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Low-resistant and high transmittance films based on one dimensional metal-dielectric photonic band gap material

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ABSTRACT

The paper shows the determination of the transmission of one dimensional metal-dielectric photonic band gap materials (1D-MD PBG) theoretically and experimentally. It has been found that the location and bandwidth of transmission can be tailored by initiatively adopting a suitable structure. We proposed a special 1D-MD PBG obtained by magnetron sputtering, in which each layer of metal film is not continuous. These structures have a number of advantages such as high transmittance (55% or better), broad bandwidth (the full width at half of maximum ranges from 400 nm to 780 nm) and high electrical conductivity (the sheet resistance can be lower than 0.98 Ω/square). Meanwhile, it has been also theoretically and experimental indicated that both the light transmittance and electrical conductivity could be improved effectively by using the $(pqp)^N$ structure.

1. Introduction

Transparent conductive films (TCF) have drawn a great attention due to their extensive applications in solar cells, eye protection devices, heat reflecting windows, light emitting diodes and liquid crystal displays [1–4]. Indium tin oxide (ITO) and doped ZnO thin films have been commonly studied extensively because of their good optical transparency as well as electrical conductivity (EC) [5–7]. However, in some cases, EC is not quite high for improved practical application [8]. Meanwhile, the metal composite or multilayer films such as AZO/Ag/AZO [9], ZnO/Ag/ZnO [10], AZO/Au/AZO [11], ZnO/Cu/ZnO [12] have been extensively studied. They exhibit lower resistance than single-layered transparent conducting oxides films. Experimental comparison of the 8 metals-Yb, Mg, In, Zn, Al, Ag, Cu and Au inserted as ultrathin layers in MoO_x envelope on glass – have shown that the maximum transmittance of 64% can be achieved based on the structure of MoO_x/Zn/MoO_x, while the lowest sheet resistance of 7 Ω/square has been demonstrated from MoO_x/Ag/MoO_x [1]. Furthermore, its optical transmittance (OT) has been fully determined by the intrinsic optical properties of an ultrathin embedded metal layer. Composite films with noble metal interlayer have better transparency in the visible range, but their transmittance rapidly decreases in the near infrared region [13,14]. As reactive metals, such as Mg, Al and Yb, they allow a more uniform OT due to the decreased losses in the visible region, but those structures employing reactive metals have slightly faded in color when they have been stored

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under laboratory conditions within a few days owing to the conversion of metals into corresponding oxides [1]. As mentioned above, both visual color and EC should be further improved for optical application [1–4].

One-dimension metal-dielectric photonic band gap (1D-MD PBG) materials consisting of periodic metal-dielectric multilayer are able to be designed to be transparent over a tunable range of optical frequencies [15–17], which is better than that of metal composite films. However, the maximum OT of the 1D-MD PBG usually has been lower to 50% and even to 20% [16]. At the same time, there have been some researches concerned about EC of 1D-MD PBG [18]. In common sense, the metal layer contained in 1D-MD PBG should have a continuous structure in order to obtain good conductivity. However, the opposite views were obtained in the paper.

The aim of this paper is to determine a desirable 1D-MD PBG structure which exhibit high EC as well as high transparency at blue and green region. Here, a special 1D-MD PBG with structure of $(pqp)^N$ is proposed, in which the discontinuous metal layer is arranged. Where N is the numbers of periodicity, p and q represents the uniform thickness of ITO and Ag layers, respectively. The results suggest that this structure has a strong contribution to high OT and EC.

2. Experiment

1D-MD PBG consisting of alternating ITO and Ag layers are shown in Fig. 1. It is periodic in z direction and uniform in x and y directions. The main difference between $(pq)^N$ and $(pqp)^N$ structure is that the innermost and outermost dielectrics thickness is half of other dielectrics thickness in the structure of $(pqp)^N$.

Transparent $(ITO/Ag)^3/ITO$ and $(ITO/Ag/ITO)^3$ multilayer films were prepared on glass substrates at room temperature using magnetic sputtering (ULVAC SIV-500RD). The ITO target (10 wt% SnO_2-doped In_2O_3) and Ag target (99.99%) were used as sputter targets. ITO films were deposited at power of 1500 W by DC magnetron sputtering and Ag layers were sputtered at 350 W by RF magnetron sputtering respectively. The target-to-substrate distance was 140 mm. During ITO films depositing, the argon (99.995% purity) and oxygen (99.995% purity) flow rate was maintained at 50 sccm and 1 sccm, respectively. In order to avoid oxidation, Ag films were deposited under single argon atmosphere (99.995% purity) with flow rate of 50 sccm. The base pressure was about 1×10^{-3} Pa and working pressure during deposition was 0.67 Pa. ITO and Ag growth rates was 2.5 and 2.0 nm/s, respectively. The films growth rates were obtained by means of dividing the films thickness by the corresponding deposition time, where thicknesses were measured by using ellipsometer (SENTECH SE8000dv-PV) and the growth times were controlled via the movement speed of the substrate transporter. Therefore, the each layer thickness can be controlled by the sputtering time which was determined by the passing time of the substrate to the target. Then the total thickness can be obtained through adding each layer thickness of the $(pqp)^N$ and $(pq)^N$ structures. After fabrication, the morphologies of Ag films were analyzed by scanning electron microscopy (SEM, JEOL Ltd., JSM6700F, Japan). Transmission spectra in UV–visible range of 300 nm–800 nm with a resolution of 1 nm performed on a spectrophotometer (Shimadzu UV-310). Electrical properties of the structures were examined using the four-point probe technique. Simultaneously, optical performance was theoretically investigated by mean of finite difference time domain (FDTD) mode [17,19]. The wavelength dependent dielectric constant of the silver layers was determined using the Lorentz-Drude model, according to Eq. (1) [20].

$$\varepsilon_m = \varepsilon' + \varepsilon'' = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + \Gamma^2} + i\frac{\omega_p^2 \Gamma}{\omega\left(\omega^2 + \Gamma^2\right)} \tag{1}$$

Where ε' and ε'' represent the real and the imaginary part of permittivity of Ag films, respectively. The plasmon frequency of $\omega_p = 14.0 \times 10^{15}$ rad/s and the damping constant of $\Gamma = 0.032 \times 10^{15}$/s were adopted from literature [20]. Besides, ε_∞ is a sum or integral value after taking all pertinent transitions into account. The empirical values ε_∞ for silver are about 5 [20]. Additionally, the ITO refractive index was taken as 1.7702, which was determined by using ellipsometer (SENTECH SE8000dv-PV). The parameters of different samples are shown in Table 1.

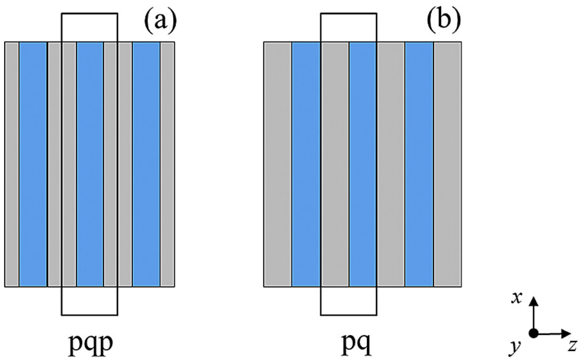

Fig. 1. 1D-MD PBG with structure of (a) $(pqp)^N$ and (b) $(pq)^N$.