技術紹介

1. 二次元シリコンフォトニック結晶

Two-dimensional Silicon Photonic Crystals

ブーレル エマニュエル	Emmanuel Bourelle	中央研究所 研究開発部　工学博士
鈴木　晃子	Akiko Suzuki	中央研究所 研究開発部　主任
岡田　正史	Masafumi Okada	中央研究所 研究開発部
加来　良二	Ryoji Kaku	中央研究所 研究開発部 微細加工技術 シニアマネージャー

キーワード：フォトニック結晶、光局在、導波路、シリコン
Keywords: photonic crystal, light localization, waveguide, and silicon

要　旨

フォトニック結晶は波長の半分程度の周期で屈折率が変化する人工結晶で、電子の制御を可能にした半導体のように光を自在に操作できる材料として高い可能性を秘めている。この10年間フォトニック結晶は主に理論家によって研究されてきたが、最近薄膜形成技術やシリコンを中心とする半導体微細加工技術分野の実験家がフォトニック結晶を興味深い技術的挑戦として取り上げるようになってきた。フォトニック結晶は超高速光コンピューティングや光通信のキーとなり得るだろう。本稿では特にシリコンを用いた2次元フォトニック結晶の研究の現状を解説し、将来の研究動向について述べる。

SUMMARY

Photonic crystals are artificial crystals, which have a periodic change of the refractive index corresponding to about half of the light wavelength. These materials have the potential to manipulate photons as semiconductors do for electrons. Photonic crystals were mainly studied by theorists in the last decade, and then experimentalists in thin films, silicon and nanofabrication technologies taken up this interesting technical challenge. In this report, the latest researches in silicon photonic crystals are reviewed, especially those concerning the two-dimensional structure. Such materials could be the key to ultra-fast optical computing and communications. Future directions in research and development are also discussed.

1 Introduction

Purcell was the first to discuss the fact that the presence of a mirror can substantially alter the radiation properties of an electromagnetic dipole. This insight was developed and the concept of photonic crystal was proposed in 1987 [1]. It is expected that photonic crystals will transform the communications and computing industries as semiconductors did in the last decades.

In semiconductors, electrons of certain energies are forbidden to propagate in a so-called band-gap region, due to Bragg-like diffraction from the atoms (Fig. 1). The photonic crystals have a photonic band-gap (PBG) that is analogous to the energy band-gap in semiconductors [2]. The PBG of photonic crystals comes from a periodic change of the refractive index instead of a periodic arrangement of atoms. Photonic crystals reflect the light of any polarization at any angle if the frequency of the light is in the band-gap range. To control and manipulate the light, the photonic crystal is the “ideal” solution.

In this report, the analogy between the Schrodinger and Maxwell equations is shown, then recent researches, applications and future directions of silicon photonic crystals are discussed in details.

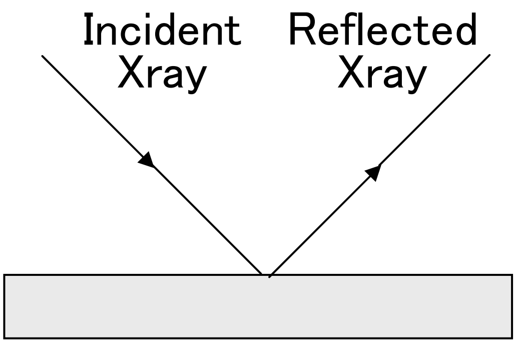

Fig. 1: Scheme of the Bragg diffraction

2 Light localization

The localization of the light originates from the coherent multiple scattering of the light and from the interference due to periodic photonic structures, which is analogous to the localization of electrons in atomic crystals. This phenomenon can be described by Schrodinger’s equations for the motion of electrons and Maxwell’s equations of wave propagation for the motion of photons. As described in ref. 3, the wave equation for the electric field amplitude can be written in a form analogous to the Schrodinger's equation. For computer calculations, this analogy allows finding the solutions for the magnetic field of a particular photonic crystal structure using eigenfunctions and eigenvalues.

We give here the main differential equation obtained by resolving the Maxwell's equations:

$$\nabla \times [1/\varepsilon(r)\ \nabla \times H(r)] = (\omega/c)^2\ H(r)$$

ε : dielectric constant
ω : frequency
c : celerity
r : radius
$\nabla \times a$: curl of a vector-valued function a
H : magnetic field, $H(r,t)=H(r)\ e^{i\omega t}$

Then, Maxwell's equations are viewed as a hermitian eigenvalue problem:

$$\Theta H(r) = (\omega/c)^2\ H(r)$$

$(\omega/c)^2$: eigenvalue
H(r) : eigenvector

Therefore, the computer calculations are performed by solving this equation:

$$\Theta H(r) \equiv \nabla \times [1/\varepsilon(r)\ \nabla \times H(r)]$$

In a practical point of view, photonic crystals can be simulated using different design tools and simulation software. The simulations presented in this report were performed using finite difference time domain and frequency domain methods.

3 Two-dimensional Silicon photonic crystals

This report focuses on the researches about photonic crystals working at a wavelength of 1.55 μm. Current investigations use semiconductors of the II-VI, III-V, and IV groups as well as oxides, polymers, and metallo-dielectric structures. Silicon has been chosen for the fabrication of photonic crystal since it is a dominant material in semiconductor industry. Two-dimensional (2D) photonic crystals are investigated hereafter because they are relatively easier to be manufactured than the three-dimensional ones.

2D silicon-based photonic crystals can have quite large photonic band-gap for some lattice structures. These structures are square or triangular lattice arrangements of air holes or silicon pillars. A pillar structure was realized, e.g. a silicon photonic crystal with a square lattice of 5μm-long pillars [4]. This structure was made by electron cyclotron resonance plasma (SF_6/O_2) etching. However, this structure does not have a low-loss confinement of the light of TM polarization in the vertical direction to the 2D plane. In fact, the triangular lattice of air holes in silicon material is the most promising structure (Fig. 2), as discussed further.

The Fig. 3 displays the band structure of a triangular lattice of air holes in silicon at $r/a = 0.46$, where r is the hole radius and a is the lattice distance. A refraction index of 3.4 for silicon was used in the computer simulations. A so-called full band-gap can be obtained. A full band-gap is the frequency region in which both TE and TM polarizations of the electromagnetic field can not exist. As shown in Fig. 4, a very large band-gap in normalized frequency can be obtained for TE polarization in a large range of r/a values. If the mid-gap wavelength, namely the central wavelength of the photonic band-gap, is 1.55 μm, the lower and upper values of the TE band-gap are of 1.163 and 1.937 μm, respectively. Noteworthy that the band-gap of the TM polarization limits the full band-gap.

A 2D silicon photonic crystal was fabricated in a silicon-on-insulator wafer [5]. Holes of 2 μm-long arranged in a triangular lattice pattern were etched out using electron cyclotron resonance plasma with a CF_4/H_2 gas mixture. This structure had a photonic band-gap in which a telecommunication wavelength of 1.55 μm is located. However, the expected remarkable photonic properties of 2D silicon photonic crystals could not be fully obtained due to limitations of the design feasibility. Although, the computer simulations assumed that holes have an "infinite" length, it is very difficult to make sufficiently long holes. Furthermore, the full photonic band-gap is obtained only for $r/a > 0.4$, where thin dielectric walls of less than 100 nm have to be remained. Therefore, 2D silicon photonic crystals involve the difficult fabrication of small and long holes, which almost touch each other.

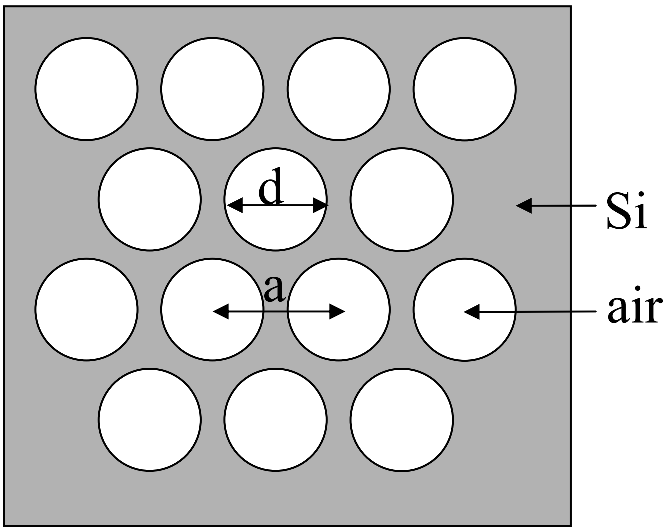

Fig. 2: Top view of a triangular lattice of holes etched in a silicon wafer, where r is the radius of the holes and a is the lattice distance

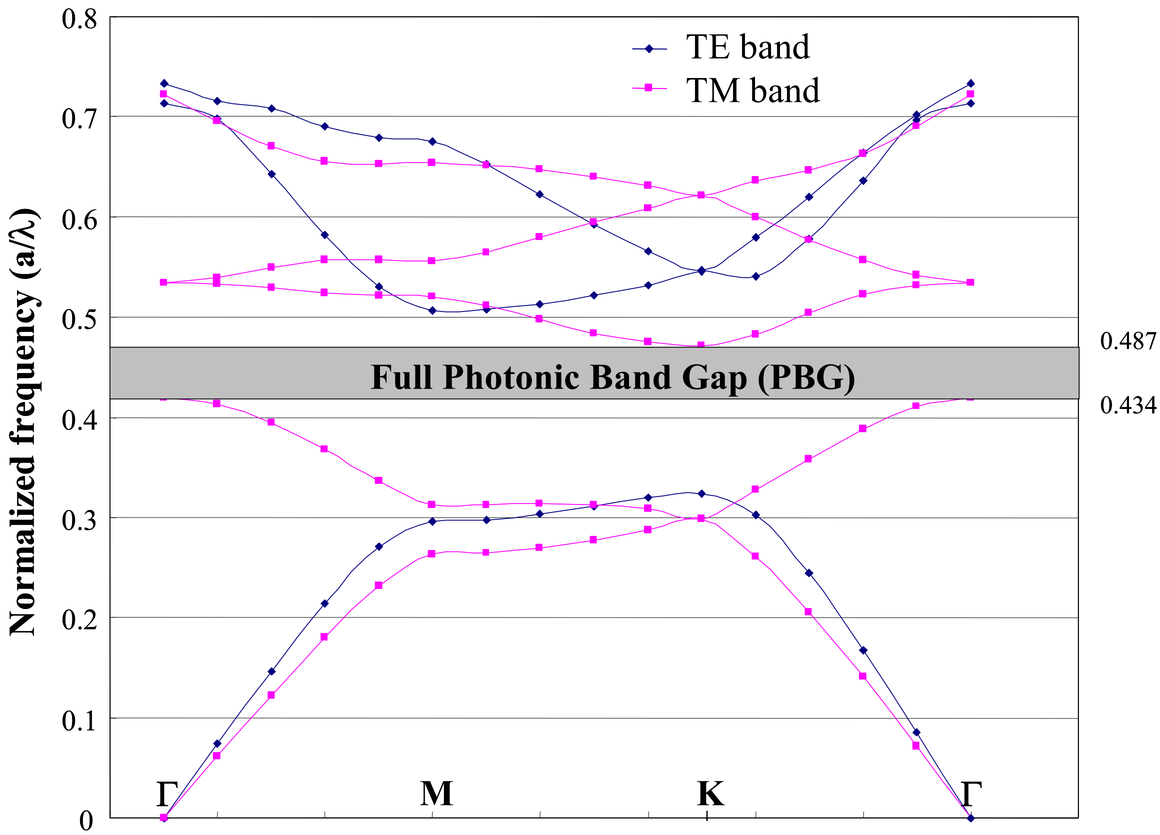

Fig. 3: Band structures of the "infinite" 2D photonic crystal of the Fig. 2. a/λ is the arbitrary unit of the normalized frequency, where a is the lattice distance and λ is the wavelength

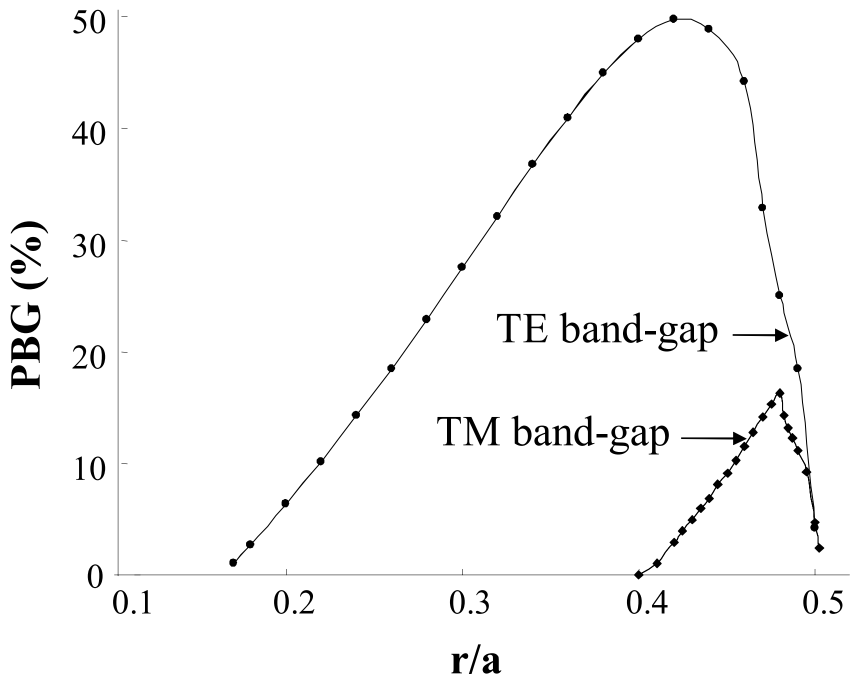

Fig. 4: Curves representing the photonic band-gap (%) as a function of r/a. The photonic band-gap is equal to the ratio of the PBG to the mid-gap, where the PBG is the photonic band-gap given in wavelength unit and the mid-gap is the central wavelength of the PBG. r is the hole radius and a is the lattice distance

There is a need for another 2D structures such as a 2D photonic crystal slab with properties quite similar to those of the "infinite" 2D photonic crystal. 2D photonic crystal slabs can also confine light in the vertical direction to the 2D plane by total reflection. A slab thickness between about 0.2 and 1.3 μm is suitable for a 2D lattice having a r/a value of 0.45 [3]. It is important that the photonic crystal slab has mirror symmetry in the vertical direction, i.e. same substrate above and below the slab. A confinement in the vertical direction is fully obtained if the refraction index of the substrate is lower than that of the slab. Therefore, the silicon air-bridge structure (Fig.5) is a powerful design. The fabrication of this structure is easier than that of the "infinite" 2D photonic crystal.

The silicon air-bridge structure was realized recently by a new fabrication technique developed on silicon-on-insulator [6]. Triangular and square lattice patterns of holes were written by electron-beam lithography on thin poly(methyl methacrylate) photo-resist layer. Chemically assisted ion beam etching (1250-V Ar^+ beam assisted by XeF_2 gas) was directly performed on silicon and an anisotropic etching of the holes resulted. The air-bridge structure was realized by HF dissolution of the sacrificial SiO_2 layer (below the silicon slab). Only a TE band-gap rather than a full band-gap was obtained.

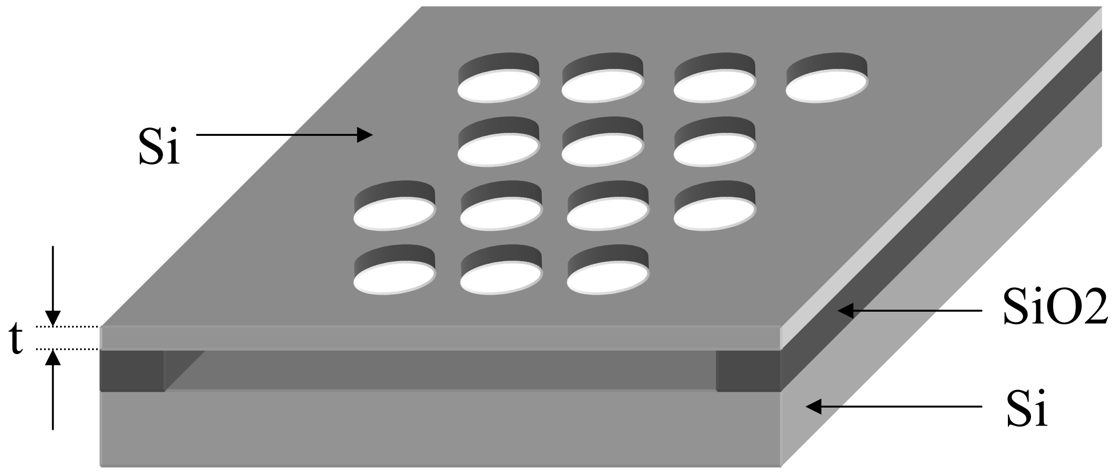

Fig. 5: Cross-sectional view of a silicon air-bridge structure. t is the thickness of the silicon slab

4 2D Silicon photonic crystal waveguides

The propagation of the light along conventional waveguides leads unfortunately to high loss (Fig.6a). One solution is a microstructure with very high refractive index contrast such as 2D silicon photonic crystal waveguides (Fig. 6b). Useful devices can be obtained by the introduction of defects into the photonic crystal. This intentional breakage of the 2D symmetry gives a specific functionality to photonic crystals. A channel waveguide can be made simply by omitting a row of air holes in the structure of the Fig. 2. The waveguide surrounded by the photonic crystal is like an omni-directional mirror, which confines the light having a wavelength in the photonic band-gap range. The photonic crystal waveguides have higher potential than conventional waveguides for applications such as couplers, power splitters and combiners as well as for ultra-compact bends.

Using a silicon-based photonic crystal, waveguides have been designed by removing a row of pillars [4] or a row of holes [5-7]. The bending of the light at 60°, 90°, and 120° were demonstrated in silicon photonic crystal waveguides [4-7]. In these waveguides a light loss could occur by scattering at imperfections. However, quite low loss was demonstrated in a silicon air-bridge structure [7]. The importance of the mirror symmetry in the vertical direction was highlighted by the comparison of the propagation of the light in two structures: silicon air-bridge and silicon-on-insulator ones.

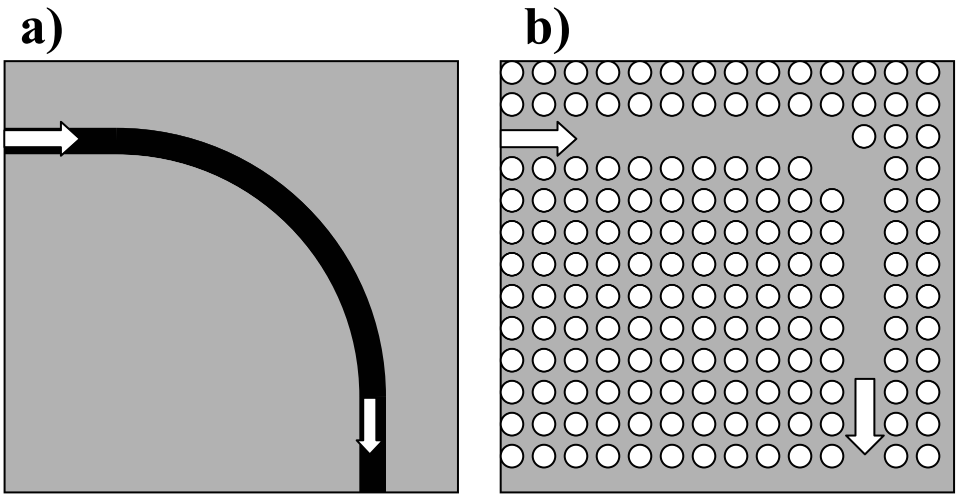

Fig. 6: Waveguides: (a) conventional, and (b) photonic crystal. The white arrows indicate the propagation of the light

5 Applications

2D silicon photonic crystals could play an important role, particularly, in the optical-communications industry. The fabrication of passive components will be probably the dominant applications of the silicon photonic crystals. It should be possible to combine a large number of components based on silicon photonic crystals in an integrated chip for dense wavelength division multiplexing systems. A possible application of the photonic crystal waveguides is as small-scale optical interconnects with tiny planar waveguides bending the light round tight corners. These waveguides are key components for new integrated optical circuits. Photonic crystals may solve the most parts of the problems that currently limit the speed and the capacity of optical-communications networks.

6 Conclusion and Future directions

Photonic crystals are now well understood from a fundamental and theoretical point of view. However, the high performance of these materials is not yet experimentally demonstrated even though, for example, the characterization of silicon photonic crystals shows very interesting features such as the waveguiding of the light. 2D photonic crystal fabricated in silicon-on-insulator appears to be a very promising material for the manufacture of passive photonic circuits at low cost.

The future directions of the research on 2D silicon photonic crystals should include the fabrication of structures with a given functionality. Another attractive research is the improvement of the connection between optical fibers and photonic crystal waveguides. At the present time, the fiber coupling involves a high loss of light due to the limited thickness of the photonic crystal. This problem might be solved using new fabrication methods such as a deep etching process with high resolution and with high accuracy of the hole arrangement. Finally, mass-manufacturing methods for devices based on photonic crystals have to be established. Therefore, the fabrication of silicon photonic crystals, which can be used for realistic applications, is still a challenge.

References

[1] E. Yablonovitch: "Inhibited spontaneous emission in solid-state physics and electronics," Phys. Rev. Lett., 58, p. 2059 (1987)
[2] J.D. Joannopoulos, R.D. Meade and J.N. Winn: "Photonic crystals: molding the flow of light," Princeton university Press (1995)
[3] S.G. Johnson, F. Shanhui, P.R. Villeneuve, and J.D. Joannopoulos: "Guided modes in photonic crystal slabs," Phys. Rev. B, 60, p. 5751 (1999)
[4] T. Zijlstra, E. Van Der Drift, M.J.A De Dood, E. Snoeks, and A. Polman: "Fabrication of two-dimensional photonic crystal waveguides for 1.5 μm in silicon by deep anisotropic dry etching," J. Vac. Sci. Technol.

B, 17, p. 2734 (1999)
[5] M.Tokushima, H. Kosaka, A. Tomita and H.Yamada: "Lightwave propagation through a 120° sharply bent single-line-defect photonic crystal waveguide," Appl. Phys. Lett., 76, p. 952 (2000)
[6] M. Loncar, T. Doll, J. Vuckovic and A. Scherer: "Design and fabrication of Silicon photonic crystal optical waveguides," J. Lightwave Tech., 18, p.1402 (2000)
[7] T. Baba: "Light propagation characteristics of microguides in photonic crystal slabs," Symposium on the development of photonic crystals and the localization of the light, Nagano-ken (July 2001)