Microsensors, Implantable Devices and Rodent Surgeries for Biomedical Applications

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Week - 04
Lecture - 14

Hello everyone, welcome to this TEA class or tutorial for the course Microsensor Implantable Devices and Rodent Surgeries for Biomedical Applications. In today's TEA session or tutorial, we will be looking at some basic examples focusing on lithography. Now, as you all know, lithography is one of the important processes in the entire microfabrication subprocess, and since the course focuses on implantable devices and rodent surgeries for micro-biomedical applications using microsensors, most of our focus will be on microstructured devices, microelectrode arrays, or some additional MEMS-based structures that can be used to draw more neural inferences from the obtained data or data obtained using sensors. In the previous classes, I have explained neural signal processing and how to make sense of the data once we obtain it. In this class, we will be going a little bit into the experimental flow; we will be covering the preliminary or earlier stages when we are fabricating a particular microelectrode array, then we will be depositing some of the materials, patterning it, and etching it.

Depositing is an additive process; how do we do that? Professor Harde could have already covered that we will be using PVDs, CVDs; PVD includes thermal evaporation, EBM evaporation, sputtering, there are some types of that in which particular process flow, what kind of central deposition should be used that needs to be known, right? Then further, if you go then for lithography, there are several approaches that are contact-based, projection-based, some additional lithography, some lithography depends on different principles of optics, some depend on diffraction-limited lithography, some are reflection-based lithography. Based on your process flow, your final design, your structure, and application, you can opt for a particular subprocess of the process.

Additionally, when there is etching, there is wet etching, dry etching, etc. So these are like some of the basic steps for microfabrication; of course, it gets evaluated by characterization, we will come to that, but in that entire micro process, a microfabrication process, today there is one important thing: lithography. Why is that important? So the aim of microfabrication or nanofabrication processes is to develop the desired structure having micrometer or nanometer dimensions. So the thing is that the final smallest dimension that you can present or pattern on your substrate is known as resolution. So for any microstructures, resolution is a very important parameter which is directly dependent on your lithography process.

So this is like the conceptual or fundamental importance of lithography in the microfabrication process. One additional thing is that lithography costs almost half of your overall microfabrication cost. So lithography not only has conceptual importance but also affects your particular company or foundry when it comes to financial aspects as well. You might have, based on your interest, searched for how many recalls happened for particular foundries or electronics industries. It is very costly, and one recall can cause the collapse of a complete microelectronics company.

So it's an important process, very vital when it comes to developing your microelectrode array, especially for neural engineering projects and all. Today we will be seeing some of the basic subprocesses of that and numerical-based on that basic subprocess which is already covered. We will see the numerical aspect in this class, and also we will see how we can approach it. Another agenda of the class is the numerical aspect; it is generally a mathematical form of your concept which you have understood. Here, what we will see is not only the mathematical aspect but also how it is connected or what is the physical interpretation when it comes to the lithography process or the overall microfabrication process, and also we will see how we can further go one step ahead to meet whatever the current standard or state-of-the-art technology.

So that is the overall agenda, to induce that particular thrust in you to identify that okay how current state-of-the-art lithography techniques would have reached a particular dimension, a particular feature size. So let us start the session; if you can see my screen, we will see the first numerical. So the problem statement says a photoresist gives a final thickness of 320 nanometers when spun at 2800 rpm. What spin speed should be used if a 280-nanometer coating of this same resist is desired? So the first point is that this depends on the spin coating subprocess of the photolithography, right? So this is the overall process flow of the photolithography; it starts with here, the wafer.

Now, a wafer means not only the procurement of the wafer, but before using the wafer for any subprocess, we do cleaning, okay? It needs to be cleaned; there can be RCA cleaning. There are two steps of RCA cleaning you can explore at your interest, pace, and convenience. The third thing is up to RCA cleaning; there is something called Pre-Rana cleaning, right? So different processes for different applications; you can use different forms of cleaning. Once the wafer is clean, you can purge nitrogen to make sure that all the moisture and all residual moisture will be removed. Once the wafer is cleaned, this is your first step. Once the wafer is clean, you have to coat the photoresist, right? So the important factor here is the thickness of the photoresist. For each photoresist, if you see the datasheet of each photoresist, you will find a graph with spin speed and final thickness, okay? So this graph would be available for each photoresist datasheet, and it is common sense that if you think your wafer is there on which you will apply or pour the photoresist, which is like a liquid with predefined viscosity, so when you spin it, the higher the spin speed, the final thickness would be less. If you spin it at a very low speed,

then you will get a much higher thickness; that photoresist bulk or that photoresist semi-liquid, which is applied on your wafer, will have a very high or more thickness if it is not spun at high speed. So more or less, it will be like this kind of graph, okay? Now for each particular photoresist, this graph, this equation, or relation between your spin speed, let me call it omega, and your thickness, let me say this is d, there will be some functions, right? So this is known for a particular photoresist for a finite range of spin speed, okay? And based on your subsequent steps, which is the first one is this, the third step is prebake, okay?

Now again, prebake corresponds to three things. Also, coating depends on not only this but also for how much time you are coating it, okay? So in this case, we are considering the same resist and the same process, so we will consider the same amount of time being provided. There is a different relationship with respect to time as well, but for now, we will consider spin speed and thickness for prebake. I was mentioning that this thickness is dependent on several subsequent steps of the entire lithography chain. For prebake, the temperature of prebake, like baking, and the time for baking, both are decided; the same goes for PEB (post-exposure bake) temperature and time. Now, this PEB is post-exposure bake; exposure is the key step in any lithography process. It starts from illumination, goes through this condenser lens, through some strategy, and known stepping and scanning, some mask; this is our main input, or design, which you want to finally pattern onto your wafer. So this key input is the mask, then the condenser lens; I have already mentioned the condenser lens, then this is the mask, then the objective lens; finally, some known optical sequential events happen, and you will be able to get your desired pattern from the mask to your wafer. So this key step is optics; this is again a very important key step. After exposure, you will be having a post-exposure bake and a prebake, both temperature and time for a particular photoresist, which is the optimal time of that, it is identified. It can be 100 degrees Celsius for 1 minute, 110 degrees Celsius for 1 minute, to remove additional residues and all these things. And further, it should be ready for development; so when you expose it, your UV rays or light from this illumination part, there are different sources; there can be xenon or lasers, other sources, and all. So that will fall onto your mask; your mask will have a certain pattern, so light will get diffracted and it will pass through some portion and get diffracted at edges, and then based on this objective lens and diffraction and several other optical known series of events, you will get it here. But when you get it here, that particular portion of your wafer will get a different chemical property, and which behaves differently during development.

So basically, in simple terms, if I may explain, exposure maps your mask design in terms of different chemical regions on your wafer, which you can further use when you develop it. Your final desired thing will either get etched or will stay there; the other part will get removed based on which kind of photoresist you are using. In lectures, the professor would have already covered positive and negative photoresists, right? So based

on that, a particular portion on your wafer will stay, and the other portion will get etched off, and you will get your device, okay? This is like an overall quick recap of the explained lithography process, just to brush up on the things that have been covered and give you a kind of feel for this particular problem statement. So now let's move ahead with the example. This example is related to the coating step, which is this step, okay, from the entire lithography process. Now we will focus on the coating step, okay?

As I mentioned, the relationship between spin speed and your thickness is already known for a particular resist.

$$D \propto \frac{1}{\sqrt{\omega}},$$

Resist thickness denoted as D, spin speed denoted as ω. We can understand that higher spin speed leads to lower thickness, and lower spin speed leads to higher thickness. But how much higher or lower can we identify the relation? This equation contains four variables, three of which are known. Finding the fourth one would be very easy. Just put the values in, and you will get the particular value. However, the catch is not just to use the equation and plug in the values. You should also understand what it conveys. When the thickness was 320 nanometers, you had to spin it at 2800 rpm. But when you want an even lesser thickness, now how much lesser or how much more you want depends on your subsequent processes, your chemistry for development, and other parameters. So, if you want a lesser thickness, how much should you increase your spin speed? That's just to understand that particular aspect. When it was 320 nanometers at 2800 rpm, if you want to go down to 280 nanometers, you have to increase it by at least almost 20% or more, something like that. You can quantify it based on this particular relationship. However, remember that how much you should increase or decrease depends on subsequent optical photochemistry and what you are aiming for.

Once everything is done, you can check your finally desired generated device using this metrology. Metrology is also known as characterization, which is very important. There are several processes for characterization; some of them are SEM imaging techniques, TEM, and other spectroscopy methods like FTIR, XRD, UV-Vis. Based on different structures and process flows, you can use different characterization techniques to evaluate whether you have achieved the correct desired pattern or not. These patterns are of micrometers and nanometer dimensions. Also, when you are working with chemicals, you should know whether a particular bond exists in that chemical or not. All these things can be identified using characterization techniques; it is like an evaluation parameter, okay? In the normal world, you can say it's for validation and so on.

So, this is the first example of a process that focuses on coating. Now, let's see another example that focuses on another subprocess of the lithography chain. I would say this complete exposure is part of the chain because lithography is at the heart of fabrication;

the entire final pattern depends on it. But if I talk about lithography optics and subsequent exposure, including illumination, optics involves illumination, exposure, and everything. This exposure happens in a very short period of time, sometimes just a few seconds, but it does the trick. It should be very precise as well. When I talk about precise exposure or optics in lithography, I mean the condenser lens. When I say lens here, including the objective lens, there are many large lenses that have been precisely placed. Even if it's off by 1 millimeter here and there, you might not get your desired pattern as the final output.

So, the entire fabrication process depends critically on lithography, and lithography depends on your particular optical step. That's why in the subsequent numerical, we will be focusing a little bit on one of the key aspects in a simplistic manner for that specific exposure step. Let's move ahead; this is the problem statement for the second problem: what is the ratio of minimum feature sizes achieved using the g-line and I-line wavelengths of a mercury arc lamp? The first question should be, what is the g-line, what is the h-line; we will come to that and consider that the same lithography system is used. Basically, this is the emission spectra where you can see there are different wavelengths and different types of illuminations provided here, and we have been provided with the wavelength of the mercury arc lamp.

These are the ranges for the mercury arc lamp. Now, there is a relationship between wavelength and resolution. Resolution is nothing but the minimum feature size achieved. There is something called a minimum half-pitch, which you can successfully reproduce on your substrate. That is known as your resolution; it depends on several things, including numerical aperture.

Numerical aperture is the ability of the lens to capture a certain particular portion of light. It depends on some process parameters; it depends on at which particular angle you are illuminating your mask and how the light has been guided from your illumination to the mask and from the mask to your wafer. So when you talk about the illumination device to your mask, then the condenser lens comes into the picture, and when you talk about the mask to your wafer, at that particular time, your objective lens comes into the picture. Again, when I say objective lens or condenser lens, there are a series of lenses strategically placed in a particular precise location. Here, in this particular case, we have been provided with two types of sources that have been used: one is the G-line, and the other is the H-line. What you get, what information you will get from this, is that you have been given two particular wavelengths, one of them is lambda G, which is nothing but 436 nanometers, and the other one is lambda H, which is nothing but 405 nanometers

Now, why I have chosen these two values? Studies and all have already been done regarding at which wavelength this emission spectra peaks. What do I mean by peaks? It means you will get a photon or a particle with the highest energy, like locally highest, and as you learn in mathematics, local maxima, local minima, etc. So, these values will give

you the photons with higher energy so that you can, with less time or optimally, get the job done. When I say 'get the job done,' I'm referring to lithography, right? So, let us see how to approach this particular problem.

Yes, this is a very important and simple equation shown here but it holds huge importance when it comes to resolution. As I mentioned, resolution depends on your wavelength, numerical aperture, and a process parameter which is K. Again, when I say resolution, ideally, the smaller resolution I want, the better. Why is that important? Because with a smaller resolution, you can have more functionality in the same device, or for the same functionality, you can have smaller and smaller devices. Just think about it, before 10-15 years, your computers or desktops used to be bulky equipment, whereas now, most of your work can be done using your mobile phones. How is that possible? That is due to the evolution of being able to incorporate more and more logic on the same chip, and that is where resolution comes into the picture.

So, how do we improve resolution? Even if you don't know anything about lithography or optics or microfabrication, you can still say that in this case, if K is less, I can improve; if lambda is less, I can improve; if numerical aperture is higher, I can improve. So, how do we do that? These are known techniques to improve resolution known as RETs (resolution enhancement techniques). Why am I mentioning all this? Because these things are important when you talk about minimum feature size, G line, I line, and all. Based on your interest, I would encourage you to go and check out all these RETs.

Let's again focus on the solution to this particular problem. The equation is given, and now you additionally know about RETs as well. I would encourage you to delve into the details of all four of them. Lowering wavelength depends on this particular parameter, and the fourth one depends on this. High shifting mask, for now, we can say it is related to this first one, right? It is related to this as well. Then it comes to immersion, which will heavily increase your NA, so the third one will come here, and off-axis illumination will definitely reduce your K. Each technique affects your formula or one of the parameters accordingly.

Now, you see that the minimum feature size and all are given. Additionally, it is given that the same photolithography system is used. So, for the same photolithography system, your K remains constant, okay? K remains constant. Also, when the same photolithography system is used, it means the lens and all arrangements will remain the same, so your NA will also remain constant. So, now the only thing is your final resolution is proportional to your wavelength. You put the values and you will get the final result, and we'll just erase this for now. Yeah, so you put the values in this case, and you will get the final value, the particular ratio, right?

So, again, putting value and getting the result is something even a calculator can do, but understanding how you reached this particular stage, how much you understand about emission spectra, how your final resolution changes based on different parameters, and all of that is very important. So, let's move quickly to an example based on resolution, then we'll move to the third example.

In the third example, an optical lithography system uses a krypton fluoride source with two-beam imaging. One thing to note is that a krypton fluoride source is used. If you look at the emission spectra previously, the krypton fluoride wavelength is identified. Going lower in terms of wavelength will give you a smaller resolution. That's why we chose to go one step lower to the krypton fluoride source. You could even consider an argon fluoride source or even something less if possible. Now, somebody might ask, "Why not use UV light with a wavelength of 13.5 nanometers directly?" But that comes with its own pros and cons. When I talk about extreme UV lithography, it wouldn't work on the same principle as excimer lasers or mercury lamps work.

Optics change, principles change, formulas change, and finally, the entire structure or arrangement of lithography changes, although it's possible. UV has been used to fabricate several things, and there are different techniques and all. For now, we'll focus on the krypton fluoride source used with two-beam imaging. Two-beam imaging means there are two types of imaging: two-beam and three-beam, which I'll explain later. It depends on how your light or source illumination happens with respect to a condenser lens.

If this is your condenser lens and this is your source, and there is a normal incidence, then it will be three-beam imaging. If there is an oblique incidence, resulting in two beams reaching the lens, it will be two-beam imaging, and your K value will change. Normal incidence, where you apply the light normally, results in three beams, making it three-beam imaging, with a K value of 0.5. When there is an oblique incidence, and three diffracted orders of light go out of range for a particular subsequent lens, only two beams reach the lens, resulting in two-beam imaging, and your K is 0.25. This is a known process parameter.

Considering two-beam imaging, let's assume the numerical aperture is 1.35. Now, when you change the medium between your mask and lenses—mask comes between the condenser lens and objective lens—when you introduce a medium in between, your numerical aperture will change, and accordingly, you will see an improvement in resolution. So, we have been given a krypton fluoride source, which gives us the wavelength, we have been given two-beam imaging, which gives us the value of K, and also the numerical aperture. What we need for resolution,

$$R = \frac{k\lambda}{NA}$$

Where R is the resolution, k is a constant, λ is the wavelength, and NA is the numerical aperture.

So, the required information has already been given, but let's see what the further problem statement says. Compute the optimal resolution that can be obtained for the given setup, put in the values, and get the final resolution that you can achieve. The next key part of the problem statement is whether the given parameters will fulfill the requirement if a process requires a 120-nanometer pitch. Slowly but surely, we are moving towards a numerical problem that is more like an actual design-based numerical. Of course, we are considering an ideal case, but they have asked whether with the given parameters, you will be able to achieve a microstructure with a pitch of 120 nanometers or not. So, let's approach this solution now. As I said, the first step is very simple. This is what I was explaining earlier, and you already know about the source, condenser, and mask.

Here, towards the mask, this particular light is illuminated normally, right? This angle of light and mask is 90 degrees, so it is normal incidence of light, which will result in, let's say, three beams—1, 2, and 3—all three are acquired by the objective lens. So then, if it's normal incidence, it's called three-beam imaging. However, in some other strategies, if you are using oblique incidence, then this would be different. Let's say, instead of this, we will be using this imaging, so this is oblique incidence. When it gets diffracted, some of them will go like this, out of the range of your objective lens, and others will come here and here.

So, only two out of three beams will be acquired by the objective lens. This is again decided by your numerical aperture. Numerical aperture, as I mentioned, is the ability to acquire a particular portion of your length, which also leads to limited fidelity of your finally acquired light on your wafer. These are the two types, so if it's like this, with oblique incidence, then it's two beams, and for this, your K value is 0.25, while for the other three beams, the K value is 0.5, which is better. Lower K value is better for us, as it will result in improved resolution. So, the overall idea is about how these optics, values, and parameters are getting changed.

Now, let's quickly see whether it will fulfill the requirement or not. So, I'll just plug in the values. As I mentioned, for the krypton fluoride rod light source, lambda is 248 nanometers, numerical aperture is 1.35, and for two-beam imaging, your K value is 1 divided by 0.25. When you put in these values, you will get a number like 42.945 nanometers, which is the smallest half-pitch that you can successfully print on your

wafer. Now, the scenario has given us that the process requires a 120-nanometer pitch. If you can achieve less than that, that's excellent. If you cannot achieve that, then there's a problem. So, we are able to achieve it, and ideally, if you want a 190-nanometer pitch, then your final desired pitch should be around 190, and then you can do it perfectly with 120 nanometers because not all the values or parameters are ideal.

So there will be some changes or process-related abrasion or optical irregularities occurring during the process, and you might have some buffer or gap. What I mean to say with that is this resolution is 42.92, which is the half-pitch that you can successfully print on the wafer. This gives me a full pitch of 91.84, or to simplify, a 92-nanometer pitch that this existing experimental setup can achieve.

Now, how much nanometer pitch do we want? That is 120 nanometers. So, a 120-nanometer pitch is your desired goal, whereas with this setup, you are able to achieve a 92-nanometer pitch very easily. Hence, if anything greater than 92 is required, obviously your system would be able to handle that. But when I say greater than 92, it's better to keep a little bit of a gap. Therefore, this gap is good enough. If I say 92, 120 is almost 30 percent more than 92. So, this gap is adequate enough to proceed with the patterning.

Yes, a structure with a 120-nanometer pitch can be printed with the projection setup. This is a very simple example when it comes to lithography or resolution, but the agenda was to help you realize how these final structures and designs are based on known aspects of lithography or lithography optics.

Now, I'll quickly summarize or give you a current picture. Over the decades, the resolution has improved. If you know Gordon Moore, the founder of Intel, he observed that every two years, the size of electronic components on your wafer, or footprint, gets halved. So, every two years, you will get a higher technological node, which refers to the feature size that you can print, and this trend has been followed for the last four or five decades. Gordon Moore recently passed away, but his observations still hold true, and now there is research known as "More than Moore," looking into how resolution or lithography-related statistics, or which parameters, have contributed more to achieving better resolution.

If you look at the improvement from 1975 to 2010, and the further improvement up to 2023, there's significant progress in each particular aspect. The resolution formula includes K, lambda, NA, and overall resolution. In 1975, we were working with technology or nodes around 2.7 micrometers. By 2020, we successfully fabricated structures as small as 42 nanometers. Now, in 2023, foundries have successfully fabricated structures as small as 3 nanometers. We can compare the 3-micrometer technology from 1975 to the 3-nanometer technology we have now, which is an

improvement of 10 power minus 3. This shows a significant improvement of 1000 parts of micrometers, and it's interesting to analyze which parameters have contributed the most to this improvement.

This is taken from, I believe, an IEEE article or something similar. So I would encourage you to look it up. Wavelength has seen very limited improvement, like 193, whereas in EUV, we are using 13.5 nanometers but with a different physical principle.

Numerical aperture is at 8.4, which is the biggest improvement compared to all the other parameters, and we are achieving 3 nanometers. I wanted to explain a little bit about how much smaller dimensions we can achieve. Consider an example: an organic argon fluoride laser. You should now know what the wavelength should be, 193. Use oblique illumination, which I have shown before, with a k value of 0.25. Consider the highest numerical aperture you can achieve.

If you cannot, just consider 1.35 and identify the smallest dimension you can achieve. This is like homework for you. Check how small you can get, and then compare that value to this value. Let's say this will give you around 100 nanometers. So, based on this projection lithography, you can consider it as 100 nanometers.

How did we reach 3 nanometers? What did we do? That is what the foundry has successfully fabricated, a resolution of 3 nanometers. How it is being done is something I would like to leave up to you to explore on your own. It's not just one particular approach. Several approaches combinedly work to achieve this particular resolution.

Quickly summarizing, we have seen different growth stages from 20 nanometers to 10 nanometers, 7 nanometers, and finally 5 nanometers. These involve different types of patterning, such as double patterning, triple patterning, quad patterning, self-aligned double patterning, which you can see here, and some other patterning techniques in combination with EUV. All these techniques are used to achieve a specific resolution.

I wanted to give you an idea of this, and of course, based on your interest and exploration, you can delve deeper. The overall gist of the session is how you can achieve the desired final resolution to incorporate more and more functionality into your device.

That's what I wanted to convey in this particular class. I believe now you will be able to relate to lithography-related optics and concepts. If you have any questions or difficulties, feel free to write us on the forum and explore these concepts on your own. Thank you.