High Speed Devices and Circuits

Prof. K. N. Bhat
Department of Electrical Engineering
Indian Institute of Technology, Madras

High Electron Mobility Transistor (HEMT)

Lecture - 33

We will discuss and continue to discuss about the high electron mobility transistor.

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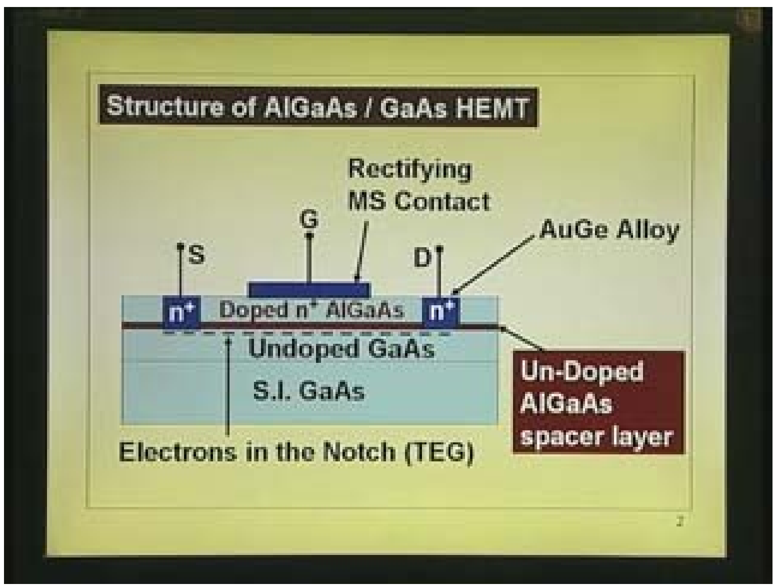

Structure of the device as I pointed out in the previous lecture is semi-insulating substrate, un-doped gallium arsenide, notice that there is another color layer added there which is un-doped aluminum gallium arsenide and then heavily doped [n] spacer layer.

I just pointed out last lecture itself that this layer here is introduced - a thin layer of 20 to 50 angstroms - depending up on applications. Mostly it is about 20, you want 20 angstroms where you want high trans-conductance - we will see that later - but that is a thin layer to ensure that the electrons here - the dashed lines showing the electrons - those electrons do not see the effect of these dopants. There is a layer un-doped which does not have the impurities. So to prevent the scattering, columbic scattering, electrostatic scattering by these dopants here, an un-doped layer is put on AlGaAs, but still the notch is at this point. The notch is at the point at which there is a change from AlGaAs to GaAs.

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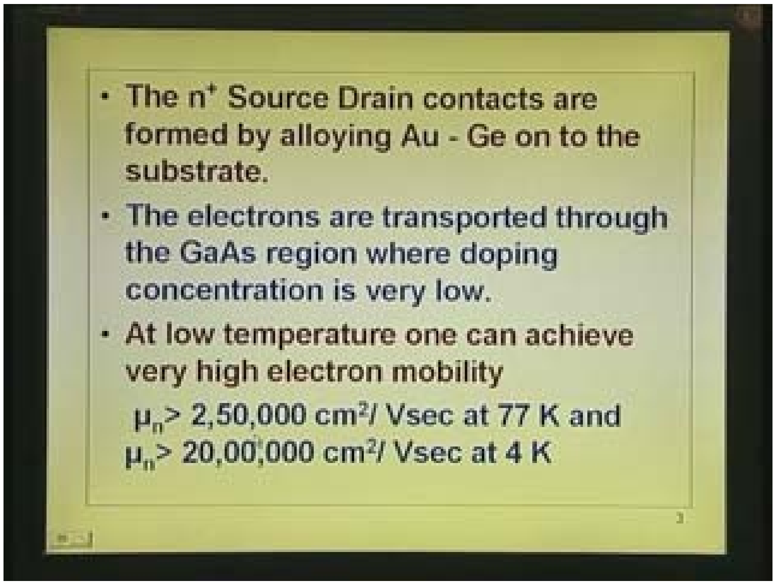

Also, you can see what you will have here is n plus source drain contacts are formed by alloying aluminum germanium on the substrate. The electrons are transported through the gallium arsenide region where doping concentration is very low; these are summing up what we discussed last time. At low temperature, one can achieve very high electron mobility because ionized impurity scattering is rock bottom and mobility is well in excess of this – I just put excess of that, because, these numbers keep on updating every year, even 10 to the power 6, people have reported at very low temperatures; so very high mobility, at low temperature. At room temperature of course, the limitation is only that is scattered; about 8500, that will be the thing you will get in the net in the gallium arsenide which is un-doped.

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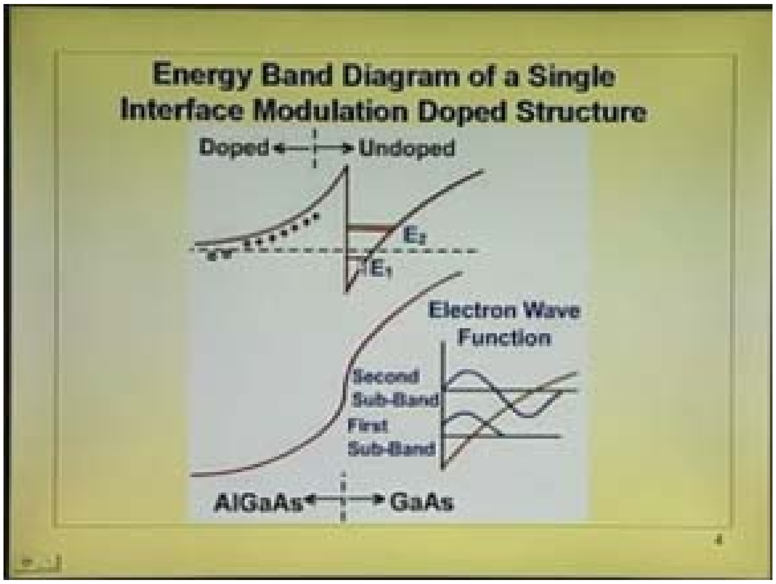

Now what we said also yesterday or in the previous lecture was the energy band diagram, the conduction band why we apply, this is the doped aluminum gallium arsenide layer here and this is the thin un-doped aluminum gallium arsenide layer, then the notch, then this is the well or the notch in which electrons are confined.

What we are trying to point out is that these electrons are not just dumped there, they are actually having quantum states with are actually satisfied; we will rather just quickly go through that today.

If this were a quantum well instead of a shape like this, if it is infinite quantum well, a flat bottom there, then what would be the distribution that is what we are seeing.

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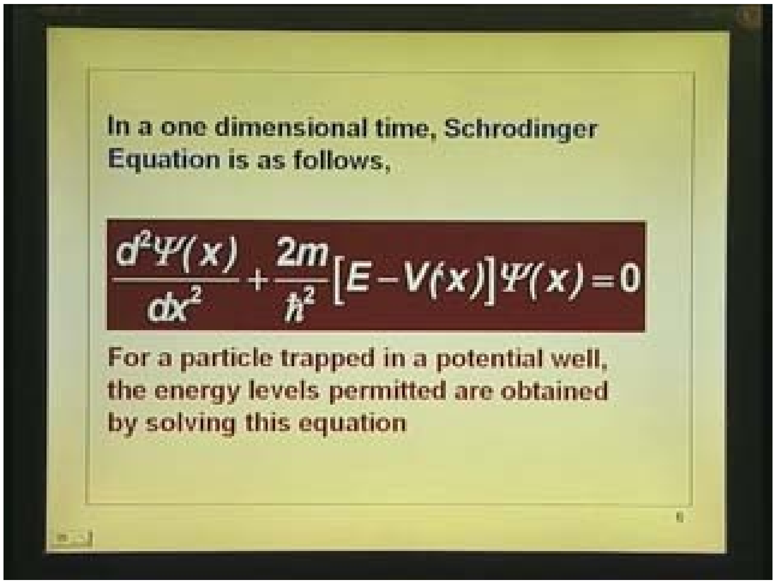

The solution or the equation that governs the state and energy of these electrons is the Schrödinger's equation in general wherever the energy and potential take these values. For a particle trapped in a potential well, the energy levels permitted are obtained by solving this equation. Whenever you want to solve an equation, proper boundary conditions.

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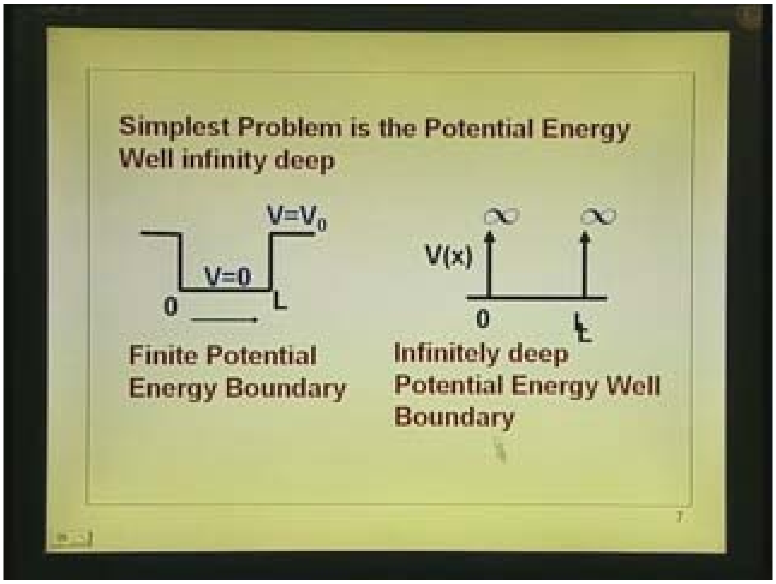

In practice, it is a finite well with a potential at the boundary which is about depth is V_0. The potential is $V=V_0$ here and V=0 here. A simpler solution which gives a good idea about what happens is obtained by an infinitely deep potential energy well boundary. It is not infinitely deep; [please note that] this depth is from here right up to the front it goes, it is not a [partical] situation, but if it is high enough, so high for the electrons it cannot move across the boundary through that. In a finite boundary, it is like this.

In a classical particle, if a particle is here in the potential well, there is no chance to cross this barrier; a classical particle will be same, it will remain all through its life here, whereas unless it gets extra energy to go through there. Whereas, in a quantum mechanical concept, the difference is that these particles which also look like waves and behave like waves, also have some probability that they can be found here; probability that they are finite. If it is infinite, of course, there is no probability that the wave functions can overlap into this. When you say the wave functions overlap into this portion, outside this well is the terrific chance that some of the electrons may be there. There are hundreds of thousands of electrons, few of them may be there; that is a chance; that is the probability; that is the implication; that is the difference between classical particle and quantum mechanical particle.

Now, quickly run through the solution that we were discussing last time. In the region where this is potential V=0, we substitute V=0 in the Schrödinger equation, you get that equation.

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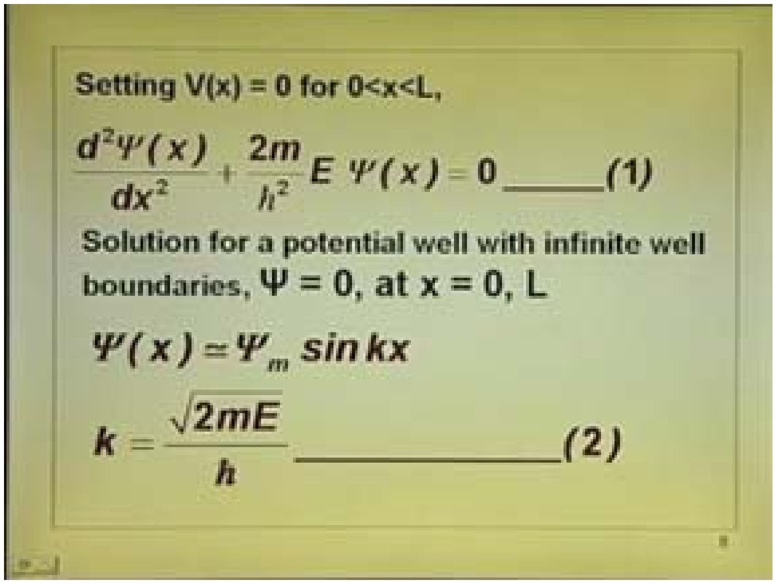

d squared psi x by dx square plus 2m by h squared E into psi of x, where psi psi star or psi square is the probability of occupation in a small volume. You cannot say probability of occupation at a particular point, it has to be a region; if it is one-dimensional it is delta x; if it is three-dimensional delta V; so that is the probability.

Psi star square into delta V is the probability that volume psi square into dx dy dz integrate over the entire volume probability is 1. The chance that you will find it somewhere here in this well that will be 1. So that is the equation which governs some of these things. Now you can see that instead of E minus E_i we have put E there because that is the equation within the value. You have to solve the Schrödinger equation within the well, the boundary condition psi is equal to 0 at x equal to 0; psi equal to 0 here, because the boundary is high, what you are telling is beyond that point probability of occupation is 0.

Similarly, beyond this thing, we write that, just looks like double l but one l there, beyond this point the probability of occupation is 0. The finding is 0 that is psi is 0; so you solve the equation with those boundary conditions; psi 0 at x equal to 0 and l. Now this is a second order differential equation; so solution will have sine k x and cos k x terms, where k is actually 2m by h square; d square psi by dx square plus k squared into E. So k is root of that. So solution will have sine kx and cosk of x. Cosine function cannot exist because, at x equal to 0 cos function is not 0; as x equal to 0 you write the solution though there is a sine kx and cos kx terms we write only this. The maximum value is sine k of x.

Now here k is that root of that quantity 2mE by x squared; E also is part of k. 2mE by h square root of that is 2m E by h bar. There is no pi here, but that is the quantity. Now, other thing that you have to say is at x equal to l also these terms should go to 0. So at x equal to l psi of x will be 0. If k into l is equal to n into pi, n varying from 1, 2, 3; n are the eigen values, integer numbers, which take 1, 2, 3, 4, 5.

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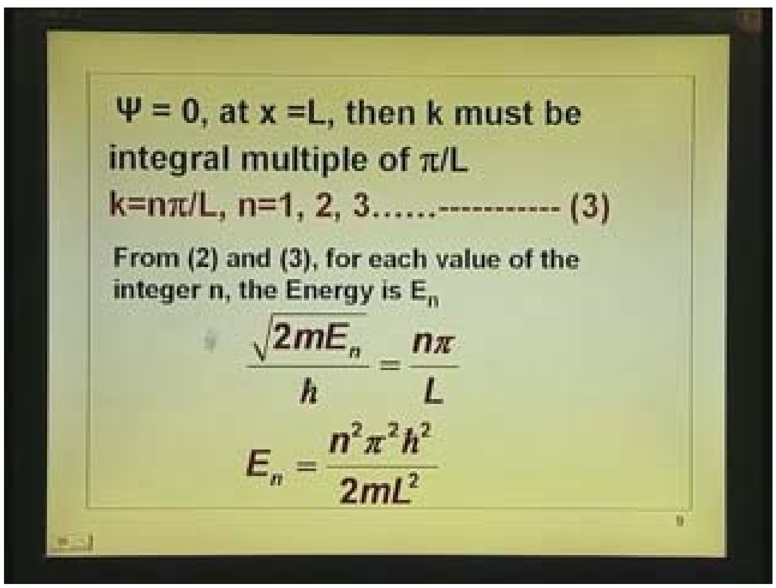

Now, with that condition, psi equal to 0 at x equal to L, then k is equal to n pi by L; where n takes 1, 2, 3 values. Now, K is equal to that quantity; k is that quantity and k also should be n pi by l. From here, you know that n takes values 1, 2, 3. If the potential well is infinitely high, you will have infinite number of energy levels; so corresponding to each n you have got one energy level.

That means actually this where you say the energy is quantized. You have got certain permitted energy levels with the permitted psi that is the wave function, we can call again psi_1, psi_2, psi_3 or phi_1, phi_2, and phi_3 corresponding to E_1, E_2, E_3.

E_1 is pi squared h square divided by 2 m l square. Now you notice how much is this quantity depends upon that l and the spacing between the two levels depends upon l. n is equal to 2, it is 4 times that E_1, but as l is made double, the width of the quantum well becomes longer, wider, the energy becomes smaller. The gap between them becomes smaller. If there is no quantum well, the huge region energy level is continuous. So that is why the conduction band where no quantum well, the energy level is continuous. L is actually tending to infinite, the energy difference remains infinite.

Continuous permitted energy levels are there, but the moment you have like in the case of a hetero junction, you have a potential varying like that you have got a finite L. In the case that we are discussing, the L is actually the notch width, but the notch is not actually flat but is actually moving like that. We cannot say what exactly L is; it is somewhere 50 to 80 angstroms, very small value. So this is the understanding that we have.

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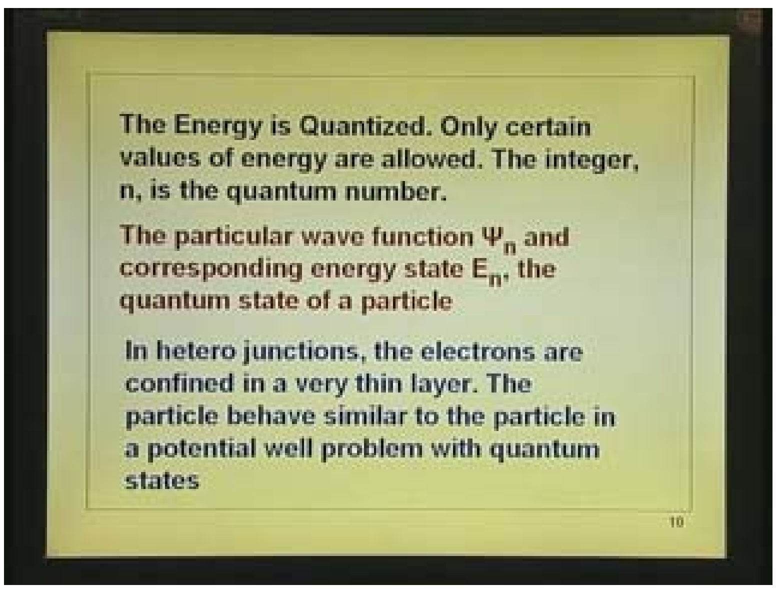

Energy is quantized; only certain values of energy are allowed E_1, E_2, E_3, E_4. The integer n is quantum number. The particular wave function psi_n, corresponding to E_n - they define the quantum state of the particle. We can say quantum state psi and E are the ones. These are of course the terminologies that are used for understanding finally is… there are… you do not permit all the energy levels in a quantum well; there are only certain levels for one electron that is considered. If there are number of electrons, they will tend to go into that particular E_1. That E_1 will spread into a sub band; similarly, E_2 will spread into sub band. So instead of having continuous energy levels you will have sub bands which are seen.

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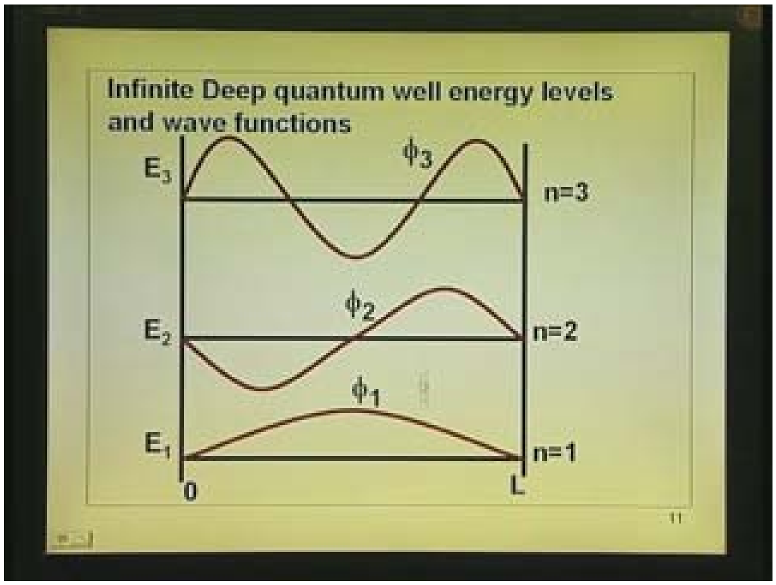

Now this is what ever we have said in the equation, see the psi_1, or phi_1, I just called phi_1 instead of phi for wave function phi_1 is a particular N=1, even at at n=1 corresponding to that the wave function is like this: psi equals 0, psi is equal 0; corresponding to n is equal to 2, we have got full sine wave function. That is the wave function 3 it is like that.

In all cases, the wave function is 0 here, 0 here at the edges and you can see the spacing here keep on increasing. If it is an infinite potential well, infinite number of levels will be there and 0 chance for this wave function to come. What is the case if there were a finite well? I am not going to solve that. It will take another one hour to solve that. In fact, you solve within the well in the same way. You solve also outside the well. In a finite well, there is chance that, there is a probability that you can find these electrons on the other side. So these wave functions will follow same, except this will not become 0. In fact, what will happen if we solve that… what you have to do is write down the equations for this region with the same 2m E by x squared as k squared. Here you write the equation k squared is equal to E m minus V_0, where V_0 is the height divided by h bar squared. Solve the equation and there should be a continuity of wave function from here to here. We are now taking that there is a chance for the electron wave function to overlap into that portion; that there is a probability that you can move into that region. So when you do that, psi continuity you get psi here, psi here, psi must be continuous there, [E square x] must also be continuous; then what happens is like this.

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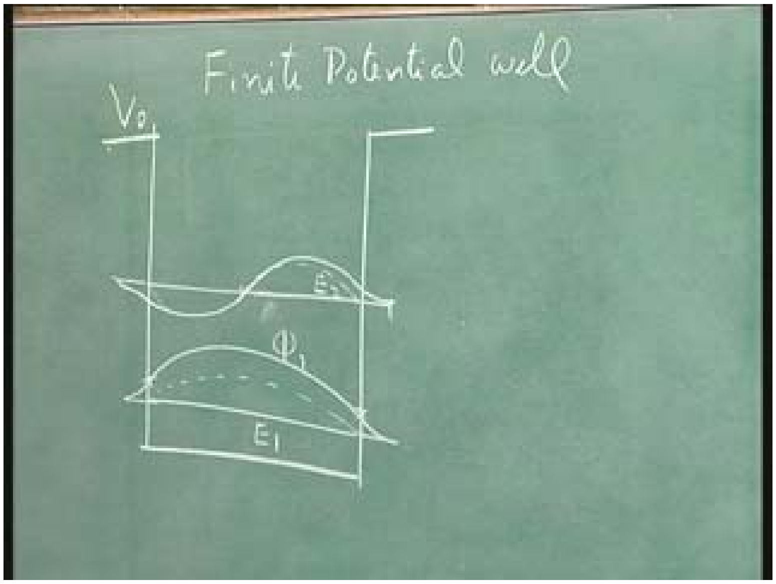

Just the purpose I am putting that, you have a finite potential V_0 - finite potential value. Generally, you can skip this, but I thought I will show this to you how it is, because, we will see that when you see all the diagrams about the HEMT, we will see those diagrams.

This is the E_1, the energy level corresponding to E_1. If it is infinite, you plot it like that psi_1 or phi_1. (Refer Slide Time: 15:28 min). If it is finite, then the probability will not go down to 0, it will go something like this; there will be some probability. The wave function psi_1 or phi_1 - what ever you want to call it, I call it phi_1 to distinguish it from the channel wave function - it will go into that region.

The classical particle will never… do not think of a classical particle being here; once it is in the well it is in the well. Higher energy you have - E_2; for E_2 what you have seen there is it is like this (Refer Slide Time: 16:17 min). That is for infinite; finite you will have the probability [ ] here and the whole thing will come something like this; again, a probability comes. Only the difference between this and this is, this extended region will be more than this region, as you go to higher and higher energy, more and more overlapping will be there; understandable. If the electron is here, sounds like it is on the other side climbing up that barrier, going up there is better; so E_2 will have extend over a longer path, longer x direction. So you have still one more, will be even more; it will go up there. That, of course, you can understand a particle which is jumping up on the wave, on the potential well, if it is at higher energy then from there it can easily go to another side; that is the meaning of that.

These look like abstract equations, but they have the meaning, in the sense, that if it has enough energy it can go up. How much is up into this layer depends upon this height compared to the energy. If the energy is up, third level very easily it can go to the other level, that is spread into that region more and if it is 0, of course, it is everywhere. So this is the general concept.

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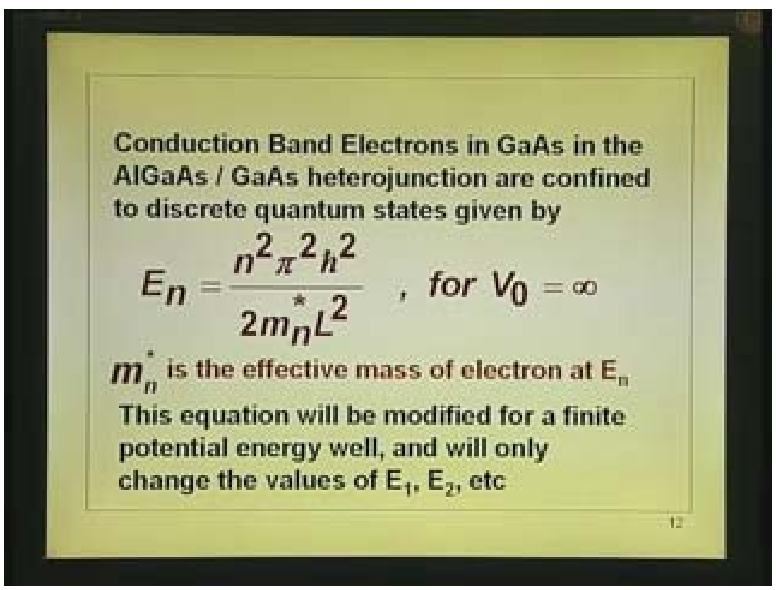

Now you can see, when you go into a finite well, you get that particular thing and you have to solve the equation with this (Refer Slide Time: 18:20 min). The equation that we wrote previously for energy n_1, 2, 3 and V_0 is infinity, then m_n star; you want to talk of gallium arsenide, you replace that m by m_n star plus the equation must be modified for a finite well, that is what I just now.

What you get will be the one that is valid for effective mass and V_0 actually has to be changed to finite V_0.

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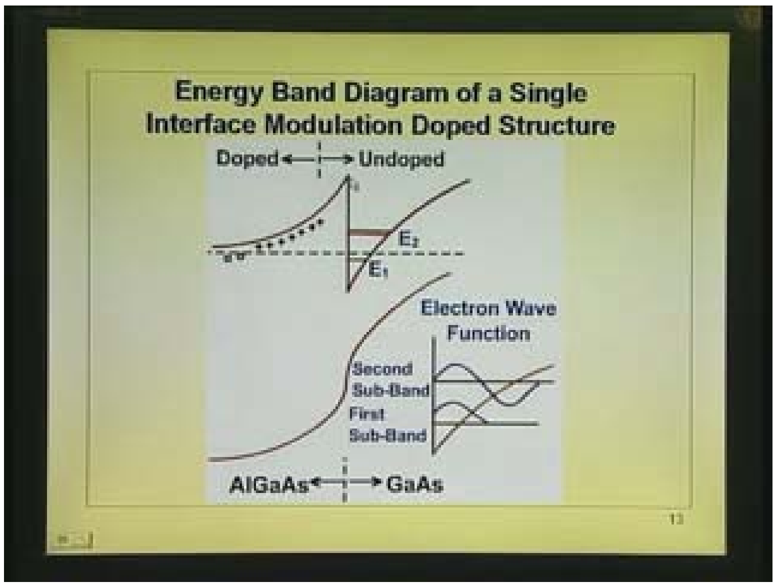

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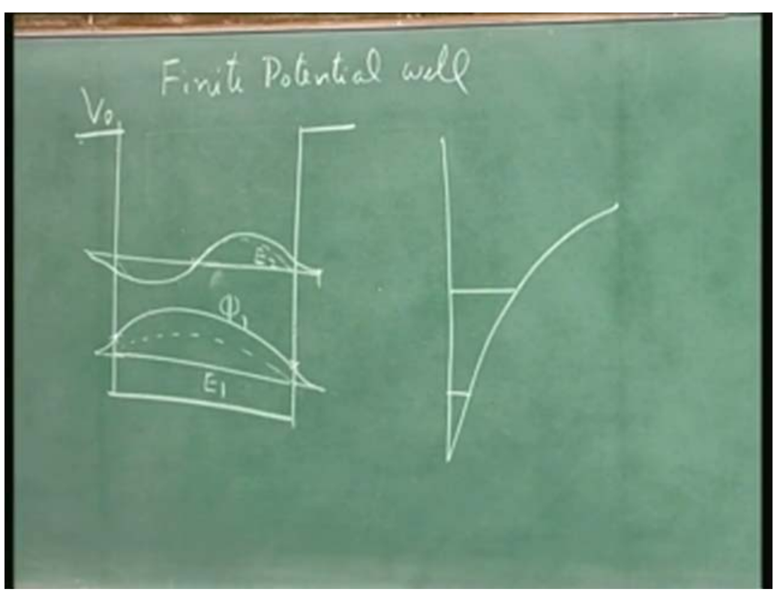

We come back to that diagram what we have been drawing. Now you can see instead of being like this, the whole thing is something like that (Refer Slide Time: 19:07 min). You have a potential well which is something like that.

You will have a level here you will have a level here and you can see also that is E_1 and E_2 and the solution is of course much more complicated. I am not attempting that here at all.

What I want you to notice is, because now it is a finite well on this side it is psi, on this side it is like that, you can see the wave function is not 0 there; that means what you are telling is these electrons which are present in the notch have a chance to be here? (Refer Slide Time: 19:46 min). If it has a chance to be here, if the dopants are here, there is a chance for them to be scattered. That is why to prevent that chance of getting scattered by dopants you put this un-doped layer here. That un-doped layer is because of that.

If the classical particle you would never had thought that I should have un-doped layer; after all, the doped layer is here, the electron is here. But now there is a probability that it is here and if that is now here, furthermore chance it can spread into that layer also and not only go up there, but it goes also into this side. You can see the dotted line right into this region that there is some variation there.

What we are now telling is most of these electrons will be occupied in this level; most of them will be confined with this layer because, higher it goes up, it can go up into that layer or spread out. As you keep on increasing electron concentration will go into this sub level here, which is not one level, it is a band there. Now when you talk of number of electrons it is not one level, it is a band; instead of having conduction band continuous energy here, you have sub bands. The second sub band, first sub band. So these terminologies in order to explain some of these things I went through analysis; understanding of that, because otherwise it leaves at least it [was vague] when I saw these diagrams initially; usually we think of a conduction band as a continuous level, but why it is like that? It is a quantum well. That is why energy levels are not continuous. Most of the electrons occupy the level E_1.

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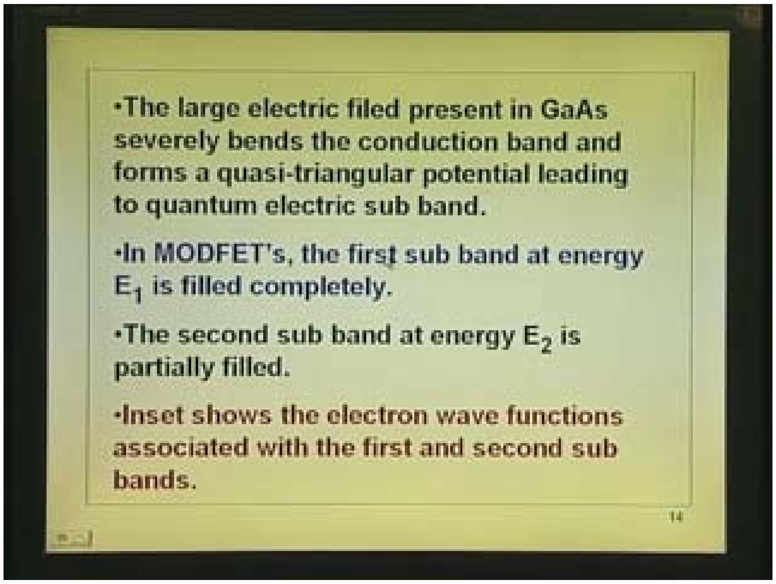

Large electric field present in the gallium arsenide are again summing up what ever we said, present in gallium arsenide severely bends the conduction band and forms a quasi triangular potential leading to quantum sub bands. The large electric field potential there and leads to this triangular quantum well, it leads to the sub bands; that is what it will say there.

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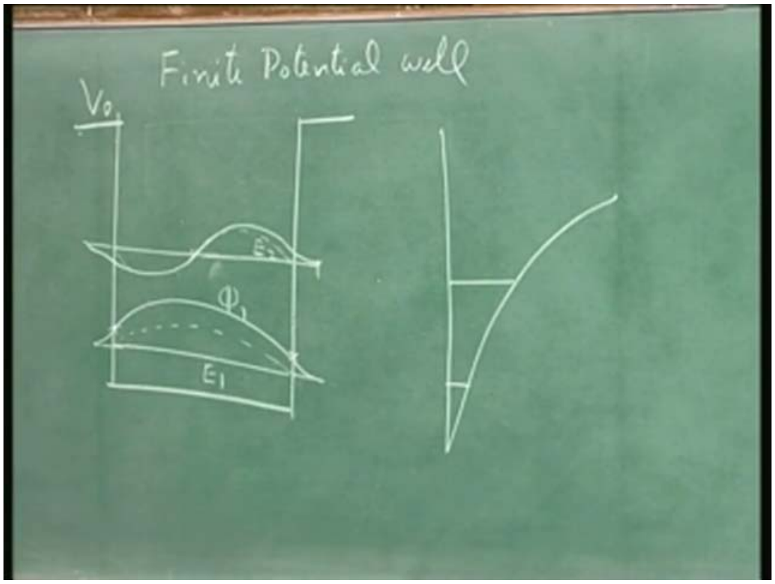

In a MODFET, the first sub well will be filled first; most of these will be filled; it is almost completely filled; this is partially filled. The mobility everything will be decided by this band mostly (Refer Slide Time: 22:17 min). There will be difference of mobility in this sub band and this sub band; you know as you go to higher and higher energy the mobility keeps on falling down into the higher energy band levels. Mobility of electrons here is better compared to mobility here (Refer Slide Time: 22:32 min). From this point of view, you would not like to dump electrons into this sub band. Many of the electrons which are resting here the average mobility will fall down; this we have seen earlier in the increased concentration or energy, if we increase the energy, the mobility are reduced, like scatterings of one level to other level; it is easy to understand that way.

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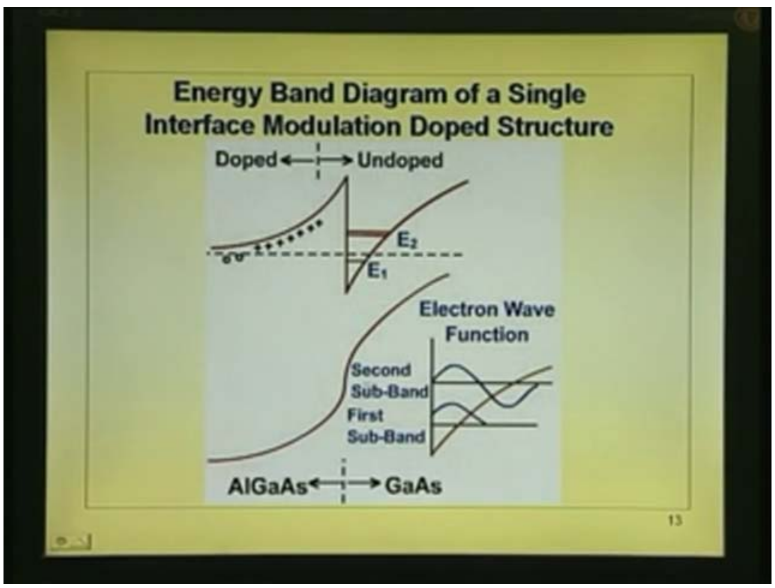

The second sub level band at energy E_2 is partially filled. The inset shows the wave function here. In fact, I was not able to provide a figure caption for this so I have given it in the next page.

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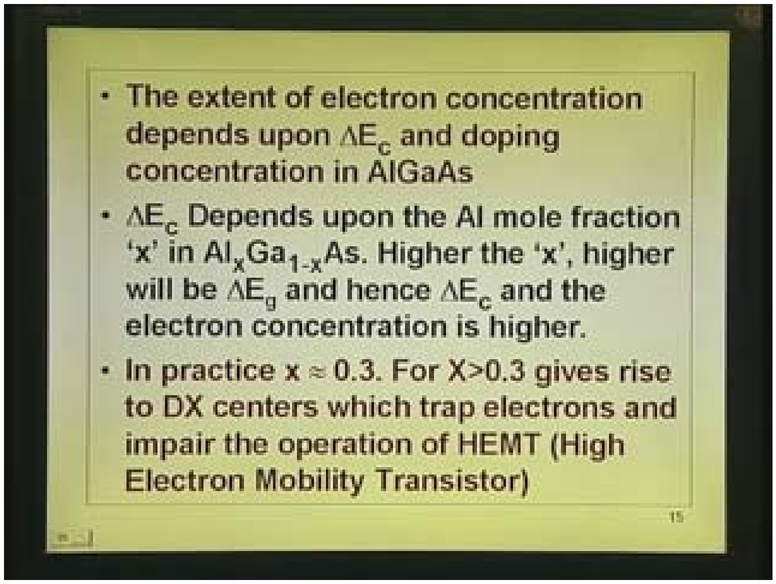

The extent of electron concentration depends on delta E_c and doping concentration in AlGaAs. The electron concentration here depends up on how much band bending is there. The band bending depends on the doping ratios. In the homo junction $N_D N_A$ divided by N_I squared logarithm of that into [V_T]. That is what we say dependence on the doping here, in this level. Here it is un-doped, so higher the doping more will be the band bending plus delta E_c.

We saw that the total band bending here (Refer Slide Time: 24:05 min) or total potential drop is equal to V_{BA} what you get for homo junction plus delta E_c by Q; that additional drop is there. So that is what we meant by saying extent of electron concentration depends upon the band bending, which depends on the delta E_c and the doping.

Delta E_c depends upon x, that is the mole fraction; higher the x, higher will be the delta E_g; higher the delta E_g, 0.64 times delta E_g is delta E_c, that is another aspect. So we think we can confine as much electrons as we want then we go right root x into one, instead of Aluminum gallium arsenide we put aluminum arsenide, but it does not work out that way, because, when you add more and more aluminum somehow there seems to be defects being introduced and all those defects centers were called some DX centers – that is the name that is called, I do not know why they call it by that name - it is a defective center, which are trap centers, which tend to trap electrons and the performance of the HEMT suffer from that, number 1.

Number 2 is so that is why limit x to be about 0.3; 0.4 gives 0.5 delta E_g slightly lower than, that it is not linearly going up like that. So you get close to 0.5, 0.45, delta E_g. You will have delta E_c which is something like about 0.3; 0.3 to 0.5 about 0.3 delta E_c which gives about 10 to the power of 12 electrons per centimeter square. That is the idea, but good enough; it is in fact larger than the electrons that you get in universal layer in a MOSFET. That is close to that 10 to the power of 11 to 10 to the power of 12 electrons per centimeter square. So charge sheet which is present there.

Now there is one more technological problem. Apart from this higher aluminum concentration introduces trap centers called DX centers, it also makes it difficult to be to make [Homie] contact. If you recall, higher the band gap material, higher is the barrier width - n type particularly - higher is the barrier rate; two-thirds of E_g and its interference state is high. Higher the band gap material, higher the barrier rate less chance of it making [Homie] contact, better [Homie] contact; where? In the source and drain regions. There are two things source and drain regions, and the gate regions. Gate region, of course, the barrier rate will be high; drain region where you make the [Homie] contact, there may must not be contact [Audio not clear 27:22 min] ; that becomes difficult. In fact, you make the n plus there n plus there by doping, but still all that happens in the situations is like this.

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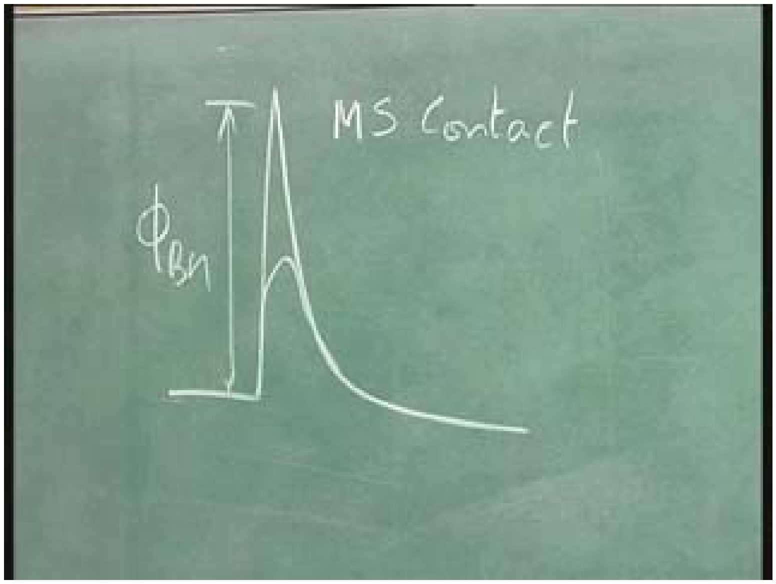

You have a high barrier head like that. You dope it heavily, then the whole thing comes down like this; lightly doped, heavily doped; these are called MS contact - metal semiconductor contact - and that is the phi$_{Bn}$ and do not make it heavily doped, it will get high; make this heavily doped, that is reduced quite a bit. How much it is reduced if it is of doping and also combination of these two.

If this is high already, it becomes difficult to reduce it to the extent that you want. The moment is not reduced to very small values, it has a finite barrier rate; finite it looks as is there is a large contact [resistance]. So, in fact, way back in 1981, when I returned from US on technological gallium arsenide, we wanted to propose a project on gallium arsenide based devices; immediately the experts here, [ ], asked me: do you know how to make [Homie] contact with gallium arsenide? It is a valid question. I am this putting across to you because everyone worries about making [Homie] contact with gallium arsenide higher band gap. Gallium arsenide at the time sorted out; the answer was yes. Today you go to gallium nitrate, much wider band gap, to go to silicon carbide; the worry of good technologies is making a good [Homie] contact.

[Schottky] barrier you just put a metal in a [Schottky] barrier. Absolutely no problem; the [Homie] contact is the problem. When you want to make the field effect of a transistor, that is where the difficulties are in the materials like gallium nitride, silicon carbide, etcetera. Same problem is present in aluminum arsenide, when you go to AlGaAs, when you go to x higher and higher; x higher and higher, wider band gap where it will be more difficult to make [Homie] contact. So, that is what I am trying to find out plus so that is the second problem.

You put x equal to 1, aluminum arsenide that seems to be unstable. You tend to lose arsenide from that. So that material is itself unstable and just keep it open or even raise the temperature slightly. With all those restrictions: worried about the trap centers, worried about making the [Homie] contacts for source and drain and also stability of that layer. From all those considerations you say 0.3 x; 0.3 is sufficient for me; fairly decent MODFET; it is not enough if you have the MODFET, you must be able to control the charge.

See what we said is let me put that diagram quickly here, because I do not want to keep on moving into the diagram.

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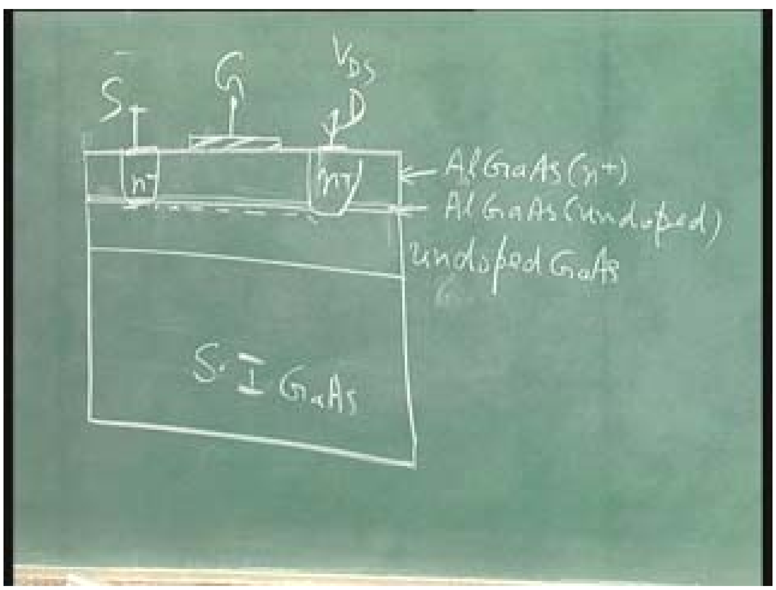

What we said is we can refer to this like this every time - gallium arsenide. Then you have the un-doped gallium arsenide. We have the un-doped gallium arsenide and then you have got the aluminum gallium arsenide. You may have a small layer put there which is undoped n plus; this is n plus.

I am leaving this diagram so that we can take a look at it undoped and then you have got that the moment you do that, that is the notch where you have the electrons locked (Refer Slide Time: 32:02 min). Then you put a n plus layer here - source, and put a n plus layer here which reaches right up to that point and then a drain, we apply VDS here, then the current flows through that, that I mentioned to you in the last lecture, because of the charges here. Let me just clean up with because it looks a bit crowded here; so I will just put it in that.

Those are the electrons which are present and that is the undoped layer. Undoped aluminum gallium arsenide, but the moment I put this point the mobility is up because scattering is reduced. There will be current through this.

To control that, how can we control that? How can I reduce this particular charge? (Refer Slide Time: 33:19 min) I should either reduce or increase. If I reduce that, I must reduce the band bending. How to do that, of course, we must have another electrode which is put here, which is the gate here. Well you come back to this now.

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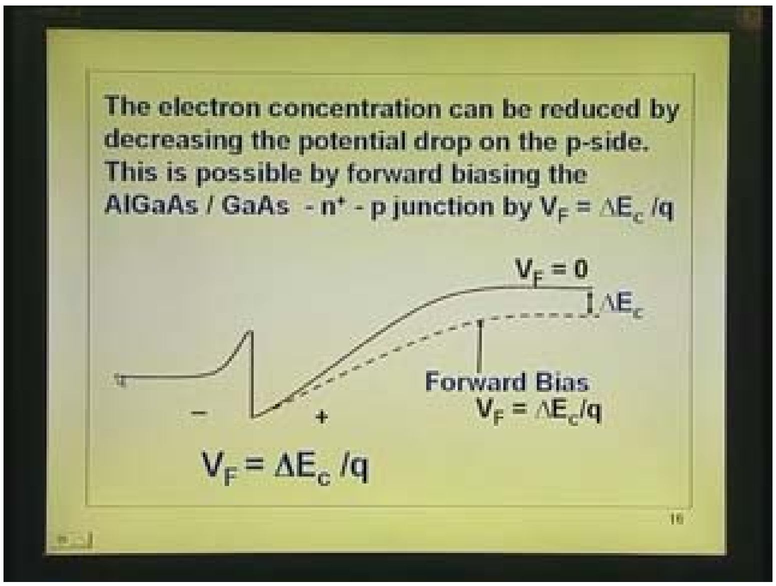

So this particular charge you can reduce; so that is the notch that we have shown here, that is the notch aluminum gallium arsenide and this is the situation where there is no gate. Just like this and that is the variation. Forward biased voltage equals 0, thermal equilibrium situation, because the electrons are locked up here and of course even in E_1 and E_2 energy, they are not just staying as gas there, though you call it as a electron gas, it is quantized electrons.

Now when I forward bias this… see what is the polarity of this potential? Plus here, minus there, because this is plus it has contributed electrons to this; so that negative charges will be as electrons and also as a decreasing layer charge.

If I want to reduce this barrier head (Refer Slide Time: 34:40 min), I must reduce the depletion layer width. If I have to reduce the depletion layer width, how is it possible? Reduce the potential drop and when we reduce the potential drop, that can be done if this is plus and this is minus; that is, this has a plus charge here, this is a minus charge. Here you have got all those immobile acceptors - plus minus. This is where the potential is and the plus is here minus is here, if you apply a reverse voltage or forward bias make it this plus and this minus that is like PN junction forward bias, the barrier rate is reduced. (Refer Slide Time: 35:35 min)

Suppose how much should I reduce the barrier rate to make charge equal to zero here? The extra potential that was present due to delta E_c, I was mentioning in the previous lecture. Charges are present in plenty here because this barrier rate under thermal equilibrium conditions is more than the homo junction by an amount equal to delta E_c by q.

You reduce that by that amount, automatically charges come down to a low value, that is, what ever was the intrinsic point here, you shifts towards this point, like in the MOSFET. The potential drop in the p region is reduced, the universal is reduced. You come out of universal.

Similarly, here, the potential barrier reduced by a forward biasing plus minus here, there was charges at here. So you must be able to apply a bias across this junction to remove those charges - plus minus. (Refer Slide Time: 36:28 min) All these charges will be removed and put over there. Supposing I have gate, if I apply a potential barrier between the two forward bias, what is the meaning of that? I remove the charge at the other side where negative terminal is there. So, this region I take it to the negative terminal, charges will be more negative when compared to this. That is why we have got that charges removed, automatically potential is reduced. Now few things we have to see here.

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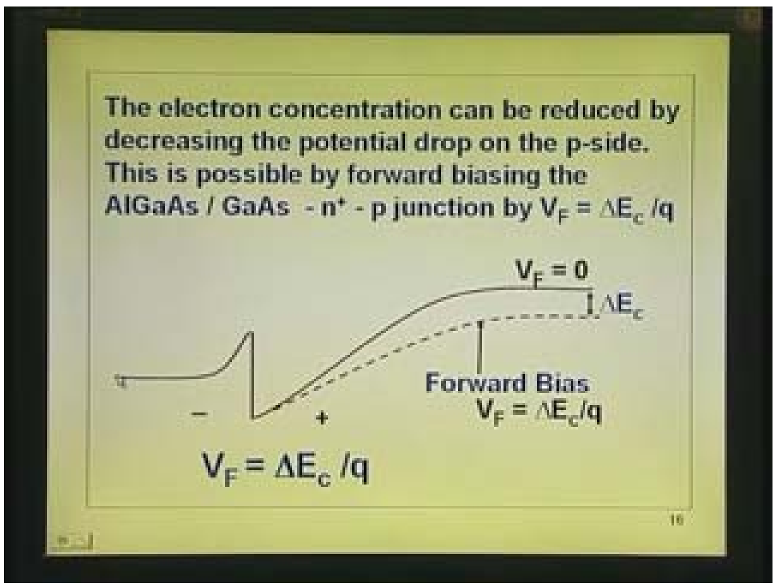

As the diagram is shown here its flat; if it is flat what is the meaning of that? There is no potential drop in the AlGaAs. If there is no potential drop in AlGaAs what you say is - only this portion of aluminum gallium arsenide is depleted, the other portion is not depleted; if it is not depleted, we have worry in our hand. What is the worry? Conduction will take place due to these electrons. Conduction will take place due to those electrons on this side here.

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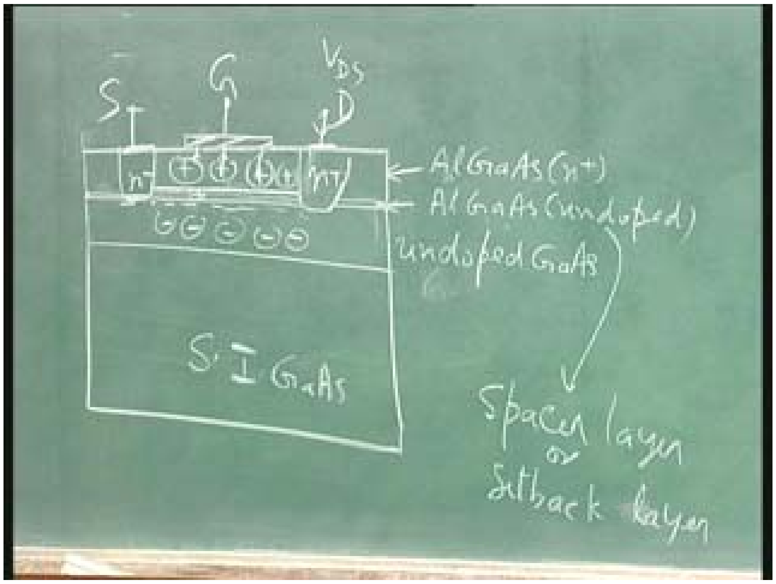

So, when the MOSFET is operating, this entire layer must be depleted. That must be depleted. Look at this portion here, above this what does it look like? Above that, I do not see these forces at all, just above this only aluminum gallium arsenide [I can see].

It looks like MOSFET. Source, drain, Homie contacts, gate, Schottky barrier and n type region. So this is a MOSFET. Now, in the MOSFET if I deplete the channel completely by the built-in potential itself or apply a negative voltage to the gate, so that the entire channel is depleted. What is the voltage required to apply to the gate so that this channel is depleted? That is the threshold voltage of the MOSFET; that is V_{Bi} minus V_{B0}; V_{Bi} of this junction, not the V_{Bi} of this junction; V_{Bi} of the Schottky barrier minus Kirchoff's voltage gives you the voltage that we have supplied to the gate at Kirchoff completely.

Now if you just pinch off here, a situation will be there the depletion layer will be just coming up to the point. Let me go back to the diagram and see, if you take this cross section here, this portion, this is a very crucial thing you must watch. Easy to understand that portion, because, you are already familiar. Now when the depletion layer. So the field for this are in this direction. The depletion layer due to the Schottky barrier use electric field in that direction.

Now let us say there is a depletion layer here (Refer Slide Time: 39:55 min), you can ignore that layer - un-doped layer - because [it is nothing]. Let us say the whole thing is doped and this is the total width and there will be a small depletion here with plus charges. I am just ignoring that small spacer layer; the un-doped layer is also called as a spacer layer or a set back layer.

Terminologies or set back layer. It is just a name, I forgot to tell you about that. This un-doped layer, it is spacing between the two, that is the thin spacer layer. Now I am just ignoring the effect of that – it is very thin. The depletion layer here will be having….

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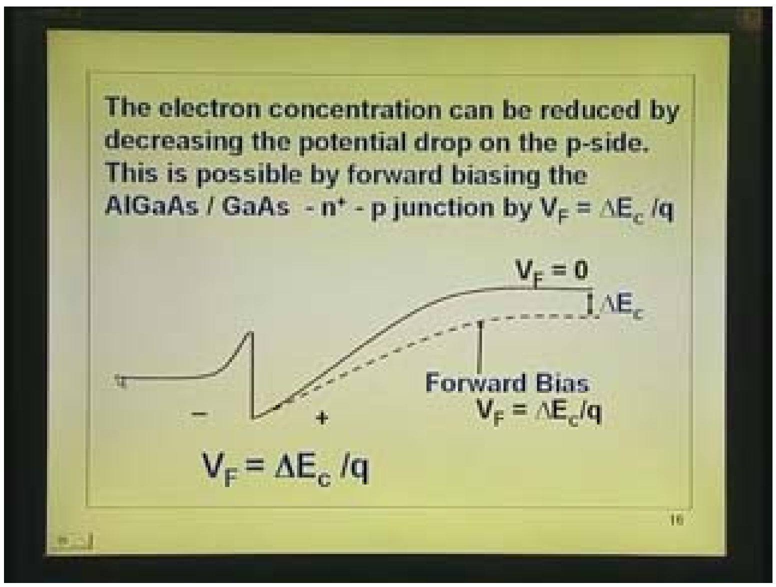

See in this portion here, we have got this portion in the depletion layer, where there is potential variation. Now what we are trying to do is, you put a gate there, Schottky barrier, whose depletion layer is spread right up to this point. The applied voltage is coming close to this point; so the field lines of this portion will be terminating on the left hand side.

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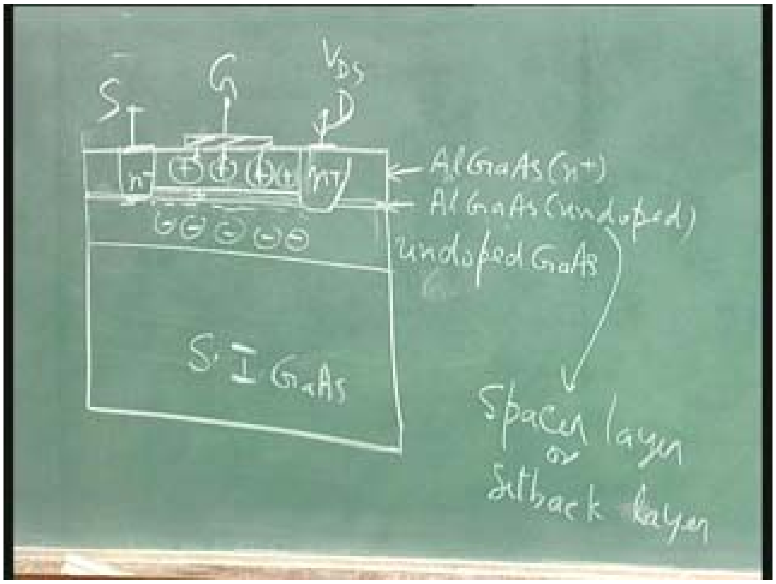

The three lines here are terminating on to the metal. Depletion layer of the Schottky barrier is going like that. Where as the field lines here, where are they terminating? Down. This is the hetero junction (Refer Slide Time: 41:50 min) that we have been talking so far. So you have a MOSFET along this hetero junction. So this hetero junction has a plus charge here, minus charge here. So the field line is like this here, field line is like that and once the depletion layer merges with that, you are safe.

Let us go into the analysis further. What is the situation now; so if that point is clear that - there are field lines, fully depleted layer is there, but most of the depletion layer is interacting with the gate Schottky barrier, part of that is interacting with the pn junction field in the upside direction.

Now ultimately, you must reduce the field in this direction (Refer Slide Time: 42:42 min). If I reduce the field in this direction what happens? This collapses and what about that boundary?

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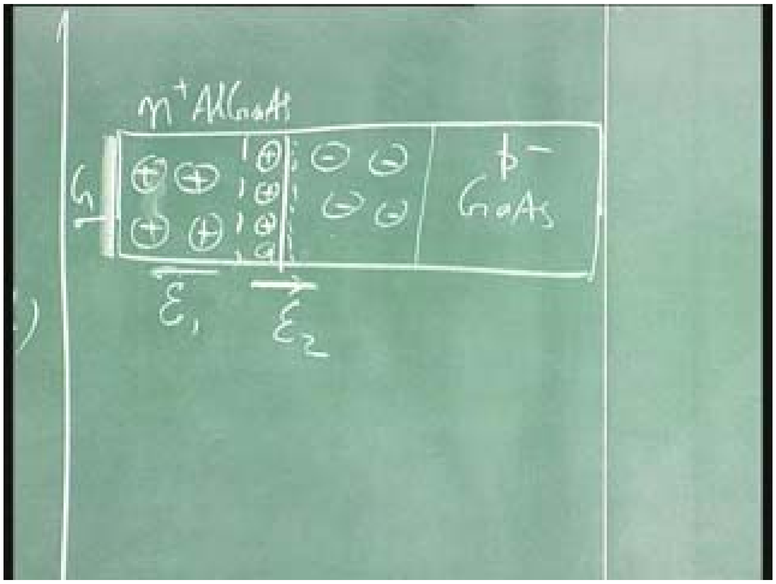

Let me draw that here. If I take n plus AlGaAs, there is a depletion layer here. I am just putting that diagram without all these things and this is the gallium arsenide p minus un-doped and there is a depletion layer here. There is a metal here; that is the gate and there is inversion layer here. There are plus charges here; these plus charges belong to the depletion layer of the Schottky barrier. They are moving field lines in this direction, here that is electric field direction.

These charges here (Refer Slide Time: 44:08 min) belong to the junction; those field lines are here, E_1, E_2. For an outsider, that is, when I apply voltage between these two the entire layer is depleted; part of it is belonging to this, part of the depletion layer is belonging to that. So long that as that condition is satisfied it is okay, but now the current flow will be through this. Current flow will be actually through this, because, the entire layer is depleted there. I drew it there because it is slightly a bit more clarity is there in this diagram.

Now this is making contact with this particular layer. If I apply voltage between these two to the substrate there we are applying, you are making contact with that here; that is making contact with that; this contact. The n plus is making contact with this layer directly; let us not worry about that.

Let us see suppose I make this more negative (Refer Slide Time: 45:46 min), see what you require to do is there is a drop here, if it goes all the way up to this point, the channel will pinch totally; that means entire depletion area belongs to that. But you do not have to go all the way up to that; you will have to go very close to that pinch off point, very close to there with minus V_{Bi} minus V_{B0} because part of the voltage is taken care by the other junction. So still, we will say V_{Bi} minus V_{B0} is the voltage required to deplete the whole thing.

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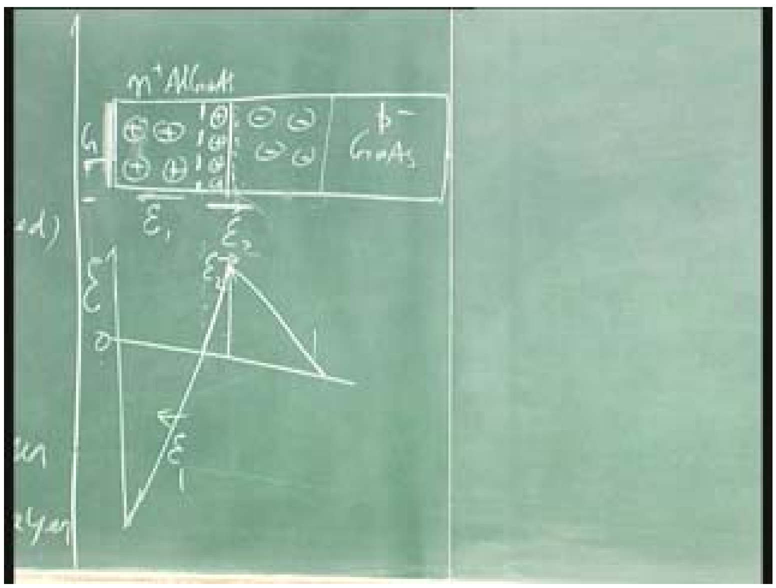

Now at this point, this is the depletion layer boundary. How is the electric field distribution now? We have slides; they are all there, but I will just put it on the board, so that you can just take a look at it. How is this? This is junction [Audio not clear 46:45 min]. That is a 0 if I take, that is the peak point as far as junction is concerned. Then we have got the field coming like this, let me just draw that slightly, I need more space there.

There is a peak point; that is the electric field uniformly doped because there is some charge present here, due to that you will have some additional field coming up here. This is takes only depleted charge, because, there are charges charge sheet here, this might slightly go up there accommodate that. I am just leaving that out and here it is coming down like that. What about the electric field here? That is negative.

What about the slope of the electric filed that I plot? Same. See the slope of the field I will take field versus x decided by doping; if the doping is same thing, it is 0 here, it comes down till you reach the boundary.

This is E_1, that is E_2, this is 0 (Refer Slide Time: 47:54 min). So this is E_1, and that is E_2. That is that direction; this is in this direction. Why I just pointed out this is, when I keep on depleting coming up to this point, what will be the potential distribution now? Now let me just go into those. So all these I just discussed now, I think I can come back to that later.

If I have this particular electric field 0 (Refer Slide Time: 48:39 min), if I move from here to here there is a potential variation where ever changes are there, where ever the field becomes 0, potential is not 0 it is minimum. So if I go from here in that direction what will the wave be potential be.

If I plot the potential $V_{B....}$ I think I have already there, I will not plot that, so plot the potential. We will go to that particular diagram, we will come back to this afterwards; all this analysis I will come back afterwards.

This is the diagram.

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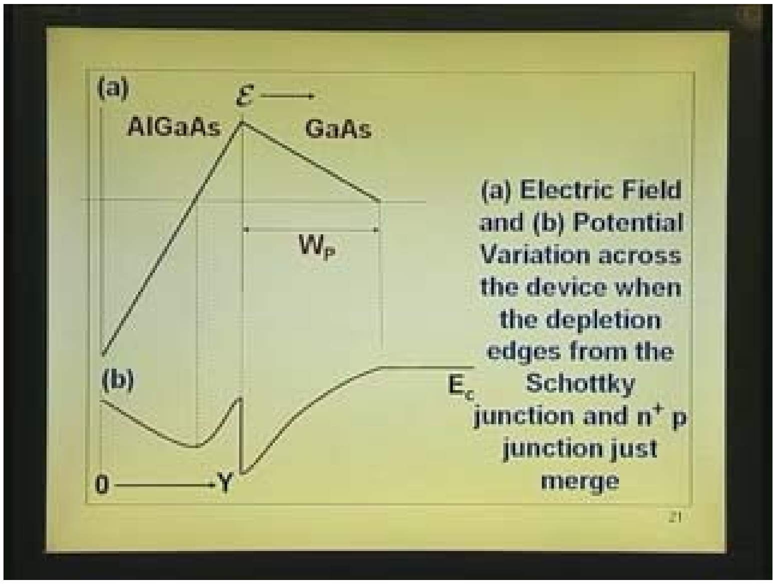

See the electric field actually is that is there, that is the gallium arsenide, this is the AlGaAs and this is the 0 electric field, which will be… the potential will actually be… this is actually the energy band diagram. See the previous diagram what we showed was coming like this and flat. Being flat, it is plus here, minus here, energy band diagram; it is plus here, minus there, energy band diagram depletion layer, plus here minus there.

This is the diagram when I applied the voltage up to this point, when I keep on increasing the negative voltage to the gate, it will be keep on moving up to this point, because till the depletion layer merges, there is a contact between this and this point (Refer Slide Time: 50:31 min).

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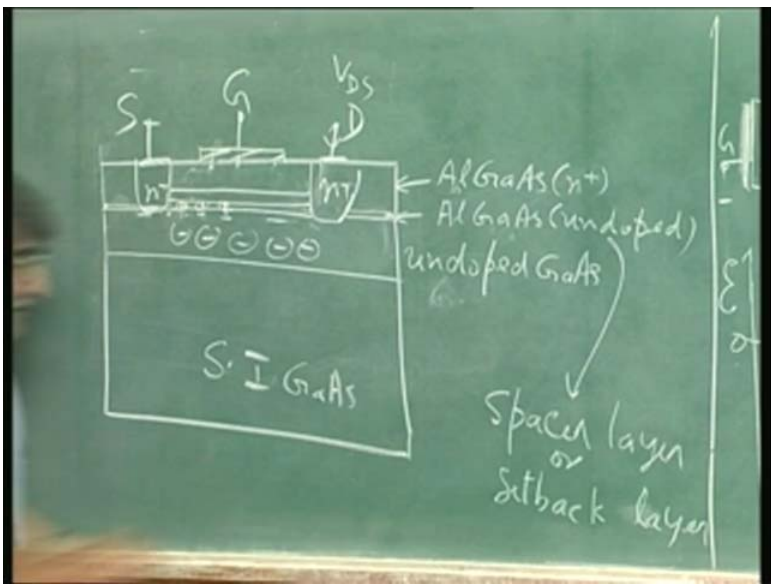

It is better to see in this diagram. Till the depletion layer reaches here, for example, even its here like this, when the depletion is like this; I have the charges, the depletion layer is up to that point and the depletion layer here is like this. As I keep on increasing negatively E_{GS}, this particular thing is already there (Refer Slide Time: 51:02 min) because of hetero junction. What I am doing is I am applying voltage between these two negative. As I keep on increasing, what happens? Depletion layer keeps on widening, because there is direct contact here This is virtually sorted out; we do not have transfer of electrons from here to there. This is the Schottky barrier which is acting. There is no control of this on this.

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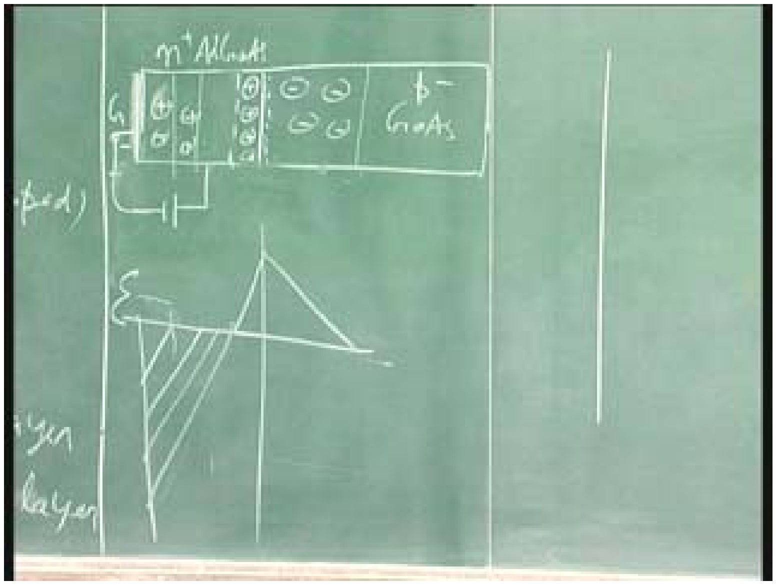

In fact, if you see this diagram, here if I have this depletion layer that is there whether this metal is there or not. When applied voltage is negative with respect to this quantity and if I keep on increasing that negatively, depletion layer keeps on moving. In fact, what will happen will be over here you have got this already, that you have got and over here what will happen will be ultimately it will come with that as I keep on increasing the voltage can you sketch the electric field? Plus minus. Electric field in that direction; depletion layer keeps on widening like that, like that, ultimately like that. Till that time, you are not touching that charge. See that, interesting part here is that when we apply voltage to the gate if the V_{Bi} is lower that V_{B0} that is easy to understand; depletion layer width is much smaller than E.

If I want to deplete I must apply negative voltage till that reaches and touches that point, this point; that is the point that you have got this depletion layer. What happens beyond that - is the question.

If I increase the voltage beyond this point, this is the point at which the entire layer is depleted and there is no contact here now. You do not have contact here, because it is a [ ] layer. If the whole thing is depleted even though there is there, there is nothing, but that is reaching to this.

So if I increase the voltage beyond that point, what happens? The charge from here will be reduced. In fact, the charge from here reduced to such a level that depletion layer will fall. In fact, the voltage appears now from here and here; actually it is here; so you are removing the charge and putting on the other side. When you apply negative voltage, if you take capacitor negative voltage some point, you are putting negative charge by applying to the other side, more negatively charged; negative terminals is more negatively charged. So if I remove that charge, automatically what happens? Potential barrier will lower. See the charge amount is removed it is possible only by lowering the potential barrier, quickly the depletion layer collapses. If the depletion layer here collapses, what about depletion layer here? Collapses; this charge reduces, but does it mean that this layer will open up?

See whole thing is you have removed the charge from here, so which has reduced the depletion layer charge, but the total thing is insulated, there is additional voltage occurring between the two. So that has gone into this layer. So what happens is this boundary is the 0 field moves to the right. You get the entire thing moving like this (Refer Slide Time: 55:17 min). Depletion layer narrowed; depletion layer here narrowed; here it is widened; the whole thing is insulated.

So you have got till that depleted condition, you can go on removing charge, in fact some more things details about that I will continue in the next lecture. The idea is this: gate control can push the depletion layer to this region and can remove the charge from here. More negative I make, less charge, less the depletion layer width, that is the forward bias appears across that, how much I must apply here is equal to delta E c by q.

We will discuss what actually is the threshold voltage of MOSFET in the next lecture.