COMPARING SILICON DEPOSITION TECHNIQUES FOR VISIBLE-BLIND DETECTOR FABRICATION

A. Emadi[1], P. Enoksson[2], J.H. Correia[3] and, R.F. Wolffenbuttel[1]

[1]*Faculty EEMCS, Delft University of Technology, Mekelweg 4, 2628 CD Delft, Netherlands*
[2]*Micro and Nanosystems, MC2, Chalmers University of Technology, SE412 96, Gothenborg, Sweden*
[3]*Dept. Of Industrial Electronics, University of Minho, Campus Azurem, 4800-058 Guimarães, Portugal*

Abstract — **In this paper the design and fabrication of a simple Si-SiO_2 interference filter is presented that can be used for the fabrication of photodetectors in silicon with a visible-blind spectral response. Sputtered silicon has unique optical properties that enable the CMOS-compatible fabrication of a highly effective interference filter on top a photodiode. The result is a silicon photon detector with an infra-red response only. Using a pair of identical photodiodes, one coated with the filter and the other not, while subtracting the photocurrents results in an optical detector with dark current compensation plus a highly reduced IR response.**

Keywords : **Optical sensors, silicon sputtering, dark-current compensation, IR compensation.**

I - Introduction

Silicon photodiodes have a spectral response that, conveniently, overlaps the human eye spectral response. However, due to the bandgap at 1.12 eV, the silicon photon detector is also sensitive to light in the near IR. Device dimensions and vertical junction profile are such, that the typical silicon photodiode has a peak response at about 550 nm and a significant spectral response in the 650-1000 nm range. This is undesirable when using the silicon photodiode to emulate the human vision, as is the case in CMOS cameras. This effect can be reduced when applying a near-IR blocking filter on top of the array of detectors. However, in a CMOS camera the detectors are already covered by an array of different filters for obtaining a colour image and additional filtering would increase device complexity.

The performance of silicon photodiodes in low-intensity light measurement is limited by the dark current. Dark current compensation is used in critical applications to reduce this effect. A dark current compensation structure is basically composed of a photodiode that is identical to the regular photodiode, apart from the fact that the photodiode sensitive area is covered by an opaque layer (a metal film) to avoid penetration of light. Consequently, this (photo) diode supplies the same dark current, but not the photo-induced current. Adding an electronic circuit for subtracting these photocurrents, results in a net photocurrent without dark current. This mechanism can be extended to compensate for other photodiode non-idealities, such as sensitivity for scattered light or stray light [1].

In this work the metal film for dark current compensation is replaced by an interference filter that has a visible-blind spectral response. The remainder of the system has not changed. The result is a photodiode with a significantly reduced near-IR sensitivity, in addition to the dark current compensation.

The special feature of the work presented here is the fact that sputtered silicon layers are used as optical layers. Sputtered silicon (s:Si) is shown to be much more suitable for this function than crystalline silicon or silicon layers that are deposited using different techniques. The microstructure of the layer proved to be crucial. The sputtered silicon layer behaves like an amorphous layer for wavelength up to about 800 nm, while is it more like a polysilicon layer when considering the optical absorption at longer wavelengths. The combined effect makes it an excellent long pass filter with a cut-off wavelength at about 650 nm.

II – Optical absorption in silicon

A ‘visible-blind’ channel requires a filter that effectively absorbs or reflects the visible light. The result is a channel that measures the near-IR content plus the leakage current. In a dual-diode differential system such a channel can be used to correct for the leakage plus IR sensitivity in a regular color channel.

Although crystalline silicon has an optical absorption coefficient that is strongly wavelength dependent due to its indirect bandgap, the absorption decreases relatively gradual with increasing wavelength between 400 and 700 nm. The optical properties of polysilicon are depending on the details of the deposition, but are in general rather similar to those of crystalline silicon. The absorption of amorphous silicon, however, increases more abruptly than crystalline silicon. More importantly, the onset to deceasing absorption (increasing transmission) with increasing wavelength is shifted to about 550 nm, which makes the material much more suitable for this purpose, as is shown in Fig. 1. Amorphous silicon has for this reason already been used as a filter to distinguish between a UV excitation signal and the resulting visible photoluminescence signal [2][3].

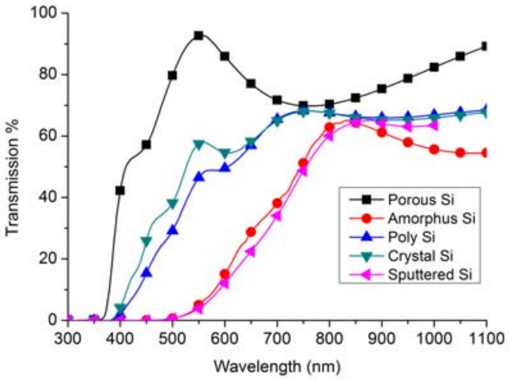

Figure 1, Spectral transmission through a 200 nm thick layer of silicon of different type. Only the sputtered silicon is measured and the other curves are from the Sopra database.

Unexpectedly, sputtered silicon is even more suitable, as is demonstrated in Fig. 1. Sputtered silicon combines the advantage of a:Si in terms of the long-wavelength onset to increasing transmission, whereas it is more similar to polysilicon at wavelength beyond 850 nm, thus with superior near-IR transmission. Although a simple layer of s:Si can already be used for long-pass filtering, a much more versatile filter characteristic can be obtained when implementing s:Si layers in an interference filter design. As is shown in the next Section, there are several optimization strategies possible.

III – Including the sputtered-Si layers in an interference filter design

Relatively simple interference filters can be designed using sputtered Si thin-film layers and SiO_2 layers for a visible-blind spectral response. There are two optimisation strategies considered here.

The first is towards maximum transmission over the entire near-IR spectral range, with a transition at about 650 nm. The second is towards a maximally steep transition at about 650 nm with transmission over the near-IR as the lesser priority.

The listing of the thickness of the layers of the filter design according to the first strategy is as follows:

SiO_2	54.71 nm
s-Si	18.54 nm
SiO_2	130.51 nm
s-Si	13.31 nm
SiO_2	109.84 nm
s-Si	21.17 nm
SiO_2	108.14 nm
s-Si	9.52 nm

This design results in a spectral transmission as is shown in the simulations in Fig. 2.

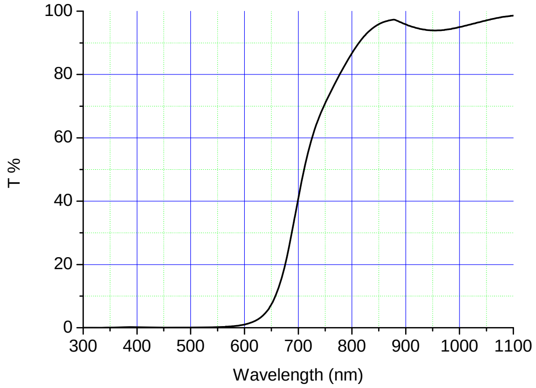

Figure 2, Simulated transmission of an interference filter containing sputtered silicon layers and optimized for a maximum attenuation in the near-IR.

Note that the total silicon thickness is less than the 200 nm layer used in Fig. 1 (about 63 nm).

The design according to the steepness criterion has been combined with the objective of shifting the onset to transmission over 50 nm to longer wavelengths. In this case the listing of the calculated nominal thickness of the layers in the filter is as follows:

SiO_2	100.89 nm
s-Si	10.05 nm
SiO_2	133.73 nm
s-Si	23.59 nm
SiO_2	347.86 nm
s-Si	33.50 nm
SiO_2	77.90 nm
s-Si	13.86 nm

The associated transmission is shown in Fig. 3:

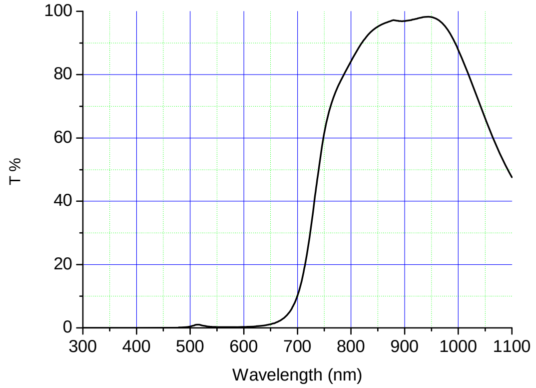

Figure 3, Transmission of an interference filter containing sputtered silicon layers and optimized for a sharp long-wavelength transition.

The figure confirms a steeper transition, at the expense of a reduced transmission at wavelengths beyond 1000 nm. This spectral range is close to the indirect bandgap of silicon, where the device has a strongly reduced responsivity. Therefore, this filter would be acceptable in many applications.

Obviously, other optimization strategies are possible.

IV – Experimental results

The filters were first fabricated on a glass substrate and the measurement results on transmission are shown in Fig. 4. The results confirm the shift of the onset to increased transmission towards longer wavelength for #1. The increased steepness of the transition is less evident.

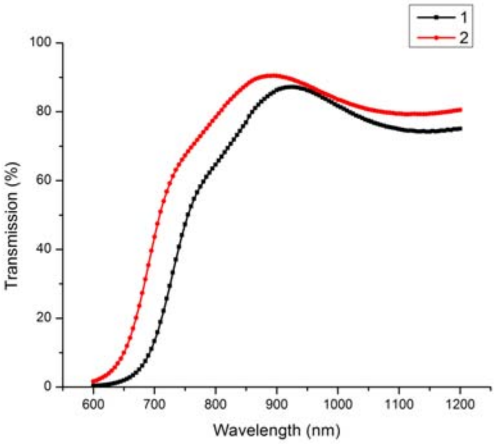

Figure 4. Measured transmission through the interference filter and a glass substrate using the two different optimization criteria: (1) maximally steep transition and (2) maximum IR-transmission.

Pairs of photodiodes have been fabricated in CMOS through a multi-user run in Europractice. This service supplies dies rather than wafers, and a special process was used to attach dies to a wafer and to subsequently apply CMOS-compatible post-processing [4].

The experimental results are shown in Fig. 5. The visible-blind spectral response of the coated diode is clearly visible.

The post-processing for visible-blind filter fabrication has not affected the performance of the photodiodes, as is confirmed by the leakage current measurement results shown in Fig. 5.

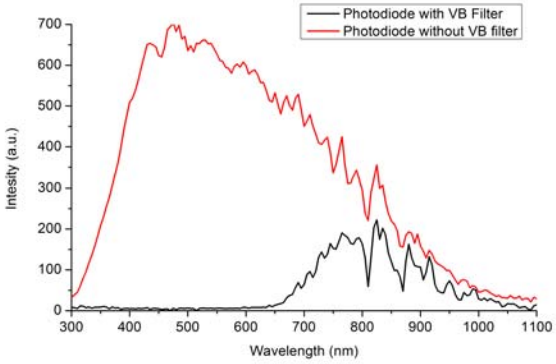

Figure 5.Measured spectral response of the photodiode with and without the filter (maximum IR transmission).

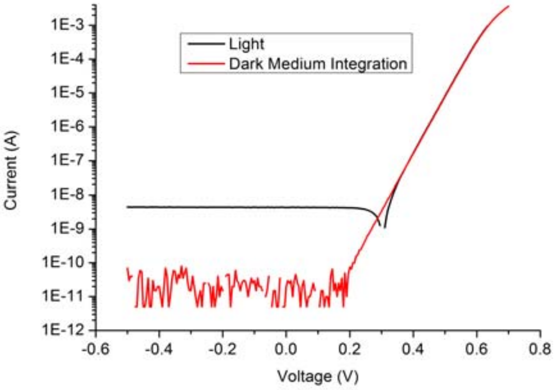

Figure 6.Measured IV-curves of a photodiode after visible-blind filter fabrication.

IV - Conclusions

Visible-blind filters have been fabricated on top of photodiodes in CMOS, using a compatible post-process. The optical properties of sputtered silicon enable the design of long-pass filters in a simple 8-layer s:Si/SiO_2 interference filter design. The intended application is in reducing the parasitic near-IR sensitivity of silicon photodiodes.

Acknowledgements

Part of this work has been funded by the Energy Delta Gas Research (EDGaR) project. Some devices have been fabricated at Chalmers university of Technology through the MC2ACCESS programme.

References

[1] M. Bartek, J.H.G. Correia, S.H. Kong, R.F. Wolffenbuttel, Stray-light compensation in thin-film Fabry-Perot optical filters: application to an on-chip spectrometer, Transducers '99: digest of technical papers, Vol. 1, 10th International Conference on Solid-State Sensors and Actuators, Sendai, Japan, June 1999, pp. 240-243.

[2] V. Iordanov, G. Lubking, R. Ishihara, R.F. Wolffenbuttel, P.M. Sarro and M.J. Vellekoop, Silicon thin-film UV filter for NADH analysis, Sensors and Actuators A97-98(2002) pp. 161-166).

[3] V. Iordanov, P.M. Sarro, R.F. Wolffenbuttel and M.J. Vellekoop, Method of performing an assay, apparatus therefore and a method of manufacturing and apparatus, Patent WO 02090945, Nov. 14, 2002 (also NL 1017989 Werkwijze voor het uitvoeren van een essay, inrichting daarvoor alsmede werkwijze voor het vervaardigen van de inrichting, EP 1390720, US 20050591 158 and CA 2 446 236).

[4] A. Emadi, H. Wu, G. de Graaf and R. F. Wolffenbuttel**,** Post-Processing of Linear Variable Optical Filter on CMOS chip at die-level**,** Proc. MME, September 26-29, 2010, Enschede, The Netherlands, pp. 185-188.