Fabrication of Three Dimensional Cu Metallic Photonic Crystal by Electroless Plating

Fabrication of Three Dimensional Cu Metallic Photonic Crystal by Electroless Plating

S-C Wu[1,5], F-J Hou[1], P-C Jang- Jian[2], M-S Tsai[1], M-C Chen[3], L-S Li[3], J-Y Huang[3], and S-Y Lin[4]

[1]National Nano Device Laboratories, Taiwan, ROC

[2]Department of Materials Science and Engineering, National Chia Tung Univrsity, Taiwan, ROC

[3]Department of photonics, National Chiao Tung University, Taiwan, ROC

[4]Physics, Applied Physics and Astronomy, Resselaer Polytechnic Institute, NY, USA

Abstract   A 3D copper (Cu) metallic photonic crystal (MPC) with 180nm line width was fabricated by electroless plating. The mold of 3D MPC for Cu replacement is poly-Si. It has been verified as an enhancing thermal photovoltaic effect while the mold was transferred into tungsten MPC by chemical vapor deposition method. The 5 layers structure of Cu MPC was clear observed with scanning electron microscopy. The photonic band-gap ranged from 1.5 to 13 μm was measured by Fourier transform infrared spectroscopy (FTIR) instrument.

Keywords: Copper metal photonic crystal, electroless plating, photonic band-gap.

1. Introduction

3D metallic photonic crystal is of use material for light source [1] and relative optics device in integrate optical circuit [2]. It has been suggested that a three-dimensional (3D) metallic photonic crystal may be useful for incandescent lamp application and for thermal photovoltaic power generation [3]. There are several methods in fabrication of MPC currently all over the world [4~8]. But it is seldom to use electroless Cu plating [9] to fabricate the nano scale 3D Cu MPC. It is also meaningful

[5] To whom any correspondence should be addressed.

to manufacture various metallic PC and investigate property of light emission on which is dependence of metal intrinsic property. At the same time, it is also important for establishing metal replacing technique on electroless plating method. Following, it will be interesting in studying the thermal emitting effect at the allowed band for different PBG samples with a thermal source [10]. In this study the 3D cupper photonic crystal is realized with a large infrared PBG > 2 μm. It is implied that thermal excitation can give rise to PBG emission with sharp emission peaks at < 1.5 μm.

2. Experiment

The 3D copper photonic-crystal sample is fabricated with a poly silicon (Si) mold which was come from a modified silicon process [11, 12]. For that process, a layer of silicon dioxide (SiO_2) is firstly deposited on Si substrate, and then preceded the pattern transferred procedure on SiO_2 film. The space between SiO_2 patterns was filled with a 0.18-μm-thick poly-silicon film and then planarized. The same process is repeated for each layer. At the end of the process, the silicon dioxide is released by BOE etching, leaving a 5 layers of poly-Si freely standing thin rod. In the Fig. 1, a scanning electron microscope image of a five-layer 3D Si photonic crystal sample is shown. The sample consists of layers of one dimensional Si rods with a stacking sequence that repeats itself every four layers [12, 13]. The rod-to-rod pitch is ~*650* nm, the rod width is 180 nm, and rod height 273 nm.

In order to transfer the poly-Si of MPC into Cu metal the electroless Cu plating method was used, in which the poly-Si likes as the seed layer for beginning the Cu metal replacing. The electrolyte of plating in our process was 7.5g/L cupric sulfate (CuSO4) and 0.5% buffered oxide etch (NH4F/HF mixture in 6:1 volume ratio) diluted with 99% DI water. The processing condition was at an ambient temperature for 15 min replacing time. The transmission of Cu MPC was measured with Fourier transform infrared spectroscopy (FTIR) that is composed with commercial Michelson interferometer and manmade optical system. The range of scanned incidence light was 0.7 ~26 μm. The transmission of pure Si wafer was adopted as the background in measuring. Two modes of P and S polarization incidence light were used to investigate the polarization dependence of MPC samples.

3. Result and Discuss

The scanning electron microscopy (SEM) picture in Fig. 2 shows the five layers of Cu metallic photonic crystal (MPC) structure. In this picture the initial poly-Si rod is now partially replaced and covered with Cu film. The rough surface is probable induced from the poly Si grain structure under electroless Cu plating. This rough surface will affect the refraction phenomena and transmitting property while the light is entering. For comparing the photonic band gap behavior with poly Si mold the Fourier transform of infrared spectroscopy (FTIR) measuring was adopted. The transmission of Cu MPC is shown as Fig 3.
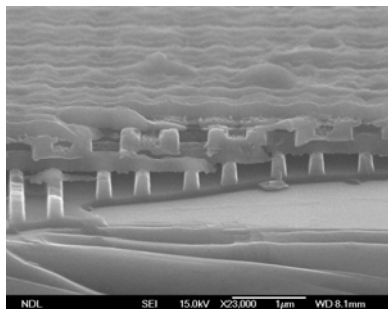
Figure 1 The scanning Electronic Microscopy photography shows the five layers poly-Si photonic crystal cross section after BOE etched out the SiO$_2$ dielectrics.
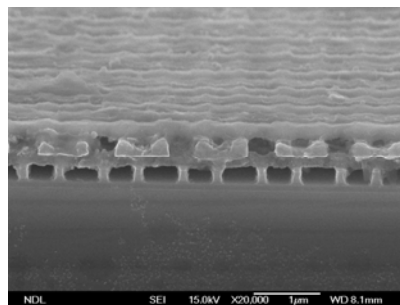

Figure 2 This SEM figure demonstrates the Cu metallic photonic crystal structure after Cu replacing the poly-Si in the five layers mold with electroless plating.
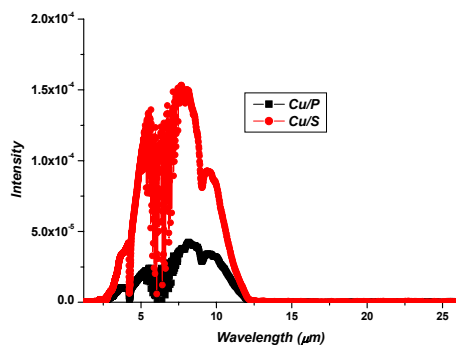

Figure 3 This spectra show the transmitting intensity of Cu metal photonic crystal at P and S polarization conditions measured by FTIR.
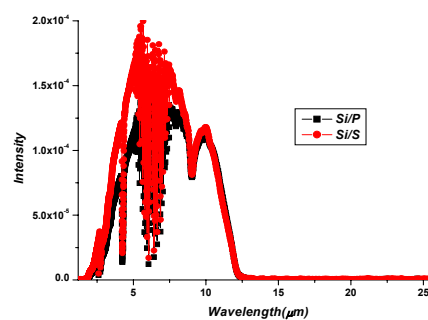

Figure 4 This spectra show the transmitting intensity of Si wafer at P and S polarization conditions measured by FTIR.

Meantime, we also measured the transmission curve of poly Si PC mold shown as Fig. 4, which can use as the background to evaluate the absolute transmittance of Cu MPC.

The absolute transmittance of Cu MPC is demonstrated in Fig. 5. Noting that there is an obvious dip region in 1.6~13 μm period under P polarized incidence. For S polarization, this region is less extended and only at 1.6~5 μm. Those regions can call as a photonic band gap under 50% transmittance criteria. The polarization dependence of transmission is coming from no sufficient layers in this PC structure. When the E field of incidence light was parallel to top Cu rod it will encounter the first, third and fifth layers of rods. Accordingly, the incoming light will be decreasing with strong interaction between Cu rods and E field. Since rods are easily polarized when the *E* field is in the direction of the long axis, the light effectively interacts with three layers. For the perpendicular case, the *E* field is aligned with the long axis of the rods for only two layers thus lowering the interacting effect between both. If the layers of PC are increasing the collection effect for both *P* and *S* polarized

incidence cases might be similar. As other searcher's work [11] while the numbers of layer in 3D PC is larger than 12, the optical properties are near isotopic. This is expected, since for an infinite crystal the two orientations will not be distinguished.
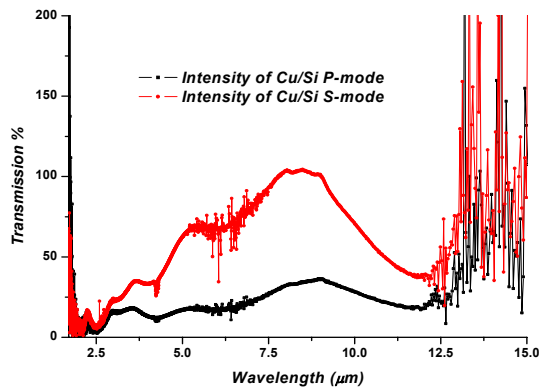

Figure 5 The transmission spectra of 5 layers 3D Cu metallic photonic crystal under a background of Si transmitting intensity. There is a photonic band gap during 1.6~13 μm period for P polarization incident condition.

On the other hand, the reflectivity of these finite woodpile crystals can be calculated based on the generalization of the method of ''exact eigenvalues and eigenfunctions'' used in the study of lamellar gratings [14, 15]. The woodpile structure under consideration can be described as a stack of gratings [15]. The substrate can be modeled as being infinite since the backside of the supporting Si wafer is unpolished. But for transmission measurement the backside of sample need polished to 0.2 μm in order to mitigate scattering effect of the incident light [16]. It was found that decreasing the width of the bars leads to a shift of the band edge towards longer wavelength. In general the measurements and theory on woodpile photonic crystals have mostly concentrated on perfect structures [15]. However, experimentally such crystals do not exist. In fact, a careful observation of the SEM images in Fig. 1 and 2 reveal a variation in pitch and rod shape that find its origin in the nature of the filet process and later influence in replacing step.

The large PBG value in this Cu MPC is same as S. Y Lin work [16] in tungsten MPC. The peak absorption in Lin's work is approximately ten times stronger than tungsten's intrinsic absorption (2–3%) and is due to an enhanced density of photon states in a narrow band [17, 18]. Accordingly, the absorption will be enhanced at a narrow band supposed by authors in ref. [11, 19], thus achieving enhanced light emission possibility. On the other hand, the densities of state at the first and second allowed bands will be enhanced because of its narrow bandwidth, i.e., flat dispersion [14]. Furthermore, the first and second bands are propagating Bloch modes, allowing for the extraction of PBG radiation into free space. Indeed, the PBG densities of states are suppressed in the bandgap and enhanced by 300% in the allowed bands [3]. The thermal emission measurement of Cu MPC was taken at the vacuum chamber of 10^{-6} torr in S-Y Lin's laboratory. Form this data, we found the emission behavior of it is almost near a grey-body material which means the Cu-replacing process was not good enough to demonstrate the real MPC effect. Therefore, the further improve and effort on replacement experiment and poly-Si PC mode fabrication are sincerely needed.

4. Conclusion

We have fabricated the 5 layers Cu metallic photonic crystal by using electroless Cu plating technique. From FTIR measurement the photonic band gaps were observed at 1.6~13 and 1.6~5 μm for P and S polarized incident, individually. In this work the polarization dependence in photonic band gap is supposed by non-sufficient layers in this metallic photonic crystal. It will be avoided when the layers of metal rods in 3D photonic crystal are increased. The thermal emission of this device is very crucial in evaluating the photovoltaic property thus we will improve the Cu replacing technique to meet the target. Even though, this is the first step to find a novel process in MPC devices fabrication.

Reference

[1]   Lin S Y, Fleming J G and El-Kady I 2003 *Optical Letts*. **28** 1683

[2]   Noda S, 1999 *J. Inst. Electron., Inf. Commun. Eng.* **82** 232

[3]   Lin S-Y, Fleming J G and El-Kady I 2003 *Optical Letts*. **28** 1909

[4]   Wijnhoven J E G.J and Vos W L 1998 Science **281**, 802

[5]   Blanco A, *et al.* 2000 *Nature* **405** 437

[6]   Lin S-Y, Fleming J G, Hetherington D L, Smith B K, Biswas R, Ho K M, Sigalas M M, Zubrzycki W, Kurtz S R and Bur J 1998 *Nature* **394** 251

[7]   Noda S, Tomoda K, Yamamoto N and Chutinan A 2000 *Science* **289** 604

[8]   Cheng C C, Scherer A, Arbet-Engels V and Yablonovitch E 1996 *J. Vac. Sci. Technol.* B **14** 4110

[9]   Lee Y-P, Tsai M-S, Hu T-C, Dai B-T, and Feng M-S 2001 *Electrochemical and Solid-State Letters* **4 (7)** C47-C49

[10] Coutts T J and Fitzgerald M C 1998 *Sci. Am*., **279** 90

[11] Fleming J G, Lin S Y, El-Kady I, Biswas R, and K. M. Ho 2002 *Nature* **417** 52

[12] Lin S Y, Fleming J G, Hetherington D L, Smith B K, Biswas R, Ho K M, Sigalas M M, Zubrzycki W, Kurtz S R and Bur J 1998 *Nature* **394** 252

[13] Ozbay E, Temelkuran B, Sigalas M M, Tuttle G, Soukoulos C M, and Ho K M 1996 *Appl. Phys. Lett.* **69** 3797

[14] Li Z-Y, El-Kady I, Ho K-M, Lin S Y and Fleming J G 2003 *Journal of Appl. Phys*. **93** 38-42

[15] de Dood M J A, Gralak B, Polman A and Fleming J G 2003 *Physical Rev.* **B 67** 035322-35329

[16] Fleming J G and Shawn-Yu Lin 1999 *Optics Letts*. **24**, 49~51

[17] Sakoda K 1999 *Opt. Exp.* **4** 167

[18] Lin S Y, Fleming J G, Li Z Y, El-Kady I, Biswas R and Ho K M 2003 *J. Opt. Soc. Am*. **B 20** 1538

[19] Lin S Y and Fleming J G 2003 *Proc. SPIE* **5000** 1