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SILICON MICRO-INTERFEROMETERS FOR IMAGING SPECTROMETER FOR GREENHOUSE GAS GLOBAL SURVEY

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ABSTRACT:

NanoCarb is a miniature Fourier transform imaging spectrometer dedicated to the measurement of greenhouse gases (CO₂ and CH₄) from a constellation of small satellites. The key element of NanoCarb is an array of Fabry-Perot micro-interferometers having a stepcase shape. Lateral dimensions and height of each step depend on the used material, the focusing lenses and the targetted optical path difference to be measured. In this paper, we describe a grayscale lithography process for a large surface patterning with high vertical resolution. This process is combined with plasma etching. Therefore, this two processes leads to a 20 nm step height resolution in resist and 50 nm in silicon. In addition to the manufacturing of this plate, we also investigated the deposit of a narrow-band filter on this plate used to select the spectral band of CO₂ (1608 nm), with promising preliminary results.

1. INTRODUCTION

The H2020 SCARBO (Space CARBOn Observatory) is a European project led by Airbus Defense and Space, involving several partners including ONERA and IPAG. The project aims at designing and assessing the feasibility of a constellation of small satellites at an affordable cost for the measurement of GreenHouse Gases (GHG), CO₂ and CH₄. NanoCarb is one of the main components of the project, a Fourier transform imaging spectrometer dedicated to GHG measurement [1]. The NanoCarb concept is based on two main features. The first one is consisting in a very compact static imaging interferometer, whose principle is presented by Ferrec et al [2]: the spectro-imager is divided into two optical sub-systems, the front optics, which consists of an afocal system with a field stop, and the interferometric core which consists of a combination of an interferometer array with a micro-lens (μ lens) array [3]. The interferometric plate has a stepcase shape fabricated of silicon, and as the surfaces are semi-reflective, each step behaves like a Fabry-Perot interferometer. We thus obtain a set of small images

on the focal plane array (FPA), each image being associated to one thickness. The second feature of NanoCarb is to measure only a partial interferogram (as shown by Gousset et al. [3]), that is a few optical path differences (OPD) well chosen, depending on the spectral signature of the target species. An interferential filter is used to select the spectral band (spectral filtering), in front of the μ -interferometer array (interferometric filtering). This principle is well suited for CO₂ and CH₄, thanks to a periodic spectral pattern over specific bands. For instance, for CO₂ around 1.6 μ m of wavelength, this OPD is about 5.2 mm [4].

This work represents a collaboration between the LTM (Laboratoire des Technologies de la Microélectronique) and ONERA, and has several objectives (Figure 1):

- Develop fabrication processes for the realization of 2D micro-interferometers array in Si whose thicknesses must be perfectly controlled at 50 nm.
- Develop optical filters located on the back side of the interferometric plate which aim to let through only the light that is in the spectral band of interest (1608 nm for CO₂).

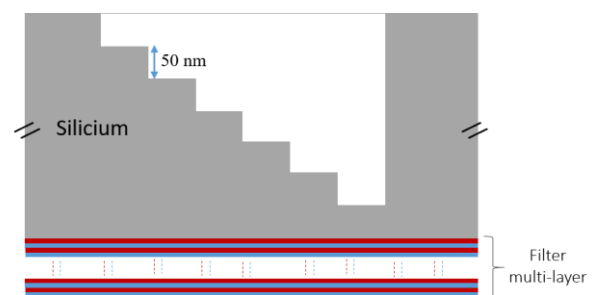


Figure 1 - Schematic representation of the objectives of our work

2. EXPERIMENTAL

The shape of the interferometric plate is quite uncommon: indeed, the transverse size of the 10 steps is about 4 mm, but their depths must be as small as 50 nm. There are several methods to fabricate perfectly controlled steps in resist and transfer them into silicon from a series of lithography/etching sequences, but in case of a large number of steps, this process is time consuming and expensive. Moreover, there are

various techniques of grayscale patterning, such as special optical masks [5], LED-projection [6], direct-write lasers [7] [8], and electron-beam lithography [9]. The latter is not effective due to long exposure times. The challenge in our work is to fabricate such a plate using only one grayscale lithography and plasma etching step. Thus, we developed a UV grayscale lithography process for a large surface patterning with high vertical resolution. This process is combined with plasma etching to transfer the as-obtained resist patterns into the silicon substrate. This method is an efficient and quick way for the realization of such arrays into silicon. Figure 2

material. For the high index material, filters based on Ta_2O_5 ($n=2.1$) and Nb_2O_5 ($n=2.2$) are demonstrated [10] [11]. It is also possible to control the transmission wavelength in the near infrared by combining Si/SiO_x with air gaps whose thickness allows to adjust the central wavelength [12] [13]. We did not choose these solutions because the architectures are complex and these high index materials are not available at LTM. Silicon has a high index of 3.4 and can be deposited on the technological platform together with SiO₂. We optimized by simulations a filter that transmits at 1608 nm and consists of 12 layers of Si and SiO₂.

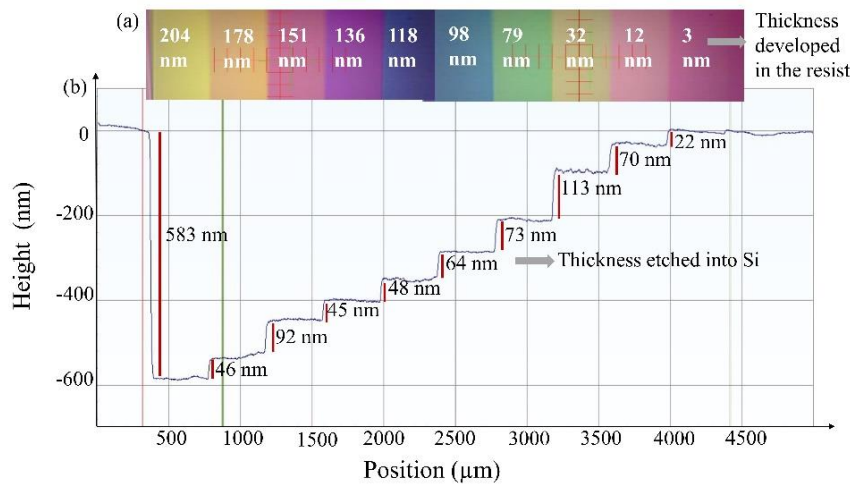


Figure 2 - (a): heights and optical microscopy image of 10 strips patterned in the resist with various power exposure ratios, (b) the profile obtained by etching into silicon

combines two measurements; the upper one is optical microscopy image of 10 strips (400×4000 μm per strip) patterned in the resist with various power exposure ratios and the corresponding developed resist thickness, and the lower one is the profile obtained by stripping those resist after etching the patterns into silicon. As shown in this figure, the depth of the 5th and the 6th step is 118 nm and 98 nm, respectively, which results in a step height of 20 nm in the resist and around 50 nm in silicon, as required by the NanoCarb design.

In addition to the Fabry-Perot function, the interferometric plate can also be used to host the spectral filter, in order to limit the number of optical components and thus unwanted multiple reflections. This interference filter is a narrowband filter, for instance, the spectral band for the CO₂ camera is centered at 1608 nm with a FWHM of 6 nm. This poses two difficulties of realization. First, it requires a very high rejection rate over a very wide spectral range. The second difficulty is that the variation of the transmitted spectral band with the angle of incidence has to be small. In the literature, it is possible to find a number of publications on the manufacture of interference filters. The objective is to use a pair of materials with a large index gap. The SiO₂ ($n=1.44$) is generally used as a low index

This study was completed by experimental realizations of filters by deposition on a PECVD CORIAL tool. This equipment allows to obtain very uniform films thanks to the uniform distribution of gases. The optical characterization at IPAG and ONERA using a Bruker FTIR and a PerkinElmer grating spectrometer respectively, shows that the filter transmits at 1614 nm with a transmission of 45.9% and a FWHM of 6.5 nm. Figure 3 shows the results obtained with the PerkinElmer spectrometer at ONERA as a function of the angle of incidence. We can notice that the spectral shift of this filter is 1 nm, 3 nm and 12 nm at 5°, 8° and 15° respectively. We deduce that the effective index of the filter is equal to 2.2. These results show that this filter corresponds to the expected specifications in terms of angle of incidence, but it is essential to use an in-situ control during the deposition in order to obtain the accuracy of the peak centering.

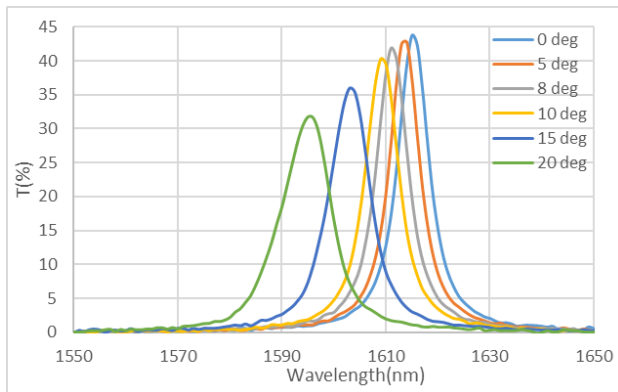


Figure 3 - Optical characterization of the filter composed of 12 Si/SiO₂ layers for several angles of incidence

3. CONCLUSIONS

In this study, we addressed the issue of realizing a perfectly controlled staircase structure in only one lithography step and subsequent pattern transfer into silicon by plasma etching. We thus demonstrated the possibility to manufacture a Si plate with 50 nm steps to be used as an array of Fabry-Perot interferometers for NanoCarb. In addition to the manufacturing of this plate, we also investigated the deposit of a narrow-band filter on this plate, with promising preliminary results.

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