

Color filters including infrared cut-off integrated on CMOS image sensor

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Abstract: A color image was taken with a CMOS image sensor without any infrared cut-off filter, using red, green and blue metal/dielectric filters arranged in Bayer pattern with 1.75µm pixel pitch. The three colors were obtained by a thickness variation of only two layers in the 7-layer stack, with a technological process including four photolithography levels. The thickness of the filter stack was only half of the traditional color resists, potentially enabling a reduction of optical crosstalk for smaller pixels. Both color errors and signal to noise ratio derived from optimized spectral responses are expected to be similar to color resists associated with infrared filter.

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1. Introduction

Color capturing by CMOS or CCD visible image sensors is currently performed by pigmented or dye-doped organic color resists, arranged in Bayer array integrated on the pixel array, below the microlenses. The technology has been optimized to provide a fine tuning of the

spectral responses of the red, green and blue (RGB) filters, and a low-cost integration with a limited number of technological steps, well controlled in micro-electronic facilities.

As organic resist filters are partially transparent in the near infrared, they are traditionally associated with an additional, non patterned, infrared cut-off filter. This filter usually lies within the imaging system. It is made of a large number of dielectric layers, providing both high transmission in the visible range, and low transmission in the near infrared, to allow a correct color rendering.

Also, as the pixel size continues to shrink, there is a need for reducing the distance between the bottom of microlenses and the silicon interface [1], to maintain a large photon collection efficiency together with low optical cross-talk. While the height of the back-end stack can be reduced by etching a cavity [2], the organic resist layers can hardly be made thinner without impacting the filtering efficiency.

Other types of color filters for visible imagers have been proposed with reduced thickness: inorganic films prepared by metal organic chemical vapour deposition [3], amorphous silicon films with variable thickness [4], or sub-wavelength patterned metallic gratings [5]. But they still need the extra filter cutting the infrared, or show spectral responses relatively different from the color matching functions, together with relatively low transmission, inevitably inducing color errors or degraded signal to noise ratio after color reconstruction. Another study focused on a photonic crystal structure alternating high and low index dielectric layers to realize complementary filters [6], based on a non Bayer arrangement including infrared filtering, eliminating the need for an external filter. However, the quality of color images is affected by the non ideal shape of the spectral responses, and by the subtraction operations required to extract the RGB signals. Also, the filter height remains high, more than one micrometer.

A recent work [7] reported the demonstration of a Ag-SiO₂-Ag Fabry-Perot etalon with variable thickness of the cavity to tune the transmitted wavelength from blue to red, combining the advantages of low thickness (a few hundred nanometers), large infrared rejection, and reduced angular sensitivity compared to a full dielectric multilayer stack.

In this paper, we propose to go further with this approach of metal/dielectric filters, using double Fabry-Perot cavities [8] to optimize the imaging system performances, and showing a first integration of RGB metal/dielectric filters, with half the thickness of color resists on CMOS image sensors with 1.75 μ m pixel pitch, without the need for an infrared cut-off filter.

2. Filter optical design

Single and multiple cavity metal/dielectric filters have been extensively studied [9] and reviewed [10]. This study is based on two of their well-known properties: first-order metal/dielectric filters do not show longwave sidebands due to the dispersion of the extinction coefficient of real metals, and multiple cavity metal/dielectric filters have a more rectangular shape than single cavity filters, at the expense of a lower transmission [10].

For imaging applications, the double cavity metal/dielectric stack including three metallic layers and two dielectric spacers (Fig. 1) was found to be the best compromise between the simplicity of the stack for a technological realization, and the agreement of the spectral responses with colorimetric requirements, ideally close to the CIE 1931 RGB color matching functions [11] as the signals provided by the camera are considered as RGB signals in this study. Ag was identified as the best metal due to its low refractive index, allowing relatively high transmission of the filters, from 50% to 70% depending on the central wavelength, with layer thickness between 10nm and 40nm. The transmitted wavelength was controlled by the thickness of only two layers, the two dielectric spacers, which is compatible with a technological process flow of limited complexity. The thickness was approximately the same for the two cavities, varying between 50nm and 100nm from blue to red, to avoid a split of the resonance. Two additional dielectric layers at the bottom and at the top of the stack acted as index-matching layers.

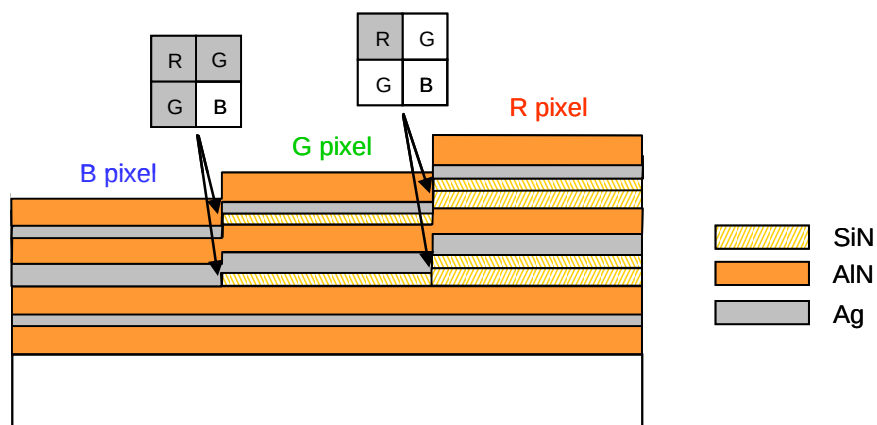


Fig. 1. Schematic cross section of patterned RGB metal/dielectric filters (vertical dimensions are enhanced for clarity).

The optical properties of Ag were carefully investigated, as they are critical for a reliable control and prediction of the filter spectral responses. A specific procedure was set up, with the realization of a set of specific metal/dielectric stacks including incomplete filters and complete filters, and the measurement of their spectral responses in transmission and reflection [12]. These responses were simultaneously fitted using an adequate multi-parameter model for the material optical properties. It was found that the optical properties of Ag significantly vary with the layer thickness, and it is crucial to take this variation into account in the design of the filters.

The suitability of color filters for imaging applications was evaluated in detail, considering the filters as part of the whole imaging system including the source, the scene, imaging optics, and the image sensor characteristics. The two major criteria impacted by the filter spectral responses are the color error ΔE and the signal to noise ratio (SNR). More details are given elsewhere [13].

Here, color errors were computed from the RGB signals provided at the sensor output, according to the Delta-E 2000 definition [14] in the CIELAB colorimetric space, for the 24 reference color patches of the Gretag-MacBeth colorchecker [11]. The signal to noise ratio was calculated for a grey patch, from the number of photons impinging on a pixel and the number of photoelectrons generated in each of the three RGB signals. The various sources of noise in the system, i.e. photon noise, noise floor and photo-response non uniformity (PRNU) of the sensor, were considered. Filter evaluation was performed considering typical conditions of a 3Mpixel sensor with $1.75\mu\text{m}$ pixels and associated imaging system: D65 illuminant [15], scene reflectance 18%, optics transmission 80%, optics aperture $f\# = 2.8$, monochrome response of a $3\mu\text{m}$ thick Si layer, frame rate 15fps, noise floor $3e^-$ and PRNU 1%.

For a given set of RGB filters, a color correction matrix and white balance were used [13] to minimize ΔE_{2000} and the value of the scene illuminance (in lux) needed to get a SNR of 10, a value typically considered as the lowest one acceptable with cameraphone applications used in low light conditions.

This evaluation of RGB filters was performed at each step of the iterative optimization process, which aims at providing the most suitable filter spectral responses. The algorithm used simulated annealing and simultaneously optimized the three RGB spectral responses. It also took into account the technological constraints, by setting identical thickness values between the three filters for some of the layers, as only two dielectric layers have variable thickness in the stack. The designs used the measured optical properties of all the materials. Although the filter evaluation used the monochrome response of Si, the designs optically assumed the presence of an infinite silica substrate below the filters. This was a good approximation of the front-side imager configuration of the CMOS demonstrator, where silica back-end layers lay over the silicon wafer covered with an antireflective coating.

The simulated performances of metal/dielectric filter without infrared cut-off filter were found to be close to traditional color resists with IR filter. Several designs of metal/dielectric filters were proposed (Table 1), optimizing either the color error, or the SNR. In particular, the SNR was favoured with a red-shift of the red filter. One good compromise led to $\Delta E_{2000} = 2.1$ (rms value, averaged over the 24 color patches) and 50lux for SNR 10, only slightly worse than color resists and theoretical IR filter with $\Delta E_{2000} = 2.9$ and 46lux for SNR 10. The corresponding spectral responses are shown in Fig. 2. Very low color errors could be obtained with another design ($\Delta E_{2000} = 1$) without any strong degradation of the SNR (57lux for SNR 10).

Table 1. Color Error and SNR Performances of Filters Simulated on Infinite Silica Substrate, Taking into Account the Monochrome Response of 3 μm Thick Si, 1.75 μm Pixel

	ΔE_{2000}	ΔE_{2000} max	scene illuminance (lux) for SNR = 10
Color resists + IR cut-of filter	2.9	6.6	46
Metal/dielectric filters, design 1	2.1	6.1	50
Metal/dielectric filters, design 2	1	2.3	57

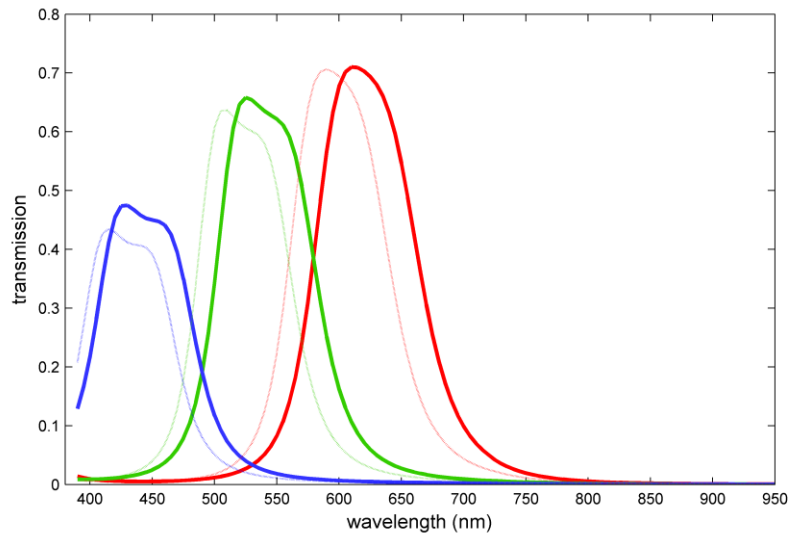


Fig. 2. Simulated spectral responses of RGB metal/dielectric filters designed on glass wafer (design 1 of Table 1), taking into account the monochrome response of Si. Only two layers within the 7-layer filter have variable thickness from blue to red. Dark curves: Spectral responses at 0° incidence. Light curves: at 30°.

In an imaging system, pixels at the edges of the sensor chip are illuminated by rays with oblique incidence related to the accessible field, typically $\pm 30^\circ$ in a conventional micro-camera module for cameraphone. Whatever the technology, either color resists with infrared cut-off filter, or metal/dielectric filters, the spectral responses change under oblique illumination, but in a different way. The transmission of color resists is only slightly reduced due to the longer path of light in the absorbing material, but the cut-off wavelength of the infrared filter strongly varies with the angle, significantly reducing the R signal while keeping the B and G signals nearly unaffected. The spectral response of all three RGB metal/dielectric filters is shifted towards the blue, under oblique illumination.

With metal/dielectric filters, the best solution to manage the spectral shifts was to vary the color correction matrix from the center to the edge of the chip, in which case the degradation of performances remained limited ($\Delta E_{2000} = 3.1$ at 30° versus 2.1 at 0° , 70lux for SNR = 10 at 30° , versus 50lux at 0° for the design 1).

The spectral responses of metal/dielectric filters are also naturally sensitive to errors on the thickness of the dielectric spacers, impacting the central wavelengths. For industrial purposes, the control of the dielectric thickness required on the surface of a wafer, and from wafer to wafer, is evaluated to $+ -2$ to $+ -4\%$ to maintain ΔE_{2000} and SNR to acceptable values, typically $\Delta E_{2000} < 5$ and an increase of scene illuminance limited to 50lux to get a SNR of 10. This tight requirement can be addressed with appropriate PVD sputtering machines for all three basic materials of the filters, or with PECVD machines for some dielectric materials. Other deposition techniques can also be considered, such as ALD providing excellent uniformity, but at the expense of low deposition speed.

3. Filter realization and demonstration on CMOS image sensor

Integration of double cavity metal/dielectric filters in Bayer array requires two dielectric layers with variable thickness between R, G and B filters. We chose to realize this staircase shape using two different dielectric materials, AlN and SiN. A uniform AlN layer encapsulated the Ag layer. It was deposited in the same machine to avoid any degradation of Ag. The AlN layer was also a selective etching layer for the etching of the SiN deposited above. The deposition and etching of SiN was repeated twice with two different masks, creating two steps to define the three different thicknesses corresponding to R, G and B pixels (Fig. 1).

Filters were realized by PVD magnetron sputtering as this deposition technique is commonly used in the micro-electronic industry. AlN and SiN were selected due to their good etching selectivity, their negligible optical absorption and the sharp interfaces formed with Ag layers, as observed by TEM (Fig. 3). These materials were successfully used in the demonstration of non patterned filters with high transmission, and negligible optical diffusion ($< 0.2\%$ in transmission measured over a 180° cone with an integrating sphere) correlated with the low roughness of the filter stack (typically 0.8nm rms). The measured spectral responses were found to be in excellent agreement with the designs (Fig. 4). These filters passed optical ageing tests under sun-like conditions (10 day cycles with 8h at 1120W/m² insulation and 55°C followed by 16h in the dark at 25°C), with variations of the spectral responses below 1%. Also, the transmission of filters was found to be unchanged on samples made up to three years ago and stored in ambient conditions.

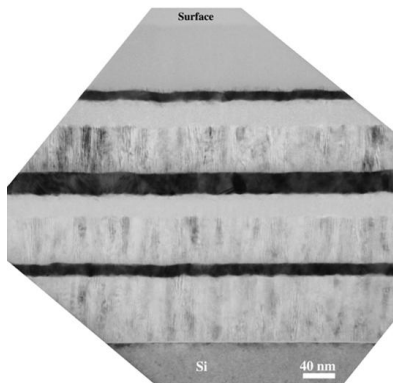


Fig. 3. TEM image of a double cavity metal/dielectric filter including two different dielectric materials.

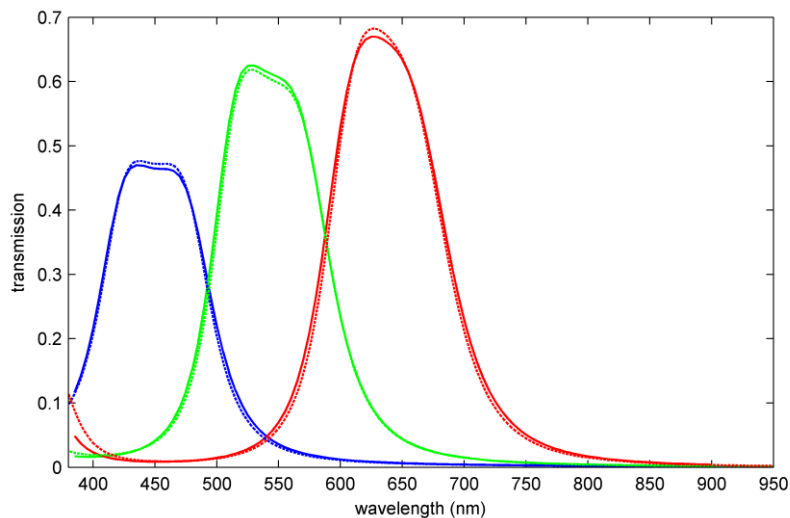


Fig. 4. Measured spectral responses (plain lines) of RGB metal/dielectric filters designed on glass wafer, compared with theory (dashed lines).

Filter integration on CMOS sensors was chosen to be realized on wafers without cavity etch in the back-end layers, to avoid potential technological difficulties occurring from filter deposition on a non-flat surface, for this first demonstrator. The whole process required four successive levels of photolithography, etching and stripping for the patterning of RGB filters: photolithography with two sets of masks (Fig. 5), dry etching, and resist stripping. Wafer cleaning was regularly performed to protect the machines from possible contamination by Ag, whenever necessary.

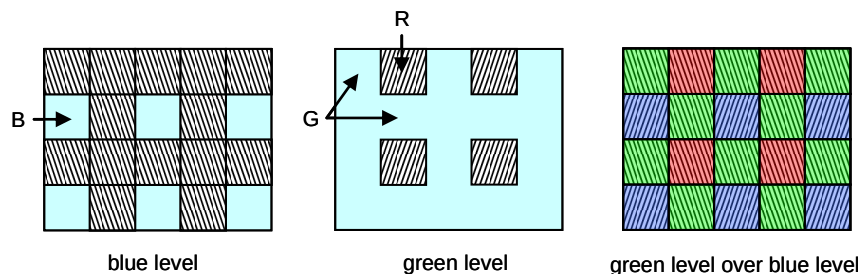


Fig. 5. Simplified scheme of the “blue” and “green” masks used for the patterning of metal/dielectric filters.

Finally, approximately 400nm thick metal/dielectric filters with 1.75 μ m pitch were realized on CMOS wafers (Fig. 6). No microlenses were realized above the filters, as the procedure for introducing wafers with Ag in this part of the clean room was not validated yet. The size of the pixels on the filters was slightly larger than expected in the blue (1.85 μ m), and slightly lower in the red (1.65 μ m). An appropriate re-sizing of the masks should help correct this effect in future demonstrators. After each individual etching step, the transition areas between two neighbouring pixels, were observed to be 70-100nm large. At the end of the process, the misalignment between the four levels was estimated to be around 200-250nm, similar to the overlap areas between two neighbouring pixels in organic resists, although the alignment parameters were not fully optimized. The misalignment of the last level was measured to be about 300nm at 3 σ with respect to CMOS alignment marks.

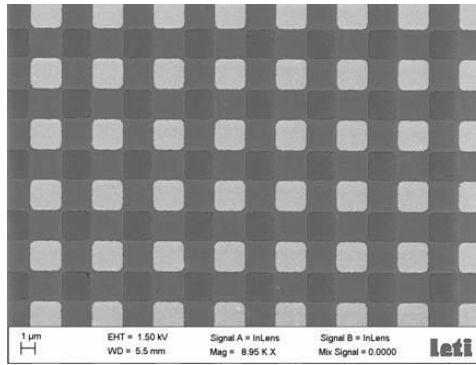


Fig. 6. SEM images of metal/dielectric filters on CMOS wafer, at mid-process.

For the electro-optical characterization, four chips were extracted from a wafer and packaged in imager module with $f\#$ 2.8 aperture. Quantum efficiency (QE) measurements (Fig. 7) were realized on large uniform stripes where neighbouring pixels had the same filter color. In this configuration, optical crosstalk was in principle compensated for between two neighbouring pixels, which would not have been the case on Bayer patterns without microlenses. The QE was below 1% beyond 770nm, without any specific infrared cut-off filter as traditionally used in visible imager modules, as a result of the metal/dielectric filter optical properties. The three RGB responses were clearly distinct. Oscillations were observed in the QE spectra, although they were absent in the spectral responses of filters deposited on glass wafers. They were attributed to interferences between the filters and thin nitride layers present within the back-end stack in the absence of cavity etch, inducing reflexions.

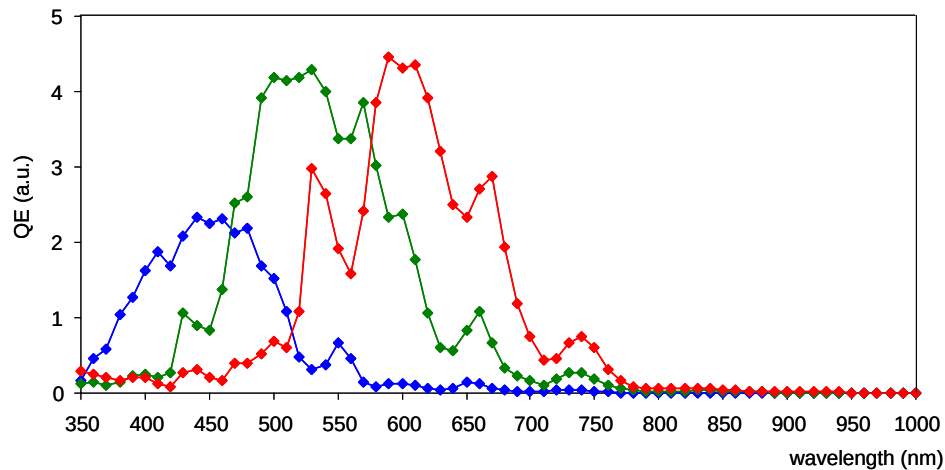


Fig. 7. QE measured on uniform stripes of metal/dielectric filters deposited on CMOS sensor with $1.75\mu\text{m}$ pixels, without any microlenses nor cavity etch.

The measured peak QE was strongly impacted by the absence of microlenses above the filters: due to the absence of focussing, a large amount of photons impinged on non photosensitive areas of the silicon surface, or on metal lines in the back-end before hitting the silicon surface.

Additional measurements showed no impact of the filter process on darkness current, temporal noise, lag, a low degradation of saturation voltage, but a degradation of PRNU possibly explained by the presence of resist residues which were accidentally remaining on some pixels.

Finally, a 3Mpixel color image was realized with the metal/dielectric filters patterned in Bayer array on the CMOS chips, without infrared cut-off filter, in imager module with $f\#$ 2.8, scene illuminance of 2000lux, temporal average on 20 frames, and frame rate 15fps (Fig. 8).



Fig. 8. First color image with metal/dielectric filters patterned in $1.75\mu\text{m}$ pixels on CMOS, without IR filter.

4. Conclusion

For the first time to our knowledge, a 3Mpixel color image was demonstrated without infrared cut-off filter, with a micro-camera module including 7 layer metal/dielectric filters arranged in Bayer array with $1.75\mu\text{m}$ pixel pitch on CMOS front-side image sensor. The thickness of the filters (400nm) was only half of the traditional color resists, which gives the metal/dielectric filter technology an additional advantage for smaller pixels, to maintain QE and cross-talk performances. The demonstration was realized in waferlevel technology.

The theoretical performances of unpatterned double cavity metal/dielectric filters, in terms of color error and SNR, were shown to be close to traditional color resists with infrared cut-off filter. They were optimized taking into account the optical properties of Ag layers with their dependence on the thickness, estimated within the stack.

From the material point of view, there is a space for improvement of the optical properties, regarding the relatively low transmission of the blue metal/dielectric filters. The relatively low transmission in the blue is linked to higher values of the refractive index of Ag at these wavelengths, and may be limited by the quality of the Ag layers or interfaces with dielectric materials.

The work is ongoing to optimize color and SNR performance. The other items to be addressed are the possibility to deal with Ag in industrial clean rooms, filter reliability additional tests, and the investigation of deposition machines with sufficient thickness uniformity.

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