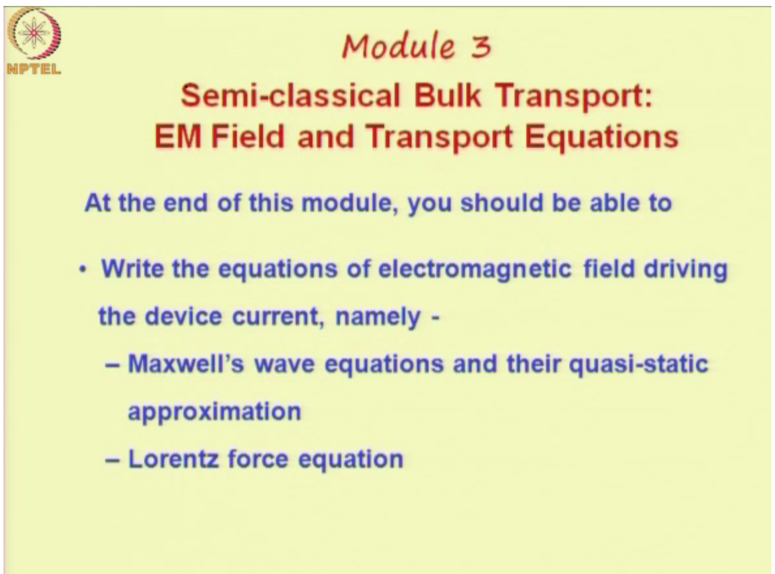
Semiconductor Device Modeling
Prof. Shreepad Karmalkar
Department of Electrical Engineering
Indian Institute of Technology - Madras

Lecture - 08
Semi-classical Bulk Transport: EM field and Transport Equations

So today we begin the third module that is Semi-Classical Bulk Transport Electromagnetic field and Transport equations. So far we have discussed the semi-classical transport from a qualitative point of view without using intricacies of any equations, so in which we intuitively visualized phenomena associated with semi-classical transport. Now we will use these understanding write down equations which will be solved to estimate the current flow in a device.

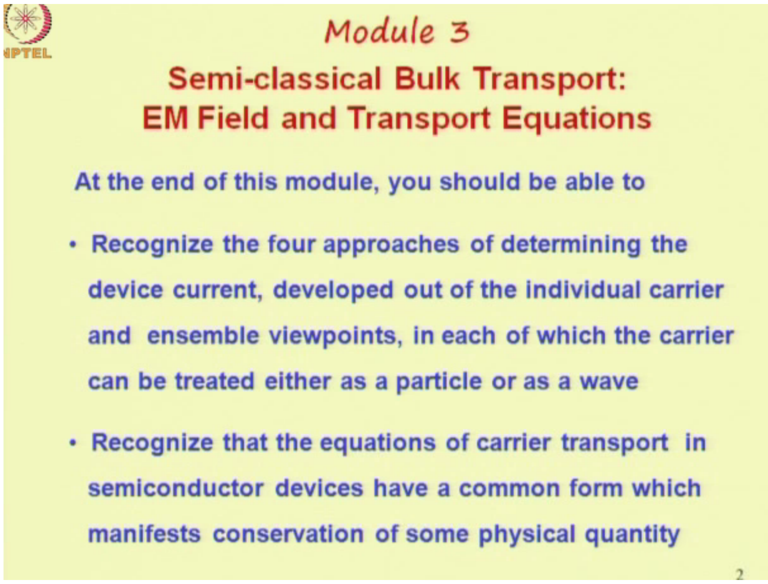
So let us first list out what we want to achieve in the course of this module.

(Refer Slide Time: 01:04)



So at the end of this module you should be able to write the equation of electromagnetic field driving the device current, so these equations are Maxwell's wave equations and their quasi-static approximation and the Lorentz force equation.

(Refer Slide Time: 01:18)

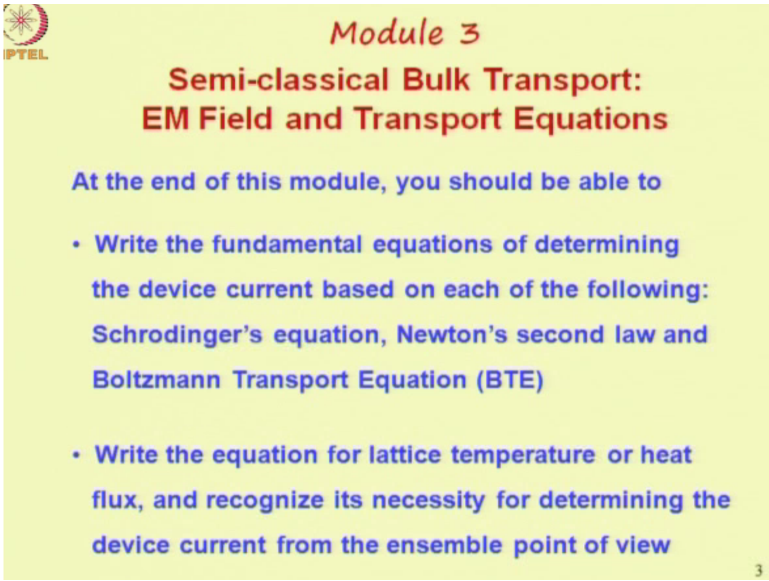


Then you should be able to recognize the 4 approaches of determining the device current, developed out of the individual carrier and ensemble viewpoints, in each of which the carrier can be treated either as a particle or as a wave. So you have individual carrier view points and ensemble viewpoint of estimating the device current and for each of these viewpoint you can treat the carrier either as a particle or as a wave.

So overall you have 4 different approaches of calculating device current. Then you should be able to recognize that the equation of carrier transport in semiconductor devices have a common form which manifest conservation of some physical quantity, now whenever students are faced with a number of equations many of them get frightened they do not like to see many equations. Now this is where this particular point is important we will find that most of the equations which are used in modelling of carrier transport or modelling of devices have a common form.

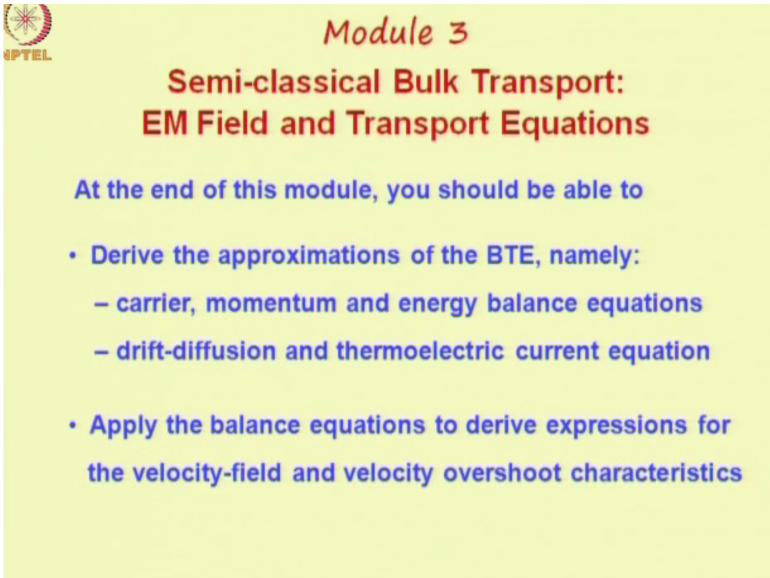
So once we recognize that they have a common form then we are much more comfortable with the equations.

(Refer Slide Time: 02:39)



Then we should be able to write the fundamental equations of determining the device current based on each of the following namely the Schrodinger's equation, Newton's second law and Boltzmann transport equation abbreviated as BTE. Next, you should be able to write the equation for lattice temperature or heat flux and recognize its necessity for determining the device current from the ensemble point of view.

(Refer Slide Time: 03:15)

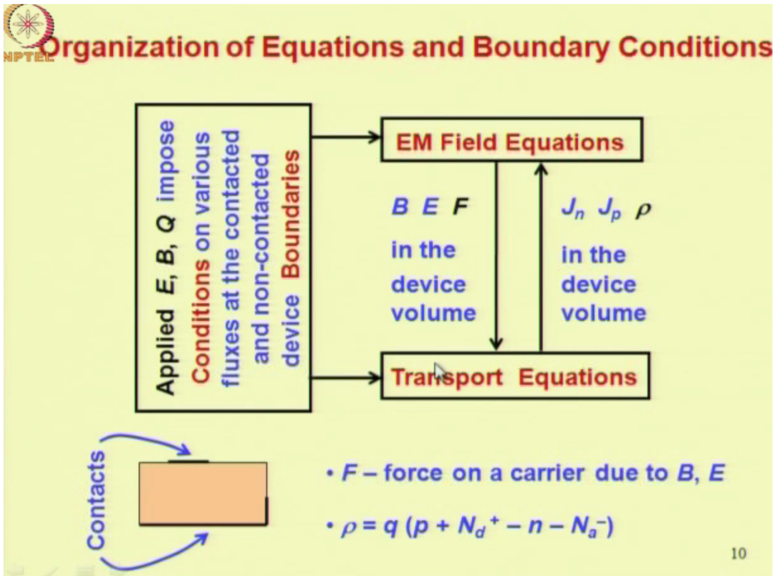


Then you should be able to derive the approximation of the BTE that is Boltzmann transport equation namely carrier, momentum and energy balance equation, drift diffusion and thermoelectric current equation. In the qualitative discussion we have remarked that you can analyze the current flow in a device using conservation of mass, energy and momentum or in the parlance of semiconductor devices kiger balance, momentum balance and energy balance.

So we are going to write down equation for these purpose and in the qualitative model we also discussed about 3 mechanisms of transport drift, diffusion and thermoelectric current. So we would like to write down expressions for this as well and show how you can drive them from fundamentals. Finally, you should be able to apply the balance equations to derive expressions for the velocity field and velocity overshoot characteristics.

So ultimately the goal of writing all these equations and understanding all these equation is that we must be able to use them and derive expressions for the current in the device which depends on the velocity. So therefore if you can write expressions for velocity field and velocity overshoot characteristics as a function of time or distance then you can model the current flow.

(Refer Slide Time: 04:49)



So let us first start with the organization of equations and boundary conditions, whenever we talk of equations we must not forget about boundary conditions, so the equation for carrier transport or in general differential equations, so whenever you want to solve these differential equations you need boundary conditions okay, so we have to always see the equations together with boundary conditions.

So the 2 sets of equations are electromagnetic field equations and transport equation. So the electromagnetic field equations give you the electric field and the magnetic flux and also the force on an electron due to these 2 and these then help to drive the current and so the transport equations tell you how if you know the electric field magnetic flux and the force on an electron you can derive the current.

So this is shown here pictorially the arrow shows that electromagnetic field equations yield in their solution the values of B, E and F, B is magnetic flux, E is electric field and F is the force on the electron due to electric and magnetic fields. Now transport equations on the other hand estimate the current density for electrons and holes abbreviated here as Jn and Jp, so these current densities are obtained taking these quantities as inputs B, E and F.

You also get the carrier concentrations for electrons and holes which together with the impurity concentration or doping level gives rise to the value of the space charge, so space charge is given by this equation q into p+Nd+ the total positive charges -n–N a- so these are the negative charges, now this space charge and these current densities are required in the electromagnetic field equations to estimate B E and F.

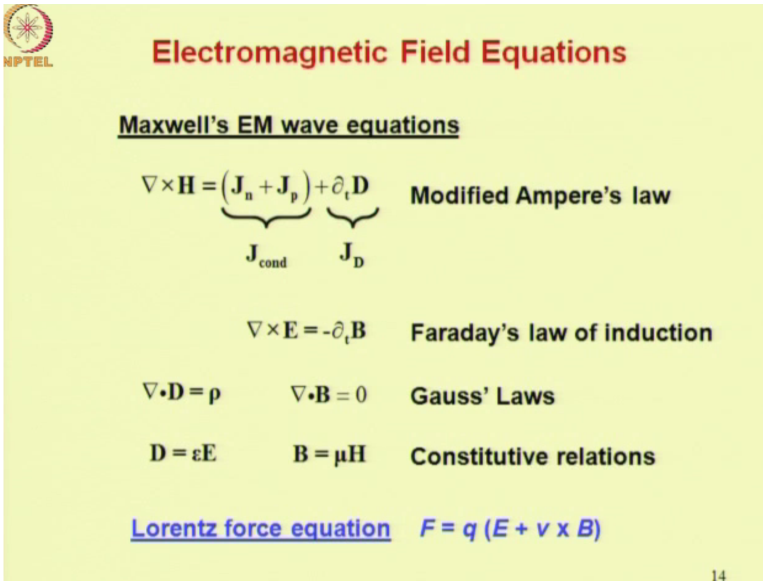
The current densities for example tell you what would be the static magnetic field around the current right and similarly the space charge will contribute to the static electric field here, so that is how these quantities are required in the electromagnetic field equations, so you see that this is the coupled situations electromagnetic field equations gives you B, E and F which are required in transport equations.

And transport equations yield Jn, Jp and rho which are required in electromagnetic field equations, so that is why equations of semiconductor devices are coupled to each other, they have to be solved simultaneously, now let us look at the boundary conditions so this is example of a device where you have 2 contacts one here and one at this end and also it is extending on the side a little bit.

So we need to know what are the values of these quantities B, E, F, Jn, Jp and rho at the boundaries of this device, so you can separate the boundaries into contacts and non-contact regions, so that is what we have shown here in the slide so the applied electric field magnetic flux and heat flux impose conditions on various fluxes at the contacted and non-contacted device boundaries.

Now let me just carry clarify where this equation for heat flux, so you see here the equations for reflex is observed in this transport equations.

(Refer Slide Time: 09:24)



Now let us write the electromagnetic field equation you have already done a course on electromagnetic fields, so you should be able to write these equations very easily, so first is the modified ampere's law which relates the magnetic field to the various current densities, so the 2 current densities here are conduction current density and displacement current density, now the word modified here actually refers to the inclusion of the displacement current density.

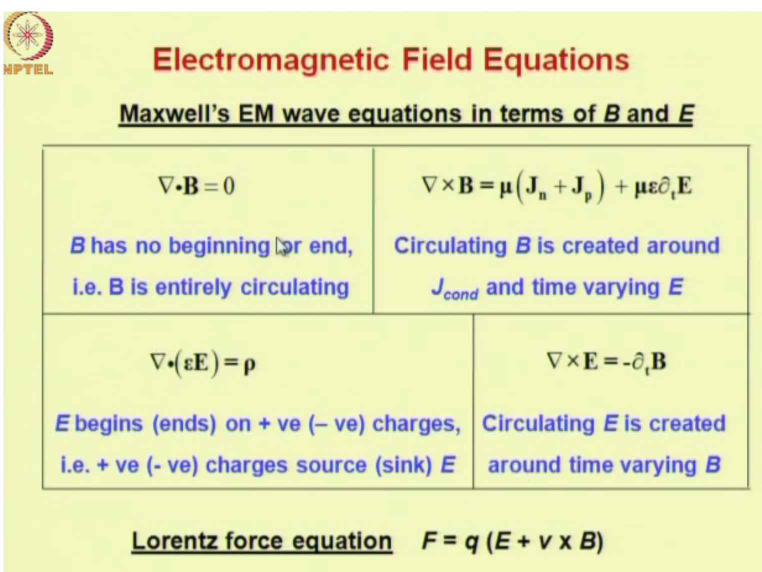
Now this is the great contribution of Maxwell so without this displacement current density you cannot predict the existence of electromagnetic waves in vacuum or free space. Next, is a Faraday's law of induction which relates the electric field crossed by the changing magnetic field, magnetic field changing at the function of time curl E = -dou B/dou t the modified ampere's law is curl H = Jn+Jp which constitute the conduction current +dou D/dou t which is the displacement current.

Then you have the Gauss' laws which tell you how the fluxes namely the displacement flux D and the magnetic flux B are affected because of various quantities, so for instance divergence of D is rho so this tells you that positive or negative static charges are sources of the electric flux divergence B = 0 this tells you that really there is nothing analogous to the positive or negative charges in the context of electromagnetic fields.

So you cannot have an isolated north or south pole right, whereas you can have an isolated positive or negative charges. So next you have the constitutive relations which relate the displacement the electric displacement to the electric field E via the permittivity of the medium epsilon and the magnetic flux to the magnetic field H via the permeability. Then you have the Lorentz force equation which relates the force on the charge q due to electric field and the magnetic flux so v is the velocity of the charge.

So F = q times E+v cross B, if the charge in the electron then q will be replaced by –q, so the electromagnetic field equations actually consists of the 4 Maxwell's equations and the Lorentz force equation, so these together constitute the electromagnetic field equations.

(Refer Slide Time: 13:02)

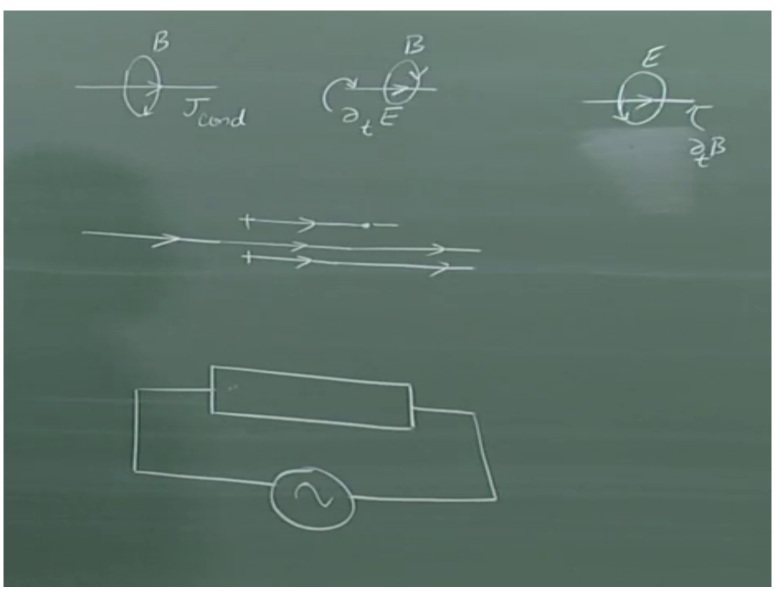


Now look at the next slide here you have written the Maxwell’s electromagnetic wave equations in terms of B and E, so previous slide consists of equations written in terms of magnetic flux B, the Magnetic field H, the electric flux or displacement D and electric field E, now since there are constitutive relations which relate D to E and B to H. We can write all the equations in terms of one quantity for the electric field or electric flux and another quantity for the magnetic field or magnetic flux okay.

That will make things simple, also you know that you can remember an equation well in your memory if you know the physical significance of the equation, so that is what we have written out in this slide for each equation what is the physical significance. So divergence B = 0 meaning of this is B has no beginning or end that is B is entirely circulating or there are no isolated north or south poles, curl B = mu times Jn+Jp+mu epsilon into dou E/dou t circulating magnetic field is created around conduction current density and time varying electric field.

So that is the meaning of this, okay. So basically this equation tells you the source of the magnetic field or the sources so magnetic field is created both by conduction current and displacement current, also since it is a curl it means that this B is circulating at circulates around J conduction and time varying so that information is also important.

(Refer Slide Time: 15:09)



So if there is a current like this then around this the magnetic field will be circulated right, so if this is J conduction then this is B, similarly if there is an electric field like this and it is changing with respect to time dou E/dou t, then also there will be a circulating magnetic field around it so this is what is meant by this equation. Let us look at the equation for the electric field so divergence of epsilon E = rho.

This means that E begins on positive charges and ends on negative charges so that is what you derive from this situations or positive charges are sources of E and negative charges are sinks of E, so if you want to show this pictorially suppose the field is in this direction and here you have positive charges then when I move to the right hand side of this I would have got extra field lines emanating from the positive charges.

So this positive recharges act like sources, on the other hand somewhere here if there is a negative charge it will sink the field line each charge with each negative charge will sink at field line, so if I pass this region and comes out I would have lost field line okay, now the accounting of all this is what is done in this particular equation divergence of epsilon E = rho divergence B = 0 and divergence of epsilon E = rho both these are the Gauss' laws.

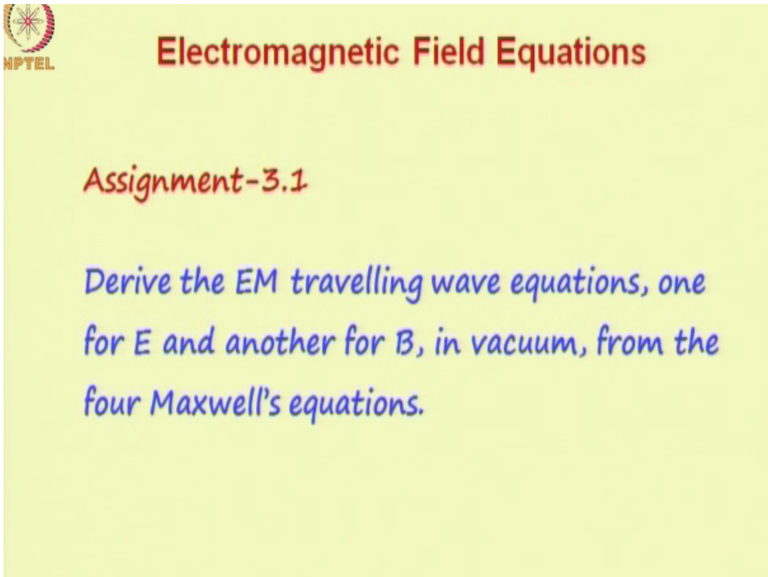
Now curl E = - dou B/dou t so this is an equation which tells you what is the source of the electric field apart from static charges rho the electric field also is created by a changing magnetic field so circulating E is created around time varying B, so again one can draw a diagrams similar to this that if there is a magnetic field something like this at any point then around it there will be a curl however there is negative sign in the relation.

And therefore the direction of the circulating field will be opposite to that what you get here, so if this is then I am sorry this is dou E/dou t, this is dou B/dou t and this is what is the circulating electric field around the changing magnetic field. Finally, of course you have the Lorentz force equation here also it is in terms of E and B so we shall use the equations in terms of E and B.

We have already clarified in the qualitative discussion of the model while why choose to use B rather why we choose to use E electric field instead of the displacement D because it is electric field E which enters into the equation for the device current as well as in the equation for the force on the charges that is the Lorentz Force equation where is it is B which enters into the force equation, so therefore we are using E and B.

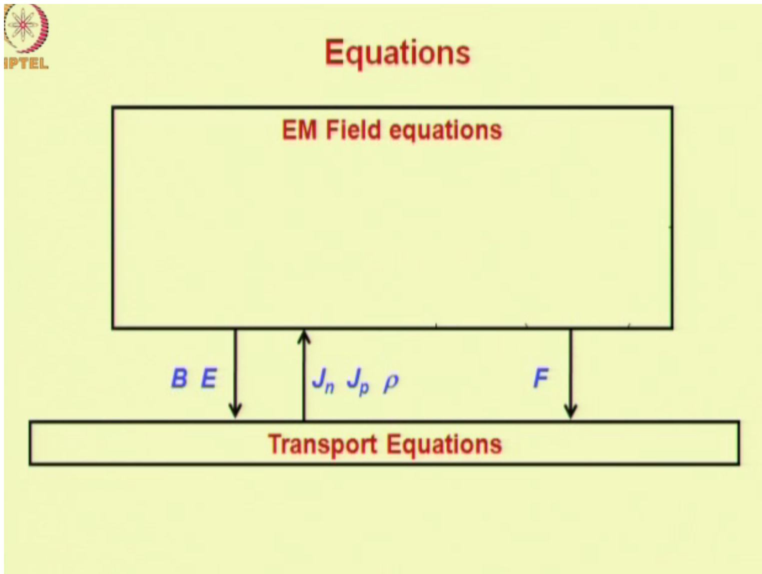
Now before we proceed further just we want to make things concrete and tell you that we are considering the current flow in device as a consequence of all this driving forces, so this is the resistor and supposing I have a changing voltage source, voltage source changing with time right AC current. So in this case as we have remarked during our qualitative understanding that when the frequencies is high you have both electric and magnetic fields here and both are varying with time, okay, so that is the kind of situations that that we are considering here.

(Refer Slide Time: 20:08)



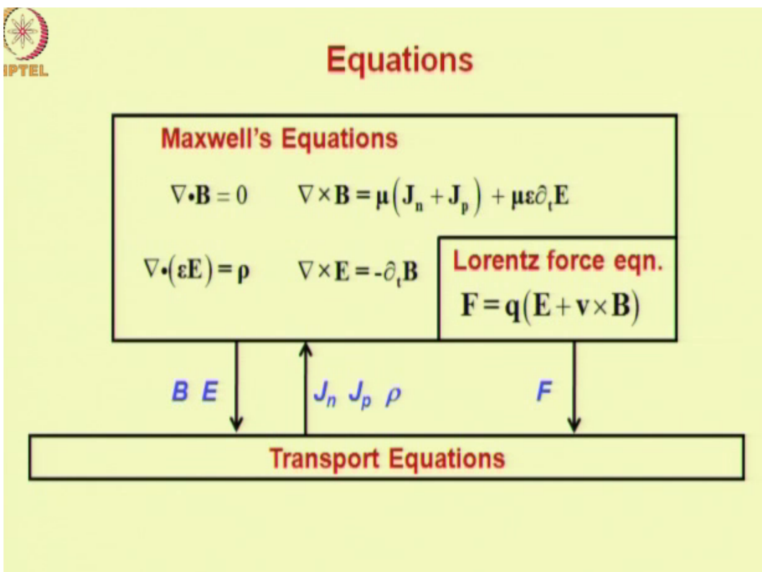
An assignment for you derive the electromagnetic travelling wave equations, one for E and another for B in vacuum, from the 4 Maxwell's equations, so if you do this exercise then you will become much more comfortable with this Maxwell's equations.

(Refer Slide Time: 20:29)



Now let us write out the Maxwell's equations and see what approximations can be made for the purpose of analyzing semiconductor devices so that we can simplify the modelling, we have already mentioned about these approximations in the qualitative reasoning here we are putting down the equations and actually showing what terms can be ignored in the approximations.

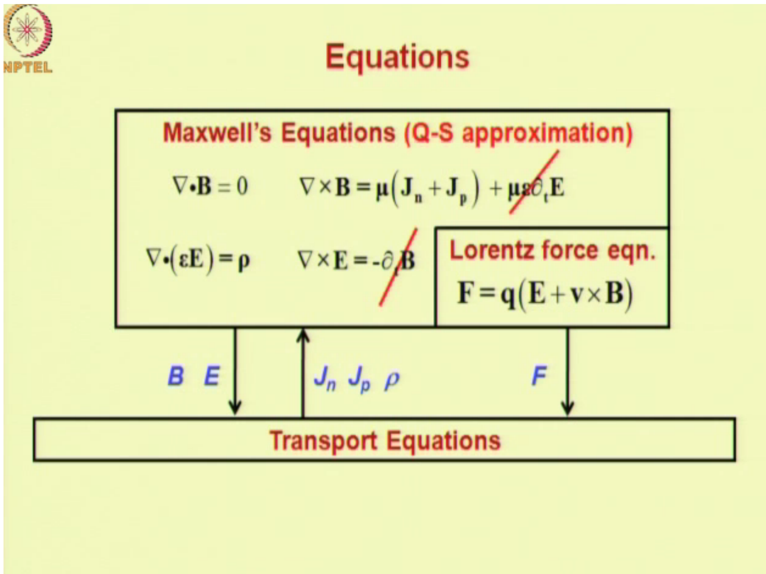
(Refer Slide Time: 20:59)



So these are the electromagnetic field equations written in this box here and the arrows here indicate that B and E are fed as solutions of or obtained a solution of these situations Maxwell equations and fed into the transport equation, similarly the Lorentz force equation gives you the information about the F, E and B are obtained from the Maxwell's equations and then fed into the Lorentz force equation.

The transport equations on the other hand yield Jn, Jp and rho and this information is required here as you can see here if I want to get the magnetic flux B I need Jn, Jp and that is obtained from here, similarly if I want to solve this equation for the electric field I need rho which is again given by the transport equations here. Now we will first discuss about the equations of electromagnetic field and their approximations and then do a similar exercise for transport equations.

(Refer Slide Time: 22:03)

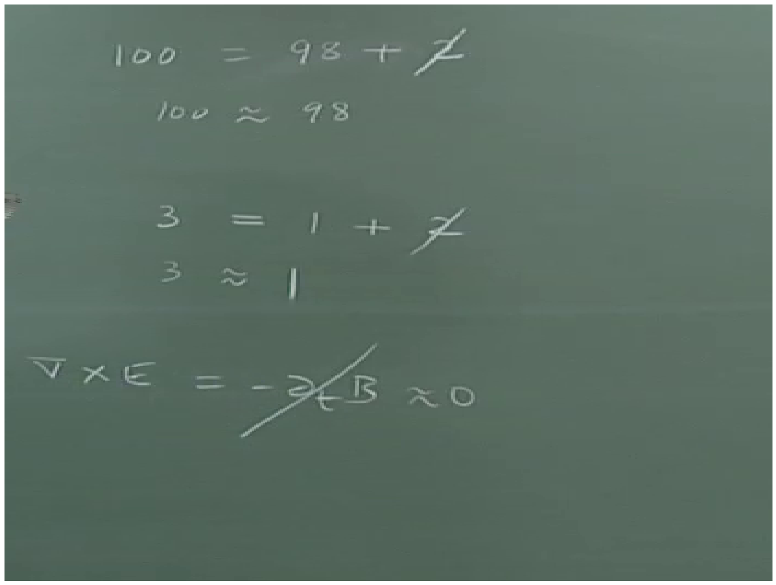


So first we made the quasi-static approximation this means we are neglecting the changing electric field here or the displacement current and the changing magnetic field here time varying electric and magnetic fields are neglected, now it is important to note that whenever we neglect a term we should not assume that the term is absolutely zero it is not as though we are setting that term is zero, we must always compare that term with the other terms present in the equation.

And so long as the term we are neglecting remains much smaller than the other terms you can neglect it, for example here when we say that this quantity is negligible does not mean this exactly is zero all that means is this is much less than either this quantity or this quantity, now this point is important to note, so we should not assume these completely static it is not at all changing with time it may be changing with time but its rate of change is not very high.

Now how do you decide whether it is high or not it is again not an absolute number, it depends on the situation and the situation as described by the other terms, so let me emphasize this point a little bit more because the students often have confusion here.

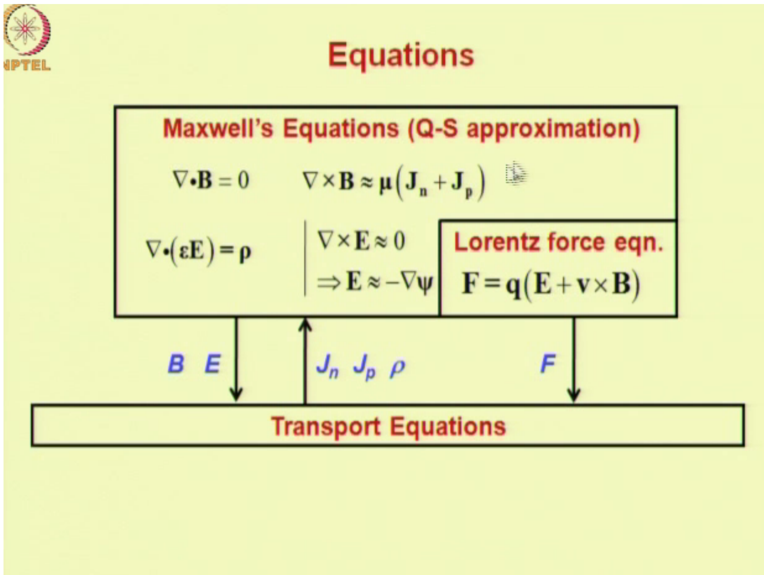
(Refer Slide Time: 23:26)



You see supposing I consider the equations 100-98 = 2 or let me write it in this form 100 = 98+2 now if I neglect this 2 it is not a bad approximation because 100 is indeed approximately = 98 with 2% error, on the other hand if I take an equation in which the same 2 appears say something like this 3 = 1+2 now when I neglect 2 I would end up saying 3 is approximately = 1 now this is evidently grossly inaccurate, okay, because 1 is one third of 3.

So we cannot make the approximation here so whether to neglect 2 or not depends on the equation in which this quantity appears right other terms so this point should be born in mind.

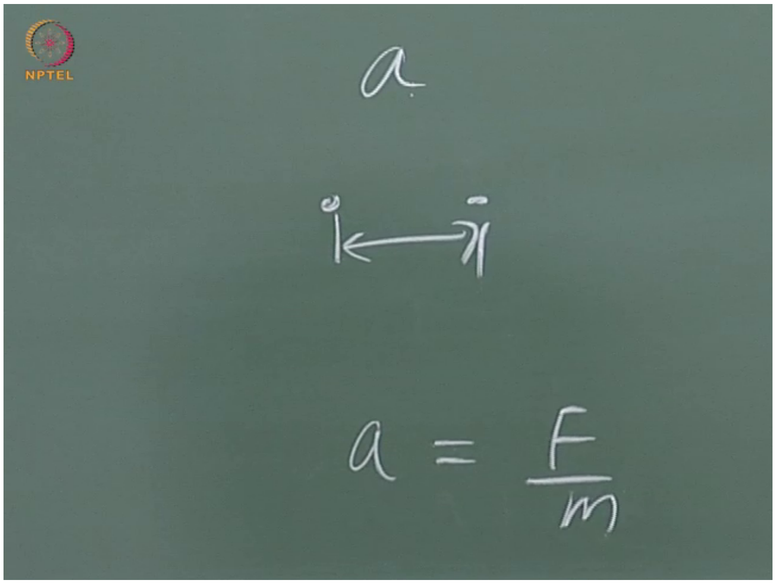
(Refer Slide Time: 24:33)



The consequence of quasi-static approximation is that the time varying electric field as removed here and time varying magnetic field is removed as a result of which curl of E becomes 0, so what we are saying is curl E = - dou B/dou t this quantity we neglect, so in other words, we are saying this is, now from the electromagnetic field scores you know that if the curl of a vector is 0, the vector can be written as gradient of a scalar.

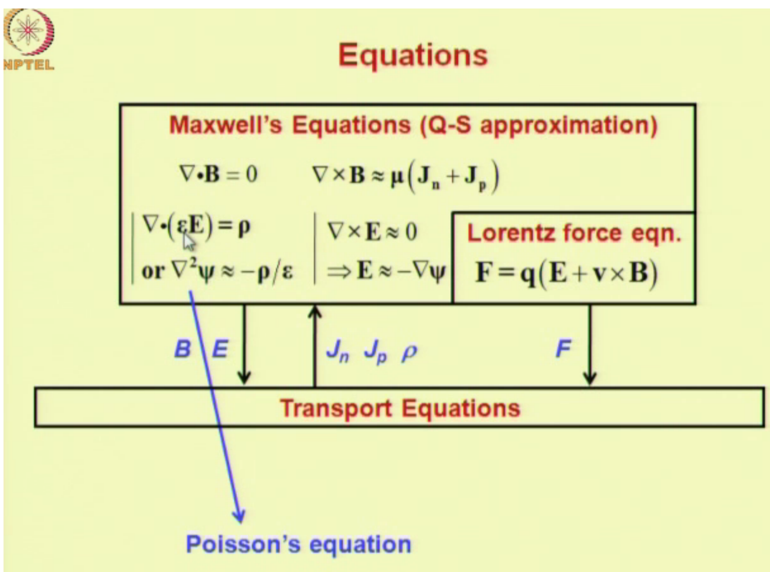
So in this case electric field is negative gradient of the potential psi, now at this point I want to just caution you that since there are many quantities are used in this particular course and we do not have as many different letters to indicate these quantities sometimes some symbols will be used for meaning different quantities, so from the context it will be clear what that symbol means.

(Refer Slide Time: 25:53)



For example, in one of the earlier lectures I have used symbol a smaller lower case a to indicate the distance between the lattice atoms or lattice constant right and also to indicate acceleration force by mass, similarly here psi is used to indicate the potential later on when we talk about Schrodinger equations the same psi symbol may denote the probability amplitude function which is used in Schrodinger equation from the context it will be clear what does the symbol mean.

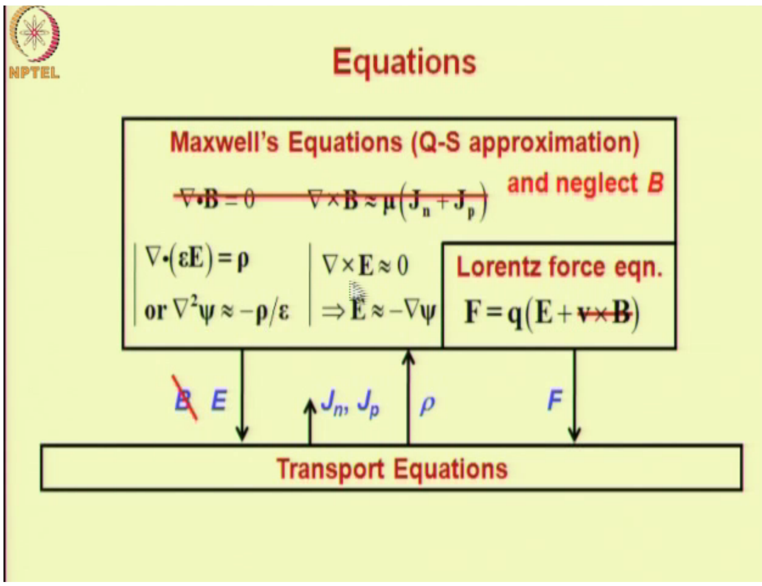
(Refer Slide Time: 26:38)



Now since you can write E as negative gradient of potential you can modify this Gauss' law if you substitute E = - grad psi Gauss' law here you will get an equation del square psi = - rho/ epsilon, so we are using this approximate sign to indicate that this is an approximation when the time varying magnetic field is neglected right so here, similarly here also there is approximation because time varying electric field is neglected here.

One more thing to be noted here is that strictly speaking I can write del square psi as –rho/epsilon only if epsilon is not varying with x so in this quantity I am taking the epsilon out so this means epsilon is a constant with x, now this assumption that you will making in this course that epsilon does not vary with x, this del square psi = -rho/epsilon is called the Poisson's equation.

(Refer Slide Time: 27:35)



Next let us neglect the result of B or the effect of B so what we are doing here is this v cross B terms we are neglecting, if a tough magnetic field is neglected, now before I proceed further you might just wonder how this v is determined, so in fact this v can be determined from the information about the current density Jn and Jp, so for example if you want to calculate the force on the electron then v corresponds to the velocity of the electron that can be obtained from Jn.

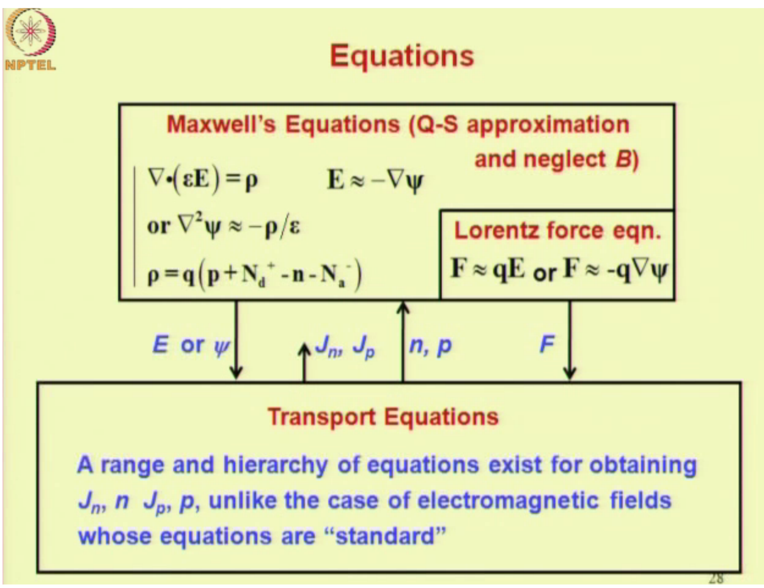
Because we know that Jn is product of - q times the concentration times the velocity, so since I know the concentration and the concentration p and I know the current density Jn and Jp I can easily derive the velocity as ratio of Jn to concentration and we also divide out the, so this is how the v can be determined if you are interested.

Now proceeding further with the approximation once we remove this term we are not considering the effect of magnetic field on the electron so force due to magnetic field on the electron is neglected we really do not need these 2 equations divergence B = 0 and curl B = mu times Jn+Jp, so this go out of the picture that is why they are crossed out here and this B also goes out of the picture.

Now once this equation has gone out of the picture you no more need Jn and Jp to solve the field equations that is why here the Jn and Jp has arrow has been terminated outside the block, so this information need not be fed into the Maxwell's equations this information is however required because in fact our aim in modeling is to calculate the current density right, so there we need Jn and Jp.

So what we have achieved is that because of neglecting of B we no more have to couple the transport equations and Maxwell equations through Jn and Jp so that coupling has been removed so this is a considerable the simplification.

(Refer Slide Time: 30:24)



Now here is the summary of the equations with these approximations the quasi-static approximation and neglect of B E = - grad psi this is the approximation of the curl E = - dou B/dou t, then divergence of epsilon E = rho that is the Gauss' law or del square psi = - rho/epsilon this is the Poisson's equation, now we are retaining both forms of these equation.

Because sometimes it is easier or necessary to find out the electric field from the space charge in which case the Gauss' law form is useful, on the other hand sometimes we would like to relate the potential to this space charge okay, so at that time the Poisson's equation form is useful, the force on the electron is given by not exactly electron force on the charge q is given by f = q times or since E is given as negative gradient of psi force is = -q times gradient of psi.

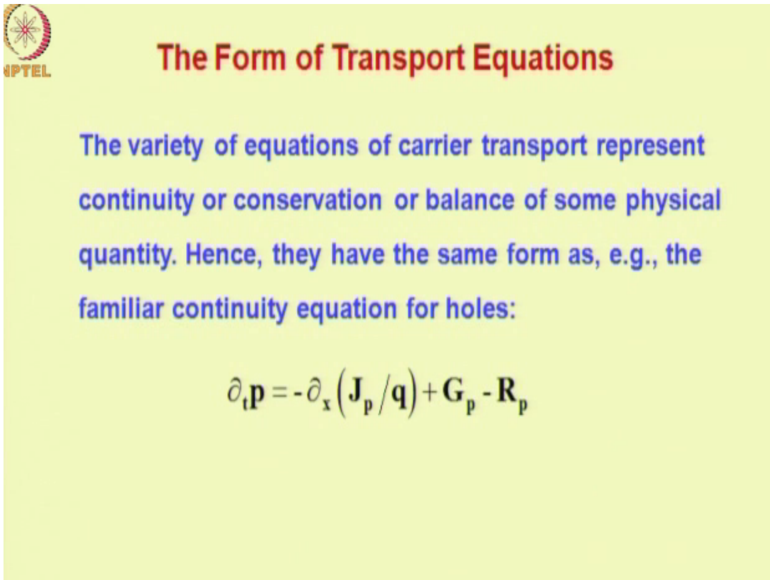
So these are our electromagnetic field equations only 3 of them, now rho the space charge which is required to solve this Gauss' law or Poisson's equation is actually of the form rho = q times p+Nd+- n-N a-, so really if you know the electron concentration and the hole concentration then you know rho that is why what we are doing now is including that rho equation along with the Maxwell's equations.

And instead of rho we now show the electron concentration and hole concentration as inputs to the field equations and these are obtained from the transport equations, now with that we are completed the discussion on the magnetic electromagnetic field equations. So we would like now to discuss the transport equation and as a comment made here shows range and hierarchy of equations exist for obtaining electron current density, electron concentration, hole current density and hole current concentration.

Unlike, the case of electromagnetic fields whose equations are standard here you can see the output of transport equations is Jn, Jp, n and p. Now the reason why you have a hierarchy and multitude of equations is the following, the situation in a semiconductor device is very complex so you have millions of particles, electrons and holes moving about randomly and also a directed motion is super imposed over this random motion.

And these particles are colliding with phonons, photons and impurity atoms which themselves are randomly located so the situations are fairly complex. So once you have a complex situation there are different ways of simplifying this picture and that is why you have a range of equations okay, so the problem of flow of charge in a semiconductor is much much more complex than let us say a 2 body collision that you might have studied in Physics, so here it is a multibody collision and multitude of collisions.

(Refer Slide Time: 34:29)

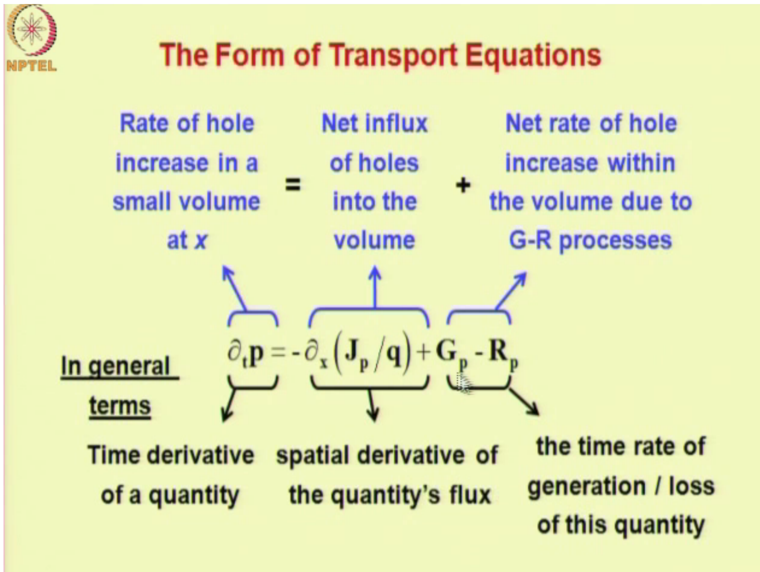


Now once we have said that the number of equations exist for describing carrier transport many students get frightened and they feel they have to deal with a large number of equations, now this is where this point that we are making now is very important as a slide says the variety of equations of carrier transport represent continuity or conservation or balance of some physical quantity hence they have the same form as for example the familiar hole continuity equation.

So that is dou p/dou t = -dou/dou x of Jp/q+G p–R p so here the question is written in one dimensional form it has a time derivative of hole concentration on the left hand side and the special derivative of the hole current density on the right hand side and this is the generation rate, excess generation rate and R p denotes the excess recombination rate, so this continuity equation of holes you would have come across in your first level course.

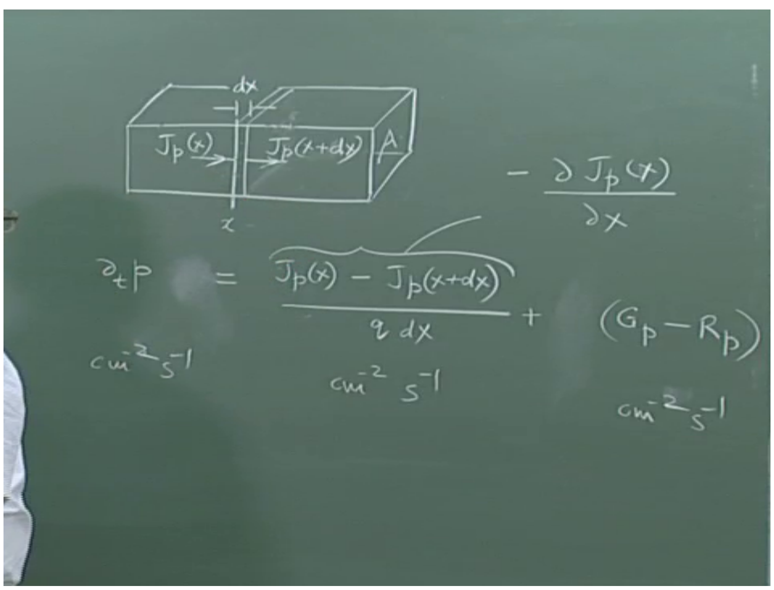
Now, what is interesting is that many of the equations of carrier transport that we are going to discuss will have this kind of a form, so let us understand the form of the hole continuity equation and see how you can extract some general patterns out of this.

(Refer Slide Time: 36:18)



So one way of looking at the continuity equation or interpreting the continuity equation in words is the following dou p/dou t it represents the rate of hole increase in a small volume at x let us draw a diagram to illustrate this point.

(Refer Slide Time: 36:41)



so let us say this is some x and you are looking at a small volume dx, now this one dimensional when we refer to a small volume what it means is that there is a cross-sectional area that is in this direction right and however the quantities are only varying in x direction, so when we are talking about the value here so it means this is the volume, so within this volume or within this region of thickness dx the rate of change of hole concentration is dou p/dou t.

Now why would the hole concentration increase in this region so as this next terms shows right hand side tells you the contributions to the rate of hole increase, so one contribution is the net influx of holes into the volume so here there may be some holes moving in and some holes moving out suppose this is Jp of x and this is Jp of x+dx, now this can be different from this so this difference may be responsible for increase in the hole concentration or decrease.

So if Jp x is more than Jp x+delta x then there is a net input of holes, so this term you will represent as Jp x–Jp x+dx and you will be divided by q, because here you are talking of only the concentration and not the charge, now further look at the dimensions here this is per centimeter cube and since there is a per unit time per second.

Now if I write this unit for this current density is coulomb per centimeter square sorry ampere per centimeter square and that is coulomb per second per centimeter square and that coulomb and this q will cancel and so this will be per centimeter square per second, so you see there is a one dimension is missing here and that is because if you are talking of input of the rate of increase of holes within this volume it will depend on this distance dx if dx is more there will be more holes inside.

So here we have to multiply this by dx when you are writing the equation okay, so when we do that this will also become per centimeter square okay and in addition you can have generation inside the volume or recombination, so that is represented here by the terms Gp – Rp, so Gp will cause an increase in hole concentration and Rp will cause a decrease, now again unit of this is per centimeter cube per second.

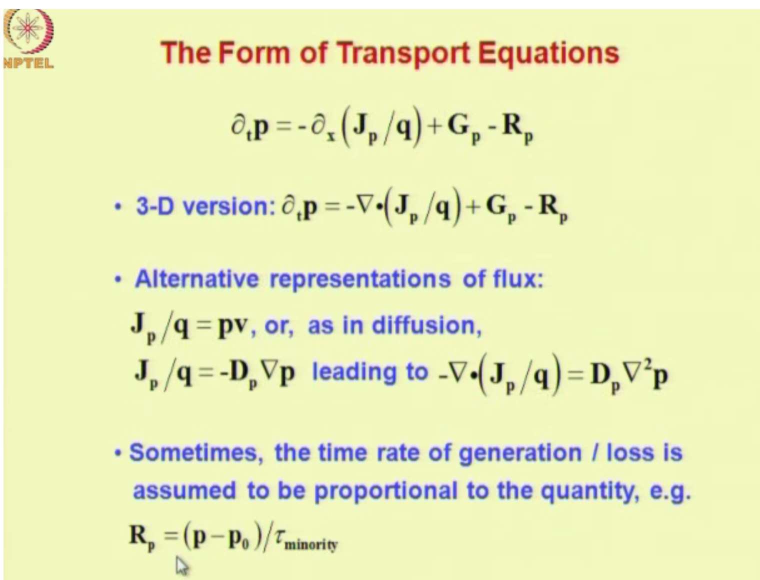
So you have to multiply this again / dx to get per centimeter square so dx is more, more quantities will be more holes will be generated, now if you divided throughout by dx then this dx gets cancelled and now this term for dx lead in to 0 is nothing but so this term you can identify it as dou Jp x/dou x with a negative sign, because dou Jp/dou x will be Jp x+dx-Jp x/dx, now we are putting a partial derivative here because things are changing with the distance as well as the time.

So while this is derivative with respect to time, this is derivative with respect to distance, so this is what is shown here this term is net influx of holes into the volume + this quantity is net rate of hole increase within the volume due to generation recombination process, so you realize that this is conservation balance or continuity equation, so this is a form of the hole continuity equation.

We will find that many of the transport equations are actually continuity balance or conservation of some physical quantity, so you will replace the hole concentration of this continuity equation hole continuity equation with the appropriate quantity to get the other transport equation, so here is the generalization of the form of this equation, in general terms we can say the time derivative of a quantity here it is p is there on the left hand side of this equation.

And right hand side you have special derivative of the quantities flux so Jp is the flux of p and time rate of generation or loss of this quantity, so Gp and Rp together this is the net generation or loss of p per unit time per unit volume, now let us look at some further things about this equation in what way can the flux Jp we written.

(Refer Slide Time: 43:17)



So before we look at that just let us put down the 3-D version of this continuity equation, so dou p/dou t = - divergence of Jp/q+Jp -R p so this is the 3-D version, so this dou/dou x is replaced by divergence, now this is where we consider the representations of flux Jp. So one way you can write Jp is Jp/q as the hole concentration into velocity or the quantity into velocity of the quantity or as in diffusion for example if the current is hole current is because of diffusion.

That is it is because of radiant of the quantity then you write it as minus the gradient of the quantity that is holes in to a coefficient or constant – Dp in this case so if such a form for the flux is used then divergence term comes out as this form, so divergence of Jp/q with a negative sign that is what you have here = Dp into del square p. So your flux term on the right hand side can be either of the form the quantity into its velocity, the quantity on the left hand side into its velocity or del square of this quantity p but with a positive sign and some coefficient over here.

Now sometimes the time rate of generation or loss is assumed to be proportional to the quantity, so this term here Rp for example from the first level course you would know it is written as p – p0/minority carrier lifetime. So you can generalized it by saying it is equal to this quantity p in general some this quantity minus reference quantity by a time constant, so this kind of form is used to represent the loss of the quantity.

So these aspects that is how the flux can be expressed either as quantity in to velocity or as del square of the quantity and how the loss can be expressed as the quantity divided by a time constant, so these features will be generalized will be used to write other equations. So once we have can cast all other equations that we discussed in this form you will appreciate that it is not at all difficult to remember all these equations.

In fact, given a new situation if you are asked to write an equation and you can recognize that equation to be a balanced conservation or continuity equation you will be able to write the form of the equation by intuition after the knowledge of from a knowledge of this discussion. So towards the end of this lecture let us make a summary of the key points. So in this lecture we started discussion of the equations which should be solved to derive the current in a semiconductor device.

So we discussed the arrangement of these equations or organization of these equations and we said that you can separate these equations into 2 sets one set is the equations of electromagnetic field and other set is the equations of transport. So these 2 sets are coupled because the equations of electromagnetic field need a knowledge of device current or rather electron and hole current densities and space charge.

On the other hand, these quantities are obtained from the transport equations and transport equations themselves need knowledge of the electric field, the magnetic field and the force due to these fields on the electron or hole charge and this is given by the electromagnetic field equations. So you have therefore 2 sets of equations coupled to each other and then we also emphasized that this equation should be seen along with boundary conditions.

So the field equations and the transport equations are both differential equations which have to be solved subject to some boundary conditions, so what are the conditions on electric field, magnetic field, the heat flux then Jn, Jp and so on, at contact and noncontact boundaries this knowledge is also important. After discussing this organization then we went on to describe the equations of the electromagnetic field in detail.

So we said there are 5 equations which include the 4 Maxwell's equations and the Lorentz equation which gives you the force due to electric and magnetic fields. Then we discussed the approximation of these equations we said that if we neglect the effect of B you neglect the force on the electron or hole due to the magnetic field then 2 of the Maxwell's equations just dropped out.

And you are left with only the 2 remaining one of these 2 curl E is approximately = 0 and the Gauss' law which says divergence of D displacement = rho. Now since in the quasi-static approximation the curl E is 0 E can be expressed as negative gradient of the scalar quantity that is a potential, so therefore we can derive the equation the electric field from the potential apply and there are no circulating electric fields.

Similarly, because of the expression of E in terms of negative gradient of psi the Gauss' law which is divergence of epsilon E = rho can be written in the Poisson's equation form as del square psi = -rho/epsilon in terms of the potential, so you can relate potential to the space charge and the Lorentz force equation becomes very simple the force on an electron is = negative q which is the charge on the electron multiplied by the electric field.

Now after discussing the equations of electromagnetic field and their approximations then we started the discussion of the transport equations and then we pointed out right in the beginning that though you will have a large number of equations because there are different approaches of solving the complicated problem of carrier motion in semiconductors most of these equations have a common form which is the same as the form of the hole continuity equation which you are introduced in the first level course.

So this form consists of a time derivative of a quantity on the left hand side and on the right hand side the negative gradient of the flux negative divergence of the flux of this quantity and rate of loss or gain of this quantity also and this form of the equation will be repeatedly seen in the various transport equations that we discuss in the next lecture.