UV BANDPASS OPTICAL FILTER FOR MICROSPECTROMETERS

J. H. Correia*, A. R. Emadi and R. F. Wolffenbuttel

Delft University of Technology, Faculty EEMCS,
Dept. ME, Mekelweg 4, 2628 CD Delft, The Netherlands
*University of Minho, Dept. Industrial Electronics,
Campus Azurem, 4800-058 Guimaraes, Portugal
higino.correia@dei.uminho.pt

ABSTRACT

This paper describes the design and modeling of a UV bandpass optical filter for microspectrometers. The materials used for fabricating the multilayer UV filter are: silicon dioxide (SiO_2), titanium dioxide (TiO_2) and yttrium oxide (Y_2O_3). The optical filter shows a bandpass response wavelength in the range 230-280 nm, with a transmittance higher than 80%. Such a device is extremely suitable for optical detection of biological molecules with optical absorption or/and fluorescence in the UV spectral range. This UV optical filter can be built using post-processing after integrated-circuit and UV photodiode fabrication in a bipolar or CMOS technology. The dielectric multi-layer stack can be deposited on top of the UV photodiode after the standard technology process has been completed. The number of layers was optimized for 11 with all layers of a thickness acceptable for reproducible fabrication. The materials used for fabricating the UV filter are silicon compatible. Applications presented are in DNA solutions (to measure the optical density of these solutions at 260 nm) and in the detection of a gas flame in the presence of ambient light based on the different emission spectra in the UV.

INTRODUCTION

Low-cost single-chip spectrometers have huge potential in systems for biomolecule identification and chemical analysis by optical absorption, fluorescence and emission line characterization. Such microspectrometers will offer significant advantages over existing instruments, including size reduction, low cost, fast data-acquisition and high reliability. Previously developed microspectrometers [1-4], fabricated using bulk or surface micromachining, contain movable parts to perform wavelength tuning or filtering functions. As a result, these are less reliable and suitable only for operation in a limited spectral band (mostly near-IR and visible). Moreover, high-voltage electrostatic actuation is necessary for resonance cavity tuning.

Most biological molecules are fluorescent. The excitation wavelengths are usually in UV (Ultra-Violet) part of the light spectrum. Operation in the UV spectral range (e.g. 230-280 nm) requires cavity length width not to exceed 140 nm. Fabrication and electronic modulation of such a narrow airgap between the two mirrors is severely hindered by capillary forces inside of the cavity. Also, electrostatic pull-in and subsequent sticking of the two mirrors limits the operating range of the device to one third of the initial air gap [3-4]. These problems explain the interest in implementing solid-state UV optical filters in post-processing steps after to complete the fabrication of the UV photodetector and electronics in a standard technology.

Yttrium oxide (Y_2O_3), has recently attracted a lot of attention because of its several particularly interesting physical properties, such as its crystallographic stability up to 2325 ºC (melting point of Y_2O_3 is 2450 ºC) [5], high mechanical strength, high thermal conductivity (0.13 $Wcm^{-1} K^{-1}$), a relatively high dielectric constant in the range 14–18 [8], a rather high refractive index and a very-low extinction coefficient. The latter two properties make the material well suited for optical applications and several deposition techniques have been investigated in deposition of Y_2O_3 thin films by: epitaxial growth, RF magnetron sputtering, electron beam evaporation, laser ablation reactive ionized cluster beam deposition and molecular beam epitaxy [5-6]. The other two materials used in this work are well known (deposition and optical properties): SiO_2 and TiO_2. The silicon compatibility of the materials used in the fabrication of the UV bandpass optical filter is also an important issue.

UV OPTICAL FILTER DESIGN

Dielectric thin-films were used to build an UV multilayer stack optical filter. An alternative option could be metallic-based coatings, but they have much higher losses than dielectric-based coatings, these can be attractive in certain applications due to the simplicity of their fabrication (only one layer must be deposited). Dielectric thin-films, when properly designed and fabricated, feature high performance (high transmission, low absorption losses). The performance of a filter is greatly influenced by random thickness variations in the deposition of the films. To be effective in a wide optical band (in this work a spectral range in between 230 and 280 nm is considered), a dielectric optical filter must consist of a large number of deposited layers. The multilayer structure is arranged in succession and characterized by the sequence HLHL...HLH. The characteristic matrix of this multilayer is now 2N+1 layers, where N is the number of times HL is used. With H and L representing the layer with higher refractive index and the layer with lower refractive index respectively. Accurate data on the optical properties of coating materials is important for designing and manufacturing coatings. Since optical properties may depend on the details of process used to deposit the coating, it is best to measure the refractive index and the extinction coefficient of layers produced by the process. Since this design is primarily intended as a proof-of-concept, the accuracy of refractive index data is less important and we can resort to material data from published sources. Obviously, we intend to use the resulting structures for optical characterization of the layers produced in our process. The simulations for Y_2O_3 coatings were done with material data provided by the database of Sopra company [7]. The optical data for SiO_2 and TiO_2 coatings (see Table I) were obtained from previous depositions and are consistent with the Sopra database [8-9]. The materials used in this work SiO_2, TiO_2 and Y_2O_3 have very low extinction coefficient (k) in the UV range. The k, for SiO_2 and Y_2O_3, is lower than $1x10^{-6}$ and it was considered zero in the simulations. The k for TiO_2 in the same range is higher and is presented in Table II. Optimization of the designs was performed using the software TFCalc 3.3, a CAD tools for optical simulations of thin-film coatings.

Table I: The refractive index (SiO_2, TiO_2 and Y_2O_3) used in the simulations in UV range Material data provided by the database of Sopra company [7].

λ (nm)	200	220	250	300	320	350	400
n(SiO_2)	1.490	1.484	1.480	1.478	1.476	1,471	1,467
n(TiO_2)	2.68	2.62	2.64	2.60	2.58	2.56	2.52
n(Y_2O_3)	2.386	2.300	2.171	2.065	2.043	2.015	1.982

Table II: The extinction coefficient (k) of TiO_2 [7].

λ (nm)	200	220	250	300	320	350	400
k(TiO_2)	0.008	0.007	0.0065	0.005	0.004	0.0035	0.002

TiO_2/SiO_2 design

First, a UV bandpass optical filter was designed based on TiO_2 and SiO_2 materials only. This structure is composed by 13 layers (see Figure 1) and shows a transmittance higher than 80% in the range 230-280 nm. The drawback of this structure is that the thickness of several layers is less than 23 nm, which makes it difficult to fabricate the filter with high reproducibility. Also, the absorbance is another issue, since the extinction coefficient of TiO_2 should also be taken into account.

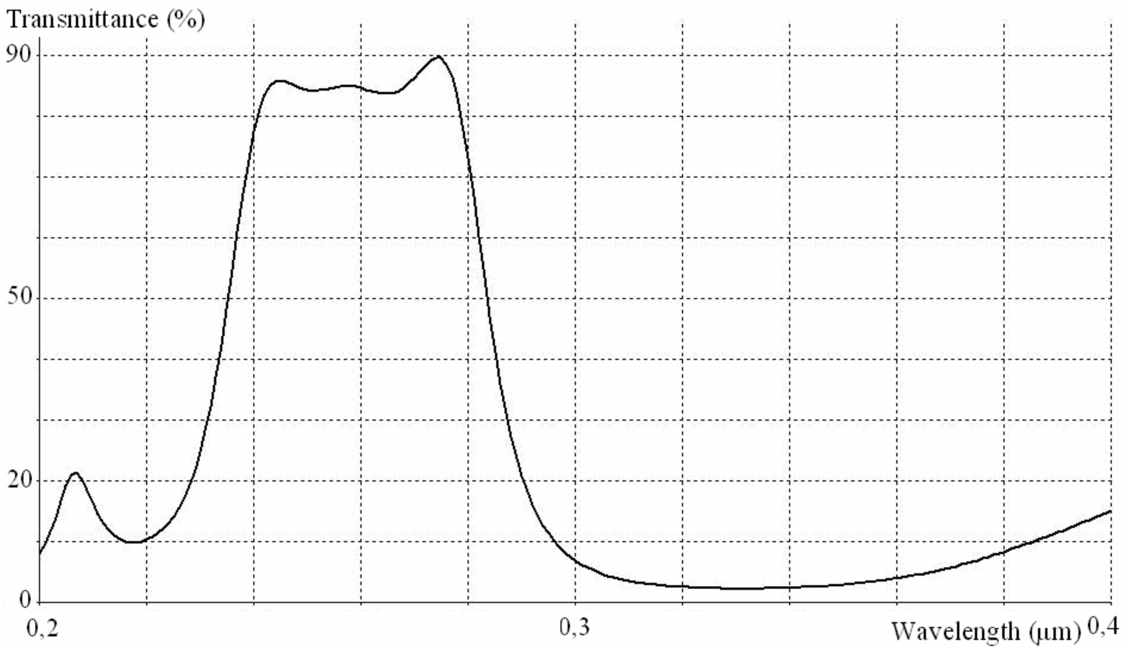

Figure 1: Simulation of the transmittance versus wavelength of a UV bandpass optical filter with 13 layers (composed of TiO_2 and SiO_2 only).

Y_2O_3/SiO_2 design

Secondly, a UV bandpass optical filter was designed based on Y_2O_3 and SiO_2 only. This structure is also composed by 13 layers (see Figure 2) and shows a transmittance higher than 90% in the range 250-260 nm. The drawback of this structure it is the poorly suppressed transmittance in the 300-370 nm range as is demonstrated by peaks higher than 50% at 320 nm and 365 nm. This is mainly due to the fact that $n_{Y2O3} < n_{TiO2}$ in the entire UV-visible spectral range and even more pronounced so in the 300-400 nm wavelength range (in comparison with Figure 1 where were used TiO_2 and SiO_2 materials). Considering the fabrication process, the thickness of the layers is acceptable.

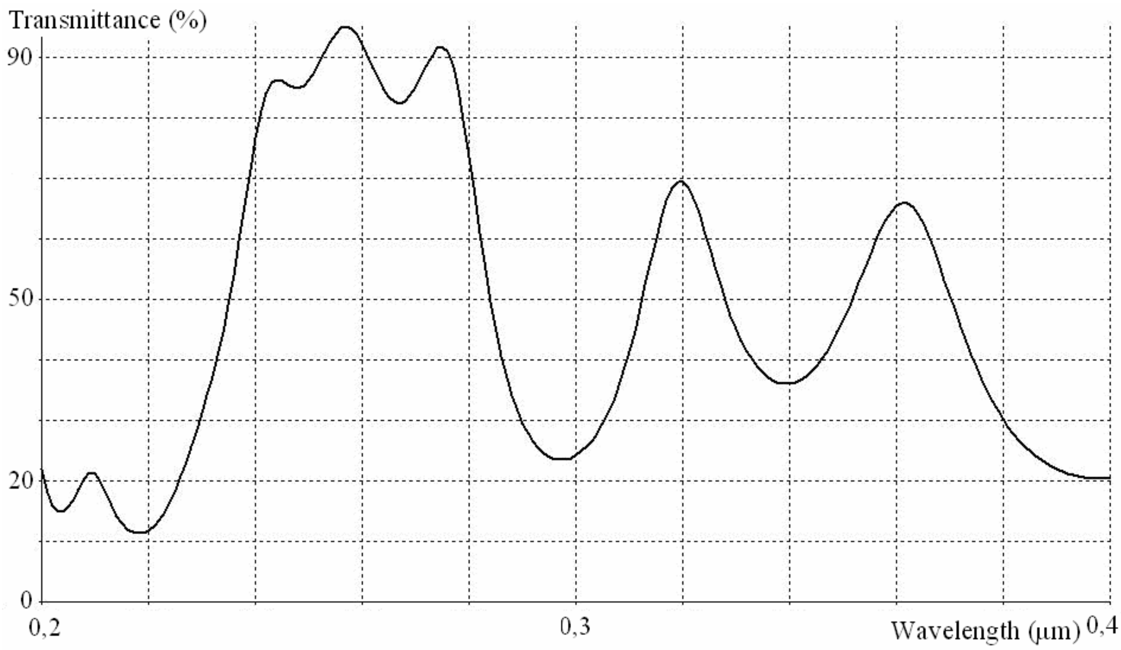

Figure 2: Simulation of the transmittance versus wavelength of a UV bandpass optical filter with 13 layers (composed of Y_2O_3 and SiO_2 only).

$Y_2O_3/TiO_2/SiO_2$ design

Based on the shortcomings of the TiO_2-SiO_2 only, as well as the Y_2O_3-SiO_2 only designs, an attempt has been made to combine the optical merits of these material combinations in a UV bandpass optical filter design based in Y_2O_3, TiO_2 and SiO_2 materials. This structure is composed by 11 layers (see Figure 3) and shows a transmittance higher than 80% in the range 230-280 nm. The number of layers was reduced and the optical response over the entire 200-400 nm range is better than the two previous solutions. The thickness of the layers is generally acceptable. Table III shows the thickness of the 11 layers. The thinnest layer is 21 nm thick (but only one), allowing a realistic and homogeneous deposition process in RF magnetron sputtering.

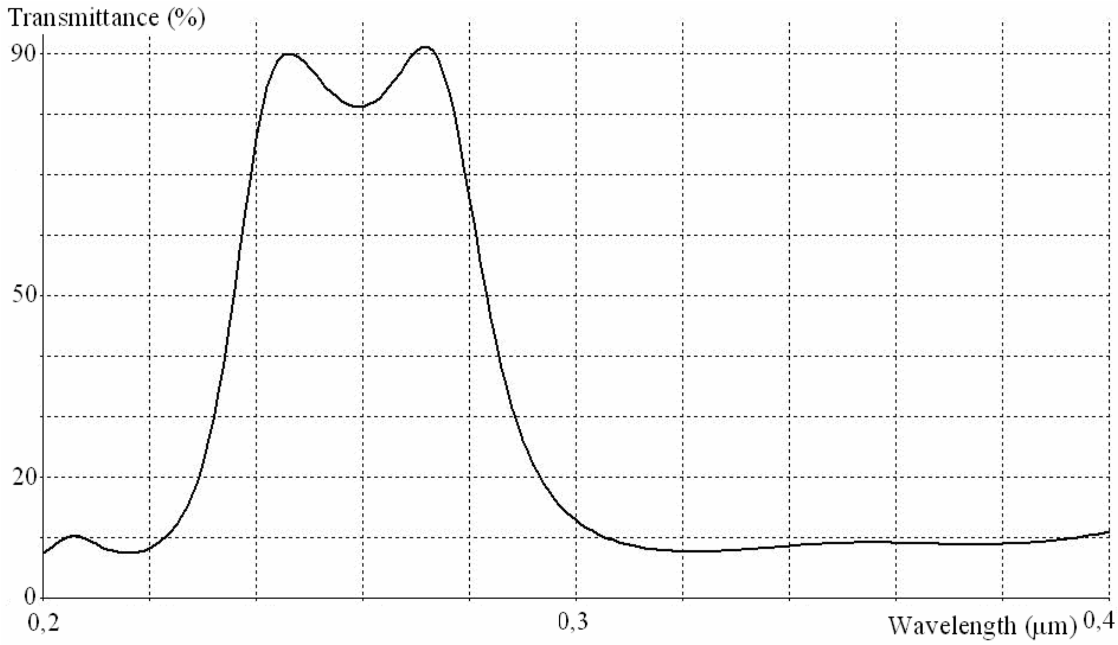

Figure 3: Simulation of the transmittance versus wavelength of a UV bandpass optical filter with 11 layers (composed of Y_2O_3, TiO_2 and SiO_2).

Table III: The optimized thickness of the 11 layers that must be deposited for fabricating the UV bandpass optical filter.

	Y_2O_3	SiO_2	Y_2O_3	SiO_2	TiO_2	SiO_2	TiO_2	SiO_2	TiO_2	SiO_2	TiO_2
Thick (nm)	67	34	21	33	23	90	25	47	39	58	37

UV MICROSPECTROMETERS APPLICATIONS

The impinging spectrum is filtered in the multilayer stack of SiO_2, TiO_2 and Y_2O_3. The intensity can be measured in transmission using an underlying integrated photodiode. On the top of the photodiode, the UV filter layer stack is deposited (see Figure 4 for an example on a CMOS photodiode). An oxide layer is present between the cavity and the photodiode to introduce a wavelength-dependent transmission of the incident radiation. Its thickness was designed for a flat transmittance over the UV spectra range [10].

In DNA tests, the waste solution of the hybridization step, containing unbounded DNA strands, is collected and then optical density of this solution is measured at 260 nm (optical density is measured to compare intensity profile before and after the separation) [11]. An UV microspectrometer will be an interesting solution for DNA analysis.

An UV optical filter can be applied to detect the spectrum emitted by a gas flame. The detector is to be used as a safety device to detect unintended extinction of the flame, which should result in the interruption of the fuel supply [10].

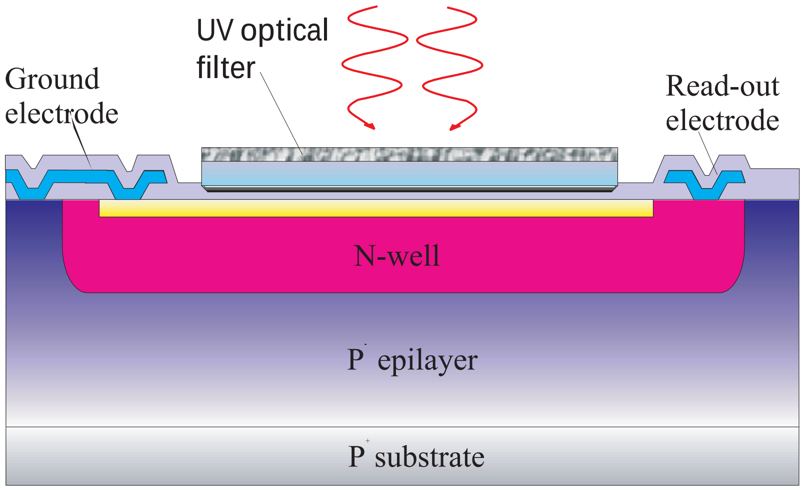

Figure 4: The UV bandpass optical filter with the CMOS photodiode underneath: a cross section view.

CONCLUSIONS

An UV bandpass optical filter (for 230-280 nm wavelength range, with a transmittance higher than 80%) for microspectrometers was designed and simulated. The UV bandpass filter is oriented for UV microspectrometers. The materials used for designing the multilayer UV filter were: SiO_2, TiO_2 and Y_2O_3. The use of Y_2O_3 material is promising, resulting in the reduction of the number of layers in the fabrication of such filter. The number of layers was optimized for 11 and the thickness of layers were optimized for allowing a reliable deposition process. A relative thickness uniformity of the layers (all are deposited in the same conditions and using the same sputtering equipment) can be achieved with a tolerance less than 5% [12]. Simulations show a shift of the UV bandpass optical in the range 230-280 nm according this thickness tolerance. Applications in DNA analysis (to measure the optical density of these solutions at 260 nm) and detection of the spectrum emitted by a gas flame (starting at 230 nm) were presented.

ACKNOWLEDGMENTS

This work was supported by Agencia Inovacao, POCI 2010, Program IDEIA, FEDER, Pellisaquae ADI/2005/M2.3/0022, and J. H. Correia was sponsored by FCT (SFRH/BSAB/483/2004).

REFERENCES

1. J. D. Patterson and B. van Zeghbroeck, *Fabrication and analysis of Si/SiO2 Micro-mechanical Modulators*, Digest IEEE/LEOS 1996. Summer topical meeting on optical MEMS and their applications, pp.25-26, (1996).
2. N.F. Raley, D.R. Ciarlo, J.C. Koo, B. Beiriger, J. Trujillo, C. Yu, G. Lomis, R. Chow, *A Fabry-Perot Microinterferometer for Visible Wavelength*, Proc. 5th IEEE Solid State Sensor and Actuator Workshop., pp. 170-173, Hilton Head Island, SC, USA, (1992).

3. J. H. Correia, M. Bartek, R. F. Wolffenbuttel, *Bulk-micromachined tunable Fabry-Perot microinterferometer for the visible spectral range*, Journal Sensors and Actuators A, Elsevier Science, **76**, pp. 191-196, (1999).
4. A. T. T. D. Tran, Y. H. Lo, Z. H. Zhu, D. Haronian, E. Mozdy, *Surface micromachined Fabry-Perot tunable filter*, IEEE Photonics Technology Letters, **8**, pp. 393-395, (1996).
5. R. N. Sharma, S. T. Lakshmikumar, A. C. Rastogi, *Electrical behaviour of electron-beam-evaporated yttrium oxide thin films on silicon*, Thin Solid Films, Elsevier Science, pp. 1-8, **199**, 1, (1991).
6. R. J. Gaboriaud, F. Pailloux, F. Panier, *Yttrium oxide thin films, Y2O3, grown by ion beam sputtering on Si*, J. Physiscs: Applied Physiscs, **33,** pp.2884-2889, IOP, UK, (2000).
7. *Optical properties of coating materials from Sopra S.A.*, website: http://www.sopra-sa.com, (2006).
8. D.P. Poenar, R.F. Wolffenbuttel, *Optical properties of thin-film silicon-compatible materials, Applied Optics*, Vol. 36, **21**, pp. 5122-5128, (1997).
9. G. Minas, R. F. Wolffenbuttel, J. H. Correia, *An array of highly selective Fabry-Perot optical channels for biological fluid analysis by optical absorption using a white light source for illumination*, J. Optics A:Pure Applied Optics, **8**, pp. 272-278, IOP, (2006).
10. R. F. Wolffenbuttel, *Silicon photodetectors with a selective spectral response*, Sensors Update, Vol. **9**, pp. 70-98, Wiley-VCH, (2001).
11. H. W. Lim, H. M. Jang, S.M. Ha, Y. G. Chai, S. I. Yoo, B. T. Zhang, *A Lab-on-a-Chip Module for Bead Separation in DNA-Based Concept*, DNA9, SCIE, vol. **2943**, pp. 1-10, (2004).
12. J.H. Correia, M. Bartek and R.F. Wolffenbuttel, *High-selectivity single-chip spectrometer for operation at visible part of the spectrum*, IEEE Transactions on Electron Devices, Vol. **47**, **3**, pp. 553-559, (2000).