INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS

J. Opt. A: Pure Appl. Opt. **7** (2005) 51–55 doi:10.1088/1464-4258/7/1/008

Silver–silica transparent metal structures as bandpass filters for the ultraviolet range

Zoran Jakšić, Milan Maksimović and Milija Sarajlić

IHTM—Institute of Microelectronic Technologies and Single Crystals, Njegoseva 12,
11000 Belgrade, Belgrade, Serbia and Montenegro

E-mail: jaksa@nanosys.ihtm.bg.ac.yu

Received 8 November 2004, accepted for publication 26 November 2004
Published 3 December 2004
Online at stacks.iop.org/JOptA/7/51

Abstract
We designed and produced silver–silicon dioxide multilayer thin-film bandpass filters for the ultraviolet range by applying the concept of ‘transparent metals’. To calculate the transmission of the designed metallodielectric filters we used the transfer matrix method for lossy structures. We fabricated our multilayer metallodielectric films using radiofrequent sputtering and characterized them by spectral transmission measurements. We achieved satisfactory suppression of undesired visible and infrared parts of the spectrum even for a small number of layer pairs.

Keywords: metallodielectric, thin films, transparent metals, bandpass filters, ultraviolet radiation

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The detection of optical radiation in the ultraviolet range is of a high practical interest, since it is directly connected with the protection of human lives (exposure to solar UV radiation through the thinning ozone layer, flame detection with the aim of preventing fires and explosions, etc). One of the most important barriers to a more widespread use of UV detectors is their high price, regardless of whether wide-bandgap semiconductor detectors are used or photoemissive devices (e.g. microchannel plates) [1–3]. An alternative approach using photographic emulsions and UV-sensitive chemicals proved to be relatively non-selective and impractical [1].

A conventional solution for significantly less expensive detectors is the use of silicon, since it is a widespread material with a mature and relatively low-cost technology. Devices with thin active area are typically utilized [2]. One of the problems with its use is the avoidance of the visible and infrared components of radiation, which in standard conditions often exceed the UV components by three to four orders of magnitude, thus completely masking the useful signal [4]. A straightforward way to avoid the problem is to use bandpass filters for the UV with strong rejection of unwanted visible and infrared radiation in the range of the detector sensitivity.

Among the structures applicable for bandpass filtering in the UV are all-dielectric filters (i.e. one or more Bragg-type all-dielectric multilayer reflecting stacks). These have a high transmission in the pass band, but have a limited range of out-of-band blocking. Compound structures with two or more overlapping stop bands may be necessary to cover the whole desired range [4, 5]. An additional blocking component, e.g. monolithic deposited silver [4, 5], may be used to remove unwanted out-of-band radiation; however, this also reduces the overall transmission through the filter.

Another solution is metal–dielectric band-pass filters, which are among the earliest and simplest optical bandpass filters. They have been described in many papers dating as far back as the 1960s (see [6] p 257 and references cited therein). The basic geometry of such a metal–dielectric filter is a thin film Fabry–Perot interferometer consisting of two semitransparent metal films spaced half the desired wavelength apart by a dielectric spacer layer. Multiple cavity metal–dielectric filters are also used for this purpose, for instance structures of the type Bragg multilayer–dielectric–metal–dielectric–Bragg multilayer [7]. Metal–dielectric bandpass filters with symmetrical periods have been described by McLeod [8].

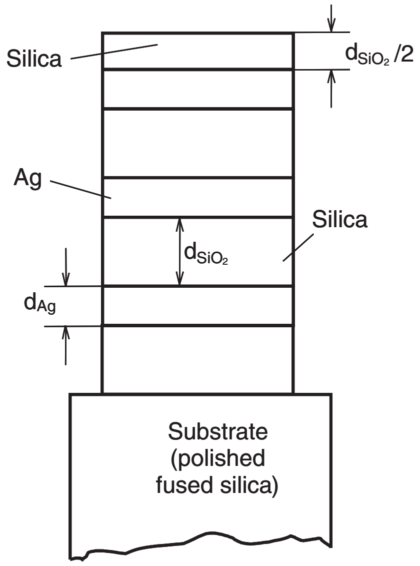

Figure 1. Schematic representation of a transparent metal structure for the pass-band optical filter.

Metal–dielectric multilayers structured like metallodielectric photonic crystals [9], but optimized for maximum bandpass transmission are sometimes described as 'transparent metals' (e.g. [10–12]). Owing to resonant tunnelling through the metal layers these structures combine certain properties of bulk metal with a high transparency in the desired wavelength range. One of their important characteristics as compared to Fabry–Perot-based structures is that no higher-order transmission maxima exist and the only peak in spectral characteristics from the ultraviolet to microwave is that at the desired frequency. Until now the transparent metal structures were designed for various frequencies ranging from the microwave to the visible [12]. One of the proposed applications was windows for microwave ovens, which are transparent in the visible, while at the same time being opaque for microwave [11]. Another important field of application are bandpass filters for visible or near-infrared which suppress all other wavelength ranges from UV to microwave.

In this paper we consider theoretically and experimentally the application of the concept of transparent metals to optimize metallodielectric bandpass filters for the ultraviolet range. We chose silver and silica as the materials for our structures. Our multilayer metallodielectric interference films were designed using the transfer matrix approach, and the experimental structures were fabricated using radiofrequent sputtering and characterized by spectral transmission measurements.

2. Design

A generic transparent metal structure (1D metal–dielectric multilayer optimized to furnish minimum absorption in a given range) is shown in figure 1. The substrate is UV-transparent (in our case fused silica), the dielectric is silica, and the metal part is silver. Besides the desired number of Ag/SiO$_2$ pairs, an additional layer of silica with a half-thickness compared to that in the structure is added, intended to serve as an antireflection (AR) coating. If a structure consists of n layers plus the additional AR layer, we denote it as an $n+1/2$ structure. Since we intended our structure to be used for weak intensities of UV radiation, we did not consider the effects of solarization [2] on our materials.

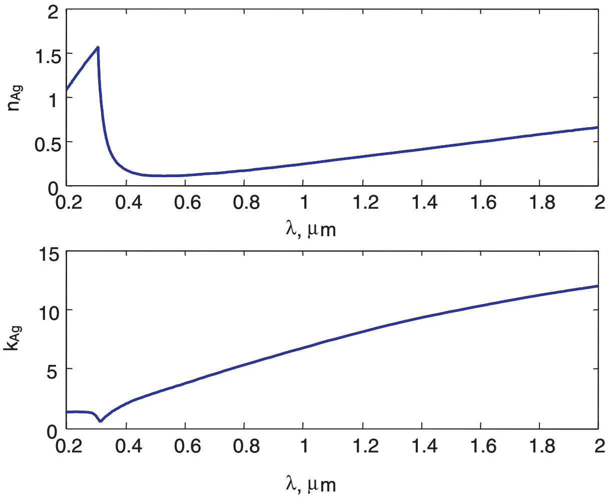

Figure 2. Fitted refractive index and extinction coefficient of silver.

We calculated the theoretical spectral transmission of the transparent metal filter by the transfer matrix method, taking into account the absorptive losses.

We fitted experimental data for the optical constants of silver from [13]. We obtained for the Ag extinction coefficient the following expressions valid in the range 200 nm to 1 μm:

$$k_{Ag} = \begin{cases} \sqrt{\dfrac{a_1 + c_1\lambda^2 + e_1\lambda^4}{1 + b_1\lambda^2 + d_1\lambda^4 + f_1\lambda^6}}, & \lambda < 318 \text{ nm} \\ a_2 + \dfrac{b_2}{\lambda} + \dfrac{c_2}{\lambda^{3/2}} + \dfrac{d_2}{\lambda^2}, & \lambda > 318 \text{ nm} \end{cases}$$

where $a_1 = 1.171\,6163$, $b_1 = -26.831\,136$, $c_1 = -23.250\,175$, $d_1 = 244.033\,36$, $e_1 = 115.583\,75$ and $f_1 = -747.728\,11$. For wavelengths above silver plasma frequency, $a_2 = 23.880\,509$, $b_2 = -46.806\,634$, $c_2 = 39.418\,581$ and $d_2 = -9.708\,619$.

The real part of the Ag refractive index is

$$n_{Ag} = \begin{cases} a_3 + b_3\lambda^{3/2} + c_3\lambda^2 + \dfrac{d_3}{\lambda}, & \lambda < 305 \text{ nm} \\ \exp\left(a_4 + \dfrac{b_4}{\lambda^{3/2}} + \dfrac{c_4}{\lambda^2}\right), & \lambda > 305 \text{ nm} \end{cases}$$

where $a_3 = 8.454\,4209$, $b_3 = -90.780\,355$, $c_3 = 118.662\,56$, $d_3 = -0.800\,760\,22$, and $a_4 = 0.483\,324\,93$, $b_4 = -4.264\,8334$ and $c_4 = 2.341\,7131$.

The calculated n, k of silver are shown in figure 2.

For silica we assumed a value of the real part of the refractive index of 1.5, while the absorption was neglected in the range of interest.

We designed our bandpass filters for the maximum transmission in the UV A range. Such a design actually means to tailor the geometry and composition of the transparent metal to shift its passband to the wavelengths near the silver plasma resonance at 320 nm. Care should be taken to ensure a silver thickness which is at the same time sufficiently small to help avoid excessive losses and sufficiently large to remove the undesired visible and infrared components.

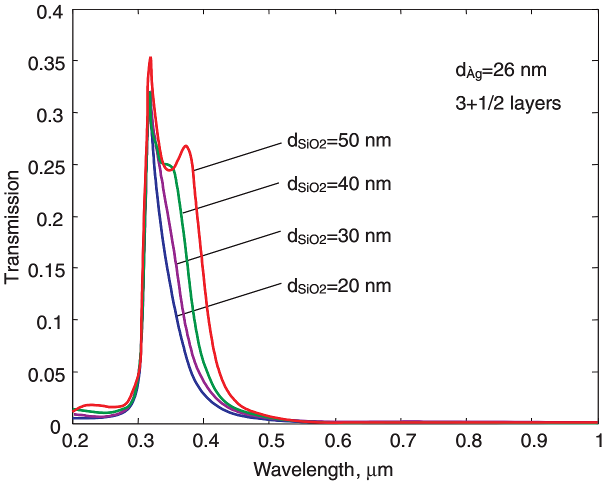

Figure 3. Spectral transmission of a silver–silica metal–dielectric multilayer for varying the thickness of silica.

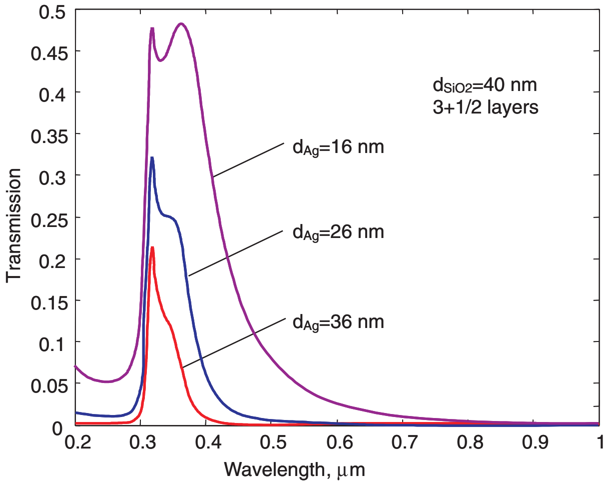

Figure 5. Spectral transmission of the silver–silica metal–dielectric multilayer for different values of silver thickness.

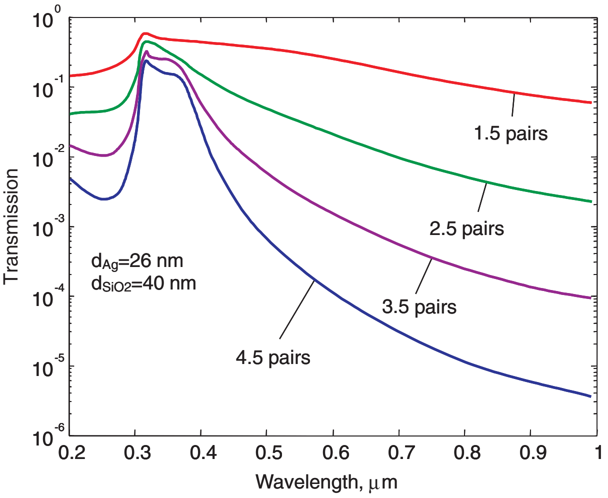

Figure 4. Spectral transmission of the silver–silica metal–dielectric multilayer for different numbers of layer pairs.

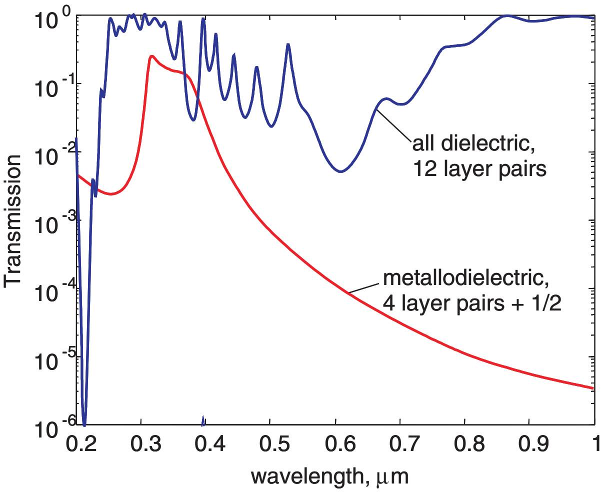

Figure 6. Comparison of transmissions of Ag/SiO_2 transparent metal and NaF/Y_2O_3 all-dielectric for a UV bandpass filter.

We performed our simulations for different values of layer thickness and different layer numbers. Figure 3 shows the designed spectral characteristics of the bandpass UV filter for different values of silica layer thickness. Figure 4 analyses the influence of the number of layer pairs, and figure 5 the influence of the changes of silver layer thickness to the spectral transmission. An increase of dielectric layer thickness causes a red shift of the characteristics, and the decrease a blue one. An increase of the thickness of silver layers only results in an overall transmission decrease. The increase of the number of layer pairs narrows the pass band and decreases the long-wavelength transmission.

In our calculations we also compared our transparent metal filter with a solution from the literature. We compared our unoptimized 4 + 1/2 layer structure with optimized 12 + 1 dielectric and 12 + 1 Ag-enhanced dielectric filters, both described in [5]. The optimized all-dielectric filters were made of three sets of four layer pairs, one of them 91 nm NaF and 49 nm Y_2O_3, the second one 86.4 nm NaF and 73.6 nm Y_2O_3, and the third one 138 nm NaF and 92 nm Y_2O_3. The refractive indexes in the range of interest are 1.326 for NaF and 1.936 for Y_2O_3. The top silver coating was 30 nm thick.

Our simulation results (figure 6) show that the metallodielectric furnishes significantly better results than the all-dielectric solution (although the metallodielectric could be further improved by making a larger number of thinner layers) even though its number of layers is much smaller.

3. Experiment

We produced our experimental structures of transparent metal by radiofrequent sputtering of silver layers (26 nm thickness) and silicon dioxide (40 nm thickness) on a polished quartz substrate on our Perkin Elmer equipment. We kept the Ar pressure at 2×10^{-5} bar and used the operating mode without substrate rotation. Silicon dioxide was deposited for 4 min at a cathode voltage of 1200 V and at 1 kW rf power. Silver was deposited for 25 s at a cathode voltage of 1100 V and at 0.5 kW rf power. Care was taken to keep the substrate cold during deposition. We sputtered two layer pairs, and the final

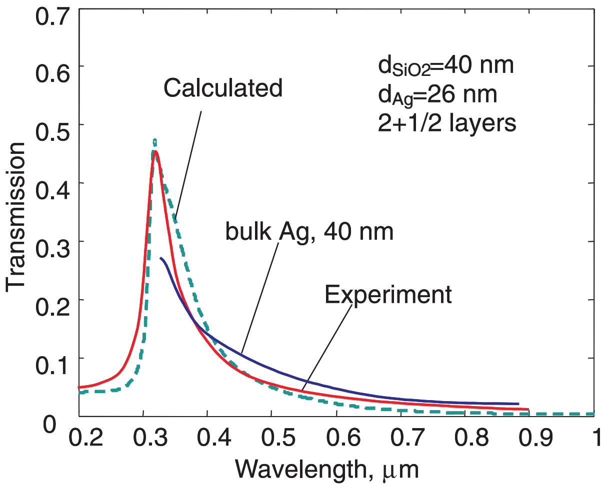

Figure 7. Measured spectral transmission of a transparent metal-based silver–silica filter.

layer was silicon dioxide with a thickness equal to half of that used in the pairs.

We characterized our samples on a UV–vis spectrophotometer Anthelie 5 Secomam. The measured transmission spectra are shown in figure 7. The theoretically predicted curve is shown for comparison. It can be seen that the agreement is relatively good, bearing in mind the accuracy of the layer thickness definition in the sputtering equipment.

Also for comparison, figure 7 shows the transmission of bulk silver with a thickness of 40 nm. It can be seen that the transmission of bulk silver in the desired UV range is significantly smaller than that of the transparent metal filter, although the total thickness of silver in the filter is more than 25% larger than that of the bulk metal, and that the filter offers in comparison to solid Ag a significant improvement of performance in all spectral ranges of interest.

Figure 8 shows the influence of the varying incident angle to the spectral characteristics. Solid curves denote the experiment, while dotted curves are calculated by the transfer matrix method. It can be seen that the peaks coincide well and that the qualitative behaviour is identical, although the width of the calculated dependences is somewhat larger. It is seen that no spectral shift of the characteristics occurs, and the only influence of the increasing incident angle is that the peak narrows with increasing angle.

4. Conclusion

We designed, fabricated and characterized metal–dielectric bandpass filters based on transparent metals intended for use with silicon UV photodetectors. The use of transparent metals can ensure a transmission decrease of several orders of magnitude in the critical range of visible and infrared wavelengths, while at the same time fully preserving transparency in the ultraviolet spectrum.

A decrease of dielectric thickness shifts the spectral characteristics toward the shorter wavelengths, while metal thickness increase decreases the overall transmission. The designed metal–dielectric structures ensure relatively wide transmissive range which is tunable by adjusting the dielectric layer thickness. No higher order transmission maxima occur in the whole spectral range and the peak position is relatively insensitive to varying incident angle.

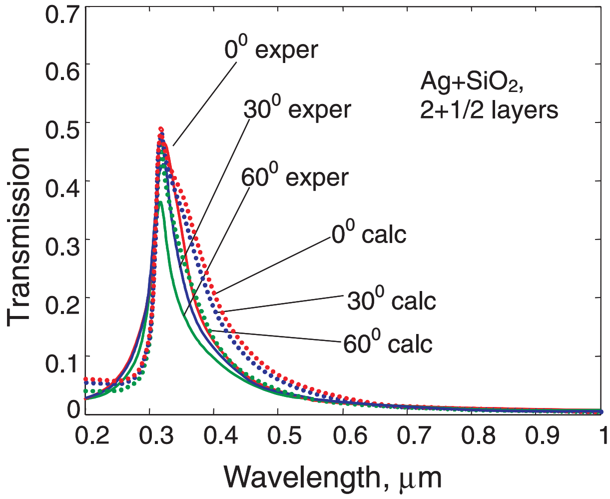

Figure 8. Measured and calculated spectral transmission of a metallodielectric silver–silica filter for different incident angles.

A further optimization of filters should include the determination of the best ratio of silver thickness to the total number of layer pairs. We also intend to consider the design of specialized metal–dielectric filters optimized for the desired parts of the UV spectrum.

The designed and fabricated filters are fully applicable for the enhancement of UV silicon detectors. The filter properties may be additionally enhanced by combining the structure with purely dielectric optical filters.

Acknowledgment

This work was partially supported by the Serbian Ministry of Science and Environmental Protection within the framework of the project IT.1.04.0062.B.

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