VLSI Technology

Dr. Nandita Dasgupta
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 30
Metallization - I

In our discussion of the unit process steps in VLSI technology so far, we have come to the very last step, so to speak. That is the metallization. You know that metal contact is the connection of the integrated circuit to the outside world. We must have a contact for the devices to be electrically connected. So, metallization is therefore a very important step in VLSI technology. Now, depending on what is the purpose of having these contacts, we can classify the metallization scheme in generally two parts. One is the ohmic contact metallization. That is as the name suggests, it simply forms an ohmic contact. You want a contact to the source region or to the drain region or to the emitter or base or collector; you want an ohmic contact.

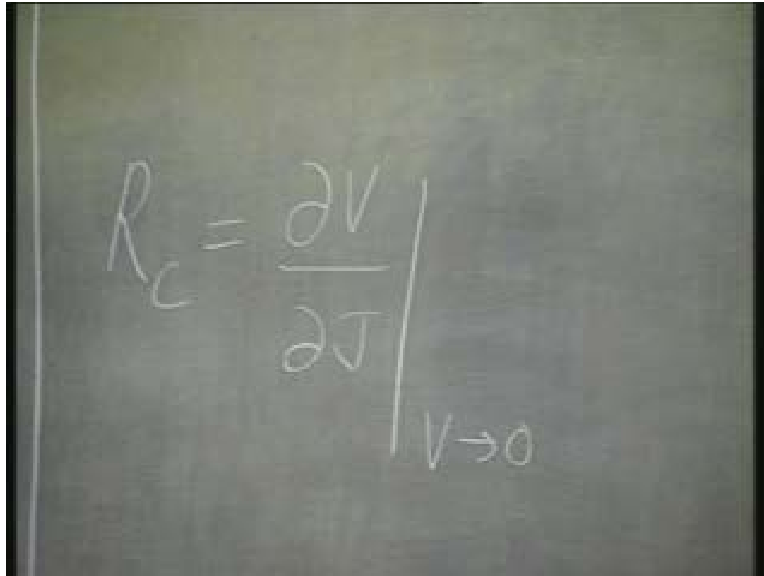
The other half of metallization involves gate metallization. I would not call it really a metallization in the actual sense of the word, because you know that, for MOSFET, nowadays gates are not really metal, right. They are mostly polysilicon and now more and more the gates are becoming silicided, silicide gate technologies; polysilicon, on top of it, we have a silicide, like tungsten silicide or tantalum silicide, something like that. So essentially, we can therefore have two classes, when we look at the metallization or the contact metallization problem. One part is ohmic contact, which is simply deposition of metal in order to form ohmic contacts and you know that the most common metal in all this metallization scheme is aluminum.

The other half is that of gate metal, which is not really metal, but doped polysilicon, topped with silicides and of course, we have to have the interconnection between the devices, because as you know, in integrated circuit all the devices are internally connected. For example, if you want to have an inverter, then the source of one MOSFET should be connected with the drain of one MOSFET; all those interconnections must be provided internally. Usually, these interconnections and the gate contact, it is provided at

the same level. That is we use the same polysilicon line for all these purposes. So, we could say that the metallization scheme is divided in two parts. One is the ohmic contact metal and other is gate and interconnections.

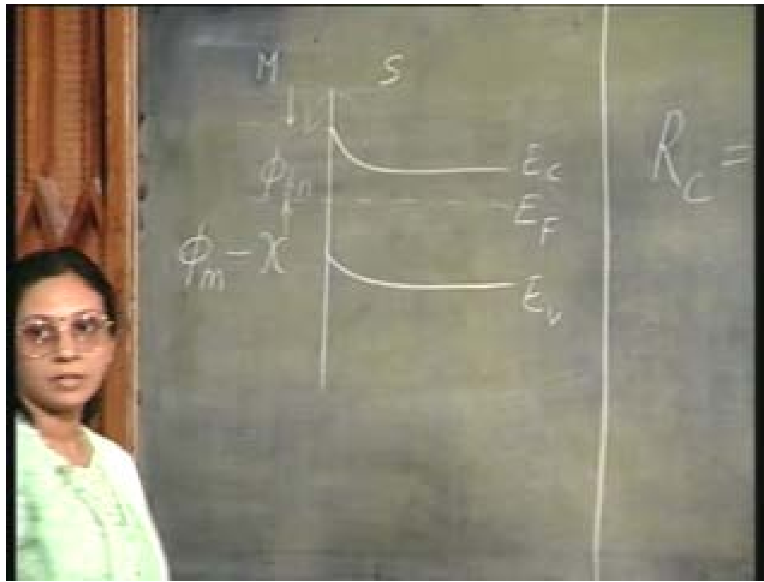
Let us first look at the ohmic contact metal. I want an ohmic contact. Therefore, the first requirement is that the ohmic contact must have low contact resistance; first requirement is that it must have low contact resistance. Now, what do I mean by this contact resistance?

(Refer Slide Time: 4:49)



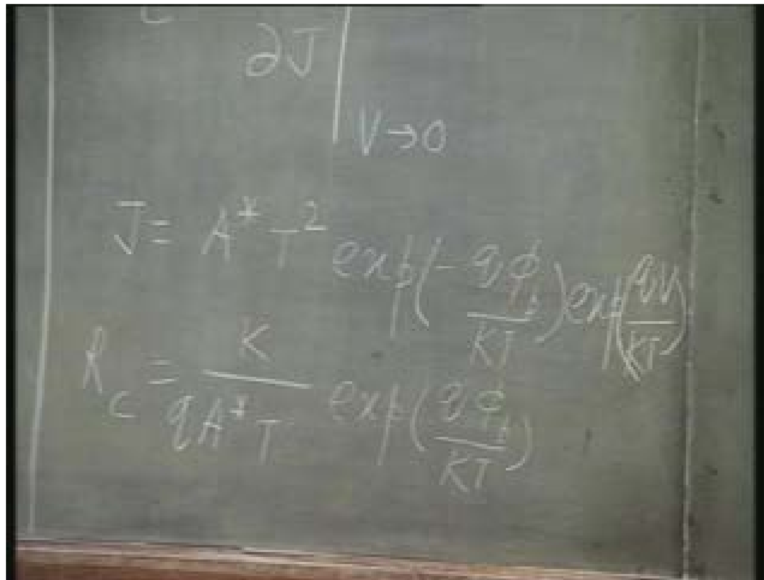
The specific contact resistance given, usually noted by R C that is the specific contact resistance, is actually defined as del V del J; V is the applied voltage, J is the current density, when the applied voltage is nearly equal to zero, for very small applied voltage. That is the specific contact resistance. Now, you know in general, when I put metal on semiconductor, what I get is a Schottky barrier, right, usually. Most generally, I would say that if I put I metal on a semiconductor, what I should get is a Schottky barrier.

(Refer Slide Time: 5:49)



For example if I have an n-type semiconductor, then this is the fermi level. This is E C, this is E V and this is the barrier, right. In general if I have a metal, this side is metal, this side is semiconductor. In general, this is how the band structure is going to look like and you also know that ideally, this barrier height will be given by the metal work function phi m minus the electron affinity of the semiconductor that is chi, right. So in general, particularly when the semiconductor is moderately doped and if I put a metal on top of the semiconductor, this is what the band structure is going to look like and you know in a Schottky, if I assume that the current is mostly due to the thermionic emission that is the transport is over the barrier, thermionic emission, right; that is the thermionic emission.

(Refer Slide Time: 7:25)



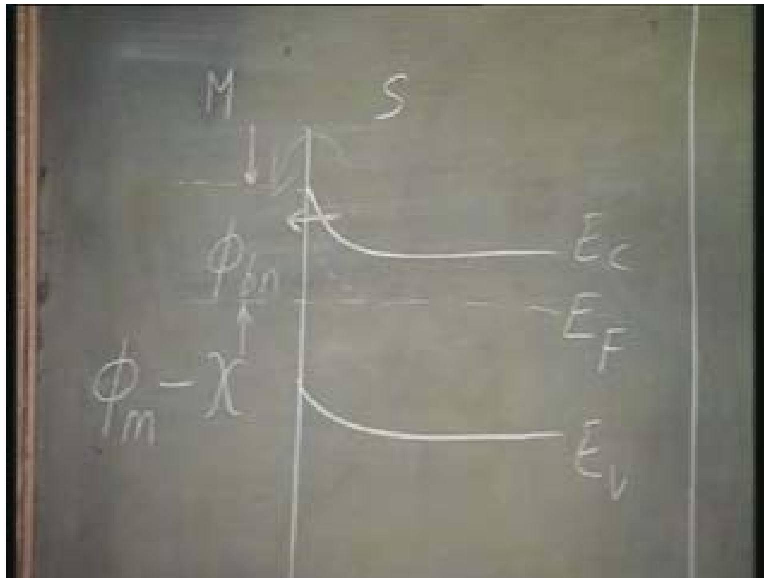
If I assume that the transport of carrier is over the barrier, by thermionic emission process then the current is given by, the current density is given by …… What does it mean? J that is the current density that is given be A star that is Richardson's constant; it is a constant, T is the temperature, exponential minus q phi b by KT. That means the bigger the barrier, the smaller is the current, obviously and exponential qV by KT that is the more the applied voltage, the bigger is the current, obviously. So, if I assume that thermionic emission is the dominating process of current transport, then the current will be given, it is related to the voltage by this equation and therefore you can very easily solve for the specific contact resistance and you can see that the specific contact resistance will be given by …, right.

If I simply take the derivative del J del V and then put V equal to zero, the specific contact resistance will simply be given by K by q A star T exponential q phi b by KT. That means all other factors remaining constant, A star is the Richardson's constant, its value is 120 for silicon, you know, T is the temperature. So, for a given temperature, the contact resistance is directly proportional to the barrier height, right; it is directly proportional to the exponential q phi b by KT. The bigger the barrier is, the bigger is the contact resistance, right. That means you have to keep this in mind, because I want very

low contact resistance for ohmic metal and phi b is a material property, ideally given by phi m minus, phi b m minus, phi m minus chi; metal work function minus the electron affinity of the semiconductor. Once you fix the metal and the semiconductor, you cannot really do anything about it. So, for moderately doped semiconductor, the contact resistance is therefore simply given by this.

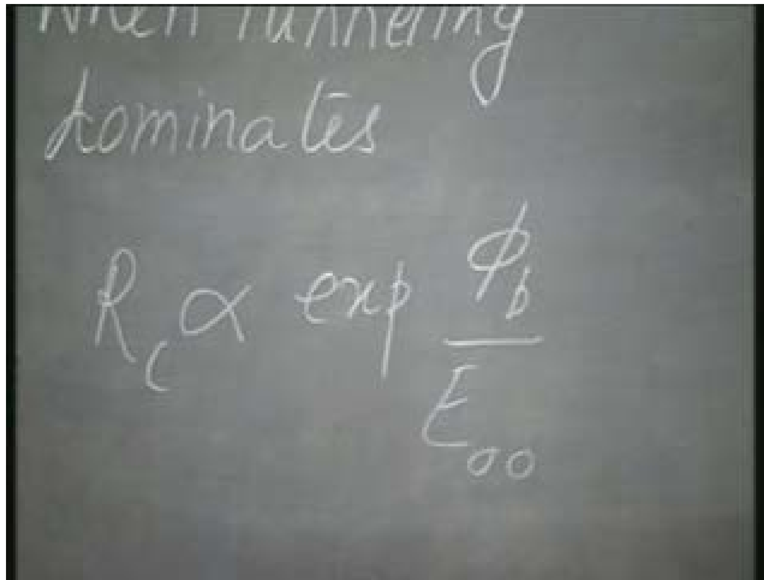
However, if the semiconductor is heavily doped, what will happen if the semiconductor is heavily doped?

(Refer Slide Time: 11:08)



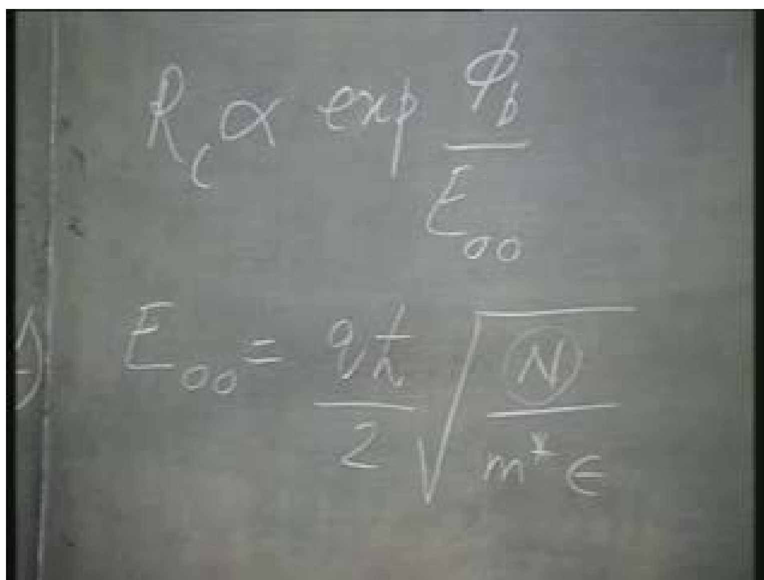
I will have a narrow barrier here, like this. That means there can be movement of carriers through the barrier, by tunneling through the barrier, right. If the semiconductor is very heavily doped, in consequence the barrier becomes narrow. It is like you are having a thin barrier, so now, physically you could view the electrons tunneling through this barrier. They do not have to cross over the barrier as in the thermionic emission process, they can tunnel through the barrier and in that case, the current will be given by the tunneling parameter and consequently, the contact resistance will also be proportional to that.

(Refer Slide Time: 12:10)



Instead of being professional to phi b by KT, when tunneling dominates, when tunneling dominates, instead of R C being proportional to exponential phi b by KT, it becomes proportional to exponential phi b by E 0 0, where E 0 0 is the tunneling parameter and that is in its turn proportional to the, it is related to the doping concentration of the semiconductor.

(Refer Slide Time: 12:58)



E 0 0, the tunneling parameter is given by q, h cross is the Planck's constant by 2 square root of N by m star epsilon; N is the doping concentration of the semiconductor. That means, you see, the higher the doping concentration, the higher is E 0 0 and the lower is the contact resistance. Now, the question is, how do I know which one dominates? How do I know whether it is thermionic emission that is dominating the carrier transport or whether it is tunneling that is dominating the carrier transport? Obviously, it will depend, answer is in the doping level of the semiconductor. For moderate doping, thermionic emission is going to be the dominating process; for very heavy doping, tunneling is going to be the dominating process.

(Refer Slide Time: 14:13)

So, usually we say that, when N is greater than 10 power 19 per centimeter cube, it is dominated by tunneling and for N less than 10 power 19, it is going to be thermionic emission. So you see, therefore if you have very heavily doped region like source, like drain, like emitter, then forming an ohmic contact is not a problem, right. If on the other hand I have moderately doped region, then the contact resistance is going to be given by, it is going to be proportional to exponential q phi b by KT and once the metal and the semiconductor is fixed, I cannot really play with this phi b at all. So, I may have a problem.

In fact, this is one reason why it is difficult to form an ohmic contact to a moderately doped n region. Why? Because you are using aluminium; aluminium to n-type semiconductor, it has quite a considerable barrier height. On the other hand, if you have a moderately doped p-type semiconductor, aluminum itself is a p-type dopant, so it is not a problem to form an ohmic contact to a moderately doped p-type region. That is one reason why in integrated circuit, we prefer to have npn transistors rather than pnp transistors, because in a pnp transistor, forming the base contact is going to be a problem, where as in the npn transistor, emitter region is heavily doped n, so contact resistance is not a problem, it is governed by the tunneling parameter and the base region, though moderately doped, it is p-type and with aluminum, the barrier height is low.

Now the question is, so I know that these are the pit falls; I have to keep the contact resistance low and therefore, either I have a heavily doped region or if I have a lightly doped region, then I should be careful in my choice of the metal. However you really cannot do much about it, because accepted practice is aluminum is used for metal contacts in VLSI technology. Therefore, the moral of the story is, avoid having moderately doped n-type region to form ohmic contacts. It is difficult; in silicon technology, it is excessively difficult to form ohmic contact to moderately doped n-type region, right.

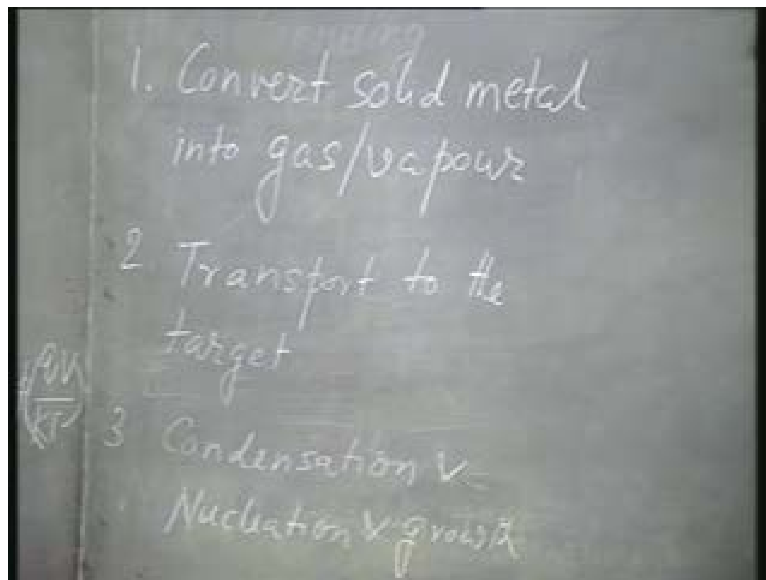
Now, the question is, how do I form the metal contact? Primarily, metal is deposited by physical vapour deposition as opposed to chemical vapour deposition, which we discussed yesterday. You have chemical vapour deposition for materials like silicon dioxide, silicon nitride; either plasma assisted or not plasma assisted. But for metal deposition, you prefer to a have physical vapour deposition, no chemical reaction; it is simple physical vapour deposition and you can have essentially two techniques. One is a simple vacuum evaporation technique; the other is the sputtering technique. Both of them have a few features in common.

Essentially, we have three steps. First is you have the solid metal, you have to form that solid into a gas or a vapour, right. That is the first requirement. For any physical

evaporation, I have a solid metal source, I have a solid source and I have to form a gas or vapour phase. Then, second step is transport of this material; transport of the material in gaseous phase to the target, where I want to the metal to be deposited. So, the second step will be transport of this material and finally, this material, remember it was in gaseous phase, now it must be condensed back as a film on the target material, on the substrate material, right; it must be condensed back and nucleation and growth of the film should take place.

So, whether it is vacuum evaporation technique or sputtering technique, essentially you have three steps.

(Refer Slide Time: 20:17)



First step is convert solid metal into gas or vapour. Second, transport to the target and finally, condensation of the vapour back and nucleation and growth of film. So, whether it is vacuum evaporation or sputtering, you have these three processes. In evaporation technique, you have a substrate which is kept at a lower temperature and you have the metal source placed on a heater. So, what happens? You heat the source, metal forms a gas vapour and because the substrate is at a lower temperature, it condenses on the substrate, simple evaporation technique and the way you heat the metal source can be

resistive or inductive or you can use RF or even electron beam heating. Most common is resistive followed by e-beam. Particularly when it is difficult, the material has very high melting point, very high vapourization point, then it is useful to have e-beam system. For example, if you want to evaporate copper, let us say, copper or nickel; you see, they have very good thermal conductivity also. So, it is very difficult to heat it just by resistive heating, so then we generally use e-beam technique.

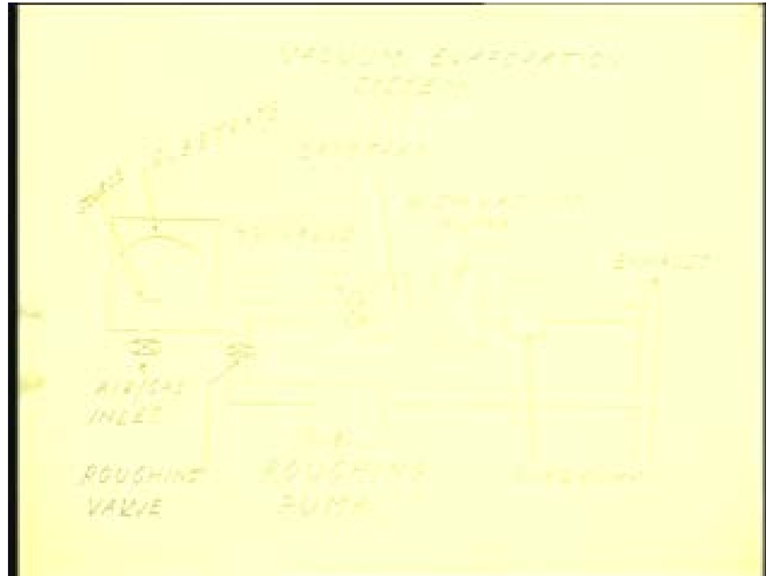
On the other hand when you have a sputtering system, sputter deposition system, there you have a big target material. You know, the metal source, it comes in the form of, usually in the form of a disc, a big disc and that target material is bombarded by energetic ions, high energy ions and what happens? Physical etching takes place, sputtering takes place. That is from the target material, some metal, some material is pulled out by force, sputtered and this material is then condensed on the substrate to form the film of metal.

One major advantage of the sputtering technique is when you are planning to evaporate an alloy. Let us say, particularly for compound semiconductors, it is a very common alloy like gold zinc or gold geranium. You have a particular composition of the alloy, let us say, 88% gold and 12% germanium. Now, what happens, if you try to evaporate this alloy, then the composition of the film may not be exactly the same as that of the alloy, because the two materials may have different evaporation rates However, if you have a sputtering target, target made of this alloy material, then because it is a physical sputtering process, it is non-selective; it is physical sputtering process, therefore the alloy composition is preserved exactly even on the film.

So, particularly for deposition of alloy with precise composition, sputtering techniques becomes very useful. But, sputtering will have a little bit of problem. You see, you are using high energy ions to bombard on the substrate. Therefore, there will be some amount of ion damage, which of course can be annealed out. The annealing temperature also is comparatively low, less than 500 degree centigrade; these damages can be annealed out. The other problem is unlike in vacuum evaporation technique, in sputtering technique, the pressure is usually comparatively higher. Therefore, the films will have some trapped

gas; also possibility of some trace of contamination in them. So, mostly for metal deposition, most common technique for metal deposition is the vacuum evaporation technique.

(Refer Slide Time: 26:03)



I have a schematic diagram of a vacuum evaporation technique here, vacuum evaporation system. First of all what we have is a chamber. This is a chamber, the chamber has an air or gas inlet and I have a combination of pumps. First of all the roughing pump; as the name suggests, it is used to create a rough vacuum and I have high vacuum pump along with cryo trap and a …. pump in order to create a high vacuum. So, you have your metal source placed in the chamber and you have the substrate placed like this. I have shown it like a circular arch. In fact, it is like this. In most modern evaporation systems, the substrate is placed on a spherical surface. Why, we will come to that a little later. So, what happens is to begin with, you have the roughing pump. You open the roughing valve and you let the roughing pump create a rough vacuum of about 10 pascal.

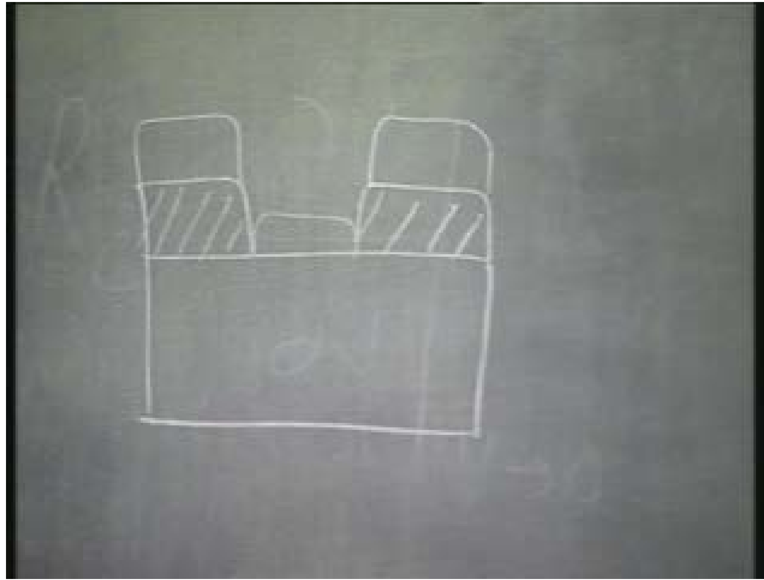
After this rough vacuum has been achieved, after that, you open the high vacuum valve, the HV valve, high vacuum valve. You open that high vacuum valve and let the high vacuum pump. Usually it could be a diffusion pump plus cryo trap or if you want better

higher vacuum, then you could use turbomolecular pump or even ion sublimation pumps, along with a cryo trap. You know what a cryo trap is? Cryo trap is where you pour liquid nitrogen in order to facilitate in forming vacuum; it traps. So, after the roughing pump has given you a rough vacuum of ....., you open the high vacuum valve and let the system be evacuated to a much higher degree. Usually we prefer to have 10 power minus 6 to 10 power minus 7 pascals for normal metallization.

After this level of vacuum has been achieved, you may want to slightly heat the substrate. That is an optional process. Usually heating of the substrate is done, so that better aeration of the films is obtained. You are depositing a metal film on the semiconductor. You want good adhesion and the good adhesion can be obtained if the substrate temperature is raised. So, that is an optional step of heating the substrate and finally of course, you will evaporate the metal to form the metal film. So, essentially 4 steps; first step is creation of the rough vacuum, second step is creation of the high vacuum, third step is heating of the substrate and fourth step is evaporation of the metal. These are the four steps in a vacuum evaporation of the metal.

Now, the question is I have deposited the metal. How do I know how much metal has been deposited? See, for various applications, the thickness of the metal layer is quite important, like for example, for some tunneling devices you may want to have very thin metal, very thin metal, which will be semi-transparent, which will allow the light to pass, for many solar cell applications; it is necessary that you have a semi-transparent metal. For other devices, it is necessary that you have a thicker metal. For many sophisticated techniques, like for example lift-off of metal, if you remember we once mentioned the lift-off technique, in which you have an underlying photoresist layer and you put the metal on top. So, only from those regions, that is, in case of lift-off, what happens is something like this.

(Refer Slide Time: 30:54)



You see, you have a substrate and you protect certain regions with photoresist. Now, you have a metal deposition by vacuum evaporation. So, metal is going to be deposited here and here and here. This is photoresist and on top of that I have metal and now, you have used positive photoresist which can be easily dissolved by using acetone.

(Refer Slide Time: 31:38)

So, if now you put it in acetone, photoresist should go from here taking the overlying metal along with this and from here, leaving only the metal in this region. So, this is called the lift-off technique. That is the metal sitting on top of the photoresist gets lifted off the substrate. But, for the lift-off technique to be successful, it is important that the thickness of the metal be less than the underlying photoresist layer. Otherwise, acetone will not have access to the photoresist. The lift-off will not be perfect. It is necessary that the photoresist layer be thicker than the metal layer. So you see, all these requirements, because of all these requirements, it is important for us to know the deposited metal layer thickness, right and the metal layer thickness can be measured either in-situ that is while the deposition is taking place or ex-situ that is after the deposition, I take out the substrate, take out the sample and try to measure the thickness of the metal.

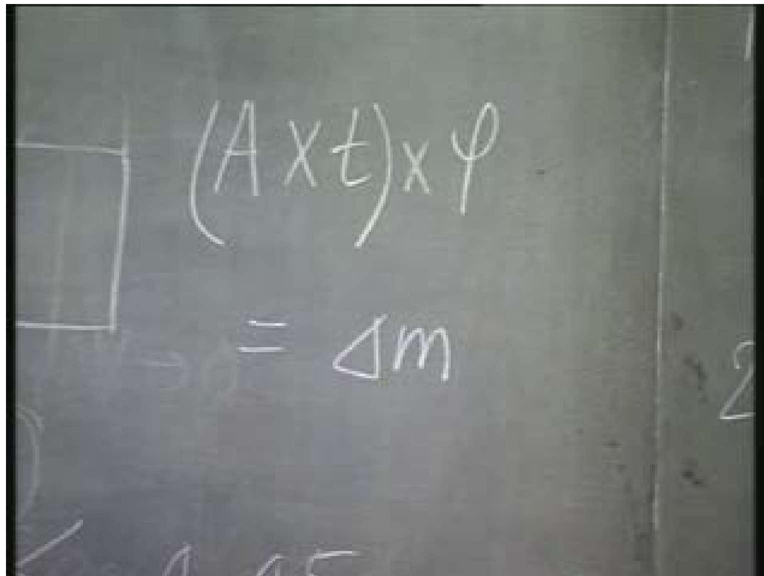
The most common and most desirable technique is of course, in-situ technique. In in-situ technique, we use a quartz crystal thickness monitor. There is a quartz crystal, which is used as a thickness monitor. Now, you know the quartz crystal will have a resonance frequency, if you keep the quartz crystal at the same level along with the substrate.

(Refer Slide Time: 34:15)

So, when metal film is getting deposited on the substrate, it is also getting deposited on the quartz crystal and any film deposited on the quartz crystal will alter its resonance frequency, provided that this change in the resonance frequency is not too much; provided that, provided that the change in the resonance frequency, delta f is actually, this change is very small compared to the original resonance frequency. The frequency change is proportional to the mass of material deposited on this. That is delta f is proportional to delta m. Do you understand? I have kept the quartz crystal at the same level as the substrate. So, while the substrate is getting deposited with the metal film, some, the same amount of deposition is there on the quartz crystal also and this deposition is going to alter its resonance frequency.

I have an electronic circuit in order to find this change in the resonance frequency and by suitably calibrating, I know that what the amount of metal deposited on the quartz crystal is, because I know this change in frequency is proportional to delta m. So, you know, what is the amount of metal that is deposited on the substrate? Of course, the other cruder technique will be, you take out the material and you measure the incremental weight gain.

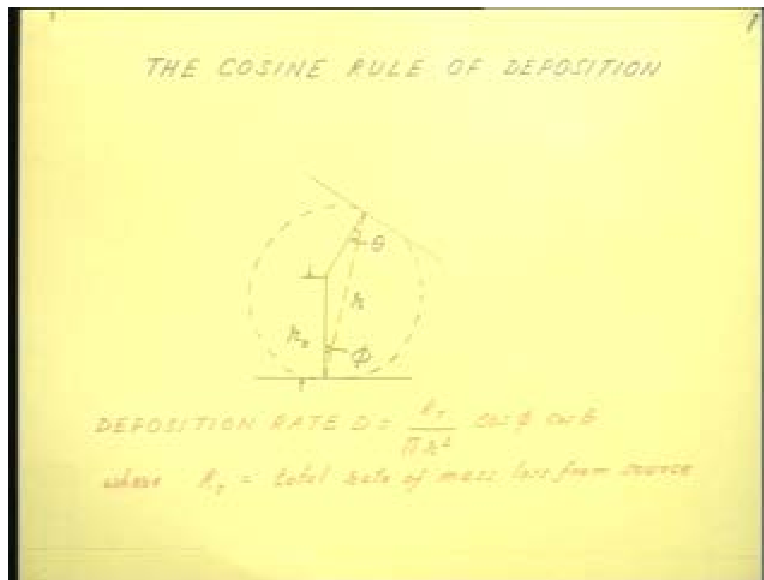
(Refer Slide Time: 36:17)



You know that the surface area of the sample, let us say it is A, so that and if the thickness of metal is t, then A into t will give me the total volume of metal that is deposited on this. So, A into t into the density of the metal, rho will be equal to mass of the metal that is deposited. You can measure this incremental weight gain and knowing A and rho, you can find the thickness of the metal that is deposited, right. But, most modern day evaporation units come along with the quartz crystal thickness monitor. This is an accessory of any vacuum evaporation unit, where you have the quartz crystal thickness monitor and it is calibrated, so that you can directly measure what is the mass of the metal that is deposited and therefore you know what the thickness is going to be.

The deposition of the metal on the substrate follows a rule, which is called the cosine rule of deposition. If you look at the next slide, then you can see what this cosine rule of deposition is all about.

(Refer Slide Time: 37:53)

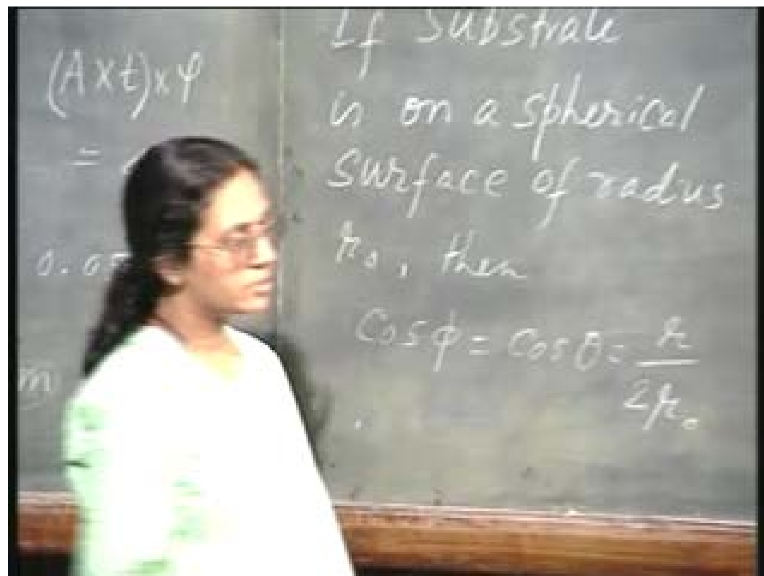


In this cosine rule of deposition, we have a metal source here and we have a substrate shown here, by this red line and you see, I have the direction of the metal deposition given by this dotted line, r. I have also specified two angles, theta and phi. Phi is actually the angle between this direction of the metal deposition and the normal to the surface of

the source. This line is the normal perpendicular to the surface of the metal source. So, the angle phi is actually the angle between this normal and the direction of metal deposition. Similarly, the angle theta is the angle between the normal to the substrate surface and the direction of the deposition and the deposition rate, D is given by R T by pi r square. r is the distance between the source and the substrate along the line of deposition; R T by pi r square cos phi cos theta. That is the deposition rate is proportional to the cosine of these two angles phi and theta.

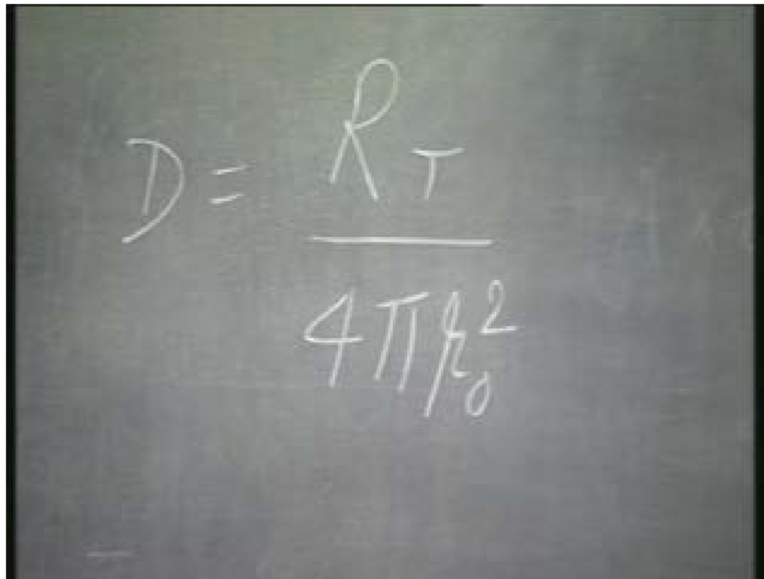
So, you see, if the deposition rate is given by this that means the total material that is deposited that will be given by multiplying both sides by the time of evaporation and R T is the total rate of mass loss from source, therefore R T into T will be given by that is the total mass loss from the source, delta m which I have already measured by using the thickness monitor. Delta m is the mass of the material that is deposited. Now, the point is what I have tried to show by this dotted spherical line is, suppose the substrate instead of being placed like this as a planar surface, if the substrate is actually placed on a spherical surface and if that sphere has a radius r 0, then both cos phi and cos theta will be given by r by twice r zero.

(Refer Slide Time: 41:47)



If substrate is placed on a spherical surface of radius r 0, then both cos phi and cos theta will be given as r by twice r 0, where r is the distance, straight distance between the source and the substrate and r 0 is the radius of the spherical surface and if that is so, then you can see that the deposition rate will be simply given by R T by 4 pi r 0 square cos phi cos theta, 4 pi r 0 square. By replacing cos phi and cos theta by r by twice r 0, this is what we will get, right.

(Refer Slide Time: 43:19)



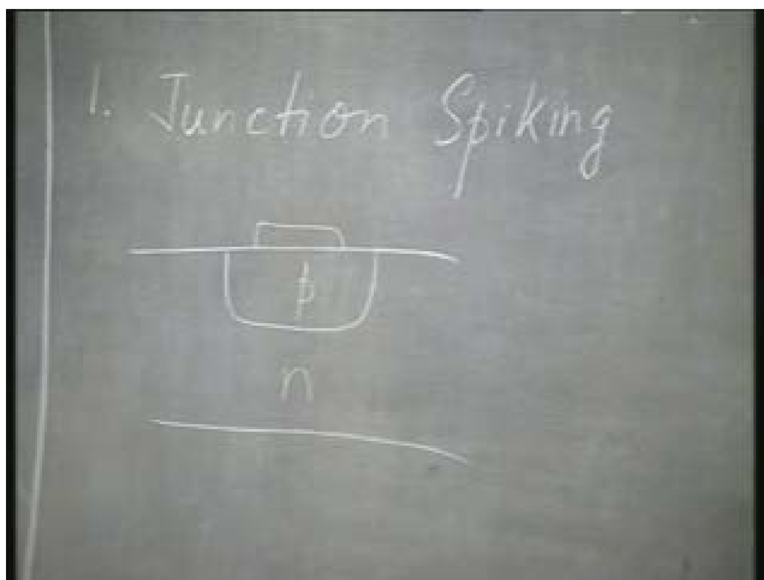
So, in that case we will have or the total deposition will be given by total material loss divided by 4 pi r 0 square. What is the advantage in having such a system? The advantage is no matter where the substrate is placed on this spherical surface, all of them will have equal metal thickness on them. All of them will have equal amount of metal, equal thickness of metal film on that, right. That is why nowadays, all of the vacuum evaporation systems, most of the vacuum evaporation systems, they have a substrate holder as a circular rail, which I showed also in the schematic diagram, right; I showed it like a circular arch. The whole thing is actually like a circular rail placed on top of the metal source, so that all the substrates placed on this substrate holder, they are going to have same amount of deposition thickness, uniformity of deposition and along with that, they are also provided with the planetary motion system. That is they can be rotated. Not

only that you have a spherical circular rail on which the substrates are placed, they can also be rotated like in a planetary motion to ensure better uniformity. So, this is actually the vacuum evaporation system for metallization.

So, for contact metallization scheme therefore, this is what we use. We have a vacuum evaporation system provided with the circular substrate holder and you create the vacuum, 10 power minus 6 to 10 power minus 7 Pascal and then, you evaporate the metal and the thickness is controlled by having the in-suit thickness controller. In general, the thickness controller comes provided with an electronic shutter, so that as soon as the required thickness is achieved, you can close the shutter, so that any further deposition will not fall on the substrate and of course, you can therefore, thereby you can control the thickness of the metal layer.

This metal deposition is not without its problems. There are various problems associated with the metal deposition. Even though you can combat the contact resistance problem, there are various other problems and one problem is called junction spiking, particularly severe, when you have very shallow junctions. What happens in case of a junction spiking is this.

(Refer Slide Time: 47:08)



These are the problems commonly encountered in metallization, after metallization. Number one is junction spiking. Suppose you have a pn junction, shallow pn junction and you are trying to form a metal contact here, aluminum contact. What happens is aluminum can dissolve silicon. So, when you are, if you look at the aluminum silicon phase diagram, you will find that aluminum can dissolve silicon in it. So, what will happen?

(Refer Slide Time: 48:24)

After we have formed the metal contact, in this region aluminum is going to dissolve silicon in it and if the junction is very shallow, it can go all the way down, like this. So, your pn junction is effectively shorted. You will have a metal spike that is called the junction spiking. The other severe problem associated with aluminum metallization is electromigration, where under a very high electric field the metal layer starts to move; the aluminum metal itself starts to move. So, suppose you have a long line of metal; along the direction of the field, it starts to move, so that you have a break in the metal line. The metal from that point has got transferred somewhere else following the direction of the electric field. So, you have a break somewhere and then accumulation in another place.

(Refer Slide Time: 49:30)

So, these are the two problems, most severe problem - junction spiking and electromigration associated with metallization, particularly aluminum metallization and aluminum is the most important contact metal in silicon technology. These are the two major problems with aluminum metallization and we will discuss more about them in the next class.