Ultra-high resolution 14,400 pixel trilinear color image sensor

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ABSTRACT

An ultra-high resolution 14,400 pixel trilinear image sensor is under development to meet customer requirements as they progress into next generation, high-end color scanning systems. High-performance features being incorporated into this device include an enhanced color filter scheme providing improved blue and green responsivity, electronic exposure control, and antiblooming protection. To our knowledge, this will be the highest resolution trilinear sensor to date and is being designed to provide common optical length to Kodak's current line of long trilinear imagers.

KEYWORDS: CCD, image sensor, trilinear, high resolution, small pixels

1. INTRODUCTION

Kodak has been manufacturing high-performance linear image sensors for over a decade. High-resolution trilinear CCD image sensors are used in a variety of applications that include: graphic art flatbed scanners; high-speed document scanners and copiers; machine vision cameras; studio photography camera backs; motion picture special effects film scanning; as well as satellite imaging. To further improve resolution and image quality of these scanning systems will require higher density arrays – either sensors having a longer optical length while keeping pixel size and sensitivity, or those that incorporate smaller pixels and retain a common optical length. From a customer's perspective, it is desirable to keep sensor length constant in order to maintain a common optical configuration. To address this progression in the scanner markets, Kodak is now developing a 14,400 pixel trilinear CCD image sensor that offers common optical length to our current 6,000, 8,000, and 10,200 pixel trilinear imagers.

2. DEVICE DESCRIPTION

The Kodak Digital Science™ image sensor consists of three identical arrays of 14,404 active, 5 x 5μm^2 low-lag pinned photodiode pixels [1]. Each color channel is overlaid with an integral red, green, or blue color filter, designed for color scanning applications. Channel-to-channel spacing is 160 µm, which is equivalent to 32 scanned lines. For each color channel, the charge generated in individual pixels is stored in an adjacent accumulation region. In addition to charge storage, the accumulation region also incorporates a lateral overflow drain to provide over exposure/blooming protection, and an independent exposure control gate, allowing for on-chip color balancing. This section is isolated from the CCD shift registers via a transfer gate. Readout of the image signal for each channel is accomplished through dual CCD shift registers utilizing double-level polysilicon, buried-channel, and true two-phase (two electrodes per CCD stage) technologies [2,3], which are charge domain multiplexed into a single output buffer per channel.

The Kodak trilinear image sensor die layout is shown below in Figure 1, and a functional block diagram is given in Figure 2.

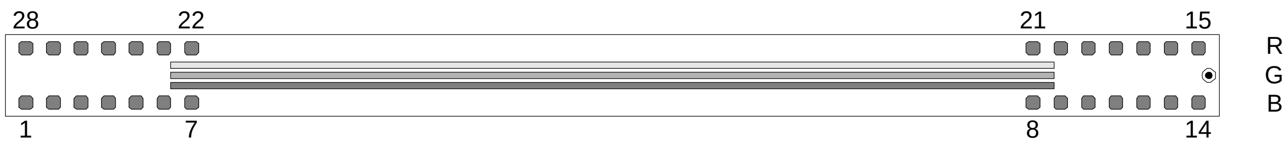

Figure 1 - Kodak Digital Science 5 x 5 μm^2 pixel trilinear sensor die layout.

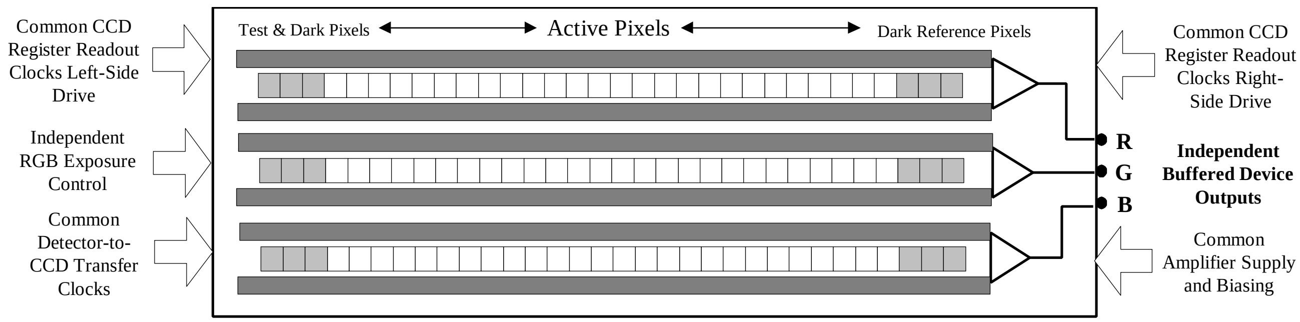

Figure 2 - Functional block diagram.

Each of the three color channels, red, green, and blue, have a total of 14,436 photodiodes - 7,218 of which are transferred out via the even CCD shift register, and 7,218 through the odd CCD register. The data stream for each channel consists of 16 dark reference pixels followed by 14,404 active pixels followed by 16 calibration/test pixels. The first and last active pixels of each color channel would not be used because they will see a different diffusion component than all the other active pixels caused by their adjacency to a dark pixel, and thereby exhibit an overall photoresponse variance. A single channel block diagram is provided below in Figure 3.

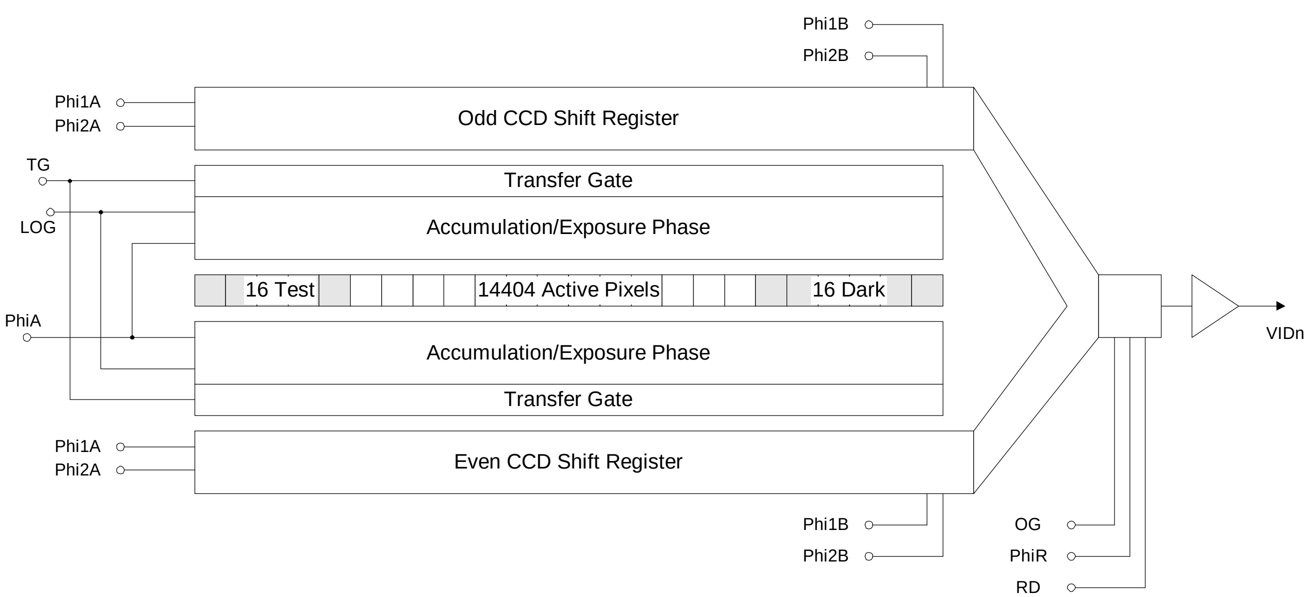

Figure 3 - Single-channel block diagram.

3. DEVICE FUNCTION

3.1 Imaging

During the integration period, an image is obtained by gathering electrons generated by photons incident upon the photodiodes. The charge collected in the array is a linear function of the local exposure. Within a given channel, the charge is stored adjacent to the photodiode in the accumulation region PhiA, which is isolated from the CCD shift registers during the integration period via the transfer gate TG, which is held at a barrier potential. At the end of a given integration period, the CCD register clocking is stopped with the Phi1 and Phi2 gates being held in a 'high' and 'low' state respectively. Next, the TG gate is turned 'on' causing the charge to drain from the PhiA region, through the TG region and into the Phi1 region. The dual shift registers receive signal from alternate photodetectors in an odd/even fashion. As the TG gate is turned to an 'off' state, residual charge is transferred into the Phi1 storage region, and the shift registers are isolated from the detector region once again. Complementary clocking of the Phi1 and Phi2 phases is then resumed for readout of the current line of data while the next line of data is integrated. The parallel connection of the shift register clocks requires that Phi1/Phi2 clocking of all three channels be momentarily suspended during the parallel transfer from channel photosites. A pixel-to-CCD cross-sectional view, depicting channel potentials for charge collection and transfer from the photodiode site to the CCD register, is diagramed below in Figure 4.

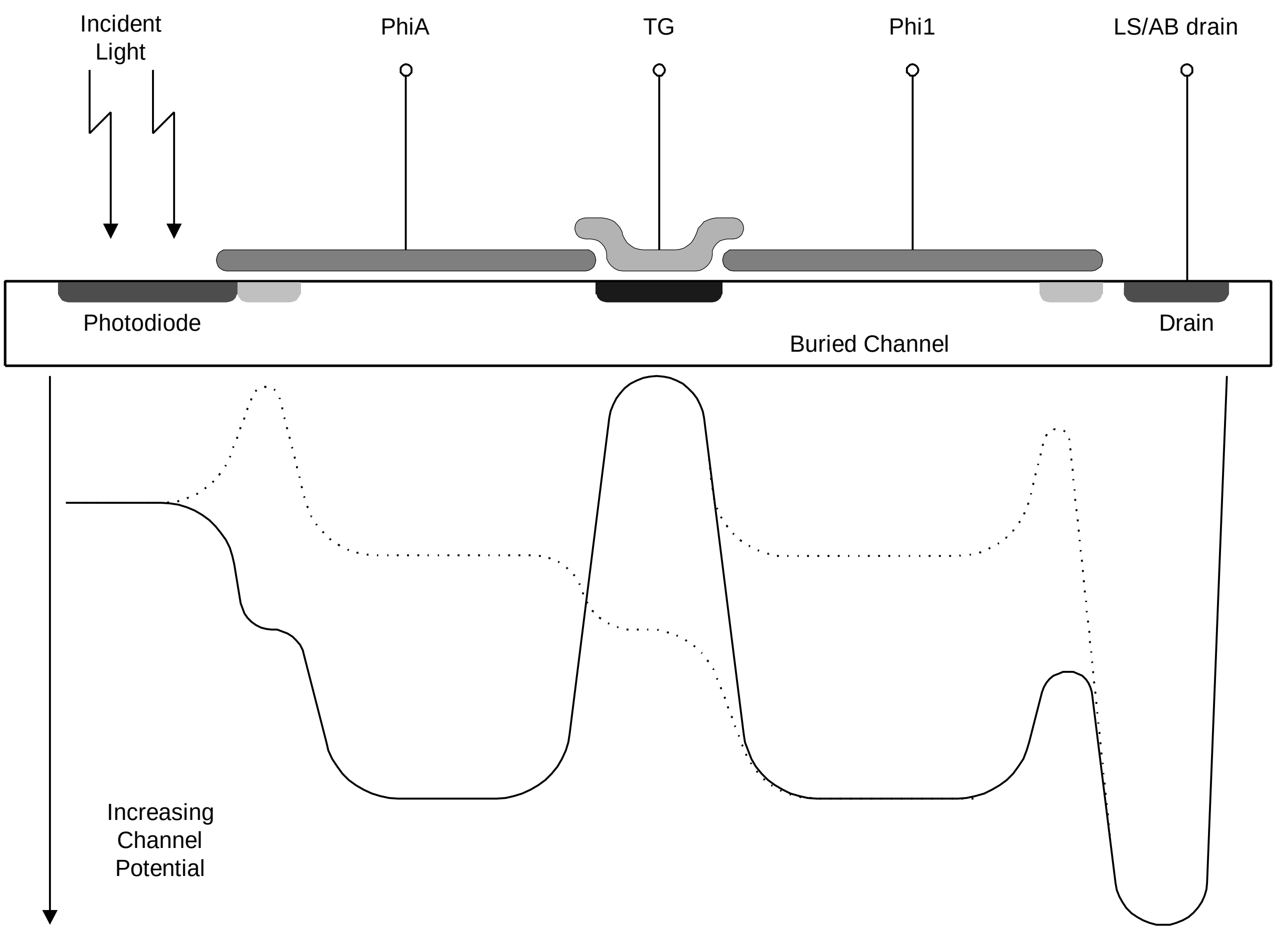

Figure 4 - Pixel cross-section.

3.2 Exposure control

Exposure control is implemented by selectively clocking the LOG gates during portions of the scanning line time. By applying the specified bias to the LOG gate, the channel potential is increased to a level beyond the storage level within the PhiA region. With TG in an 'off' state and LOG appropriately biased, all of the photocurrent will be drawn off to the drain. The exposure can be controlled by pulsing the LOG gate to a 'high' level while TG is turning 'off' and then returning the LOG gate to a 'low' bias level sometime during the line scan. The effective exposure time is the net duration between the falling edge of the LOG gate and the falling edge of the TG gate (end of the line). Separate LOG connections for each channel are provided enabling on-chip light source and image spectral color balancing.

3.3 Antiblooming

Antiblooming circuitry is provided to accommodate overexposure conditions, which may lead to blooming and loss of image integrity. The antiblooming level is preset during manufacturing and requires no external biasing or control. The Kodak Digital Science™ image sensor can manage up to 6 times the saturation exposure with minimal effect upon the adjacent imaging sites. The effects of diffusion crosstalk between photodiodes and smear between the photodiode array and the readout shift registers, must be backed out when evaluating antiblooming performance.

3.4 Charge transport and sensing

Readout of the signal charge is accomplished by two-phase, complementary clocking of the Phi1 and Phi2 gates. The register architecture has been designed for high-speed clocking with minimal transport and output signal degradation, while still maintaining low ($6.25V_{p\text{-}p}$ min) clock swings for reduced power dissipation, lower clock noise, and simpler driver design. The data in all registers is clocked simultaneously toward the output structures. Because of the dual shift register design, the odd pixel data is offset by one-half clock phase with respect to the even pixel data, for a given color channel. The signal from the odd and even shift registers is transferred to a common output structure, with odd pixel data being valid on the falling edge of the Phi2 clock, and even pixel data being valid on the falling edge of the Phi1 clock. Resettable floating diffusions are used for the charge-to-voltage conversion while source followers provide buffering to external connections. The potential change on the floating diffusion is dependent on the amount of signal charge and is given by $\Delta V_{FD} = \Delta Q / C_{FD}$, where ΔQ is the signal charge and C_{FD} is the sense node capacitance. Prior to each pixel output, the floating diffusion is returned to the RD level by the reset clock, PhiR.

4. DEVICE PERFORMANCE

The response linearity characteristics of a representative device are illustrated in Figure 5, showing the illumination linearity plot. Full well capacity for the trilinear image sensor is 230,000 electrons (2.5 V) with a noise floor of 35 electrons, yielding response linearity over the 76dB dynamic range of +/- 1.0%.

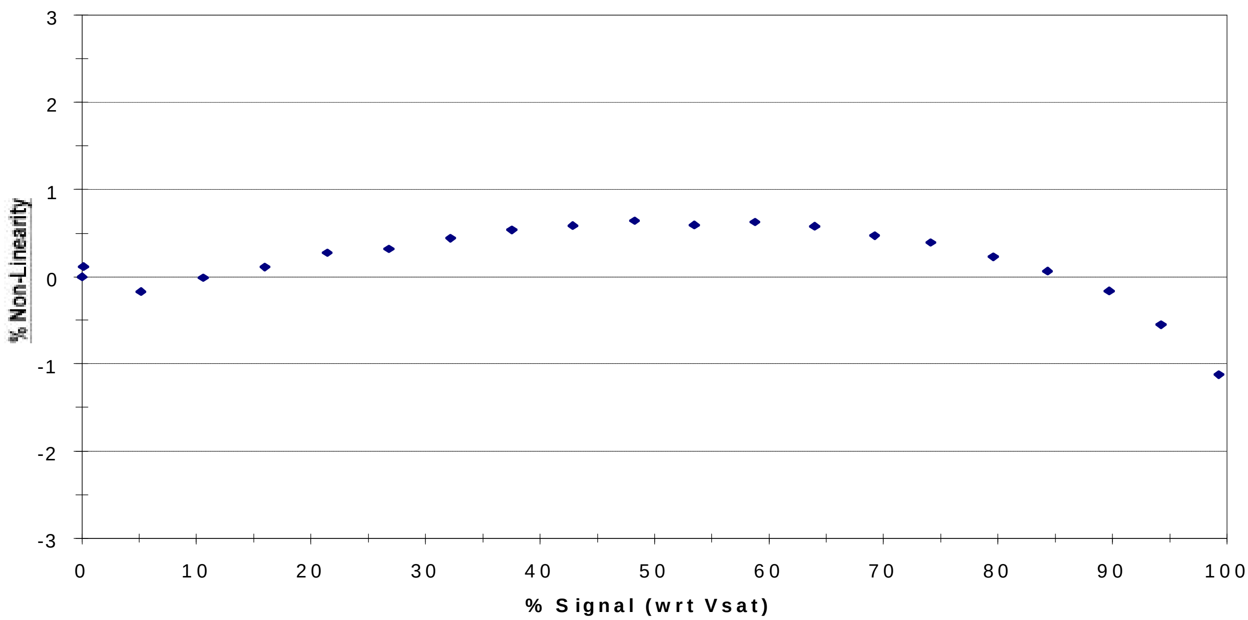

Figure 5 - Response linearity of the 5 x 5μm^2 pixel trilinear sensor (measured data on α-samples).

The spectral response of the 5 x 5 μm^2, enhanced color filter array pixels, is displayed in Fig. 6 along with our standard color filter array technology used on the 7 x 7μm^2 pixel Kodak Digital Science KLI-10203 image sensor. Since the area of the 5 x 5μm^2 pixels is approximately one-half of that of the 7 x 7μm^2 pixels, the responsivity of 5 x 5μm^2 pixels would be half that of the 7 x 7 μm^2 pixels under the same color filter scheme. The comparison plot in Fig. 6 reveals a significant gain in the blue responsivity using the enhanced color filter scheme, nearly making it equal to that of standard color filter array on the larger 7 x 7μm^2 pixels. A plot of the 5 x 5μm^2 enhanced color filter array pixel quantum efficiency is given in Figure 7.

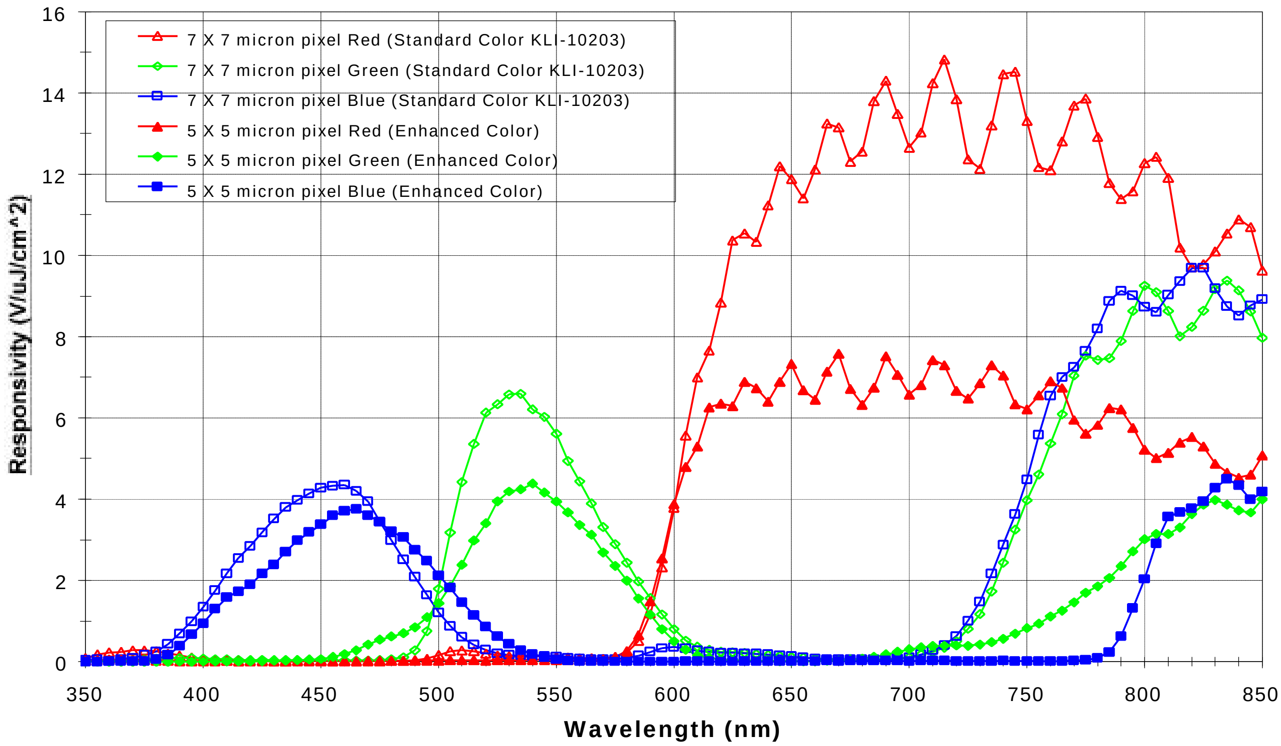

Figure 6 - Responsivity comparison of the 5 x 5µm^2 enhanced color filter array pixels to the 7 x 7µm^2 standard color filter array pixels (measured data on α-samples).

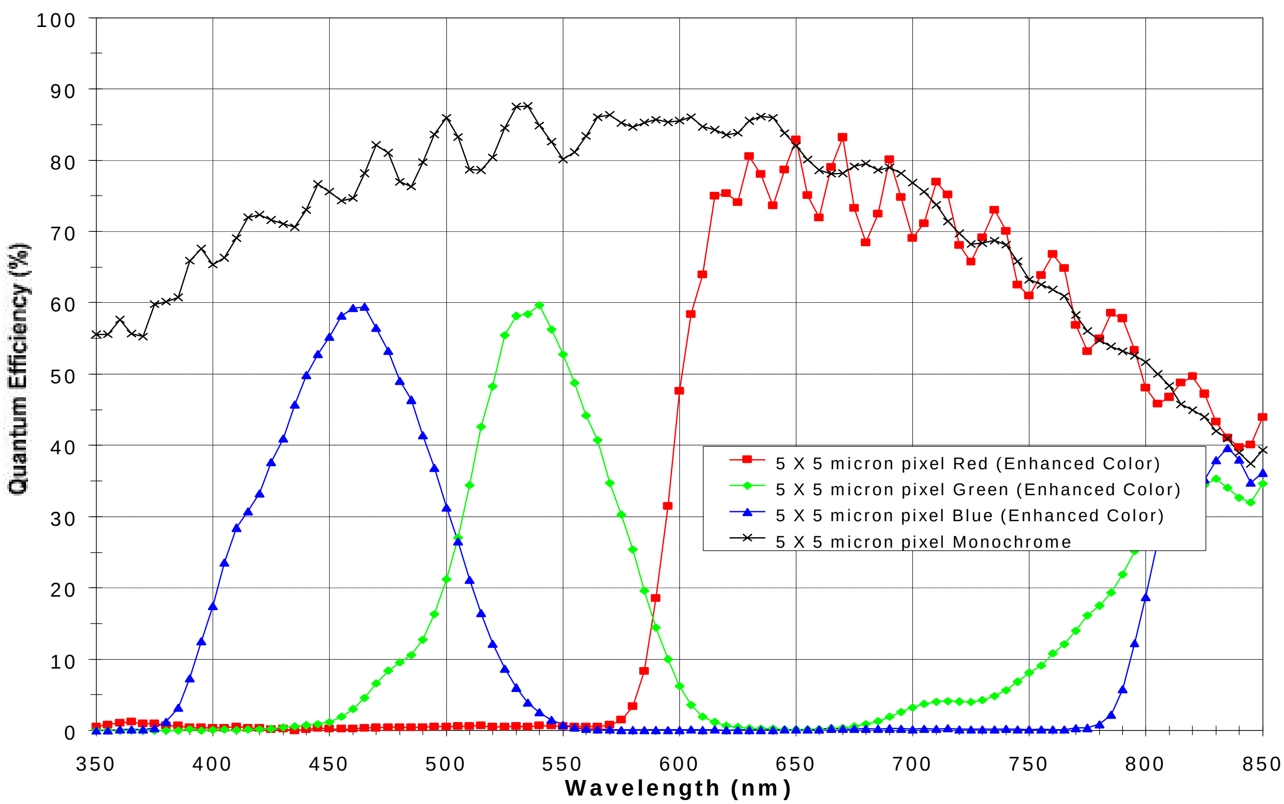

Figure 7 - Quantum Efficiency of the 5 x 5µm^2 pixel trilinear image sensor (measured data on α-samples).

Dark signal refers to the background signal present in the sensor readout when no light is incident upon it. The dark signal is dependent on the pixel unit cell area (photodiode plus CCD) and operating temperature. Temperature dependence of the dark current for the Kodak Digital Science image sensor with its 5 x 5μm^2 pixels is seen in Figure 8, showing a dark current doubling rate of approximately 7 degrees Celsius. Room temperature (25^oC) dark current is approximately 2 x 10^{-15} amperes per pixel (3.74 x 10^{-10} amperes per cm^2)

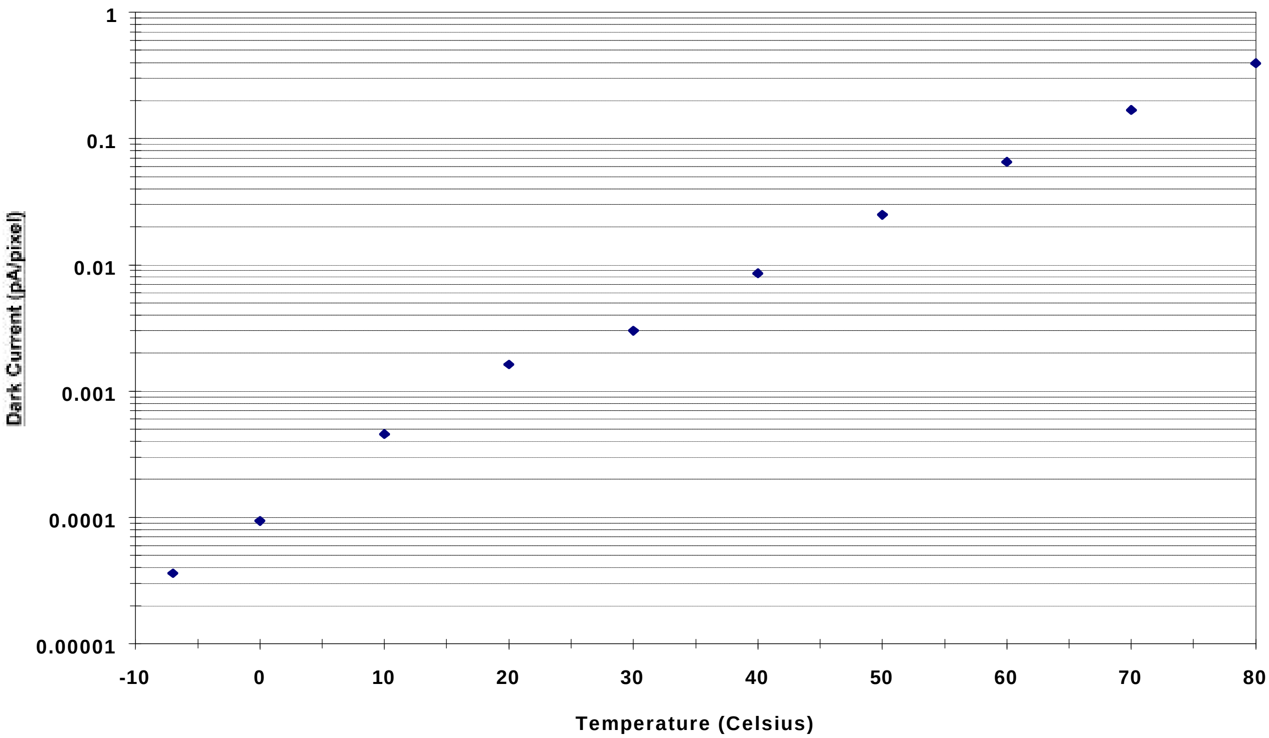

Figure 8 - Temperature dependence of the 5 x 5μm^2 pixel dark current (measured data on α-samples).

Image smear (photosite-to-shift register crosstalk) results when charge originating below the space-charge region of the photosites diffuses into the adjacent CCD. This results in added signal to each charge packet being transferred out through the CCD, which compromises spatial integrity. Smear increases at longer wavelengths, because of the photons being absorbed deeper into the silicon, allowing for generated photoelectron diffusion in random directions. The architecture of the Kodak 5 x 5μm^2 pixel image sensor provides sufficient photodiode-to-CCD separation resulting in superior smear performance as shown in Figure 9.

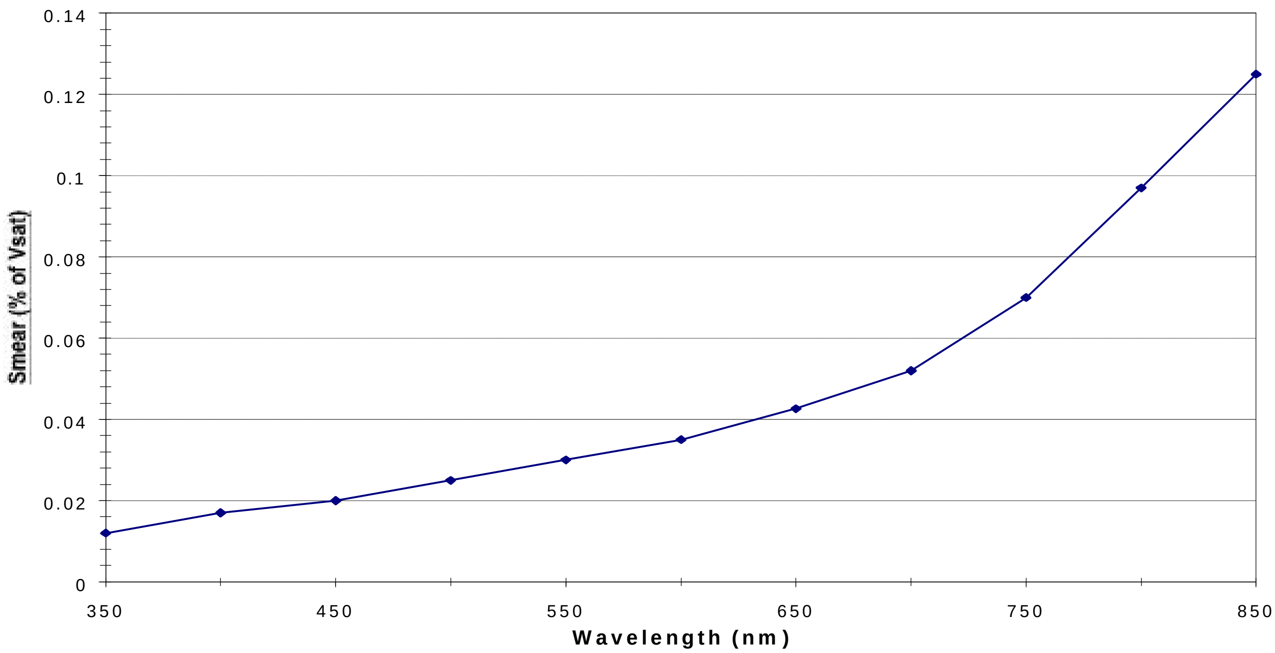

Figure 9 - Smear performance of the 5 x 5μm² pixel image sensor (measured data on α-samples).

Image blooming results when the maximum charge capacity of the photodiode or CCD is exceeded and the excess charge spills to the adjacent sites resulting in image degradation of the surrounding pixels. The 5 x 5μm² pixel trilinear sensor antiblooming structure provides approximately 6X image blooming protection as shown in Figure 10.

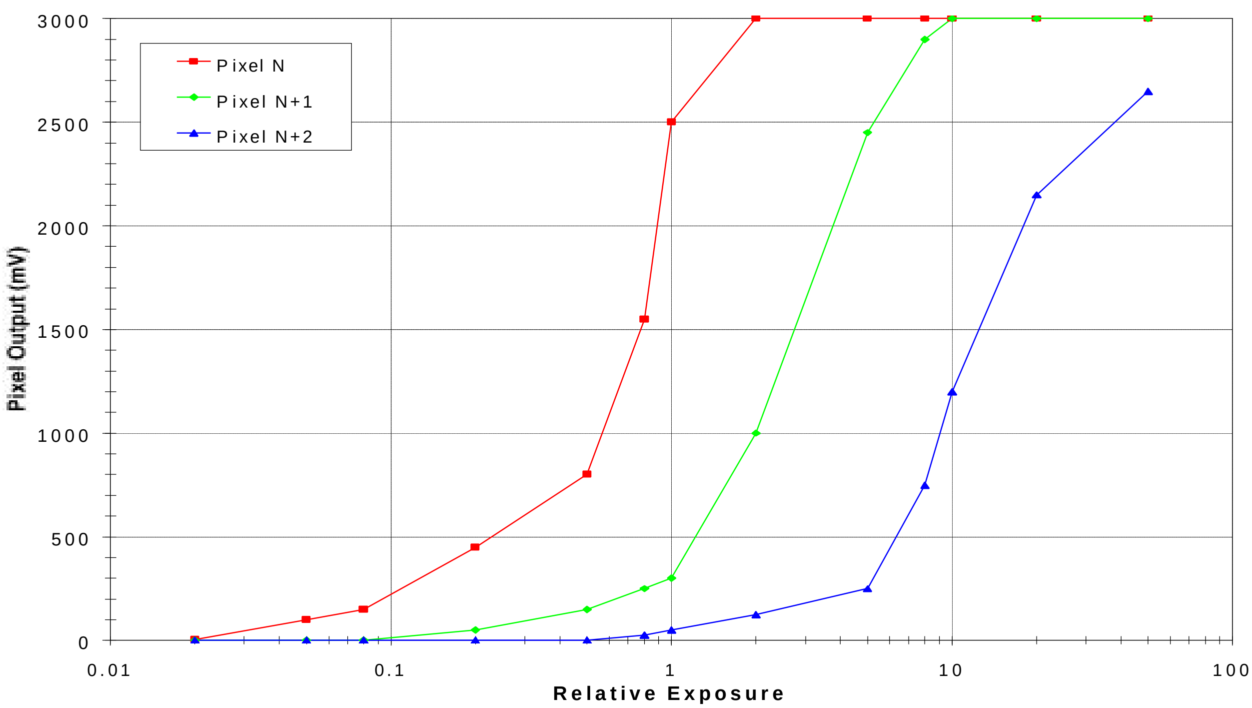

Figure 10 - Antiblooming performance of the 5 x 5μm² pixel trilinear image sensor.

The resolution of the Kodak 5 x 5μm² pixel trilinear sensor as compared to Kodak's other long trilinear sensors is shown in Figure 11. Here the resolution is defined as the number of photosites (dots) per inch in the object plane.

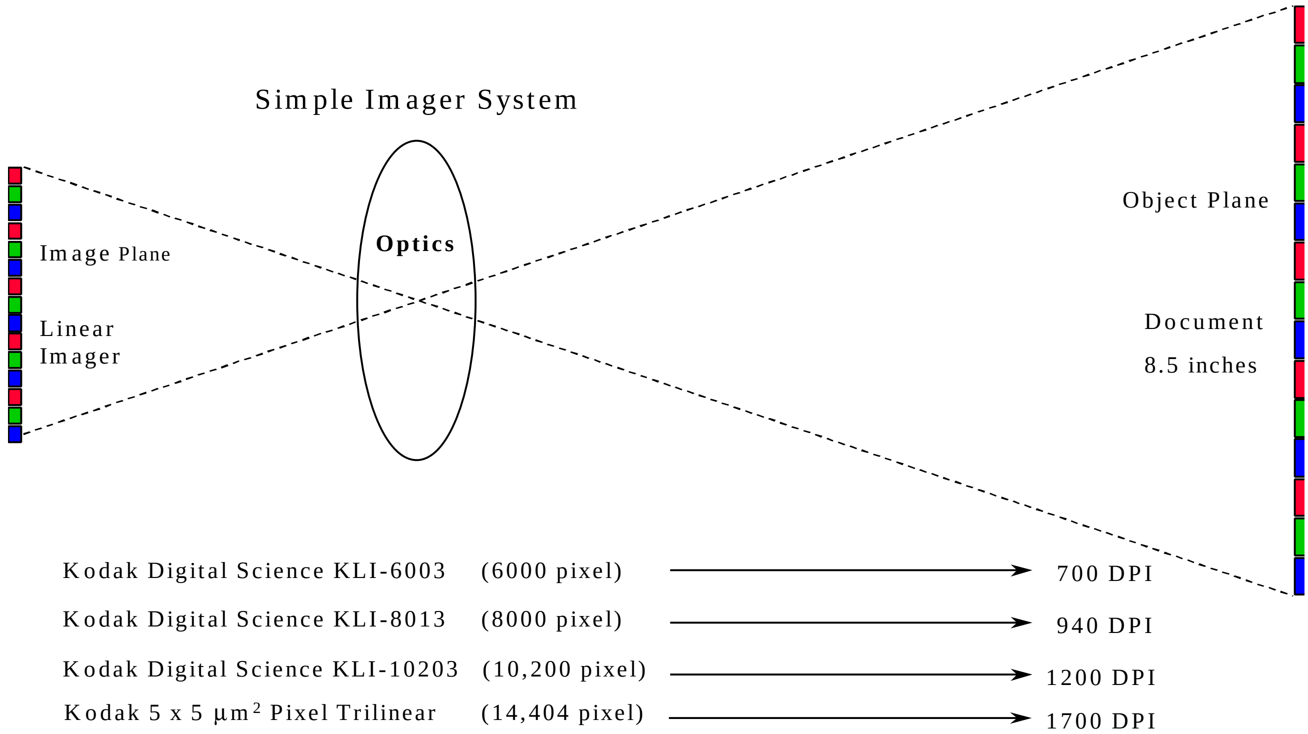

Figure 11 - Scanning resolution comparisons of Kodak's family of long (72 mm) trilinear image sensors.

5. SUMMARY

An ultra-high resolution trilinear sensor is under development for applications in high-end scanning systems. A Performance summary of Kodak's family of long trilinear image sensors is given below in Table 1.

Imager Name	Number of Pixels	Pixel Size (µm)	Saturation Signal	Dynamic Range	Responsivity (V/µJ/cm^2)	Output Sensitivity (µV/ e$^-$)	Dark Current (pA/pixel)	Charge Transfer Efficiency	Maximum PRNU	Maximum Data Rate
KLI-6003	6000 x 3	12 x 12	275,000 e$^-$	>72 dB	11.7 (λ = 460 nm) 14.8 (λ = 550 nm) 32.3 (λ = 650 nm)	8	<0.02	>0.999995/T	<15%	10 MHz/Ch.
KLI-8013	8000 x 3	9 x 9	400,000 e$^-$	>84 dB	7.5 (λ = 460 nm) 11 (λ = 550 nm) 21 (λ = 650 nm)	14	<0.01	>0.999995/T	<15%	5 MHz/Ch.
KLI-10203	10,200 x 3	7 x 7	224,000 e$^-$	>74 dB	4 (λ = 460 nm) 6 (λ = 550 nm) 12 (λ = 650 nm)	12.5	<0.01	>0.999995/T	<15%	10 MHz/Ch.
Kodak Trilinear	14,404 x 3	5 x 5	230,000 e$^-$	>76 dB	3.8 (λ = 460 nm) 4.2 (λ = 550 nm) 7 (λ = 650 nm)	11	<0.005	>0.999995/T	<10%	10 MHz/Ch.

Table 1 - Performance comparisons of Kodak's family of long trilinear image sensors.

ACKNOWLEDGEMENTS

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