Monolithic integration of flexible spectral filters with CMOS image sensors at wafer level for low cost hyperspectral imaging

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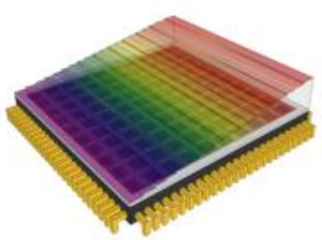
Abstract

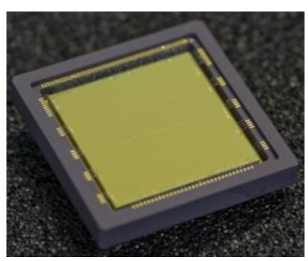
To enable industrial adoption of hyperspectral imaging we have developed a unique integrated hyperspectral filter/imager technology. The spectral filters are monolithically deposited/integrated on top of CMOS imagers at wafer level. The materials of the filters are chosen such that they are compatible with the production flows available in most CMOS foundries. The result is a compact & fast hyperspectral imager made with low-cost CMOS process technology. We have demonstrated this hyperspectral technology on two specific instances – a wedge based line-scan hyperspectral imager and a tile based snap-shot imager. The line-scan imager is based on a CMOSIS CMV 4000 image sensor and the spectral specifications are 100 spectral bands in the range of 600-1000nm and the FWHM of each band is around 10nm. The snapshot imager is based on a CMOSIS CMV 2000 image sensor with the following spectral specifications: 32 spectral bands in the range of 600-1000nm and also with FWHM of each band around 10nm. Furthermore, both technology is flexible such that many system parameters like number of spectral bands, layout of the filters, FWHM of the filters and the spectral range can be tuned to match specific application requirements.

1. Integrated Spectral Filter Approach

Hyperspectral imaging is an advanced imaging technique which captures and processes multiple narrow band images over a spectral range. Capturing spectral images of an object enables detailed analysis and identification of the objects as often different objects contain unique information at different wavelengths. The potential of hyperspectral imaging has been demonstrated for several applications using laboratory setups, it is currently mostly still a scientific tool. Indeed, many of the commercial hyperspectral cameras available today are targeted for the research market, e.g. remote sensing [1] and food science [2]. The adoption of hyperspectral imaging in mainstream industrial applications like machine vision or biomedical has so far been limited, due to the lack of fast, compact, and cost-effective hyperspectral cameras with adequate specifications.



(a)

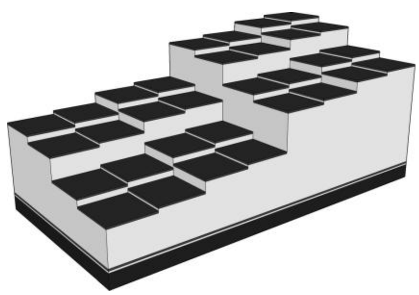


(b)

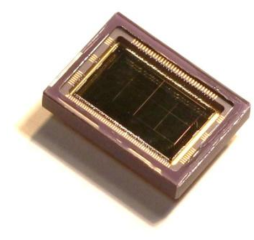
Spectral range	600-1000nm
# Spectral bands	100
FWHM	< 10nm, using collimated light
Filter transmission efficiency	~ 85%
Imager	CMOSIS CMOS CMV 4000 imager
#lines/ spectral band	16
#spatial pixels/line	2048
scan rate in #lines/sec	2880
Pixel pitch	5.5 µm

Figure 1: (a) concept of wedge layout (filter heights exaggerated for illustration) (b) a packaged wedge based hyperspectral imager (c) Table with key specifications of wedge based spectral imager

We have developed a unique integrated hyperspectral filter/imager technology [3][4], where the spectral filters are monolithically deposited/integrated on top of CMOS image sensors at wafer level. The materials of the filters are chosen such that they are compatible with the production flows available in most CMOS foundries. This is achieved using a set of CMOS compatible production steps, like deposition, patterning and etching, which allows pixel level accuracies in filter alignment. The key features and benefits of this approach are as follows. The spectral filters designs are based on the Fabry Pérot principle [7], which enables the design and fabrication of ranges of optimized filters at various wavelengths with flexible/customizable layout (covering different groups of pixels) and customizable spectral bandwidth. It is important to note that, unlike grating or linear filters, in our approach, imagers can be covered with only selected spectral bands in a certain range instead of the complete spectral range. A wedge layout, where the filters are arranged in a staircase-like structure over the pixel array, is useful in applications where the scene of interest has a natural translation movement (e.g. in a conveyor belt) and the hyperspectral imager will be used as a line-scanner. An alternative design is a tiled layout, in which filters are laid out in rectangular or square shapes on top of (groups of) pixels. This tiled layout is e.g. useful in applications where the scene of interest has objects that are static or have random movements. The wedge layout enables the acquisition of hyperspectral images with high spectral and spatial resolution, while tiled layouts inherently dictate a trade-off between spectral and spatial resolution. As a result, both designs will enable a different set of target applications. Another advantage of the integrated filter approach is that the number of discrete & bulky optical components can be reduced, which results in a more cost-effective and very compact imaging system. Since this integrated production method can utilize the mass manufacturing facilities, the cost & time of production can be substantially reduced for volume applications.



(a)



(b)

Spectral range	600-1000nm
# Spectral tiles/bands	32
FWHM	< 10nm, using collimated light
Filter transmission efficiency	~ 85%
Imager	CMOSIS CMOS CMV 2000 imager
Imager resolution	2Mpixel
Resolution per tile/band	256x256 pixels
Frame rate in # hypercubes/sec	340
Pixel pitch	5.5 µm

Figure 2: (a) concept of tiled layout (filter heights exaggerated for illustration) (b) a packaged tile based hyperspectral imager (c) Table with key specifications of tile based spectral imager

The direct post-processing of the filter structure on top of an active IC, in this case the image sensor, introduces additional restrictions on the type of materials and processing steps that can be used, in order not to compromise the functionality of that IC. The additional process steps and materials should be compatible with the contamination level, mechanical, temperature and other limitations of that IC. This means that none of the process steps can use materials or tools that would damage the image sensor below. Fabry-Pérot filters with high quality and good spectral resolution can only be obtained by using highly reflective mirrors. These mirrors should also have a minimal absorption of the light to maximize the transmission efficiency of the filter. Additionally, if a full range of Fabry-Pérot filters has to be constructed over a certain wavelength range, it is beneficial that both the reflectivity and absorption stay as constant as possible over this spectral range. Metal mirrors have the advantage that only a single layer is needed, reducing the cost. However, this single layer typically has a high absorption, which limits the thickness of the mirror layer. A certain thickness is however required to achieve the desired reflectivity. Silver is the best available metal, as it can reach a reasonable reflectivity at a reasonable absorption over the complete VNIR spectral range. Unfortunately, this metal introduces contamination risks into the standard IC processing flow as it tends to diffuse into the different layers and into the tools. Because of the high absorption of metal mirrors combined with the fact that silver is not found in classical CMOS fabrication line due to contamination risks, we have chosen to use a distributed Bragg stack as the mirror. Distributed Bragg stacks are formed by combining two types of dielectrics into an alternating stack of these two materials: one material with a low refractive index and one material with a high refractive index [9].

The basic Fabry-Pérot filter structure is then extended into a set of filters by varying the cavity height. Wedge filters or tiled (snapshot) filters for different wavelengths are built by varying the cavity height across the active area of the image sensor. Using design and simulation tools, e.g.TFCalc, one can calculate the difference in height for the different steps in the wedge or tiled for a certain spectral resolution. A straight-forward implementation is given in Figure 1(a) for wedge design & in Figure 2(a) for tiled (snapshot) design, which varies the height of the cavity over the imager (note that the height difference between the steps is exaggerated for illustrative purposes). Furthermore, we can account for process variations (e.g. layer thicknesses) by adding additional filter structures that cover a safety zone on either side of the desired spectral range. The actual extra bands can be calculated from the maximum tolerances of the involved semiconductor processing tools.

2. Novelty of our approach/Related work

The core of a hyperspectral camera is a spectral unit, which is an optical component that splits the light into its separate wavelengths. A first, well known and often used dispersive element is the grating [5], which is sometimes used in combinations with prisms for an optimal performance. Gratings are very sensitive to the angle of incidence of the light and, therefore, often require complex fore-optics, such as telecentric lenses, narrow slits, collimators and/or focusing lenses. While in our approach, we integrate the filters directly on top of the imagers at wafer level and remove the requirements of discrete optical components, complex system assembly and alignment issues, thus enabling a solution that is scalable to volume applications.

Other types of spectral units use tunable optical filters for selecting the correct wavelength [6]. Examples, typically used in frame cameras, are the Liquid Chrystal Tunable Filters (LCTF) and Acousto-Optic Tunable Filters (AOTF). An LCTF however suffers from reduced light throughput, which limits acquisition speed. In addition, tuning the wavelength requires the crystal to react on a changing voltage, which is known to be slow. Hence the sequential selection of many different wavelengths leads to a slow overall acquisition of a full hyperspectral image. An AOTF uses acoustic waves to tune the filter properties of the filter structure. The transmission efficiency is high, but these devices are expensive and consume power because of the RF source. While this approach offers flexibility to tune the filter to select different wavelengths, these have lower acquisition speed. In our approach, especially in the snapshot layout (Figure 2) for the filters [4], images at different wavelengths are captured simultaneously, thus achieving high speed. However, in our case the spatial resolution is traded-off for high speed acquisition. Nevertheless, our approach becomes scalable since large area imagers can be fabricated at relatively low-cost to compensate for loss of spatial resolution.

Thin film filters like absorption filters are another approach which are generally constructed of dyed glass, lacquered gelatin, or synthetic polymers (plastics), and have a wide range of applications. While these offer several advantages like low cost & high stability, the most important disadvantages are the limited spectral resolution (30nm - 250 nm) and low peak transmittance of the bandpass filter (20-30%). Another type of filters are Linear Variable Filter (LVF) [8] which a step-wise approximation for creating filters in a certain wavelength range. These filters are processed on a substrate and then integrated separately with the imager, leading to a longer distance between the filter and the imager when compared to a monolithic integration. This increases the amount of stray light and reduces the performance of the filter. Additionally, alignment of filter substrate and imager is needed, which increases the production cost. Furthermore the LVF selects a continuously varying wavelength over its width and hence does not allow the parallel acquisition of multiple lines at a fixed wavelength. Additionally, it does not have any flexibility to cope with the process variations that are inherent to the processing of these chips. This leads to a lower performance, decreased yield or additional development costs to reduce the tolerances on the processing variations.

3. Prototype Results & Summary

We have demonstrated this integrated hyperspectral technology on two specific instances – a wedge based line-scan hyperspectral imager [3] and a tiled layout based snap-shot imager [4]. The line-scan hyperspectral imager is based on CMOSIS CMV 4000 image sensor with demonstrated specifications as outlined in Figure 1. The snapshot imager is based on CMOSIS CMV 2000 image sensor with demonstrated specifications as outlined in Figure 2. Both of these instances were generated in a single production flow on the same wafer (Figure 3). These imagers have been diced, packaged, integrated into a machine vision camera, measured and compared against a state of the art (grating based) spectral camera (Figure 5). Spectral response of few selected filters from the wedge imager are also shown in Figure 6. The overall filter height is < 1µm, thus significantly reducing the form factor of the spectral unit compared to a state of the art grating based solution. Furthermore, to facilitate easier adoption of this technology by industries we have also developed an evaluation system (Figure 4), which is available to enable application development, and is including illumination system, translation stage, host PC, and related software modules. The underlying technology is flexible such that many system parameters like number of spectral bands, layout of the filters, FWHM of the filters and the spectral range can be tuned to match application requirements.

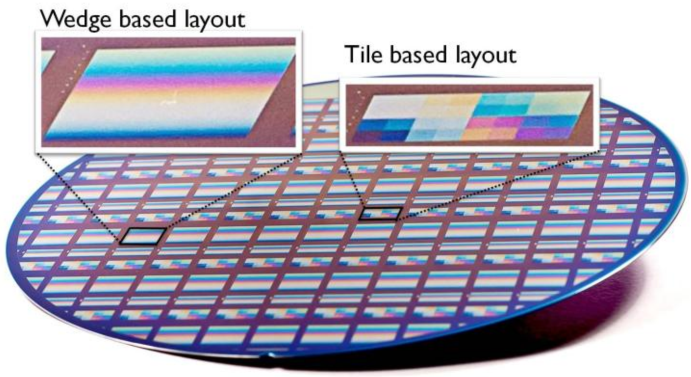


Figure 3: A wafer image both types of spectral filter layout monolithically integrated with CMOS image sensors

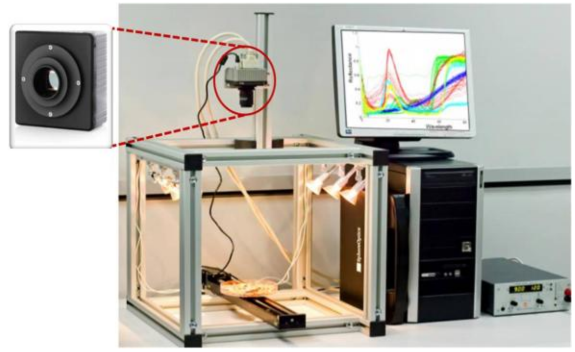


Figure 4: Illustration of our evaluation system including spectral imager, camera, translation stage, illumination system, host PC and related software modules

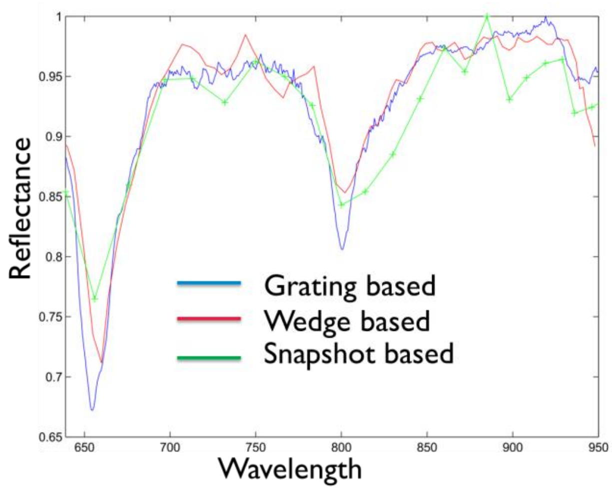


Figure 5: Spectral measurements on an Erbium reference tile with 3 different hyperspectral cameras. A state of the art grating based camera, our wedge based camera, and our snapshot (tiled) based camera

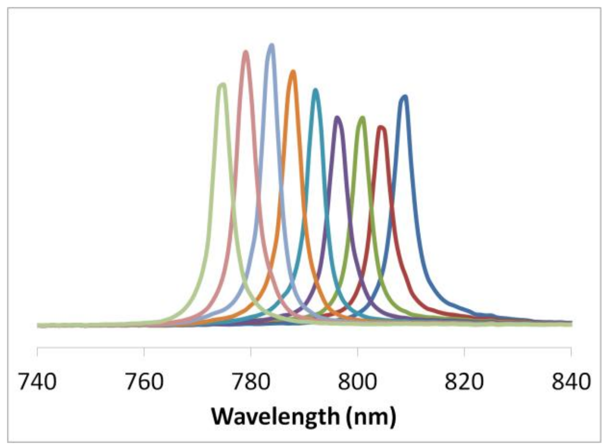


Figure 6: Spectral response of few selected filter bands from the wedge based spectral sensor

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