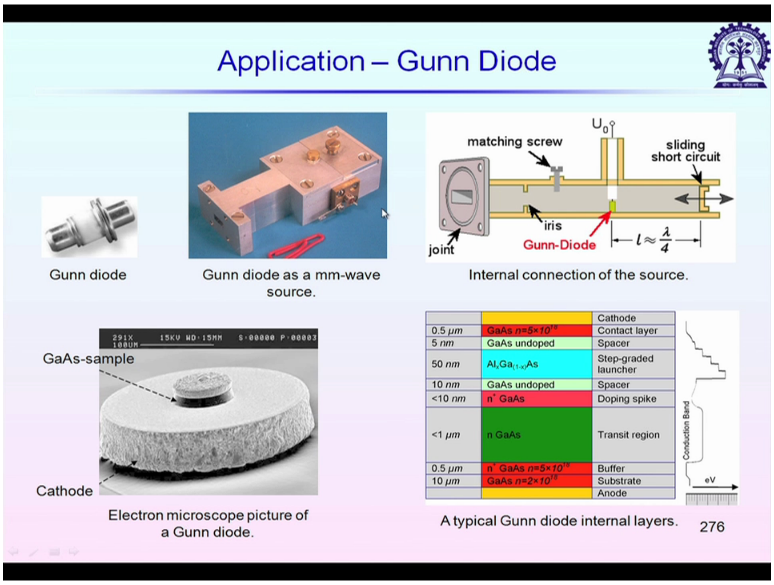

Application – Gunn Diode

Gunn diode

Gunn diode as a mm-wave source.

Internal connection of the source.

Electron microscope picture of a Gunn diode.

		Cathode
0.5 μm	GaAs $n=5\times10^{18}$	Contact layer
5 nm	GaAs undoped	Spacer
50 nm	$Al_xGa_{(1-x)}As$	Step-graded launcher
10 nm	GaAs undoped	Spacer
<10 nm	n^+ GaAs	Doping spike
<1 μm	n GaAs	Transit region
0.5 μm	n^+ GaAs $n=5\times10^{18}$	Buffer
10 μm	GaAs $n=2\times10^{18}$	Substrate
		Anode

A typical Gunn diode internal layers.

Now, let us see how a Gunn diode is used as a millimetre wave source. It is very popular in laboratory experiments, it shows a waveguide-based system and here in top right figure you can see a cut way view of the waveguide source based on Gunn diode. So Gunn diode, it is placed inside the rectangular waveguide, on top of it we have the biasing arrangement, which will provide that E th value and now the resonant frequency of the source frequency, it is determined by a tank circuit. Here it is realised by using a cavity resonator waveguide cavity resonator, so you can see left-hand side we have 1 Iris. Basically we have a shorting valve and a slot in that shorting valve we call it Iris and equivalent impedance looking from the Gunn, it is inductive and right-hand side we have a sliding short-circuit.

So then the resonant frequency is determined by the cavity length from this Iris to this short-circuit length and we can, we have a usually mechanical tuning arrangement so that we can slide the short-circuit position and we can change the cavity length so that the resonance frequency changes and it will generate different millimetre wave signals. Now, due to the external arrangement we have different impedance loading, usually for the Iris we will be facing inductive loading and we have cancelled somehow the inductive loading, because of that matching screw is used and it is usually capacitive and it can nullify the effect of this Iris.

So you can see the assembly from outside using split block technology and this bottom left figure, it shows a electron microscope photograph of a Gunn diode. You can see the black colour gallium arsenide Sample in between copper metals, this copper is used just for connection.

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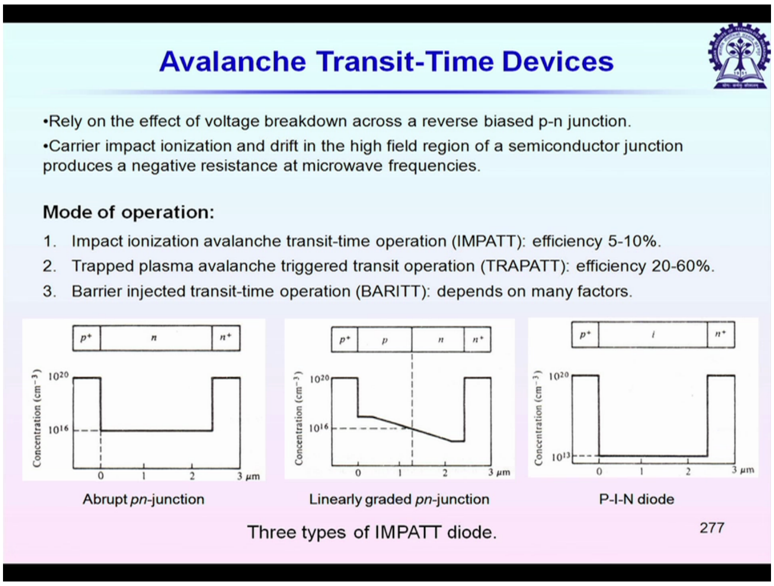

Avalanche Transit-Time Devices

- Rely on the effect of voltage breakdown across a reverse biased p-n junction.
- Carrier impact ionization and drift in the high field region of a semiconductor junction produces a negative resistance at microwave frequencies.

Mode of operation:

1. Impact ionization avalanche transit-time operation (IMPATT): efficiency 5-10%.
2. Trapped plasma avalanche triggered transit operation (TRAPATT): efficiency 20-60%.
3. Barrier injected transit-time operation (BARITT): depends on many factors.

Abrupt *pn*-junction

Linearly graded *pn*-junction

P-I-N diode

Three types of IMPATT diode.

Next device is avalanche transit time devices, so in this type of devices it is associated with breakdown phenomena, avalanche breakdown phenomena the same phenomena what we see for a PN junction diode at low frequency. In addition to a simple PN junction, here usually a drift zone is intentionally provided where the electrons can accelerate under given electric field and it can gain sufficient kinetic energy from that so that when it will strike any silicon or any semiconductor atom and it can break any covalent bond and generate electron hole pairs. So, two basic conditions they are used in avalanche breakdown condition and we need a drift zone to accelerate the electrons. So because of this impact we call it impact avalanche device, so some basic properties - rely on the effect of voltage breakdown across a reverse biased PN junction and then carrier impact ionisation and drift in the High field region of a semiconductor junction produces a negative resistance at microwave or even at millimetre wave frequencies.

Now, depending on mode of operations we have 3 different types of popular diodes. The 1st one is called Impact ionisation avalanche transit time operation or simply IMPATT diode, but the efficiency is very poor typically 5 to 10%. The next one is Trapped plasma avalanche triggered transit operation or TRAPATT diode, efficiency is little higher 20 to 60% and then the 3rd category is Barrier injected transit time operation or BARITT diode, but the efficiency depends on many factors. So here we are going to discuss on IMPATT device, IMPATT diodes mainly they are used as power amplifiers and it can generate even kilowatt order millimetre wave signal and successfully it has been used at 90 (())(25:02) and even as high as 300 gigahertz. So the basic before basic operations, here are 3 different schematics for 3 different types of IMPATT diodes.

The 1st one is abrupt PN junction and you can see, P +, N, N +, so N middle layer it is slightly doped and it is used as the drift region. Next one P +, P , N, N +, so this lightly doped P-N part, it is used the drift region and the next one is P +, I, N +, so I intrinsic layer this is used as the drift region, where electrons will accelerate and gain sufficient energy from the electric field so that it can break one covalent bond, when impact.

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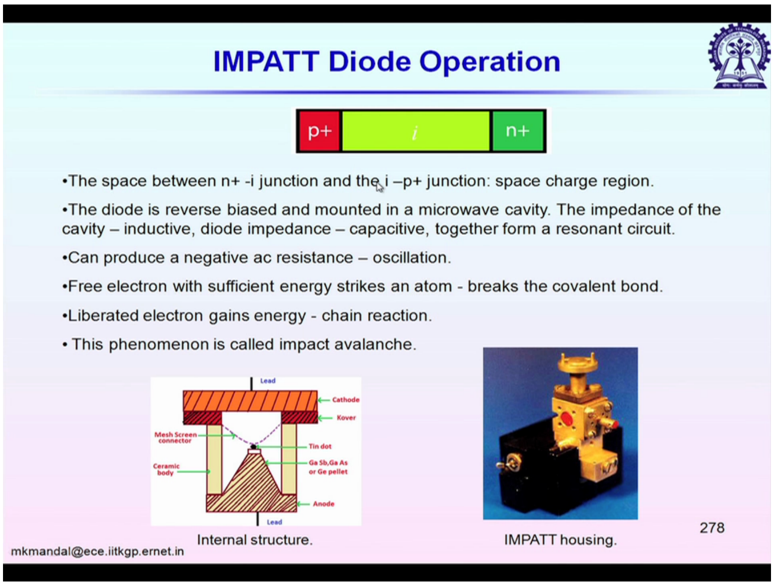

IMPATT Diode Operation

- 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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So let me discuss about the very basic operation of a P +, I, N + type IMPATT diode. So we will assume that electric field is high enough inside so that when the electrons accelerate inside the intrinsic layer and it inside N +, it will hit covalent bonds and generate electron-hole pair. And under high electric field it will keep on impacting and then we will have more and more electron-hole pair generation inside. Again this newly generated electron-holes pair, they will again accelerate and they will also create more electron-holes pair and this is that is why it is called an avalanche procedure. It can produce a negative AC resistance so since negative AC resistance we can have oscillation at microwave and millimetre wave frequencies. So how it operates? Okay it will be little lengthy so let us take 5 minutes break then we will start again, thank you.