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Fabrication of diamond-like carbon-based two-dimensional photonic crystals

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A B S T R A C T

In this paper, we discuss the development of a process for fabricating diamond-like carbon (DLC)-based two-dimensional photonic crystals with a wider electronic bandgap and better thermostability than silicon (Si), which is used widely in nanophotonics. In the developed process, the DLC film was deposited on an Si substrate by RF plasma chemical vapor deposition, and the refractive index of the film could be changed from 1.8 to 1.95 by varying the RF power. We also theoretically show that a wide photonic bandgap can be obtained with these DLC-based photonic crystals, even though they have a low refractive index compared to pure diamond. Finally, we develop a process for fabricating DLC-based photonic crystal structures by using electron-beam lithography and inductively coupled plasma (ICP) etching techniques.

1. Introduction

A two-dimensional (2-D) photonic crystal slab structure, which is one of the commonly used nanophotonic structures, can control light in a tiny space with cubic wavelengths by taking advantage of the photonic bandgap (PBG) effect to control the light in the in-plane direction and total internal reflection (TIR) for the vertical direction [1,2]. The light can also be guided and confined by intentionally introducing defects [2,3] in the periodic photonic crystal structures. Because of these properties, 2-D photonic crystal slab structures have been widely investigated to realize various optical devices such as optical filters, switches, waveguides, lasers, and biosensors [4–6].

Conventionally, silicon (Si) has been used to fabricate photonic crystal structures because it has a high refractive index and the Si-based fabrication process is well established. However, Si-based photonic crystal devices have limited operational stability because of the small electronic bandgap (~1.1 eV) of Si. For example, two-photon absorption (TPA) frequently occurs in Si-based photonic crystals, resulting in optical loss and distortion of the optical spectrum of the devices [7,8]. Furthermore, the resonant wavelength of Si-based photonic nanocavities is changed by local temperature fluctuations, which results in detuning and instability of their optical properties due to the large thermo-optic effects of Si [9]. In order to address these limitations of Si, diamond material has been considered because of its wide electronic bandgap (~5 eV) and ability to significantly suppress TPA, and also because it has only small thermo-optic effects [10]. However, the fabrication process for a single-crystal diamond thin-film and the formation of 2D photonic crystal structures with an air-bridge is complicated [11,12]. As an alternative, diamond-like carbon (DLC) films that exhibit quasi-diamond properties including a wide electronic bandgap and small thermo-optic effects have been considered [13,14].

In this study, first of all, a DLC film was deposited on an Si substrate using the RF PCVD method and the refractive index, extinction coefficient, and thickness of the DLC film were investigated. Next, we investigated the feasibility of DLC-based photonic crystals, because the refractive index of DLC is lower than that of pure diamond. Finally, we developed a process for fabricating a DLC-based 2-D photonic crystal slab with an air-bridge structure by using electron-beam lithography and inductively coupled plasma (ICP) etching techniques.

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2. DLC film fabricated by RF PCVD

2.1. Fabrication of DLC film

In this section, we discuss the fabrication of the DLC film on an Si substrate by RF PCVD. We investigate the refractive index, extinction coefficient, and thickness of the fabricated films as functions of RF power, because the properties of DLC film deposited by RF PCVD method are highly affected by the RF power [15]. First, the Si substrate was processed by hydrogen H_2 plasma treatment to improve the adhesion between the Si substrate and the DLC film [16]. Here, we emphasize that the Si substrate does not affect the optical properties because light is confined in the air-bridge DLC photonic crystal slab structure. Next, the DLC film was deposited on the substrate by RF PCVD with CH_4 and H_2 gas. The gas flow rates were set to CH_4/H_2 = 20/80 sccm, and a processing pressure of 13.3 Pa was maintained during the entire deposition time of 10 min. The refractive index, extinction coefficient, and thickness of the deposited DLC were measured by an ellipsometer (M-2000D, J.A. Woollam) at the optical communication range of 1.55 μm. Different DLC samples were deposited by varying the RF power from 110 to 170 W. Fig. 1 shows a plot of the refractive index, extinction coefficient, and deposited thickness of the DLC films as functions of the RF power. The refractive index of the DLC films changes from 1.85 to 1.95 because the ratio of sp^3 bonding to sp^2 bonding in the DLC film is affected by the RF power. The extinction coefficients vary from 10^{-1} to 10^{-6} at various RF powers, which implies that the absorption of DLC is controllable using the RF power. The extinction coefficient can be converted into the propagation loss in a material. For example, an extinction coefficient of 10^{-6} corresponds to a propagation loss of 0.3 dB/cm in the DLC material, which is negligibly small considering the required size of several micrometers for the photonic crystal's function. The thickness of the DLC film also decreases with increasing RF power, because higher RF powers lead to faster etching of the DLC film.

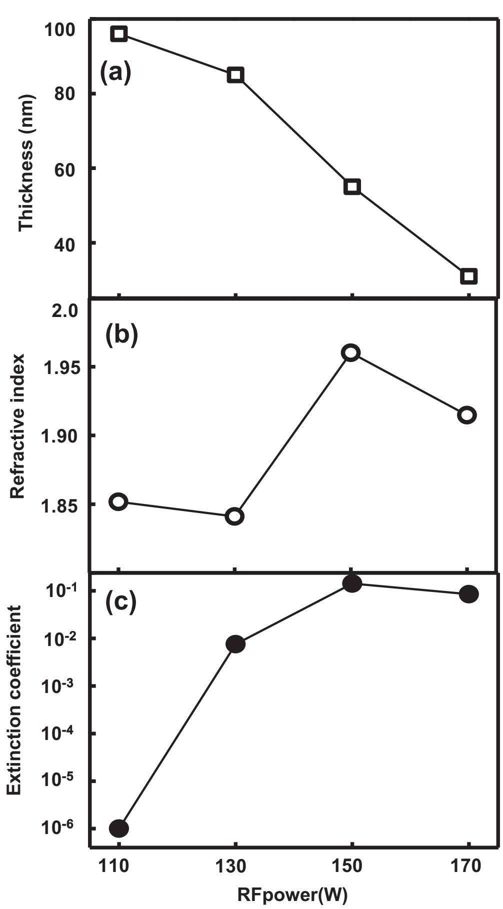

Fig. 1. Plots of experimentally measured (a) thickness, (b) refractive index, and (c) extinction coefficient of the DLC film deposited for 10 min as a function of RF power.

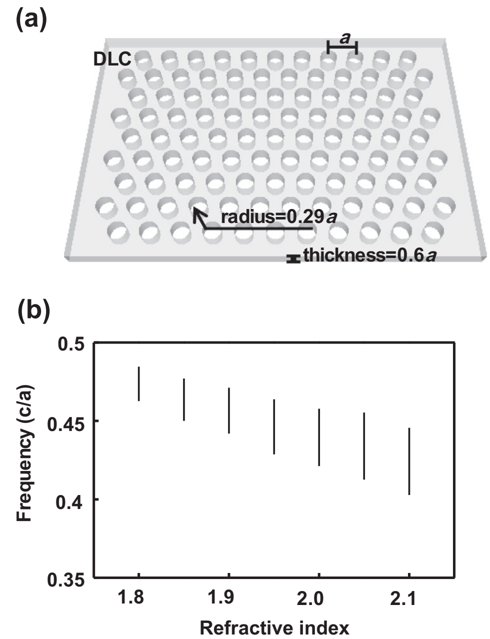

Fig. 2. (a) Schematic of the DLC-based 2-D photonic crystal structure with lattice constant *a*. The radius (*r*) of the air holes and the slab thickness (*t*) are 0.29*a* and 0.6*a*, respectively. (b) Plot of the PBG of a 2-D photonic crystal structure as a function of the refractive index of the DLC film.

2.2. Feasibility of DLC-based photonic crystals

Before we fabricated the DLC-based photonic crystal structures, we investigated their feasibility, because the refractive index of DLC is lower than that of pure diamond. For this purpose, we calculated a photonic band diagram of the DLC-based 2-D photonic crystal structure using a three dimensional (3-D) finite difference time domain (FDTD) method. Fig. 2(a) shows a DLC-based 2-D photonic crystal structure consisting of a triangular pattern of air holes. The radius (r) of the air holes and the slab thickness (t) were set to 0.29a and 0.6a, respectively, where a is the lattice constant of the photonic crystal. The refractive index of the DLC slab was assumed to be from 1.8 to 2.1, which is within the approximate range for the fabricated DLC film. Fig. 2(b) shows a plot of the photonic bandgap (PBG) of the photonic crystal structures as a function of the refractive index of the DLC film. It is apparent that a PBG exists even for a refractive index of 1.8 and the PBG becomes wider with increasing refractive index. At the refractive index of 1.95, which is the highest value obtained in the experiment described in Section 2.1, a PBG exists in the frequency region from 0.430 to 0.464 (c/a). This PBG corresponds to the optical telecommunication range of 1507–1628 nm when a = 700 nm, which implies that the slab thickness must be 0.6a (t = 420 nm).

3. Development of a process for fabricating DLC-based 2-D photonic crystal structures

On basis of the results presented in Section 2, we fabricated DLC films of 420 nm in thickness by increasing proportionally the