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

Tracy Dutton, Jaewon Kang, Terrence Lomheim, Richard Boucher, Ralph Shima and Mark Nelson
The Aerospace Corporation, Sensor Systems Subdivision
P.O. Box 92957, Los Angeles, California, USA 90009-2957

Bedabrata Pain, Christopher Wrigley, and Xinyu Zheng
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, California, USA 91109-8099

Abstract

In this paper we describe MTF and spot scan measurements and associated analyses aimed at understanding and separating the behavior of the geometric and diffusion MTF components of active pixel sensors (APS) designed at the Jet Propulsion Laboratory.

For insight into the pixel geometric MTF, especially for complex APS pixel topologies, maximum information is gained by spot scanning the pixel. This is followed by the 2-dimensional Fourier Transform of this spot scanning data (with appropriate normalization) to obtain the pixel geometric MTF. Figure 1 displays the results of scanning a focused spot (< 2 microns at helium neon laser wavelength) in two dimensions across a single pixel of a JPL APS (the so-called A1K device) which has a 9-micron pixel pitch. The focused spot step size was 0.3 microns, so the pixel geometric response map in Figure 1 corresponds to a grid of about 900 data points. The pixel architecture of the A1K device has a "dog-bone" shaped photodiode in the center of the 9 micron pixel and a fill factor of about 35%, with the readout circuitry located at the top and bottom of the figure and metal bus lines to the right and left in the figure. Figure 2 shows orthogonal slices of the 2-dimensional MTF calculated from the pixel response data. As expected, at the Nyquist sampling frequency of 55.6-line pairs/mm, the MTF exceeds the value of 0.64 that would occur if the photodiode area were to fill the entire area corresponding to the pixel pitch. The differences in the x and y directions correlate to the A1K photodiode approximately rectangular shape.

For insight into diffusion processes, measurement of the MTF as a function of color is essential. Figures 3 and 4 show color-dependent pixel MTF data obtained using an extended tilted knife-edge method for an older JPL APS device (the so called VIDI device). The pixel pitch for this device is 12 microns with a rectangular photodiode (about 6 by 11 microns) located in the upper half of the pixel area. At a wavelength of 400 nm, Figures 3 and 4 respectively show the effects of the rectangular photodiode in orthogonal directions. The color dependence of these MTF curves reveals a shallow depletion depth (< 1 micron) and a diffusion layer thickness of about 8 microns. For wavelengths greater than 500 nm, light is absorbed below the 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 1.5 Nyquist are higher than expected. This is possibly related to optical effects associated with the pixel layout of the APS imager.

For typical APS designs, differences can occur in the vertical and horizontal extension of the depletion region. Figure 5 shows the schematic cross-section of an n-well photodiode pixel with LOCOS isolation. The cross-section consists of an n-well with an n^+ contact in the middle. The junction photodiode can be thought of as a parallel combination of two diodes – an area diode formed between the n-well and the p-epitaxial layer, and the other, a perimeter diode formed between the n-well and the p-well under the field-oxide isolation. Typically, well dopings are ~ $1\text{-}2\times10^{17}/cm^3$, resulting in small depletion widths of ~ 0.1 μm. On the other hand, the doping in the epitaxial layer can be reduced below $1\times10^{15}/cm^3$. This results in longer vertical depletion widths (~ 1-2 μm). Figure 6 shows the simulated depletion widths around the n-well junction diodes for two different biases. It can be seen that the depletion region is asymmetric due to the difference in doping profiles in the lateral and vertical directions (with the vertical depletion width being larger than the horizontal depletion widths). Investigation of this effect, on diffusion MTF asymmetry, is currently underway.

Clearly the wavelength dependence of the diffusion MTF, as well as the pixel geometric MTF of an APS pixel, is different than that of a typical CCD pixel. This paper investigates experimental and analytical methods of relating APS pixel geometric and diffusion MTF data to both surface topology (pixel layout) and the 3-dimensional depletion/diffusion layer structure of these devices.

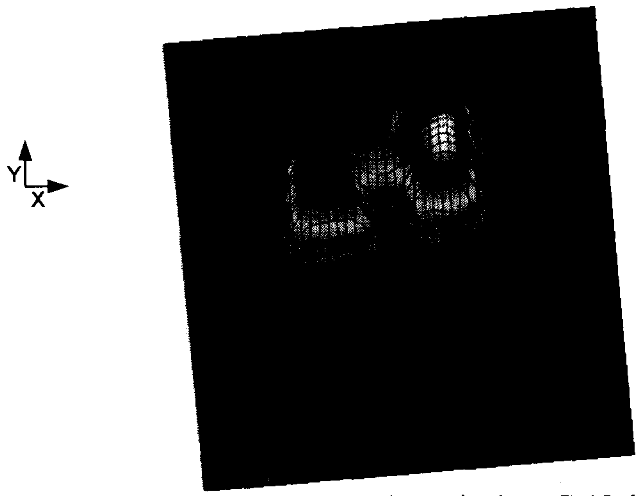

Figure 1. Result of a 2-dimensional spot-scan (< 2 microns in size at HeNe laser wavelength) across a 9-micron pixel of a JPL A1K APS device. The spot was formed using a Mitutoyo M Plan APO SL 100X objective lens. The APS was translated under the stationary spot using Newport Corporation 426 and 443 linear translation stages equipped with Newport 850F precision actuators. The translation step size was 0.3 microns. See text for more details.

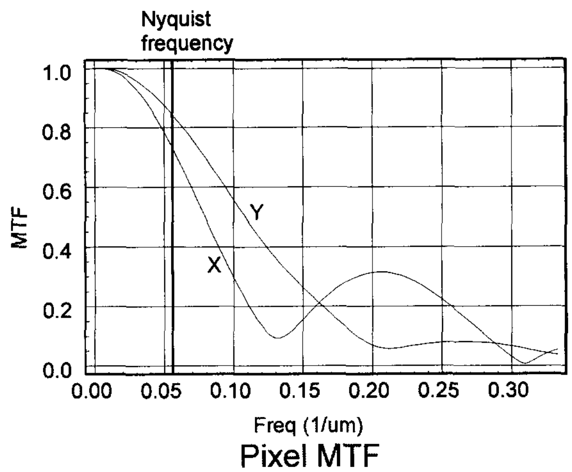

Figure 2. Slices along the orthogonal array directions of the pixel geometric MTF resulting from the 2-dimensional Fourier Transform of the data in Figure 1.

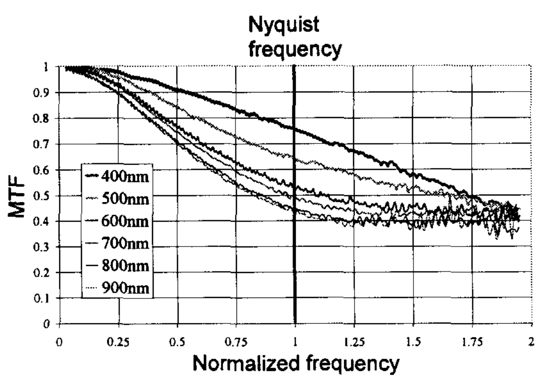

Figure 3. Composite color-dependent MTF (pixel geometric and diffusion) of a 12-micron pixel-pitch JPL VIDI APS device along the short dimension (about 6 microns) of the photodiode. The MTF of the imaging optics have been removed using a color-dependent correction.