Integrated Photonics Devices and Circuits
Prof. Bijoy Krishna Das
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 32
Tunable Devices and Reconfigurable Circuits_ Post Fabrication Phase Error Corrections

Hi everybody in the last lecture we discussed that slightest fabrication error processors can cause a lot of concern to any integrated optical devices when it is designed for passive operation. So, those type of things whenever you are talking about wafer scale fabrication etcetera. So, you can get you may not get the repeatability of devices in one region one location of the wafer to another location of the wafer particularly whenever you are talking about boundary level manufacturing fabrication of photonics chip.

So, it is very important that to have a device fabrication if there is any error if possible that can be corrected. So, that all the devices fabricated across the wafer should be uniform or any specific location or a specific chip you are fabricating in a lab level. So, that if any deviation happens because of the fabrication error that should be corrected. So, that is why this actually this sub sections I am trying to discuss I will be trying to explore the possibility how post fabrication phase error corrections can be done can be achieved.

There are various methods proposed to do that but three important method I will be discussing here which may be very interesting and useful for manufacturing photonics chip. First thing is that method one physical trimming of waveguide surface using reactive imaging. Suppose you have a device fabricated and certain dimensions you already get already got and because of that your deviation is there expected desires performance you are not getting.

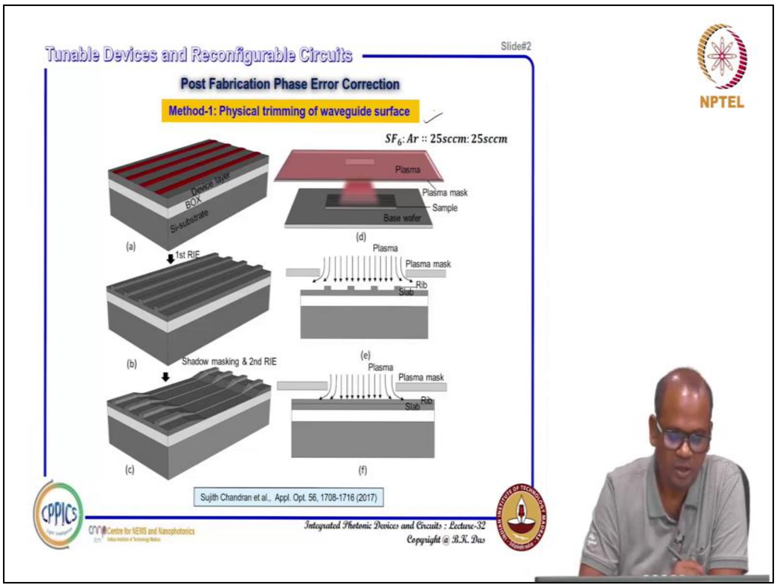
So, what you could do you can trim your surface waveguide surface by physically, physically removal of reducing the dimension. So, that is one method I will be discussing and then second method is that you do not need to change what you call that physical structure the dimension you do not need to change rather what you do you do some kind of laser radiation. So, called femtosecond region that means pulse will be of a laser it is a kind of pulse laser and with width duration of the pulse is about femtosecond range.

So, that type of laser with a certain wavelength range if you directly illuminate irradiate on the surface of the waveguide. So, the structural change can happen inside the waveguide surface volumetric change will not happen dimensional change will not happen but due to structural change you can change the refractive index. So, you can correct any deviations of your device performance.

So, that is one method I will be discussing. And the third method that is the most interesting method and very much feasible for a large scale wafer scale correction of the devices that is called heat treatment in a germanium implanted waveguide using microheaters. So, there will be internal machinery internal circuitry component you can integrate in every individual devices and then after fabrication you use them to fine tune your refractive index wherever you want whichever device you want.

So, that is actually very nicely very recently invented technology and published in this 2021 and I personally feel that that is going to be a huge impact for fabrication yield in photonics industry and cost wise also photonics cheap cost will be reduced if we adopt this type of technology. So, I will be discussing them one after another and let us see.

(Refer Slide Time: 04:35)



Tunable Devices and Reconfigurable Circuits

Slide#2

Post Fabrication Phase Error Correction

Method-1: Physical trimming of waveguide surface

$SF_6 : Ar :: 25sccm : 25sccm$

Sujith Chandran et al., Appl. Opt. 56, 1708-1716 (2017)

Integrated Photonic Devices and Circuits : Lecture-32
Copyright @ B.K. Das

So, first thing method one physical trimming of waveguide surface you know first I will discuss I will just explain how one can get in simply simplest way how one can get a waveguide simple web guide instead of device example given for a waveguide. These are the mask layer this red colour regions if you see mask layer to just define wave guide. So, mask means of some kind of resist photoresist or photoresist or e-beam resist you can do that and then that particular region will be protected device layer will be protected.

And rest of the region you can do some kind of reactive ion etching some kind of reactive gases you can pump into a chamber where your substrate is there and then you can use trigger them to create some kind of plasma. So, that that plasma that ions different type of ions specifically fluorine ion if it is there in the plasma that chlorine ion actually interacts with silicon and then it can create Si F 4 which is a volatile gas.

So, that gas can be pumped out. So, in that case silicon will be consumed to create Si F 4 and that is how you can age and you can define a set of waveguide it is shown here one waveguide number one we have got number 2 waveguide number three and we have got number four. Now suppose you want certain region this waveguide dimension let us say you want to reduce suppose you wanted a waveguide you have fabricated waveguide of width in the order of say one micrometer.

Now suppose you want to reduce it to 500 nanometer or maybe 900 nanometer height as well as width. Suppose you have a waveguide cross section if you see this is your width and this is your height. So, you want to trim that both guide width as well as height. So, that refractive index can be tuned. So, this is the method we called shadow masking and secondary RI. Then you can see that locally the dimension of the waveguide is reduced.

You see this is the initial waveguide at the input side and output side and the technique allow that adiabatic tapering both are with height as well as width of the waveguide and then in this region where you want to reduce the waveguide width or height that is actually indeed can be done. So if you launch light from here it is a larger waveguide cross section and then adiabatically it will be coupled to lower dimension waveguide structures where you want to trim maybe your refractive index or you want to tune the phase or so on.

So, this is the whole concept if we can do that could be very good. Wherever necessary you want to trim that particular region you can use a shadow masking. Shadow masking means I will just explain how it is in the next column. So, shadow masking you can do and shadow masking allow you by chemically you can etch the surface of the waveguide that is why it is called physical trimming, you are trimming the waveguide dimensions.

So, that you can actually control the refractive index as you know an effective of a waveguide earlier we mentioned that ineffective is a function of waveguide width, waveguide height, slab height as well as also temperature dependent operating temperature I am not considering your operating temperature dependencies here because it is just kind of permanent change you want after fabrication that is why it is a post fabrication phase error correction.

So, only waveguide width, height and slab height that can be changed. So, the method it is something it is depicted in this cartoon figure. So, suppose you have a you want to do that type of trimming this particular process this is well known you can come to know with a VLSI technology CMOS fabrication process. So, it is also CMS fabrication process just little modification after your device cheap fabricated what you do you use a plasma mask.

So, normally in the chamber plasma flux will come from top everywhere and you make a some kind of metallic or some kind of plate you can make it can be a silicon wafer also dummy silicon wafer just silicon wafers you can use. And wherever you want to reduce or you want to trim that region you make a rectangular hole and you maintain a distance you hold this mask. So, called it is called shadow mask because you are just creating a shadow over your sample this is your sample.

Where your device already fabricated earlier and you locate way in which region in which particular region of the waveguide you want to trim you that particular area window you should adjust here accordingly. Then plasma flux. So, plasma flux is created with SF 6 gas and you just make some kind of dilution along with some inert gas argon and here in this case so called 25 SCM is 25 SCM meaning 25 standard cubic centimeter per minute this is SF 6 flow rate and this is argon fluoride the 50-50%.

And we control according to our chamber we can actually control the flow flow of sf6 and argon into the chamber and then you create with a RF hour plasma will be generated because of the collisions molecular collisions and that plasma can be again it is basically when you call about pulse when you talk about plasma that is actually combination of pre charge ions electrons and positive ions and negative ions.

And those ions can be attracted by giving a suitable bias between the your sample and somewhere in the another electrode will be there then when it is coming back because of the phase mass this region plus plasma will not be directly heating to the substrate your sample. But whenever it is opened through that plasma will be penetrated and if you see since there is a distance this plasma plugs directly on the top of the substrate if you just think their plasma density will be higher.

And as it can be if you see the plasma profile the plasma profile will be plasma density profile through this mask if it is a rectangular you can see something like this type of plasma profile you can just think about. Plasma flux profile plugs of the plasma and this is your distance. So, here uniform plasma where you can actually trim your waveguide surface uniformly and towards the edge because flux will be here it is shown that plus will be reduced and because of the reduced plasma flux that region it will be trimmed less.

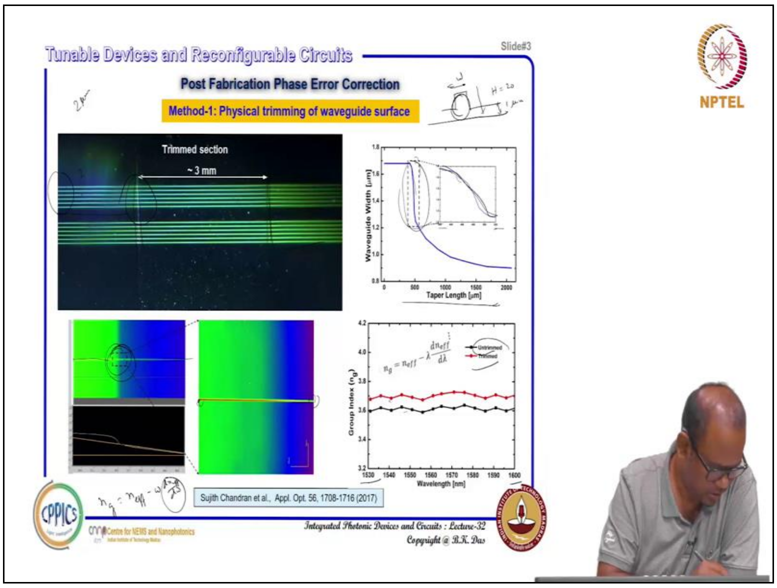
So, relatively lower trimming will happen. So, that is how you can get this region. So, because of the gradation, gradation of plasma flux you can see that gradation in trimming and that trimming if it is isotropic trimming isotropic etching happens. That means isotropic means sometimes an isotropic etching just directly from height will be reduced since it is a chemical reaction.

So, normally chemical reaction can be can happen all around wherever these chemicals are available. So, surrounding regions will be etched. So, in this region what will happen the gradation of height reduction will happen also gradation of width reduction will be happened. So, that actually help you to adjust the guided modes for such converter you can expect that in the input side this waveguide and this waveguide larger cross section more size will be higher.

So, if it is adiabatically tapered trimmed then the more size will be adiabatically will be shrinked to adjust the again trim to waveguide surface here trim waveguide dimension there it can be guided and you can again take it out. So, this is some method we invented here in IIT, Madras and we got a US patent also on this and it can be utilized for local trimming wherever you need waveguide dimension you can change wherever you need larger cross section you can use wherever you need lower cross section you can use that and you can get your expected outcome.

So, this is the method and if you want to know little bit more detail about it, it is published in a journal applied optics in 2017 you can download this paper you can learn more about it.

(Refer Slide Time: 13:32)



Tunable Devices and Reconfigurable Circuits

Slide#3

Post Fabrication Phase Error Correction

Method-1: Physical trimming of waveguide surface

Sujith Chandran et al., Appl. Opt. 56, 1708-1716 (2017)

Integrated Photonic Devices and Circuits : Lecture-32

Copyright @ B.K. Das

And there are some results of this method. You see this is the mark here it is given here it is taken through microscope this is the input side where it is masked. So, no trimming happened this output side also no trimming happened. So, between these 2 mark point if you see this streaming that wave guide dimension is changed basically and if you just zoom in this region you can see this one this region actually higher dimension.

And slowly you see dimension is reduced that this has been again zoomed to this area it is looking like that you see it just needed like very smooth adiabatically trimmed. If you see the how height is reduced as a function of length from this point to this point you see height is slowly reduced there is just a step here of course because their flux density suddenly increases plasma flux density.

And then but still it is adiabatically it can be several micrometer length several micrometer length is sufficient to have a adiabatic shrinking of your mode size also. So, you can get a lower dimension in this region and higher dimension in this region. So, that is how you can control you can control your flux density control your etching time and in that way you can control how much you want to trim?

Suppose you want to trim maybe a few nanometer it is possible you can adjust your timing you can stop your plasma etching and if you want more etching then you can go for longer time. So, in this particular method what we did we have 2 micron device this region it is about 2 micron device that is also designed something like that with this type of revive gate structure this is 2 micron.

And this height also slab height also h equal to 2 micron and then this one is about one micron this dimension also allows single mode guidance. And then if you trim here and this region it is actually sub micron nano dimension in the order of 500 to 800 nanometer dimension this type of waveguide can be useful for your ring regenerators. So, that compact bending tight bending is possible footprint can be reduced and so on.

So, that is actually done. So, here it is shown how in the transition region how height is changed and in this region it is as a function of length how waveguide width is also reduced. So, as a function of length waveguide width it is a little bit in this region it is showing that almost sharp falling of the waveguide width. But it is not if you just zoom this region it you will see that 420 to 500 to about 100 micrometer region the slowly waveguide width is reduced.

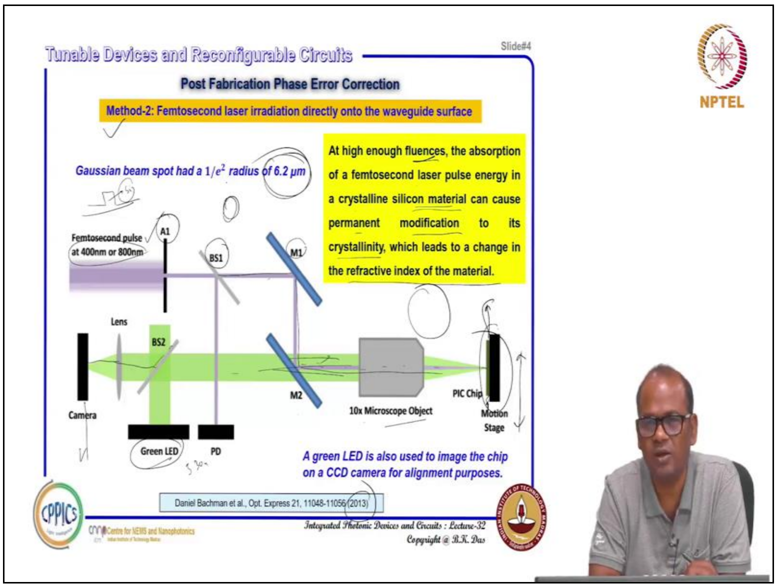
So, it is you can consider 100 micron region waveguide width is reducing means it can be adiabatic. So, that you can imagine that waveguide height is also reducing and also waveguide width is also reducing. So, your mode profile here. So, it can be maybe in the order of 2 micron or so, slowly it can strain adiabatically it can shrink without losing much energy from the mode and then you can go for the sub micron waveguide structure where it can guide which is just single motor dimension.

Again that trimming should happen such a fashion that that trimmed region also it should be single moded also. So, in this case we have shown that we have the we have also invented the method how to extract the group index n g you know n g equal to expression is n f n effective minus omega d n effective by d omega or in lambda terms you can write in g equal to n effective plus lambda d n effective by d lambda.

So, this group index we have just extracted that when it is not trimmed what is the group index and group index changing means either your slope is changing or ineffective is changing that is what you want to tune basically. So, when untrimmed that the black this curve it is following untrimmed the group index is in the order of 3.6 as a function of wavelength 1530 to 1600 nanometer.

When we monitor but when you trim it reduce the waveguide with waveguide that mode will be confined more. So, in that case the d n effective d omega term actually it will be larger it will have a large value. So, group index will be increased. So, this group index now you see it is increased to about 3.7 now group index for all wavelength. So, that way you can actually you can modulate permanently the group index or n effective according to your requirement wherever you need in a particular location of your device you can trim and you can get your desired outcome. So, this is one method that is called fast method.

(Refer Slide Time: 18:35)



Tunable Devices and Reconfigurable Circuits

Slide#4

Post Fabrication Phase Error Correction

Method-2: Femtosecond laser irradiation directly onto the waveguide surface

Gaussian beam spot had a $1/e^2$ radius of 6.2 μm

At high enough fluences, the absorption of a femtosecond laser pulse energy in a crystalline silicon material can cause permanent modification to its crystallinity, which leads to a change in the refractive index of the material.

A green LED is also used to image the chip on a CCD camera for alignment purposes.

Daniel Bachman et al., Opt. Express 21, 11048-11056 (2013)

Integrated Photonic Devices and Circuits : Lecture-32

Copyright @ B.K. Das

And then another interesting method that was actually demonstrated long back 2013 and published in optics express you can if you want you can also learn more about that you download this paper and then you can get every details. So, what happens in this method you have a photonics integrator circuit chip here and that chip is actually mounted on a motion stage.

So, that you can actually move you can change the location coordinate you can change on the surface of the photonic integrated circuit chip. What you do you use a femtosecond pulse at 400 nanometer 800 nanometer. So, any of the wavelength you can use operate femtosecond laser where peak wavelength is around 400 nanometer. So, you have aperture 1 a 1 where you can control the beam size.

And then you have a beam splitter one, 1 part 50% or whatever it goes to the mirror one reflect here and again mirror to reflect towards your microscope objective where this beam is focused tightly focused here and that focused region is about 6.2 micrometer. So, 6.2 micrometer that particular spot size the femtosecond laser is falling here. Here may be in the millimeter range of something beam size and once it is coming here you are using microscopic objective that means 10 times you can reduce in the focus part. So, 10x we are saying that. So, originally may be 62 micrometer and it is coming down to 6.2 micrometer.

At the same time what you do you use a green led green led means wavelength is in the order of some 530 nanometer or so, green led you are using just for imaging purpose you will need to know where actually it is you need to observe when actually it is falling the this beam. So, that beam also you use a beam splitter and goes here and this partial mirror that will transmit here there is a bigger beam and that also actually focus here.

And after focusing that beam reflects back that image taken care accordingly it will return path and goes to your again through this and goes to lens and then I ultimately you can imagine the camera this camera actually see using this green led where is the spot because you know that this light that is green led light and the femtosecond laser light they are in line. So, if you just change; if you change here this one if you are changing in this direction you can see you can ensure that your femtosecond laser.

And the position they are actually what you see look through the camera they are at the same point. So, now you see at high enough fluencies, fluencies mean flux. So, energy of the that means you have femtosecond laser you have a pulse width and you can have a peak power peak energy. So, based on that you just calculate fluences the absorption of a femtosecond laser pulse energy in a crystalline silicon.

So, you know you have a waveguides silicon on insulator waveguide this is silicon which is actually crystalline structure. So, when this femtosecond pulse laser comes that will be absorbed and because of the absorption this silicon material can cause a permanent modification to its crystallinity that means this crystallinity silicon crystalline structure that will be actually some way it will be destroyed a bit depending on the fluence.

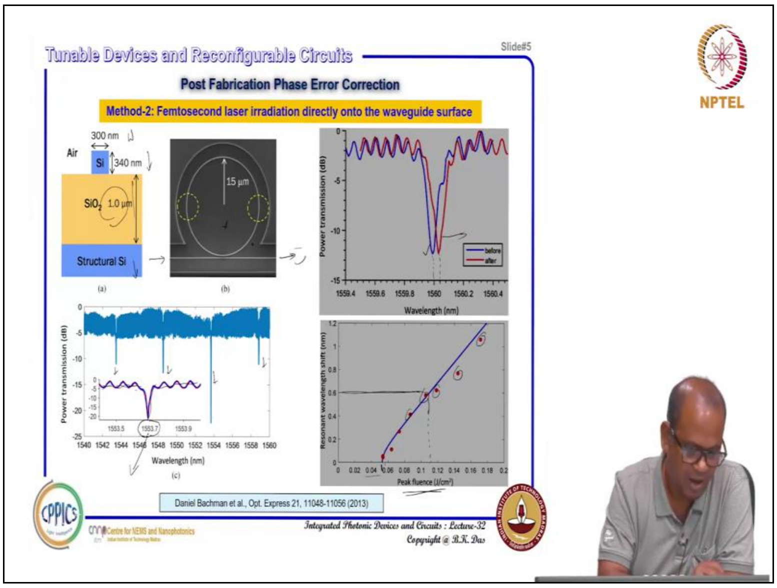
More fluence that means the crystallinity will be broken more which leads to a change in the refractive index of the material that is what you want. So, you can actually wherever at a particular device you want to change you want to change the refractive index to adjust your desired specification of the device. And then you can change the location go to other device and again you just change the fluence and see what results coming out.

And you can inline also you can monitor the performance also optical characterization you can do you can couple light one side and you can see the output and you see that if it is desired performance if you are not getting so you can control the fluence and adjust that and you can change permanently. So, if you have a wafer 300 millimeter wafer. So, you need to program that and you need to every device you have to check you have to test after post fabrication.

The post fabrication you can check and see that if any division is there to control your fluence and you can control your refractive index. So, that you get a desired result. So, this thing also very interesting till last several years people were just testing more and more and trying to do some kind of post fabrication error phaser are corrections. However this method which appears to be very expensive because you have to use femtosecond pulse laser and also one thing is that the spot size here is about 6.2 micrometer you cannot actually control this spot size.

So, you can have a only spot this much spot will be 6.2 micrometer diameter 1 by e square radius that region it will be change you cannot make a very smaller region to control. So, this is this appears to be expensive but it is quite interesting.

(Refer Slide Time: 24:26)



Tunable Devices and Reconfigurable Circuits

Slide#5

Post Fabrication Phase Error Correction

Method-2: Femtosecond laser irradiation directly onto the waveguide surface

Daniel Bachman et al., Opt. Express 21, 11048-11056 (2013)

Integrated Photonic Devices and Circuits : Lecture-32

Copyright @ B.K. Das

Now some of the results of this femtosecond laser irradiation directly onto the waveguide surface here results. Suppose you have a waveguide width you have w 300 nanometer height 340 nanometer silicon dioxide one micrometer box layer. They have used and structural silicon and this is the ring fabricated this is your bus wave guide. Both side you can have it is this is this region it is actually oxide this is an oxide and this particular region it is just structure something like that this ring it can be input and it can be output you can consider here.

So, if you just see the transmission as you know that particular wavelength this one this way one this wavelength this wavelength they are actually missing in the transmission that means at this particular wavelength energy is being stored in the ring resonator. If you zoom bit then you can see that the resonance would be something like that this is the output some modulation is there.

Because the device some have some kind of defects probably and then you see this resonance deep that means you ensure that at exactly 1530. 1553.7 nanometer wavelength the field inside the ring enhanced and the energy missing in the transmission line. So, device to device after fabrication you can see that suppose you wanted to have the wavelength resonance wavelength at 1553 not all the ring resonator is fabricated throughout the wafer may not be appearing at exactly 1553.

So, this type of femtosecond laser irradiation that can actually adjust a bit of resonance wavelength according to your desired specification for example here given before it radiation you have this transmission curve. So, it is giving your resonance around 1560 nanometer. So, after irradiation you see that has been tuned resonance curve is red now. It is tuned if it is 0.2 nano 1516.2. So, about 1516 point some pico meter things could be detuned.

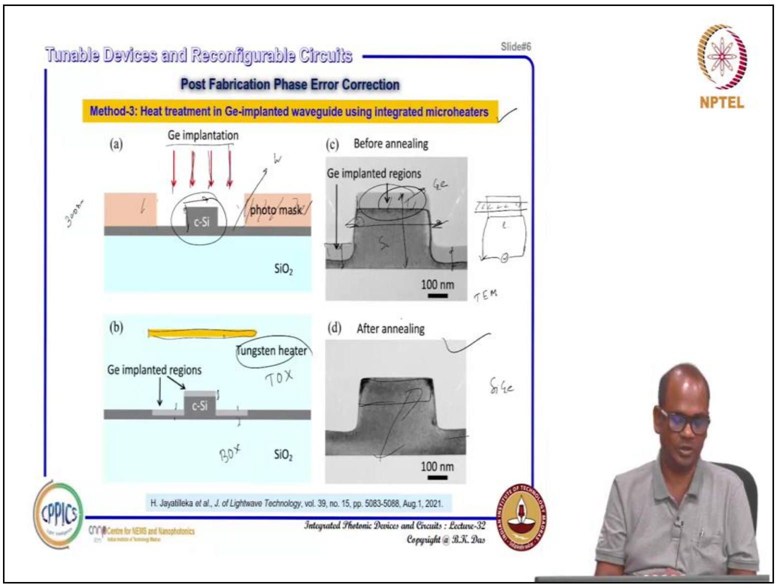
So, you can adjust and you could actually radiate more fluence more intensity more of the pulsed laser then you can detune further also. So, according to your requirement here it is soon peak fluence joule per centimeter that is energy per centimeter area that means kind of intensity you can say. And that if you increase so, up to here nothing happens. So, after this power peak fluence or joule per centimeter square.

So, that much joule coming joule means how much power you are giving for a particular time period time slot that multiplied by power multiplied by time that is your joule and if you it is just you have to see how much area it is covering. So, per centimeter square centimeter square how much energy is being deposited. So, that is called fluence basically and then resonant wavelength shift you see.

So, it starts shifting this is the experimental results this dots as a function of fluence and this curve is some kind of model theoretical model they could see. So, you know that this is my theoretical model I suppose you want to shift for example 0.6 nanometer resonance wavelength resonance wavelength I need a detuning because of the fabrication error it is it needs to be detuned 0.6 nanometer after fabrication.

So, you just influence up about between 0.1 about 0.11 joule per centimeter square then you can get this much detuning. So, this model could be used for post fabrication permanent phase error correction.

(Refer Slide Time: 28:15)



Tunable Devices and Reconfigurable Circuits

Slide#6

Post Fabrication Phase Error Correction

Method-3: Heat treatment in Ge-implanted waveguide using integrated microheaters

H. Jayatilleka et al., J. of Lightwave Technology, vol. 39, no. 15, pp. 5083-5088, Aug.1, 2021.

Integrated Photonic Devices and Circuits : Lecture-32
Copyright @ B.K. Das

And then the last one this is what I said that method three which is actually heat treatment in germanium implanted waveguide using integrated micro heaters. So, this is I find this is most attractive one and very easy method and everything can be done according to your demand and all the component you can integrate during fabrication. You do not need external laser source expensive femtosecond laser source for this type of treatment and you can also do it in a wafer scale 300 millimeter wafer scale and like jayatileka et al there are group of authors they published a article in journal of light of technology.

And just published in august this last month to 2021 and I find it very interesting I think it I thought that it could be very useful information for this course. So, it is a technique is following you see you have your weight guide crystalline we have got see silicon means crystalline waveguide you have a slab region say h some value is there and this is your height in this case this height I think they have used like 300 nanometer.

And width also in that range they have used some width particular width they have used but just for experimental purpose. What you do after fabrication you have waveguide structures like this and some location you want to detune the refractive index for example because fabrication error gives you different dimension. And your device is giving completely different results as you expected.

And maybe some of the some devices are giving good results on some devices for the other region of the wafer is not giving correct results. So, you have to throw them instead of throwing them what you do you use a photo mask. So, you just find a location where you want to change after testing you find that this particular device is problematic. So, what you do you may use a photo mask photo resist coating you just do and you open the area here just surrounding web guide and you do germanium implantation.

Normally you know in semiconductors silicon germanium gallium arsenide all the semiconductors you need to do p-type doping n-type doping that is actually in CMOS industry they do implantation technique. the high-energy germanium the energetic germanium flux comes to your surface of the substrate and because of the energy penetrates inside the sample.

So, that method is utilized here you just implant germanium where you want to change your refractive index. So, once you implant then what happens implanted regions it goes through silicon surface because of its energy it go little deep inside and while travelling through the surface into the silicon substrate it actually deform the crystalline structures somehow it destroy the structure up to certain height.

Here also in the slab region also here up to certain height germanium is implanted and you have actually deteriorated crystalline structure in that region. So, when it is deteriorated crystalline structure you can expect that some kind of loss will be added and if there is only a certain length maybe some few micrometer length you want that loss can be negligibly small compared to overall loss of the insertion loss of the device.

So, you can ignore that and but what happens in the process because of the implantation this crystalline structure will become amorphous. So, once it is becoming amorphous it will show you some different type of refractive index. But what you will do you use a tungsten heater on the top because you know in the silicon waveguide on the top you have a tox top oxide layer will be there for protection purpose.

And box is this one this is the device layer and within that when you are depositing your top oxide layer you can buried a micro heater of this much width that is actually tungsten heater. You can introduce here then what happens suppose this is your waveguide length this is your web guide top view and in the top of it you have a micro heaters also there tungsten micro heater of length L. If you just pass current through it you just give a bias some voltage source here voltage source here.

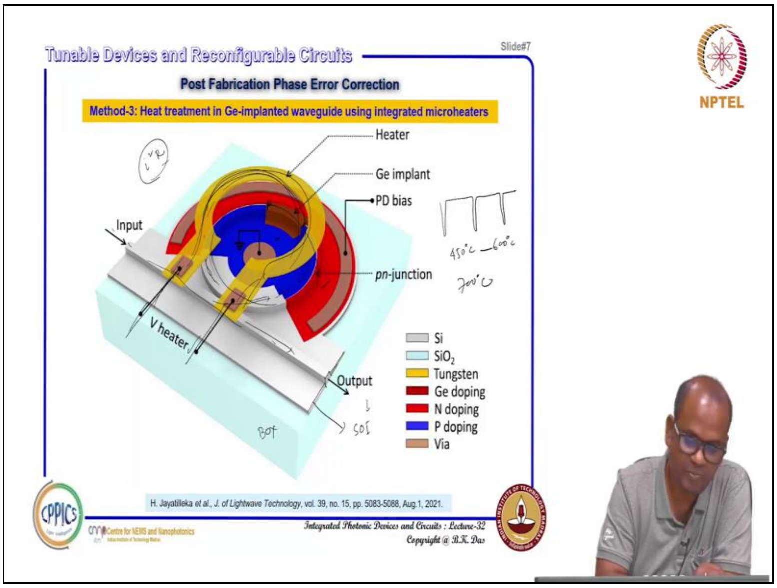
Then what happens current will flow through this it will be heated and temperature will go up when temperature goes up that time this implanted region that will start little bit of annealing, annealing means it will try to restore its crystalline structure. As it comes back to crystalline structure step by step depending on your heat power here it will actually keep on changing its refractive index dielectric constant keep on changing refractive index keep on changing.

You want how much refractive index change is required to determine your device that much power you apply to the heater and then you can convert this amorphous structure into a crystalline structure. So, that you can actually completely change completely restore the device specification as you desire as you designed. So, here in this case if you see before annealing it is shown actually it is actually some image called tunneling electron microscopic image in the cross sectional region it is shown.

You see this is your silicon and this is the germanium implanted region this is the region and also slab region also implanted this is the total slab height total slab height total height of the waveguide. And this is the width sidewise it will not come because your energy germanium implanted things comes normally vertically. So, it will be just here implanted. So, after annealing what happens you see this amorphous region now it is no more existing.

It is almost throughout it is actually similar that means this region probably your germanium is there but it is like a silicon germanium crystalline structure alloy type things is there silicon germanium is a good material for silicon electronics industry as well. So, you see it is uniform. So, that means how much the degree of crystallization happening because of the annealing because of the heating purpose actually decides how much refractive in exchange is happened in this type of things.

(Refer Slide Time: 35:10)



Tunable Devices and Reconfigurable Circuits

Slide#7

Post Fabrication Phase Error Correction

Method-3: Heat treatment in Ge-implanted waveguide using integrated microheaters

H. Jayatilleka et al., J. of Lightwave Technology, vol. 39, no. 15, pp. 5083-5088, Aug.1, 2021.

Integrated Photonic Devices and Circuits : Lecture-32
Copyright @ B.K. Das

So, what is there the actual cartoon figure it is shown here a sketch three dimensional sketch how it will look like for particularly for a ring regenerator. For example you want to determine the resonance wavelength of bearing resonator. For example here it is it is actually your box layer. So, for example box here this one and then this is your device layer says SOI silicon insulator and you have a slab region both side and you have your waveguide this is your waveguide it is called bus waveguide.

And then if you see this one this another ring regenerator is there embedded here and bus waveguide whenever launching light will be coming here and something will be coupled to the ring and something will be going out. And ring regenerator as you know you supposed to get resonance regularly depending on the pre spectral range and depending on the quality factor you can see the loss in the cavity you can see what is extension.

And then this particular ring resonator is actually designed for having a modulator applications I will discuss about modulator later for the moment you just think you just consider that this is a simple structure modulator structure based on lingering regenerator is a simple structure what you do one side will be p type doping and another site will be blue region may be n type doping. So, this is kind of p-n junction is created across the waveguide.

So, that p-n junction depending on the bias control you can actually modulate the refractive index actively that is how once you modulate the refractive index your resonance can be detuned you can have intensity modulation at the output here. So, that is the modulator I will discuss more details in future classes but for the moment they you just consider that is just used for monitoring purpose that how much refractive index change already happened same device has been used.

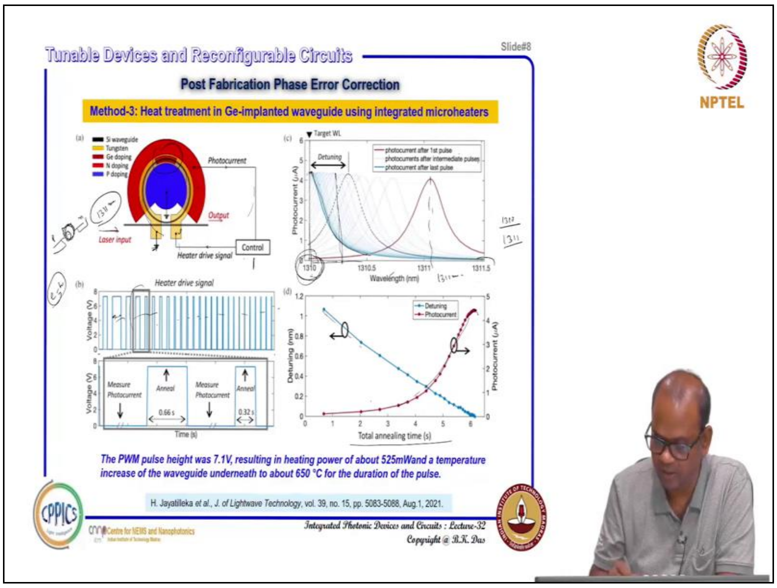
So, what up how that is used I will discuss and this region this particular if see if this is your ring this particular region this colour this bit of brown colour that particular region actually germanium is implanted using some kind of CMOS processes and in the top of it you see this is the oxide there will be buried oxide will be there top oxide will be there and the top of it this is your tungsten heater is given.

Along the curved waveguide ring and then this heater can be supplied some voltage here. So, that current can pass and because of the i square R joule heating effect resistance of the tungsten heater. Here this one that joule heating that energy the temperature will be will be raised waveguide raised and when temperature raised that time this germanium implanted region will be recovering restoring its crystalline structure.

Normally you know it is sufficient that 450 degree celsius to 600 degree celsius temperature is required for annealing purpose for restoring crystalline purpose. But this type of heater in this paper they say that you can actually supply the power sufficient power through the heater and you can raise up to 700 degree celsius temperature. So, that is sufficient higher temperature for annealing.

And here you see all this is the very nice way represent it with a colour 3D pictures and they implemented for post fabrication trimming purpose how that is done you see.

(Refer Slide Time: 38:41)



Tunable Devices and Reconfigurable Circuits

Slide#8

Post Fabrication Phase Error Correction

Method-3: Heat treatment in Ge-implanted waveguide using integrated microheaters

The PWM pulse height was 7.1V, resulting in heating power of about 525mWand a temperature increase of the waveguide underneath to about 650 °C for the duration of the pulse.

H. Jayatilleka et al., J. of Lightwave Technology, vol. 39, no. 15, pp. 5083-5088, Aug.1, 2021.

Centre for NEMS and Nanophotonics

Integrated Photonic Devices and Circuits : Lecture-32
Copyright @ B.K. Das

So, schematically again it is soon what you do this is your ground heater is grounded here and what you do it is a heater drive signal it is a control unit power supply basically, You can connect to the positive signal here. So, that current will flow this direction this is the germanium implanted region this is tungsten heater. Now this voltage drive signals you can have a pulse width modulation.

So, this can be a pulsed voltage signal there is a reason pulse why it is not see DC instead of dc you can have some kind of programming. So, that pulse width can be varied as a function of time. So, for example this is the thing heater drive signal in this particular case that you see this is the pulse width and then off then again pulse width reduced off pulse is reduced and reduced results you can reduce something like that you can program that according to your requirement.

And what happens you can have you can have this p-n junction is there if you have a wave guide and then suppose this side is p type and this side is n type doping this is p type doping and type doping and this region light is propagating. What happens when light propagates through silicon in this case this waveguide was designed to operate around 1310 nanometer o band operation 1310 nanometer it is transparent normally silicon 1310 nanometer supposed to be transparent.

But because of the defects etcetera what happens some defect states will create will absorb the photons operating at 31 nanometer then it will create some electron hole pair. When it is electron whole pair is created you have already p-n junction here if you give a reverse bias you can actually get that carriers generated excess carrier generator that can be extracted and depending on the carrier density you can see the current flowing across the waveguide.

So, depending on the current you can actually measure what is the intensity inside the ring regenerator. So, for example it is shown here if you just detune the wavelength 1310 to 1311 nanometer. So, you can see that you have a photo current because exactly at 1310 your resonance is there that means in inside the ring a lot of power will be enhanced intensity will be enhanced and lot of pre carrier electron whole pair will be generated.

So, you can see more current you can get this one here maximum as you detune the wavelength it will be just dropping because here resonance determine the wavelength it is going off resonant energy will not be stored inside the cavity ring resonator no photo current will be generated. So, it will be dropping. Now what you do after first pulse photo current after first pulse this is showing photocurrent after immediate pulses.

You see again another pulses are coming then you see photo current again it is shifting just looking into the wavelength sweep where it is for example you are getting here that means resonance shifted to this point here you are seeing the photo current maximum as you tune your wavelength is tuning here. And you are sweeping initially the maximum photocurrent was there around 1310 where you can expect that that was the resonance one.

Now because of the voltage pulse you are actually annealing the germanium implanted region and refractive index being changed and that is why your resonance wavelength is getting detuned and depending on the pulse photocurrent photocurrent just monitoring the photo current you can actually you can find out where is your resonance is going. So, initially the pulse width is more. So, you can say that see that as the pulse width more initially your detuning will be more and slowly slowly you want to control more.

Because suppose you have a 1310 nanometer original wavelength a resonant wavelength now you want to reach the wavelength resonance wavelength to 1311 nanometer. So, initially you do not you can have a longer pulse width. So, that it can actually detune very fast. Now whenever it is approaching to 1311 nanometer that is the reach desired wavelength. So, you can program that it can be slowly reduced and when pulse is not there voltage pulse is not there that time that particular window you use for photo current measurement.

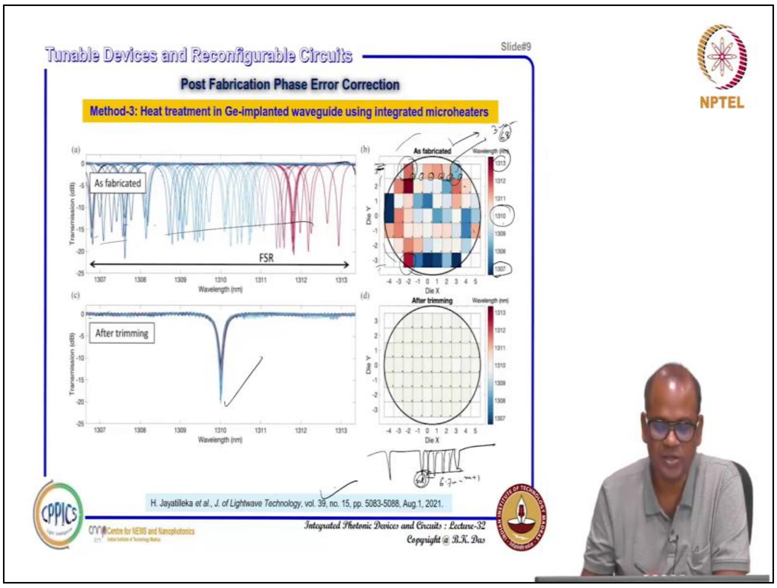
So, what is the photo current measurement as a function of particular wavelength. For example you want x you exactly want around 1311 nanometer resonance. In that case what you do you your resonance originally are 1310 nanometer. Now what you do you launch 1311 nano meter wavelength. So, since it is not at resonant. So, this laser light will not be coupled in the ring. So, photo current will be less.

So, whenever you are annealing, annealing because of the heating as you anneal then what you see that your resonance wavelength keep on shifting as you are shifting 1311 nanometer approaching to the resonant deep the resonant peak is approaching towards 31 nanometer. So, your laser light will start storing energy. So, photo current will be increasing you see photocurrent is increasing.

So, when it is becoming maximum it is almost inflecting that means you can say that your resonant wavelength is reached you can stop that time. So, you can program entire structure and you can test optically that in-situ you can find out your things are actually happening or not. You wanted this device you wanted to operate at 1311 nanometer but it is operating at 1310 nanometer you program it you supply the energy then you can have 1311 nanometer.

Suppose you want further little bit more that next time you want maybe it should operate at 1312 nanometer you again little bit send current program it and it will crystalline. So, after sometimes it will be saturated of course but you can up to certain level it can be done and you see as the increase and the as the total annealing time is there you can see how detuning can happen. In this case it is more than over one nanometer detuning 0 to 1 nanometer it is detuning can happen, fine.

(Refer Slide Time: 45:31)



Tunable Devices and Reconfigurable Circuits

Slide#9

Post Fabrication Phase Error Correction

Method-3: Heat treatment in Ge-implanted waveguide using integrated microheaters

H. Jayatilleka *et al.*, *J. of Lightwave Technology*, vol. 39, no. 15, pp. 5083-5088, Aug.1, 2021.

Integrated Photonic Devices and Circuits : Lecture-32
Copyright @ B.K. Das

Now you see this is the actual scenario I would say what is that you have a entire wafer it can be it is actually they have shown 300 millimeter wafer and 300 millimeter wafer you can think of there are total you see these each of them are dies 68 dies if you just count overall in that thing 68 dies and they have a particular dimension you can just calculate. This is suppose 300 millimeter this is actually 3 – 3, 2 + 3 it is shown the scale accordingly you can.

So, that and every dye you have the micro ring regenerators everywhere you just take micro ring resonator in one corner of the dye every corner you just select what is the resonance you can expect that within this dye whatever resonances are happening. For all micro ring resonators in this dye nearly same because they are close by their variations will be less. So, as you sample one of this ring from each dye then you can map what is the resonance wavelength coming for the micro ring resonator fabricated in each of these 68 dyes.

And you see that resonance varying from 137 nanometer to 1313 nanometer you know in ring resonator normally you see you see we have a resonance every FSR. In this case the FSR it is soon say about 137 nanometer 13 and 6.5 nanometer or so. This resonance FSR is 6.7 nanometer. So, it is 137 to 1330 nanometer that means about 67 nanometer. So, that means if this is mth order this is m + 1 with order.

So, if this resonance for a particular micro ring resonator it is resonating at this wavelength here another resonator neighbouring resonator may be here another resonator may be here another resonator may be here another resonator may be here it is shown as fabricated and 68 different micro ring resonator if you see their transmission characteristics you see the image order resonance for example it is varying from 137 nanometer to 1313 nanometer everywhere.

So, this is the as fabricated best boundary if you just use then you see all the micro ring resonator if you see in all 68 dies they are just everywhere all around. So, your yield is gone you can design a micro ring resonator for passive application but you see this is the resonance is everywhere. So, you can suppose someone you are sending this chip you are selling someone this cheap and you are selling someone this cheap their resonance is completely different. So, it is not useful basically.

So, that is why this method is used this annealing method is used and after annealing individual ring resonator they test it and anneal it. Such that it should come for example they fixed the resonant wavelength should be 1310 nanometer all the microwave regenerators would have a image order resonance at least at 1310 nanometer. So, they annealed individually 68 different device they have considered assume that this particular region one device is annealed means or one elements we can consider similar type of annealing can be done for all other things and you can just yield that.

So, after annealing you see all the 68 results they are coming exactly at 1310 nanometer. So, different micro ring resonator it require different type of power of course because their resonances will be everywhere depending on how much it will be tuned depending on that how much power you want to apply that much you have to give. So, accordingly it is perfectly done now it is permanent.

And they have seen that even after several hours several days after this treatment all the ring resonators they are showing at the same resonance wavelengths. So, in this way you can actually detune whatever the fabrication error tolerances are there in the wafer scale they have programmed everything. All the any even for electronics also if you fabricate if you fabricate a wafer scale devices using nanotechnology.

So, everywhere their device performance will be different you need forced surgery to correct location wise you have to correct those things. So, that this is called trimming method here also for photonics devices you have to do some kind of trimming and you can correct your all the performances. So, this is one method. So, once you fabricate if it is deviated performance is deviated you can do some kind of first post trimming post fabrication trimming method three methods it is described in this lecture.

Out of this method was found to be very attractive to me that is why I gave a little more time to explanation for explanations but I suggest those who are interested for how this things are done and how it is efficient whether it is really low cost or not you just download this paper and go through it and that will give you it is a very 4-5 pages I think very nice article anyone can read and can understand very easily.

With this I stop here next thing is that in next lectures what I will be discussing is that post fabrications and you can correct the fabrication errors that are fine. But sometimes it will be useful you can if you can reconfigure the device suppose according to your demand for example one particular ring if you take one ring if you take now it is giving you resonance at 1310 nanometer.

Now for some other applications I want to have it to operate at 13 nanometer. According to your demand for circuit application I want to have a resonance wavelength now 10.5 nanometer instead of 1310 nanometer. And for other application again I can come back to 1310. So, this is called detuning sometimes in a circuit in a large scale circuit if you just detune all the device and you can reconfigure entire circuit operation.

So, that is why this chapter we call it as a; so, called tunable devices and reconfigurable circuits. So, actively control according to your demand this is giving perfect after post fabrication you have corrected all the devices are alike their performance are alike that is fine now how to reconfigure them in a circuit level in a circuit for example I if you have a number of devices are there.

Maybe 100 of microwave resonators are there 100 and 100’s of mercenary interferometers are there then how to reconfigure them one after another program them one after how to do programmable circuits? So, for that purpose we need active control instead of permanent change I want to control I want to detune and then I want to get back to its original position whenever needed. So, that thing I will be going to discuss in next lectures. Today I just stopped for this lecture here, thank you very much.