Design of Photonic Crystal with Silicon Nitride Media for Light Confinement in Infrared Detector

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Abstract —The photonic crystal is a prospective method for carbon nanotube based infrared detectors to improve its photocurrent by increasing local photon density. The photonic crystal with silicon nitride slab is studied to make incident light trap in photonic crystal. The band gap of silicon nitride photonic crystal is calculated for both TE and TM modes. The TE mode has bigger band gap than TM mode. The energy distribution characteristics are responsible for the band gap difference. The quantum resonant cavity for light trap is analyzed. By changing the central defect arrangement, the incident infrared light is trapped to enhance the number of photons for infrared detectors. The electrical field profile in photonic crystal is obtained, and the energy gain is increased about 50 times.

I. INTRODUCTION

The problem for carbon nanotube based infrared light detector is that the photocurrent of infrared light detector is too low if the carbon nanotube is directly exposed under infrared light source. So we should collect more photons from the infrared source, and then put these photons to carbon nanotube, in order to obtain high photocurrent because of stronger photon-electron coupling. In literature [1], the nanoantenna is adopted to enhance the local electrical field at the contact of carbon nanotube based infrared detectors in order to increase electron–phonon coupling through Schottky effect. In literature [2], the photonic crystals of parylene and silicon media are adopted for performance enhancement of carbon nanotube based infrared sensors.

There are some published papers which cover photonic crystal studies, such as photonic crystal wave guide, optical filter and resonant cavity. In literature [3,4], a high-Q nanocavity in a two-dimensional photonic crystal with point defect is analyzed, and the air hole of photonic crystal is fine-tuned to obtain high Q factor. The characteristics of silicon photonic crystal with line defect and a nanocavity at various incident light powers are investigated in literature [5]. In literature [6], the special wave guide of photonic crystal with line defect is analyzed, and the light propagation loss from TE–TM coupling is discussed. In literature [7], the hetero photonic crystal with point defect is used in a channel drop filter, and its polarization mode are investigated.

On the base of above carbon nanotube based infrared detectors and photonic crystal studies, in this paper the design of quantum resonant cavity in silicon nitride photonic crystal for infrared detectors is conducted. The photonic crystal of silicon nitride media has a central point defect, which is actually a quantum resonant cavity to trap infrared light and collect more photons of incident light.

II. PHOTONIC CRYSTAL AND CALCULATION PRINCIPLE

The carbon nanotube based infrared detector with silicon nitride photonic crystal is depicted in Fig.1. In Fig.1(a), the photonic crystal of air holes in silicon nitride slab is shown, and there is a point defect of removed air hole in central position. The point defect acts as quantum resonant cavity to confine infrared light. In Fig.1(b), the infrared detector consists of silicon nitride photonic crystal, carbon nanotube and two microelectrodes. The central point defect of silicon nitride photonic crystal is just above the microelectrode and CNT. The microelectrode and CNT are fixed on the dielectric substrate to form electric current measure circuit. At the contacts of two microelectrode and CNT, the photons and electrode are coupled. By the point defect of quantum resonant cavity, the local electrical field of CNT and two contacts is improved to obtain high photocurrent.

$$H_k(r) = e^{ik.r} u_k(r) \tag{1}$$

$$u_k(r) = u_k(r+R) \tag{2}$$

$$\hat{\Theta}_k \, \mathrm{u(k)} = \left(\frac{\omega(\mathrm{k})}{\mathrm{c}}\right)^2 \mathrm{u(k)} \tag{3}$$

$$\hat{\Theta}_k = (ik+\nabla)\times\frac{1}{\varepsilon(r)}(ik+\nabla)\times \tag{4}$$

The calculation model of silicon nitride photonic crystal is expressed in Equ.1 to Equ.4. The magnetic filed H(r,t) in photonic crystal is considered as a harmonic mode. The field H(r) is the product of a planar wave times a periodic function u(r)(Equ.1 and 2), where u(r) means the periodic function of silicon nitride slab in two dimensional plane, and R is the lattice vector in photonic crystal, and k is Bloch's wavevector. The electromagnetic solution of light transmission in photonic crystal follows the Bloch' theorem in periodic dielectric materials, and the magnetic field distribution can be seen as Boch's state. The photonic crystal problem can be solved as eigenvalue problem of electromangtism, and the Hermitian operator is given in Equ.4.

III. BAND GAP OF SILICON NITRIDE PHOTONIC CRYSTAL

Fig.2 shows the band gap of TE mode and TM mode in silicon nitride photonic crystal when radius of air hole is 0.25 if we assume that the lattice constant is unity. The horizontal axis is Bloch's wave vector in two-dimensional plane, and the vertical axis is normalized frequency of incident light. For TM mode, there is no obvious stop band. But for TE mode, there is an obvious band gap from 0.247 to 0.283 of normalized frequency.

Fig.3 shows the band gap of TE mode and TM mode when radius of air hole is 0.35. For TM mode, there is still no obvious stop band. For TE mode, an bigger band gap exists from 0.272 to 0.377 of normalized frequency. So we can adjust the geometry arrangement of photonic crystal to obtain better band gap characteristics for light confinement. The reason for big band gap of TE mode can be explained by energy distribution and contrast of light bands which are close to stop band.

IV. LIGHT CONFINEMENT AND DEFECT DESIGN

In the central position of silicon nitride photonic crystal, we design the point defect to make the resonant cavity, in order to confine infrared light. Fig.4(a) is the electrical field profile of silicon nitride photonic crystal with removed air hole, the wavelength of infrared light is 2 micron, and the lattice constant is 0.75 micron, radius of air hole is 0.3 micron. The energy of central defect in an area of diameter 0.75 micron is 44% of total incident light. The field profile is a monopole field pattern with a single lobe in the central defect. Fig.4 (b) shows field profile of photonic crystal with central defect of dielectric constant 20. The lattice constant is 0.652 micron, and the radius of air hole is 0.228 micron. The cavity energy is 49% of total incident light. And the resonant mode has a dipole pattern with one nodal plane in the defect, which means that the mode in Fig.4(b) has higher resonant frequency. Fig.4(c) shows the light cavity with a central air hole of 0.2 micron radius. The field profile is similar with Fig.4(a), but the energy in the central air hole is only 5.4% of total light energy due to the smaller radius. By changing the radius of central hole, dielectric constant and neighbor air hole arrangement, we can obtain more designs for infrared trap in infrared detector.

V. REFERENCES

[1] C. K. M. Fung, N. Xi, B. Shanker. "Nanoresonant signal boosters for carbon nanotube based infrared detectors" *Nanotechnology*, 20, 185201, pp1-6, 2009

[2] J. Lou, N. Xi, C. K. M. Fung. "Design and Analysis of Photonic Crystal for Performance Enhancement of Carbon Nanotube Based Infrared Sensors", *Joint 2010 IEEE NMDC*, Monterey, California, USA, 2010

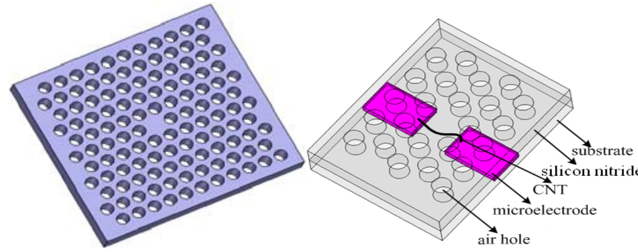
[3] O. Akahane, T. Asano, B. Song, S. Noda. "High-Q photonic nanocavity in a two-dimensional photonic crystal". *Nature*, vol.425(30), pp944-947, 2003.

[4] Y. Akahane, T. Asano, B. Song, S. Noda. "Fine-tuned high-Q photonic-crystal nanocavity". *Optics Express*, vol.13(4), pp1202-1214, 2005.

[5] T. Uesugi, B. Song, T. Asano, S. Noda. "Investigation of optical nonlinearities in an ultra-high-Q Si nanocavity in a two-dimensional photonic crystal slab". *Optics Express*, vol.14(1), pp377-386, 2006.

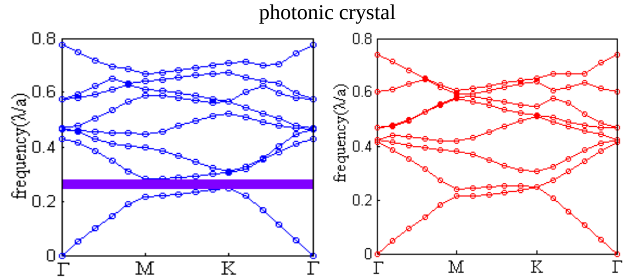
[6] Y. Tanaka ,T. Asano, R. Hatsuta, S. Noda. "Analysis of a Line-Defect Waveguide on a Silicon-on-Insulator Two-Dimensional Photonic-Crystal Slab"[J]. *J. of Lightwave Technology*, 2004, 22(12), pp2787-2792.

[7] B. Song, T. Asano, Y. Akahane. S. Noda. "Transmission and reflection characteristics of in-plane hetero-photonic crystals"[J]. *Applied Physics Letters*, 2004,85(20):4591-4593.



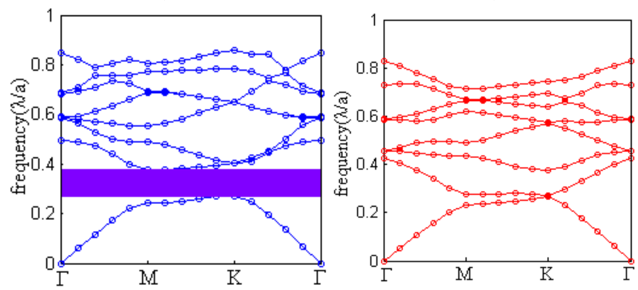
(a) photonic crystal in silicon nitride slab (b) infrared detector

Fig.1 Carbon nanotube based infrared detector with silicon nitride photonic crystal



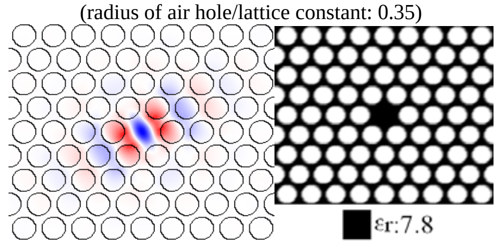
(a) TE mode (b)TM mode

Fig.2. Band gap of photonic crystal with air holes in silicon nitride slab (radius of air hole/lattice constant: 0.25)

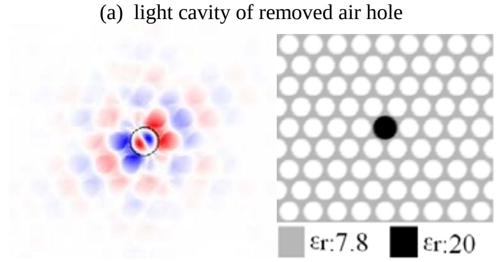


(a) TE mode (b)TM mode

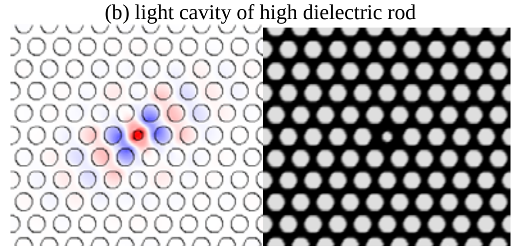
Fig.3. Band gap of photonic crystal with air holes in silicon nitride slab (radius of air hole/lattice constant: 0.35)



(a) light cavity of removed air hole



(b) light cavity of high dielectric rod



(c)light cavity of central air hole with smaller radius

Fig.4. The electrical field profile of silicon nitride photonic crystal