Experimental Characterization of a CMOS Pixel with a Tunable Color Space

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Abstract

The Transverse Field Detector (TFD) is a pixel device proposed for imaging without color filters. Color separation is obtained with a suitable generation of transverse electric fields in a semiconductor single depleted region and is based on the Silicon absorption properties. Thanks to this working principle, this device has a unique characteristic to have an electrically tunable native color space. In this paper we review the operation of color devices based on the Silicon absorption properties, then we focus on the potential advantages of the TFD with respect to previous solutions. We present opto-electrical experimental measurements on the characterization of a prototype, and we suggest and simulate a re-designed structure that can improve the device color detection capabilities. We then propose a dual use of the TFD: in "standard imaging" mode it can achieve performance comparable to those of commercial cameras (in terms of mean color reconstruction error and color conversion matrix coefficients); in "high color accuracy (HCA)" mode it can achieve optimum color reproduction (mean $\Delta E_{a,b}$ = 0.3 for the Macbeth Color Checker). This result is obtained simply through three consecutive image acquisitions with electrical tunings of the device color space.

Introduction

Most of the color pixels used in modern digital cameras base their color detection capability on a Color Filter Array (CFA) deposited on top of the Silicon active layer [1]. Many industrial patents and studies in the scientific literature can be found about the choice of filters shape, pattern, and number for optimum color reproduction [2-4]. Beyond typical GRGB Bayer patterns, other solutions (e.g. four or more color CFAs) are mounted on cameras available to the end user. Nevertheless, the problem of the choice and implementation of the optimum filters set is still an open issue.

Optimizations reported in the scientific literature are typically designed on the basis of a reference color chart, like the Macbeth Color Checker (MCC), with a reference illuminant, like the standard D65 [2]. In other situations, the optimum choice of the filters shape, and corresponding Color Correction Matrices (CCMs) can be those which give the best results averaging over different color charts (with more or less saturated colors) and different illuminants (in the typical interval of interest for digital imaging, ranging from incandescent bulbs to cold standard sources like the D75). The optimization is required by the fact that the shape of the filters determines a priori the camera color space, which is not a linear combination of the tristimulus functions, while the conversion techniques have to be linear for sake of computational simplicity. No change or adaptation to the scene is possible for the CFA camera color space.

Some color pixel topologies are different from the ones mentioned above in that color detection is performed without using CFA, but relying on the relevant physical dependence of the Silicon absorption coefficient from the wavelength in the visible and near infrared range.

This particular approach to color acquisition dates back to 1975, when Layne and Ford proposed a device based on two superimposed diodes of carefully chosen thickness [5]. A similar device has been developed by Burkey et al. at Eastman Kodak in 1978 [6], almost at the same time of the first CFA, developed at Kodak by Bayer. In this kind of devices carriers generated at different depths, and therefore related to different portion of the spectrum, are collected separately by means of a vertical structure made of alternating p and n type silicon. The percentage of radiation collected by each of the stacked diodes depends on the absorption coefficient which in turn is a function of the wavelength. Similar detectors were subsequently proposed in many other researches, as for instance by T. Yoshikawa et al., from Sharp, in 1979 with two junctions for wavelength detection and by D. L. Gilblom et al, of Foveon in 1999, with three junctions and therefore suitable for color detection [7-8].

A hybrid approach between the use of CFA and the absorption properties of Silicon was proposed by Sharp in 2009 [18-19]: in their device the use of a magenta filter, deposited over two stacked pinned photodiodes, and of a green filter, deposited sideways over a further photodiode, allowed to use a 2-color CFA, still obtaining three different spectral functions suitable for color imaging.

A different approach to exploit the wavelength dependence of the Silicon absorption coefficient has been proposed by several authors, as for instance David D. Wen et al. in 2005 [9]: the spectral sensor device is made by a single junction where the depth of the depletion layer can be varied by changing the bias voltage. In this way the spectral quantum efficiency can be tuned. Subsequent acquisitions with different voltages give signals related to different portion of the spectrum of the incoming radiation and therefore can be utilized to determine the color.

Within all the mentioned detectors, the one who found the widest application for the realization of color pixels in CMOS-like technologies is the one of Foveon mentioned above. In this device, three different electrical junctions (and thus three depleted regions) are built at selected different depths, stacked one another. Taking advantage of the mentioned dependence of the absorption coefficient from the wavelength, the junction built closest to the surface collects mainly carriers generated by blue photons, the intermediate junction collects mainly carrier generate by green photons and the deepest junction those generated by red photons. The junctions thus behave as if there were color filters, but there is no physical filter, so that there is no loss of light and no need for color reconstruction at each position through demosaicking as each pixel is itself color sensitive.

We define the *equivalent filter* of this kinds of structures as the ratio between the spectral response of a single collecting contact and the spectral response that would be obtained using a white pixel (i.e. without specific doped region designed to implement the stacked junctions), made in the same technology.

The mentioned advantages (no filters, no demosaicking) are common to another pixel topology, proposed in 2008 by the authors of this paper. Their pixel device, named Transverse Field Detector (TFD) is based again on the absorption properties of Silicon, but the pixel structure and the collection of photo-generated carriers are different (see Fig. 1) [10, 11]. In detail:

- the pixel structure includes a single active region (for instance a few µm thick P-type epitaxial layer of Silicon), where photocarriers are generated;
- a single depletion region is obtained in the epitaxial layer through the reverse biasing of at least three different N-type regions closely designed over the P-type layer;
- a proper biasing of the different N-type electrodes V_1, V_2 and V_3 (suitably isolated through surface P-type implants) allows obtaining a transverse electric field configuration inside the epitaxial layer (see the electric field streamlines schematically represented by arrows in Fig. 1). In this way photocarriers are gathered at different electrodes as a function of their generation depth.
- as each electrode – V_1, V_2 and V_3 – collects carriers up to a different depth, it has a different spectral response (or a different equivalent filter as defined above).

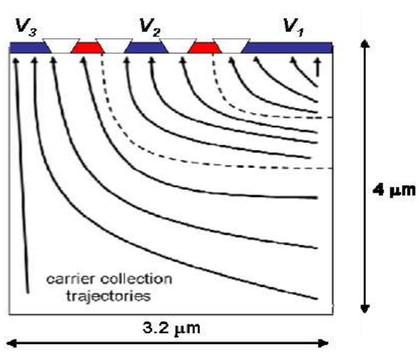

***Figure 1**. Schematic representation (not to scale) of a TFD pixel. Three N-type regions (biased at voltages V_1, V_2 and V_3) determine a single depleted region in which the carrier collection trajectories depend on the biasing values. The contact biased at V_1 collects carriers generated mostly by photons in the blue range. The contact biased at V_2 collects photons up to a greater depth. The third contact collects carriers generated in the remaining region, with a significant portion determined by radiation in the red range. The different spectral responses obtained in this way can be tuned by changing the applied voltage, thus changing the way the three contacts share the carriers generated in the single depleted region. Surface P-type implants are used for isolating the collecting electrodes, thus allowing their bias at different voltage values.*

There is another strong advantage that is peculiar of the TFD structure. As the electric field streamlines (which represent the carrier collection trajectories) depend on the biasing of the (at least) three N-type contacts, a change in the applied voltage values results in a change in the collection trajectories, and thus in the equivalent filters.

As a consequence, the TFD features a color (equivalent) filter set (i.e. a color space) that is not determined a priori on the basis of an optimization made as described above. In the TFD there is an initial optimization of the equivalent filters that mostly depends on the chosen technology and the designed device geometry. This choice allows to use the TFD for “standard imaging mode” acquisition. Besides, among a certain range which is set by constraints on the maximum biasing conditions, the equivalent filters can be tuned so that the color space can be changed [12]. The tunability of the device color space can be used:

1) to implement a white balance algorithm in which the pixel color space is adapted to the illuminant prior to image capture, as demonstrated in [13];
2) to enhance the saturation of certain colors, somewhat adapting the color space to the scene chromaticity as proposed in [20];
3) to capture consecutive images with different color spaces in order to enhance the color reconstruction fidelity, as will be proposed for the first time in this paper.

Points 1) and 2) above can be clearly implemented also through post-acquisition digital image processing. However, as a general rule, changing the color filter set *a priori* instead of correcting the captured image after the acquisition, has an advantage in terms of signal to noise ratio, in case of poor SNR (whenever a large coefficient is digitally applied in an image correction process, both signal and noise are amplified) [13].

In this work we first review an implementation of the TFD built in a standard (not optimized for imaging) CMOS technology, in terms of dark current and color conversion characteristics. In particular, we show that the realized TFD structure, which includes several N-type and P-type regions, does not cause worsening in the dark current (and thus in the associated noise) with respect to a standard photodetector structure. Then, through the comparison of experimental results and novel FEM simulations, we show improvements that can be obtained in the shape of the spectral responses, simply by supposing the use of a micro-lens over the structure. Advantages are both in terms of average color reconstruction error $\Delta E_{a,b}$ (> 3 in the experimented device, < 2.5 in the new simulations) and in terms of noise propagation (maximum negative coefficient in the CCM ~ -12 in the experimented device, ~ -3 in the new simulated device). Finally we present the “High Color Accuracy” (HCA) acquisition mode: the device consecutively captures 2 or more images with differently tuned color filters, and through the combination of the acquired information a very faithful reproduction of colors can be obtained ($\Delta E_{a,b}$ ~ 0.3 with three consecutive captures).

Device characterization: overall dark current and responsivity

The experimental device consists in a prototype of a TFD pixel like the one schematically represented in Fig. 1, with a side of 3.2 µm, built in a 90 nm standard CMOS technology, not optimized for imaging applications. There are three shallow *N*-type implants (their junction depth is ~ 250 nm) designed over a lowly doped *P*-type epitaxial layer (N_A ~ 10^{15} cm^{-3}) and isolated one another by means of Shallow Trench Isolation (*STI*) and P^+ implants. Note that all these technological parameters are common to several other standard CMOS technologies. The pixels are designed as strips and a large number of pixels are paralleled to increase the output signal. The prototype has no pixel-level electronics; the readout is performed using an out-of-chip board-level transimpedance stage. A (110 µm x 46 µm) diode built through an N^+ implant drawn over the epitaxial layer is also designed on the chip as a reference white pixel. This structure includes neither *STI* nor P^+ implants.

The pixels are initially characterized with a semiconductor analyzer (Agilent B1500A). The measure is performed connecting the epitaxial layer contact at ground and reversely sweeping the N^+ contacts up to 3 V, while measuring their current through the analyzer. Fig. 2a and 2b reports the dark current measurements of the standard diode, compared to those of the TFD 3 color channels (and their sum). The theoretical curve in Fig. 2a is obtained assuming the electron lifetime τ_n as the fitting parameter (a value of τ_n around 10 µs is found: this value is low, as the technology is not optimized for imaging applications). In operation, the TFD can be biased with contacts at slightly different voltages to obtain the transverse field configuration. Thanks to the good isolation provided by the STI/P^+ structures, this requirement does not introduce significant punch-through current between anodes, as the P^+ implants are suitably designed to stop this leakage [14]. Though the current density value is high and the corresponding shot noise would be relevant, we conclude that the problem can be ascribed to the technology, not to the specific TFD structure, as the measured dark current density is the same for the TFD and the *white* pixel and could be therefore reduced using a specific imaging process.

Thanks to the absence of the CFA, the measured responsivity at 520 nm is > 0.35 A/W, obtained on the overall device (sum of the three responses). This value corresponds to a very high value of quantum efficiency QE > 80 % at the given wavelength.

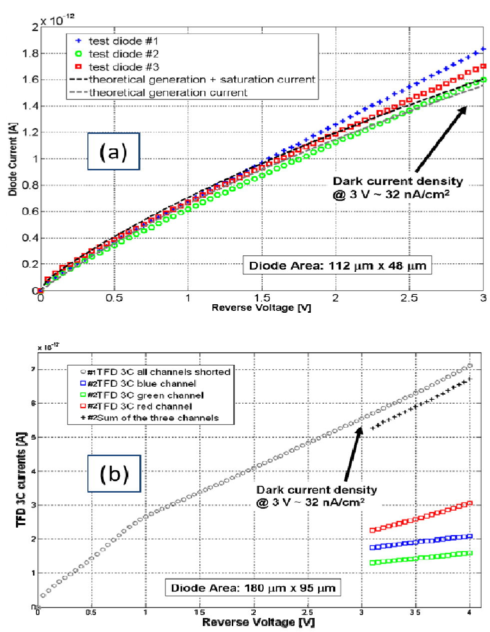

***Figure 2**. Dark current collected by three reference diodes (a) and by the three contacts of the TFD prototype (b), as a function of the reverse voltage applied to the junctions. As the overall dark current density is quantitatively very close, we can conclude that the presence of several N+ and P+ implants and STIs in the TFD does not cause a significant worsening of the dark current.*

Device characterization: equivalent filters

The readout board hosting the chip and the readout electronics is housed in a dark metal box, which is mounted on an optical table top with microcontrollers. The light of a Dolan Jenner Fiber Lite MI-150 (correlated color temperature 3200 K), is passed through a Digikrom 240 monochromator and the output spot is focused on an area larger than the whole chip. The illumination can be thus considered uniform across the device. Between the monochromator output and the chip an optical chopper (Thorlabs MC1000A) provides light modulation at a frequency of 620 Hz, so that the signal can be read out with a lock-in technique to improve the SNR. A *Labview* program controls the setup in this way: the monochromator is firstly set to a wavelength (1300 nm) beyond the Silicon absorption cut-off, so that the measured current of each color channel represents the dark current. The monochromator is then swept from 400 nm to 700 nm, with a wavelength step that can be adjusted between 1 nm and 10 nm. During each step we measure the current of the reference white pixel and the current of each TFD color channel. We then subtract the dark current and evaluate the three *equivalent filters*, as defined in the Introduction.

Fig. 3 reports the measured equivalent filters in a typical biasing condition which is optimized – considering this specific prototype – for color reconstruction on the basis of the 24 patches of the MCC, illuminated by the D65 standard source. The selected technology has, on top of the substrate, a series of 7 alternated layers of two materials with a different dielectric constant (probably SiO_2 and Si_3N_4). These materials are almost transparent means in the optical band, but the impact of such an *alternated structure* on the optical behavior of a photodiode built with this technology is strong. This is the reason of the peaks and valleys observed in the spectrum of the equivalent filters.

Starting from the obtained experimental results, the imaging chain and the color conversion procedure are entirely performed using the ISET® software [15, 16], in which we simulate the scene, the optics and, in the sensor window, we substitute the default CFA spectral responses with the measured equivalent filters. The resulting Color Conversion Matrix (CCM), obtained through a LMS algorithm, is:

$$M_1 = \begin{bmatrix} 1.91 & -7.45 & 5.54 \\ -0.13 & 12.00 & -11.60 \\ -1.30 & -4.16 & 6.77 \end{bmatrix}$$

This conversion leads to a color reconstruction error $\Delta E_{a,b}$ ~ *3.1*. Though this value can be considered good for photographic applications, the CCM shows some large negative coefficients (-11.6) that would be source of noise amplification during the conversion procedure. For this reason we have simulated the effects of using a micro-lens to illuminate only the region of the pixel, where carrier separation as a function of depth is maximized (approximately 1 µm wide beneath contact V_1) [17]. The simulation is performed using the ISE-TCAD® software. This time these simulated equivalent filers are substituted in the sensor window of the ISET® software. In Fig. 4b these new equivalent filters are reported, for which the new CCM turns out to be:

$$M_2 = \begin{bmatrix} 1.49 & -2.67 & 1.28 \\ -0.53 & 3.68 & -2.57 \\ -0.19 & -1.02 & 2.16 \end{bmatrix}$$

The equivalent filters are now more sharpened, with a lower overlap. As a consequence of a better balance between the green and the other spectral responses, the coefficients in the matrix are now smaller. The overall color reconstruction error is $\Delta E_{a,b}$ ~ *2.5*.

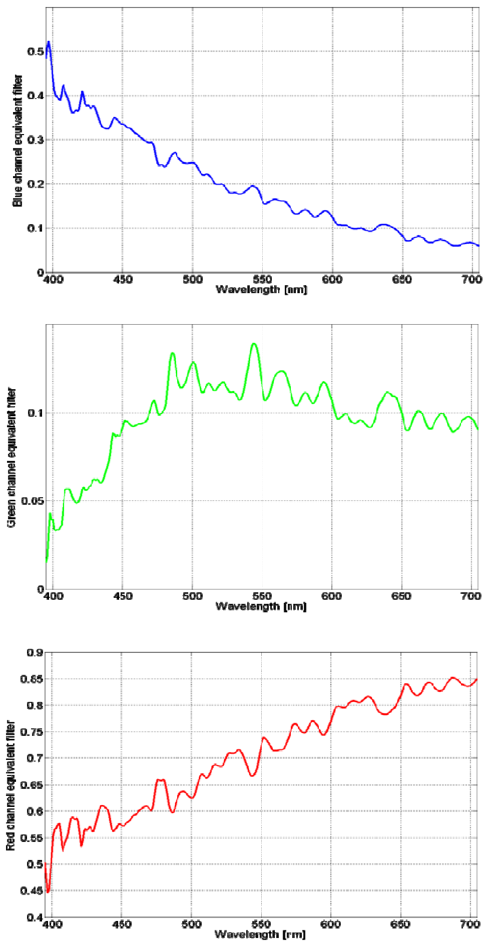

Figure 3*. Experimental equivalent filters obtained for the TFD tested prototype. The top graph refers to the contact biased at V_1 in Fig. 1, the second to the one biased at V_2 and the bottom one to the contact biased at V_3. The curves are not smooth due to 7 alternated protective layers, made of two different dielectrics deposited on top of the structure, forming a sort of interference filter.*

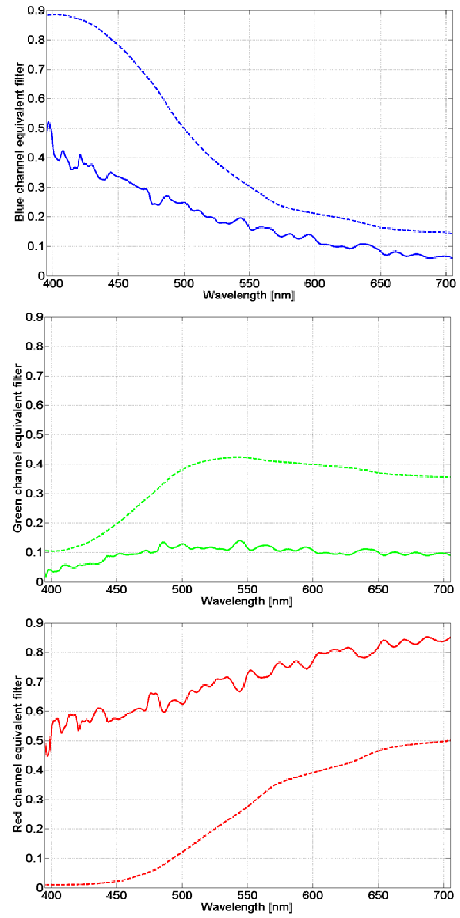

Figure 4*. Comparison between experimental equivalent filters (solid curves) with light impinging on the whole pixel area, and the equivalent filters obtained simulating a radiation impinging only on one third of the device area (dashed lines), as it could be in case a micro lens is used. The improvement is both in terms of the shape of the responses (reduced overlap) and in terms of better balance between the curves.*

High Color Accuracy (HCA) acquisition mode

The results shown at the end of the previous section for the improved TFD equivalent filters are quantitatively comparable to those obtained, using the same evaluation algorithm based on the MCC, on commercial filters like CFAs or the Foveon equivalent photoresponses. This means that the TFD can be used in a standard acquisition mode, sharing with the Foveon solution the advantages of no filter absorption and no need for demosaicking algorithm. In this way the TFD is still used as a non-colorimetric device, meaning that its three equivalent filters are not a linear combination of the CIE standard observer responses. This is generally accepted for commercial imaging but it is a relevant problem for precise, color-critical or scientific record of scenes.

Fig. 5a shows the spectral functions of the standard observer $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$. Together are reported their best approximating functions $x'(\lambda)$, $y'(\lambda)$, and $z'(\lambda)$, obtained through a Least Mean Square (LMS) algorithm based on a linear conversion starting from sample TFD equivalent filters reported as dotted curves in Fig. 6 [21]. It can be seen that the result is quite different from the target.

We propose here a method that can be used for a quasi-colorimetric acquisition, reaching a High Color Accuracy (HCA) in image capture, using the same TFD device presented above. The technique consists in capturing consecutive shots of the same image, each shot having a differently tuned set of equivalent color filters. The issue of acquiring a scene with multiple captures is common to other techniques that try to improve photographic quality. For instance in High Dynamic Range (HDR) imaging an acquisition at short integration times captures high-light regions, and is combined with another acquisition at long integration times that captures low-light regions [22]. Similar techniques are nowadays available on market cameras. Up to 9 consecutive captures with high-speed cameras were also demonstrated [23].
In a similar way, our approach does not require a change in the integration time but in the sensor color space: thanks to the TFD tunability, for 2 consecutive shots the camera behaves as it has 6 filters, for 3 consecutive shots as it has 9 filters and so on. The main result of this operation is that the larger is the number of consecutive shots, the better is the approximation of the standard

observer responses that can be obtained using a linear conversion algorithm. As an example Fig. 5b and 5c shows the results obtained through the same LMS algorithm [21] used above for the single shot mode, in cases of 2 and 3 consecutive shots, obtained using the filters tuning shown in Fig. 6 through dashed and solid curves.

We have finally checked the capability of the best reconstructed curves $x'''(\lambda)$, $y'''(\lambda)$, and $z'''(\lambda)$ to accurately reproduce colors, obtaining the results shown in Fig. 7: the color reconstruction error $\Delta E_{a,b}$ for the 24 patches of the MCC illuminated by the D65 standard source is always lower than 0.82, with a mean color reconstruction error $\Delta E_{a,b} \sim 0.3$, which is an order of magnitude lower than the result presented for the standard acquisition mode. A larger number of consecutive shots would allow an even better color reconstruction error but the algorithm convergence speed to the target functions $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ decreases with increasing the number of shots.

This HCA acquisition mode is enabled by the TFD working principle, because the device has a tunable color space and each tuning is not a linear combination of another one. A similar approach cannot be implemented with a CFA camera because its color space is determined a priori. Implementing a CFA camera with several filters having different spectral transmittances would imply an increase in the camera cost and an increase in the demosaicking computational complexity and resulting artifacts.

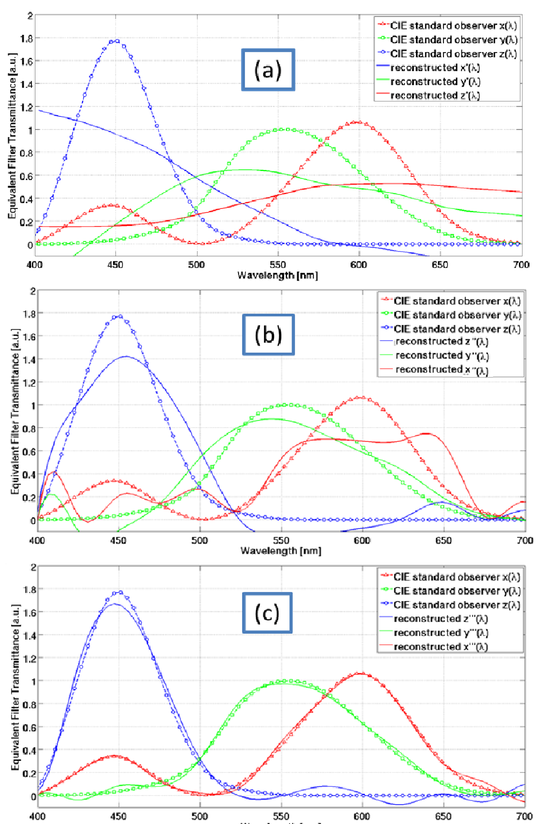

Figure 5*.* *Tristimulus function (curves with symbols) and their best approximating functions (solid curves) obtained through a LMS method starting from one (a), two (b) and three (c) consecutive tunings of the same TFD pixel, as represented in Fig. 6 (20 wavelengths in the range 400-700 nm are used for the optimization algorithm; an interpolation on 80 wavelengths is shown).*

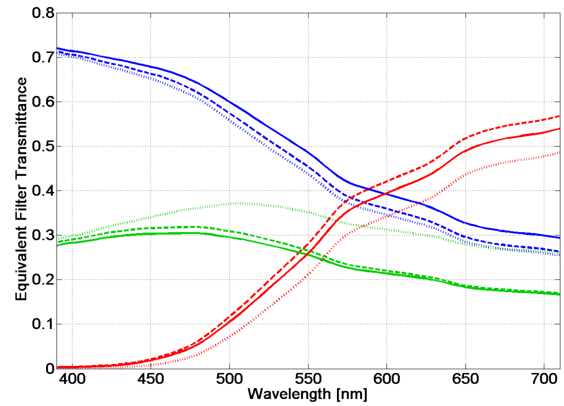

Figure 6*. ISE-TCAD® Dessis Simulation results obtained for the TFD structure of Fig. 1, showing three different equivalent filter tunings. These filters sets are used in this work to simulate High Color Accuracy image capture through 3 consecutive shots.*

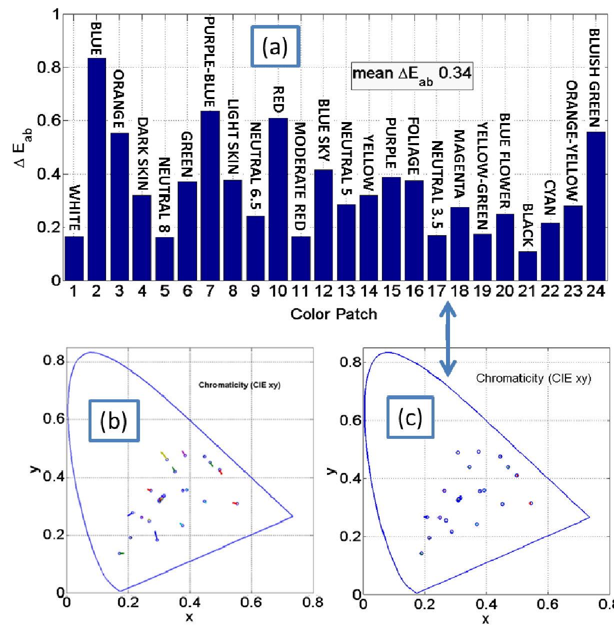

Figure 7*. Chromaticity reconstruction error $\Delta E_{a,b}$ for the 24 patches of the Macbeth Color Checker illuminated by the D65 standard source (a), for the simulated TFD in case of HCA mode. Error bars between the original and reconstructed points for the same color chart are also reported in the CIExy color space, depicted both for the case of standard acquisition mode (b), and for the HCA mode (c) analyzed above.*

Conclusion

The TFD is a peculiar Silicon color pixel whose structure allows color space tunability. This feature can be in principle used to implement a *dual acquisition mode* camera, with a standard acquisition mode (as in traditional cameras) and a High Color Accuracy (HCA) acquisition mode, obtained through consecutive shots. In this paper we have introduced this principle, showing its potentialities through simulations. We have also characterized some TFD prototypes from an optical and electrical point of view, suggesting possible improvements in the TFD structure. In particular, the use of an imaging technology instead of the used standard CMOS process would allow a reduction of the dark current and associated noise, and an improvement, possibly through the use of micro-lenses, of the color detection performance in standard acquisition mode. An experimental campaign to evaluate the color rendering improvements that can be obtained thanks to the HCA technique in this improved device will be object of future research.

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Federico Zaraga received the degree in nuclear engineering from Politecnico di Milano, Italy in 1969. He was a Research Associate with the Chemical Department, University of California, Berkeley, where he worked on laser photochemistry. He is currently an Associate Professor of optoelectronic systems at Politecnico di Milano. He is an Inventor of several patents, particularly of a color imaging detector. His main research interests include several aspects of optoelectronics and microelectromechanical systems. He is author of more than 70 refereed scientific journal publications.

Antonio Longoni received the degree in nuclear engineering in 1972 from Politecnico di Milano, Italy, where he is currently a Full Professor of electron devices. His research concerns semiconductor devices and radiation detectors. He contributed to the development of the "Semiconductor Drift Detector" and other detectors for X- and Gamma-rays. He has conceived and participated to the development of a new color imaging detector. He is author of more than 100 publications on international scientific reviews. Prof. Longoni was the recipient of the "Accademia Nazionale dei Lincei" prize for the development of instrumentation for artworks diagnosis.

Cesare Buffa received the B.S. and M.S. degrees from Politecnico di Milano, Italy, in 2007 and 2009 respectively, specializing in radiation detectors and related readout electronics. He is now attending the Ph. D. program at the Department of Electronics and Information Technologies, Politecnico di Milano, focusing on research aspects related to MEMS for magnetic field sensing.