Quality Factor of Thin-Film Fabry-Perot Resonators: Dependence on Interface Roughness

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SUMMARY

Thin-film Fabry-Perot (F-P) optical resonators are studied for application as wavelength-selecting elements in on-chip spectrometers. The interface roughness between the different resonator layers (Al / PECVD SiO_2 / Ag) is identified to be the primary source of light scattering and energy losses. It is demonstrated that conventional IC fabrication yields layers with RMS interface roughness easily exceeding 10 nm. When applied to the visible spectral range, such a roughness causes significant degradation of the F-P filter quality factor. Moreover, the scattered light contributes to transmittance outside the narrow resonance band to which the F-P filter is tuned and overall device performance is decreased.

Keywords: *Fabry-Perot resonator, quality factor, spectrometer, surface roughness, light scattering.*

INTRODUCTION

In previous work [1], it was demonstrated that thin-film Fabry-Perot (F-P) resonance filter can be used as an effective wavelength-selecting element for application in optical spectral analysers. Moreover, it was shown that an array composed of fixed cavities of different width has several operational advantages compared to devices that involve mechanical scanning. Based on this principle, a 16-channel, IC fabrication compatible, on-chip spectrometer operating in the visible spectral range was realised.

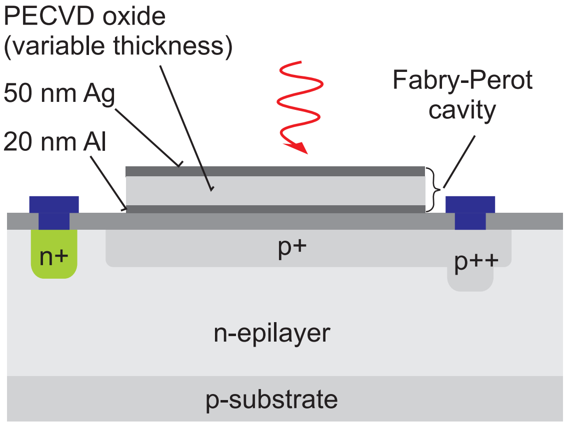

Fig. 1: Schematic cross-section of one of the spectrometer channels based on a Fabry-Perot resonance filter integrated on top of a pn-photodiode.

Each of the 16 channels is composed of an F-P thin film optical filter (tuned to a certain wavelength) integrated on top of a pn-junction photodiode. The cross section of one of the channels is shown schematically in Fig. 1. The realised on-chip optical spectrometer is shown in Fig. 2.

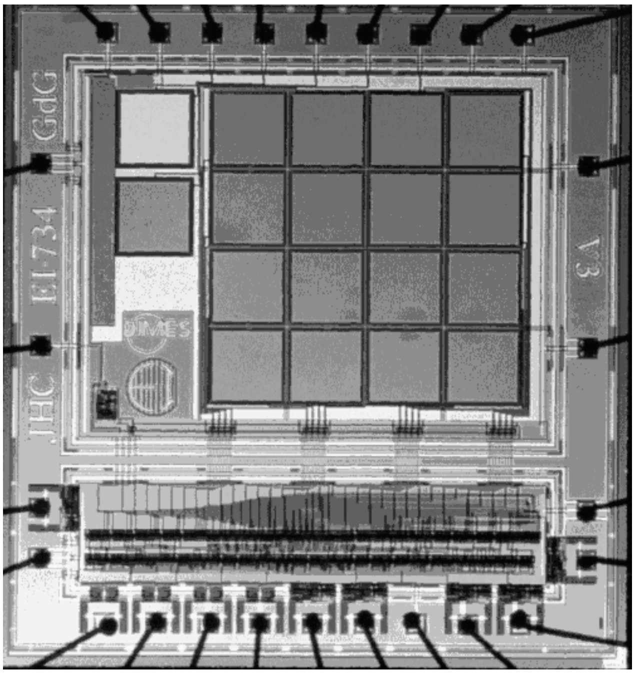

Fig. 2: Photograph of the single-chip optical spectrometer.

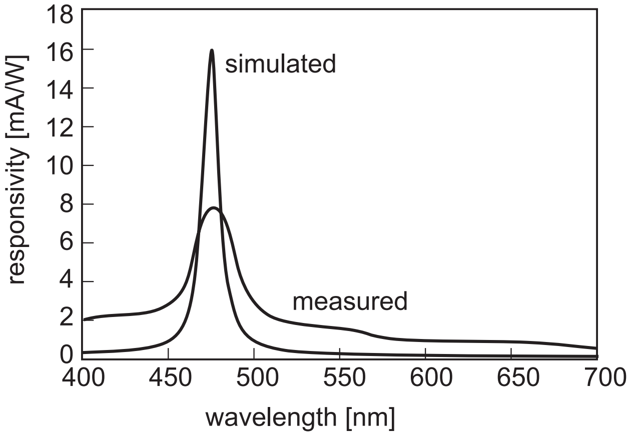

Fig. 3: Simulated and measured spectral responsivity of one of the spectrometer channels.

As can be seen in Fig. 3, such a device suffers from relatively high background signal levels caused by imperfections in the measured light beam and F-P structure. Previously presented compensation technique [2] can significantly improve the performance of F-P-based on-chip spectrometers, but any improvement of the F-P structure itself would be beneficial. In this paper influence of the interface roughness (between the different resonator layers) on F-P filter performance is analysed.

FABRY-PEROT RESONATOR

Ideally, when light beam of normal incidence interacts with an ideal F-P resonance cavity, only a narrow spectral band around the resonance wavelength is transmitted (Fig. 4).

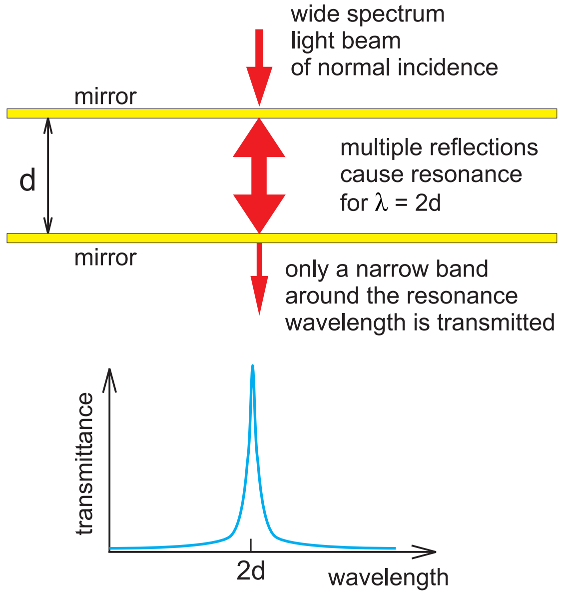

Fig. 4: Interaction of an ideal light beam with an ideal Fabry-Perot optical filter.

In a real F-P structure (Fig. 5), composed of a stack of deposited thin-film layers, the interfaces between different layers are not ideal. The boundaries between different layers are not perfectly planar and exhibit certain degree of roughness. As an example, Fig. 6 shows a F-P resonator composed of a 20 nm Al / 250 nm SiO_2 / 50 nm Ag layer stack in cross-section. It is clearly visible that the metallic mirrors (deposited by evaporation) are not perfect in respect to the interface roughness.

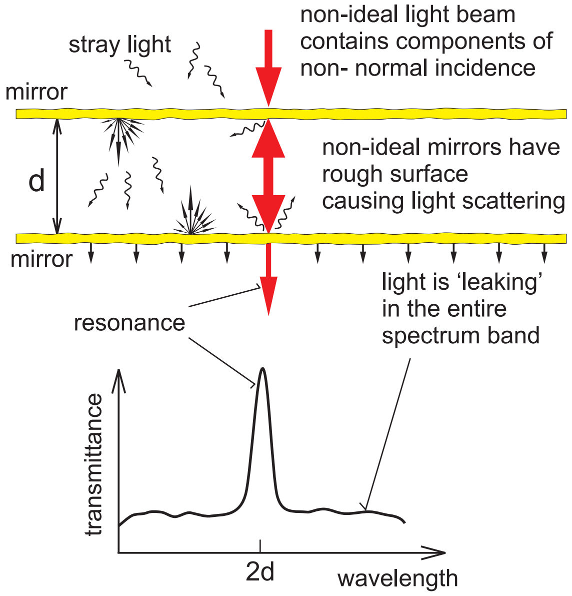

Fig. 5: Interaction of a non-ideal light beam with a non-ideal Fabry-Perot optical resonator.

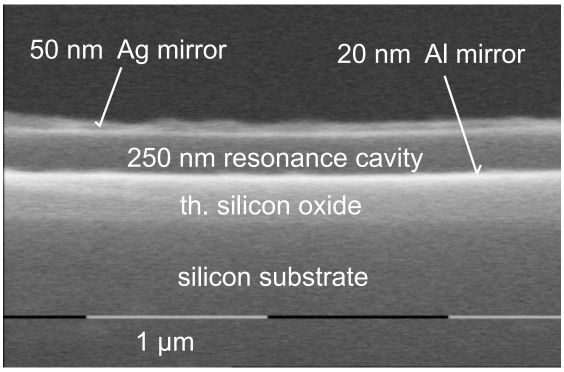

Fig. 6: SEM photograph of one of the channels in cross-section.

From AFM roughness measurements on the realised structures (Fig. 7), typical root mean square (RMS) surface roughness values between 8 to 15 nm were determined. Such a roughness cannot be neglected for the visible spectral range and yields total integrated scattering (TIS) for the visible light that can be as high as 10 % (see Fig. 8).

Any light scattered inside the Fabry-Perot resonant cavity results in the increased transmittance outside the narrow resonance band to which the F-P filter is tuned (Fig. 3). Quality factor of the F-P resonator is decreased resulting in a widened resonance peak.

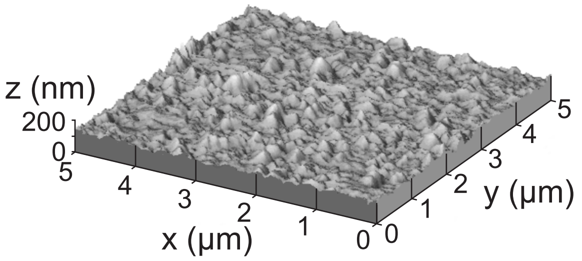

Fig. 7: AFM surface scan of a 50 nm silver layer forming the upper mirror of the F-P resonator.

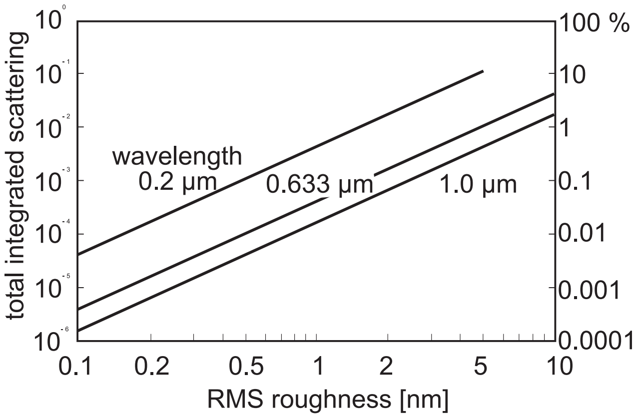

Fig. 8: Total integrated scattering as a function of RMS roughness for different wavelengths [3].

In Fig. 9 calculated normalised transmittance of an ideal F-P resonator is depicted for three different mirror reflectivities. Light scattering at rough mirror surfaces can effectively be compared to the decreased mirror reflectivity and will have the same influence on the resonance peak broadening.

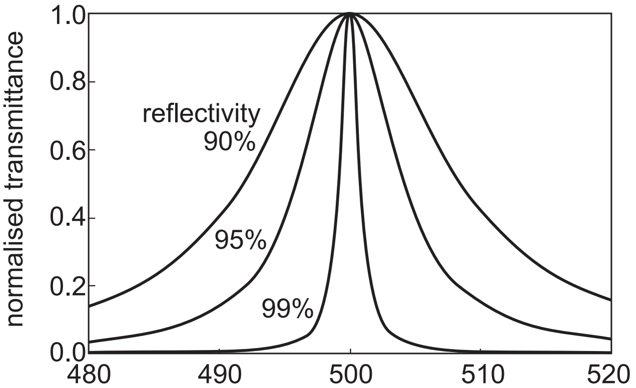

Fig. 9: Normalised F-P filter transmittance with mirror reflectivity as a parameter.

When metallic layers (Ag, Al) are used as F-P mirrors, the absorptance in these layers is inevitably the limiting factor of the F-P resonator quality. To improve the F-P filter performance, the interface roughness should be decreased to levels where TIS can be neglected or has less influence than the absorptance in metallic layers. By careful process optimisation it is feasible to decrease the interface roughness to a level (2-5 nm) [4], where TIS can be neglected when compared to other parasitic effects involved.

DISCUSSION

“Subtractive” fabrication method

In the current version of the spectrometer devices, the individual channels are fabricated using Al or Ag evaporation and a “subtractive” tuning of the resonance cavity. Firstly, the bottom Al mirror (20 nm thick) is evaporated. Then a PECVD oxide layer is deposited with thickness equal to the maximum optical length required. Subsequently, in 4 plasma etching steps (each using a different etching mask), the initial oxide layer is thinned. This results in 16 channels, each with a different thickness of the PECVD oxide layer forming the resonance cavity. Finally the upper 50 nm Ag mirror is formed using evaporation.

This “subtractive” fabrication technique has advantage in its simplicity, but does not give optimum results in respect to the surface roughness.

“Additive” fabrication method

Currently an “additive” fabrication method is under investigation. This tuning method is, in contrary to the previous one, based on subsequent deposition of the layers. Firstly, a layer with thickness equal to the minimum optical length is deposited. Then in 4 deposition steps (again each using a different mask pattern), 16 channels tuned to different wavelengths are formed.

Sputtering of Ag, Al, and Yttrium oxide layers, used in this experiments, together with the “additive” tuning method is expected to provide better control of the surface roughness when compared to the “subtractive” one.

Polishing

Further improvement and minimising of the boundary roughness would be possible using CMP (chemical mechanical polishing). However this can have a negative influence on the economics of the entire fabrication process.

CONCLUSIONS

Thin-film Fabry-Perot optical resonators have been studied for application as wavelength-selecting elements in on-chip spectrometers. The interface roughness between the different resonator layers used (Al / PECVD SiO_2 / Ag) is identified to be the primary source of light scattering and energy losses. It is demonstrated that conventional IC fabrication yields layers with RMS interface roughness easily exceeding 10 nm. When applied to the visible spectral range, such a roughness causes significant degradation of the F-P filter quality factor. Moreover, the scattered light contributes to transmittance outside the narrow resonance band to which the F-P filter is tuned and overall device performance is decreased. “Additive” fabrication and polishing are discussed as possible methods to minimise the layer roughness.

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