

Chapter 4 Fabrication and measurement

4.1 Fabrication of photonic crystal waveguides

To fabricate the photonic crystal waveguide, first 1400 Å SiN grown on InGaAsP wafer by PECVD and use E-Beam to lithography. Before E-beam lithography, 3000Å PMMA was coated on the SiN film. Then we defined the pattern by E-beam and cad files which was drawn by Auto-cad software. After lithography we use Inductively-coupled plasma etching system (ICP) to etch the SiN and transfer design pattern to SiN, soon PMMA is removed by ICP again. After pattern is transferred to SiN film ICP heats the chamber to dry etch InGaAsP layer to host InP and remove the hard mask SiN film. After E-beam and ICP process, we want to undercut the sample to form a membrane structure. We use acid solution to wet etch the InP but not etch InGaAsP to undercut the photonic crystal waveguide. After undercut the wafer, wafer was scribed by scribed machine. A diamond-tipped scribe is dragged across a wafer creating a scratch in the wafer surface. When the wafer is stressed, the wafer separates along the scribe lines. The breaks follow the crystal structure of the wafer, creating a right-angle edge direction. Finally we get photonic crystal waveguides membrane samples. The procedure of membrane photonic crystal waveguide is shown in fig. 4.1. the detail will be discussed in later parts.

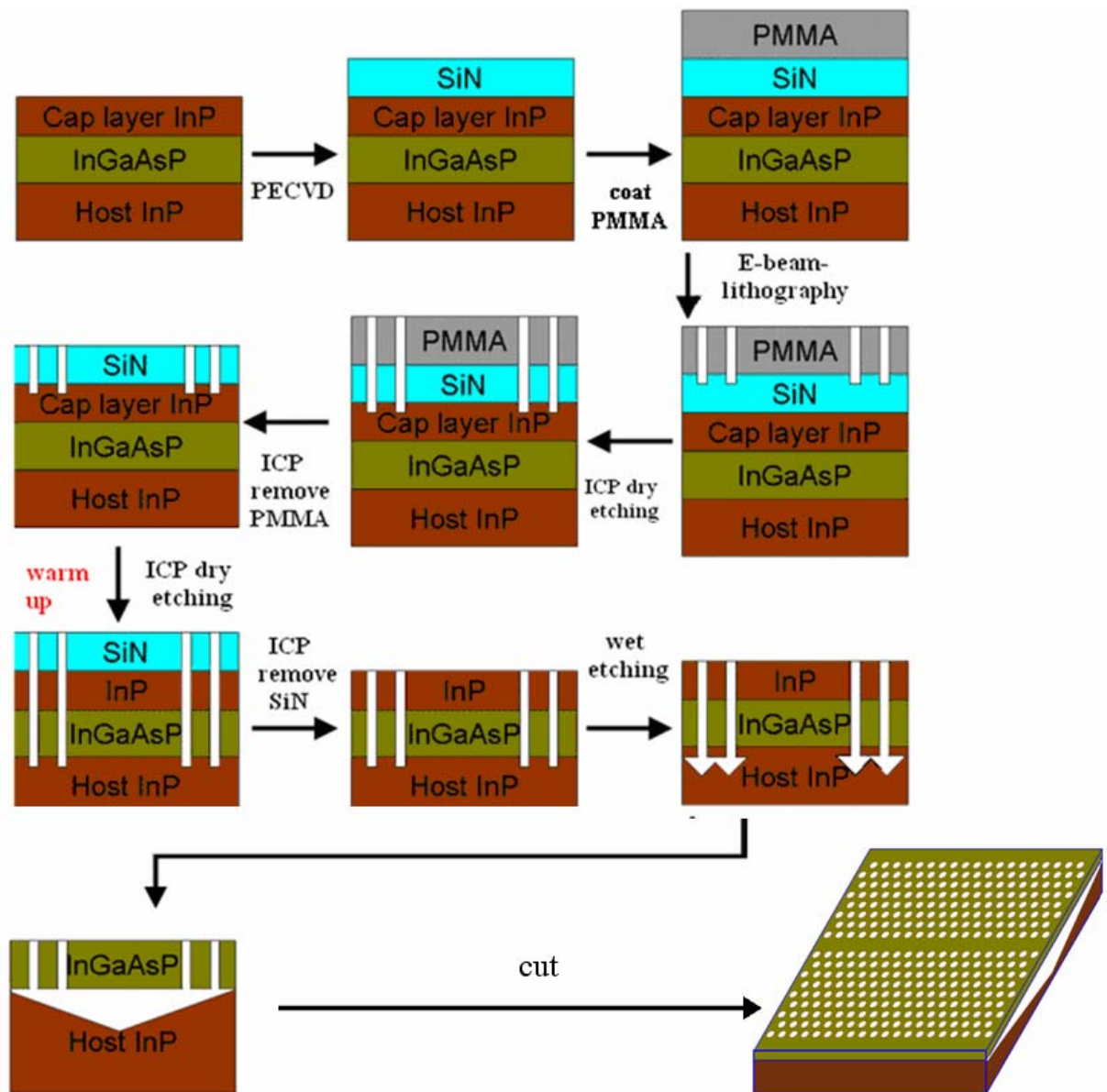


Fig. 4.1 The fabrication of photonic crystal waveguide.

4.1.1 Hard mask deposition

In the first step the SiN layer with a thickness 1400\AA is deposited on the InP cap layer by Plasma Enhanced Chemical Vapor Deposition (PECVD) system with a mixture of $\text{SiH}_4/\text{NH}_3/\text{N}_2$. The thickness of SiN layer is chosen to sustain the later deep etching of InGaASP/InP layer, taking into account the InP/SiN etch selectivity and allowing for an etch lag in deep holes.

4.1.2 E-beam lithography and cad design

The cad files are important to later fabrication process, so cad design is discuss first. In our cad files, the length of photonic crystal is $\sim 300\mu\text{m}$ and at the edge of photonic crystal waveguide, there are two big windows $30\mu\text{m} \times 13\mu\text{m}$, it is designed to be cut. We want the broken plane thorough these two big windows to avoid destroy of photonic crystal waveguide. Then around photonic crystal waveguide, there are many small windows $5\mu\text{m} \times 5\mu\text{m}$ which are crisscross. It can let acid solution permeate the host InP and undercut sample more easily. The cad files design is shown in fig. 4.2, the windows sizes are very important to undercut sample and cut device.

Before E-beam lithography we use Auto-Cad software to define our design pattern and transform our cad-files to NPGS file. Then we chose suitable size wafer to coat positive resist A5 PMMA ($\sim 3000 \text{ \AA}$) on it and use electrons to lithograph the wafer and define pattern on PMMA. After E-beam defined pattern MIBK solution is used to clean the positive resist. Because we want to undercut our device to remove the host InP which is under waveguides, the photonic crystal waveguide will be along $\langle 0, -1, -1 \rangle$ direction of wafer after E-beam writing. The E-beam lithography is not difficult to do, but the machine has it's limitation magnification to write pattern. The limitation magnification of E-beam is 200x, then photonic crystal waveguide that we can just achieve $300\mu\text{m}$ length. The top view of the $300\mu\text{m}$ and $500\mu\text{m}$ photonic crystal waveguide which are defined pattern on PMMA In fig. 4.3(a), the pattern of $500\mu\text{m}$ photonic crystal, the air holes have serious mismatch. In fig. 4.3(b) the pattern of $300\mu\text{m}$ photonic crystal, the air holes have good profile.

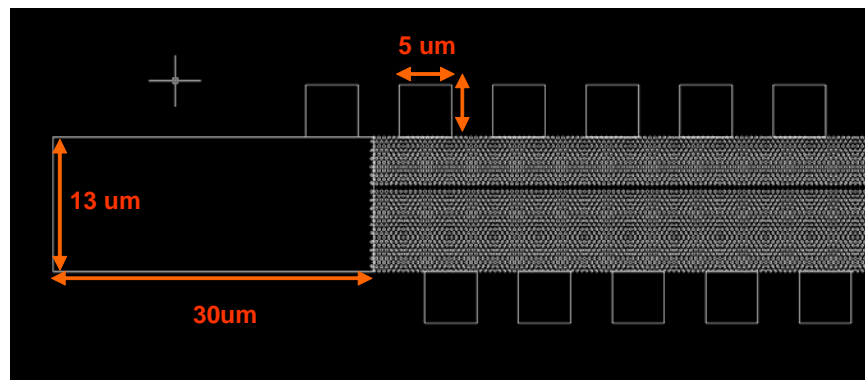


Fig. 4.2 The cad file of photonic crystal design.

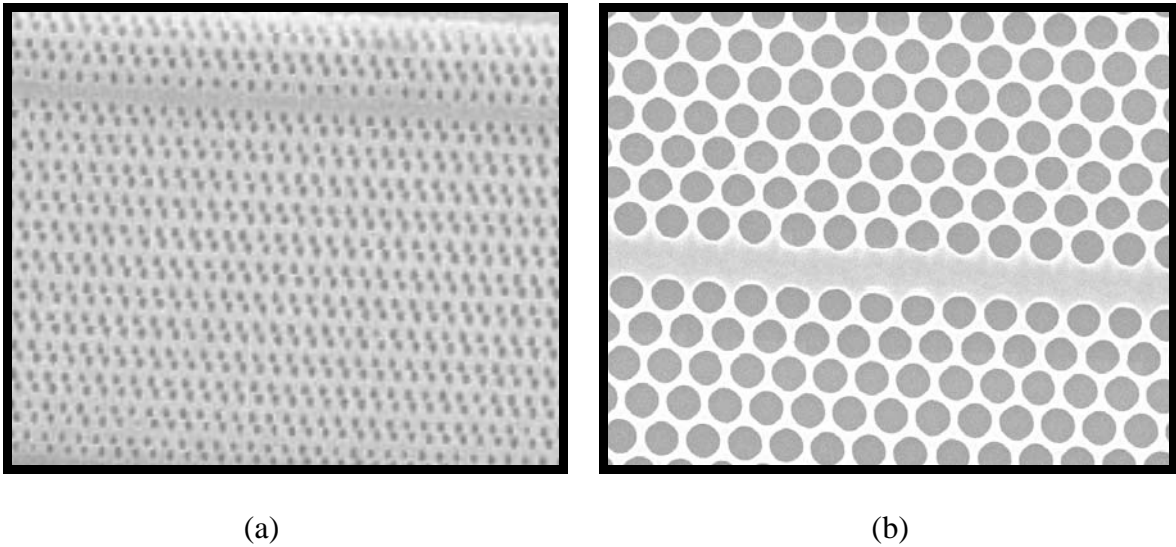
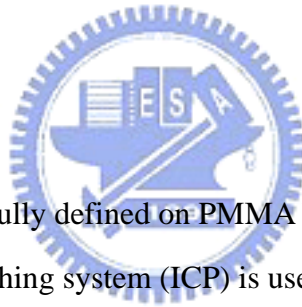


Fig. 4.3 (a) Defined pattern 500 μ m length on PMMA and writing magnification is \sim 200 x.
 (b) Defined pattern 300 μ m length on PMMA and writing magnification is \sim 300 x

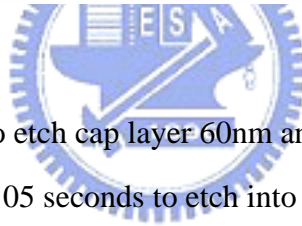
4.1.3 ICP dry etching



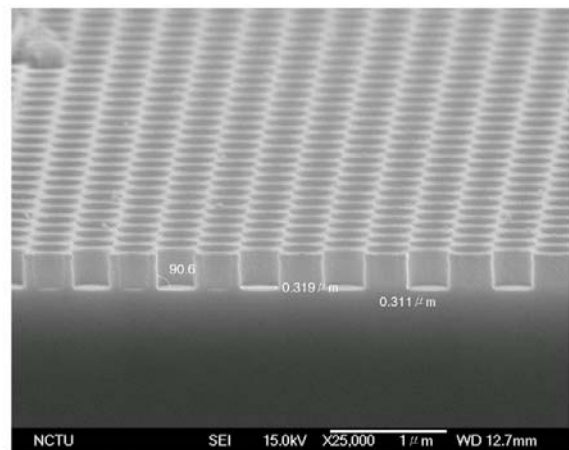
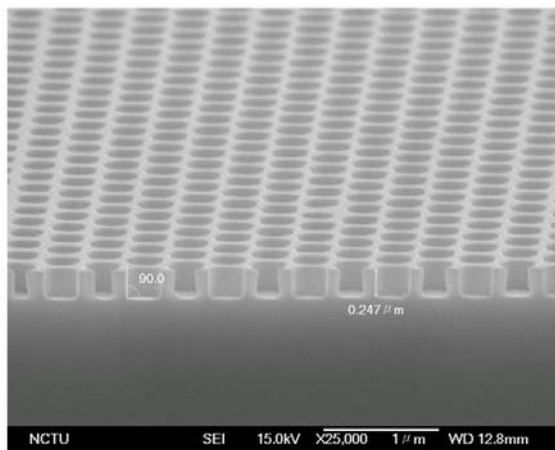
After pattern was successfully defined on PMMA by E-beam lithography, the Inductively-coupled plasma etching system (ICP) is used to etch the SiN film and the pattern will be transferred to SiN film, the recipe to etch SiN is used mixable gases of CHF₃ 5sccm, O₂ 50sccm, RF power 150W, temperature is 20⁰c and 2mins, the etching rate about 1000A/min. Then we remove PMMA by O₂ plasma etching and clean chamber 5mins. To etch the InPGaAsP layer, we first warm up the chamber temperature to 150 degree, and use mixture gases H₂/Cl₂/CH₄, the recipe is on table 5, gases flow and ICP, RF power, selectivity and etching rate are shown. Finally we remove SiN by ICP again or use BOE solution.

Table 5 InP etching rate

Depth	0.25 μm	0.3 μm
InP etching recipe	H ₂ (~0.8mT)	19sccm
	Cl ₂ (~0.3mT)	14sccm
	CH ₄ (~0.4mT)	23sccm
	ICP power	2000W
	Pressure	4mT
	Temperature	150°C
	He	10
	Struck	8
	Ramp	5
	RF power (W)	
	73	
	Time (S)	
	45	55
Selectivity	5.9	Not available
Etching rate (/min)	0.33	0.33



In our structure we want to etch cap layer 60nm and InGaAsP 250nm, over 300nm must be etched. The etching time is 105 seconds to etch into host InP in our design structure. The SEM figures of InP dry etching are shown in fig. 4.4.



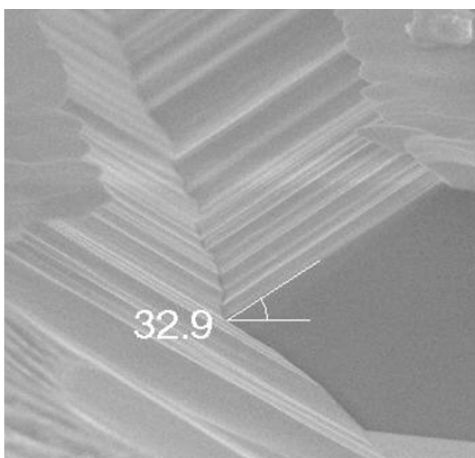
(a)

(b)

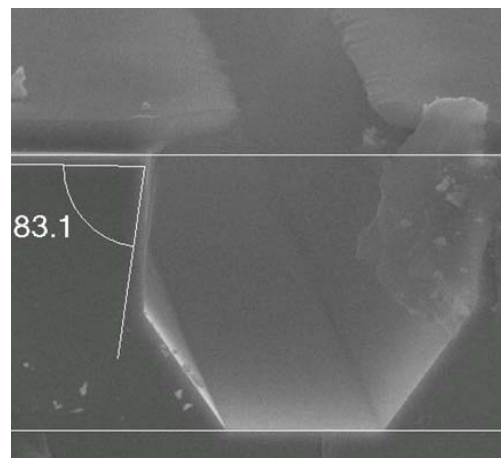
Fig. 4.4 (a) The SEM figures of ICP dry etching ~250nm (b) The SEM figures of ICP dry etching ~300nm

4.1.4 Undercut the PCWG

The last step to fabricate the membrane photonic crystal waveguide is to undercut the waveguide. We first glue the sample on glass by PMMA instead of clip the sample, because the stress may break the sample. Then we use the acid solution HCL : H₂O =3:1, 80mins, 30°C to etch the host InP and cap layer but InGaAsP. There are two etching stop plane for InP etching, the two directions are 40° in <0, 1, -1> direction, 95° in <0, -1, -1> direction, the profile is shown in fig. 4.5. Then along <0,-1,-1> direction the bottom of waveguide would penetrate and form a membrane. This step is very important and critical to our devices but some small mistake always cause serious destruction. For examples, if the cad file is not well design, then the waveguide would collapse, in Fig. 4.6 the waveguides are collapsed, fig. 4.6(a) is the top view SEM of waveguide broken by wrong cad design for connection of photonic crystal waveguide and ridge waveguide, fig. 4.6(b) is the SEM of broken waveguide by tilted angle. So the cad file is very important to design. Second, the wet etching time is very important too, if the time is too short, the membrane structure will not penetrate the host InP, the fig. 4.7 (a) show the SEM figure of fail undercut sample which soaked time is 10mins, fig. 4.7(b) show the SEM figure of successful undercut sample which soaked time is 80mins. The fig 4.8 is the magnification of the photonic crystal waveguide after undercut process of Fig. 4.7(b), fig. 4.9 is the tilt view of fig. 4.8



(a)



(b)

Fig. 4.5 (a) the 45° etching stop plane (b) the 95° etching stop plane

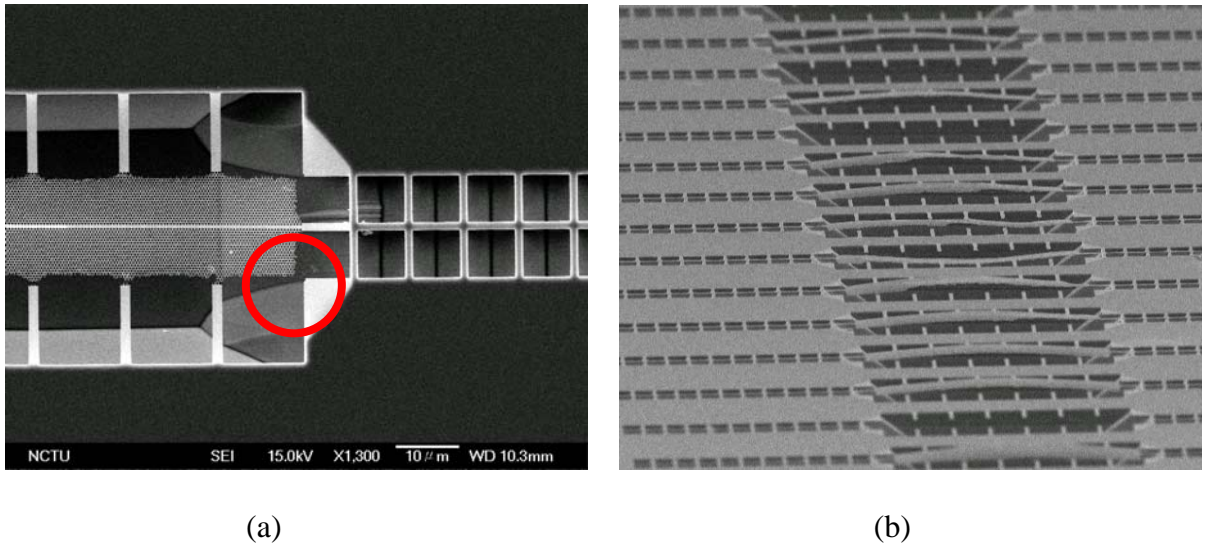


Fig. 4.6(a) The top view SEM of waveguide broken by wrong cad design (red circle). (b) The SEM of broken waveguide by tilted angle.

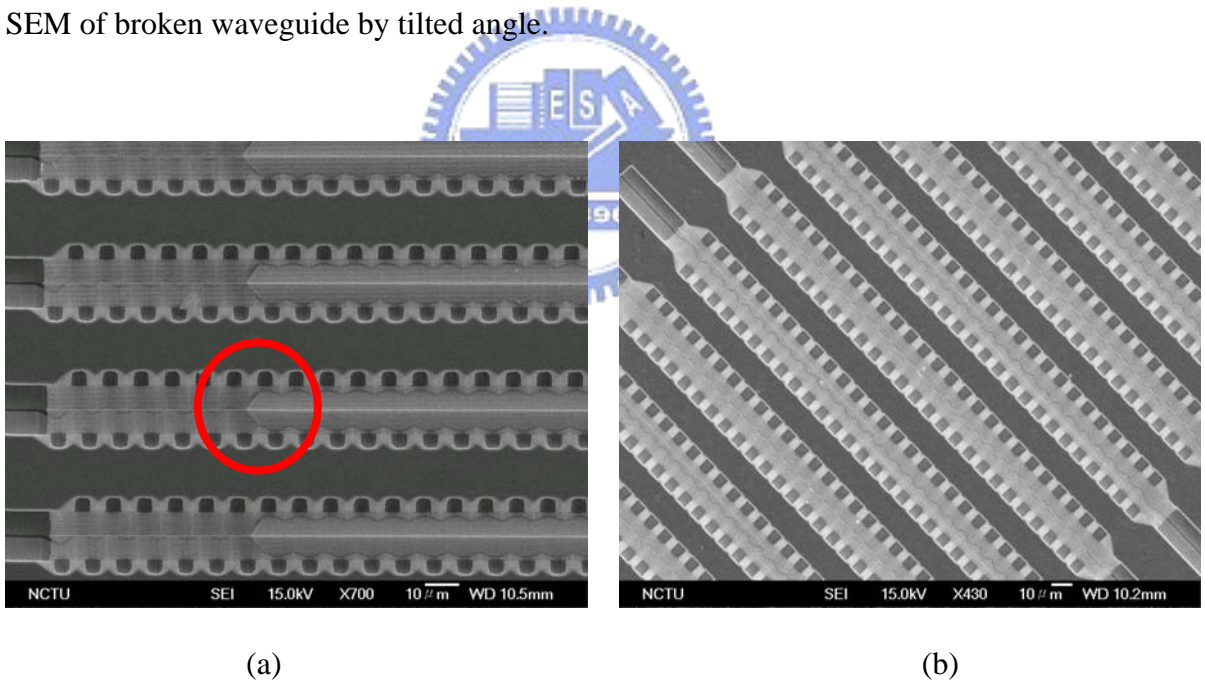


Fig. 4.7 (a) The SEM figure of fail undercut sample (red circle) which soaked time is 10mins (b) The SEM figure of successful undercut sample which soaked time is 80mins.

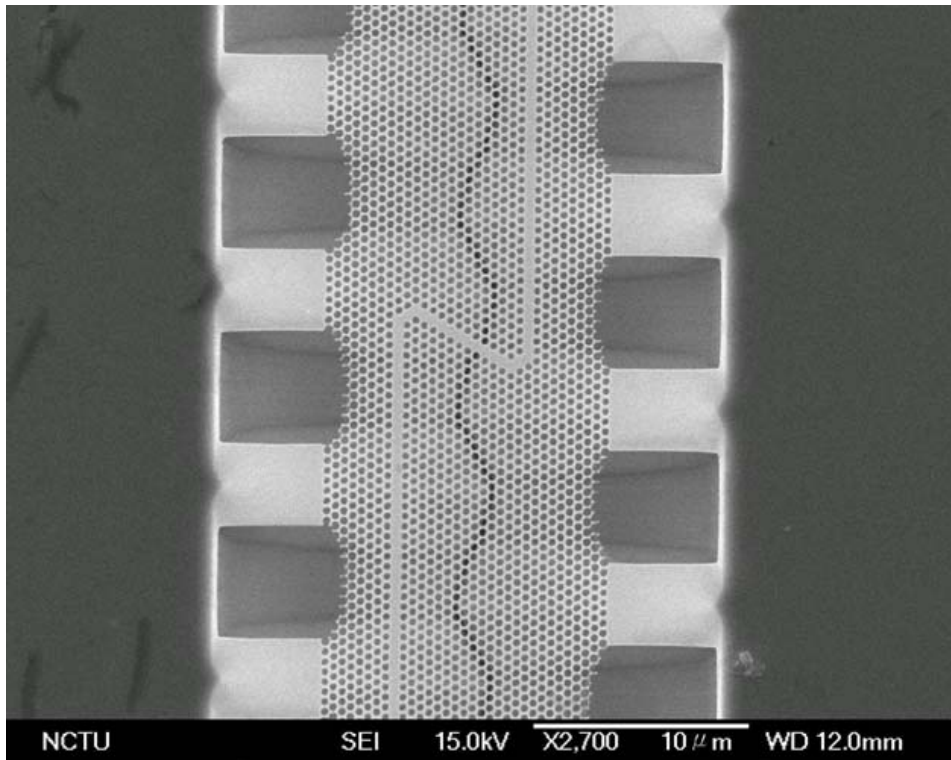


Fig.4.8 the top view of the PCWG membrane after undercut process of fig. 4.7(b)

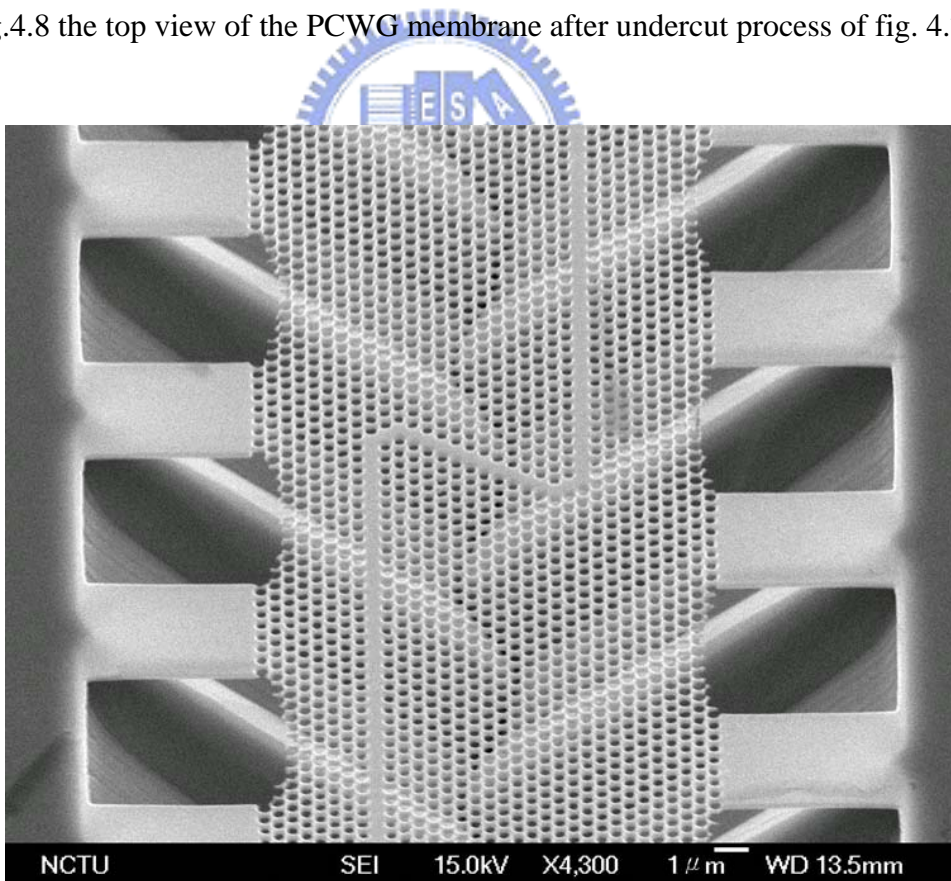


Fig. 4.9 The tilt view of fig. 4.8

4.1.5 Polish the wafer

Form E-beam lithography, we find that the waveguides length must be short than 300 μm . To measure the transmission spectrum of photonic waveguide, we want to cut the waveguide form sample and use fibers to measure. But there has a problem, if we want to cut $\sim 300\mu\text{m}$ length, the thickness of our sample must be shorter than 200 μm . Before we cut the waveguide, we must first polish the sample, and we chose acid solution HCL : H₂O = 4:1, room temperature and 20min to thin our wafer. After polishing the thickness of wafer become short than 200 μm , The fig. 4.10 show the thickness of wafer and after polish, fig. 4.10(a) is the thickness of wafer. fig 4.10 (b) is the thickness after polish (20mins < 200 μm). The etching rate is about 8 $\mu\text{m}/\text{min}$.

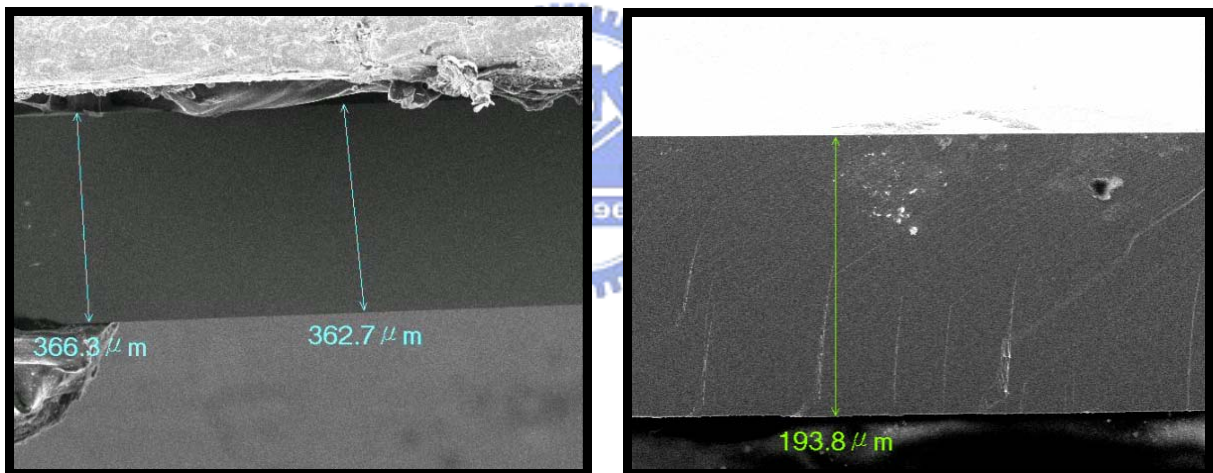


Fig. 4.10 (a) The thickness of wafer is about 360 μm . Fig 47 (b) The thickness of wafer after polished is about 200 μm (HCl:H₂O = 3:1 20mins).

4.1.6 Cut the PCWG

After undercut the wafer, we use wafer scribe to scribe samples. A diamond-tipped scribe is dragged across a wafer creating a scratch in the wafer surface. When the wafer is stressed, the wafer separates along the scribe lines. The fig. 4.11(a) is the diamond-tipped scribe system, fig.4.11(b) is the concept after diamond-tipped scribe is dragged across a wafer.

The breaks follow the crystal structure of the wafer, creating a right-angle edge direction. But there are some problem in it, if the stress is on PCWGs it will break the PCWGs very well, in fig. 4.12 is the broken PCWGs. Finally we get photonic crystal waveguides membrane samples, in fig. 4.13 it is the device we have cut the wafer.

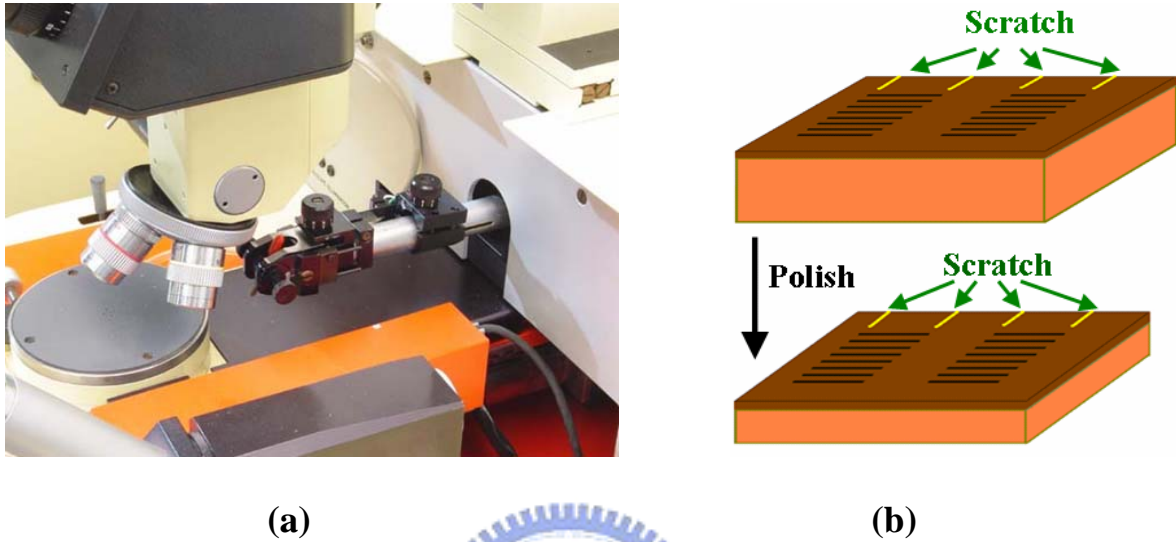


Fig. 4.11(a) the diamond-tipped scribe (b) the scratch is created by diamond-tipped scribe system.

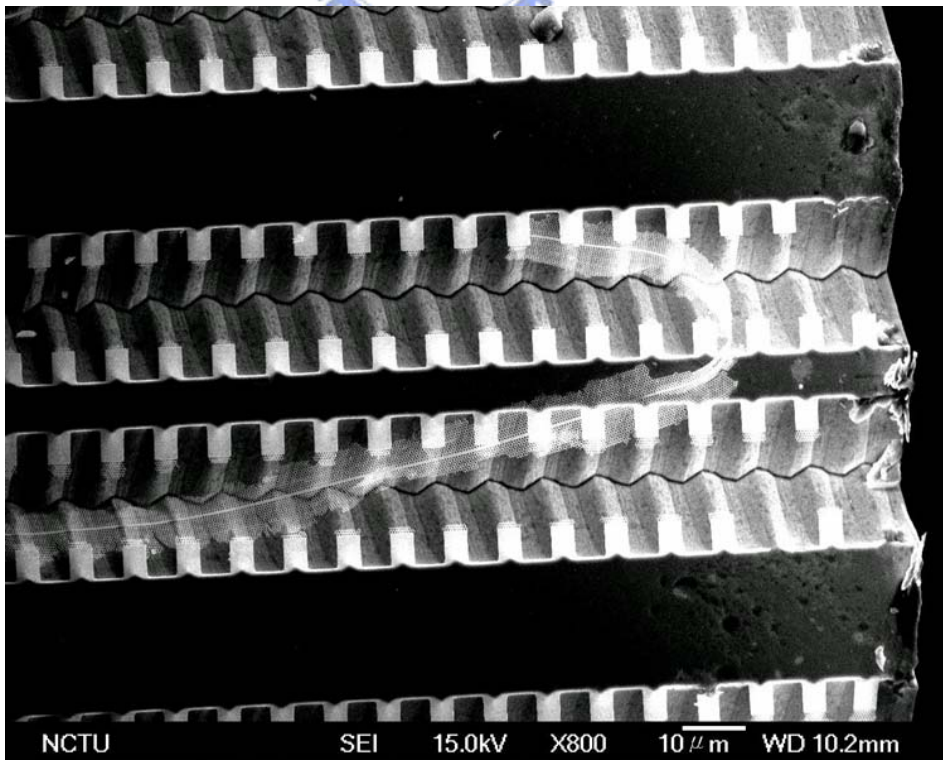


Fig.4.12 The broken PCWGs by stress.

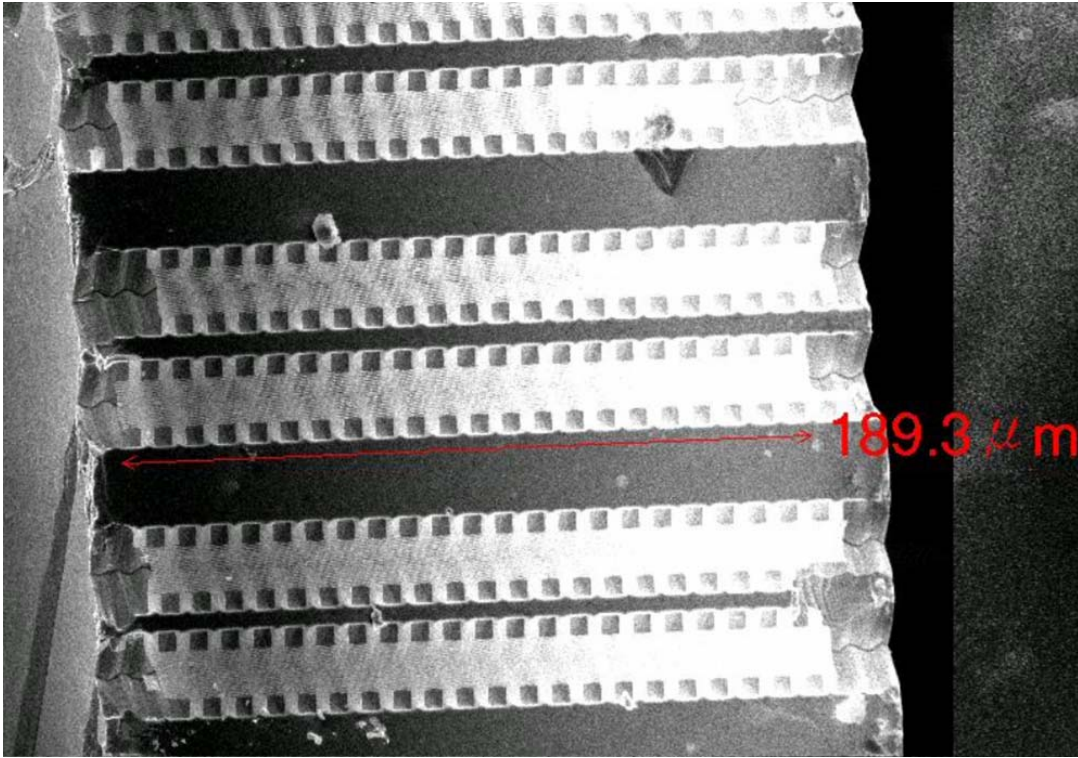


Fig.4.13 The PCWGs

4.2 Measurement of photonic crystal waveguides

To measure the photonic crystal waveguide, we first set up the measurement system. The light is a tunable laser, the spectrum is from 1475~1590 nm, then use FC-connector to connect the taper fiber and focus the laser light about 2um and become the input light for waveguide. In back of photonic crystal we use the objective lens to make the output light be a parallel light and use iris to filter the noise signal. Finally we use lens fiber to focus the output light to the optical spectrum analysis (OSA) and power-meter to record the value of transmission. The measurement system is shown is fig. 4.14.

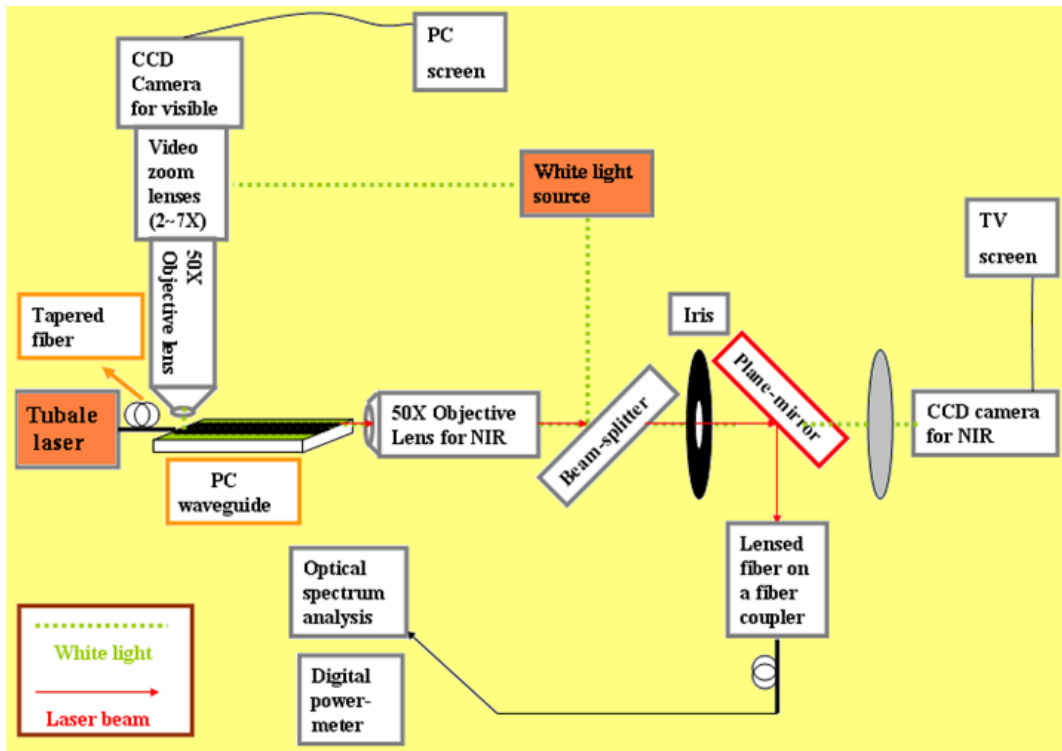


Fig. 4.14 The measurement system is set up to measure photonic crystal waveguide.

In this system, there are two CCD cameras to observe and tune the positions of photonic crystal waveguide. Fig. 4.15(a) show the top-view of the taper fiber and the edge of photonic crystal waveguide. Fig. 4.15(b) show the side view of the membrane structure of photonic crystal waveguide. When the input laser couple to the waveguide core and receive by the taper fiber and lens fiber. Then we measure the photonic crystal waveguide, the radius of air holes is 300nm, lattice constant is 500nm, the SEM image is shown is fig. 4.16, the simulation of this waveguide is shown in fig 4.17. The transmission spectrum is shown in fig 4.18, in this figure, we can find the vibration of the transmission spectrum, it is because light propagation is from air to membrane waveguide to air, and it cause the Fabry-Perot interference.

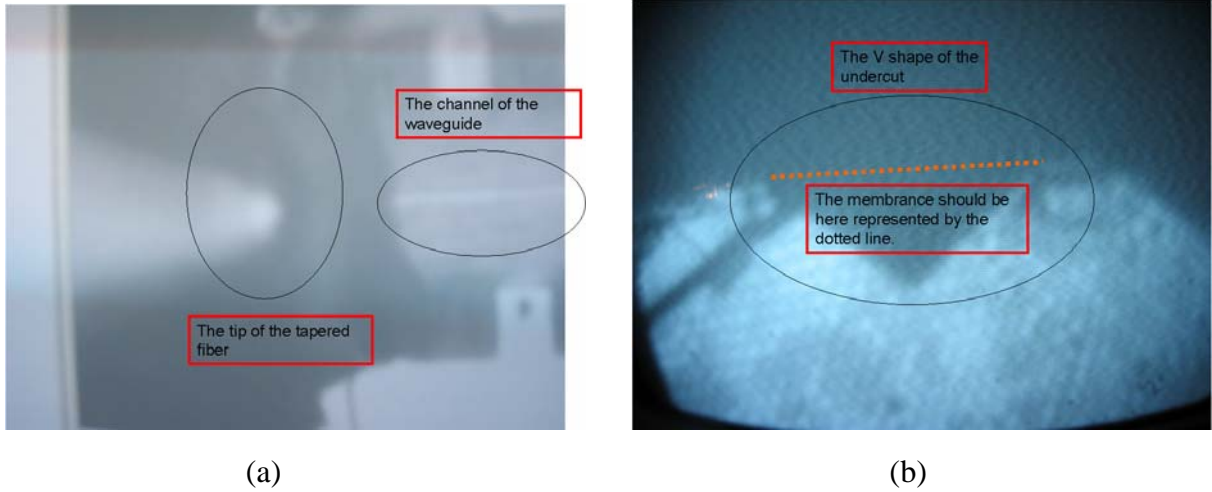


Fig. 4.15 (a) The top view of the taper fiber and the edge of photonic crystal waveguide. (b) The side view of the membrane structure of photonic crystal waveguide.

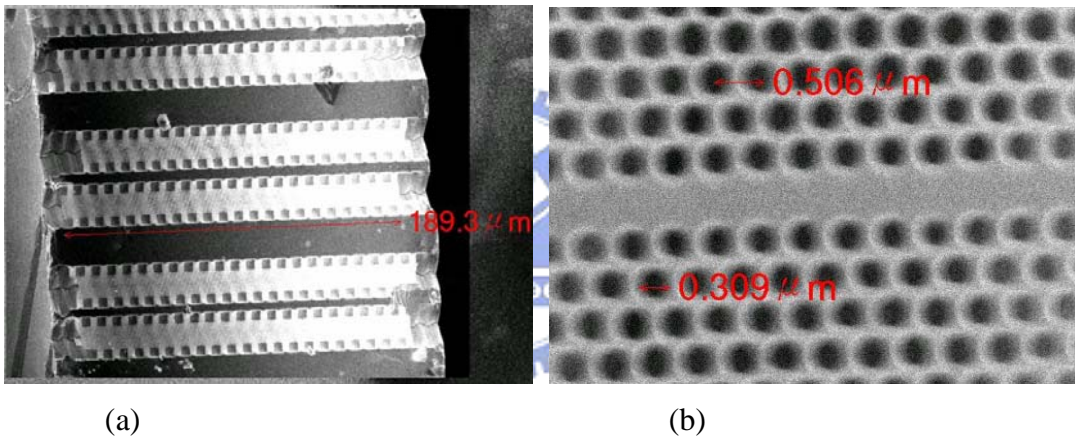


Fig. 4.16 (a) The SEM image of PCWGs (b) The magnification of PCWGs.

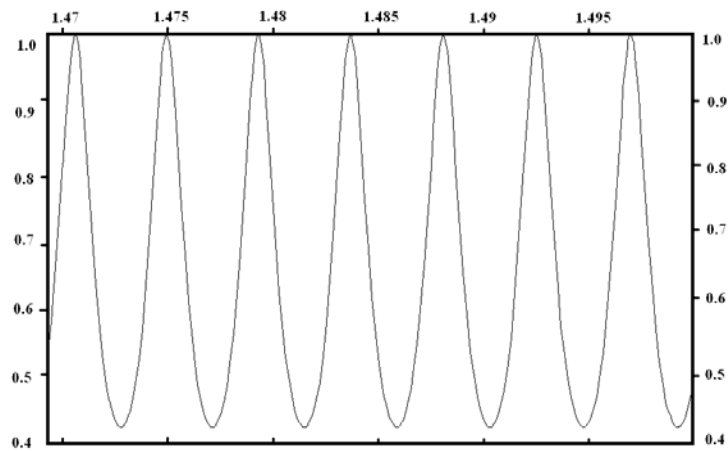


Fig 4.17 The simulation spectrum of PCWG, the Fabry-Perot interference is exit.

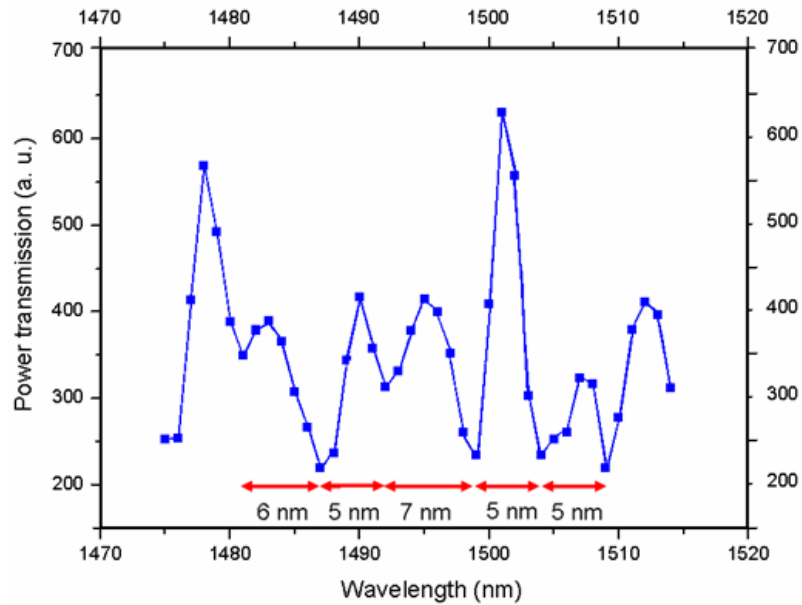
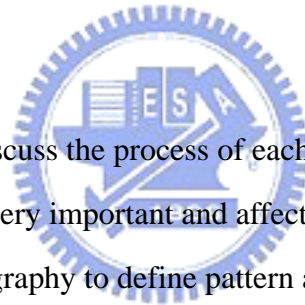


Fig 4.18 The transmission spectrum of straight line-defect photonic crystal waveguide.

4.3 Summary



In this chapter, we first discuss the process of each step in photonic crystal waveguide fabrication. The cad design is very important and affect to later process has presented. Second, we used E-beam lithography to define pattern and ICP system to transform pattern to InGaAsP layer, then we remove the hard mask by ICP-system again. To form a membrane structure, we use acid solution to etch InP blow InGaAsP layer and polish the wafer by acid solution again. Finally we cut the waveguide and measure it.

Chapter 5 Conclusion

Photonic crystal has become an important research topic nowadays due to its excellent capability to control light propagation and the potential to be applied to realize photonic integrated circuits. In this thesis we discuss the light propagation in photonic crystal waveguide, the broad-band and high transmission photonic crystal bending waveguide is important to photonic integrated circuits. Now the topics of photonic crystal are more and more, it is believe that there will be more and more excellent achievements in the days to come. Photonic crystal is powerful to design many optical devices and fit our need in the future. And it's applications will bring us to nano-life in the future.

In chapter one, the basic characteristics of photonic crystal has been explained and applications of photonic crystal has been introduced. Light propagation is forbidden by the photonic crystal band-gap and the polarization of electric and magnetic wave has introduced in chapter 1-1 , the applications of photonic such as photonic crystal cavity of laser, photonic crystal fibers in chapter 1-2 and some typical photonic waveguides in 1-3,. In last chapter, we will discuss the design for bend region for high transmission and broad-band photonic crystal.

In chapter two, the Maxwell's equations are first introduced and the formulas will vary in no source space. Then we explain the primitive vectors and reciprocal vectors in solid physics and introduce two calculation methods. The plane wave expansions use the concept of solids physics and Maxwell's equation to solve the eigen-values problems of photonic crystal and the band gap of photonic crystal can be calculated. FDTD method use the finite difference method but put the term of time in the calculation. In this method, the object in the finite space would divide into many cubic cell, the cell is called Yee's cell.

In chapter three, designs for broadband transmission double-60°-bend and double-120°-bend photonic crystal waveguides are investigated using 2D finite-difference-time-domain method. Planer mirrors are added at the bend region for total

internal reflection and adjust the widths and positions of mirrors for maximum transmission bandwidth. The transmission result is very sensitive to the widths of the mirrors and the position of mirrors. Planer mirrors are set at bend-region for double 60° -bend and 120° -bend photonic crystal waveguides to get broad-band and high transmission around $1.55\mu\text{m}$. There are two ways to add mirrors at the bend region for double 60° and double 120° bend photonic crystal, one is to dig rectangular mirrors at bend region and increased the width of mirrors uniformly, it's called type-A. Another way is also to add mirrors at bend-region, but increased the width of mirrors parallel the channel, it's called type-B.

For double 60° photonic crystal waveguides, when the width of mirrors is 440nm in type-A, it has 189nm band-width, when the width of mirrors is 240nm in type-B it has over 270nm band-width. For double 120° photonic crystal waveguides, when the width of mirrors is 500nm in type-A, it has about 168nm broad-band, when the width of mirrors is 480nm in type-B, it has 145nm band-width. But the mirrors shift toward channel 20nm, 242nm band-width and high transmission around $1.55\mu\text{m}$ can be achieved.

In this chapter, we first discuss the process of each step in photonic crystal waveguide fabrication. The cad design is very important and affect to later process has presented. Second, we used E-beam lithography to define pattern and ICP system to transform pattern to InGaAsP layer, then we remove the hard mask by ICP-system again. To form a membrane structure, we use acid solution to etch InP blow InGaAsP layer and polish the wafer by acid solution again. Finally we cut the waveguide and measure it.

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