Particle Characterization

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Module No. #12
Lecture No. # 36

Practical Relevance of Particle Characterization: High-technology Manufacturing

Welcome to the 36th lecture in our particle characterization course. In the previous lecture, we were focusing primarily on filtration, which is a technology that really leverages the properties of particles in order to produce a clean stream of material, and then we also talked about the design of clean manufacturing environments in particular clean rooms, and again, how the characteristics of particles really dictate, how these clean rooms are designed and; how filtration systems and airflow can be modeled and optimized, in order to obtain a minimum concentration of particles in the clean room. Now, the end effect of particles, in a clean manufacturing facility, is their impact on, as I was mentioning in the last lecture, yield and reliability. So, these are two very important parameters for any manufacturing facility.

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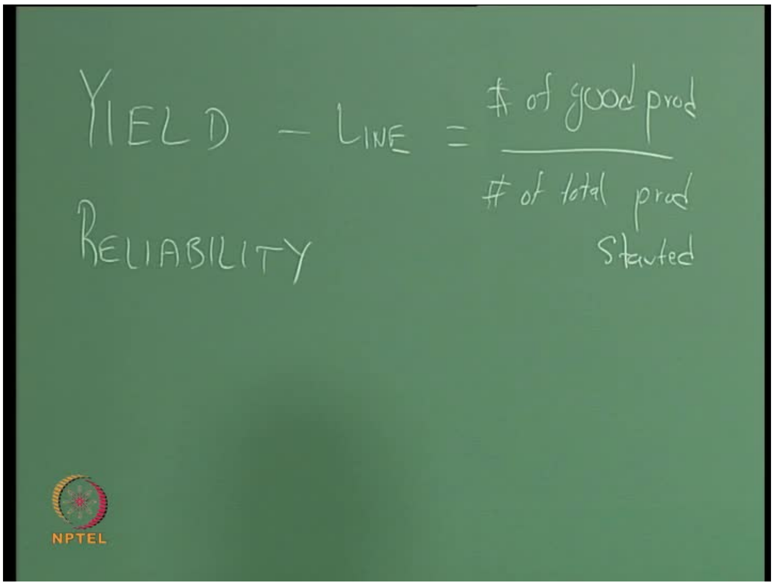

$$\text{YIELD} - \text{LINE} = \frac{\text{\# of good prod}}{\text{\# of total prod started}}$$

RELIABILITY

Now, yield is a parameter that should have relevance to your manufacturing line. So, it is a measure, essentially of number of good products, to the number of total products started. In other words, if you start the manufacturing sequence, first thing in the morning by the end of the day, you take a count of how many products you have produced whatever it is, it may be silicon wafers or it may be circuits or it may be hard drives. Whatever it is, if you take the ratio of number of good ones, when we say good ones that means customer shippable products to the total number of products started that gives you what is known as yield.

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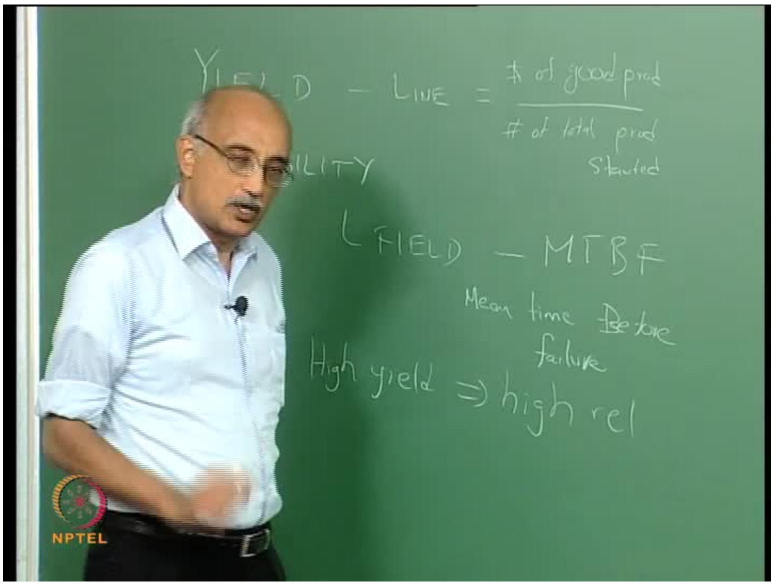

Reliability, on the other hand, is something that is measured by your customer in the field. So, when they buy a product, they want the product to last for a certain period of time, and that is called the reliability measure. In fact, the seller has to specify something called m t b f - which stands for mean time to failure. And the customer expects that the product will meet the M T B F specification. So, for example, for a hard drive that you use in your laptops, m t b f may be only 2 years. You know the hard drive will start failing within 2 years, as I am sure, you have all experienced.

On the other hand, if you are talking about a storage system for the high end enterprises, for example, if you have hard drives that are managing bank transactions or airline reservations; those systems have to be a much more robust, and rugged, and reliable. So, the reliability requirements for those products are likely to be of the order of 5 to 7 years.

So, the mean time to failure or Mean Time Before Failure for the high end products can be much longer than the mean time before failure for the low end products. So, it is a measure of, essentially the quality of the product. How good is it? You know, this simply says that the product is good, leaving your line, it does not say anything about the long term stability and the long term reliability of the product. Whereas, this is a measure of, how well your product does in the field over an extended duration of time. So, the two are different, but obviously, they are related.

Usually, High Yield will also imply high reliability, but not always, it all depends on how you measure yield; I mean, what is your definition of a good product leaving the line? If your requirement for goodness of the product leaving the line, is very stringent then, yes, there is going to be high degree of correlation. But as a manufacturer, if your end of line specifications are too loose and you are trying to get as much product out the door as possible, then it is possible that you may have a situation where you have high yield in your process, but what you are shipping to customers, is basically, you know, garbage; it is not good enough for the customers needs; it is only good, based on your definition of what is good.

Whereas, reliability is more a measure of goodness from the customers view point. So, clearly, yield and reliability are absolutely essential, particularly in high technology manufacturing; when you are talking about silicon chips or hard drives or circuits, these are high value components that customers absolutely relay on, to last them for very long periods of time, without un-expected failures and so on.

So, how do you achieve that? Well, if you look at yield losses or reliability losses, there are many different causes. Particles are one of them; I mean, a device may fail simply because it is not put together correctly, because something wrong in the assembly process or it may be that the electronics are not mounted properly. So, there are many reasons why a device can fail. But one of the reasons is that, particles can be at the wrong place, at the wrong time.

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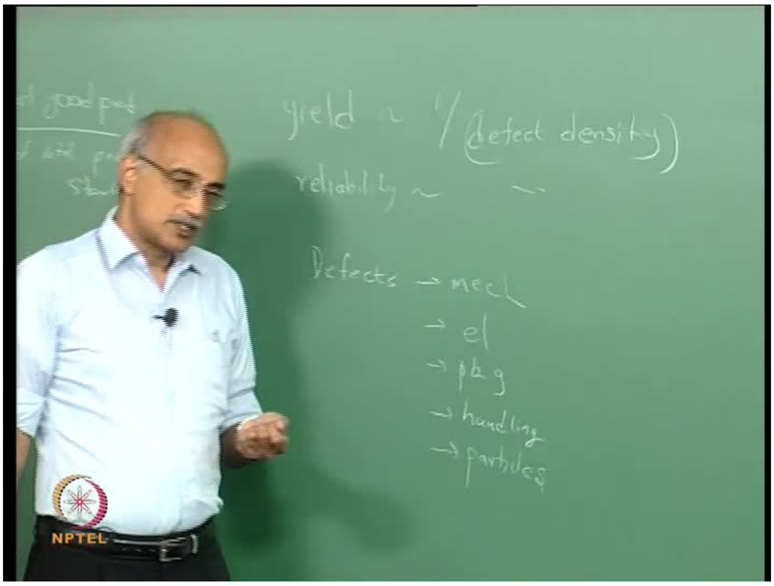

So, yield is inversely related to, what is known as, defect density. So, as the name suggests, defect density is basically the number of defects on a product per, could be unit length, could be unit area or it could be unit volume, depending on what the product is. And the higher the number of defects on the product, the lower will be the yield. And similarly, reliability will also scale the same way. So, what that means is, for the product manufacturer it is very important to control and minimize the defect density parameter.

So, if you look at this defect density then or defects in general, as I was saying, there are many kinds; there could be mechanical defects, there could be electrical defects, there could be packaging defects, handling defects, I mean a device can fail, simply because the customer drops it on the floor. Right? So, it has nothing to do with the inherent quality of the product, you just miss handling on product of the customer. But it is also counted in your failures, unfortunately.

But one of the causes for defects is, particles. Now, how does a particle cause a device failure? Well the mechanism is different, for different products, obviously; if you take any semiconductor product, which could be a semiconductor wafer with conductive paths on it, for the electrons to flow through, or it could be any integrated circuit, where you are trying to force the electrons to flow in a certain path. Right? That is basically what these devices do.

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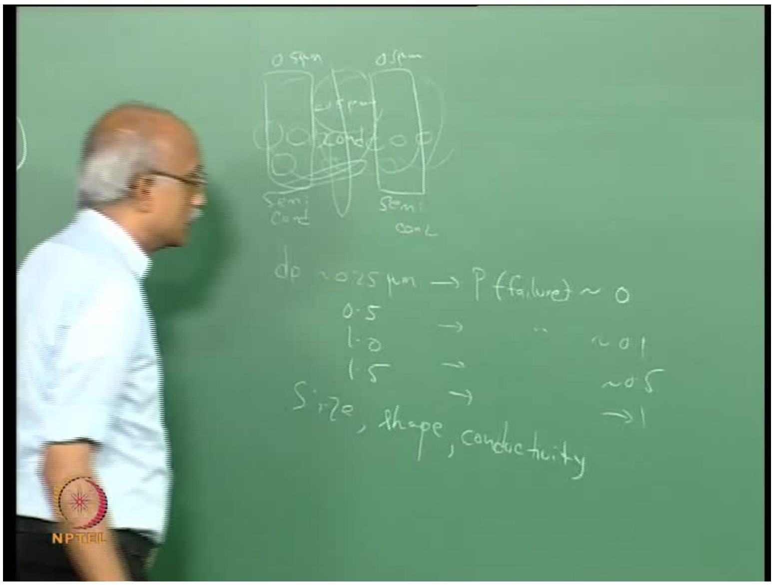

You may have a situation, where you have a device that is look like this, and another device that looks like this; and let us say that these are semiconducting materials. This is semiconductor; this is semiconductor, and in between, you have a conductive path. So, essentially the semiconducting layers have been deposited on a conducting surface.

So, you want the circuit integrity to be maintained, you want to make sure that, over the life of the product, conduction only happens through the conductive path ways and not in the insulating or semiconducting path ways. So, that is fine, that is what will happen in this case.

Now, let us suppose that, this is let us say 0.5 microns wide, this is point 5 microns wide, and the gap here, is also point 5 microns. Now supposing, a spherical particle of diameter, let us say 0.25 microns, happens to fall on this product. What is going to happen?

The 0.25 micron particle can fall here or it can fall here or it can fall here, but there is no way, that it can bridge the two semiconducting paths. Right? So, if b p is of the order of 0.25 microns, probability of failure is approximately 0. Supposing now, this increases to point 5 then what happens?

Well here again, unless it happens to be exactly at the wrong place. So, it has fall right here, so that it bridges like that; that is a only way a failure can happen, if the same particle fall here or here, it is not going to anything for you, right? So, if d p is 0.5 microns, the probability of failure is not 0; may be 0.1, there is a 10 percent chance of failure. Now, suppose the particle size increases to 1 micron then what happens? So, if the particle is of 1 micron size then it can easily land in this fashion or it can land in this fashion. But. It is also possible that it will land in such a way that, it does not extend between the paths right? So, again the probability higher not still a 100 percent but roughly 0.5 or so.

And finally, let us say, you have a 1.5 micron size particle. Then the probability of failure starts to approach 1, it is pretty much guaranteed that as you are going to have a shorting, you are going to have essentially a conductive path way that is going to bridge the semiconductors.

So, this is what we mean by particles causing a yield loss in this case. The particle size, obviously is a very important characteristic from this view point, the properties of the particle whether, it is conducting, non-conducting, semiconducting obviously, plays a role as well about the shape.

What if the particle were non-spherical? You know, we have been assuming here that the particles are spherical; so, we are doing this probability analysis based on a spherical particle. But if a particle is highly non-spherical then you can have much larger particles that are present, but if they happened to be you know, in a certain position they would not cause the failure. So, interestingly enough a spherical particle is more likely recalls the systematic failure compare to a non-spherical particle and so, shape plays an important role as well. So, there are at least three characteristics that are of importance here that we have discussed at length earlier in this course. Let us look at another example, hard drives, all of you have used devices containing hard drives and you know that basically data are stored on magnetic disks and there is read-write head that flies over the disk; it writes data, reads data. I mean that is basically how a magnetic storage device works.

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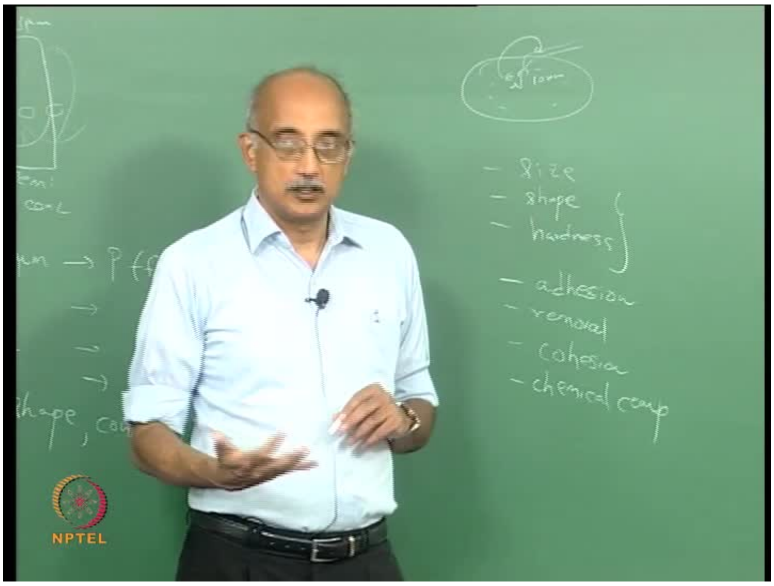

So, essentially you have these disks on which data has been written and we have the head on flying on top of it, you know, that is trying to read the data. So, how does a particle cause a failure in this case? It can actually do it by several mechanisms.

First, again is size based. If the particle, let us say that the head is flying above the disk at, I think, I mentioned in one of the earlier lectures, the flying height of a head about a disk today in a magnetic storage devices is of the order of 10 nanometers or so.

So there is only a 10 nanometer clearance between the read-write head on the disk. So, if you have a particle that is, let us say larger than 10 nanometers, and it happens to be caught at this interface, what is going happen?

The head is going to essentially crash into it, and you are going to get essentially hard error, so, it is a data loss at that location; or what can happen is that, even if the particle is slightly smaller than 10 nanometers, as the head flies over it, it can essentially get pounded into the disk. And eventually, that will also register as a hard error. Another thing that can happen is, as the particle flies over this particle, it can get scooped up by the head. So, that the particle that may be sitting on the disk because of the air flow, now collects on the actuator mechanism that is a driving the heads, then what happens?

It causes a change in the trajectory of the head, so instead of flying at a constant 10 nanometers above the disk, it may either fly lower in which case, it will crash again or it may fly higher, in which case, you lose sensitivity in your data reading capability or data writing capability. So, that is called a soft error. So, when particles gets scooped up by the head, you essentially get either a hard error or a soft error, depending on where the particle binds up and what it does to the trajectory of the head.

So, you look at all these possible ways in which particles can cause failures and by the way another mechanism is, if you have sufficiently large particles, you know if you look at a disk drive I am sure you have heard it working sometimes, it is very loud, right? The reason for that is, the disks are spinning at 10,000 r p m; and so, you can imagine that the centrifugal forces that are being created inside the hard drive are very high. So, if you have a particle that is 10 microns in size and it is get caught in this air flow, it is going to fly around inside this enclosure with very high velocities.

So, it can actually go and physically impact on the disk and dig a little hole in it; it literally digs a crater. So, that mechanism is called ballistic damage; and that happens primarily because of larger particles, which have sufficient kinetic energy and momentum to cause this type of failure mechanism to occur.

So, clearly there are many ways in which a hard drive can fail, because of particles being present. But, to tied back to our course, what are the characteristics of particles that are important?

Clearly from our discussion, size is again important, because it determines, you know what failure mechanism comes into play. Another parameter that is, that is important here is shape once again, because in the in this case, shape in combination with hardness.

If you have, for example a ceramic particle like alumina, flying around inside a drive, the probability that it can cause a failure is much greater than, if you had a plastic particle flying around inside the drive; because, it is a combination of shape, hardness and size that really drive many of these failure mechanisms. Because if you have a hard particle and you impact a disk with that hard particle, the likelihood that it can do damages, obviously, much higher. And also, the probability that it can scratch the disk if it gets caught between the head and the disk, it is again very high; and similarly the propensity to cause damages much greater for non-spherical particles compared to spherical particles. And so shape and hardness play very important roles in a hard drive.

Now the other mechanisms are characteristics that are important or adhesion to surfaces. If there are particles inside this hard drive and they stick to the disk, then that is a huge concern. If they are simply flying around, there are filtration mechanisms, every hard drive has a filter built into it. So, as the air is getting re-circulated the particle will eventually get filtered out, but that is only if, it does not stick to a surface inside the drive. So, adhesion properties or adhesion characteristics are very critical in determining, whether a particle is going to cause a failure for the drive or not and similarly removal.

If a particle that is inside a disk drive happens to land on a non-critical location and just stay there, then we do not worry about it; but if it can be re-entrained because of airflow and re-enter the air, and then deposit on a more critical surface that can become an issue.

So, adhesion and removal of particles from surfaces is a big issue, an important characteristic for us to keep in mind. And, cohesion of particles is an issue, primarily because of static effects; because again, a hard drive has a spindle motor that is running at very high r p m, it is a very dry environment, and static charges can develop very easily. So, particles can easily clump together and become larger particles. So, a drive that might have been fairly low, in terms of particle counts for a certain size and higher to begin with, eventually because of these cohesive forces, the particles just start agglomerating become larger and larger and eventually cause a failure to occur. So, all these factors are important; and here again, the chemical composition is an important parameter; primarily because, if the interaction is purely physical, the damage to the surface may be limited, but for example, if you have a sea salt particle flying around inside a drive, it is not only going to cause these physical failures to happen, but also it is going to start corroding the materials that are inside the hard drive. So, the chemical nature or the composition of the particle will also play a major role. So, the point here is that whatever process you take, particle particles in the system do have an influence.

Many of the applications we talked about earlier, they had a beneficial influence; but in such in these examples, they certainly have a degrading impact on the performance of the product. So, how is how is this related to the yield that we talked about earlier? How do we tied yield process yield to things like defect densities and particle sizes and so on?

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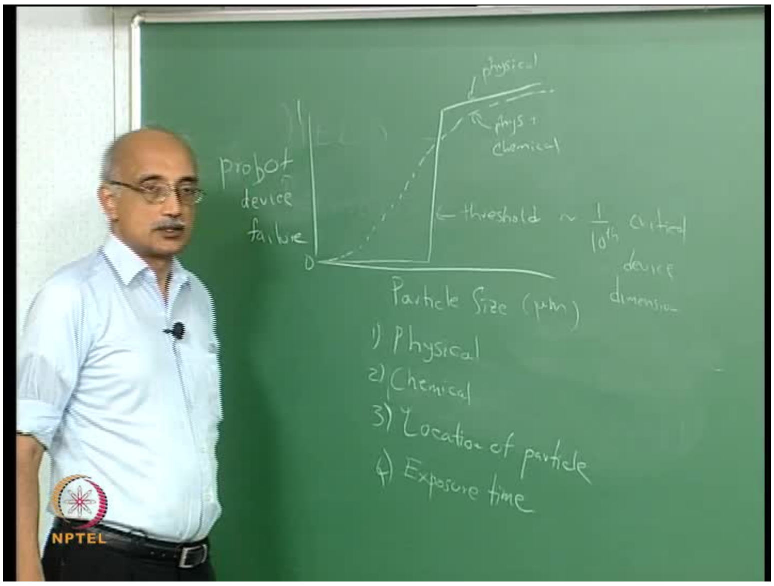

There is a classic chart that looks like this, if you plot Particle Size in let us say microns verses probability of device failure. It has a very interesting shape, it essentially looks like this; there is a threshold value, below which, a particle will not cause any problems. But as soon as you reach that threshold value, all of a sudden your probability or percentage, quickly goes up to 1. So, let us plot this in terms of probability rather than percentage. And so, this threshold size at which the probability of failure suddenly raises, is obviously related to the functionality of the device. And as a thumb rule, it is taken to be roughly one-tenth of the critical device dimension. So, for example, in this illustration, the critical dimension is really 0.5 microns, right?

So, the all particles that are larger than 0.5 microns will be considered as having potential to cause failures, even though, it may be a low probability until that size grows to a certain extent.

Similarly, in the case of the hard drive which is flying 10 nanometers above the disk, 1 nano meter will be taken for design purposes as a critical size; and all containment strategies will be developed for one-tenth of the critical dimension. Again, the reason for that is to build in a safety factor, if you know that 10 nanometers is going to cause a failure, you do not try to control particles below 10 nanometers; it is too risky. And so, you essentially build in a 10 x safety factor and try to control all particles that are less than point… In that case 1 nanometer.

Now, if you look at this schematic, there are certain assumptions here. The first is that the interaction is purely physical; in other words, up to a certain size, nothing happens, beyond that size failure start happening; clearly, what that is indicating is, there is a very close relationship between size and defects. But if only size is causing defects to happen then clearly it is a physical phenomenon, right? So, that is an assumption that this type of ah device failure map makes… But on the other hand, if you look at actual failure mechanisms, it can be very different. I mean there can be certainly chemical interactions. So, if you look at all possible ways in which failures can be induced by particles, physical interactions will essentially give you a signature that is looks like this, but if chemical interactions can also have an effect, then the curve will essentially get smoothed out; so that, if this is your assuming only physical interactions, this would be physical plus chemical interactions. What that has is that that mean effect that, it has, it pushes the threshold even further below, if you only have to worry about physical interactions, you would only start worrying about particles that are this size and larger. But if you also have to worry about chemical interactions, then you have to worry about much finer particles also in terms of your contamination control strategies and so on.

So, the sea salt example, you know, if you talking about a salt particles, for a salt particle to cause physical damage, it have to be pretty large; but, for a salt particle to cause chemical damage, it can be even submicron and it will be sufficient to cause an erosive, to start a corrosive reaction happening.

So, the difference between chemical and physical modes of particle related failures is important for us to understand. The other thing that you always have to bear in mind is that, the Location of particle is an important parameter. This again assumes that the particle is at a critical location where it can cause a failure. But, as you can see from the two examples, we have coated, if the particle happens to be in a location that is not functionally critical, it is not going to cause any damage, right?

So, you really need both things to happen; you need particles to be present and you need them to be at the… Again, the wrong place of the wrong time for a failure to happen. Otherwise, most devices today are extremely robust and they will withstand very high levels of particles in them. For example, a hard drive you know it is always a miracle that a hard drive ever works, because if you actually looked at all the particles flying around inside a hard drive are literally millions of them. And so, how do they even function? It is because their design to be very robust; they can actually accommodate a very large number of particles and still function quite reliably.

And similarly, yeah here, if a particle just happens to be somewhere on the outside of the disk surface, there is usually a band around the outer diameter, which is not used for data storage. So, if particles happens to land in that non-critical location, they do not cause any problems. Or if you look at a hard drive, the whole thing is encased in a cover, and a base, and all that, right? So, if the particles happen to land on those areas, again they are not going to cause a failure. So, it is not just the absolute number of particles that are present in your system, but where they are on the product? With reference to the product?

And the fourth important parameter is the exposure time. How long they stay on the product? The longer a particles stays on the product, the greater the probability that it will eventually cause a failure. And that is why these adhesion mechanisms come into play; if a particle lands on a on a circuit like this, it is only a momentary contact, the device will survive it; but when it lands, if it gets permanently stuck there then obviously the device is going to fail.

Similarly in the case of the disc drive, if a particle is only temporarily present on a critical surface and then it gets dislarged because of the airflow, or the movement of the head or whatever; then it is not something you need to worry about. It is only particles that is stay on the device for a long period of time that really increase the probability of failure to virtually 100 percent probability.

So, all of these are important things to take into account, and again particle characterization becomes important, because in order to understand these interaction mechanisms, you have to be able to measure them, quantify them and control them. So, that is why particle characterization is a very important discipline in most microelectronics and other high technology manufacturing industries.

If you look at semiconductor manufacturing in particular, you know it is a… I think, right now, it is a 500 billion dollar industry worldwide. And if you look at yield in micro electronic manufacturing, back in the 1950-1960, the U S companies used have very low yield in their process - 10 to 20 percent; the Japanese companies had much higher yield-60-70 percent. And the reason for that was, that the Japanese bought into particle control philosophies without waiting for hard evidence, whereas the U.S companies said, we are not going to do that until there is hard data linking failures to particle levels in the product; by the time they got that hard data, it was too late, they had setup processes that were inherently high in in terms of particle levels, and leading to lower yields. You know, U.S has always had this, what I would call, show me kind of an attitude. Unless the data are clearly there on the table, they are not going to take proactive measures just because it is a right thing to do. Whereas the Japanese have always tended to play it safe, so, they would take measures just because it is in the direction of goodness.

So, it is a difference in philosophy, but all of that changed in the nineties or so, and now a days if you look at U.S based manufacturing plans, verses Europe, verses Japan yields, reliability numbers they are virtually the same. Because now, they all understand that particles are hard to see; and it is actually very difficult to collect data that correlates particle levels and particle characteristics, to associated device failures, and yields, and reliability and so on.

So, you do have to take some of this on faith, you know, you have to believe that if you have high levels of particles, or if the particles size is larger than a certain level, it is going to cause a failure. So, that level of faith or belief is needed; and so, if you strategize based on your fundamental understanding of how particles behave, then your process is going to be healthy.

If you keep waiting for hard data, hard evidence, then by the time you get the data, you may be out of business, right? So, semiconductor technology has been developing a road map, every 5 years, the technology gets updated. Primarily, looking at the size of critical features on the wafer; and also, the number of such features on any given wafer. And what is been happening in the last 20 years or so, is that the critical dimensions have been getting smaller, because you have been trying to pack more and more, you know, functionality into smaller and smaller chips. So, if you look at this as a years and you look at the Critical dimension back in the eighties, it was of the order of microns.

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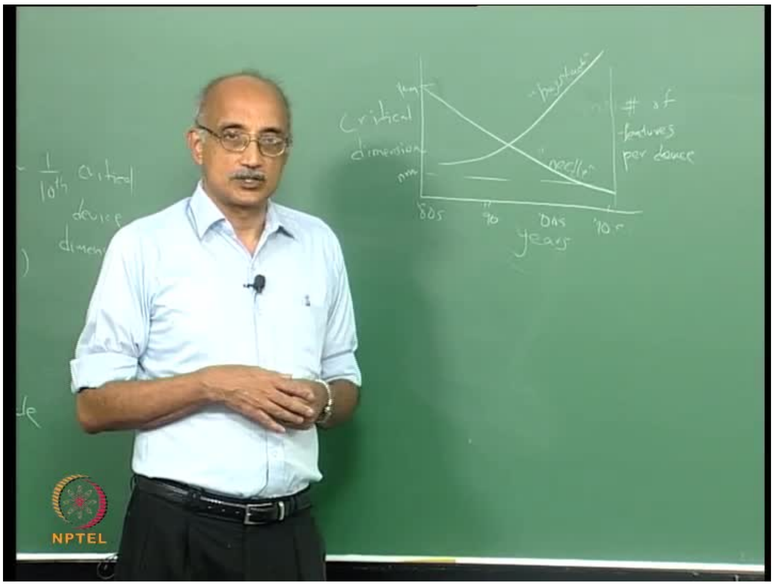

So now, ninety’s o o’s tens and so on. There is been a rapid reduction, in terms of the critical dimension. Now, it is actually down in the nanometer range. For example, if you look this spacing between two semiconducting elements, you know, here I have sketched the case where it is point five microns; today, this is more likely to be 0.5 nanometers. Everything is shrinking, you are trying to do more and more with less and less materials, right?

So, this is what is happening but at the same time, something else has been happening, and that is, the number of features per device; and that is, has actually been increasing rapidly, because again, we are trying to build more and more functionality, you know cell phone at one time as used make phone calls, right? Now, you do everything else except making phone calls with a cell phone.

So, clearly, this is basically the picture. So, what is happening is, you kind of look at this as, the needle, you look at this as the haystack. Looking for particles that cause problems, is always looking like looking for needles in a haystack, because you have to go in and search for these minute fragments in a very large surface.

For example, the product. But the double jeopardy is, as the needle size is getting smaller, the haystack is getting larger. So, this whole science of contamination control, looking for particles, assigning possible cause, understanding particle behavior, characterizing the particles and eventually developing corrective actions and process optimization schemes to minimize particle related device failures, is becoming increasingly challenging.

Which in a ways, is a good news for engineers and scientists, because, you know, your services are needed even more today, than they were 10 years ago, because as dimensions shrink and as the number of features on a product increase, the sensitivity of the product to such defects increases. So, companies are willing to invest more in the support services. You know, particle technologist, particle scientist, who understand how particles are generated, how do they move around, how do they deposit, how do they adhere to surfaces, how do they stick to each other, how are they transported, you know, all of these things are really mechanisms and phenomena that only a particle scientist understands. And that is why, if you look around Intel, I B M, all the major chip manufacturers employ a lot of particle scientists in their roles. Because they realize that control of particle behavior in the devices on the products, it is absolutely essential to their continuing to survive in the game, so to speak.

Quantification, as I said is always important, because unless you quantify, you really cannot measure something, you cannot control something, and you cannot optimize something. So, how do you quantify the effect of particle contaminants on Yield?

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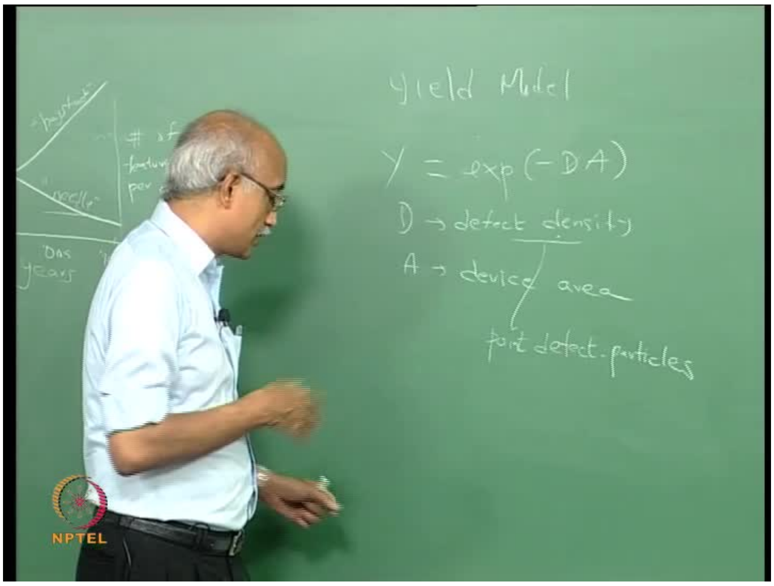

You develop something called a yield model. So, you relate the yield parameter Y to exponential of minus D times a, where D is your defect density, and a is the device area.

So, as the defect density increases, your yield drop exponentially, as the area of the device increases, again your yield decreases exponentially, because it is a multiple of d times a, that gives you total defects in a product. So, basically all these expression is saying is that, there is an exponential decrease in yield, as the number of defects in the product increases.

Now, this is a general model that is applicable to virtually any process, particularly one, where defects play a very sensitive role in promoting failure of the product. Now, as we have discussed earlier, the defect density can have other contributors as well; but one of the contributors, is particles. Particles essentially cause what are known as point defects.

A particle essentially causes a defect to happen at one location at a single point; now that defect can then propagate over the entire device but the starting point is a single location or a single point. So, it is known as a point defect. So, when you, when you are trying to control particle related defects, you resort to the same type of pareto-analysis that I had the talked about in the last lecture. So, in this case, what you would do is, plot percent of defects that are attributable to various causes.

So again, this could be electrical, this could be mechanical, assembly handling and so on. And one of the defect types would be particles, and when you do a Pareto type of analysis, you try to understand, what is a relative role, all these mechanisms play in causing defects.

Now, if the picture looks like, you know, electrical, mechanical, assembly handling, and then particles; clearly, you have to go after particles in your process and try to reduce them, because they have a huge impact on your defect density. And so, this type of data collection and analysis is very important. Now, how do you ascribe a defect to one of these causes? These are actually easy, you know, if the, if the device has failed because of an electrical shorting, [you know], it is fairly easy to spot; or a device fail because something banged into something else; you know, all you have to do is, take a look at the product and you know that something mechanical happened.

Particle related failures are the hardest to detect. Because, usually the product that cause the failure is gone. It is not going to stay around for you to analyze it, it causes the failure and then it gets dislarged, flies away somewhere, you never see it again. So, in a sense, what people do is, if they are not able to assign any of these as a cause, they will just put it on the particle bucket, and they will say that, it happened probably because of a transient particle. That was flying around and cause to failure and then disappeared.

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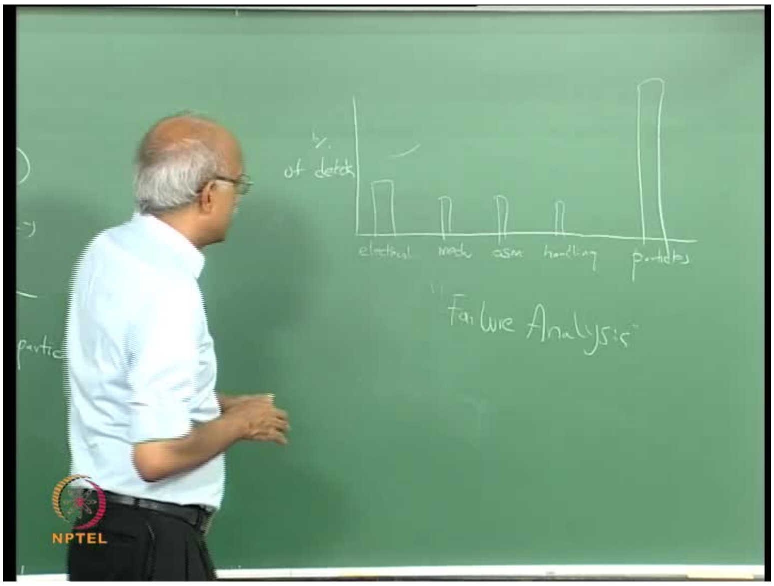

But sometimes, the particles does stay with the defect; then where there is a discipline called failure analysis. Failure analyst, essentially get paid to capture these particles that cause fails and analyze them to death. You know, they do everything that we have talked about in earlier lectures. They isolate the particle, put it on a filter, bring it to an optical microscope, take a look at it, then decide is it organic, inorganic, put it under an s e m, t e m, try to get a more detail morphology of it, three-dimensional characterization, and then if it is inorganic, they then take it for e d s analysis, and w d s and so on; if it is organic, then take it for a f t i r or raman micro micro probe. The whole reason for doing all these is, to find the source.

This particle bound up here and cause the defect, but where did it come from? In order to do source identification, you have to very clearly characterize the particle in terms of its size, shape, chemical composition and so on. Because once you know all that, you can go back through your process and figure out where it came from. For example, if the particle turns out to be, let us say, P E T, and you know that you are using P E T trays to move components in your process from one place to another, you will quickly home in on the trays as being the potential contributor of this P E T particles.

So, but, to be able to do that, there is so much characterization and analysis involved, and without the necessary expertise, you will never get that answer. I mean that is a kind of, you know, multimillion dollar kind of decision, that companies make based the work done by particle analyst, you [ ] they wait for this particle characterization expert to tell them, what is this particle and where did it come from and based on the information that they get, they then take appropriate steps in the process to address it, right? So, again, the whole point is that particle characterization is an absolutely key discipline in high volume, high-tech manufacturing, where the reliability of the device is as important as price. For many of these devices, price is not the major differentiator; it is a quality and reliability that people look for; they will pay a premium, to get a product that gives them a longer life or more reliable transactions and so on. Now, the other interesting thing about the way defect densities work on yield, you know normally, you would like to see a process, in which the process deviation is minimum, right? Because excessive variability is considered not good, from a process view point. But in the case of defects that are caused by particles, if you have a defect density that is very uniform in your product, the associated yield loss is much higher compared to a random distribution of defects. Now, the reason for that is that, when you have a completely random distribution of defects, you do not really know which of these wafers has more defects compared to which; you know, when you when you talk about variability, it is really three kinds of the variability.

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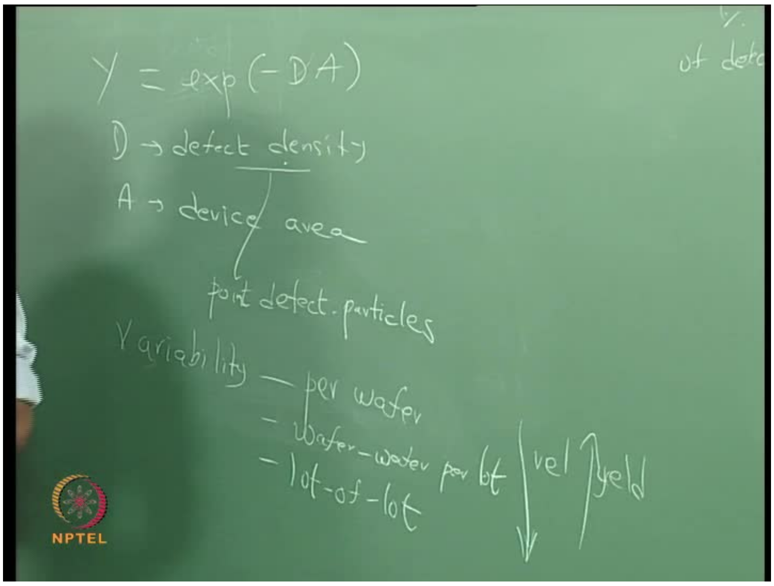

The Variability could be per wafer, so, on the same wafer you may have a lot of defects in one area and few defects in the other area. So, there could be a variability per single wafer or there could be wafer to wafer variability per lot. So, let us say that, you run the shift and you produce 100 wafers, it is, it is possible that some of those wafers have high defects and some have low defects.

The third type of variability is lot-to-lot variability. So, in the same lot, the variability between wafer to wafer may be very low; but if you look at different lots made, for example, three shifts of production in a day, the lot-to-lot variation may be high. So, there are 3 very distinct different types of variability's that you have to be aware of in your process. The variability per wafer, would say that, you know that virtually every wafer is at risk; because every wafer has locations of high defects and low defects.

Whereas, if the wafers are uniform within a lot and the variability is only from wafer to wafer per lot, then you can at least screen them, you know, you can screen out the good wafers, keep them aside, and through away the bad wafers. And similarly, if every wafer in one lot is very similar, but there are variations from lot-to-lot, then you can keep several batches of wafers [that] was being good and only throughout the bad batches of wafers. So, in terms of net reliability, the impact is very different, and the reliability essentially increases in this direction; because these two situations give you the ability to screen out the bad stuff and only shift the good stuff. Now, that is true for reliability, but for yield that is not necessarily true; because, yield essentially means that, you are throwing out bad stuff. So, that is good for the field, it protects your customer. But from your process yield view point, the more bad stuff you through away the lower is your yield, right?

So, yield actually goes the other way. So, this is a clear illustration of a case, where reliability and yield are almost inversely correlated. You are essentially taking a hit on your process yield, in order to protect your field or protect your customer.

So, many times a low yield can result in high reliability, but that is not a, you know, healthy situation; it means that you are really not improving your process and getting rid of sources of defects, instead your relying on inspection and screening to through away bad stuff of an only ship good stuff. I mean, obviously, it does not make any economic sense, because what you would like to do is shift every product you make, right? I mean, that is an ideal situation, you do not want to waste anything. But you cannot do that unless, you have a high quality product.

So, it becomes very important to particularly from a particle view point. Again, the reason why particle characterization is important is because, during the design phase itself, you have to assess your product, for its products, for its particle sensitivities; and decide what type of particles are going to cause harm to this product? What is going to be the size range that is going to be particularly dangerous for this product? What is going to be the shape of particle that is going to cause damage the most? What type of chemical reactivities can exist? And you design your manufacturing environment, you design your tools, you design your product, you design your process in such a way, that you minimize these specific types of particles that can cause harm to the product.

So, if you have a good and thorough understanding of particle behavior or particle characteristics, particle properties, you can incorporate this knowledge, this inside in the design phase of your product, and thereby, essentially eliminate problems, it can happen later in your production, where the cost impact can be very high. So, we have looked at some examples here, of where products, our particles on products can cause problems. The reason that, it is, it is important to identify particle related issues, early in the design phase is, it becomes harder and harder to make changes, once a process matures.

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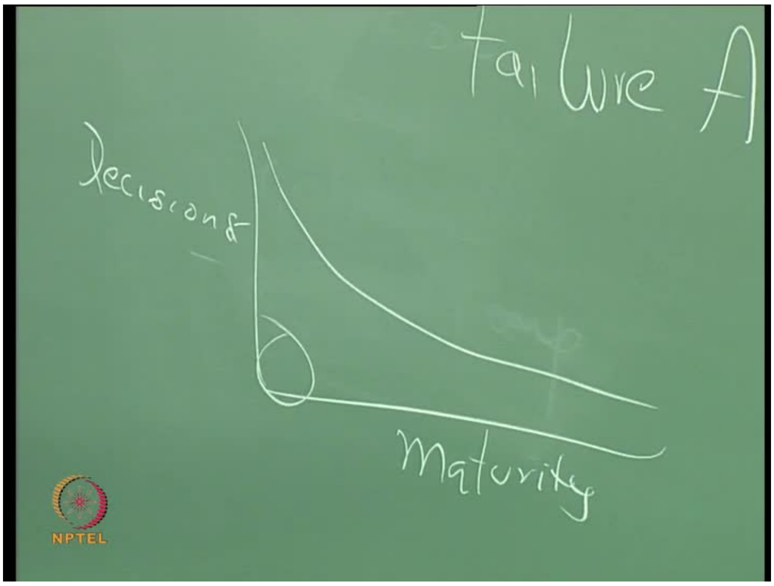

So, in fact there are some road maps, that is, say that, if you plot process maturity on this axis, and decisions on this axis; [you k]now as a process matures, you make fewer and fewer changes, you know decisions, you kind of let things just settle. So, if a particle problem happens at this stage, when the product is relatively immature, just getting introduced, then changes will be made quickly.

But as a process matures, as product gets matured, management is not going to support many quality improvement activities. You know, they are well just going to tell you let it go to end of life, the next product will make much better. So, again, as a particle technologist, you want to make your influence felt, you want to make your opinions understood at this stage. So, the right place for a particle scientist and a particle technologist to be in a high tech company is in the r and d environment, rather than in the manufacturing environment. Even though, if you look at the reality, most particle scientist and engineers are employed in manufacturing rather than in design.

And that to me is a, is a problem, which you know, in a way, it is, it is a job security, because if you are not doing your design right, there are always going to be particle related problems in manufacturing. So, you know, you are going to be permanently employed. From the other hand, the smart way to do it is, get the particles scientist; get that knowledge into the design of the product, so that, problem do not even happen during the high volume manufacturing phase of the product.

So, that brings us to the end of the lecture for today. We have looked at various aspects of particles and how they actually can have very direct impact on the profitability of an enterprise, which ultimately is what everybody cares about. In the next lecture, we will talk about some applications of particles, in situations that involve explosion and fire hazard, as well as, environmental aspects, where certain characteristics of particles become particularly important. So, we will deal with that in the next two lectures.

Any questions on what we have discussed today? See at the next lecture then.