Indian Institute of Science

NPTEL

Photonic Integrated Circuits

Lecture – 10
Fabrication and Characterisation

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Now let us look at some technological issues in the fabrication and characterization of photonic integrated circuits.

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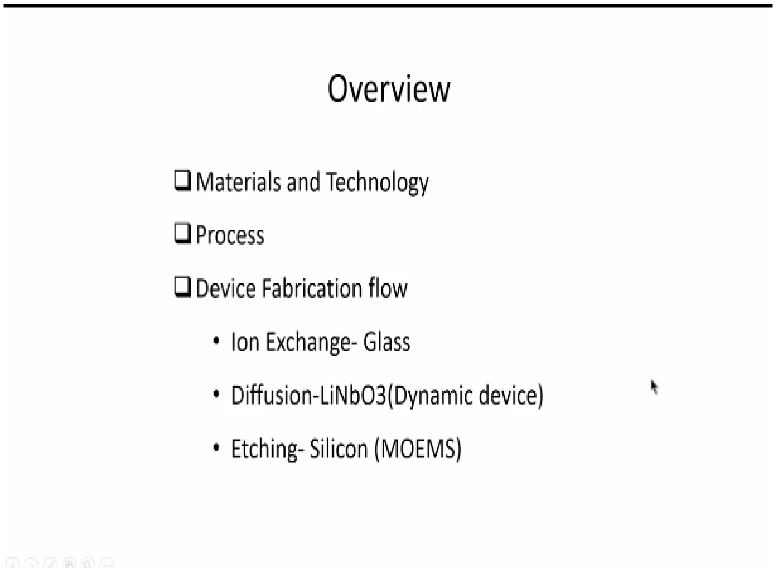

So broadly this is the outline of the presentation , we will look at materials and technologies that is involved with various processors that we can used to make these photonic integrated circuits. And then we will take up some specific fabrication and process. I have chosen three processors for three different application one is the glass based process, and other one for dynamic devices and one for silicon based devices.

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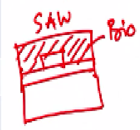
Materials

Materials	Advantages	Disadvantages
Polymers	Low cost, High EO modulation freq >100GHz	
Glass	Transparent to both visible and to IR	Not an Active medium
Silicon	CMOS Compatible	Not an Active medium
$LiNbO_3$	Direct band Gap, EO Active medium	Unpredictable Drift phenomena due to material propertis
III-V	Direct Band Gap, CMOS Compatible and good e-o properties	



So if you look at the various materials that are useful for photonic integrated circuits, the most common ones are as follows. So the most prominent optical materials are glasses, they are very transparent in both visible and infrared frequencies. But they do not have any active properties, so they could be used with passive devices like branches, couplers, waveguides and so on so forth.

They of course there are the lithium niobate crystal, there are many, many crystals which have got very useful properties like electro optic property and so on, and they can be used with tiny devices. But some of the important problems with the lithium niobate or the drift due to variations of metal properties that is not very desirable. So the stability of the material and the device properties is an important problem that is the negative point of that.

And as we know silicon is the most prominent material for electronic devices and it is one of the important candids for photonic integrated circuits also. And determine is called the silicon photonics and you can make optical devices and photonic integrated circuits compatible with CMOS devices. But of course it is not an active medium which means that there is no electro optic effect or migrate optic effect of others.

So you cannot control the properties of the devices externally, but of course it has got very good opto electronic properties, you can make detectors and more importantly silicon has become very important material system for MOEMS applications. So you can make a lot of mechanical devices it has got a very good mechanical properties, so you can make mechanical devices on silicon and of course if you couple or combine passive photonic integrated circuits with silicon you can make very good optical MOEMS so to say features talk will be looking at, what are called optical MOEMS or MOEMS.

So this is another important reason why silicon has become important. And of course looking into the features we need compounds make conductors like gallium arsenide, Indium phosphide and so on and combinations of that gallium aluminum arsenide and so on. The three, five materials are very important, because they have very properties which means that we can make very active devices that like laser diodes could be made with these materials.

And of course the technology is growing and in future it is possible that we have electronic devices also compatible and with good, and of course in addition it has got the properties active properties like electro optic properties and so on. So they patriot most promising candidates, but the only limitation at this moment is the technology is expensive and limited as compared to silicon.

There are lots of other materials like polymers which are important candidates for many applications particularly from an application point of view polymers and biomaterials and many other materials are useful as candidates for photonic integrated circuits. So these polymers of course are slightly lossy that is the degree point, but they have, they are very cost effective, sometimes they have good properties like electro optic effect and so on.

And the fabrication process also sometimes are very simple, so polymers also going to be an important materials. And other material system that we can also have a look at are for example, the magnetic materials, if you want to make magnetically active devices like what we have seen earlier polarization control and so on. Then there are specific materials which are useful for SAW device applications, frand use surface acoustic waves you can use.

Of course lithium niobate is one of the candidates for SAW applications, but you can think of materials which have got very good acoustic optic effects. And also we need to think of materials which can be deposited over this standard materials to create more devices. For example, if you would like to make a biosensor, we can have a silicon device or which you can create cladding layers over that, and we can use them as biosensors. So we need to deal with additional materials as biomaterials as a technological point of view.

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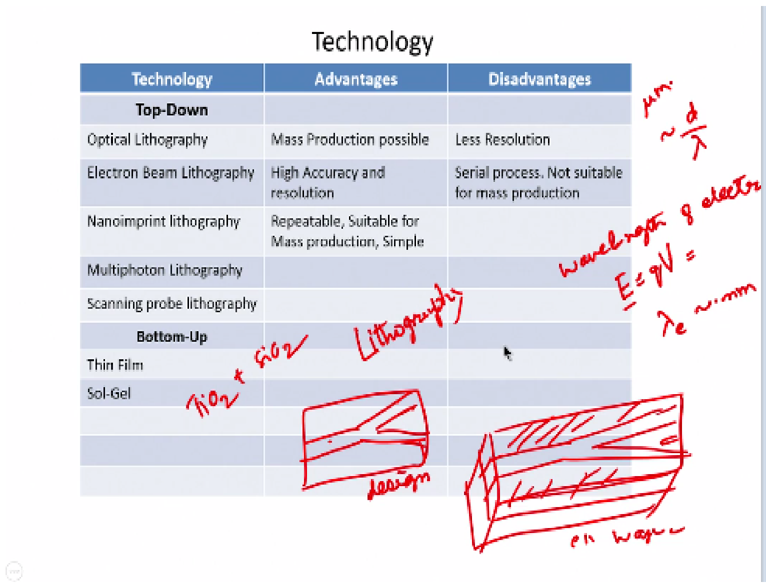

So let us look at some of the various technological process that will be useful for fabrication of these devices. The first preliminary description is in terms of a broad range of technological processes, then we will look at more specific issues. As you can observe that these are adapted or improved from the existing technologies of CMOS and thin film, and thick film processors. So in a few technological issues which can be route under, what can be called as lithography.

Lithography is a process used to transfer given design or pattern on to the vapor or a sub state. So if you have a mask pattern, if you have a design of a structure like this for example, one of the important steps involved in the fabrication of this device is to start with the design. And then we have to translate onto the vapor, first of all the pattern, then comes the other process like the diffusion of itching.

So this is the top view or cross-section, we have transferred one of these, so we have transferred this pattern onto the vapor. This is only a pattern later on it will be itched out or diffused for example, I may itch out all the unnecessary portion to make carriage we do not see all. So the process of transferring these desired pattern onto FL can be called as lithography and it is very important process and it may have to be used repeatedly to realize the device.

For example, if there is a electrode to be deposited or patterned on the waveguide or adjacent waveguide we have used lithography once again to make the electrode pattern. So there are various lithographic mechanisms in practice, so they can be categorized under up down approaches and bottom approaches. So you have optical lithography various light waves or ultraviolet light waves to transfer these patterns on to the vapor.

Then this is a technology which is well suitable for a mass production, but their resolutions are limited by the wavelength of light that is used, the resolution limit is described in terms of the size of the features that you can get with respect to the optical wave length, so similarly we can use electron beams for as a lithographic patterns and you can call them as electron beam the process is called the electron beam lithography.

Instead of using the light waves use electron beams and you can find out the energies with electron beams and their operating wavelengths, wavelength of electron. So it is also known that electrons can also be considered as waves and we can define a wavelength for electron based on energy of the electron beam for example if E is the energy of electron give out by charge if we accelerate an electron beam through a potential difference of V volts.

You can say that just got the qV is the energy and if you say that it has got a wavelength of and of course you know the mass with the electron, so we can say that we can determine the wavelength of electron. So if the speed is V, mv is the momentum and ½ mv^2 is say velocity and we can determine the wavelength of electron beam so once again the feature size that can be obtained is of the orders of d/λ and which is much smaller than the wavelength of electron is much smaller of the orders of nanometer or flowing optical and so micro meters.

You can calculate the wavelength of electron which can result in very high resolutions. And it is a CL process you did you do not have mass but point by point you write the pattern and is a, but slow process and is not very suitable for mass products, similarly you have other process like nano imprint lithography which is a repeatable process and is suitable for mass productions quite simple, similarly you use multi-photo lithography is similar to other electron in optical beam lithography where you use several photons if the fence of the photons can result in very good beams which can be useful for lithography process.

Similarly there is what you call as scanning probe lithography where you scan the entire pattern and then write wherever you would like to have the pattern, the other processes which can be consider as a bottom of the process earthling film processes you need to for a thin film or uniformly and then use a lithography to pattern these devices, sol gel is a process where you have a combination of titanium lithium oxide and silicon dioxide in the form of a gel and which can be applied on top of these substrates to. And then later on pattern if using the earth above lithography processes.

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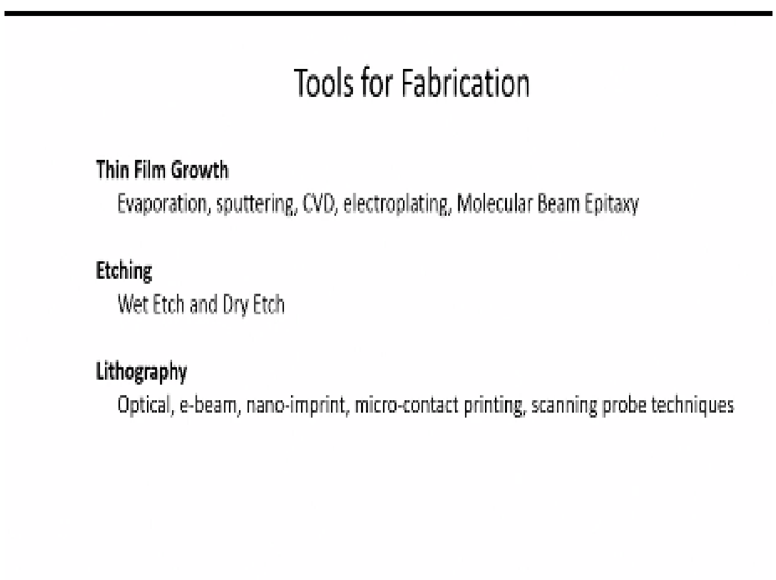

So there are several tools for fabrication they are categorized as thin film processes like vacuum, evaporation, sputtering, the chemical wave articulation, electro plating and then with the epitaxial methods like molecular beam epitaxial and so on. So the etching processes are used to etch out unwanted reagents from the wafer, so suppose you want to create an optical waveguide their regions where optical guidance is required can be retained and other regions can be list out. We have already seen that lithography processes are needed for patterning.

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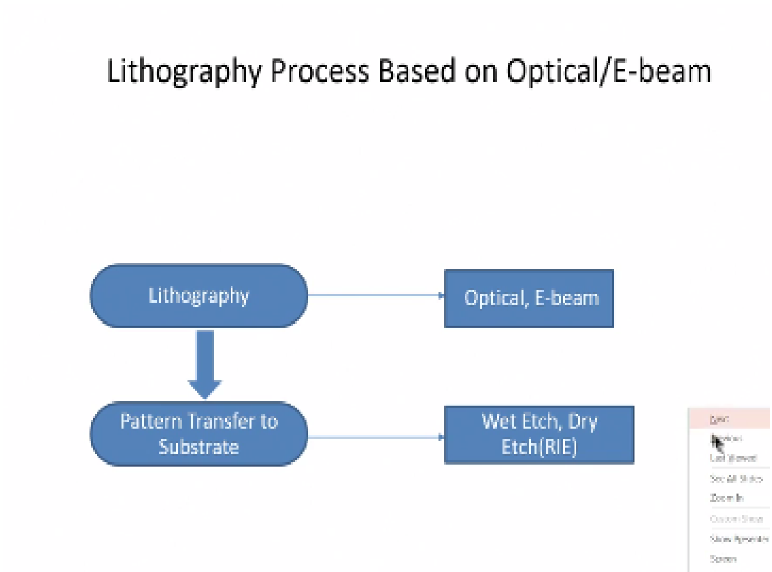

So let us quickly look at the operation of lithography process based on either optically beam lithography you have to transfer a pattern to its substrates and then use etching dry or wet etching to create this pattern so this is a simple process starting with a pattern transfer and then etching this is the two important steps in the lithographic process at realization of the device.

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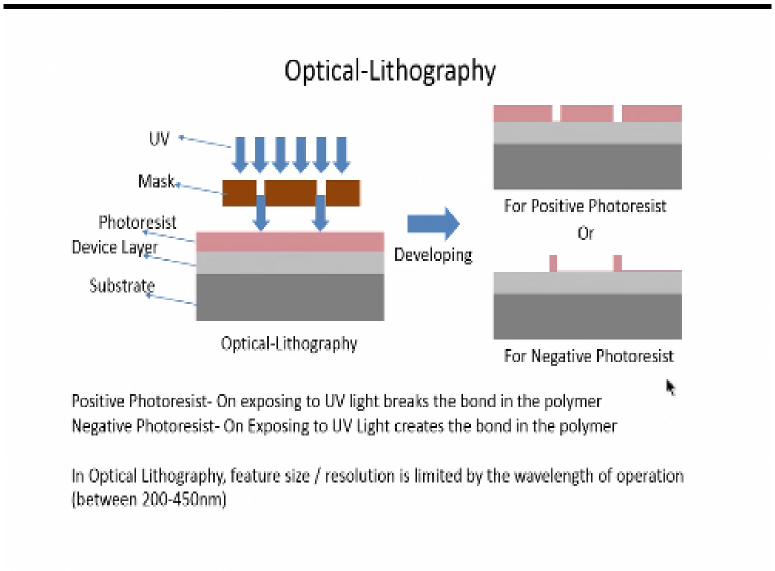

So slightly watch some more details about the lithography process the optical lithography basically consists of using the ultra violet light to expose a photo resist which is coated on to a substrate so you start with the substrate then you have a device layer like for example in off sight into which you will like to create the layers and then use a photo resist and expose the photo resist through the mask.

So typically an ultra violet light is used to expose this photo resist on exposing to UV light the photo resist bonds of the polymer brick and they will become enable to removal or etching so you have different types of photo resists there are what are called positive photo resist which result in a pattern on the wafer which is same as that of the given mask and then negative photo resist where opposite happens.

So negative photo resist on exposing to ultra violet light leads to creation of the modes rather than breaking of the bonds and so the pattern can become the opposite of what is realized, so in optical lithography the features size, resolutions are limited by the wavelength of operation typical of orders of a few 100’s of nanometer this is ultra violet light.

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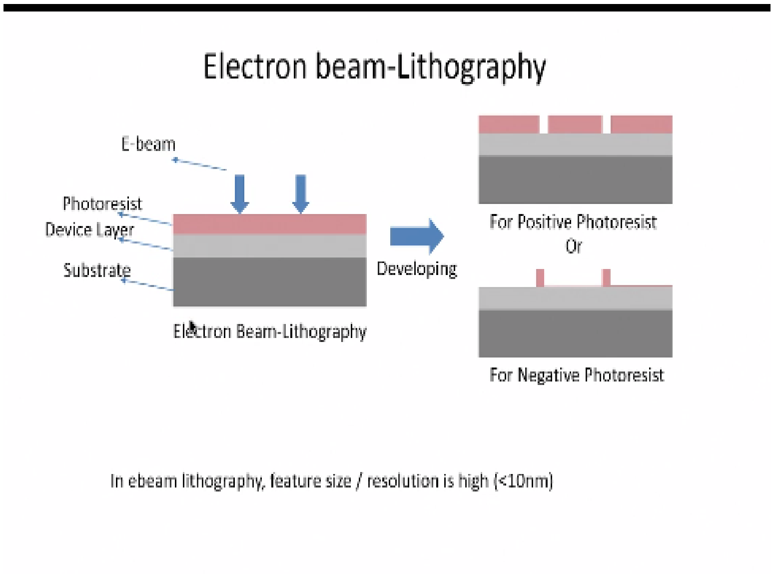

See in electron beam lithography we do not have a separate mask but you have a photo resist which is sensitive to its electron beam and etches, so you have a substrates and the device layer and quarter uniform layer of photo resist typically by spin coating for example and then expose you have a design pattern in a computer for example and then directly the electron beam can expose the pattern the photo resist to the pattern.

So that is one of the important recent developments where you need not make a separate mask for exposing this photo resist, once again you have positive photo resist or negative photo resist as we discussed for the optical lithography, so the resolutions possible are of the orders of few nanometers.

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So let us get a few device fabrication processes.

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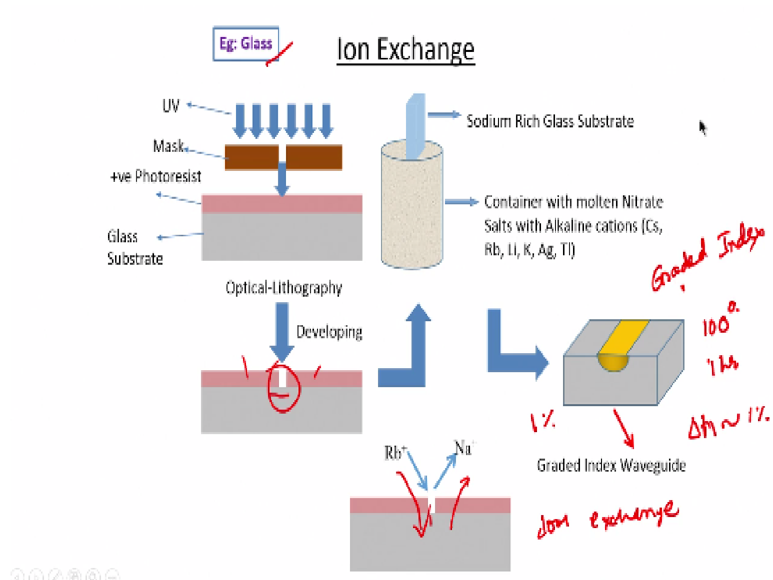

So illustrated here is an ion exchange process which is at level as an example to for glass optical waveguides we have a you can make waveguides in glass by using the ion exchange process. So this is the device that is designed at the end and you start with a glass substrate at typical it has got say few think of a soda lime glass you have got a sodium ions you got a positive photo resist and you expose the photo resist through a mask to ultra violet radiation.

And it create a in this particular case we create a tough region like this where the, this can be called as protective region is retained except in this region where you would like to create the waveguide. So then you have a bath of diffusion and you melt it if necessary in particular cases have a nitrate molt for example silver nitrate in the container you melt it to a certain degree whatever you require.

And then you dip this entire wafer to that replace entire wafer into the melt and allow it to diffuse, so we have the specific case the sodium ions of the glass can diffuse out and rubidium or silver ions can diffuse into these waves, so this is called an ion exchange process that is why we called an ion exchange process sliver ions are rubidium ions are exchange for sodium ions. So finally leading to a and of course in end we need to remove to H out this protective layer resulting in a device configuration that is required, so you may note that this results in a gradual diffusion of the materials into the sub state and may result in gradient index graded.

So the refractive mix profile for a typically diffused configuration is graded index is a very simple process it does not need very complicated clean environment except for the lithographic process the diffusion could be done in a slightly lesser low environment and very commonly used for making optical passive, optical devices class, so typical temperatures are of the hours of a few 100 ^{0}C for about 8 hours or wait let me say in the case of class wave guides it can go for 1 hour less than 1 hour.

So it is not a very complicated process compare to other set will see later on and diffused times typically are of the hours of a few hours and few minutes few hours, concentration is necessary or of the hours of few percentage and the refractive index difference the refractive index contrast that we can obtain it depends on the concentration of the sliver that we diffuse typically of the orders of percent, few percentage 1% change in 1% diffusion concentration of 1% and typically lead to about a few percent change in the refractive index that is the order of few that is possible with ion exchange process in class.

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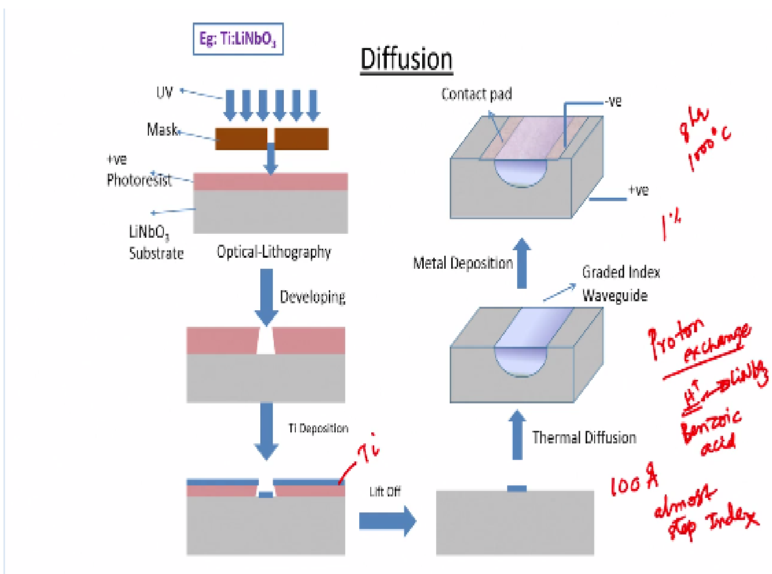

Next we look at another important process that is also commercially important and well established is called the diffusion process where talking the example of a lithium near bit device into which titanium element metal can be diffused to create a very good optical wave guides, so you can make titanium may diffused wave guides into lithium so this is the configuration that we have you start with a sun state of Lithium niobate.

This is very commonly used for titanium diffusion lithium in a bit start with a sub state we have photo resists positive photo resists informally coated on the lithium niobate by either repine coding or some other process and then you have a mask can expose the photo resist to ultraviolet radiation then of course we have to develop this photo resists and then you deposit a layer of titanium on this is a titanium film over this we observed there is a so due to the development and lithographic process there is an opening in this region and titanium is deposited only in the region where we need.

So after you H out or lift of the process is called lift of all this photo resists and titanium on your on what the titanium film can be removed resulting in a small titanium film of the Lithium niobate sub state this is of the hours of the few 100 A so now you this process is called thermal diffusion you put it the vapor in the a furnish controlled temperature control and the allow it to diffuses.

So the final result is in diffused optical wave guide like this once again this also results in a graded index optical waveguide in lithium niobate and we have already seen earlier that we can make active devices in lithium niobate for that we need to deposited additional layers for examples in this in this case you note a electors adjust into the wave guide so the is a negative electrode this is an positive electrode can apply electrified and change a refractive index power is of this lithium but.

So using a process similar to depositing the titanium film you can deposit a metal electrons either gold or titanium or whatever suitable material you can create electrodes this is a two process in the first step we have deposited the titanium and diffused and next step you created electrodes so typically the parameters for the lithium niobate process are about typically 8 hours after the 100 ^{0}C and the concentrations once again are of the orders of few percentage 1% change in the refractive index is sufficient to make very good optical wave guides.

Once again we have result in the graded index configuration for this another related process I can motion for the lithium niobate devices called proton exchange where we use a hydrogen ions to diffuse into lithium niobate and so we take metal of like what we absorbed for the in class wave guides you take a moleton benzoic acid which contains hydrogen ions and they could be diffused into the lithium niobate so this proton exchange process is at a low temperature and it could result in almost step index wave guides. So this could be done at a room temperature.

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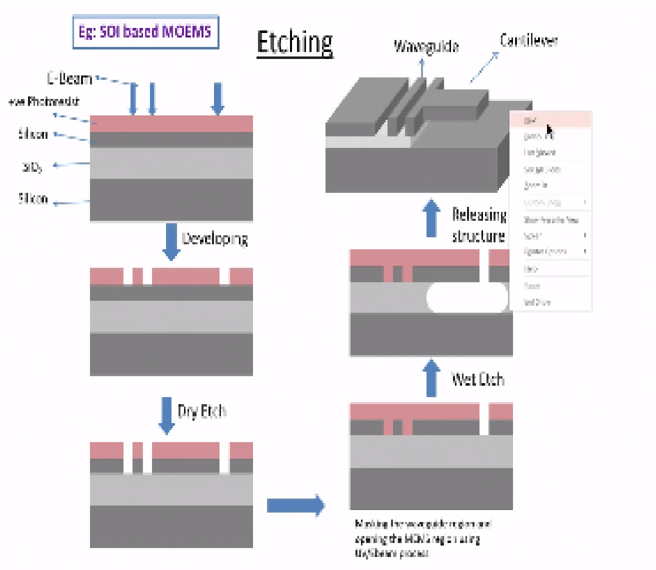

So an important process that is used in part is call the silicon photonics the subject is called the silicon photonics and in this particular example where illustrating etching of the materials or different layers that is deposited on the silicon vapor creating optical devices combined with MOEMS structures so MOEMS structures are mechanical structures as we see later on is next in the feature discussion you can combine MOEMS with optical waveguides to create what are called MOEMS.

So in this example where showing a device which as got a cantilever beam this is a cantilever beam on silicon vapor and also the optical wave guide on the same sub state, so a silicon vapor and in head hearing oxide layer on top it you have other layer of silicon into which you create wave guides and mechanical structures so this is a typical structure you as to illustrate the silicon photonics you start with a silicon vapor and you already have an oxide buried inside a silicon and there is one more layer of silicon top of this.

Silicon oxide and silicon so the vapors are available in this configuration in the SOI configuration silicon on insulation configuration sub state is silicon then you using lithographic process start with a positive photo resists using electron beam to create patterns in this and after development you retain only the photo resist the unwanted regions and openings in the regions where you would like to etch, so the process called dry etching is used to etch out the silicon device region so this top layer can top silicon can be called as device region this is called, so the silicon of the design with the device region can be etch out by using what is call this dry etching process.

That is also what is called a wet etching process where you use liquids to etch out chemicals to etch out the materials and you can also etch into the vapour for example in this particular case you are seen that using this opening you have etch out oxide in this region, so this is possible by using the chemical wet etching and the structure remains on the top of it, this one here we are observing a cantilever beam being released at this point.

So of course by using the other etching process you can etch out the top in photo resist layer result in the given structure, so this is the process in this particular illustration which one give process where you make optical waveguides reached optical waveguides on silicon along with a cantilever beam.

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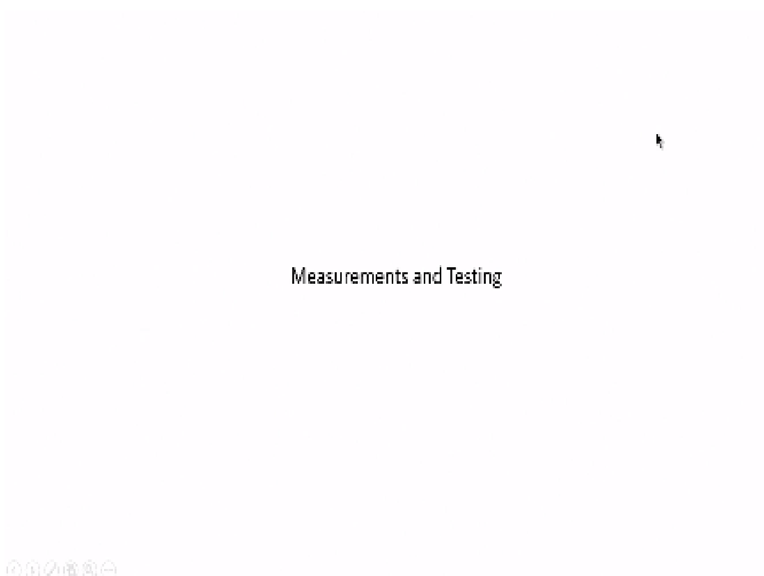

So let us look at a few techniques for measurements and characterizing these optical integrated optical devices.

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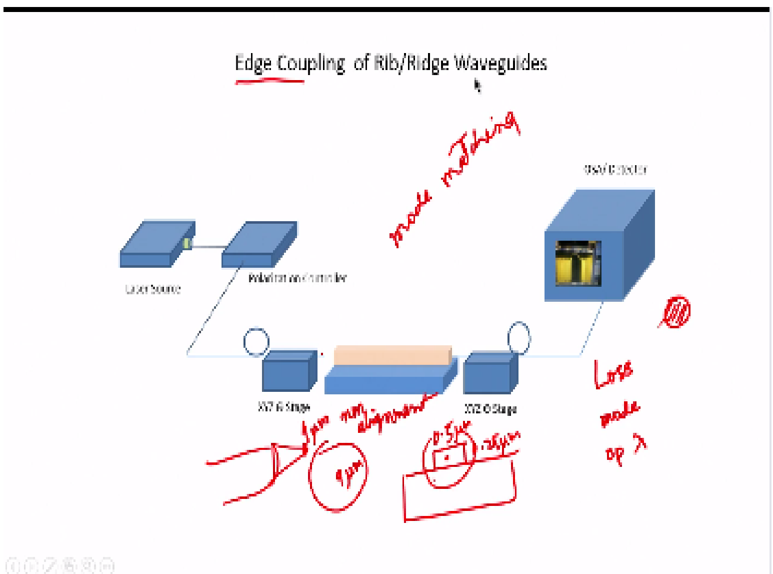

So the most common techniques involved in measurement of integrated optical devices in a laboratory consist of using a laser source sometimes trimble laser source depending on the properties at you would like to mention and devices for polarization control and the XY stages to position the input beam with respect to the photon integrated circuit and then finally a detective integrated system like spectrum laser or a photo detector to measure, so the basic photonic integrated circuit is placed on the platform like this and excited with an input optical beam coming through an optical fiber.

Typically the optical fiber itself as you know has got a diffractive index or a cross section circular cross section of 9 micron and the typical integrate optical waveguide devices have dimensions of the orders of 0.5 micron/ 0.25 micron so on silicon typically, on a typical silicon waveguide you have ½ a micron by 1/4th micron which is a very, very small compared to the dimensions of the optical fiber.

So lensed fiber is used to focus light on to this even then we have a circular mode spot in between which is slightly more than so there is no mismatch between the input light and the mode of the optical waveguide this one of the important feature or characteristic of the image emit process, so we need to have mechanisms where we can inject light into this integrated optical device very efficiently.

At this moment we are considering the characterization where we would like to measure the properties of these devices like loss of the waveguide then the modes, mode field properties and so on and so forth. So in case we want to study the properties of this waveguide with operating wavelength then we need to have trimble laser source, and in optical spectrum analyzer is a very where stale device which can be used to display the whole spectrum of light that is coming out of this.

Otherwise it is also possible to have a conventional screen to image the beam coming out of this. For example, we can observe the mode spot on a screen and correlate this will be the properties of the modes in the optical waveguide. So this is, this process is called edge coupling where we are launching light from the optical fiber up to this, this XY stages are very important and are useful to position this accurately with respect to the center of the waveguide.

So the resolutions required or the some of few nanometers, nanometer alignment the tolerances are need this using this lensed fiber we can focus this we want to as of the orders of a micron still it is bigger than the waveguide mode spot so we need to have alternative waveguides to match the mode with the waveguide beam, mode matching is what it has to done, matching of the input field with the mode.

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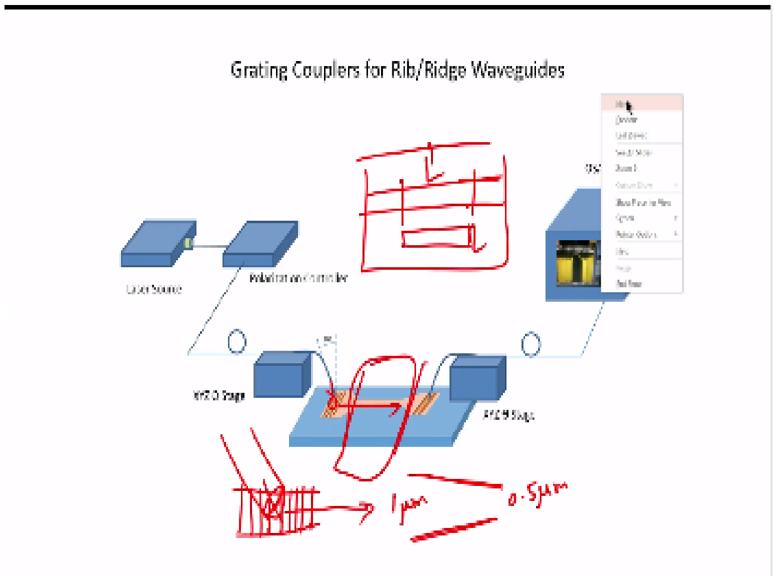

So this is another new process this is which has become important recently call the grating couplers on the same vapor where you have the optical circuit this optical circuit required you create waveguide gratings, waveguide grating has we have seen is a periodic waveguides or the refractive waveguides and it is possible to work out when light is launched from an optical fiber on to the grating light could be just coupled into the optical waveguide, so the light coming from an optical fiber falls into the grating and couples into the photonic integrated circuits.

We also note there is a tapering region, so from mode spots side of a micron and waveguide width of ½ a micron we need it is a taper waveguide to gradually launch the light into the optical waveguide. Once again you need the other optical elements like the polarization, controller, the XY stages, spectrum laser and so on and so forth, not measure loss of the waveguide for example we can improve, we can consider fabricating different lens of the waveguide or the same substrate and say for example, where here to here is one I will make that smaller waveguide and loss difference can be measured.

For example, this is an extra length l and l′ this is l and this is l′, so the extra length the propagation loss for the extra length will be estimated where measure in the output optical power.

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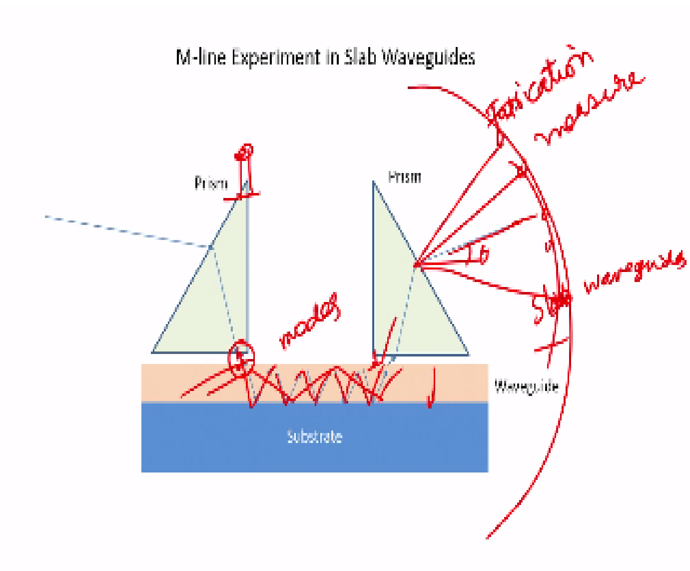

So there is in a laboratory there is another very simple and useful technique called M-line experiment to access the properties of the integrated optical waveguides, this is more particularly useful for characterizing the fabrication process, so important required in the development of the photonic integrated circuit is the fabrication measurements. Until now we have seen the measurement of optical devices it is necessary to estimate and measure the fabrication conditions, fabrication conditions could be very well estimated and measured by using slab waveguides.

For example, we would like to measure how much is the different depths and what are the concentration and how it behaves with respect to the fabrication conditions like temperature, concentration, time of diffusion and so on and so forth. The M-line experiment or the prism coupling experiment is a method to launch light into a slab waveguide and launch these modes we can excite the modes of the slab waveguide all the modes are possible to propagated in slab waveguide can be excited by using the prism coupler.

Here we at this divide waved in prism is located at the base of the prism we apply small pressure by using their tatin mechanism so the gap between the prism and the waveguide can be adjusted so that by advanced coupling the light incident at the base of this prism can be tunnel into the slab optical waveguide. In a similar reverse process the light could be ejected out of the waveguide through this prism by controlling the gap between this.

So by measuring the field output or the angles at which the light comes out we can estimate what is the propagation so the angle of exit can be related to the angle of light that is propagating inside the optical waveguide, so if there are several modes propagating at different angles in the film we get output at different angles. So each one can be said to correspond to a different mode, and we can put the entire thing on a spectrometer stage and rotate this such that you can measure any specific angle of the mode that is propagating and you can correlate with the properties of the optical waveguide.