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Progress in thin film coating on space IR detectors

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ABSTRACT

Improvements as well as new functionalities can be implemented in IR sensors by depositing a stack of thin film layers on top their surface. For this purpose, Safran Reosc has developed and qualified various processes, from conventional deposition methods to planar structuration approaches. In this article, the usefulness of thin film AR coatings are addressed and the latest results obtained on projects like Sentinel-5 and Microcarb IR focal planes are presented and discussed. We also address our progress in pixelization of the coating by structuration of these optical layers. Eventually, the most recent developments of sub-lambda photonic filtering structures are discussed.

Keywords: IR, detector, sensor, pixel, pixelated coatings, sub-lambda

1. MULTILAYER ANTIREFLECTIVE COATINGS ON DETECTOR

In order to improve the efficiency of IR detectors, Safran Reosc developed multilayer antireflective coatings deposited directly on the detector. Indeed, the photosensitive parts of IR detectors are widely made of high refractive index materials such as:

- Indium Antimonide (InSb, n=4)
- Indium Arsenide (InAs, n=3.51)
- Gallium Arsenide (GaAs, n=3.9)
- Aluminium Gallium Arsenide (AlGaAs, n=3.97)
- Other IR materials (n>3).

With such refractive indices, the beam loses around 30% of the incoming intensity at the interface for InSb and Other IR materials. The consequences of this reflection are flux losses at the interface and ghost imaging. These phenomena are illustrated in figure 1.

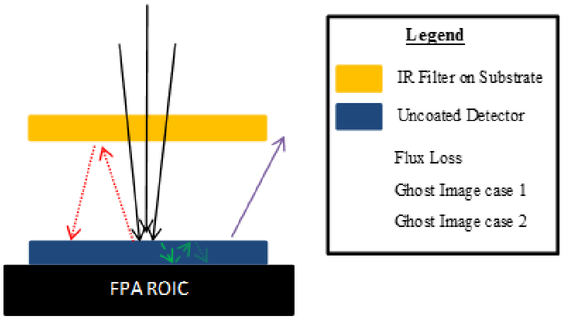


Figure 1. Schematic view of ghost imaging and flux loss with uncoated detector. The nominal incoming flux is shown in black. The flux losses path is indicated by a purple arrow. The red and green light rays illustrate the optical paths that induce ghost images.

These critical items have been identified by industrials many years ago. In order to improve the performances and protect the sensitive surface, the method applied has been to deposit a protective layer with a low refractive index. The materials used (oxides, fluorides, sulfides…) generally have low refractive indexes so as to increase the spectral transmittance at the wavelength of interest. Still, a reflectance up to 20 % in average remains on the total spectral range of the photodetector. For multispectral detection, the monolayer antireflective coating isn't efficient enough.

Safran Reosc, with its unique expertise in the infrared domain, developed multilayer coating deposited directly on detector. The parameters that were taken into account were the followings:

- Low strain coatings,
- Low reflection on the specified bands,
- Low temperature process,
- Process compatibility with the FPA electronic sensitivity.

The following case study may show the advantages of this technical solution. Let us consider a customer wishing to make multispectral detection. The following figure compares the theoretical performances attainable with a classic monolayer anti-reflective coating and that provided by Safran Reosc multilayer solution.

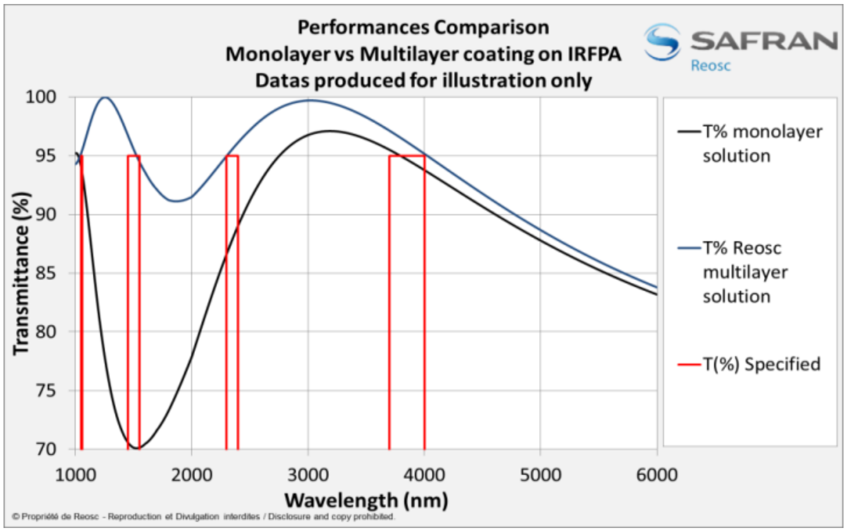


Figure 2. Performance comparison between a single-layer AR coating and Safran Reosc multi-layer solution.

The flux gain can clearly be seen in this case. Detectors were coated to demonstrate the feasibility and confirm the flux gain. Coating performances were compliant with the specifications. The coatings passed the qualification test sequence and the prototypes were delivered fully functional.

We developed and qualified 2 Anti-Reflective coatings on HgCdTe detectors (VNIR/IR):

- AR - Sentinel 5 (2016-2018) : Detection of O3 - Qualified for Humidity (24h, 49°C, 95% HR), Hot Storage (15 days, 90°C, 10-4 mbar), Thermal Shocks (100 cycles 77K – 310 K)
- AR – Microcarb (2016-2018): Detection of CO2 - Qualified for Humidity (480h, 60°C, 85% HR), Hot Storage (15 days, 80°C, 10-4 mbar), Thermal Shocks (100 cycles 100K – 310 K)

2. PIXELATED FILTER COATINGS ON DETECTOR

High-end applications in infrared detection benefit from the use of several well-identified spectral bands. Current multispectral imaging systems either use filter wheels to detect one spectral band at a time, or complex optics that separate the incoming light flux into multiples optical paths, each corresponding to a spectral band of interest, as shown in Figure 3. As a result, these systems are bulky, sensitive to stray light, and are not all suitable for real-time acquisition. Besides, infrared (IR) photodetectors often suffer from signal loss at the air/detector interface, due to low-performance antireflection coatings (ARC) (see Figure 1).

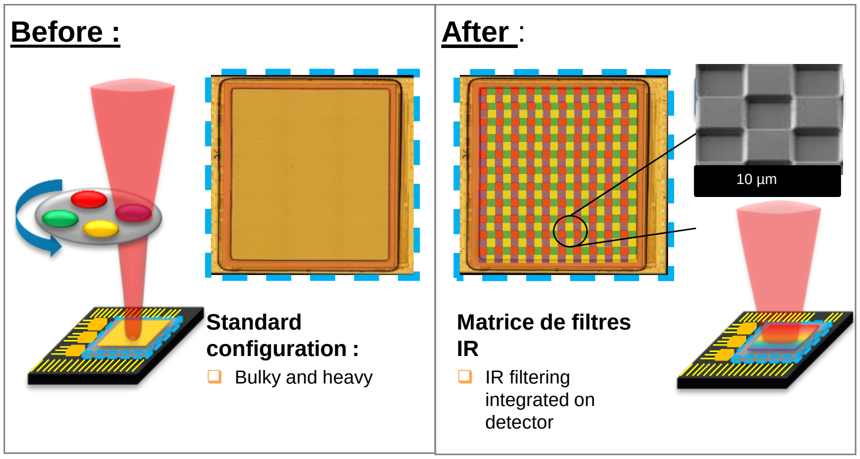


Figure 3. Filter wheel versus Safran Reosc pixelated filter solution.

Such issues are significantly reduced when the multispectral filtering is performed at the detector level. Compared to the conventional imaging systems described above, a multispectral camera comprising individual filtering elements deposited on the detector surface can achieve higher compactness, lower flux loss at the interface, as well as real-time acquisition.

2.1 Simulation

The pixelated matrix has been modeled in 3D in order to optimize its design, as shown in Figure 4. The verticality of the etching sides of the coating are taken into account to ensure the accuracy of simulation. The diffracted fields can be computed at the detector level or anywhere within the whole simulation volume (see Figure 5).

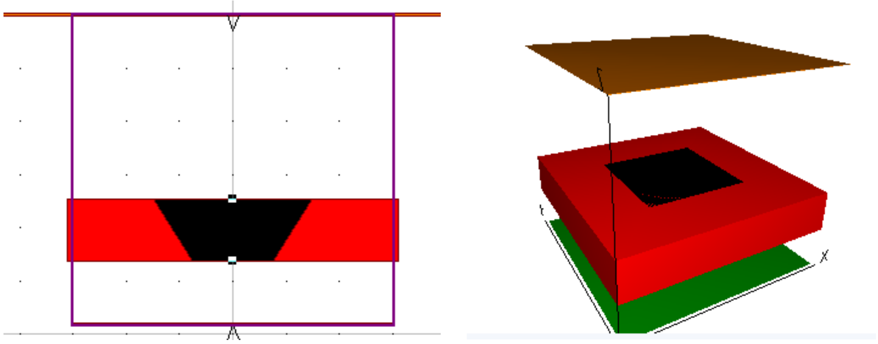


Figure 4. Configuration used for the simulation of a pixel. The etched multi-layer coating is shown in red.

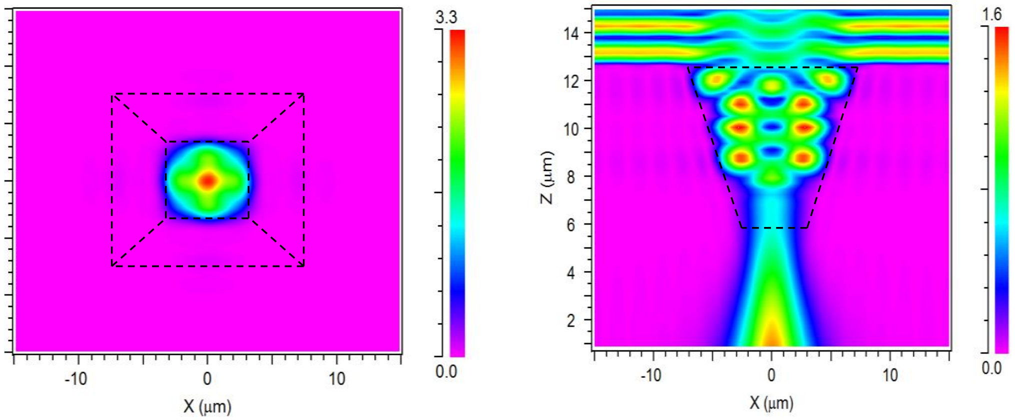


Figure 5. Top view and side view of the diffracted beam within the simulation domain shown in Figure 4.

Safran Reosc then developed skills to calculate and analyze the diffraction in any thin film stack. Indeed, the classical models are not applicable to compute the near field diffraction in a multilayer stack. A simulation method using the Rigorous Couple Wave Analysis (RCWA), combined with Safran Reosc data on optical material allows to determine the influence of the geometric parameters on the structure's diffractive performance.

The RCWA method [1,2,3] is a mathematical method dedicated to the resolution of the Maxwell equations in an infinitely periodic structure. The electromagnetic fields is represented as a sum of coupled plane waves, while the periodic permittivity function is represented as a Fourier series. The higher the number of coupled waves (harmonics number), the better the convergence of the solution. This method is called rigorous because no approximation is made when solving the full vectorial Maxwell's equations.

Safran Reosc's model takes into account the following parameters:

- Optical functions (multilayer stack structure),
- Geometrical pattern formed by the coating,
- Angle of Incidence of the beam,
- Real and Imaginary Index dispersion,
- Detection Zone.

The data are obtained anywhere in the simulated volume:

- Power spatial function,
- Integrated Power,
- Electric and magnetic fields.

Figure 6(a) shows the results in 3D mode while Figure 6(b) shows the simulation results for a full matrix array on the same scale. With these tools and its heritage on coating materials, Safran Reosc can today provide an accurate study of the performances of optical microstructures deposited at the surface of the IR focal plane array.

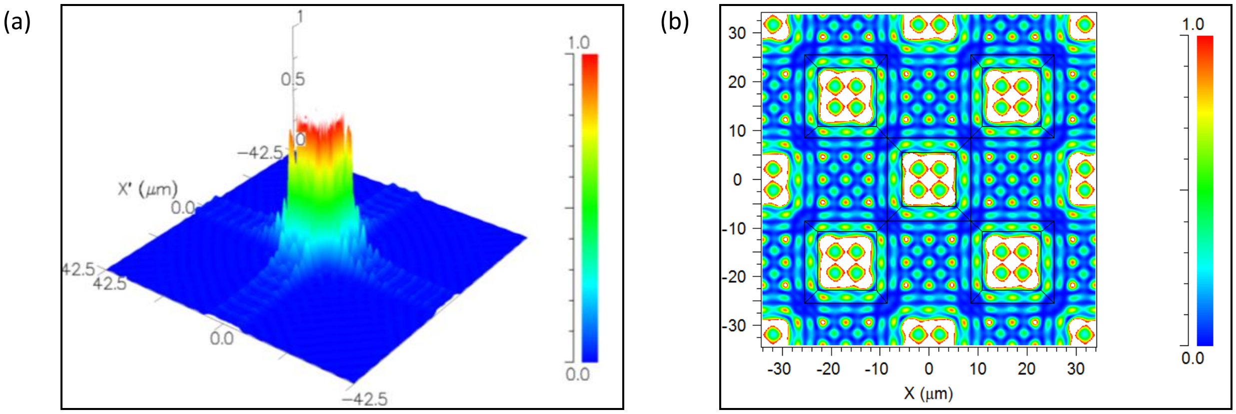


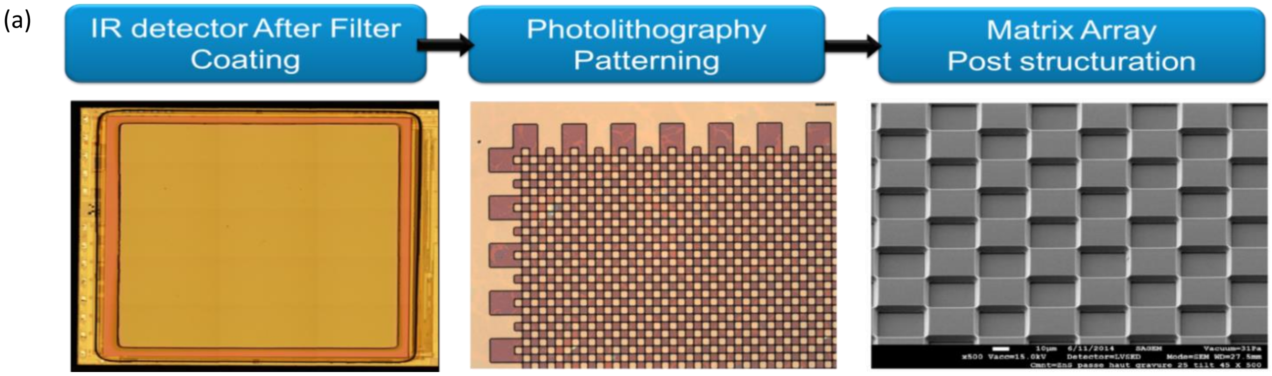
Figure 6. (a) 3D view of the power going through the aperture in the IR filter. (b) Power at the detector surface for one wavelength.

2.2 Manufacturing

Technological constraints appear when manufacturing pixelated filters directly on a photodetecting device. The complex spectral responses required for space and defense applications can only be achieved by interference filters with typical thicknesses of 3 to 20 µm with a nanometer precision on the layer thicknesses. Therefore, structuring these multilayer stacks down to the pixel pitch (about 10 µm wide) requires state-of-the-art microfabrication techniques. Also, both the coating and the patterning process might degrade the photodetecting device sensitivity.

Safran Reosc, with its unique expertise in IR thin film coating, was able to manufacture thick pixelated multilayer stacks on IR-focal plane arrays (IR-FPA) for bi-spectral imaging systems, thus demonstrating high-performance filters, low crosstalk, and no deterioration of the device sensitivities. The aim of current developments is to improve the patterning process in order to ensure the pixel uniformity and reduce the pixel size down to 10 µm. Additional work was also carried out on a patterning process for multispectral Fabry-Pérot filters. The critical issue is the precise control over the cavity thicknesses, which governs the transmission peak wavelength.

Figure 7 illustrates the fabrication process and associated performance of a bi-spectral IR-FPA photodetector for detection in the SWIR-MWIR range. The latter was designed and fabricated in close collaboration with Sagem. The multilayer stacks were designed in order to reach the performance level of standard IR optics. The total thickness of the stack (including both filters) is above 10 µm. The initial patterning process was affected by the significant extent of the coating sidewalls (see Figure 4), as well as by the non-uniform etching depth. Thanks to new technological developments, both limitations were addressed successfully. Safran Reosc has now the capacity to pattern thick coatings (typically 5 µm) on small pixels areas (<20 µmx20 µm²), with coating uniformity over >75% of the pixel area. Pixel-filter alignment precision is smaller than 500 nm.



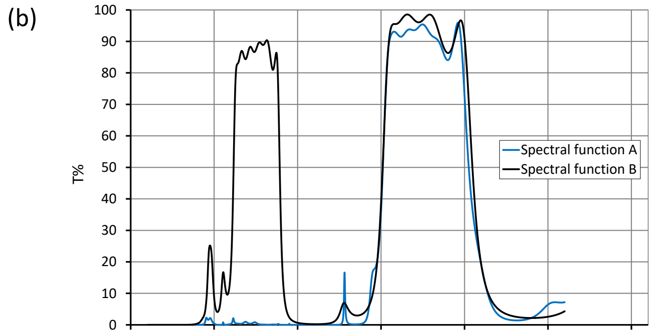


Figure 7. (a) Illustration of the manufacturing process of bispectral pixelated filters. (b) Spectral functions of the two different pixels.

Concerning the Fabry-Pérot interference filters, it is well-known that such devices exhibit transmission peaks which central wavelength depends solely on the thickness of the cavity layers. Thus, multispectral interference filters are obtained simply by patterning these few layers, making the manufacturing process much simpler than for thick multilayer stacks. The key issue is to control the cavity thickness with a precision of a few nanometers to tune each filter to its target wavelength. Two different configurations of Fabry-Pérot filter's cavities can be produced within Safran Reosc facilities: linear gradient filters (see Figure 8). A 5-pixel step-filter matrix was designed and fabricated on Germanium substrates using different microfabrication techniques for comparison, with 10, 30 and 50 µm pitch sizes on each sample.

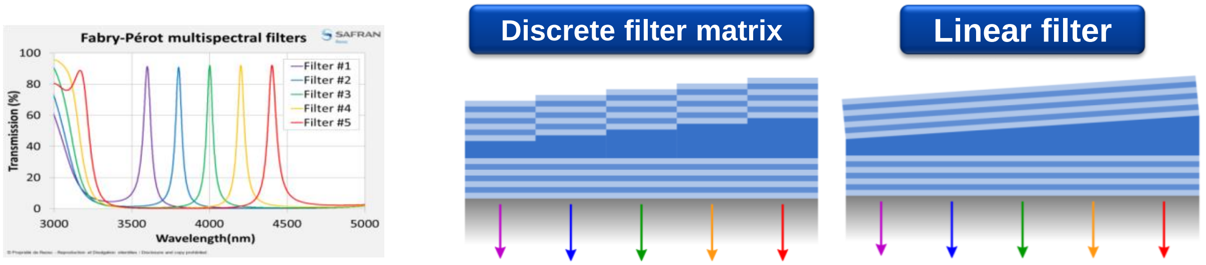


Figure 8. Different configurations of multispectral filters at the detector level.

3. SUB-LAMBDA PHOTONIC FILTERS

Always to stay on the pixelated filtering, Safran Reosc is also working on photonic filters in collaboration with LAAS-CNRS. More precisely, Zero-contrast grating (ZCG) filters are investigated [4,5]. Such filters don't rely on thin film interferences to build the spectral response, but on guided-mode resonances. Such filters possess two principal advantages compared to conventional thin films devices described above. First, they don't require the use of thick thin film stacks, even in the mid-IR range [6], but of just a few partially etched layers. Second, their central wavelength can be tuned by adjusting only the lateral dimensions of the patterns, not the thickness of the layers, thus allowing for the simultaneous fabrication of adjacent pixels of a mosaic using a planar structuration approach (see Figure 9).

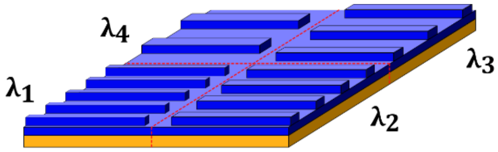


Figure 9. Schematics of a pixelated filter based on a basic GMRF structure. All pixels share the same vertical stack and only the lateral dimensions change from pixel to pixel. Basically, the larger the periodicity is, the longer the resonance wavelength of the filter is: $\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4$.

In a precedent article [6], we demonstrated the possibility of designing ZCGs in the mid-IR range using germanium as for the grating and calcium fluoride as substrate. Narrowband transmission filters which spectral response possess a full-width at half-maximum (FWHM) below 2 nm were shown (see Figure 10(a) and Figure 10(c), black curve). The major drawback of such filter is that they remain efficient only when implemented into 1 mm-wide pixels. Besides, their FWHM is too small considering the low photon flux in the MWIR range, which would induce SNR issues. Therefore, we demonstrated wideband filters (FWHM=40nm, see Figure 10(c)) using a double corrugation scheme (see Figure 10(b)). We showed that this kind of filter can be scaled down to pixels with a pitch of about 140µm.

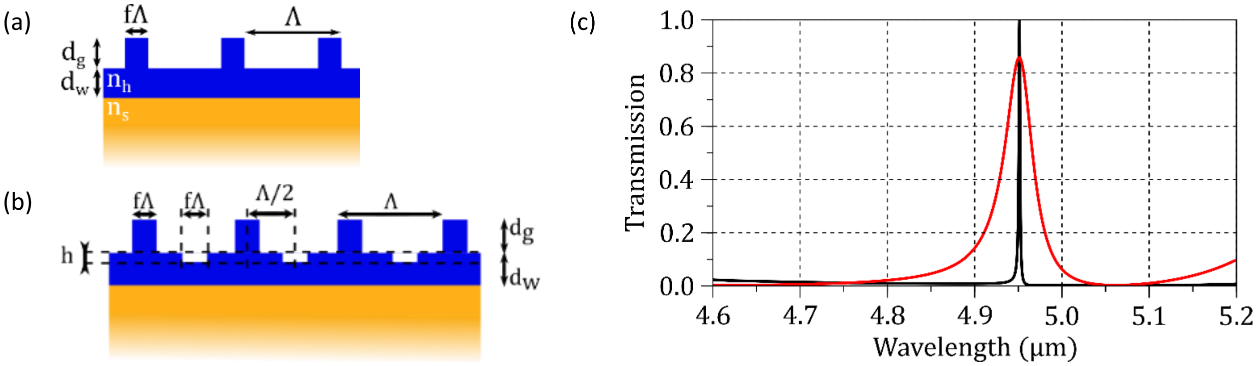


Figure 10. Schematics of a (a) simply- and (b) doubly-corrugated ZCGs. (c) Spectral response of the narrowband filter presenting a simple corrugation (black curve), and of the doubly-corrugated wideband one (red curve). The dimensions of the narrowband filter are the following: d_w=0.84µm, d_g=0.87µm, Λ=2.703µm and f=0.24. The dimensions of the doubly-corrugated filter are identical, except for the period and the secondary corrugation: Λ=2.767µm and h=0.1µm.

Very recently, we have demonstrated the fabricability of such devices. The doubly-corrugated design is the more difficult to process since it requires two different etching steps. The alignment accuracy between the etching level must be of less than 100nm in order to have an efficient response of the filter. Because of the precision required for the alignment and since we want to pattern several cm² with a pixelated matrix of different pixels, we chose to use a fine pattern aligner stepper with a field reduction of 5 for the exposure in our photolithography process. The process development was conducted using germanium coated Si substrates. For the final samples, we used a 2-inch, 525-µm-thick CaF_2 wafer coated with germanium. Both etching procedures include two consecutive reactive-ion etching with inductively-coupled plasma: a first etching of the high index layer with a mixture of C_4F_8 and SF_6, followed by the photoresist mask removal which is performed with oxygen.

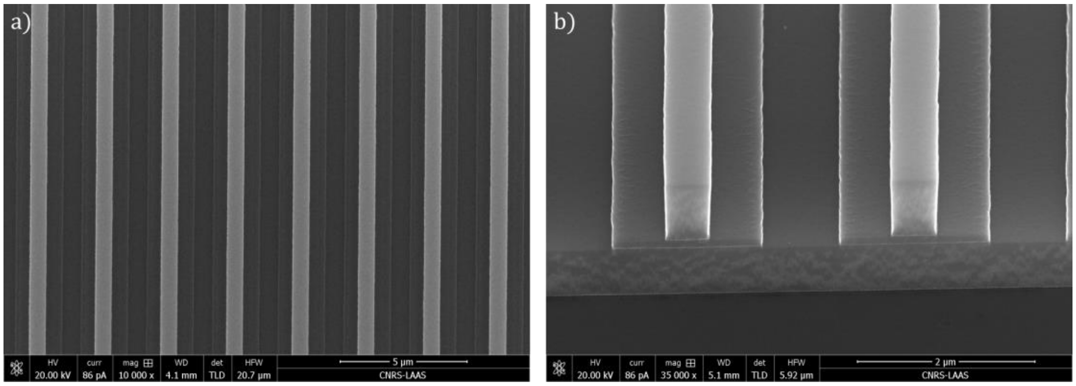


Figure 11. (a) Top-down SEM view of the grating ridges for a doubly-corrugated sample with CaF_2 substrate. (b) Cross-section SEM view of a doubly-corrugated sample with a silicon wafer.

Figure 11 presents the fabrication results for the doubly-corrugated device. In Figure 10 (a) is shown a top-down view of the sample processed on a CaF_2 substrate. The estimated parameters of this device are all within the parametric tolerance range. In particular, the misalignment of the two etching levels is of 47±10nm. In Figure 11(b) is shown a cleaved sample produced on a Si substrate. Such a picture can't be obtained with a CaF_2 substrate because the cleavage planes are oriented at 60°. We can see the very steep sides of the grating as well as the almost perfectly flat etching bottoms.

A characterization bench is currently under development in order to measure accurately the optical performance of these devices. Besides, theoretical work is currently performed in order to obtain polarization-insensitive filters.

4. CONCLUSION

In conclusion, we have presented in this article several strategies aiming at the improvement of the performances of photodetectors in the mid-IR range using thin film deposition methods and patterning methods.

First, we demonstrated that a performant multi-layer anti-reflection coating can be deposited directly ontop of the photodetector surface in order to avoid flux losses and ghost images, with much better performances than a conventional mono-layer coating. Second, additional functionalities can be added at the pixel-level using planar structuration approach. We have shown that multi-spectral imaging applications can greatly benefit from pixelated coatings structured directly at the surface of the detector. Pixel dimensions in the range of 10µm.can be fabricated. Eventually, photonic filtering structures have been investigated. We have illustrated the relevance of wideband doubly-corrugated zero-contrast grating filters for pixelated applications, but also their fabricability using conventional photolithography and etching methods.

Safran Reosc continuously improves its process for coating and patterning thick multilayer optical stacks directly on IR photodetectors, and is currently developing new processes for a more diverse offer in the field of multispectral filters. Our ambition is to propose, in a near future, a broad set of solutions for multispectral IR real time imaging systems.

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