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The research and progress of micro-fabrication technologies of two-dimensional photonic crystal

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The novel material of photonic crystal makes it possible to control a photon, and the photonic integration will have breakthrough progress due to the application of photonic crystal. It is based on the photonic crystal device that the photonic crystal integration could be realized. Therefore, we should first investigate photonic crystal devices based on the active and the passive semiconductor materials, which may have great potential application in photonic integration. The most practical and important method to fabricate two-dimensional photonic crystal is the micro-manufacture method. In this paper, we summarize and evaluate the fabrication methods of two-dimensional photonic crystal in near-infrared region, including electron beam lithography, selection of mask, dry etching, and some works of ours. This will be beneficial to the study of the photonic crystal in China.

photonic crystal, fabrication method, mask, electron beam lithography, dry etching, semiconductor material

Due to the existence of photonic band gap, researchers can control the behavior of a photon by designing and regulating photonic band gap. More important, many kinds of photonic crystal (PhC) devices with different functions can be integrated on one chip together, and the size of the whole device is only several micrometers. Therefore, this photonic band gap material makes the dream become possible for manipulating and controlling the photon, and it opens the door of information technology to the photonic era, and its significance may be equivalent to the discovery of semiconductor. After nearly 20 years of development, the research about PhC transfers from the theory to the application, the design and the fabrication. By now, scientists have proposed various theories and methods to construct PhCs into optoelectronic devices, and made great progress in the fabrication and characterization technique. Yablonovitch et al. fabricated the earliest three-dimensional PhC possessing complete band gap in the lab in 1991[1]. In 1997, Joannopoulos et al. fabricated a one-dimensional PhC with a cavity on silicon using X-ray lithography and plasma etching, where the cavity resonant wavelength was 1560 nm with quality factor 256[2]. In 1999, Painter, from California University, successfully fabricated a two-dimensional PhC microcavity laser at wavelength 1509 nm[3]. In 2004, a research group from Korea designed and realized an electrically driven two-dimensional PhC laser at wavelength 1520 nm with quality factor 2500, where the current is injected through a very thin micro-rod[4]. S. Noda, from Kyoto University, fabricated a two-dimensional PhC filter formed by the coupling between a straight PhC waveguide and two cavities, where the resonant wavelengths of the cavities are 1546 nm and 1566 nm, respectively[5]. They also realized a high-Q cavity with Q of 45000 experimentally by optimizing the structure of the cavity[6]. The study of the practical PhC in near-infrared region in our country was

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relatively late. Study did not start until the past three years, while it had already started abroad in the early 1990s. We have a disparity with foreign countries in the manufacture technology and the characterization technology. Recently, the Integration Technology Center was constructed successfully at the Institute of Semiconductors of Chinese Academy of Sciences, where it can offer research of the PhC and nano-devices necessary for key technologies and apparatus. Relevant facilities were also set up at the Institute of Physics of Chinese Academy of Sciences, Peking University, etc. The earliest work about the fabrication of two-dimensional PhC in near-infrared region has been launched at the Institute of Physics of Chinese Academy of Sciences[7]. The fabrication technology of two-dimensional PhCs has already been explored at the Institute of Physics and the Institute of Semiconductors, and above average results were obtained. At present, the investigations of the PhCs and the devices still remain at the laboratory level, having not been applied. Under the energetic support of our country, we should make good use of our own condition, find the correct direction, and tackle key problems, and then we can narrow the disparity with foreign countries, and catch up to the competence of study abroad in some aspects. Therefore, we have summarized and evaluated the fabrication technology of two-dimensional PhC with the hope that it will be beneficial to the related study in our country.

1 Micro-fabrication method of photonic crystal

Figure 1 shows the general fabrication process for two-dimensional PhC. Based on the materials of Si, GaAs and InP, we sum up the technique process as follows[8]: 1) material preparation, growing the waveguide slab material, such as SOI (silicon on insulator), by using MOCVD or MBE, etc.; 2) deposition of SiO_2, coating the resist on the surface of SiO_2; 3) defining the PhC pattern on the resist by electron beam lithography (EBL); 4) transferring the pattern into SiO_2 by RIE or ICP dry etching method; 5) removing the resist using acetone and CCl_4; 6) transferring the PhC pattern from the SiO_2 into semiconductor material using RIE or ICP dry etching; 7) removing the surface residual SiO_2 by HF acid; 8) wet etching the SiO_2 sacrificial layer to form a free-standing structure, which is a symmetry waveguide, confining the light effectively.

1.1 Lithography

Many types of two-dimensional PhCs in the near-infrared region on the planar waveguide were patterned by EBL. Considering the small size of the PhC lattice (periodicity between 200 and 700 nm range) with small feature size (sub-100 nm), the conventional photolithography cannot meet the demand. The most popular method is EBL, which has been broadly exploited to fabricate PhC in near-infrared and visible regions. Since the electron beam's Doppler wavelength is smaller than 0.01 nm, the EBL is not limited by the diffraction, and can obtain high resolution and large focal depth, where the feature size can reach less than 10 nm. It is a main method to pattern a nano-device and nano-structure. The quality and the precision are mainly determined by the precision of the instrument, besides which, focus, stigamation, exposure dose, mask quality, developing and fixing time, etc., are also the influencing factors. The main steps of EBL methods include the following: coating a proper thick resist (generally, the PMMA polymer) on the sample surface; designing PhC pattern and exposure dose, and adjusting the machine to exposure; developing and fixing; post-baking to harden the polymer

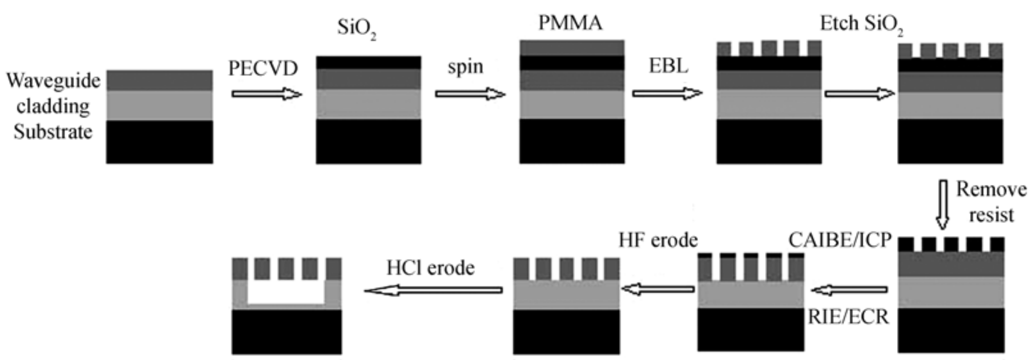

Figure 1 General fabrication process for two-dimensional photonic crystal in the near-infrared region, including deposition of SiO_2, electron beam lithography, drying etching, and eroding of sacrificial layer.

mask. We have explored the technology of EBL to define PhC pattern on the PMMA resist[8]. Recently, the advanced EBL machines (such as type of Raith 150) were bought by the Institute of Physics of Chinese Academy of Sciences, the Institute of Semiconductors of Chinese Academy of Sciences, Sun Yat-sen University, etc., these machines can offer the apparatus foundation for processing nano-structure, such as PhC and device.

Some researchers also used the multiple-exposure holography to define triangular pattern, and to produce some two-dimensional periodic lattice. In addition, the deep UV lithography, the X-ray exposure, the electron beam projection lithography[9] , etc., also have been exploited to define nano-structure.

1.2 Etching

The most suitable structure of a two-dimensional PhC is one that consists of periodic holes etched deeply into a semiconductor membrane. The etching method requires high resolution and a large aspect ratio, and the conventional wet erode method cannot meet the demand. Dry etching is the main method to make PhC. Certainly, there are some other methods, such as vertical selective oxidation[9], electrochemistry[10], porous silicon[11], building up method[12], etc.

1.2.1 Dry etching method. The main dry etching methods to etch PhC include chemically assisted ion-beam etching (CAIBE), reactive ion etching (RIE), electron-cyclotron resonant etching (ECR), ion coupling plasma etching (ICP), etc. The ICP is the updated method of RIE, and it can realize quick and deep etching. These methods above have all been used to make PhC, where the RIE etching method was used mostly.

The standard etching gas to etch GaAs/AlGaAs semiconductor is chloride, such as $SiCl_4$ in a standard RIE reactor. CAIBE is regarded as the most suitable dry etching technique available, which can achieve a high aspect ratio >20:1 (etching depth 2.5 μm for 120 nm holes). In CAIBE, a collimated high-energy ion beam impinges on the sample, so the verticality of the hole is well, and the RIE lag is reduced. T. F. Krauss studied the standard etching process for GaAs/AlGaAs like the following: defined PhC pattern on PMMA resist (200 nm thick, 350 K molecular weight), transferred the pattern into SiO_2 using $SiCl_4$ in RIE reactor. They obtained an aspect ratio of 6—8∶1 (e.g. 100 nm holes etched 600—800 nm deep), which is sufficient to demonstrate a range of photonic band gap effect with moderate loss[9].

The PhC based on InP can be etched in either CH_4/H_2 or chlorine-containing plasmas. Though the etching in CH_4/H_2 environment can reach vertical sidewall and non-selective etching, this process is difficult to realize the PhC with the lattice constant smaller than 0.5 μm due to the buildup of polymer resist. This problem can be overcome by the etching assistant with chlorine chemistry[9].

1.2.2 Electrochemistry method. The electrochemistry method, also namely anodic etching and growth, can fabricate two-dimensional PhC, and can reach high aspect ratio in silicon and aluminum material. Gruming et al., first used this method to fabricate PhC[10]. These etched structures were up to 340 μm deep and exhibited band gaps around 40 μm wavelength. The etched holes had a diameter of 6.2 μm, which constitutes an aspect ratio larger than 50:1 and compares favorably with the ratios <10:1 that are typically achieved by dry etching. Due to the electrochemistry method generally produces "macroscopic" structure with the diameter of 1—50 μm, this method is thus used to fabricate "macroporous" silicon. The fabricated photonic band materials possess band gap in the mid-infrared and far-infrared region. The PhC displaying photonic band gap in near infrared and visible regime can be realized by the related technique of anodic growth of aluminum pores. These pores were grown on a surface of aluminum embossed with regular arrays of concave dimples that acted as seeds for the growth. Masuda, et al., have obtained impressive aspect ratios for holes with lattice periodicities 100 nm and diameters 70 nm[13].

2 Category of mask

To etch PhC successfully, the selection of mask is a very important factor. To allow deeper etching and to obtain a high-quality result, a dielectric pattern-transfer layer should be added. This layer (often SiO_2 or Si_3N_4) is etched by fluorine-chemistry-plasma etching. To avoid eroding the resist too quickly, researchers prefer CH_3 to CF_4 and C_2F_6. The thicker the mask, the longer it withstands the plasma and the deeper one can etch the semiconductor. On the other hand, the thinner the mask, the thinner a resist one can use to pattern it, and thus achieve higher resolution. Therefore, selection of the thickness of the mask is often a compromising method, and the type of thickness is around 100—200 nm. Generally, the eroding rate for the above dielectric mask (such as SiO_2, Si_3N_4) is around 15—20 nm/min.

Moosburger et al. have investigated and compared three different masks for fabricating two-dimensional PhC[14,15], which has the reference value to select a mask for fabricating PhC. The first one is a triple metal mask of Ti/Cr/Ti; the second is the mask of wet chemical oxidation of the AlAs layer; and the third is the single SiO_2 mask. The material they used was InGaAs/AlGaAs single quantum well grown by MBE. Their concise process for fabricating PhC is as follows: after depositing a mask (one of the masks mentioned above) on the sample surface, a 500 nm PMMA was coated on the mask, and a two-dimen- sional pattern on the PMMA was defined in a EBL system with working voltage 100 kV. Then, the PhC was etched into the semiconductor by dry etching. To bring out the photonic band gap characteristics, the hole needs to be etched into the cladding layer of the semiconductor. The detailed processes for those three masks are listed in the following paragraphs.

2.1 Triple metal mask

The triple metal mask consists of 20 nm Ti, 100 nm Cr, and again 30 nm Ti, respectively. The PhC pattern on PMMA resist was transferred into the upper 20 nm Ti layer by ECR-RIE using CCl_2F_2/Ar plasma. Subsequently, the pattern was transferred into 100 nm Cr layer using Cl_2/O_2Ar chemistry, and then the pattern was again etched into 30 nm Ti layer between Cr and the semiconductor with a CCl_2F_2/Ar plasma. Finally, the two-dimensional PhC was patterned into the semiconductor material using Cl_2/Ar plasma. The typical etching depth can reach to about 600 nm. After etching the PhC, the metal needs to be removed from the small hole; otherwise, the metal layers close to the active region might degrade the optical properties. This metal mask is very durable and allows dry chemical etching in Cl_2/Ar plasma for several minutes. Moreover, it is independent of the material system that has to be patterned. However, it is a quite complicated iterative etching process, and it is important to rely on optimized etch rates in order to stop etching the lower Ti layer exactly on the surface of the semiconductor, and it often forms a conical shape of the holes due to incomplete etching of the lower Ti layer.

2.2 The mask based on wet-oxidation of AlAs layer

This mask technique is based on wet chemical oxidation of an AlAs layer. During the growth of material, one AlAs layer with 60 nm thick was introduced into the up cladding layer. Firstly, 500 nm PMMA was spin coated onto the sample without depositing an extra mask, and the PhC pattern was defined on the PMMA by EBL. The PhC pattern then was directly transferred into the upper cladding using Cl_2/Ar chemistry, leading holes to penetrate the AlAs layer. Subsequently, the AlAs layer was transformed into an Al_2O_3 mask by using wet chemical oxidation. This Al_2O_3 mask is stable enough to endure the dry chemical etching of the holes through the waveguide into the lower cladding. The advantage of this mask is that no additional mask has to be patterned by dry chemical etching. The shortcoming of the mask is that this mask technique strongly depends on the epitaxial material structure, only GaAs material; thus, allowing no choice of a different material system. Moreover, there is the question of long-term stability for this mask. Figure 2(b) illustrates the high quality of the PhC patterned with this mask technique.

Cheng et al. also demonstrated that the oxide AlGaAs (Al_2O_3) was a good choice[16]. They observed that if Al-content was Al=80%, then the endurable eroding rate was about 3 nm/min, compared with the deposited dielectric mask (such as SiO_2 or Si_3N_4), the endurance was much enhanced. The wet-oxidation of $Al_xGa_{1-x}As$ was performed in a hot steam environment at 400—

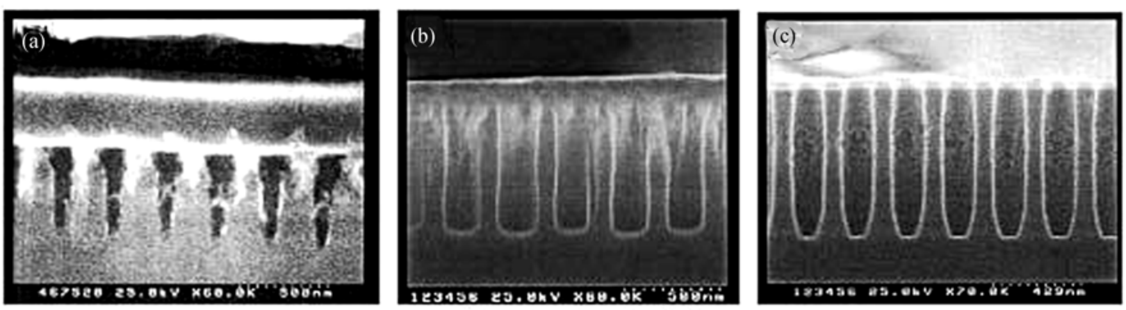

Figure 2 The SEM pictures of photonic crystal fabricated using different masks. (a) Triple metal mask; (b) wet-oxidation AlAs mask; (c) single SO_2 mask.

450℃. This oxidation method is applied broadly in forming optical aperture for the vertical-cavity-surface-emitting laser. One metal mask layer can be added on the sample surface. After the PhC is transferred into the metal mask layer, it can be etched into the Al_2O_3 layer by dry etching. This method can offer a good mask, but those additional works are complicated; every technique slows down the fabrication process.

2.3 Single SiO_2 mask

A 100 nm thick SiO_2 mask is the optimal thickness of a mask for patterning PhC. The PhC pattern was directly transferred from 500 nm PMMA resist into the SiO_2 mask using CHF_3/Ar ECR-RIE. Using this mask, high quality holes can be obtained, and the maximum etching depth can reach to about 700 nm. Figure 2(c) shows a SEM picture of a high quality cleaved PhC patterned with a SiO_2 mask. This SiO_2 mask does not depend on the material category, the thickness of SiO_2 is often between 100 nm and 200 nm, and it is the most extensively used mask[15].

The researchers fabricated a ridge-waveguide laser using the former two methods, measured the slope efficiency of the laser, and found that it depends on the PhC lattice constant. For the first mask, good laser performance characterized by threshold currents of 18 mA and a slope efficiency of 0.17 W/A was achieved for a period of a=350 nm in ΓK orientation. They also calculated the reflection spectrum using the transfer matrix method. If the quality and the depth of the holes are superior, then the experimental result excellently agrees well with the theory.

2.4 The resist mask

The direct mask is to use the resist itself. We know, in the process of dry etching, the resist will be eroded quickly, and then the etching depth is shallow. Especially, when one wants to realize a high-resolution pattern, the thinner resist is needed. Therefore, the resist used as the directive mask is limited. However, Ryu et al. developed a method using PMMA resist itself as the mask[17]. Firstly, a 2% PMMA with 100 nm thick was coated on the top of an InP/InGaAsP wafer, and two-dimensional PhC patterns are defined by EBL. After developing the exposed PMMA, an Ar^+ ion-beam was irradiated for a moderate time to harden the PMMA layer. This hardened PMMA can be used as a perfect etching mask for the following dry etching. The PhC can be etched into InP material by argon and chlorine gases in CAIBE. The etch rate was >1 μm/min. The remaining PMMA was removed by O_2 plasma. At last, the InP sacrificial layer under the fabricated PhC slab was removed to form a free-standing structure by using high-selection HCl wet etching. The whole fabrication procedure is schematically drawn in Figure 3.

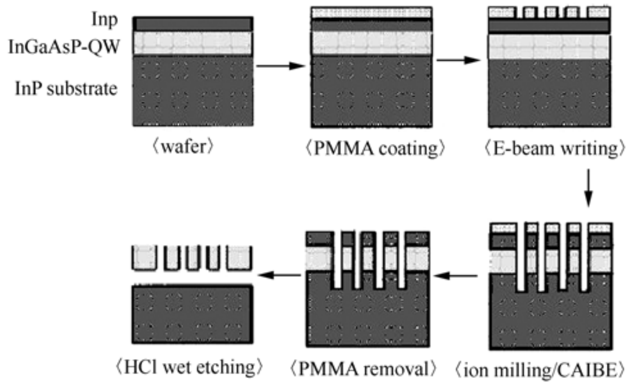

Figure 3 The fabrication procedure for a free-standing photonic crystal on InP material using PMMA resist mask. The process includes: preparing material, spin coating PMMA, E-beam writing (EBL), dry etching by ion beam, removing PMMA, and wet etching with HCl.

The PhC can also be etched into Si, GaAs, and GaN semiconductors by only using the resist mask. At the same time, the quality of the resist and the hardness of the resist are the key factors that affect the etching effect. We can only use PMMA resist as the mask for etching PhC and other nano-structure into silicon and III-V materials using the ICP facilities in the Institute of Semiconductors of Chinese Academy of Sciences.

3 The micro-manufacture method for different semiconductor materials

3.1 Si material

Recently, the main silicon materials for fabricating PhC are SOI (silicon-on-insulator) materials, which are composed of a bottom cladding layer of SiO_2 with about 1μm thick, and a top silicon waveguide layer about 200 nm thick, guaranteeing the single-mode condition for the light at near infrared wavelength. This material has attained much attention due to the compatibility to the conventional silicon technology. The fabrication procedure in Ref. [18] likes the following: firstly, a SiO_2 layer with thickness about 200 nm was deposited as mask on the silicon surface, or evaporated a Ni/Ti metal mask. Then, the polymer resist was coated on the SiO_2 mask or metal mask, and the PhC pattern was defined by an electron beam machine. Then, the Ni/Ti mask could be etched by CF_4 plasma and Ar ion, while SiO_2 could be etched by CHF_3/Ar or CH_4/H_2 reactive ions. At last, the PhC pattern was transferred into the top silicon by using CF_4 and Xe gas. After removing the Ni mask, the PhC was completed[18].

Tokushima et al. investigated experimentally high-transmission of 120°-bend two-dimensional PhC waveguide[19,20]. The methods they used are the follows: first, a 150 nm-thick SiO_2 layer was formed by thermal oxidization. The wafer was coated with a photoresist, and the pattern for the triangular lattice of holes was defined with an I-line optical stepper and a grating-pattern triple-exposure technique. The photoresist pattern was transferred into the silicon-dioxide layer on top of the silicon layer by a magnetron reactive-ion etcher using CH_4 and H_2 mix gases. Then, the PhC was etched into the Si layer from SiO_2 by a mixture of chlorine and oxygen gases etching in ECR. The lattice constant is 0.8 μm with a hole diameter of 0.76 μm, and the air-filling factor is very high. They also measured the refection spectrum in ΓM direction, where the light source was coupled into the Si waveguide by a tapered-fiber; the reflected light was also collected by the same fiber and part of them was fed into an optical spectrometer. They estimated coupling loss between the PhC and the fiber to be about 15 dB. The reflection coefficient was calculated by the ratio of the reflection light and the injection light. The photonic band gap was observed in the wavelength range from 1.5 to 1.7 μm with a peak at 1.6 μm. They then used a 1.55 μm wavelength laser diode as a light source to characterize the PhC waveguide. The output power of the laser diode was –2 dBm, and the laser light was introduced into a tapered-end fiber coupled to one end facet of the single- defect waveguide in a straight line. Near-field light output from the opposite end facet of the waveguide was measured by scanning another tapered-end fiber near the end facet perpendicularly to the waveguide. The total length of the waveguide was 877 μm, and the 120° bend was near its midpoint. The sample was large enough, and the two tapered-end fibers were at least 400 μm apart during the measurement, to ensure that direct coupling light was not detected in the background. A maximum peak power was detected right in front of the waveguide end, which demonstrated that the light transmitted through the waveguide. The measurement result showed that they fabricated PhC successfully.

3.2 InP material

The InP material for fabricated two-dimensional PhC is an InGaAsP membrane with thickness about 200—300 nm; this layer is often grown by metalorganic chemical vapor deposition (MOCVD). The InP active membrane contained four 1.2% compressively strained InGaAsP quantum wells separated by about 20 nm unstrained InGaAsP barrier layers[21]. The photoluminescence (PL) spectrum of these quantum wells showed emission between 1400 nm and 1650 nm. A 60 nm InP layer was grown on the top of the last barrier layer to protect the quantum wells during the etching process, and this layer can be selectively removed at the end of the device processing. After the material was prepared, the mask layer was deposited on the sample surface. Perfect masks are multiple pattern-transfer layers; such as 160 nm SiN_x deposited by plasma enhanced chemical vapor deposition with 5 nm of Cr, and 45 nm Au deposited by electron-beam evaporation. Finally, a 100 nm 2% PMMA resist was deposited by spin coating. The triangular and square PhC was defined on PMMA by EBL, and the lattice constants ranged from 460 nm to 560 nm with the ratio of radius and lattice constant changing from 0.21 to 0.42[21]. The PMMA resist was developed for 50 s in a mixture of 2-eth- oxyethanol and methanol with a ratio of 3:7. After EBL, the PhC pattern was transferred into a Cr/Au mask by Argon ion etching in an ion beam etching (IBE), where the acceleration voltage reached 500 V. Then, the pattern in the Cr/Au layer was transferred into SiN_x layer by using CF_4 dry etching in a RIE. This process can fabricate a high-resolution and robust SiN_x mask for the next step of ECR etching. Then, the PhC pattern was transferred deeply into the semiconductor layer by ECR etching, where the etching gas was the mix gas CH_4/H_2/Ar with flow of 38/24/12 sccm. The radio-frequency power was set as 300 W, and the microwave power was set as 600 W. After ECR etching, the metal layers were removed completely. The excessive polymer can be removed by O_2 plasma in RIE, where the excessive polymer is generated by CH_4 chemistry after ECR etching. In the etching process of ECR and O_2 plasma, the selectivity of etching for SiN_x and InP was about 1:6. After the metal was removed, the CF_4 plasma in RIE could be used to remove SiN_x mask. Those methods above can obtain high-quality and high-verticality structure. The final step was a wet etching, which undercut the membrane and striped the 60 nm InP cap to achieve a smooth surface. This process also smoothed most of the sharp features on the sidewalls of the holes, which decreases the optical loss caused by the roughness. Wet etching was performed in an HCl∶H_2O= 4∶1 mixture at a temperature of 0℃. This wet etching is anisotropic, which has important effect in the fabrication of a free-standing PhC membrane. If the directions of the open aperture and the PhC are not suitable, and the holes are small, the free-standing structure is difficult to form. A method, which is efficient for all types of PhC lattices, regardless of the relative orientation to the InP crystal, is to form large openings at the ends of the pattern merging on the edges of the PhC along the $\langle 0, 1, -1\rangle$ orientation, as shown in the right picture of Figure 4. Owing to their dramatically different physical dimensions compared with the PhC holes and their asymmetric shape, these opening windows prevent the etch-stop planes from forming. In about 10 min, a V-undercut under the PhC with more than 10 periods can form[21].

Painter et al. fabricated and characterized the two-dimensional PhC cavity laser[3]. The light is controlled by a two-dimensional PhC consisting of arrays of air holes in the plane, and confined in a $\lambda/2$ high-refractive-index slab in the vertical direction by the total-interior reflection effect at the air-slab interface. The active material was InGaAsP quantum well with emission peak at wavelength 1.5 μm. The active layer was grown on InP substrate by MOCVD. The active region consisted of a four 9-nm 0.85% compressively strained InGaAsP quantum wells separated by 20 nm quaternary barriers. The two-di- mensional PhC was defined by an EBL system modified from a field-emitting microscope; the pattern was transferred into a metal mask, and then into a SiN_x mask by a RIE. The PhC was etched into InGaAsP with chlorine assistant ion etching, where the holes penetrate through the active region and into an underlying sacrificial InP layer. The sample was then dipped into a diluted HCl∶H_2O (4∶1) solution at temperature 1℃ for eroding the bottom InP layer to form a free-standing membrane (shown in Figure 5(a)).

Loncar et al. fabricated another type of PhC cavity laser based on a triangular lattice, shown in Figure 6[22], where P_i (i is an integer) is the elongation parameter.

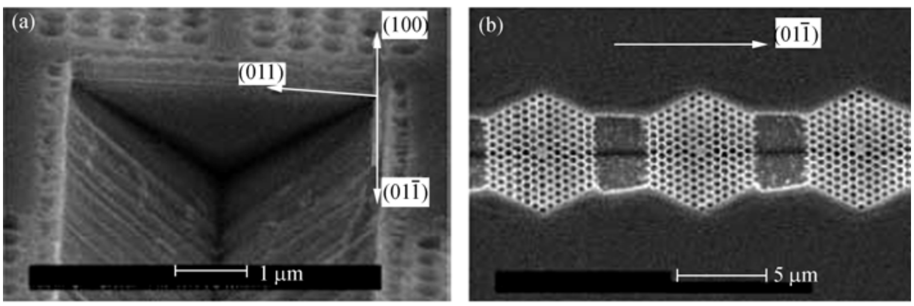

Figure 4 SEM imagine of the photonic crystal on InGaAsP by micro-fabrication. (a) “Wedge” formed by etching stop planes; (b) opening areas at the ends of PhC structures along the $\langle 0, 1, -1\rangle$ direction[21].

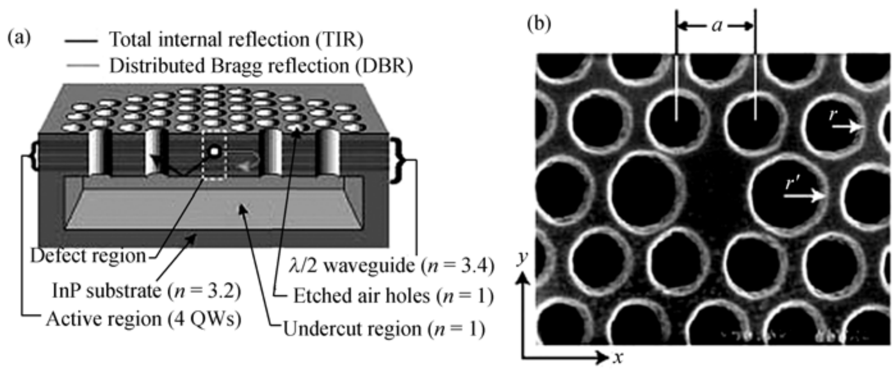

Figure 5 (a) Cross section through the middle of the photonic crystal microcavity; (b) top view of a micro-fabricated 2D hexagonal array of air holes in a thin membrane with a central hole missing. The lattice constant (a) is 515 nm, and radius (r) is 180 nm. The two optimized holes have a radius (r') of 240 nm[3].

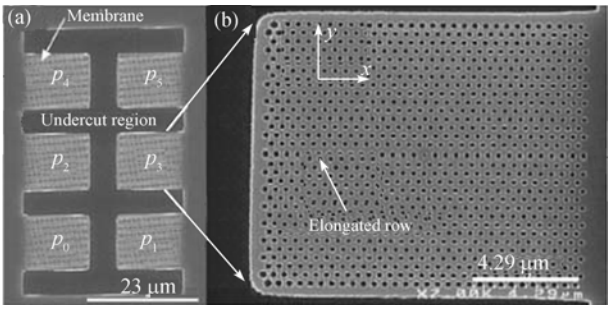

Figure 6 (a) The photonic crystal sample fabricated by Loncar with different elongation-parameter with p_0 = 0, p_1 = 0.05*a*, p_2 = 0.1*a*, p_3 = 0.15*a*, p_4 = 0.2*a*, p_5 = 0.25*a*. *a* is the lattice constants, *a* = 435 nm, radius 138 nm. (b) Blowup of p_3 cavity[22].

The material they prepared is similar to that prepared by Painter. The active material was placed in the center of a 330 nm thick InGaAsP slab with a 1 μm thick sacrificial InP layer underneath the slab. They defined PhC pattern on 150 nm PMMA with EBL, etched the pattern into a metal mask using Argon ion milling, and followed this step by a C_2F_6 RIE to transfer the mask from Au into SiON. Finally, the pattern was transferred into the InGaAsP material from SiON mask layer. At last, the remaining mask was removed in HF acid, and the InGaAsP membrane was released from the substrate by wet etching in 4∶1 water solution at 4°C.

3.3 GaAs material

Yoshie et al. fabricated a two-dimensional PhC with a triangular lattice on a GaAs slab[23,24], where a single smaller hole replaces a larger hole within the center of the slab to define the optical cavity. In the *x* direction, in line with the smaller hole, ellipsoids rather than circles were fabricated at lattice spacing (*a*) with an elongated major axis, and then holes were moved away from the *x* axis by *p*/2 toward +*y* or –*y* direction. Three stacked InAs quantum dot layers were clad by $Al_{0.16}Ga_{0.84}As$ layers on top of a 400 nm-$Al_{0.94}Ga_{0.06}As$ layer by MBE. A GaAs cap layer was then added to protect the top on the final layer. The researchers also defined the two-dimensional PhC on PMMA by EBL, and then the pattern was transferred into a quantum well waveguide by chlorine assistant ion etching. Following this step, the $Al_{0.94}Ga_{0.06}As$ layer under the cavities was oxidized in steam to define a perforated dielectric slab structure on top of an AlO_x cladding layer. Subsequently, this AlO_x layer was dissolved completely by KOH resolution. The thickness of the PhC slab was 240 nm with lattice constant 370 nm, and the peak emission wavelength was 1240 nm at room temperature. They fabricated samples with four different *p*/*a* values (*p*=0, 0.10, 0.15, and 0.20*a*, *p* is the elongated parameter, and *a* is the lattice constant). The holes radii defining the PhC ranged from 0.28*a* to 0.29*a*, whereas the radius of the smaller hole defining the cavity was in the range of 0.20—0.23*a*. A laser beam with light wavelength 830 nm and with peak pumping power 1.4 mW was focused onto the sample with a spot diameter of 2 μm. They found that the light emissions from the cavities were dependent on *p*/*a*, and they observed the *y*-dipole and the *x*-dipole mode. The cavity Q reached 2800 with *p*/*a*=0.2, and the experimental result was consistent with the theoretical one.

Kamp et al. fabricated the PhC waveguides including resonant cavities, and measured their spectra[25]. The PhC waveguide was formed by removing two rows of holes in a PhC with triangular lattice, and the cavities were formed by adding two rows of holes perpendicular to the guiding direction inside the waveguide. They fabricated four different cavities. They introduced three layers of InAs quantum dots into a 240 nm GaAs waveguide, which was between a 300 nm thick $Al_{0.2}Ga_{0.8}As$ upper and a 400 nm thick $Al_{0.8}Ga_{0.2}As$ lower cladding. The photoluminescence (PL) of these quantum dots severed as an internal light source for the transmission experiment. A 100 nm thick SiO_2 mask was sputtered on the sample. The two-dimensional PhC was defined on 500 nm PMMA by 100 kV EBL. Then, the pattern was transferred into the SiO_2 layer by CHF_3/Ar based dry etching. The holes pattern was then transferred into semiconductor material with a Cl_2/Ar based ECR process. The etched hole reached 800 nm deep, and the PhC lattice constants included 240 nm and 260 nm with air-filling factor 30%. The obtained photonic band gap for TE-polarized light lied in the range of $0.21 < a/\lambda < 0.30$.

3.4 GaN material

Researchers pay much attention to GaN material, because it is the main material to fabricate blue LED and white LED. For the high stabilities of the temperature and the chemistry, GaN material is difficult to erode by wet etching, so dry etching must be used. The methods that are usually used for etching GaN include ICP, RIE, ECR, CAIBE and MIE (magnetic ion etching), etc.

If the feature size of PhC is small, the EBL and dry etching should be used. For the case of larger lattice constants, the conventional photolithography can be applied. The PhC on GaN is usually obtained by multiple pattern-transfer masks. The technology steps are as follows: firstly, a 300 nm SiO_2 mask is grown on GaN sample, Au/Ni is deposited as a metal mask, and then a PMMA layer with proper thickness is spin coated on metal mask surface. After defining the pattern on PMMA, the pattern is transferred into a Au/Ni layer by Ar etching, and then transferred into SiO_2 by C_2F_6 ion etching. The pattern from SiO_2 to GaN layer can be realized by CAIBE with Cl_2 assistant etching, where Xe splashing ion can be used to enhance the etching rate. To make the hole vertical and sidewall smooth, the GaN can be etched in the chlorine environment at 220°C with etching rate 0.6 μm/min, and then a hole deeper than 1 μm can be obtained (the deepest hole can reach 1.5 μm)[26−28].

Recently, we explored the technology to fabricate PhC GaN LED by using micro-manufacture machine. Two methods were used: one was to drill the hole directly by using focused ion beam (FIB), which is a simple and maskless process, only using Ga^+ ion drilling. Another method is the combination of lithography and dry etching. We deposited SiO_2 on GaN as a mask, coated the resist on the SiO_2, and then defined the PhC pattern using photolithography. The pattern was transferred into GaN material by dry etching. Both RIE and ICP etching can be used to transfer the patterns into SiO_2 or into GaN. We also explored the method that only uses PMMA resist as a mask to etch PhC into GaN with gases BCl_2/Cl_2 at low temperature.

4 The other methods

As shown above, we have introduced the fabrication methods of the two-dimensional PhCs based on the semiconductor planar technology. In fact, besides those methods mentioned above, there are some other methods to fabricate PhC, such as interference of multiple laser beams, laser vapor deposition[29], embossing method[30], self-organized method[31], focused ion beam, etc. Here, we introduce the interference of multiple laser beams with fs laser and focused ion beam method.

One-dimensional, two-dimensional, and three-dimensional PhCs have already been fabricated by using femtosecond (fs) laser interference. In this method, a diffractive beam splitter was used to divide the laser into several beams, and then was focused and overlapped by two lenses. The experimental system that the researchers set could reach a high adjusting resolution, guaranteeing the *fs* pulses temporal overlap. The researcher used the harmonic of fs pulses as an irradiation source for fabrication with laser wavelength 380 nm, pulse 80 fs, repetition frequency 82 MHz. For a typical process, the irradiation laser power is about 100 μW, and the ir- radiation time is about 20 s. The pattern can be defined on SU8 polymer with thickness of 25 μm. After irradi- ating, it is developed and postbaked, and then the PhC in polymer forms. In ref. [32], the lattice constant of the obtained PhC is 700 nm. In this method, the component of diffraction beam splitter (DBS) is very important. For example, the DBS type of G1029A (MEMS Optical, Inc.) can split one beam into 9 beams, and we can realize the PhC with different dimensions by selecting different beams with different angles. If we select two of them, a one-dimensional PhC can be realized, and a two-dimensional PhC can be realized by selecting four beams, while a three-dimensional PhC can be realized by the interference of six beams with proper angle. This method can also fabricate a two-dimensional or three-dimensional PhC by laser interference through two-photon absorption, where the resolution could be enhanced[32,33]. In addition, one research group from Japan used 800 fs laser to peel off the SiO_2 to form a micro-grating, the lattice constant of the grating was 430 nm, and the depth of the valley reached to 150−200 nm[34].

Using similar methods, Gampbell et al. fabricated a two-dimensional and three-dimensional PhC in near-infrared and visible region using 355 nm Nd:YAG laser, where the smallest feature size reaches 50 nm on SU8 polymer[35]. Also using the multiple laser beam interference of third harmonic 355 nm Nd:YAG laser, Divliansky et al. made the PhC mask on SU8 resist, then the pattern on this SU8 mask was transferred into a CdSe membrane deposited by Electron Beam Deposition, so they obtained PhC on CdSe[33].

Some researchers also utilized the FIB method to fabricate three-dimensional PhCs. The characters that the ion beam and stage of FIB can rotate flexibly were utilized. Drilling the holes along defined direction in porous, then three-dimensional PhC of Yabnovitch structure could be realized[36]. One-dimensional grooves were also etched in a multiple layer membrane by FIB to form a two-dimensional PhC working in near-infrared region[37].

Several companies from America, Japan, Germany and France can produce an FIB facility, where the products from the FEI Company in America occupy a dominant position. For example, the FIB type of DB235 from FEI Company possesses double beams, ion beam and electron beam. Usually, the energy of gallium ion can be tuned from 1 kV to 30 kV, the ion beam current can be tuned from 1 pA to 20 nA, and the highest resolution of the ion beam can reach 4—5 nm. FIB can be used to etch, repair, produce a mask, deposit some material, etc.[37].

The main merit of FIB for fabricating microstructure is maskless etching; moreover, FIB can be controlled flexibly, and it can drill holes along different angle. However, it also has some shortcomings: firstly, the material sputtered by gallium ion deposits on the surface of the sample; secondly, in the process of etching, the gallium ion erodes the sidewall of the hole, and then the verticality is not high; thirdly, gallium ion contaminates the material, and the chemical contamination of gallium ion will change the character of the material, which is more serious to active materials. However, researchers have already adopted some methods to reduce the disadvantage of this method[37].

We have fabricated a two-dimensional PhC in near-infrared and visible region on several semiconductors by FIB firstly, and measured their optical properties[7,38]. The experiment demonstrated that the FIB method can fabricate high-quality PhC, and can realize perfect photonic band gap effect for passive PhC. However, it may not be suitable for fabricating PhC on active material, where the emission efficient decreases. Figure 7 shows two SEM pictures of the two-dimensional PhCs we fabricated by FIB.

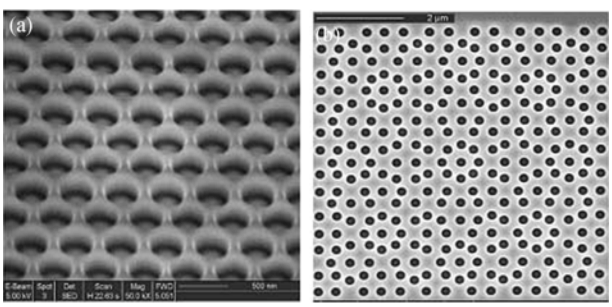

Figure 7 (a) Triangular photonic crystal fabricated by FIB with lattice constant a=500 nm, radius r=200 nm. (b) Eightfold quasiperiodic photonic crystal, where the side-length of the square unit is 400 nm, and the radius of hole is 130 nm.

5 Forecast of the investigation

By now, the research of PhC is still at the lab-level. It is less than 20 years until now since the concept of PhC was proposed, and it is still a hot topic for studying PhC and its devices. The advantageous features for the PhC, the PhC waveguide, and the PhC cavity indicate the broadly potential application prospect in photonic integration. Many applications, such as control of spontaneous emission, capturing photons, low threshold laser, large bend PhC waveguide, etc., can be realized by PhC or introducing the defect into it. Two-dimensional PhC and three-dimensional PhC can control a photon effectively, and they will have important potential application in photonic circuit, functional device and photonic integration. The most important development direction of PhC may be photonic integration; there will be a breakthrough progress due to the application of PhC, and whether the PhC integration could realize or not, which is based on the PhC device. The promotion of the PhC and its device to move towards being practical mainly depends on the micro-manufacture technology. There are many difficulties in fabricating and designing the PhC integration circuit, and thus the development of the research of PhC integration is slow. To start exploration in this respect, there are important meanings to our country to take one seat in the photonic integration in the photonic era in the future, and to promote the development of national economy and national defense. Therefore, we should firstly study and realize passive device and active device on semiconductor material, and then try to realize the photonic integration by using PhC devices, which is useful for our country to obtain independent intellectual property right of ourselves for the PhC device and integration circuit. However, the domestic experiment research of PhC at home starts relatively late. By now, relevant studies have only begun in several units in our country. On the other hand, the experimental investigation had begun abroad soon after the concept of PhC was put forward. Moreover, there are high-level semiconductor techniques in Japan, USA, and Europe; these countries have the basic facilities to fabricate PhC. Therefore, we should recognize the disparity in this aspect between abroad and us, and recognize our own deficiency. We cannot catch up with the foreign level within a short time, but we cannot do nothing either. According to our condition and character, we should grasp the research direction and goal, try to innovate, do some important things and leave some unimportant things undone. Several research units in our country are still exploring the fabrication technology of PhC at present, lagging behind abroad for nearly ten years. Recently, our country has paid much attention to the experimental study of PhC; the National Basic Research Program of China, the Hi-Tech Research and Development Program of China, the National Natural Science Foundation of China, etc., have a degree of support in a more cost-effective manner. We suggest that we can begin our works from the following several aspects: firstly, by utilizing our existing condition, we should explore the fabrication technology and characterization technology for PhC in near infrared region and visible region. The most important thing is to explore and store up the technologies of EBL and dry etching to fabricate high quality PhC, cavity and waveguide, where the quality and the depth of the etched holes should be paid more attention. The characterization method of PhC is also important; we will set up the measurement system for charactering a passive PhC slab, and grasp the characterization method. Secondly, we should emphasize the investigation of some basic PhC devices, such as the PhC cavity laser and the PhC waveguide. Recently, the PhC laser, the PhC waveguide, wavelength division multiplexes, modulator, filter, etc., have been realized experimentally abroad. The most important and basic devices are the PhC cavity (as well as PhC cavity laser) and PhC waveguide, all of the others can be composed of those two devices. We should lay a solid foundation on these two kinds of devices, which is the basic research for the photonic integration in the future; other devices can be laid aside for the moment. Thirdly, on the basis of research of the device, we can make some exploration about the method and technology for the coupling and integration of passive devices and active devices. We should explore some novel methods, novel technologies and novel concepts to investigate photonic integration. The PhC laser arrays and the PhC wavelength division multiplexes should be given much attention. Fourthly, we will launch the work of studying according to domestic character and condition in such aspects as semiconductor material and apparatus. For example, our country has a good foundation in the InP and GaAs materials, both of them are suitable for making active device and passive device, including lasing, detector and waveguide, which are useful for the small-size photonic integration based on PhC. In addition, we can also combine the PhC cavity with quantum dots, such as GaAs quantum dots, to explore a single photon source. The development of PhC offers a helpful opportunity; we should utilize the existing condition, seize the opportunity, innovate hard, and contribute to the realization of photonic integration based on PhC. Therefore, we summarized and commented on the fabrication technology of a two-dimensional PhC on several semiconductor materials; we hope it is helpful to the practical study of the fabrication of PhC.

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