High Speed Devices and Circuits

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Lecture - 40

Heterojunction Bipolar Transistors (HBT) - 3

(Continued)

We have spent a couple of lectures on heterojunction bipolar transistor and this is our third discussion we would be continuing that.

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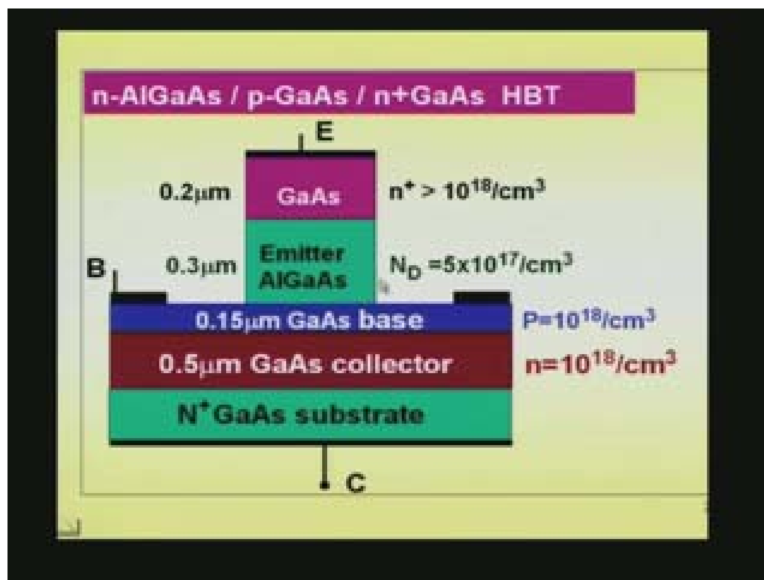

The structure that we pointed out last time was this that I will put it on the board, but I thought it is better to put it on a diagram like this. This is just to show that we have got the gallium arsenide to make good ohmic contact, the lower band gap, material emitter is AlGaAs, base is gallium arsenide, dimensions are all there 0.2 micron, 0.3 micron, and 0.15 micron. This is one of the typical structures that they have made, people now talk of even smaller base widths like 0.5 microns to get frequency like 100 GHz; that is the frequency people talk about, unloaded of course, just the individual capacity of the device. Collector - gallium arsenide; so we have got AlGaAs, GaAs, GaAs structure. We

just quickly run through what we have been discussing to sum up what we have been telling.

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$$\beta = \frac{D_{nB}}{D_{pE}} \frac{N_{DTE}}{N_{ATB}} \frac{n_{iB}^2}{n_{iE}^2}$$

$$= \frac{D_{nB}}{D_{pE}} \frac{N_{DTE}}{N_{ATB}} \frac{e^{-E_{gB}/kT}}{e^{-E_{gE}/kT}}$$

$$N_{DTE} = \int_{\text{Emitter}} N_D(x)\, dx$$

$$N_{ATB} = \int_{\text{Base}} N_A(x)\, dx$$

The beta of the transistor depends on the ratio of the total integrated doping in the emitter and total integrated doping in the base and of course ratio of the intrinsic carrier concentration in the base and the emitter. In the homo junction, this is cancelling each other; the same. Now here we have got this contributing to the beta also. It is a big factor delta E_g by kT. So I have rewritten the same thing putting the delta E_g which is actually positive if the emitter has wider band gap compared to the base. In fact, in the bipolar conventional transistor you have the problem other way.

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$$\Delta E_g = (E_{gE} - E_{gB})$$

$$\beta = \left(\frac{D_{nB}}{D_{pE}}\frac{N_{DTE}}{N_{ATB}}\right) e^{\Delta E_g/kT}$$

Typically , $\Delta E_g = 0.3eV$, $e^{\Delta E_g/kT} = 1.63 \times 10^5$

When, $\beta \approx \frac{N_{DTE}}{N_{ATB}} = \frac{1}{200}$ and $\frac{D_{nB}}{D_{pE}} = 2.5$

$$\beta = 2.5 \times \frac{1}{200} \times 1.63 \times 10^5 = 2038$$

You have problem where the band gap in the emitter is smaller than the band gap in the base due to heavy doping effects. In fact, when we do a device like this you overcome even that. Just to point out what actually is happening, just one or two sentences I would like to bring out in a conventional bipolar junction transistor, the band gap in emitter even though it is silicon, silicon emitter, silicon base, the band gap in emitter is slightly smaller than that of the base, which actually can lead to the beta, which is lower than what we get.

You have N_D in the emitter and a base a big ratio but this brings that down if delta E_g is negative.

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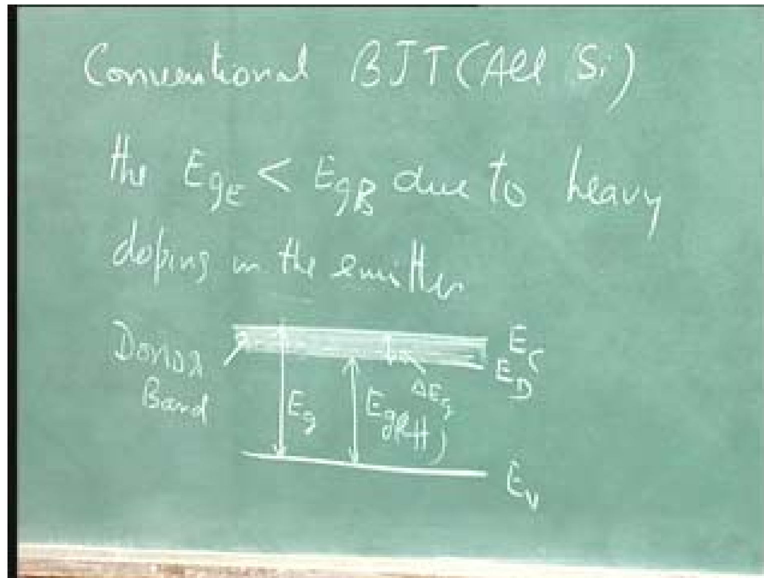

The reason is just I want to point out just in a conventional BJT silicon, all silicon. The E_{gE} is less than E_{gB} due to heavy doping in the emitter. Just to point out what it is I will just draw the energy band diagram. This is not a heterojunction, still band gap in the emitter is smaller because of the heavy doping effect. The reason is this: if we have a material which is rather lightly doped, we represent the donor level like this. We do not represent it as a continuous level; we represent it by dotted lines like this. This does not imply negative, if we really want to put we will put plus there; say we can put it like that, but I am putting just now dashed lines to tell you that there is sufficient space between the atoms. So they do not interact with each other, because, they do not interact with each other, the Pauli's exclusion principle holds good still; there are number of states in the same level.

If we increase the donor concentration to the 10 to the power of 19, 20 in the emitter or 21, what happens is each of these levels will interact with each other. What is one level, splits up into a band. So we get an impurity level like this; band like this and once the concentration goes 10 to the power of 19 or so or upper 10 to the power of 18; this is the donor band. (Refer Slide Time: 06:15)

We can see what happens is if this is the discrete level that is the conduction band edge. The donor level band has split up into a band and merges into the conduction band; there is no distinction between the conduction bandwidth and this level now. In fact, we do not get a carrier freeze out effect etc., because, all these electrons are in communication with the conduction band. The E_g… that is supposed to be E_g, but the effective band gap is that, because, once the electrons have raised up to this point, there is a continuous distribution of energy level; it is as if the conduction band is coming here.

This is actually delta E_g in the case of silicon homojunction, conventional BJT, delta E_g is like this and in fact, this is one of the topics which were topic of heavy discussion in 1980s. In fact, people used to fight over this issue in the conference issues saying how much is the band gap reduction? I think that is all for now, so depends up on the doping concentration, more the doping concentration more is separating and larger is this delta E_g. In this case, the delta E_g is negative; less than the actual band gap. The actual effective band gap is less than actual band gap. This is the heavy doping effect. In fact, if we switch over to a heterojunction, we will have band gap in the emitter larger and also we can go down to lower doping concentrations.

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$$\Delta E_g = (E_{gE} - E_{gB})$$

$$\beta = \left(\frac{D_{nB}}{D_{pE}} \frac{N_{DTE}}{N_{ATB}}\right) e^{\Delta E_g / kT}$$

Typically, $\Delta E_g = 0.3eV$, $e^{\Delta E_g / kT} = 1.63 \times 10^5$

When, $\beta \approx \frac{N_{DTE}}{N_{ATB}} = \frac{1}{200}$ and $\frac{D_{nB}}{D_{pE}} = 2.5$

$$\beta = 2.5 \times \frac{1}{200} \times 1.63 \times 10^5 = 2038$$

We do not have that narrowing effect at the emitter, if at all we have the narrowing effect in the base because we may go to higher doping concentration. We will have the band gap difference even more augmented. So in the heterojunction, we have got this quantity positive and we just saw… now that I just brought this in, because, I just wanted to point out to you the additional benefit that we get from the heterojunction bipolar transistor. We do not have to worry about the band gap narrowing effect in the emitter; once we do not have to worry about that, we do not have to be concerned about some of the temperature effects coming in there or beta getting lower because of that. These equations we have seen using some values like delta E_g 0.3 and doping ratio as 1 by 200 we would have spread that current gain in terms of 2000; that is, beta dependant only on the emitter efficiency.

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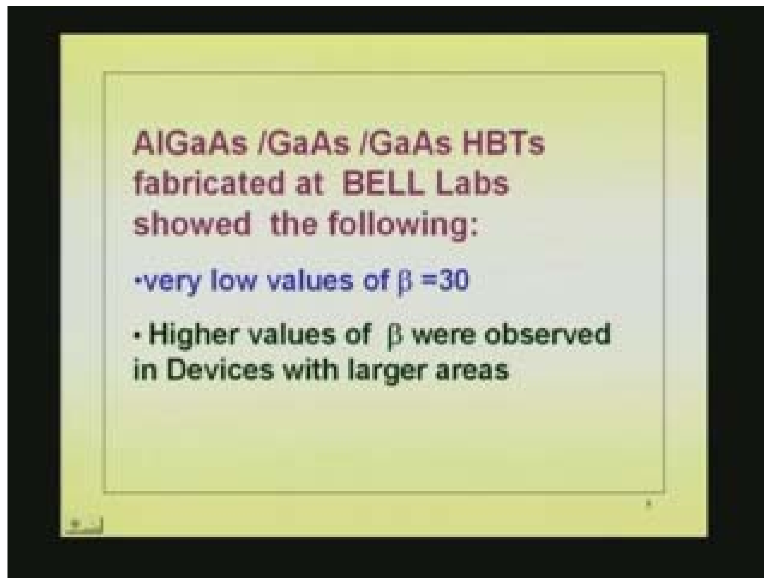

We also pointed out last time that the AlGaAs GaAs HBT's fabricated in BELL lab, USA, they found that initially the beta was about 30 to 32, in that range and also beta dependant on this area.

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Emitter efficiency is very high.

β governed by recombination?

$$\beta_0 = \frac{I_{nc}}{I_{vR}} = \frac{qD_n n_p(0)}{W_B} \frac{2\tau_n}{qn_p(0)W_B} = \frac{2L_n^2}{W_B^2}$$

$$= \frac{2 \times 100 \times 10^{-7}}{10^{-10}} = 2 \times 10^5$$

This is too large to be concerned about

Going back further into that; so just wanted to see whether it is the volume recombination that is effecting, because, we saw the beta was only due to… what we estimated is due to the emitter efficiency. If we calculate the beta due to the volume recombination, electron current injected to the collector divided by recombination current. This is the current injected qD_n D_n by d of x; D_n by d of x is n_p0 by W_B divided by stored charge by lifetime, the recombination current; so that is that quantity. When we plug in the numbers, reasonable numbers, 2 into D_n is about 100 centimeter square per second, 10 to the power of minus 7 lifetime; we pointed out last time why it is low; it is low because the direct band gap material divided by W_B square. I took 0.5 microns; so W_B squared is 10 to the power of minus 10; that is 2 into 10 to the power of 5. So if we have got 30 beta, we do not have to be thinking about - is it this quantity that is affecting the beta?

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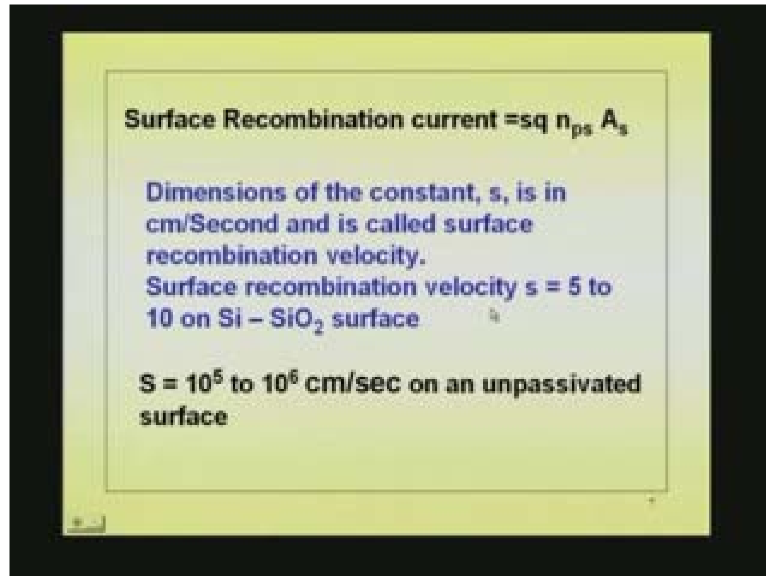

What we said further is what we have eliminated or what we have not considered with the recombination on the surface. So I just draw the diagram instead of going back and forth.

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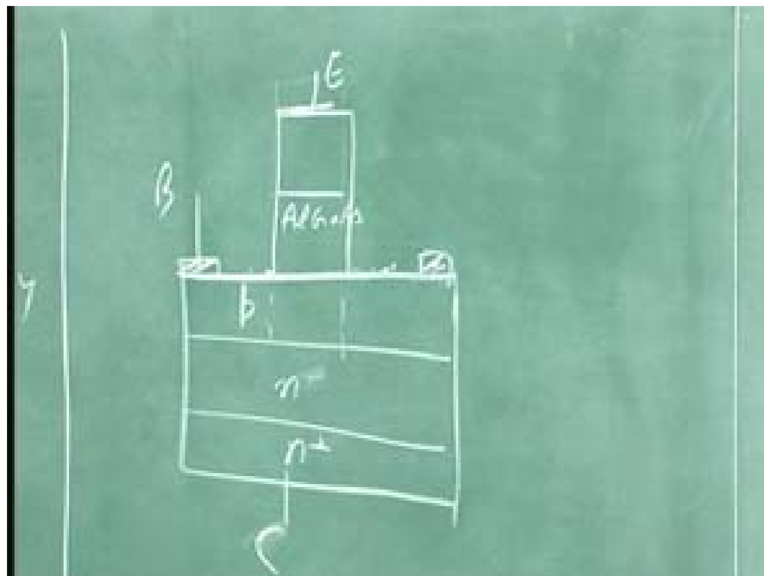

n plus or n minus or n and then the [p base]; I am drawing it too large. The p base, we have it in diagram, I draw this and all that, but it is already available there. So that is the contact; that is the base, collector; dimensions of about 0.5 microns, 0.3 microns etc.;

then, this is the AlGaAs. What we have been considering is only this portion, one dimensional analysis that current flow is in this direction; there is nothing happening beyond this point, but what we see is this particular surface (Refer Slide Time: 12:29) is active, in the sense it is very sensitive, because, it is left open like that. There is no oxide; in the case of silicon BJT, we have got oxide on surface. So that we can come back to that and see one more diagram for silicon.

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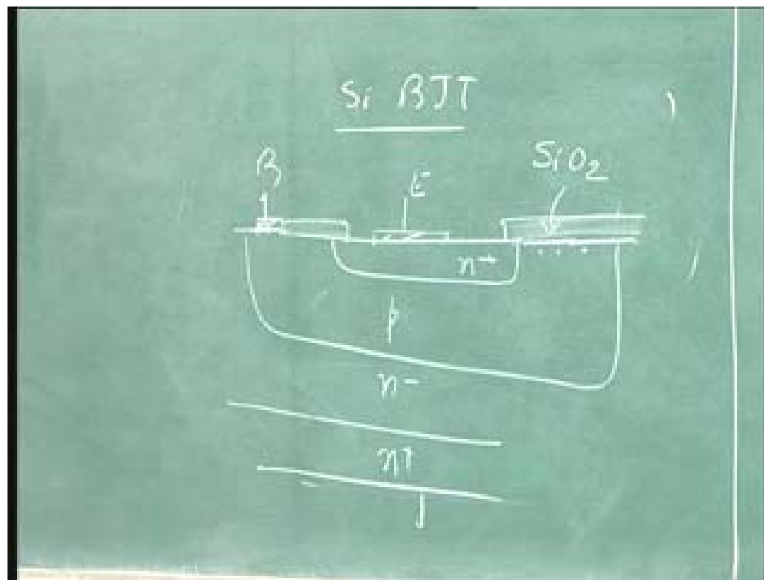

Silicon BJT - what do we have? We have got a junction like this n plus and then we have got p type base n minus then n plus. I am showing the contact at the bottom; it can be at the top also like an IC; there is a contact here; base, then, of course, emitter. Here we have got an oxide. We have got the oxide here. So this surface here (Refer Slide Time: 13:42) has a protective layer of oxide. So that is silicon dioxide, good thermal oxide. The recombination velocity what we talked of last time, in the sense just like in the case of bulk where total charge divided by lifetime is the recombination current. We have got recombination current into the surface. The current or the electrons are lost to the surface due to transport of electrons from here to here. In fact, whatever bulk concentration is here nearby diffuses into the surface to recombine there. What we said is the surface recombination velocity, surface recombination component, is the one that we are talking of.

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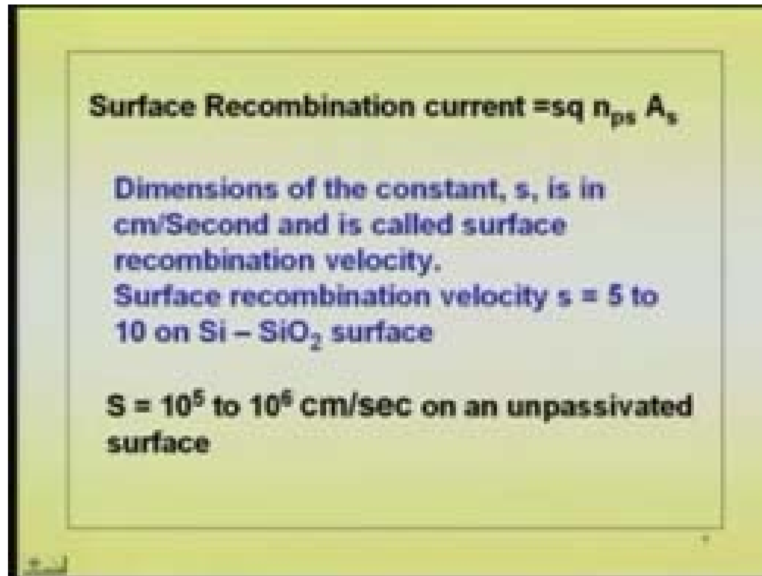

Just like the bulk recombination is proportional to the carrier concentration, the recombination at the surface is also proportional to the carrier concentration n p near the surface, just adjacent to surface, so it is per centimeter cubed. S is the proportionality constant, proportional to the carrier concentration multiplied by the area over which the recombination phase takes place. If we see here, in this case, that is the area that is recombination is taking place; because, all the carriers which are injected are flowing like this, but many of them go into that like that.

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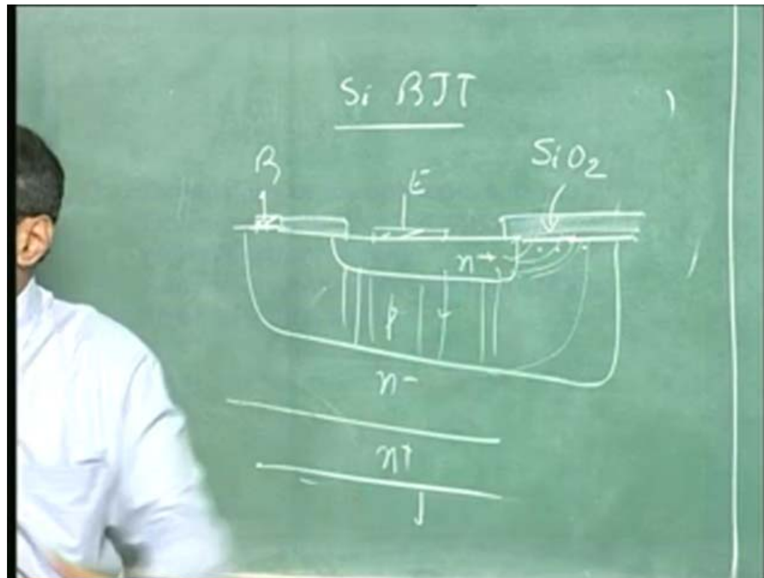

A width up to which it will be reaching will be practically equal to that width. I can say that carrier concentration decay from large number that is why it is normalized as 1, 1 to 0 here or n_p0 to 0 (Refer Slide Time: 15:36). Similarly, here it decays from n_p0 to 0. So we have to take this area into consideration and the current going in reaching into the surface is due to the recombination there, which actually is the recombination current which gives us base current. So that is what we have put here so the carrier concentration on surface which decays from the emitter edge to 0 n_p0 to 0 into the area.

The product of these two gives me actually 1 by centimeter cubed into centimeter squared; this gives 1 by centimeter. This current is actually charge per second. So the proportionality constant must have dimensions of centimeter per second. So if we put it centimeter per second, the whole thing is charge per second. So this is the current and this S has dimensions of velocity. We call it as recombination velocity; it is not the velocity with which the electrons are moving into the surface; in fact, electrons are moving into surface by diffusion. If we want to solve a two-dimensional equation what will we do would be we will write down the equation: del square n minus n by tau equals 0; that is the three-dimensional equation and on the surface we will write on the surface we will write q_n into S is equal to qD_n by d of x or in this direction.

(Refer Slide Time: 17:09). So that is the boundary condition that we put when we solve two-dimensional equation.

Leaving aside that what we are trying to point out is in the case of silicon that recombination velocity is very small, because, that is passivated with silicon dioxide. We do not really have to worry about the recombination on the surface and if we use that one-dimensional equation it gives fairly close to experimental results; whereas, here it is far off. So let us see what the magnitude of this is.

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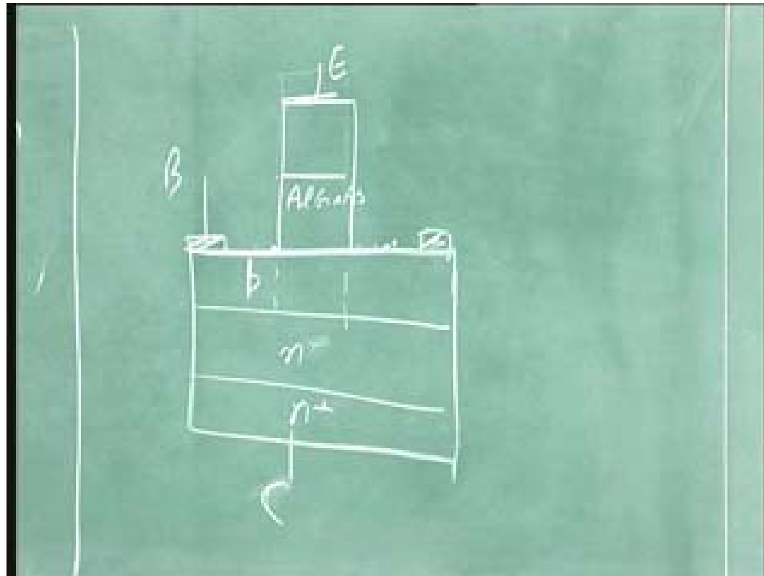

In the case of unpassivated surface, like the one that we have got here, like this one where we have got the gallium arsenide, a bare surface. In fact when the BELL lab people made that device, initially it was bare surface and a large number of density of dangling bonds are present which give rise to the recombination centers, which gives rise to high recombination velocity of 10 to the power of 6 or even higher than that recombination velocity, which would mean that the electron current injected here, quite a bit of that will be reaching here, because, recombination here is not much, but quite a bit of that will be recombining here also on the surface. What we have to do is compute that current and see if we compute the beta by finding out collector current divided by base current how much will that be?

Collector current will be actually I_{NC}; base current will be volume recombination current plus recombination surface, because, after all whatever electrons are lost here by recombination will be replaced by the base or the electrons will be recombined, they will recombine with the holes no holes are replaced by the base.

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Surface Recombination Current I_{SR}

$$I_{SR} = \frac{qn_p(0)\, s\, A_s}{2}$$

$$I_{VR} = \frac{qn_p(0)\, W_B\, A_E}{2\tau_n}$$

$$\frac{I_{SR}}{I_{VR}} = \frac{s\tau_n}{W_B}\frac{A_s}{A_E}$$

A_s is the effective area over which surface recombination takes place. A_E is the emitter area

Surface recombination effects dominate in small area devices

Now let us see that. Surface recombination current I_{SR} is actually, this is the same equation that we have written here, except I have written n_{PS} I have put it as n_p0 by 2.

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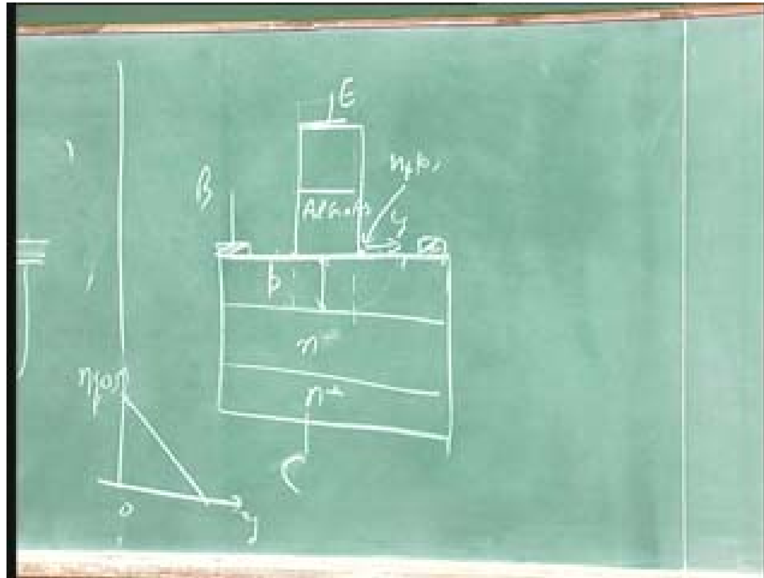

Because if we move from this direction, it is decaying from n_p0 to 0. Similarly, if we take with here, that quantity is n_p0 and up to a width equal to W_B practically it decays from n_p0 to 0, in the boundary condition here and if we see the carrier concentrations if that is 0 that will be 0 there. So this is W_B base width at width equal to that. The area over which the recombination takes place is decided by that width equal to the base width. The carrier concentration over this area is decided by the average value on this. We can take this area multiplied by the average carrier concentration and the average carrier concentration is like this. (Refer Slide Time: 20:33) I call this as y, n_p0 at the edge; let me draw it properly; y and n_p0 at the edge y equal to 0. Average of that is n_p0 by 2. So what we are telling is the recombination takes place over a width equal to W_B from the emitter and the average value is n_p0 by 2.

That is why we can say the current due to recombination is actually equal to q into S - that is the recombination velocity - into the average carrier concentration n_p0 by 2 into that area; area is actually corresponding to this width. How we take it will depend up on what is the emitter shape is. Suppose it is circular emitter of radius r_e, pi r square is the emitter area and this area will be pi r plus that width square minus pi r square. We can see now if this area becomes larger and larger, this area compared to that will become

smaller, because this is fixed by that width. For a given base width, this area is fixed by that. So the equations we will see much more clearly.

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Surface Recombination Current I_{SR}

$$I_{SR} = \frac{q n_p(0)\, s\, A_s}{2}$$

$$I_{VR} = \frac{q n_p(0)\, W_B\, A_E}{2\tau_n}$$

$$\frac{I_{SR}}{I_{VR}} = \frac{s\tau_n}{W_B}\frac{A_s}{A_E}$$

A_s is the effective area over which surface recombination takes place. A_E is the emitter area

Surface recombination effects dominate in small area devices

What I am trying to point out here is there is a recombination velocity is q_S into area surface area into average carrier concentration and volume recombination we know that is proportional to area and the volume, volume is emitter area into base width and q n_p0 by 2 and 2 by tau; the whole thing is 2 by tau. The ratio what we are trying to find out is should we worry about the surface recombination if I_{SR} equal to volume recombination, we do not have to worry, because, we found out that the beta decided by volume recombination is very large.

Ratio of I_{SR} to I_{VR} is given by… these 2 terms cancel, qn_p gets cancelled and s is there I put it here; A_s by A_E is greater and this tau n goes into the numerator, because, we are dividing by that and W_B is there in the denominator. Just canceling the common term n_p0 we get this. So now we can see how much is the surface recombination relative to volume recombination depends upon - One recombination velocity, if the recombination velocity is very small we do not have to worry about it all; so that will be negligible. Suppose it is 0, the recombination velocity is 0 or tending to 0, this I_{SR} tends to 0, that is the case of well passivated device like silicon BJT.

If it is finite, 10 to the power of 5, 10 to the power of 6, then it will depend upon the ratio of the surface area to the emitter area. We can see this actually gives us clue why the beta of those transistors depended on the area of the emitter. Larger the emitter area, smaller is this ratio. Larger the device area, surface defect is less. So that is why in literature we will see, one should be concerned about surface characteristics in smaller and smaller devices. It will make a smaller device, particularly in the case of VLSI, we make the device area small, then, we have to be concerned about the surface condition. There we are making the emitter area small, still we can get negligible surface recombination effect if x is small. A_s is the effective area over which surface recombination takes place; A_E is the emitter area. To sum up what is said here the surface recombination effects dominate in small area devices; area is small that becomes large.

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Current Gain, β (unity emitter efficiency)

$$\beta = \frac{I_C}{I_B} = \frac{I_{nc}}{I_{VR} + I_{SR}}$$

$$= \frac{I_{nc}}{I_{VR}\left(1 + \frac{I_{SR}}{I_{VR}}\right)} = \frac{\beta_0}{1 + \frac{I_{SR}}{I_{VR}}}$$

$$= \frac{\beta_0}{1 + \frac{s\tau_n}{W_B}\frac{A_S}{A_E}} \quad ----(1)$$

β_0 is the β when s=0 and emitter efficiency is unity

Let us see the current gain; let us for the time being pretend, that the emitter efficiency is unity; we can do that because it is large. It is very close to 1, if we take the beta width about 2000. When we start to take a look at this, the beta is much more than that; so let us not neglect I_{VR} also, take this into account. The beta is… the emitter efficiency is unity the beta is I_{NC} electron current injected to the collector divided by volume recombination plus surface. I can pull this I_{VR} out and then comes I_{SR} by I_{VR}. So what is this quantity I_{nc} by I_{VR}? That is the one that we have just now calculated as 10 to the power of 5 beta;

that is I_{nc} by I_{VR} would be the beta, if emitter efficiency is unity and surface defects are negligible; that is this is 0; so that is $beta_0$; I put $beta_0$ is the beta when surface defects are negligible plus emitter efficiency is unity and we just calculated that as if we look back as 10, for this example, 2 into 10 to the power of 5.

We get beta $beta_0$ divided by this quantity. We can see the beta can get affected if the surface recombination current becomes large compared to I_{VR} and that ratio, we have just now estimated as s tau by W into A_s by A_E; the previous slide I_{SR} by I_{VR} is that quantity by taking these ratios. I just put that term here as tau by W_B into A_s by $A_{E.}$ Now we can see very clearly, that ratio of surface current to volume recombination current, plays a major role in deciding the current. Let us put some more numbers and see so $beta_0$ is the beta when S equal to 0 and emitter efficiency gamma is 1.

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Circular Emitter of radius, r_E.

$$\frac{A_s}{A_E} = \frac{\pi\{(r_E + W_B)^2 - r_E^2\}}{\pi r_E^2} \approx \frac{2 r_E W_B}{r_E^2} = \frac{2W_B}{r_E}$$

Sustituting in (1)

$$\beta = \frac{2x10^5}{1 + \frac{2s\tau_n}{r_E}} = 50$$

taking $r_E = 1\mu m$ *and* $s = 2x10^6 cm/sec$

Let us take circular geometry device; surface area pi r_E plus W_B whole square minus r_E square, because this is like this now.

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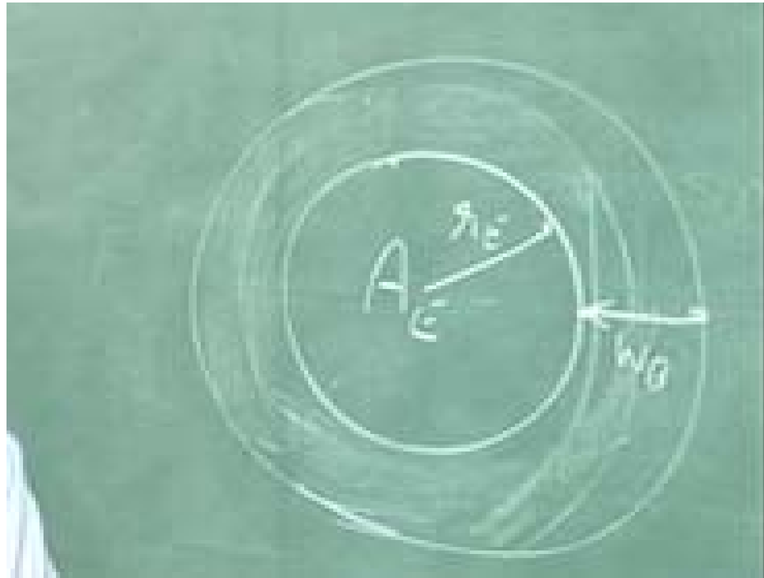

Looking into the emitter and A_E, top view, that is where the recombination takes place around a ring of width… so this is r_E and this is equal to… that is equal to base width almost; so that is the base width. We are trying to find out surface area over which recombination takes place; that is, actually equal to pi r_E plus W_B square minus pi r_E squared that is A_s, and area of the emitter pi r_E squared.

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$$\frac{A_s}{A_E} = \frac{\pi\{(r_E + W_B)^2 - r_E^2\}}{\pi r_E^2}$$

Circular Emitter of radius, r_E.

$$= \frac{2 r_E W_B}{r_E^2} = \frac{2W_B}{r_E}$$

Sustituting in (1)

$$\beta = \frac{2 \times 10^5}{1 + \frac{2 s \tau_n}{r_E}} = 50$$

taking $r_E = 1 \mu m$ *and* $s = 2 \times 10^6 \, cm/sec$

The ratio now depends upon r_E ultimately, because, W_B is fixed; for a given W_B we are calculating. We have got pi gets cancelled, r_E squared and r_E squared gets cancelled in the numerator and we have got twice r_E into W_B divided by r_E squared. I have neglected one term here which is W_B square; because, W_B is small compared to r_E. Even if the r_E is 1 micron W_B is 0.1 micron; this is 100 times smaller compared to r_E squared or 10 times smaller compared to r_E W_B. Usually it is much smaller compared to that. This is ratio r_E gets cancelled; we can see ratio depends upon W_B by r_E. So finally it brings down how much is the base width, decides how much is the ring width? How much is the area depends upon r_E depends upon this ratio?

Let us put that number into that; beta is $beta_0$ that is substituting in 1, one equation is this: $beta_0$ divided by s tau_n by W_B into A_s divided by A_E. In fact, we have just now seen A_s by A_E is equal to 2 W_B by r_E. That is how the r_E squared gets cancelled, because r_E in the denominator and W_B in the denominator gets cancelled; 2 W_B by r_E; W gets cancelled. This was square r_E squared, r_E gets cancelled we get the term. Just plugging in for area ratio, this quantity, we get that. Now substituting that is equal to 50, for I have just taken from a value which is really small area, where r_E is 1 micron, very small emitter and S is 2 into 10 to the power of 6. It can be even higher than this, 10 to the power of 7 of that order. I just took some numbers to magnify the effect and show that your beta can be 50. In fact, what they have seen in the BELL Lab compared to the W_B is actually slightly different of 0.15 micron and areas are slightly different. It is not circular it is square type.

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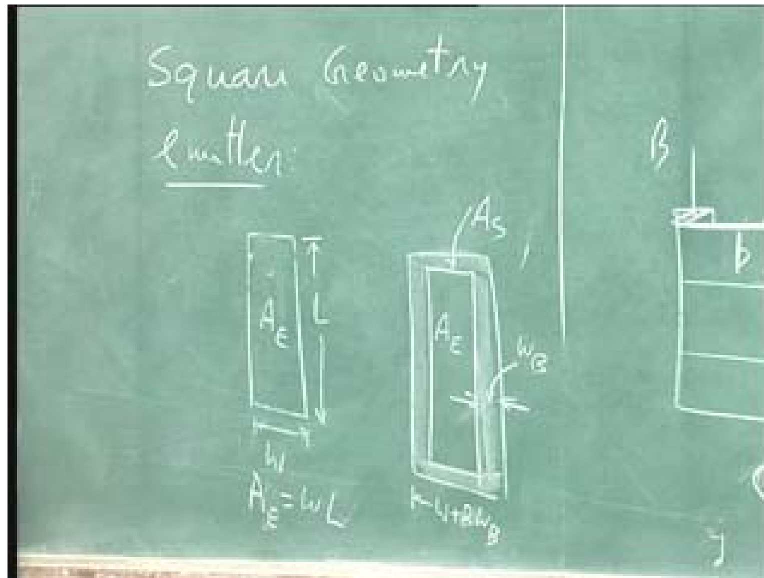

So top view is like this. I think we have got dimensions which are even as low as 6 microns by 20 microns. Here this is the emitter area; let me not put that down; this is the emitter area W_B into length. (Refer Slide Time: 31:59) I call this as W; so A_E is w into L is area. How we calculate surface area surface area? Surface area if we want to calculate, what we need to do is find out a periphery around this of width equal to that which is equal to that.

We have, that is W, that is L. Take this width; that is A_s; this is A_E and this quantity is W plus 2 W_B, W_B, W_B - W is the width of the emitter, W_B is the base width. The key thing to note is that find out the recombination current here by finding out the width, which is equal to base width and see what is the area here. The carrier concentration n_p0 here 0 at the other edge, corresponding to that.

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Circular Emitter of radius, r_E.

$$\frac{A_s}{A_E} = \frac{\pi((r_E + W_B)^2 - r_E^2)}{\pi r_E^2}$$

$$= \frac{2 r_E W_B}{r_E^2} = \frac{2 W_B}{r_E}$$

Sustituting in (1)

$$\beta = \frac{2 x 10^5}{1 + \frac{2 s \tau_n}{r_E}} = 50$$

taking $r_E = 1 \mu m$ *and* $s = 2 x 10^6 cm/sec$

This is an example if we have to calculate the beta of the transistor for a square geometry device all that we have to do is find out the periphery area of width equal to W_B. So it would matter a quite a bit when it becomes smaller and smaller the length and width and we have made device which are large; W quite large and length quite large. There the beta is closer and closer to what they have estimated?

We cannot say go ahead make the device area big, so that we can get beta of the surface effect. So if I make r_E larger here, that effect goes off. If we take a device of 1 centimeter area, 1 centimeter square area perfect beta is 2000 we will get, but what they did is once they saw this they realized that the effect is due to the surface. Once they realized that surface is good surface because we do not see it in silicon even in small area devices, they just try to passivate the surface. The surface recombination velocity is large because there are lots of dangling bonds here. These atoms in bulk they are surrounded by four neighbors.

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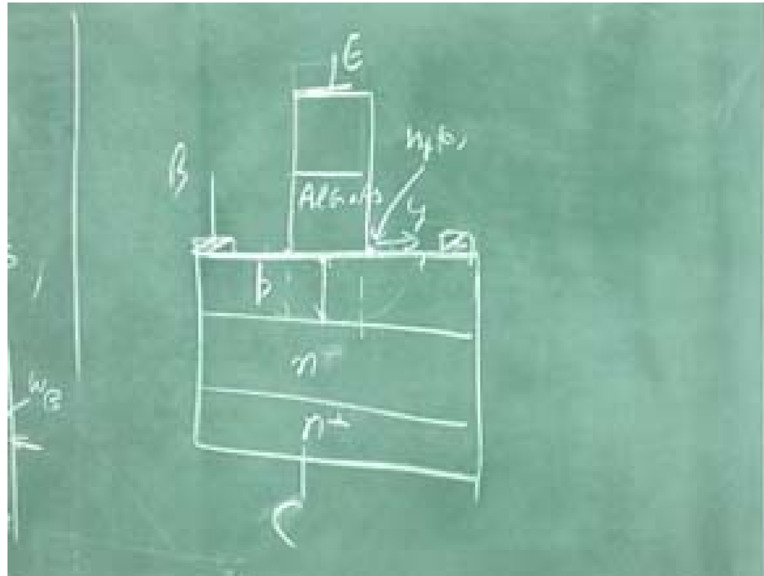

All those bonds are tied to each other, there are no dangling bonds; whereas, here the atoms in the surface has three neighbors below; no neighbor; here so dangling bond is there which is very highly reactive; that is the one that acts as recombination center. It is deviation from the periodicity. Any deviation from periodicity acts as a deep level and as I pointed out in the case of Schottky barrier they are distributed all over the surface, all over the energy band diagram, these recombination centers. How do we reduce the recombination velocity? Grow thermal oxide; that is how silicon people did, but we cannot grow thermal oxide in gallium arsenide, because, when we do that we get gallium trioxide, arsenic trioxide and arsenic trioxide reacts with gallium arsenide to convert it to gallium trioxide and to release arsenic.

We will have arsenic on surface; we are not worried about arsenic because it is arsenic. It is the one situation where it is poisonous to human beings and also bad for the device. We are just putting a metallic layer; it is similar to putting a layer, an elemental layer on the surface that actually increases the recombination current drastically. Thermal oxide or native oxide of gallium arsenide does not work. So do not think of putting native oxide on the top of it. If at we have to get good passivation, remove the top side completely and deposit some oxide on the top. If we deposit oxide, people try to deposit nitride oxide etc. on surface; no question of putting, because, that oxide reacts with gallium arsenide to

release arsenic. There is no chance for you to use silicon dioxide even by deposition or passivation. See what I am trying to point out is over here we must deposit layer. (Refer Slide Time: 37:24)

Let me remove that entire thing now; what we require to do is put a coating on this. If it is here we have to remove it by lithography; this is the passivation layer which protects the junction, which protects the surface. We cannot put the deposited oxide here. When I say we cannot, its possible for us to deposit, but it would not serve the purpose because that SiO_2, any oxygen containing layer will react to gallium arsenide to release gallium arsenide; but when we say we put nitride, then these are the steps taken by people which have oxide put nitride, when we put nitride what happens? We do not get good passivation because after all if we have a layer, if we have a surface, if we want to satisfy those dangling bonds, the deposited layer must be intimate contact with the surface; it should interact with the dangling bonds. Some sort of chemical reactions have to take place for the surface to get passivated; when we know silicon dioxide, it is native oxide; silicon is converted into silicon dioxide.

So those dangling bonds are wiped out because of the SiO_2. Here if we deposit, it is there lying on the top of the semiconductor layer. We measure the beta still not good; even if it is good it is not so stable, because, the dangling bonds are still there. Here came the BELL Lab people finally realized that we need to do some chemical treatment. So they started dipping it in all chemicals. It was a very intelligent way of doing on a chemical treatment that they were doing or dipping in the chemical was ruthenium.

This was happening in 1980-81. In fact, I used to hear that because I was working on this passivation work at that time, they were dipping in the solution. Some bit of success they got, but the real success came much later in late 1980's; in between, we were trying all deposited oxides, nitrides, nothing worked.

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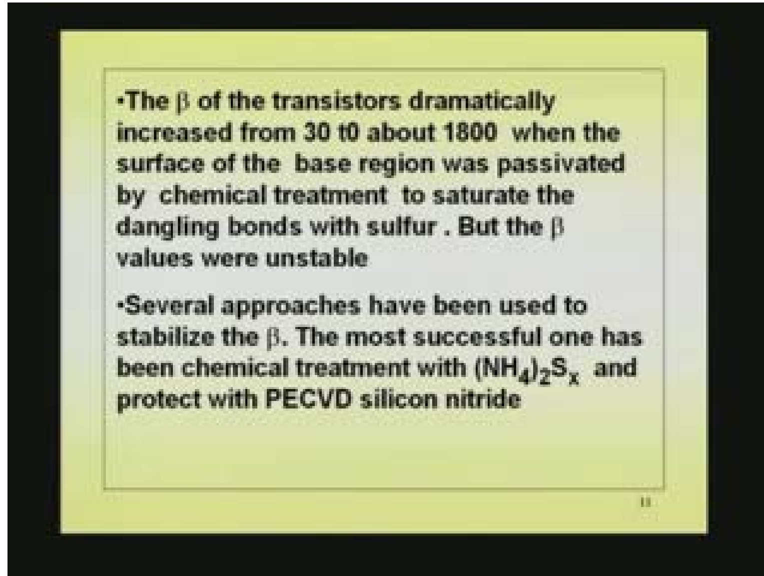

Somewhere in 1987 or 1988, they went ahead and that did it; dramatic increase; in fact, a paper was published about that saying dramatic increase in the beta from 30 to 1800. If we have gone to 1800 we know what we have done, we have removed that surface recombination velocity; plot it down to 0; that means we have passivated very well. This was actually done, the beta of those transistors which were very poor improved 1800 when the surface of the base region was passivated by chemical treatment to saturate the dangling bonds with sulphur, gallium sulphide, arsenic sulphide. So that is a sort of stable compound. So what they did was they treated…. I think I will spend little bit on this, because, this was one of the problems which was close to the heart in many in our laboratory including myself. At least couple of PhD’s have come out of this from our laboratory related to this area - passivation and making MIS devices.

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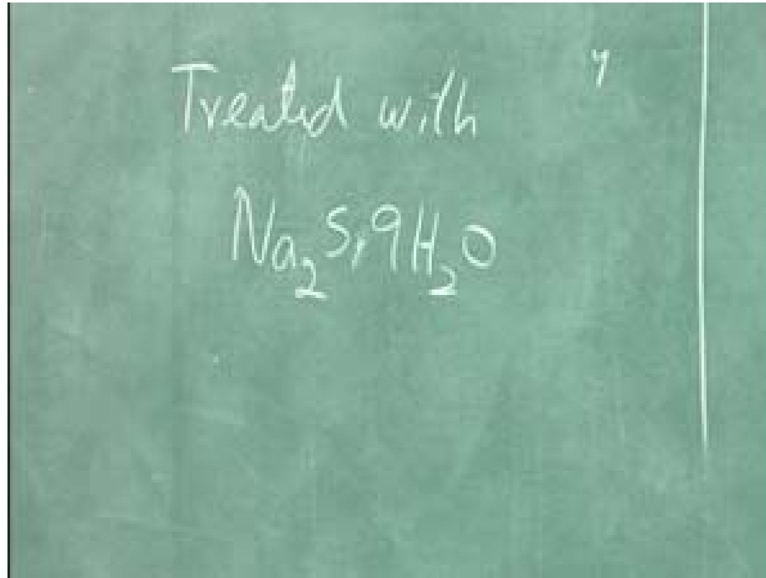

What they did in BELL Lab or they treated with sodium sulphide 9 H_2O. It is a salt of sodium sulphide; this is the composition; actually, this is what they did - sodium into the chemical composition of sodium sulphide. So the sulphur from here when we have dipped it in the chemical solution, we dipped it in the chemical, we dissolve this in water we get the solution and then we keep the wafer, the finished wafer we can keep it in the solution for some time. We can heat it up 50-60 degree C so that the reaction takes place at the surface. So sulphur from here passivates the device very well.

The person who have did has the name same as mine - Rajaram Bhatt, In BELL Lab. I know him very well because I worked in RPI with Professor Gandhi, I went to BELL Lab during that work.

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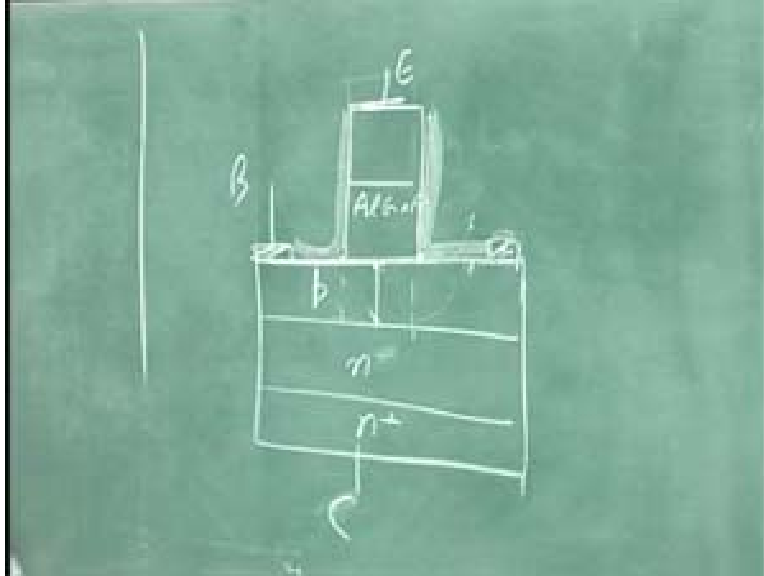

The joy was very short lived. Go up call the boss, the boss comes up and sees the beta is down to hell; in the sense it is not so stable – 1. Number 2, the sodium sulphide layer which is on surface gives rise to some leakage current across the junction here; we do not like any sodium potassium contamination. The sodium sulphide gives rise to k there. So barring the leakage the beta went up. So to remove the leakage, it was dipped in water; the whole thing went off. So these sort of problems were encountered in that, but ever since then people said there is something which does the trick and even for some of the compounds.

Then people came up somewhere in 1990's - ammonium sulphide solution, no sodium - when we fuse ammonium sulphide solution, no leakage current. The layer on surface can be retained; because, the sulphur and of course this we do at about 70 to 80 degree Centigrade and dip it in the solution keep it say 15 minutes, 20 minutes; for about 80 degree Centigrade it gives quite good passivation; no surface leakage, because, junction does not have a ohmic layer on the surface. There is no ohmic layer on surface; so leakage current is low; people made solar cells, but then somewhere around 1991, one of the persons were working on that came to India in a conference in IWPSD, Delhi.

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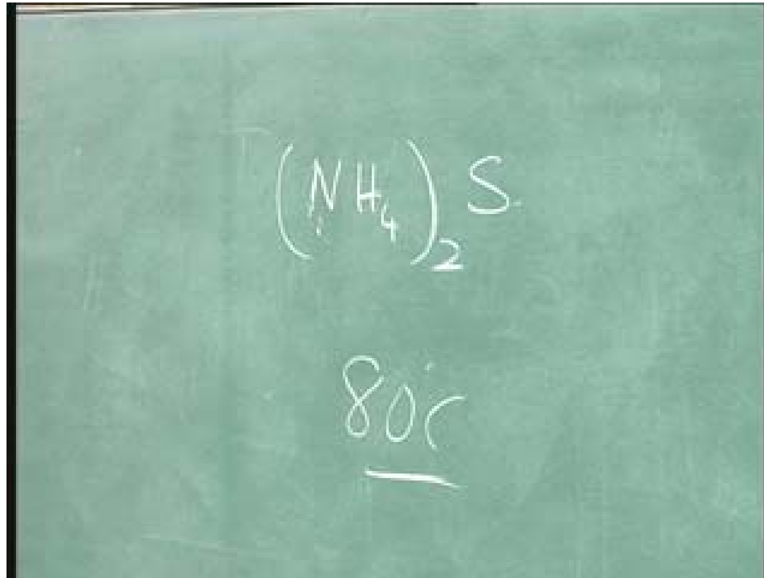

Since I was interested in that I asked him how that ammonium sulphide work out. There was the paper already published in the applied field; when I asked how it works out, he just shrugs the shoulder and says almost same as sodium sulphide, but the leakage current is not there. What is the problem? There is some stability problem. The stability problem is because when we put this particular layer - that was found out little later - the surface will be very clean, there should not be any oxide layer; if there is any oxide layer, then that oxide layer will react with gallium arsenide to release arsenic; that sort of happening.

The surface recombination velocity was not low enough as we wanted it to be. There is still lot of recombination taking place; still they observed instabilities. So next following up chemical was, a chemical which was in fact there was a lot of work went on; people said I will do all this treatment in high vacuum, take it, prepare it in to where we do this depositions, treatments etc. In systems all sort of complication things are done, number of wafers appear, but part of the things that have succeeded which was still simple was: stick that to this particular solution, but modify the composition. In fact, we can buy this type of solutions; ammonium sulphide is available in market.

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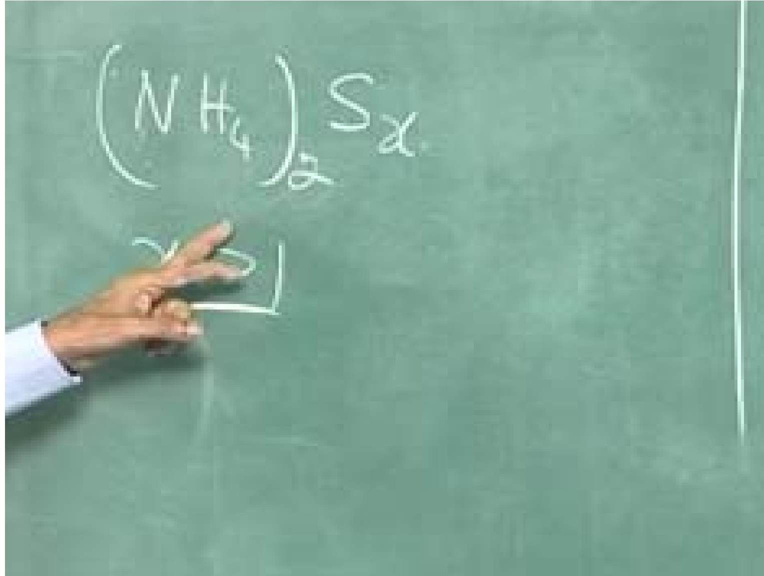

Next level is ammonium sulphide x, where x is greater than 1. This is called ammonium sulphide solution which is rich in sulphur; the sulphur rich ammonium sulphide x is not 1, x is greater than 1. This solution - there are lot of reports which have come around at 90's which said that if we use ammonium sulphide x is greater than 1 to 2, in that range, we can buy the solution; If we use that two things happen: one initially that oxide is etched the thin oxide layer, we know it is a native oxide which is always present. We take silicon wafer, we keep it open to atmosphere, it reacts with oxygen, we have got S_iO_2. Similarly, gallium arsenide, we keep it open, it reacts to give we oxide of gallium and arsenic.

If we just put chemical treatment we get that oxide thin layer is always present which will actually react, which will respond when a temperature goes up a bit, release arsenic. With this solution, what happens is this solution reacts with the oxide layer; it removes the native oxide, when it is in the chemical, plus it also removes the thin layer of gallium arsenide.

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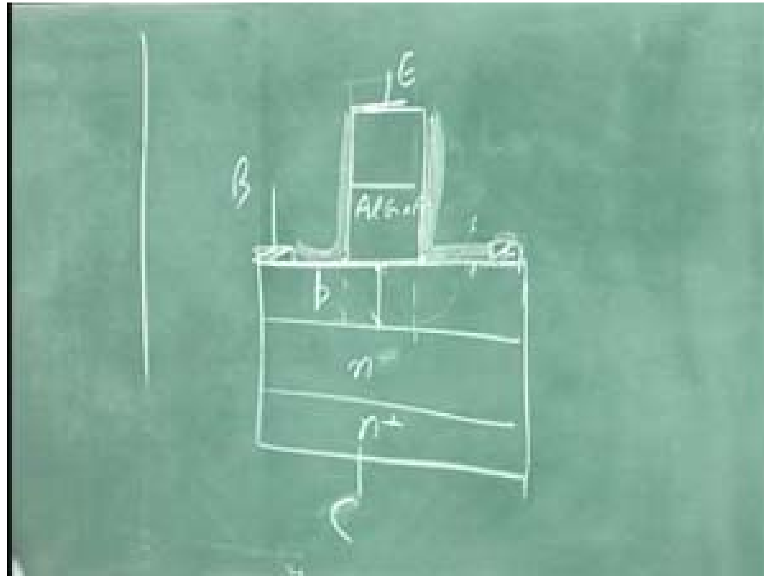

When we do the treatment, we have got the surface cleaned up from the oxide layer and surface also a layer etched out; any junk - that is to use that language - any bad layer that is present on the surface that is also removed. We have got a fresh surface exposed with which ammonium sulphide will be react and. This was fairly good enough, but we know even then the stability problems appear, because this is the thin layer that is put there covering the gallium arsenide layer, we need to further production. In fact, this is where we did lot of work in IIT, in the microelectronics laboratory, as a part of one PhD program where ammonium sulphide treatment, extensive studies were done with deposit nitride.

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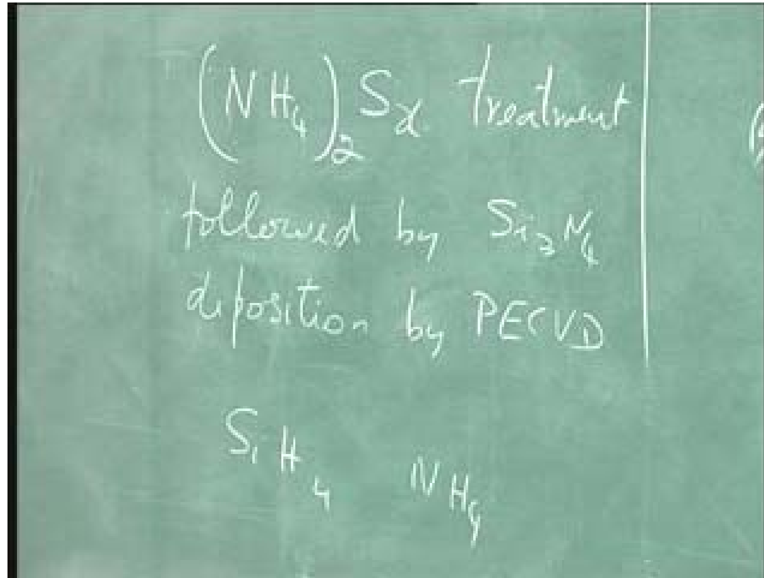

Ammonium sulphide treatment followed by silicon nitride $S_{i3}N_4$ deposition by plasma enhanced chemical vapor deposition; silane and ammonia S_iH_4 and ammonium gas, they react at low temperature when we put it in plasma; plasma reacts with energy at electric field. So we can do this deposition at temperature like 300 degree Centigrade or even 250 degree Centigrade, nothing happens to that layer. On the top of that, we deposit this layer.

The ammonium sulphide does the job of removing the oxide, exposing fresh surface and passivating the layer. So PECVD put on the top does the job of protecting it from further coming into contact with the outside world. When we make device, in fact when these devices have been made fabricated using epitaxial layers, when we make devices with this, the field effect…. See actually the way we test it is use this PECVD as nitride territory, take gallium arsenide layer, passivate it with ammonium sulphide, put nitride, put a metal gate, source-drain contacts put, we get instead of MOSFET, we have got MESTFET - metal insulator field effect transistor - we call it insulator because it is not oxide.

It can be anything nitride when we put it we get excellent field effect transistors. In fact, if we like to see an article on this we can open up the IEEE transactions on electron devices, so that tells whole story of passivation.

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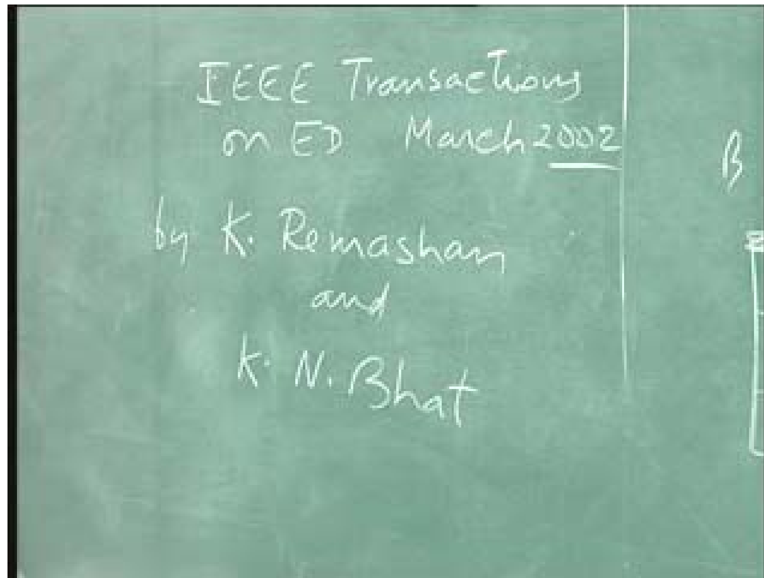

I just write down that - IEEE a full-fledged paper running to about 14 pages or so – Transactions on Electron Devices, March 2 2002; that brings it very close to the present day; 2002 I do not remember; the date March is sufficient… See this is an article written, I think I will put an advertisement for this by K. Remashan and yours truly. So these are two authors who have written this article, which has got in this stable MIS field effect transistor. Subsequently, which appeared last year or last March or last April or so 2003 around that time, there was another article which came from IIT MicroEectrons laboratory on passivation of detector, PIN detector. In fact, if you recall previous lectures we said indium gallium arsenide or indium phosphide can be used as a PIN detector for fiber optic communications.

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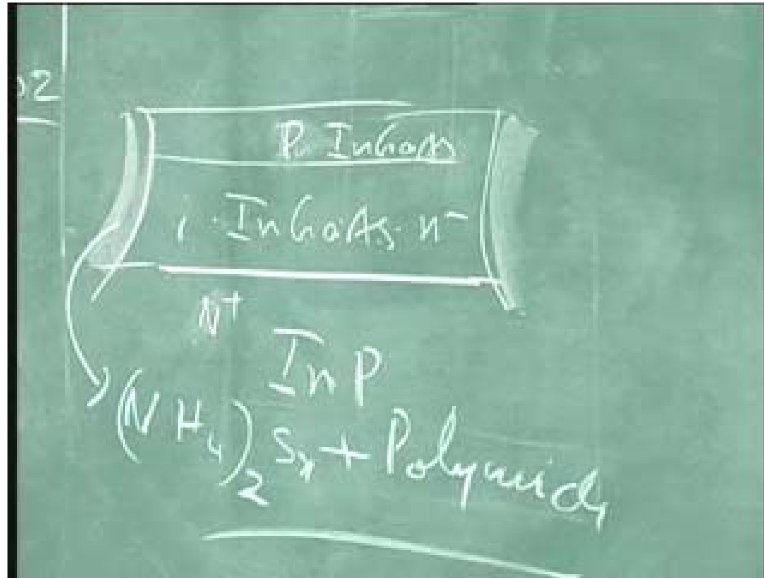

There, the same problem. I can have indium phosphide, indium gallium arsenide undoped and then I can have the indium gallium arsenide p type or in a MOSFET it does not matter. So p type it is intrinsic; this is p type, n plus. These are different layers which are there. What I am trying to point out is this is slightly n minus; then we prepare it and etch them down like this. We have the junction exposed here; when we have the junction exposed, the whole thing what we to remember is a pn junction is fabricated using epitaxial layer, we etch down so that isolates one device from other one; because, on the way number of devices are there. This surface is exposed. That gives us large leakage between the p and n layer; we passivate it and this passivation, again ammonium sulphide, which is being used. So when we use ammonium sulphide, it is not sufficient if it is ammonium sulphide, we put a quoting of anode dielectric material.

One of the things that is done is nitride which worked out very well with annealing etc., because when we deposit PECVD there are some damages which come up because of…., but here what we have tried out, in fact, as a part of an M.S degree program, passivate this ammonium sulphide and then deposit polyimide; just polyimide, very easily we can put a quoting of that; that gives excellent leakage current. In the sense, there is excellent leakage what we mean is very low leakage current. We have got excellent, very good

leakage current; if somebody comes and says I have got very good leakage current means very small leakage current; good from that point of the point of view.

Polyimide that is ammonium sulphide passivation, followed by polyimide plus polyimide - that give excellent results. In fact, authors of that slightly lashed out on the work of nitride deposition saying that gives better results because PECVD gives some damages. But to be honest in PECVD if we put when we put the gate if we heat the aluminum at 400 it leaves all the damages out. These are some of the work which has been done on the passivation which is important when we make compound semiconductor devices.

I will not touch upon other devices. In the next lecture, I will touch up on several other types of hetrojunction bipolar transistor including silicon germanium. We have taken germanium completes the gallium arsenide. We will see this in next lecture.