Measurement and Analysis of Pixel Geometric and Diffusion Modulation Transfer Function Components in Photodiode Active Pixel Sensors

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Introduction

In this paper we describe MTF measurement methods aimed at providing maximum insight into the photodiode layout and vertical layer structure of complementary metal-oxide-silicon (CMOS) active pixel sensors (APS). Our approach is taken because of the distinctly different physical characteristics that APS sensors have compared to CCD's that are related to MTF performance. MTF modeling of CCD devices is well established in the literature. For the past ten to fifteen years it has been the practice of the industry to build CCD's on epitaxial silicon. The standard diffusion MTF models must be modified to account for the epitaxial layer structure as discussed by Blouke and Robinson [1], and Stevens and Lavine [2]. The latter researchers developed an approach wherein the pixel aperture and diffusion components of the MTF are treated in a unified manner. Their mathematically complex results show that the pixel aperture MTF function, a sinc function [where sinc(x) = sin(x)/x], cannot be treated as multiplicative with the diffusion MTF function in describing the overall sensor MTF, except in the case where the pixel dimension and the pixel pitch are equal (100% fill factor). Blouke [1] uses a simpler modeling approach where the above restriction does not appear: the pixel aperture and diffusion MTF's are assumed to be multiplicative.

Lin, Mathur, and Chang [3] make the case that the CCD-based diffusion models do not work well for APS imagers because these devices have field-free regions between and surrounding pixel photodiodes that contribute to diffusion currents. Recent APS MTF modeling and measurement research has also been reported by Yadid-Pecht [4], and Shcherback and Yadid-Pecht [5]. In reference 4 the MTF APS photodiodes of connected rectangular geometric shapes (i.e. L-shapes are typical) are computed analytically using the Fourier transform of these shapes. In reference 5 a semi-empirical approach is used that measures the APS pixel response by scanning a small, single wavelength (Helium-Neon) spot over the pixel area. The corresponding 2-dimensional (2D) MTF is obtained via a (2D) Fourier transform of this empirical spot scan data. This is then compared to an MTF estimate based on the 2D Fourier transform of the convolution of the known pixel aperture response (or point spread) function with a symmetrical diffusion spreading model that uses a diffusion length determined by fitting the spot scan data at distances relatively large from the pixel center. Since the convolution of separate aperture and diffusion point spread functions occur in the latter approach, this is equivalent to multiplying the corresponding aperture and diffusion MTF functions: this is in agreement with the approach by Blouke [1], but in contrast to the assertion by Stevens [2] that this is not appropriate for situations with a fill-factor of less than 100%.

In our work we seek to exploit the strong wavelength dependence of the diffusion component of the MTF to separate aperture and diffusion effects by empirical measurement. The various diffusion MTF models described above include this wavelength dependence but not sufficiently to exploit it as tool for understanding the key pixel geometric and layer thickness parameters that matter most in determining the overall or unified MTF of typical APS devices. In the next section we discuss a different method of measuring the MTF of APS devices, one that still provides significant insight into pixel aperture MTF behavior, but allows a lot more insight into diffusion MTF processes.

MTF Measurements using aTilted Knife-Edge

For insight into diffusion processes, measurement of the MTF as a function of color is essential. We use an all-reflective Offner reimaging optical system [6] to focus optical bar patterns and tilted knife-edges onto APS devices in a precisely controlled manner. The optical system has been characterized to ensure diffraction-limited performance as a function of color (from 400 to 900 nm). Hence the optical system MTF is known at all of the measurement wavelengths. The MTF extraction methods used for the bar patterns and/or tilted knife-edge measurements have been described in detail elsewhere [7]. Figures 1 and 2 show color-dependent pixel MTF data obtained using an extended tilted knife-edge method [7] for an older JPL APS device (the so called VIDI device) consisting of an n^+-p-substrate photodiode. The MTF characteristics of our Offner imaging system have been divided out – these data reflect only the APS MTF performance. The pixel pitch for this device was 12 microns with a rectangular photodiode [about 6 microns (y-axis) by 11.5 (x-axis) microns] located in the upper half of the pixel area.

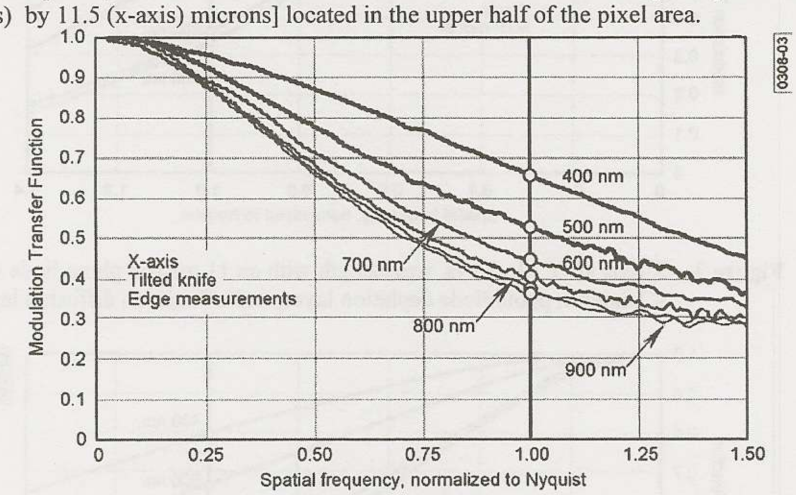

Figure 1. X-axis MTF measurements for the VIDI JPL APS

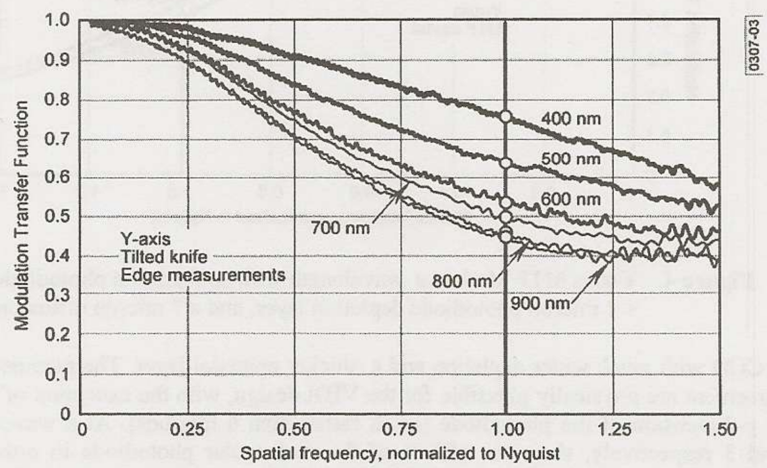

Figure 2. Y-axis MTF measurements for the VIDI JPL APS

Figures 3 and 4 show MTF calculations made using the product of the sinc function aperture MTF multiplied by the Blouke and Robinson diffusion MTF model [1]. The model parameters chosen for Figures 3 and 4 correspond to a shallow photodiode depletion width (< 1 micron), a diffusion layer thickness of 7 microns and assumed rectangular photodiode dimensions of 8 (y-direction) and 11 microns (x-direction) , respectively. For this choice of model parameters, excellent agreement is obtained between the data [Figures 1 and 2], and the relatively simple MTF model [Figures 3 and 4]. Contrary to what was found by Stevens [2], the Blouke diffusion MTF [1] is sufficient to describe the MTF behavior of this simple APS pixel configuration. This its most likely due to the fact that the APS device characteristics (thin depletion layer and relatively thin epitaxial layer) are substantially different than the case Stevens was

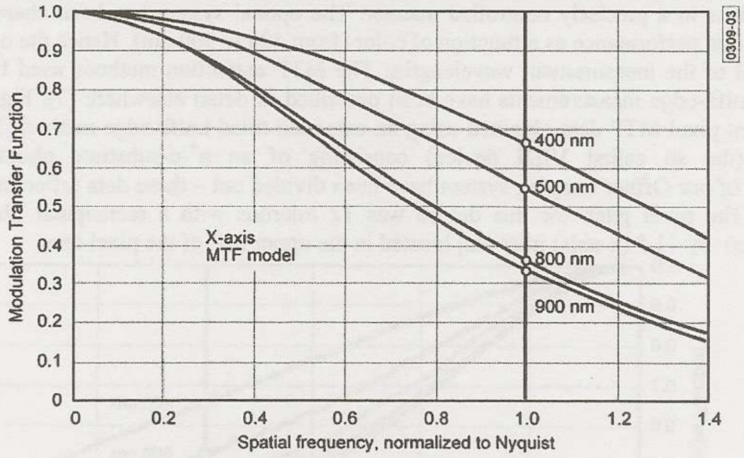

Figure 3. X-axis MTF Model vs wavelength with an 11 micron photodiode width, < 1 micron photodiode depletion layer, and a 7 micron diffusion layer.

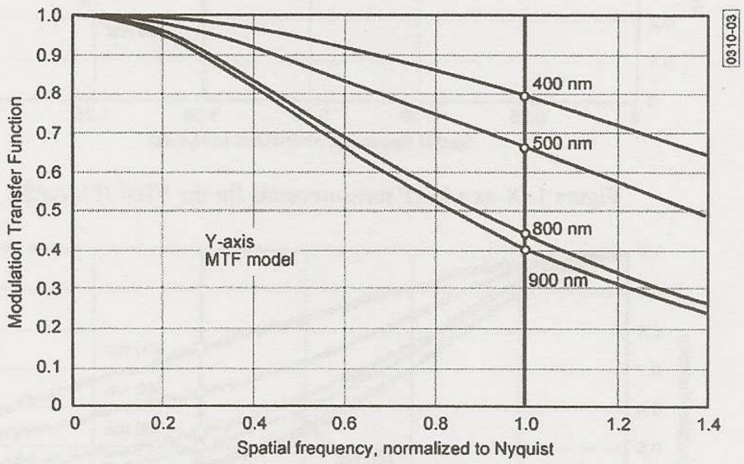

Figure 4. Y-axis MTF Model vs wavelength with an 8 micron photodiode width, < 1 micron photodiode depletion layer, and a 7 micron diffusion layer.

analyzing: a CCD with much wider depletion and a thicker epitaxial layer. The parameters used to obtain the above agreement are physically plausible for the VIDI design, with the exception of the use of a larger width in the y-dimension of the photodiode [i.e. 8 rather then 6 microns]. At a wavelength of 400 nm, Figures 2 and 3 respectively, show the effects of the rectangular photodiode in orthogonal directions. However, the fact that a pixel aperture of 8 rather than 6 microns along the y-direction best fits an analytical MTF model (Figures 3 and 4) of the empirical MTF data (Figures 1 and 2) is an indication of lateral diffusion current from the pixel area adjacent to the photodiode; this is where the pixel electronics resides. More precise modeling of this effect can be likely accomplished using the approach by C.S. Lin, et.al. [3]. They refer to this lateral diffusion component as current from "region IV". Another approach is to follow a method used by H. Hosack [8] that involves a trapezoidal aperture function. Either method would have the effect of lowering the MTF in a more physically plausible manner than simply increasing the effective size of the photodiode width.

The behavior of the MTF curves in Figures 1 through 4 illustrates clearly the structure of the APS device in the z-dimension. For wavelengths greater than 500 nm, light is absorbed below the rather shallow depletion layer boundary and the onset of diffusion is evident in the subsequent increasing wavelength MTF curves. For wavelengths greater than about 800 nm the MTF curves coalesce indicating that the light is penetrating deeper than the diffusion layer thickness (poor red quantum efficiency also results). The MTF characteristic in Figures 3 and 4 above about 1.4 times Nyquist are higher than expected. This is possibly related to optical effects associated with the pixel layout of the APS imager. In the next section, we describe the precision spot scanning of a 9 micron APS imager.

Spot Scanning

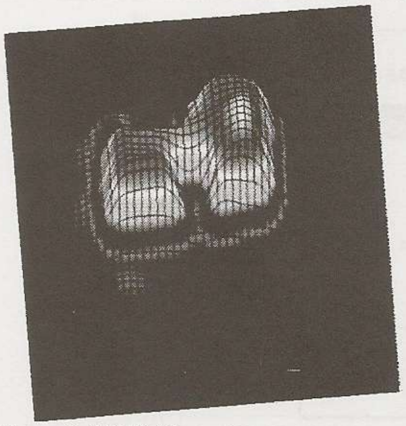

Figure 5. 2D HeNe spot scan across a 9 μm pixel of a JPL A1K APS

For insight into the pixel aperture or geometric MTF, especially for complex APS pixel topologies, maximum information is gained by spot scanning the pixel with short enough wavelength light to restrict, as much as possible, the resulting photocurrent to that generated from the photodiode depletion region. Figure 5 displays the results of scanning a focused spot (< 2 microns at helium neon laser wavelength or 0.6328 microns) in two dimensions across a single pixel of a JPL APS (the so-called A1K device), which has a 9-micron pixel pitch. The spot step size was 0.3 microns, so the pixel aperture response map in Figure 5 corresponds to about 900 data points. The pixel architecture of the A1K device has a "dog bone" shaped photodiode in the center of its 9-micron pixel area and a fill factor of about 35%. The readout circuitry is located at the top and bottom of the figure and metal bus lines are located to the left and right sides of this same figure. We see the maximum response in the area defined approximately by the shape corresponding to the boundary of the photodiode, but in the areas where to the pixel electronics and bus lines reside, there is little if any response to light. The "notch" shown at the bottom of Figure 1 is a region with essentially no response to light – this is the location of the photodiode contact to the gate of the pixel source follower field-effect transistor (FET). The 2D aperture MTF is obtained by performing a 2D Fourier transform on the spot scan data. Compared to the VIDI device, any diffusion effects that are present for the A1K device at this wavelength are subtle and at a very low level. Obtaining more insight into diffusion processes requires systematic spot scanning with different wavelengths of light. The challenge associated with doing is this that the spot size increases with increasing wavelength due to diffractive effects.

It should be noted that the relatively smooth transitions between the responsive regions in the spot scan in Figure 5 are due in part to the finite size of our spot. In our spot scan system the spot was formed with a Mitutoyo Plan APO SL100X objective lens. This lens was described by the following optical parameters: numerical aperture = 0.55, focal ratio = 0.91, focal length = 2 mm, aperture = 2.2 mm, working distance = 13 mm, and depth of focus = 1 micron. The diffraction limited spot size at the helium neon laser wavelength is easily computed from these parameters to be 1.4 microns (diameter of the Airy disk). It was not clear if this diffraction-limited spot size was being achieved. The very large working distance of this lens was a significant advantage - the translation of the APS under this spot was facilitated by the large working distance. In order to produce the smallest spot size the illumination source must fill the lens aperture. The cross section of the HeNe laser beam was about 1 mm and somewhat non-uniform. Consequently two lower power objective lenses were used along with a spatial filter to clean up beam and expand it by a factor of 2X for injection into the high quality 100X objective. (Although we have plans to perform spot scanning at different wavelengths, we expect that verifying the spot sizes quantitatively of the relevant objective lenses at these various wavelengths of interest, will be challenging.) Newport Corporation 426 and 443 translation stages equipped with Newport precision 850F actuators were used to translate the APS under the stationary spot produced by the 100X objective lens. These precision actuators were carefully characterized and found to have a stepping capability of 0.3 +/- 0.03 microns. This is very similar to spot stepping capability reported by Kavaldjiev and Ninkov [9] using a similar set-up, but aimed at 9 micron CCD pixel spot scan characterization. We were able to characterize 3 by 3 grids of pixels in a single computer-controlled spot scanning sequence. It should be noted that the 1-micron depth of focus also required the use of an 850F actuator for precise focus control.

The improvement in diffusion MTF for the A1K device results from the use of a pixel with a n-well to p-epi diode. The cross-section of the pixel is schematically shown in figure 6. Implemented in a 0.5 μm process, the pixel consists of a photodiode formed between the n-well and the p-epitaxial layer. The doping levels shown are typical of what may be expected in a 0.5 μm process. The in-pixel MOSFET's for resetting , selection, and source-follower input reside in the heavier doped p-well. On the other hand, the epi-doping is lower, since it is does not carry any MOSFET. While for simulation purposes, an epi-doping of $1\times10^{15}/cm^3$ is used, in principle, the doping can be lower, allowing further increases in the depletion width. The simulation was carried out with a symmetric n-well with 1.5 μm width , and a depth of ~ 1μm is used.

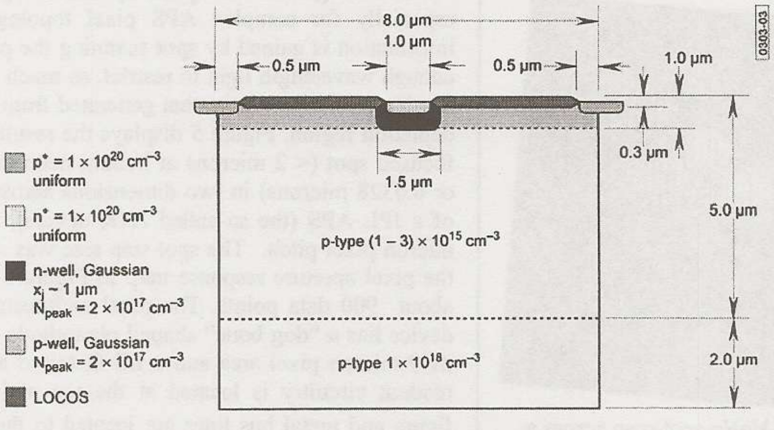

Figure 6. Schematic cross-section of the n-well pixel

Figure 7 shows the simulated depletion width for the cross-section shown in figure 6. It indicates that the depletion width extends vertically nearly 2 μm into the p-epi layer, depending upon the reverse bias on the n-well. With the n-well depth of ~ 1 μm, this implies that the field region extends almost 3 μm deep, providing for efficient collection of longer wavelength photons.

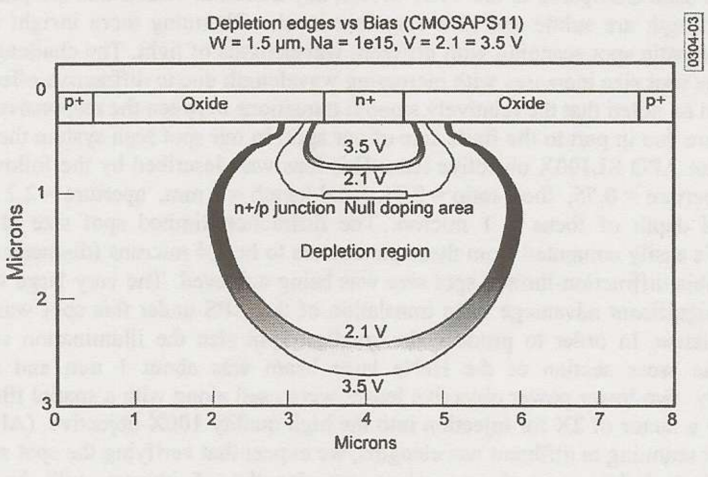

Figure 7. Simulated depletion depth.

As shown in figure 7, the depletion region is asymmetric between the horizontal and vertical directions. While the vertical junction is formed between n-well and p-epi, the lateral junction is formed between the n-well and p-well, both of which are relatively heavily doped (~ $1\times10^{17}/cm^3$). The heavier doping is needed for restricting the junction depletion widths in sub-micron MOSFET. The presence of the p-well prevents the depletion width from spreading as much horizontally.

Compared with a n^+-pwell pixel, the junction for the nwell pixel is formed deeper into silicon. On the other hand, the latter has a much larger vertical depletion region. As a result, the nwell pixel is expected to provide substantially increased red MTF compared with the n^+ pixel, but with somewhat degraded blue/green MTF. We are in the process of confirming this through wavelength dependent MTF measurements using knife-edge techniques.

Conclusions

Spot scan and direct MTF measurements taken together permit experimental confirmation of the photodiode aperture response behavior and the depletion/diffusion structure of APS devices. There are advantages and disadvantages to these two methods. Spot scanning requires the use of high quality objective lenses with known color-dependent point-spread function characteristics along with precision micro-positioning hardware. However direct insight into pixel spatial response is possible. MTF measurements require a well-corrected and characterized optical imaging system, along with appropriate patterned reticles and associated light sources. Furthermore the APS output data must be carefully analyzed in order to extract MTF information. While it is relatively difficult to gain extremely detailed insight into the pixel aperture response, diffusion effects are readily apparent and easy to interpret in the MTF data.

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