Optical Materials 83 (2018) 157–164

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Tellurite suboxide based near-infrared reflector and filter

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ARTICLE INFO

Keywords:
One-dimensional photonic crystals
Photonic band gap
Tellurium suboxide
Sputtering
Reflector
Filter

ABSTRACT

$TeO_{1.4}/SiO_2$ one-dimensional photonic crystals (1D PCs) were prepared using radio frequency (RF) magnetron sputtering to fabricate a reflector and a filter with photonic band gaps (PBGs) in the near infrared (NIR) region. Stoichiometry and phase state of the TeO_x thin film were characterized via X-ray photoelectron spectroscopy (XPS) and X-Ray Diffraction (XRD), respectively. The microstructural and optical characteristics of the 1D PCs were evaluated using scanning electron microscopy (SEM), atomic force microscopy (AFM) and ultraviolet visible near-infrared spectrophotometer (UV-VIS-NIR). The experimental reflectance spectra were consistent with the theoretical results simulated using the transfer matrix method (TMM). For the reflector, a PBG of 1273–1676 nm ($\Delta\lambda$ = 403 nm) was achieved in the NIR region. For the filter, the introduction of a defect layer in the 1D PC led to a resonant peak at the central wavelength of 1461 nm within the PBG of 1250–1733 nm ($\Delta\lambda$ = 483 nm). The effects of the structural parameters, including the incident angle, the state of polarization and the thickness of the defect layer, were also theoretically analyzed.

1. Introduction

Since the introduction of photonic crystals (PC) by Yablonovitch and John in 1987 [1,2], there has been considerable attention on their specific electromagnetic characteristics and potential applicability to photonic devices [3–7]. PCs are artificial structures with periodic arrays of dielectric materials characterized by photonic band gaps (PBGs) that are functionally analogous to electronic band gaps (EBGs) for semiconductor crystals [6–8]. According to the geometry of the structure, PCs can be generally categorized into three types: one- (1D), two- (2D) and three-dimensional (3D) PCs [4]. Ideal 3D PCs refer to so-called omnidirectional (omni-) PBGs, where the propagation of light is thoroughly forbidden for arbitrary polarizations, transverse-electric (TE) and transverse-magnetic (TM), in any direction [5]. The 1D periodic structures are well known to have a high optical reflectivity [9]. An omni-PBG is feasible through a well-designed 1D PC, and it does not absolutely need a 2D or 3D PC [10–13]. 1D PCs can be easily achieved through simple deposition techniques when compared to 2D and 3D PCs. In addition, 1D PCs can acquire a defect level by introducing a localized defect layer into their structures, with light that can be manipulated by the 1D PCs with the defect layer [14]. These defect modes within the PBG of the 1D PCs have given rise to various attractive phenomena and applications, including optoelectronic devices or humidity and bio sensors [15–17].

To date, several research groups have reported on attempts to fabricate a reflector or filter consisting of 1D PCs by using various deposition methods, including rf sputtering, pulsed laser deposition (PLD), electron beam evaporation, plasma enhanced chemical vapor deposition (CVD) and sol-gel [18–22]. The deposition techniques mentioned above can be utilized to fabricate a reflector or filter consisting of 1D PCs using TiO_2/SiO_2 and Al_2O_3/TiO_2 for the visible region [23,24], GaAs/AlAs and $Ge_{25}S_{75}/Sb_{40}Se_{60}$ for the near infrared (NIR) region [25,26] and ZnS/Ge and $Ge_{25}S_{75}/Ge_{15}Te_{85}$ for the infrared (IR) region [27,28].

In prior works, we proposed an informative design rule to acquire an omni-PBG within a 1D PC based on the transfer matrix method (TMM) [29]. We also demonstrated a multiple wavelength transmission filter fabricated using a heterostructural Si/SiO_2 1D PC [30], and an omni-reflector fabricated with multiple-periodic Si/SiO_2 1D PCs [31]. We also reported the photoinduced effect of $TeO_{2.33}/SiO_2$ 1D PCs while considering the photodarkening effect in tellurite glasses [18].

TeO_x glasses present outstanding optical characteristics such as large transmittance from the visible to the near infrared, low phonon energies, large acceptance of rare-earth ions doping, high linear refractive indices and high third order nonlinear susceptibilities [32]. These characteristics allow its application to optical devices. Moreover, TeO_x possesses different optical properties, such as a refractive index and transmittance according to its stoichiometry [33]. In particular, tellurium suboxide (TeO_x, $x \le 2$) shows a high refractive index (approximately 2–3) [34,35] and high transmittance [33] in the NIR

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https://doi.org/10.1016/j.optmat.2018.05.086
Received 18 April 2018; Received in revised form 30 May 2018; Accepted 31 May 2018
0925-3467/

Table 1
Deposition parameters of $TeO_{1.4}$ and SiO_2 thin films.

Parameters	Thin films	
	$TeO_{1.4}$	SiO_2
Target	Composite TeO_2 (2 in. diameter)	Composite SiO_2 (2 in. diameter)
Ar flow rate [sccm]	50	50
RF Power [W]	50	150
Base pressure [Torr]	3×10^{-6}	3×10^{-6}
Working pressure [Torr]	3×10^{-3}	3×10^{-3}
Target-Substrate distance [cm]	10	10
Deposition rate [nm/min]	11.8	5.6
Substrate Temperature [K]	Room Temperature	Room Temperature

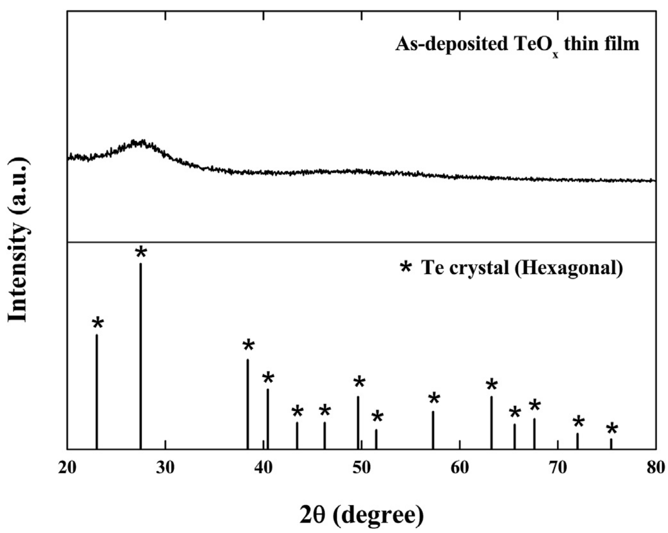

Fig. 1. XRD pattern of the as-deposited TeO_x thin film prepared via sputtering.

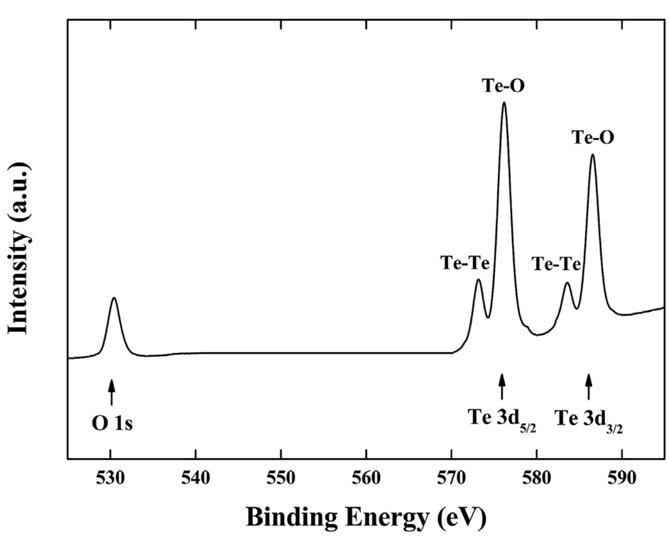

Fig. 2. XPS spectra of O 1s and Te 3 d for the as-deposited TeO_x thin film.

region. However, there is little research on the optical properties of 1D PCs, including the tellurium suboxide. Therefore, in this work, tellurium suboxide, which has a specific refractive index, was utilized as a high-index material to realize the photonic band structure within the NIR region. The effects of the structural parameters on the optical properties of the 1D PCs were theoretically and experimentally studied according to the absence or existence of a defect layer, incident angle,

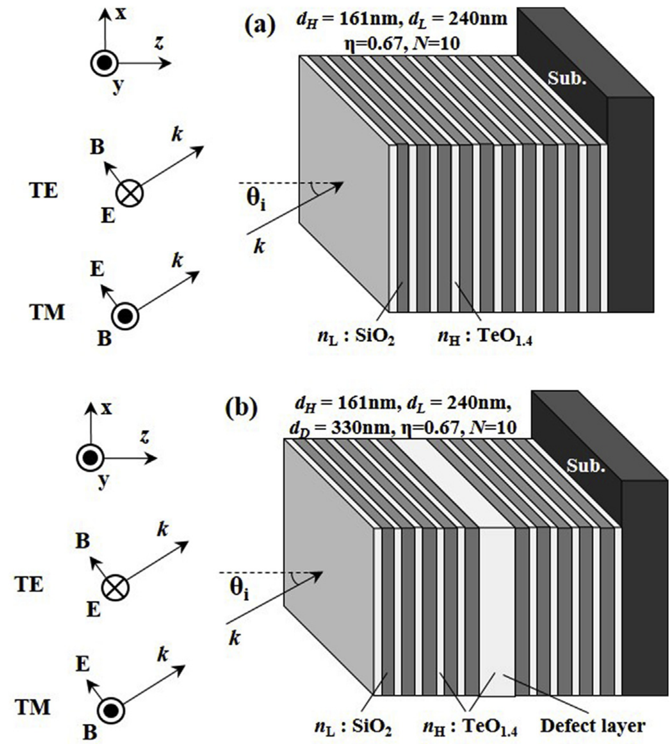

Fig. 3. Schematic diagrams of (a) the reflector and (b) filter consisting of the $TeO_{1.4}/SiO_2$ 1D PCs.

state of polarization and thickness of the defect layer.

2. Experimental details

The processing conditions for single-layer $TeO_{1.4}$ and SiO_2 thin films were optimized to achieve suitable refractive index contrast and thickness. The single-layer $TeO_{1.4}$ and SiO_2 thin films were deposited using a radio frequency (RF) magnetron sputtering system. To acquire the appropriate samples for various characterizations to be carried out, two types of substrates were inserted into the processing chamber. Fused quartz and p-type Si (100) were utilized as substrates after being successively cleaned with acetone, trichloroethylene, isopropyl alcohol and deionized water to remove the organic and metallic contaminants. The SiO_2 thin films were deposited via RF magnetron sputtering using a 99.99% ceramic SiO_2 target. The processing chamber was first evacuated to a base pressure of 3×10^{-6} Torr, and then the working pressure of the processing chamber was increased to 3×10^{-3} Torr by introducing Ar gas at a flow rate of 50 sccm. The RF power was 150 W during the sputtering process. As mentioned in the introduction, TeO_x thin films with various atomic ratios of O to Te have been confirmed to be obtained by changing the O_2 concentration in the sputtering gas (Ar and O_2) mixture. So far, some research groups have investigated the optical characteristics of the amorphous TeO_x thin films depending on their chemical compositions [33,36]. In particular, the refractive indices of the TeO_x thin films changed as a function of x. Therefore, the TeO_x thin films with specific refractive indices can be obtained by controlling the operating conditions, such as the sputtering gas and power. To acquire the optimum TeO_x thin films in the range of x form 1 to 2, tellurium suboxide thin films were prepared via RF magnetron sputtering with a 99.99% ceramic TeO_2 target at an rf power of 50 W. Since a composite TeO_2 target was used in this work, the working pressure of the processing chamber was maintained at 3×10^{-3} Torr by introducing Ar gas only without O_2 gas at a flow rate of 50 sccm. Pre-sputtering was carried out for approximately 15 min prior to depositing the thin films onto the substrates, in order to eliminate any impurities