Silicon Compatible Fabry-Perot Optical Filter for mid-IR Microspectrometer Applications

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Summary: The design and modeling of two arrays of Fabry-Perot types of IR optical interference filters for micro-spectrometers is described. The materials used are PolySi and SiO_2 only. The design is complicated by the rapidly increasing extinction coefficient for SiO_2 beyond 2 μm wavelengths, however it is shown that having relatively thin layers it can be used up to 8 μm wavelengths. A 7 layer Fabry-Perot filter, including substrate, is designed using layers thicknesses in between 200 and 400 nm for fabrication in a sputter system. The first filter is designed for maximum range and can be tuned to 13 different channels between 2.2 and 3.5 μm, by changing the thickness of middle SiO_2 layer. A second design is optimized for resolution and is composed of 11 layers to yield 20 passband channels between 2.2 and 2.86 μm.

Keywords: Fabry-Perot, infra-red optical filter, micro-spectrometer.

Introduction

Single-chip optical micro-spectrometers have huge potential in many applications, such as bimolecular identification and chemical analysis, because of their properties such as low-cost and low sample volume. The system can be designed for different spectral ranges from ultra-violet (UV) to infra-red (IR). An important design consideration is whether to design for high resolution or for cost. Obviously, the choice depends on the actual application. An approach based on an array of optical filters composed of IC-compatible materials with proper optical properties over the spectral range of interest offers a highly flexible solution. An IC-processed wafer with circuits and a micro-fabricated array of IR detectors can be used as a generic platform and accommodated to suit a particular application by post-process sputtering of layers of appropriate thickness.

In this project two arrays of Fabry-Perot (FP) multi-layered interference filters are designed. A FP optical filter consists of a resonant cavity in between two parallel mirrors. The mirrors are composed of a stack of dielectric layers. Changing the thickness of only the center layer the tuned wavelength is changed.

Silicon Compatible Materials

Since the filter is intended for use in an integrated system, it is important that the materials used are IC-compatible. For this work we have used PolySi as the high-***n*** and SiO_2 as a low-***n*** material. Silicon has an extinction coefficient smaller than 10^{-3} at wavelengths beyond 1.2 μm and further reduced to below 10^{-5} at 1.5 μm. SiO_2, however, is transparent in the visible range and its extinction coefficient increases sharply beyond 3 μm wavelengths, as shown in figure 1.

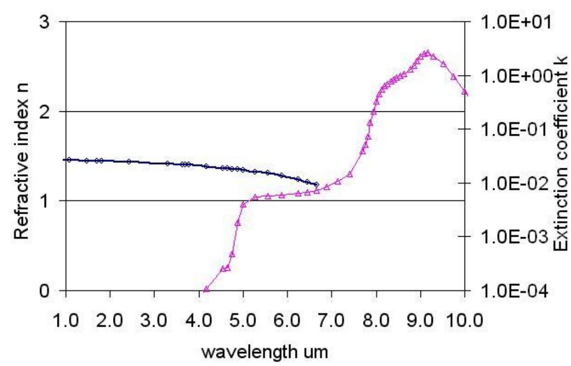

Figure 1. Refractive index and extinction coefficient of SiO_2 in the infra-red.

Absorption is proportional to ***k*** and SiO_2 is not usually considered to be a good material in IR applications. However, we will show here that because of the small thickness of layers in IR interference filters, it can still be used with acceptable loss of transmission at resonance. According to Lambert's law of absorption:

$$P(x) = P_0.\exp(-\alpha x), \qquad (1)$$

in which α denotes the absorption coefficient, is expressed in terms of extinction coefficient as:

$$\alpha = \frac{4\pi k}{\lambda} \qquad (2)$$

Assuming the central wavelength at 3 μm and total thickness of all SiO_2 layers to be 500 nm, and assuming that we accept a loss in transmission of 20% it can be found that:

$$\exp\left(-\frac{-4\pi k}{3000}\times 500\right) > 0.8 \rightarrow k < 0.1 \qquad (3)$$

Therefore, from figure 1 it can be concluded that the use of SiO_2 in optical filters up to 8 μm is acceptable when considering the total thickness of the SiO_2 layers and tolerable loss.

Optical Simulation and optimization

A thin-film optics software package (TFCalc 3.3) was used for simulation and optimization of layers of optical filters. Apart from the IC-compatibility, the filters can be optimized for either maximum Free Spectral Range (FSP) or resolution at minimum number of layers. The first approach is optimized for maximum FSR and is a FP filter composed of 7 layers (including the Silicon substrate) of SiO_2 and PolySi. The three (Poly)Si and SiO2 layers that comprise a mirror have the same thickness, irrespective of the resonance frequency, which is set by the thickness of the middle SiO_2 layer. Changing thickness between 750 nm and 1440 nm enables tuning to 13 different channels from 2.3 to 3.5 μm, as shown in figure 2.

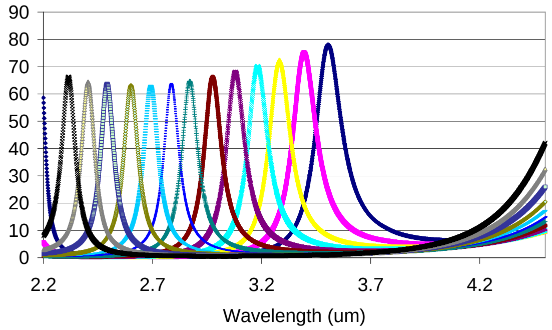

Figure 2. Simulated responsivity of 7-layer FP filters.

Table 1. Thicknesses of the layers of FP filters.

Layer number	Material	Thickness (nm)
1	Si (Substrate)	-
2	SiO2	444
3	PolySi	176
4	SiO2	Table 2
5	PolySi	176
6	SiO2	444
7	PolySi	176

Table 2. Thickness of the middle SiO_2 layer vs. tuned wavelength.

Filter #	Peak (μm)	SiO2 thickness (nm)
1	2.3	750
2	2.4	800
3	2.5	850
4	2.6	910
5	2.7	960
6	2.78	1010
7	2.88	1060
8	2.98	1120
9	3.08	1180
10	3.18	1240
11	3.28	1300
12	3.4	1370
13	3.5	1440

Table 1 shows thicknesses of the layers of Febry-Perot filter and table 2 the thickness of the middle SiO_2 layers and its corresponding tuned wavelength. The quality (Half-Power BandWidth-HPBW) of these optical filters is designed to 100 nm. To do the optimization with the software, We first had to exclude losses in the layers so that the optimization procedure of the software could more easily converge. Losses are added later for the final simulation when the thickness of the layers are known.

If the desired application requires higher resolution, The HPBW can be improved to 30 nm using 11 layers structures (including the substrate). Figure 3 shows simulated response of an array of FP filters in which the thickness of the middle SiO_2 layer ranges from 660 to 1020 nm with 20 nm increments, resulting in 20 resonance peaks from 2.2 to 2.86 μm with 30 nm wavelength increments.

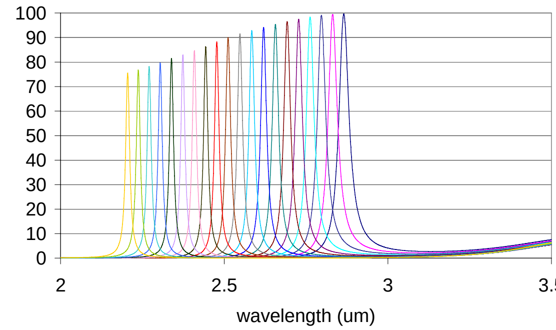

Figure 3. Simulated responsivity of 20 channel FP filters.

The thickness of the layers of this filter is shown in Table 3. Since the thickness of the middle SiO2 layer changes with 20nm steps in these filters, technological challenges should also be considered. The deposition system used should have an accuracy of at least 20nm.

Table 3. Thicknesses of the layers of the second FP filters.

Layer number	Material	Thickness (nm)
1	Si(Substrate)	-
2	SiO2	321
3	PolySi	144
4	SiO2	463
5	PolySi	216
6	SiO2	660-1020
7	PolySi	216
8	SiO2	463
9	PloySi	144
10	SiO2	321
11	PolySi	116

For a comparison between SiO_2 and Si_3N_4 as low- ***n*** IC-compatible materials, the oxide layers of the first filter are replaced by nitride layers of the same optical thickness and the filter performance is simulated. Figure 4 shows the result and indicates a reduced selectivity, due to the increased ***n***, with negligible difference in transmission, due to the design for acceptable loss in the oxide-based filter.

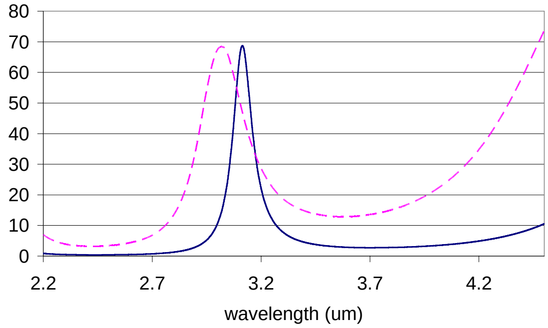

*Figure 4. Comparison between FP filter with SiO_2 (solid line) and Si_3N_4 (dashed line) as low-**n** material.*

Conclusions

It is possible to design Fabry-Perot multilayer optical filters in IR region in which changing the thickness of only the middle layer shifts the peak wavelength of the filter. The design can be optimized for wider Free Spectral Range (FSB) or higher resolution. In order to have higher resolution number of layers will be increased and also technological challenges should be considered since the thickness step for the middle layer is just 20nm. Despite the high value of the extinction coefficient of SiO_2 in the mid-IR spectral range it is yet the better choice in filter design, as has been demonstrated for two different design approaches. The filters can be used in combination with standard CMOS processes to fabricate low-cost microspectrometers.

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