High Speed Devices and Circuits

Prof. K. N. Bhat

Department of Electrical Engineering

Indian Institute of Technology, Madras

Lecture - 2

Requirements for High Speed Circuits, Devices and Materials

In our last discussion, we introduced to you the concept of high speed devices, some of the basic aspects. Particularly, we discussed how silicon is all pervasive that is one thing that we saw. Then, we took up what are the basic characteristics of devices which decide the high frequency performance. I will just go through briefly some of those things which we discussed towards the end of our discussion because I might have rushed a little bit.

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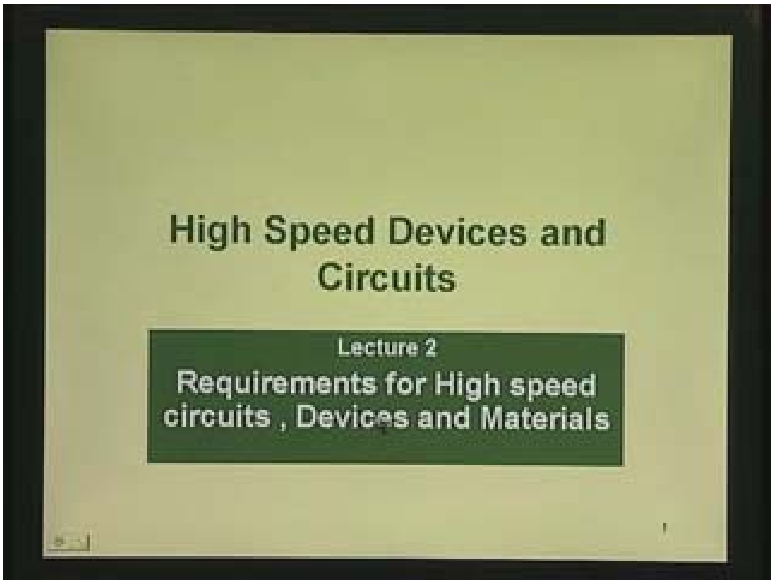

High Speed Devices and Circuits

Lecture 2

Requirements for High speed circuits , Devices and Materials

I have given a title for this second lecture as Requirements for High speed circuits, Devices and Materials.

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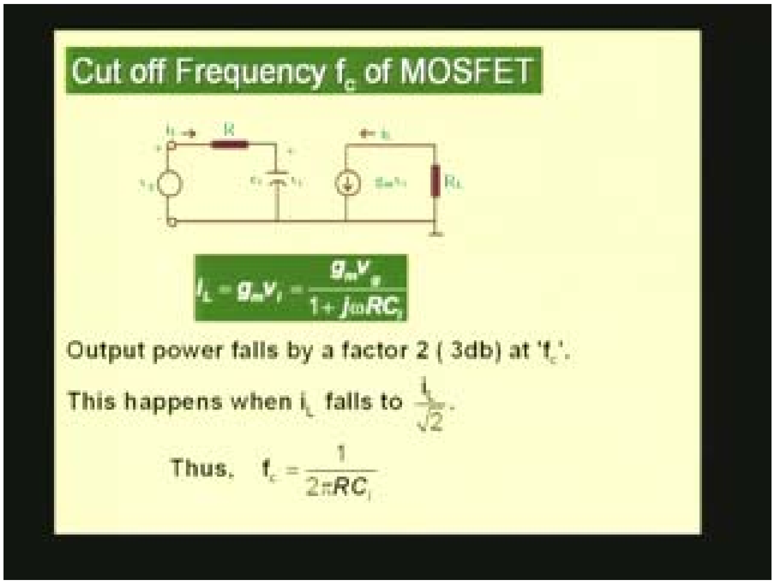

Cut off Frequency f_c of MOSFET

$$i_L = g_m v_i = \frac{g_m v_g}{1 + j\omega RC_i}$$

Output power falls by a factor 2 (3db) at 'f_c'.

This happens when i_L falls to $\frac{i_L}{\sqrt{2}}$.

Thus, $f_c = \frac{1}{2\pi RC_i}$

So that just go through quickly what we did last time. We saw what is meant by cutoff frequency of the MOSFET. We discussed the characteristics frequencies, there are two. One is the cut off frequency and the other one is transit frequency and the cut off frequency, we discussed with respect to the equivalent circuit of the device. R is a resistance which comes externally to the device. It can be the resistance of the gate or it can be the ON resistance of the previous devices which drives the transistors and this is the gate capacitance here. So, we have seen in detail that let me not go through that. You can easily work it out also, the cutoff frequency of the device is the frequency at which the power gain falls to half; output power powers half. That is, 3db point, that is 2 pi RC is the frequency.

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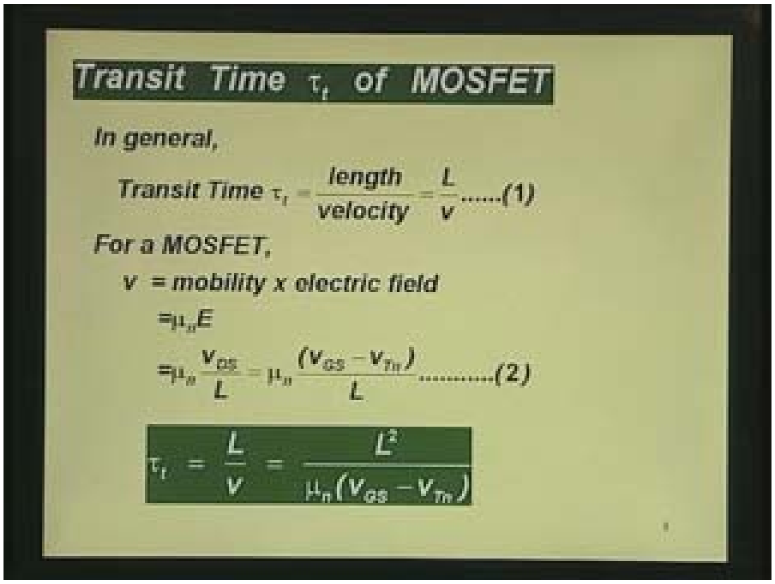

Transit Time τ_t of MOSFET

In general,

$$\text{Transit Time } \tau_t = \frac{\text{length}}{\text{velocity}} = \frac{L}{v} \text{......(1)}$$

For a MOSFET,

$$v = \text{mobility x electric field}$$

$$= \mu_n E$$

$$= \mu_n \frac{V_{DS}}{L} = \mu_n \frac{(V_{GS} - V_{Th})}{L} \text{..........(2)}$$

$$\boxed{\tau_t = \frac{L}{v} = \frac{L^2}{\mu_n (V_{GS} - V_{Th})}}$$

Now, the other parameter that we were discussing was the transit time. Now, the transit time is defined as the length divided by velocity. We also gone through this in details. Now, it so turns out that the velocity is proportional to the electric field. Product of mobility and electric field and electric field is drained source voltage by the length and that electric field is actually the voltage drop across the channel divided by the length. So, that it is the electric field and when the substitute of this together, transit time is actually equal to length square divide by mobility and the voltage dependent term. So, you can see that, it is very important to reduce the channel length to have a smaller transit times because the transit time actually decide what is the transit frequencies?

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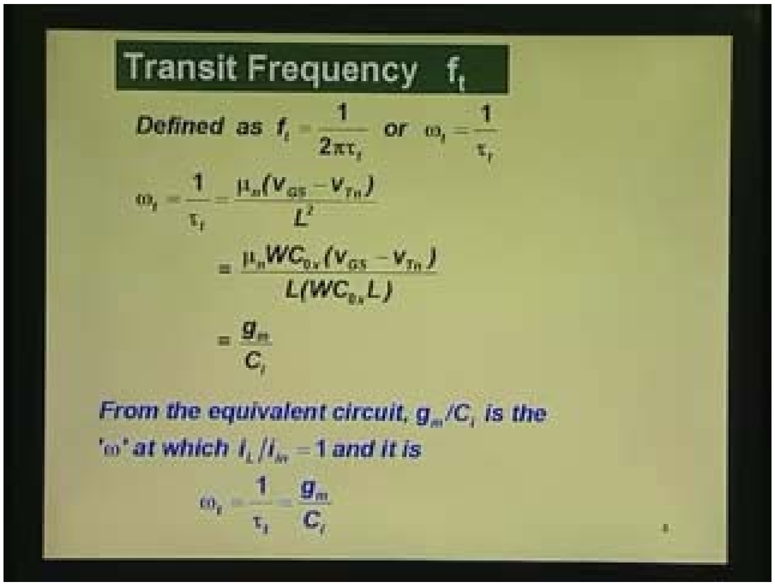

Transit Frequency f_t

Defined as $f_t = \frac{1}{2\pi\tau_t}$ or $\omega_t = \frac{1}{\tau_t}$

$$\omega_t = \frac{1}{\tau_t} = \frac{\mu_n(V_{GS} - V_{Tn})}{L^2}$$

$$= \frac{\mu_n W C_{0x}(V_{GS} - V_{Tn})}{L(WC_{0x}L)}$$

$$= \frac{g_m}{C_i}$$

From the equivalent circuit, g_m/C_i is the 'ω' at which $i_L/i_{in} = 1$ and it is

$$\omega_t = \frac{1}{\tau_t} = \frac{g_m}{C_i}$$

The transit frequency is actually the frequency at which the output current to the input current becomes equal to 1. That we saw yesterday, we derived it with respect to the equivalent circuit. So, you can see here, the transit frequency f_t into 2 pi that is omega$_{t,}$ is defined as 1 by tau$_t$ transit time that becomes ultimately equal to g_m by C_i. So, what we are saying is you need to have, if want to keep this omega$_t$ or the transit frequency high, you need to keep the transit time low which actually can be achieved by reducing the channel length and also having high mobility at all we saw last time and in terms of the parameters for this circuit engineer, we can say the g_m transconductance must be high and the capacitance associated with the device including the stray capacitance must be low.

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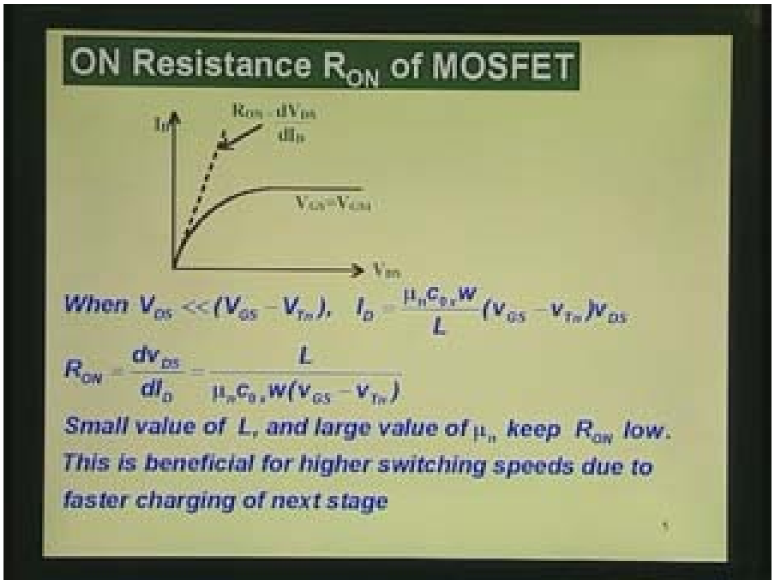

ON Resistance R_{ON} of MOSFET

When $V_{DS} << (V_{GS} - V_{Tn})$, $I_D = \frac{\mu_n C_{ox} W}{L}(V_{GS} - V_{Tn})V_{DS}$

$$R_{ON} = \frac{dv_{DS}}{dI_D} = \frac{L}{\mu_n C_{ox} W(V_{GS} - V_{Tn})}$$

Small value of L, and large value of μ_n keep R_{ON} low.
This is beneficial for higher switching speeds due to faster charging of next stage

Now, what we saw in that series that resistance R which was coming at the input which decides the cut off frequency is actually the ON resistance of the previous device. So now I will tell you what is ON resistance? I have put this diagram. Here, this is the output characteristics, one characteristics of the MOSFET for one voltage $V_{Gs,}$ gate to source voltage. So, here, we can see this curve is linear in the initial portion and that linear portion has a slope which is actually delta V_D by delta I_D that is the volt resistance. So, this change in voltage divides by change in current which actually the inverse slope of this that is actually the ON resistance. The resistance of the device when is just in ON state. That is actually what we are seeing here. So this ON resistance on what does it depends. We want to keep it minimum. Any resistance, any capacitance would be kept to a minimum. So, we want to keep the resistance to minimum that means the slopes should be as steep as possible. It is governed by certain equations of the MOSFET. This portion of the MOSFET characteristics is called the linear region, to go out here is called saturation region on this portion. So, in the linear region, the I_D is related to V_{DS} and the gate voltage by this particular relationship. I_D is equal to some constant. It depends upon the mobility, gate oxide, channel width, and also channel length. Notice everywhere, these two terms, the channel length and mobility will haunt the speed of the device. It is the one which troubles the speed of the device because that is the one which controls the cutoff frequency of the device through this ON resistance.

So, this is the well known equation, I_D is linearly related to V_{DS} in this portion. If you increase V_{Gs}, this quantity if you increase that becomes less. I_D becomes more that means V_{DS} divided by I_D becomes this quantity or delta V_{DS} by delta I_D is actually this quantity. I am just putting it to differentiate it. So instead of putting delta I_D by delta $V_{DS,}$ I am putting delta V_{DS} by delta I_D. That is the resistance and that resistance is inverse of this quantity which actually proportional to length and inversely proportional to the mobility. Very clearly, you must reduce the channel length and also you must have device mobility or carrier mobility should be high.

Other parameters, of course are the oxide capacitance and all it goes without telling that, those should be larger but you cannot tolerate large oxide capacitances. So, do not try to maximize oxide capacitance, maximize this quantity, may be this voltage can be increased There is upper limit to V_{Gs}. What is the upper limit? It is the Supply voltage. If you are using just 1 or 2 volts V_{GS} will be just 1 or 2 volts and V_{Tn} is the threshold voltage.

So ultimately, what we are telling is small value of L and large values of mobility, mu_n keep R on low. There is the key to the success of achieving higher speeds. So, you can get higher cutoff frequencies and also higher switching speeds. Because when R is small, the charging time is small, faster charging that is about ON resistance.

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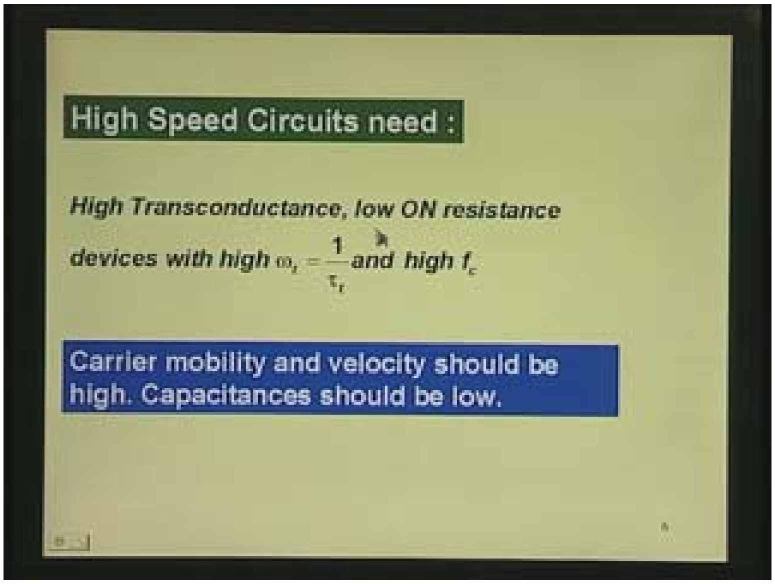

High Speed Circuits need :

High Transconductance, low ON resistance

devices with high $\omega_t = \frac{1}{\tau_t}$ *and high* f_c

Carrier mobility and velocity should be high. Capacitances should be low.

So, the high speed circuits ultimately need devices with high transconductance, low ON resistance and of course high cutoff frequency, and high transit frequency omega$_{t.}$ All these can be achieved by tailoring the key parameters in the channel length and mobility. Increase the mobility, reduce the channel length that is what we saw just now. So, carrier mobility which governs the velocity should be high for achieving all these things. Capacitances should be low. Because after all this quantity, that is the cutoff frequency is g_m by c.

You need to keep the capacitance low so that cutoff frequency is high or R must also be kept low. So, these are some of the key things that we look forward to in the high speed circuits and when you say mobility, you want to keep it high. If you saw some of the previous slides.

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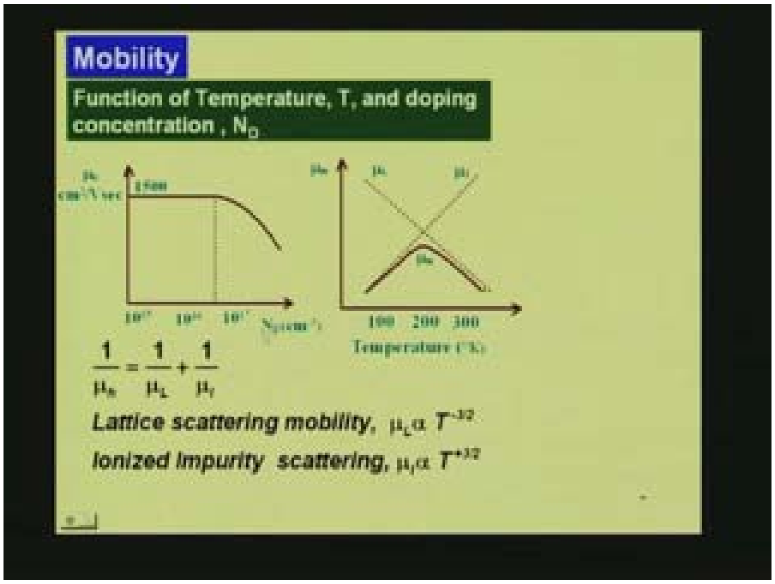

Mobility

Function of Temperature, T, and doping concentration , N_D

$$\frac{1}{\mu_n} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

Lattice scattering mobility, $\mu_L \alpha\, T^{-3/2}$

Ionized impurity scattering, $\mu_I \alpha\, T^{+3/2}$

What is this mobility? Mobility is actually a proportionality constant which decides what the velocity for a given electric field. Now, this mobility depends upon doping and also temperature. So, actually you please remember this to grasp.

Later on, we may have occasion to recall this. So, the doping affects the mobility. Once the doping concentration is somewhere around five times ten to the power of sixteen. Till that time, the mobility in silicon, what I have put these on mobility of silicon because we are talking about silicon for the time being that mobility is constant for the electrons that is about 1500 centimeter square per 1 second. But once, you go down to doping concentration which are 10 to the power of 17, 18 etc. which you may not like to do because mobility will fall and this mobility fall is due to the scattering of the carriers by those ionized impurities. If you have more dopents are there those dopents prevent the electrons from moving smoothly. They get knocked or they get scattered by these impurities. That is why, when the doping becomes high, scattering becomes more, the velocity fall. Now this particular value of thousand five hundred that we have put here, that is the mobility at room temperature. So, if I take a look at the mobility, total temperature dependence of mobility a qualitative picture I have drawn here, lower temperature mobility will be low decided by this graph, mu_i. There are two graphs which I have plotted. One is growing up that is mobility, Mu_i which is ionized impurity scattering that keeps on increasing with temperature. That is because if the temperature is higher, the electrons have energy to move faster and they do not get bothered by the scattering of these ionized impurities, higher the temperature less is the scattering. So, we get higher mobility.

That is what is shown here, that is one mechanism of scattering. There is another scattering mechanism which I have put by this line. That is Mu_L that is called lattice scattering mobility. I am just touching upon some of the things though it might have been discussed in somewhere else in some other basic courses in circuits and also in devices.

But, this is necessary to have some idea of the parameter variation temperature. That is why I am just touching upon this. This lattice scattering mobility keeps on falling with temperature. This is because scattering increases if the temperature increases, scattering by this lattice atoms. What is that due to? When the temperature increases, lattice atoms vibrate more and more. If they vibrate more and more, when an electron comes like this, you can see it gets scattered more and more. If the temperature is small, the vibration is small, somewhat less therefore, the scattering is less. So, when the scattering is less, the lattice scattering mobility is high. When you go to higher temperature, it falls.

So you can see the combined effort of scattering from the ionized impurities because that scattering is electrostatic scattering charged ions, which deflects the electrons. This is actually due to the vibration of the atoms. The vibration depends upon temperature. The electrostatic scattering reduces the temperature because electron has got better velocity.

So, as to combined efforts give the mobility variation increasing initially governed by ionized impurity scattering, then falling decided by lattice scattering. Now, the total effective value is actually just like putting two resistors in parallel, 1 by R is equal to 1 by R_1 plus 1 by R_2 which equivalent of that. Let us not get into derivation of these but ________ is the effective mobility is governed by these two equations. Finally, this is the variation.

So, if you go to lower temperatures, there is a chance for you. Please remember, because we will be evoking this concept later. There is a chance for you to have higher mobility that is higher velocity for a given material provided there are no ions which are scattering. In other words, in the path in which the electrons are moving; there should not be ionized impurities.

So, you can separate out the ionized impurities and these electrons. Then, there is no ionized impurities scattering. That means, this term is not there, entire mobility was the temperature curve will be like this, totally like this. If that is the situation, you go down to lower temperature, mobility can be high. So, this is one concept, please remember. Later on, we will see when you go to high electron mobility transistor with gallium arsenide; those devices depend upon this property. In the sense, there is the ionized impurity and electrons are not in contact with each other. There are two regions which are created; We will separate them out. Till there are enough electrons, but the dopents supply those electrons are kept in some other region. They are isolated from each other. So that way, we can make use of this. That is what we want to discuss later on when I come to gallium arsenide devices. So some idea of the temperature dependence, the lattice scattering mobility is T to the power of minus 3 by 2 and ionized impurity scattering is T to the power of 3 by 2 and of course slight variations in that parameter here that is T to the power of plus n and you can call other one as T to the power of minus n.

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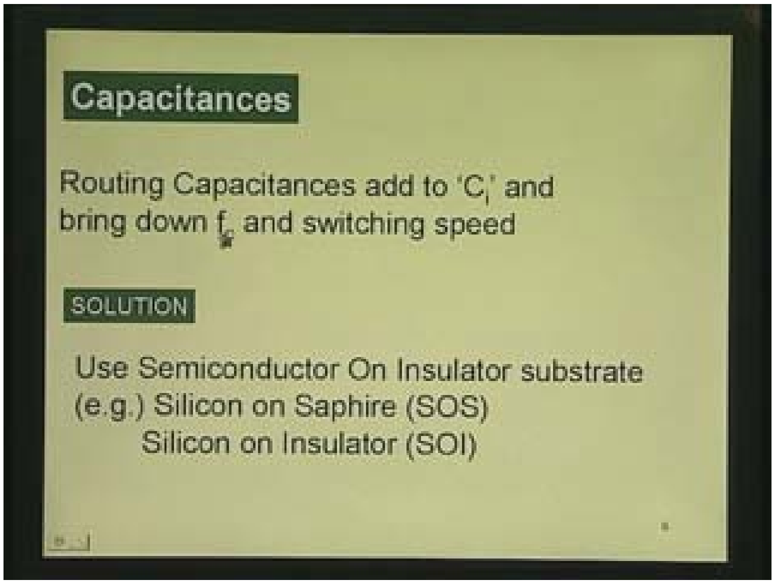

Capacitances

Routing Capacitances add to 'C_l' and bring down f_c and switching speed

SOLUTION

Use Semiconductor On Insulator substrate
(e.g.) Silicon on Saphire (SOS)
Silicon on Insulator (SOI)

The other thing that we have to be concerned is the mobility is not so much dependent on frequency. Because the frequencies that we talk of they did not vary. They are dependant on field and temperature. If we have to go to very high field, they will be changing. Otherwise, the frequency does not change that is the constant. In fact, even at high frequency they used that concept, constant mobility.

Thus, all those equations that one develops are based on the constant mobility with frequency. Now the capacitances, you never like the capacitance to be large at the input side from the point to increase the cutoff frequency and bring down the switching speed. In fact, when I say bring down it will improve the f_c routing capacitance. You must reduce the capacitance to improve the cutoff frequency. What I have written here is, the routing capacitance will add to the input capacitances and will bring down the frequency and also ________ the switching speed. That is what, I have written here. Now, solution for that is, the solution is reduced to stray capacitances. For example, when you have a silicon wafer on which you have a wire running, then there is a capacitance of these wires with the respect to substrate.

Now, usually that capacitance is large because it runs on a thin oxide on this semiconductor. So, all through the length, you have the capacitance like a transmission line, you have the capacitance coming up. Now, if I increase that insulating layer or if I use a substrate which is actually a silicon on insulator, we have a substrate which is totally insulating material and a silicon layer is there, then when you run the wire here, the capacitance of the wire with respect to the insulating substrate, a thick substrate that will be small because after all capacitance is forced proportional to area, but if the thickness is more, capacitance reduces.

So, thickness is more because that insulating layer present. That is why, the capacitance is small plus usually till the capacitance of this silicon layer if it is coming, you will have epsilon R which is 12. If it is insulating layer which is epsilon R is smaller like oxide, then the capacitance is automatically small.

So, what I am trying to point out is, we will have occasion to discuss more about this later. You can reduce this capacitance if you use an approach where semiconductors on insulator like silicon on saphire.

Saphire is an insulator, a thin layer of silicon which is used for making the MOSFET. Then, run the wire across on the top of the oxide and then the capacitance is small. I will leave _________ more of these later on when we discuss more of gallium arsenide with devices. The other thing is, instead of sapphire, just an insulating layer that is SiO_2 itself is okay. We will see when we go to gallium arsenide, you do not have to worry about sapphire or insulator. Materials like gallium arsenide themselves which can be very high resistivity materials, you call it as semi-insulating material.

Instead of insulating material, semi–insulating; insulator will have resistibility of about 10 to the power 13 and 10 to the power 14 ohms centimeter. Semi-insulating material will have about 10 to the power 10 and 10 to the power 9. It is much higher compared to a semiconductor.

So, those concepts, in fact I just giving the flavor today on this; more about this we will have occasion to discuss. So, the concept is not only increase the mobility if possible by going to lower temperatures or you may have to change the material and use also small channel lengths which will increase the velocities and also transconductance. The other thing is reduce the capacitances by reducing the stray capacitances, the capacitance of the routing capacitance with respect to substrate by using insulator substrate. Those are the concepts which are important to you.

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Requirements for High Speed Devices

Small Transit Times

Short channel lengths &

High carrier mobility and velocities

So that means to reiterate what we are telling, the requirements for high speed devices and small transit times, I have sent it more than once but put it black and white here or in color white and black, white and blue, short channel lengths and high carrier mobility and velocities.

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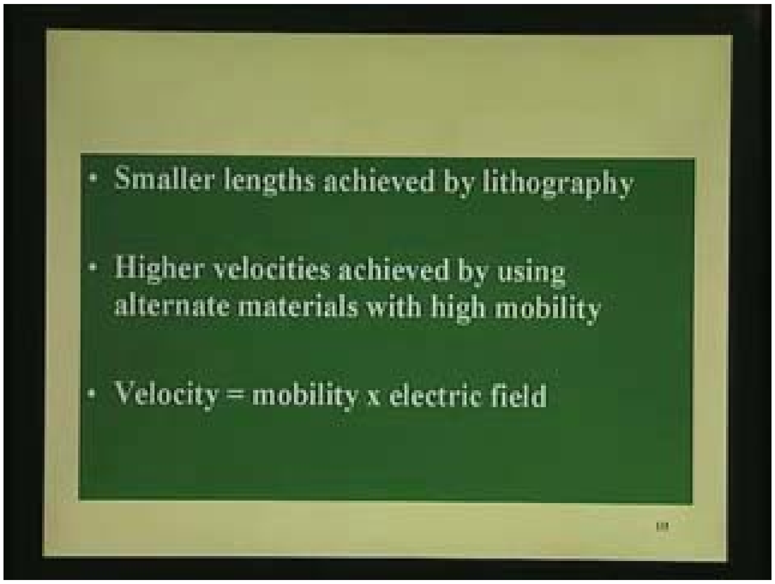

- Smaller lengths achieved by lithography
- Higher velocities achieved by using alternate materials with high mobility
- Velocity = mobility x electric field

Now, what we said is short channel lengths and other one is mobility. These are the two things, one have to remember throughout to get to higher speed. Short channel lengths, how to achieve? that is the _____. A short channel lengths are achieved by the lithography. After all, you keep the source and drain at certain distance. When you do that that gap which you decide is, for example,

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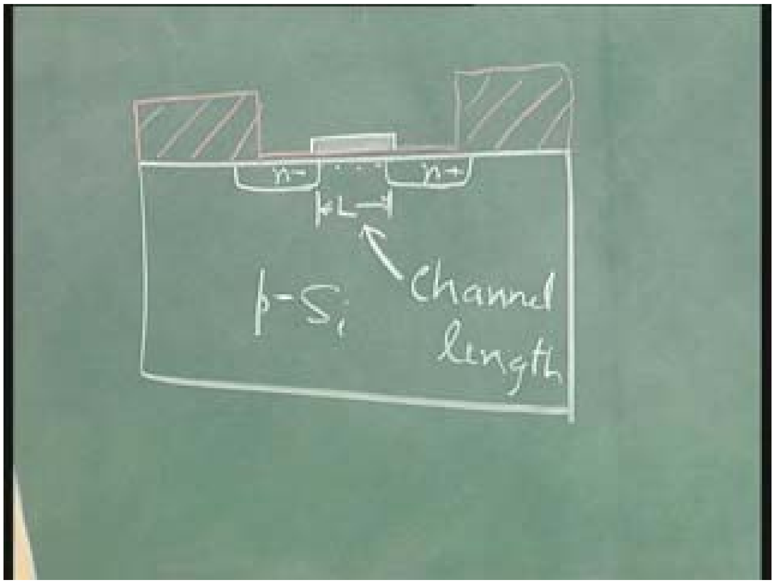

What we are talking of is, if I take the substrate silicon, for example, p-type silicon if I take and I have this oxide which defines the active region of the MOSFET and then you have this oxide which will form the gate oxide and then on the top of that you will have poly-silicon deposited or a metal-deposited for example and then you define this region, that is the channel length. This is the channel length, because once you do that, afterwards you can define your source and you can define your drain by introducing impurities through this. We can implant through this oxide. To take on tight, of course; you have to open the windows and all.

Now, what I am trying to point out is, this is that L that we are talking of right through that is the channel length. You want to keep that minimum and the electrons are actually will be transported through this layer, you want to keep the mobility high in that layer.

So, this channel length is decided by, we can make it smaller and smaller. What is the limit? Limit is how small length you can etch and that is decided by lithography.

The lithography decides this length, photolithography. So the ultimate limit is lithography. That is what people are talking of now. We can go down to 0.1 micron that is the technology today. If you have to get down 0.1 micron, it is very difficult in India. We do not have 0.1 micron technology today. What we have is, we can define channel lengths in semiconductor complex, I think about 0.8 microns. So, we are far lagging because when we go down to smaller and smaller channel length, small or better and better lithography, the technology is more and more complicated. It gets more and more costly. So, if you can handle this problem with longer channel lengths, still has a higher transit times; we are in business. So, I hope this part is clear. This is what we are trying to reduce which you decided by the gate length and which you decided by lithography. So, photolithography that is what I mean by saying smaller channels are achieved by lithography. Let us go back to that one.

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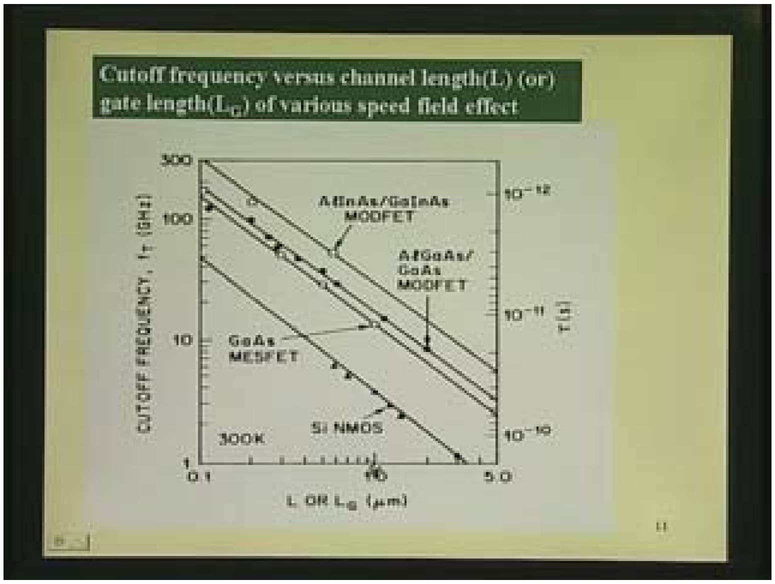

Cutoff frequency versus channel length(L) (or) gate length(L_G) of various speed field effect

This is actually a diagram which I deliberately put which shows the cutoff frequency which has been achieved, is points are the actually the measured cutoff frequency with silicon MOSFET. This is of course, the estimated cutoff frequency. You can see on the x axis, we have the channel length L and on the y axis we have the cut off frequency f_t or f_c what we are calling. So, we can see here, if I go from 0.1 micron, 1 micron; 5 micron mobility talk of these things except maybe in some academic institution where they want to try out some things even in our laboratory, we have 1 micron technology.

You can see for 1 micron, you can get about 2 to 3 gigahertz and we will go down to 0.1 micron with Intel is boosting off 10, 20, and 30 gigahertz used to have cutoff frequency. That is why we are able to make this Pentium and all with frequencies which are in few gigahertz range by reducing the channel length. So, in silicon, we get this entire curve by varying the channel length by lithography, totally controlled by the lithography.

Now, you can see if I have an alternate material. We will see how it is later on we will see, but we can see this particular diagram there, this graph. All these open circles, that one the cutoff frequencies are higher than silicon. For example, you can see what you get with 1 micron with these gallium arsenide based Field Effect Transistor that is here, that is something like 10 to 15 gigahertz range. Same thing if you want to achieve with silicon devices, we have to go down to smaller channel length at least about 0.3 microns. If you go, you can get what you can get with gallium arsenide from micron. What we are telling is why I am not telling now? I am just giving you the result in ahead. You change your material from silicon to a material like gallium arsenide and make Field Effect Transistor there you can get higher speeds with longer channel length.

What is the advantage? The advantage is the constraint that you are putting on here to achieve 0.1 micron technology is relaxed. You can go to 1 micron and 1 micron, a laboratory which does not have that extra facility can accommodate. That is what I am trying to point out here. You can go and have a longer channel length and get much higher cutoff frequency for the same channel length or a cutoff frequency which can achieve in much smaller channel length. To put it simply, the entire curve get shifted up. What is the reason?

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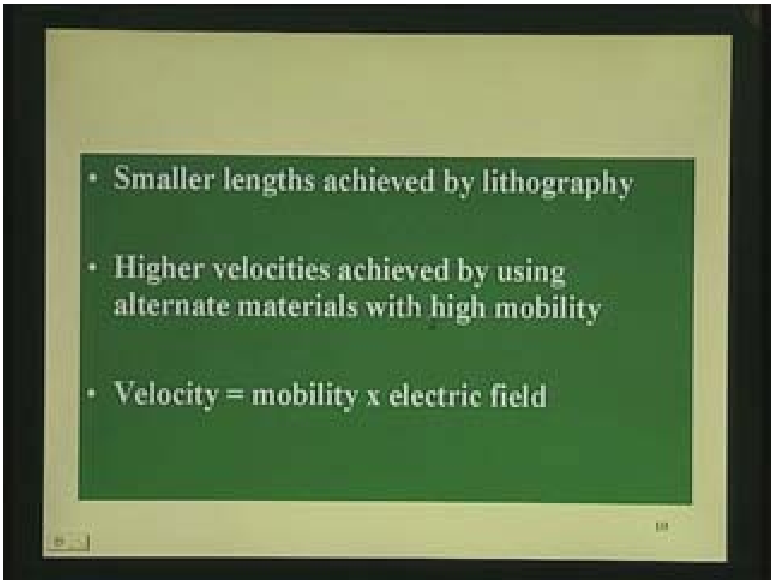

- Smaller lengths achieved by lithography
- Higher velocities achieved by using alternate materials with high mobility
- Velocity = mobility x electric field

The reason is the different material what we said just now is smaller lengths if we need, we can achieve by lithography. But, if you do not have the lithography here, you can go to higher velocities or even if you have the lithography, you can go to higher a velocity which is achieved by using alternate materials with high mobility. So, it is L by Mu ratio always. L should be reduced and Mu should be increased. So, if I keep same L to increase the mobility, I get higher frequencies. That is the idea. Now, velocity is of course mobility into electric field. So, I hope that is understood. Now, these are some of the curves we can see. Then we can see there are curves are keen keeping shifting up, silicon MOSFET and above that we have gallium arsenide MESFET. Then above that, we have got aluminum gallium arsenide MODFET and above that, you have got another material. We do not worry about these terminologies look like a big jargon. But notice one thing, this curve is even above this curve that is this based on gallium arsenide material where higher mobility is there. The next curve on the top is based on another device consisting of gallium arsenide and aluminum gallium arsenide. In fact this is where the trick is done. The trick that I was mentioning separates the electrons from the dopents. Electrons are confined to this gallium arsenide layer and the dopents are confined to the elements of the gallium arsenide layer, a ternary compound. What it is we will see later, but two different materials.

Electrons are confined to the high mobility region. So, the ionized impurity scattering is removed from the picture or reduced and here if we go to lower temperatures, you can get this curve up even further. Because, if you remember we plotted the temperature versus mobility like that and you have this curve here, this curve I am removing that that is the lattice scattering mobility by separating the donor from the electrons then the whole thing is like this. If, I go down to temperature, you can get you would not believe the mobilities of thousands, tens of thousands you can get from thousands or hundred thousands you can get, if you go to liquid nitrogen temperature. No doubt at that point you have to worry yourself.

In silicon, you cannot do that because in silicon when we go to lower temperature and if you separate those electrons from donors, you may have advantage, but still in silicon there is one problem. We will see that carriers get frozen; carriers are not available for conduction. Where do you talk of mobility if there are no electrons which are moving? They are frozen, you freeze them whereas if you go to materials like gallium arsenide you will see there is no freezing effect. So, carriers are available, you can separate them from donors, and you can go right up to this curve here to get better mobility. So, these are some of the benefit that you can get by switching over to some of the materials which has superior properties. So, this curve I deliberately put just to show you the improvements that you can get, you can see almost from 10, 20, 30, 40 gigahertz goes to 300 gigahertz that is by changing the material.

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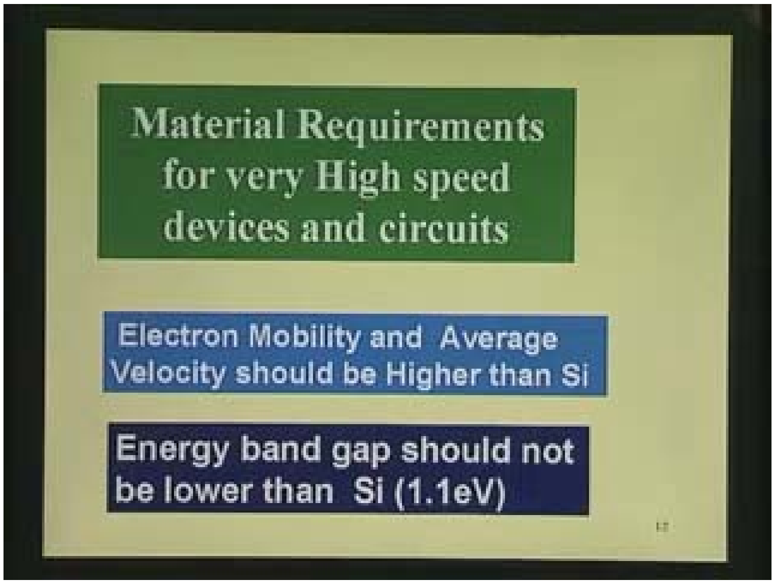

Material Requirements for very High speed devices and circuits

Electron Mobility and Average Velocity should be Higher than Si

Energy band gap should not be lower than Si (1.1eV)

So, ultimately then what we see is, now we see we have come from the circuits to the devices, then from devices we found now we have to go to new materials, different materials. This is the theme of high speed circuits. Finally, we have to go to better materials. So, material requirements for high speed devices and circuits. Requirement is very clear. Electron mobility and average velocity therefore should be higher than silicon. You cannot buy anything which has velocity or mobility lower than that of silicon. On the same count you cannot choose any material arbitrarily. You cannot go and say okay I have, for example; germanium has a better mobility than silicon. Silicon has electron mobility of 1500 centimeter square per volt second.

Germanium has almost double, 3000 but, you do not look at germanium, why? Band gap. The band gap is 0.72 which makes it leaky. It prevents you from operating at higher temperatures. You may ask why do we want to operate at higher temperatures? After all, we are using room temperature. The devices are at room temperature. Why do we worry about high temperature? The reason is just see that Pentium chip, how hot it becomes because of the so many hundreds of thousands of devices which are in the chip, the whole thing gets heated up, the power dissipation so much, several watts. So, the result is the temperature rises. So, if temperature rises, you do not want the devices loose their property, junctions should behave like junctions. So, you would like to have if we cannot tolerate germanium in those devices, silicon with fan and all that you are able to tolerate. So, you are looking at materials which have band gap definitely higher than that of silicon, higher mobility and higher.

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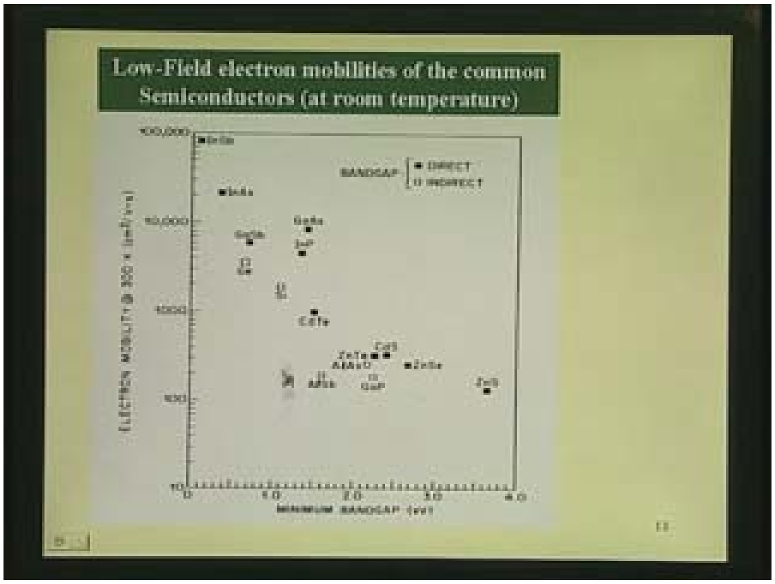

Low-Field electron mobilities of the common Semiconductors (at room temperature)

Now, you see, we have got the entire range of devices. On the y axis, we have the electron mobility at 300 degrees Kelvin. I hope it is a scanned one because I thought it is better to put that because it is something which is standard projected everywhere 100, 1000, 10000, and 100000 centimeter square per volt second. You will not believe unless you see this point there which we really put that you can have electron mobility at room temperature as much as about 80,000 centimeter square per volt per second.

So, you do not want to jump into that I will take this indium antimonite and make use of it for making my high speed devices. A high speed devices with that material if it has to work, what to you do? You must cool down drastically because at room temperature itself we will have plenty of electrons and junctions not work like a junction. It will look like a leaky diode.

You cannot choose those materials even though mobility is high. Please note here what I put here in this diagram. Electron mobility on the y-axis and on the x-axis the minimum band gap. Just now, you take it as a band gap.

A band gap will vary in certain directions. So we are taking the minimum value of the band gap. That is, if there is electron at the conduction band, what is the energy must lose to go to the valence band? That is the minimum energy. That is what is meant by conventionally you cannot just say energy band gap. That is, put here. For example, silicon you see, it is here, that is silicon, that is the arrow there showing you the silicon and you can see the band gap is about 1.1 electron volts and you can see the mobility is about 1500. You can see germanium band gap is 0.72 and mobility is about 3000, 3600 to be specific. So, any material which lies to the left of this curve is vertical this line to the left of that line, you cannot take because left of that, the band gap is small. You do not like to take a look at any one of these materials though the mobility is high.

So, it is interesting that it so turns out that all those low band gap materials have got very high mobility. But now, you saw micro-electrons. It may be useful for some other detectors etc.

Now, IR detectors are our example. Now, take a look what we want to see is materials which are to be the right side of that silicon, that is band gap higher than that of silicon. So, ultimately what so turns out is we are looking at devices or materials which are above this horizontal line and which are to the right side of this line and how many are you left with? Only two of them that are gallium arsenide with mobility which is about 8500 at room temperature and band gap 1.43 electron volts higher than frequency though we are very happy that band gap is high. So silicon we go to 150 centigrade, you can go to 200 degree centigrade instead or 250 degree centigrade. In other words, you cannot only use for high speed; you can use them also for use application in harsh environment. Harsh means high temperatures. There is one of the harsh environment and other harsh environments are radiation environments. So, we can use them.

Indium phosphate that has mobility slightly smaller than that of gallium arsenide about 4500 electron mobility, band gap is higher than that of silicon. So, to give the numbers, gallium arsenide band gap is 1.43 electrons holes; mobility is 8500 centimeter square per volt second. Indium phosphide, band gap is 1.35 electron volts and mobility is 4500 centimeter square per volt second that is at room temperature. Now, let us take a look at.

So we have chosen gallium arsenide and indium phosphide, it could be potential candidates for high speed devices. These are compound semiconductors.

For example, silicon and germanium are elemental only 1 element. Gallium arsenide has 2 elements: gallium and arsenide. Silicon is from the fourth group of the periodical table and gallium is from the third group and arsenic is from the fifth group. You have on either side of the fourth group, gallium and arsenic. When you allow them together, single crystal material, you will get gallium arsenide, so that is called gallium from third group and arsenic from fifth group. Sometimes, we call it as three - five compound, three-five, three third group and five fifth group.

Gallium arsenide is three-five compound semi conductor. What about indium phosphide? Indium phosphide is also three-five, indium from third group and phosphorus from the fifth group. So, we are looking at three-five compound semiconductors. What are these things? Indium antimony and indium arsenide etc., are all these are three-five. Though, they are all third group and fifth group and if you take a look at cadmium telluride that is also a compound semiconductor. It is not three-five. It is two-six compound. Cadmium belong to second group of the periodic table, tellurium belongs to sixth group, two-six Similarly, you have zinc telluride and zinc sulphide etc., belonging to two-six compound.

So, now we have said three elemental in the fourth group, silicon germanium, three-five: gallium arsenide, indium phosphide, gallium antimony, indium arsenide, and indium phosphide all those three-five. Two-six: zinc sulphide, cadmium telluride, and cadmium sulphide are all these two-six. So, we open see it opens up the entire galaxy of materials by mixing two elements from second group, sixth group, third group, and fifth group. You have left out one thing what about mix two from same elements and same group. For example, you can take silicon and carbon, silicon carbide. That is what, both from fourth group, we call four- four compound. Silicon germanium, we hear so much about silicon germanium. Both are fourth group. It is an alloy. It is a compound semiconductor.

So, when you say compound semiconductor, we must remember we are saying words like a mantra it contains so much, just like saying Om. It contains so much rich information, when you say things like compound semiconductor and when you say compound semiconductor, we also talk of these are only binaries, two elements. We can mix three, four we can see. It is a wide open domain. We will see more about that subsequently.

So, you have much more flexibility. Now, we have said about electron mobility. I had been silent about hole mobility. I had been silent, because it does not look attractive. We can see here, silicon. Silicon, for example is there. Hole mobility is about 400-450, hole mobility for silicon is that, but if you see gallium arsenide, it is lower or almost the same. Indium phosphide is even lower. So, you see, you jumped up with joy when you saw the gallium arsenide having electron mobility much higher than that of silicon, but you look up the hole mobility it is way down.

So do you throw these materials out? You do not. You make devices which depend only on electron. You do not make devices which depend upon the whole transport. So, avoid making devices which depend upon the transport of charges involving holes. Make devices, which involve for the transport of electrons. So, that means we are in business. That is why, I just put this diagram to tell you that, do not think of making CMOS with gallium arsenide. Because, you can have n channel devices, no p channel devices.

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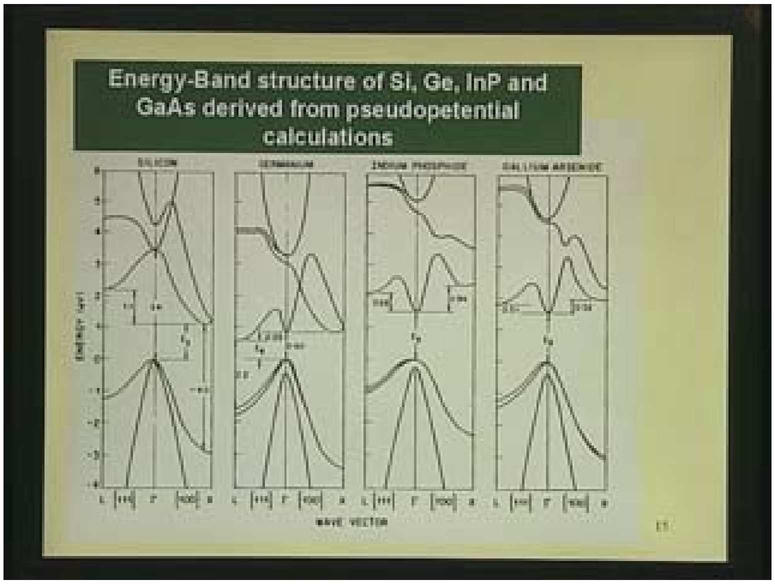

Energy-Band structure of Si, Ge, InP and GaAs derived from pseudopetential calculations

This is just a diagram which looks bit complicated. If you go back to these curves, you will see all these, some of these are put with the filled squares. Squares, which are dark and some others are made silicon, germanium, aluminum antimonite, and gallium phosphide etc., are made with open squares. This is a specific thing about the material.

They are termed as direct band gap materials. Wherever I have put the black or this filled square, they are called as direct band gap materials. The materials which are open here that is the materials which have just a square without filling it in, they are called indirect band gap materials.

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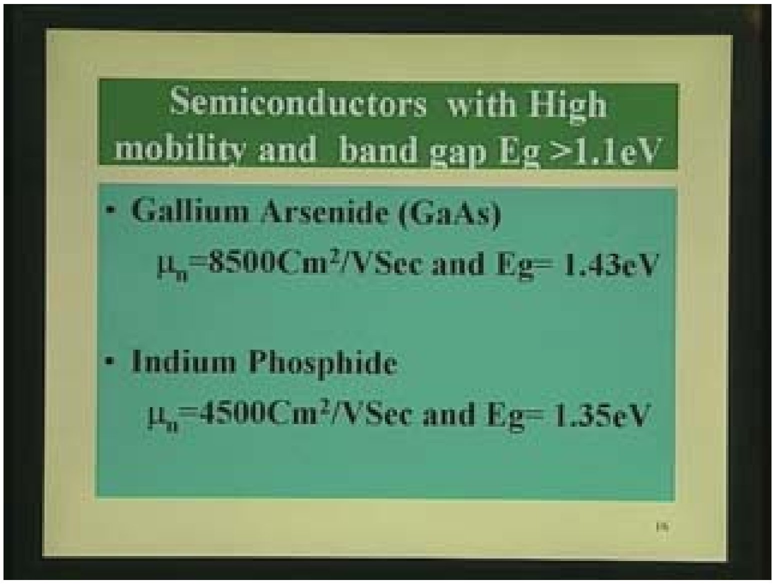

Semiconductors with High mobility and band gap $E_g > 1.1eV$

- Gallium Arsenide (GaAs)
  $\mu_n = 8500 Cm^2/VSec$ and $E_g = 1.43eV$
- Indium Phosphide
  $\mu_n = 4500 Cm^2/VSec$ and $E_g = 1.35eV$

So the difference is, to show the difference, I have put it here. Before I go into that, I will just show this, this I orally said all the mobilities of gallium arsenide, band gap, indium phosphide, and electron mobility etc. I already told you. Let us go back to this now. To see what is the meaning of direct band gap and what is the meaning of indirect band gap?

This looks horrify this diagram, but do not worry about that. All that you have to take a look at is for example, if I take this material here let us see. Let us take a look at gallium arsenide. The gallium arsenide, these are the energy versus momentum graph for different states of electrons. So the energy versus momentum graph in the valence band, that valence band means you understand and conduction band you understand. Within the valence band, how the energy versus momentum varies, that is the bottom curve here.

The energy of the electron varies like this. Do not worry about the other lines. Because, those are the holes usually the valence band occupy the highest energy position. The electrons in the conduction band occupy lowest energy position. So, this is the way the energy versus momentum will vary in the conduction band and the lowest energy position is this. So, normally, when you plot the energy versus energy band diagram, you plot it like this.

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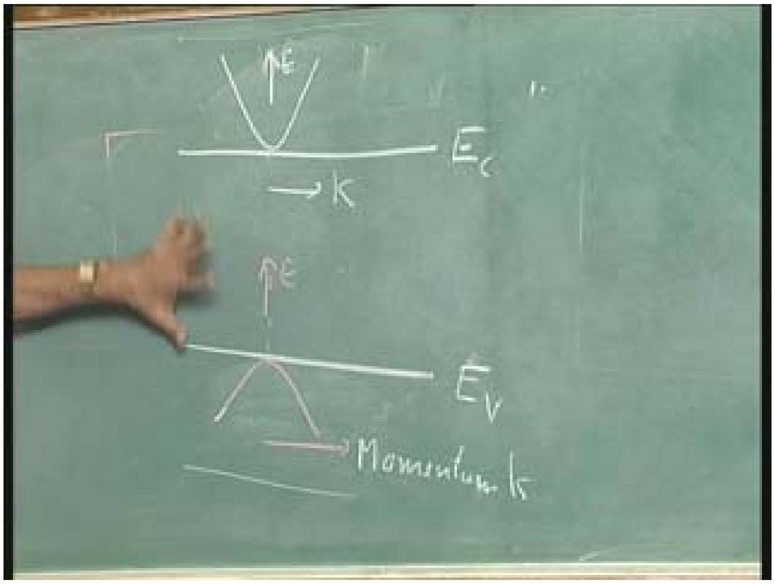

Conduction band and valence band; you plot it like that and this is of course, the conduction band here and the valence band here. What is plotted there? From here to here is in this region and what is plotted here? Below is in that region. We do not have to worry on 101 lines. In fact, I need not even have shown that. I can just say in the case of gallium arsenide that curves; the energy versus momentum.

I have shown only one curve. What is important is where the tip is. In fact, the holes will tend to occupy this position top of the valence band. So, the tip of that you plot as the valence band top. So, this is the curve that I plotted, this portion only. That is what matters and in the conduction band, this is the portion. So that portion is like this. Exactly above that like that, that is the energy versus momentum or K. So, what we are telling is this is actually a simplified representation of the energy band diagram. This is what is within the energy band diagram. Electrons will be occupying this position or this position like that. But, generally they will not be here and generally the holes will be here. Any transition here will be from here to here. Losing that energy it can just moved on to valence band.

So, a direct transition is possible. That is why in cases where the minimum of the conduction band here. If directly above the maximum of the valence band such materials are called the direct band gap materials and any transition of electrons from here to here, just will be accompanied by emission of light because it is only the energy conservation that has to be taken into account. These are used for photonic applications, direct band gap materials. For microelectronics application, it does not really matter, whether it is a direct band gap or indirect band gap. Those who talk of photonics, they will say I am interested in direct band gap materials whereas if you take, see indium phosphide for example, minimum there and maximum here.

So, this also have same value. So, the gap from here to here, what is that? That is the $E_{g.}$ Similar diagram for indium phosphide, only difference is smaller. For gallium arsenide this 1.43 electron volts. For indium phosphide that is E_g is 1.35 electron volts, so that is the situation here. Now, you take a look at silicon. This diagram, see this diagram comes like this from that edge, this goes up like this.

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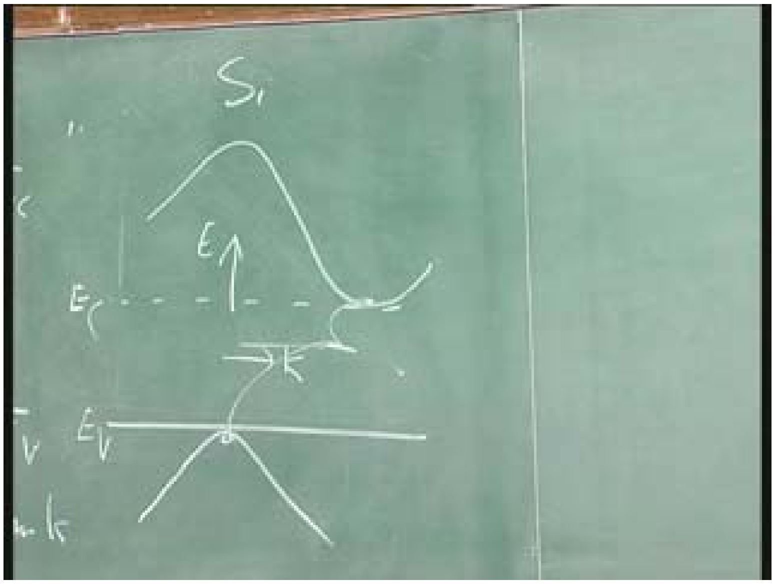

So for, silicon the diagram is; silicon and germanium for example. If you can see that it goes up like this in the conduction band. This is the conduction band minimum, because the electrons will go and occupy the lowest position in the energy so that is the conduction band minimum and if you take the valence band, you can see that, that is E_C. If you take the valence band minimum E_V the variation is something like this. We are not bothered about other regions, do not worry about other lines, only one line. This is the highest position for where the holes are occupying and this is the lowest position where electrons will be occupying and this is the energy and this is the momentum. Notice the electron here, if it has to make a transition from the conduction band edge to the valence band edge.

It will have to have satisfied energy conservation and you should look for a particle which will observe the energy, it should also look for a particle which will observe that difference in the momentum that makes the transition difficult. As a result, the transitions directly from here to here do not take place. They will takes place in two steps, that is they will move down to one level here like this then like that and in this one level they will just change their momentum and then make a transition. So, this is like a half-step jump. Instead of one high jump here, this is a half step jump.

So here, suppose an example, here the result is the transition is not taking place directly from here to here. The transition is taking place indirectly through another intermediate level. That is why it is called as indirect band gap semiconductor.

So, you have got direct band gap and indirect band gap materials. Direct band gap is gallium arsenide and indium phosphide; indirect band gap is silicon and germanium. So, you have got two varieties, that is what I depicted there when we showed it. We do not get into the physics of how it happens direct or indirect band gap, if so turns out that.

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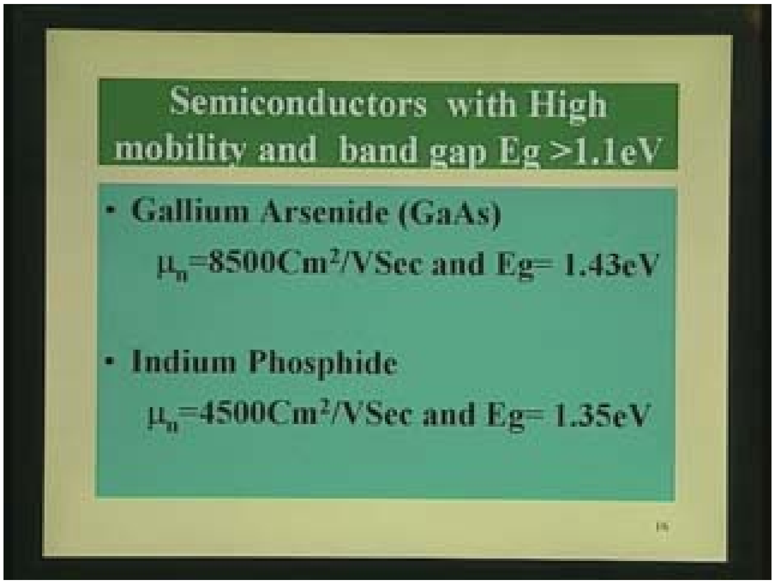

Semiconductors with High mobility and band gap Eg >1.1eV

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So, I will actually ultimately what we are telling is you can use gallium arsenide for applications in microelectronics because of this property high mobility which is actually higher than that of silicon and band gap which is higher than that of silicon. Similarly, indium phosphide which has got higher electron mobility three times that of silicon and also higher band gap. All these things make it very useful and very attractive for high speed devices. In fact, they are being made in India, Hyderabad, Getech Company makes as I said earlier NMICS, one of basic micro-integrated circuits with gigahertz frequency ranges; they are making that. So, it is not a myth; it is a reality, the high speed devices. This is mainly for different applications. So, with that I stop the today’s lecture. We will discuss next time further about these things.