Application Note

True Two-Phase CCD Image Sensors Employing a Transparent Gate

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by

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ABSTRACT

This paper describes the performance of a family of full-frame sensor designs where a transparent electrode replaces one of the polysilicon gates. The sensors are all fabricated with a true two-phase buried channel CCD process that is optimized for operation in multi-pinned phase (MPP) mode for low dark current. The true two-phase architecture provides many advantages such as progressive scan, square pixels, high charge capacity, and simplified drive requirements. The uncomplicated structure allows large area arrays to be fabricated with reasonable yield. Inclusion of a transparent gate increases the response by a factor of 10 at 400nm and 50% at 600nm.

Keywords: Charge coupled device, CCD, image sensor, transparent

1. INTRODUCTION

Full-frame charge coupled device (CCD) image sensors are utilized in the most demanding imaging applications because of their high dynamic range, low noise floor, high optical fill factor, and availability in large physical formats. The architecture is the least complicated to manufacture of all the available image sensor technologies. This allows large optical format sensors to be produced with reasonable manufacturing yields.

Full-frame sensors are the technology of choice in low signal applications because they exhibit the lowest dark current of available image sensor technologies. The low dark current produces the best signal-to-noise ratio when sensors are operated at low signal levels. The low dark current results from operating the photo active area in multi-pinned phase (MPP) or accumulation mode. In this, mode the gate electrodes are held at a voltage that accumulates the silicon surface with majority carriers and quenches the dark current component because of generation at these surface states.

The highest manufacturing yields result from illuminating the sensor from the electrode (front) side eliminating the need to thin the sensor substrate. The disadvantage is a reduction in the response caused by the absorption of photons by the polysilicon gate structure. This is especially apparent at blue wavelengths between 400 and 500 nanometers. Approaches that have been attempted to remedy this have the undesirable effect of increasing the manufacturing process complexity and/or compromising other sensor performance parameters.

The best solution is to replace one or both of the polysilicon gates with a more transparent material. This improves the response while preserving the other benefits of manufacturability and performance.

2. PIXEL ARCHITECTURE

True two-phase CCD registers consist of two gate electrodes per pixel. The signal charge is separated using a blocking region that is an integral part of each of the two gates.[1] Pixel sizes from 6.8 to 24 microns have been realized using this same fabrication process. An example of a pixel design is shown in Figure 1 which shows the two gate electrodes and the barrier regions within each electrode.

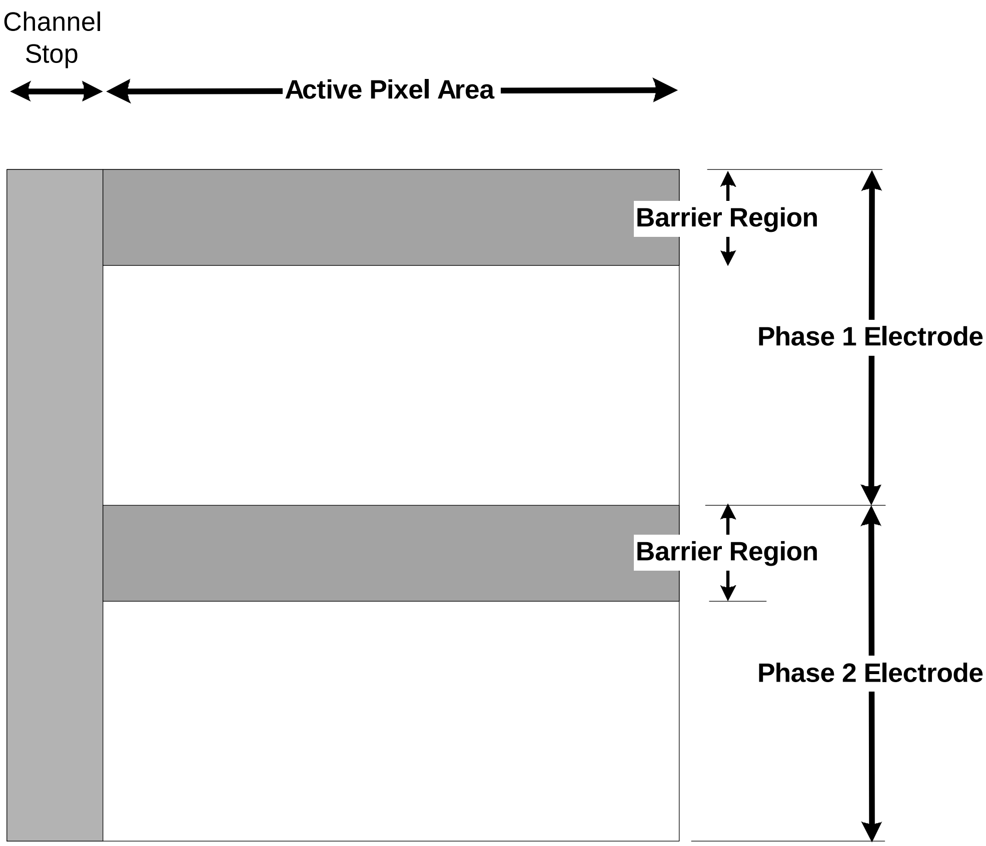

Figure 1 True Two-Phase Pixel

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An antiblooming structure has been incorporated into the two-phase technology as a lateral overflow drain.[2] Figure 2 shows the same pixel design with the lateral overflow drain (LOD). For a 9 micron pixel the antiblooming structure consumes 30% of the pixel area and leaves it with a 70% fill factor. The fill factor becomes proportionately larger for larger pixels. The LOD preserves the sensitivity at extreme red wavelengths that is compromised using the vertical overflow drain common with interline imager architectures.

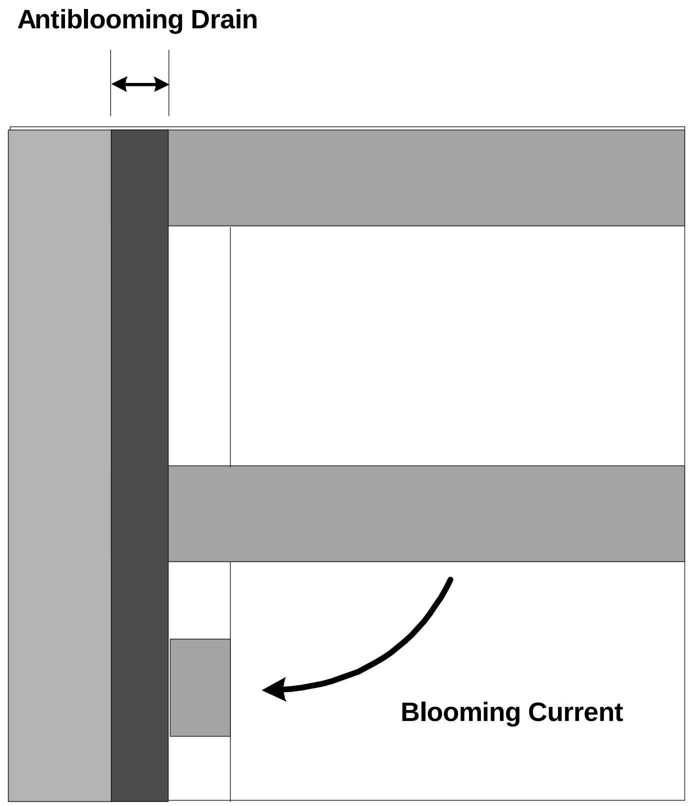

Figure 2 True Two-Phase Pixel with Lateral Overflow Drain

When both gates are held in accumulation to minimize dark current generation, the photo-generated charge is split between both gates. It is recombined under one gate prior to shifting from one pixel to the next. The unidirectional transfer and separation of adjacent signal packets is possible with optimal device design of the various regions within the pixel. The result maintains the normal charge capacity obtained as when operated in non-MPP mode, at the same time realizing the dramatic dark current reduction with MPP mode operation. When the pixel is made larger the charge capacity utilization of the pixel approaches 50% while a three-phase CCD is limited to 33%. Figure 3 illustrates the potential in the silicon within the pixel during these two conditions.

True two-phase CCD imager sensors have other advantages. The number of clocks required for operation is less than that required for three-phase and four-phase CCDs. The simpler gate structure allows smaller pixels without resorting to an interlaced scan format. Only two electrode layers are required simplifying the manufacturing process Because each patterned electrode contains the same clock, intra-level defects do not result in an electrical short further enhancing the manufacturing yield.

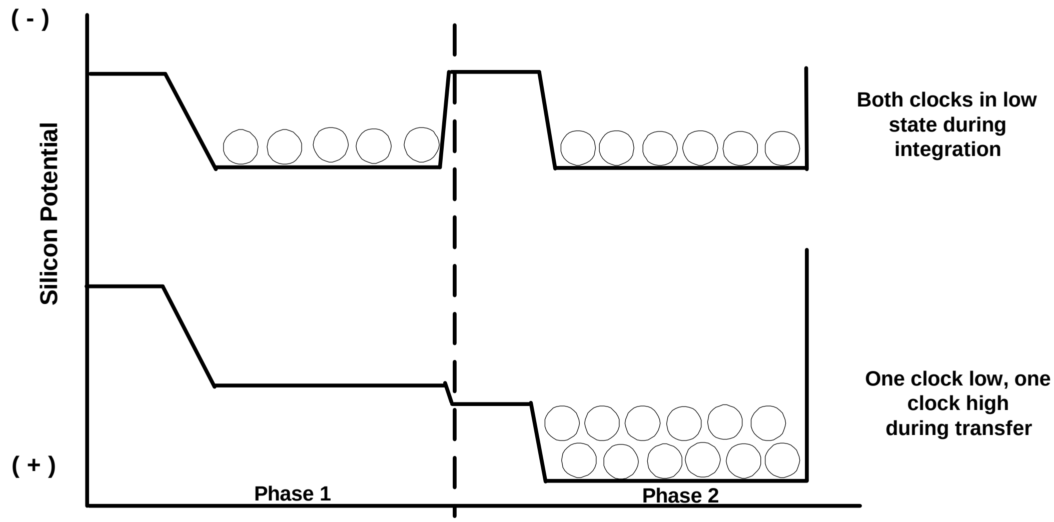

Figure 3 Potential Beneath Regions of Two Adjacent Pixels

3. TRANSPARENT ELECTRODE

The highest manufacturing yields results from illuminating the sensor from the electrode (front) side which eliminates the need to thin the sensor substrate. The disadvantage is a reduction in the response because of to the absorption of photons by the polysilicon gate structure. This is especially apparent at blue wavelengths between 400 and 500 nanometers. There have been attempts to reduce this effect, such as the virtual phase architecture[3] and light windows in the gates.[4] These have the undesirable effect of increasing the manufacturing process complexity and/or compromising other sensor performance criteria, such as charge transfer efficiency and noise floor.[5]

To address the low blue response of front side illuminated full-frame sensors Kodak has developed a process that replaces one of the gate electrodes with an electrically conductive, transparent material. The result is a dramatic increase in the sensor response. The quantum efficiency has increased from 2% at 400nm to 30%. The peak quantum efficiency occurs from 575 to 675nm and increased from 40% to 63%. This approach does not sacrifice other performance parameters such as charge capacity, noise floor, and dark current. It allows the same high yielding true two-phase process to be used to manufacture the sensors.

4. PERFORMANCE

The following sections present the dark current and spectral response measured on samples fabricated with the transparent gate process. The results are compared to those from the traditional two polysilicon electrode process and to those from other technologies when appropriate. Other performance parameters such as charge capacity and noise floor have been confirmed not to vary with the process technology and are summarized in Table 1.

4.1 Spectral Response

The spectral response was measured from 350nm to 1100nm. The results for the 6.8 micron one hundred percent full fill factor pixel design is presented in Figure 4. The response from the traditional double polysilicon full-frame sensor is included for comparison.

The response of an interline architecture design with similar pixel size and micro-lenses is also presented for comparison.

The transparent gate results in blue sensitivity equivalent to the photodiode of the interline sensor at 400nm. Above 500nm, the response of the transparent gate sensor is superior to the other two technologies because :

- The transparent gate is less absorptive than polysilicon.
- The index of refraction of the transparent electrode provides a better match between overlying oxide and the silicon substrate than the polysilicon resulting in less reflective losses.
- The full-frame architecture has a larger collection volume than the interline sensor, caused by the absence of a vertical over flow antiblooming control drain.

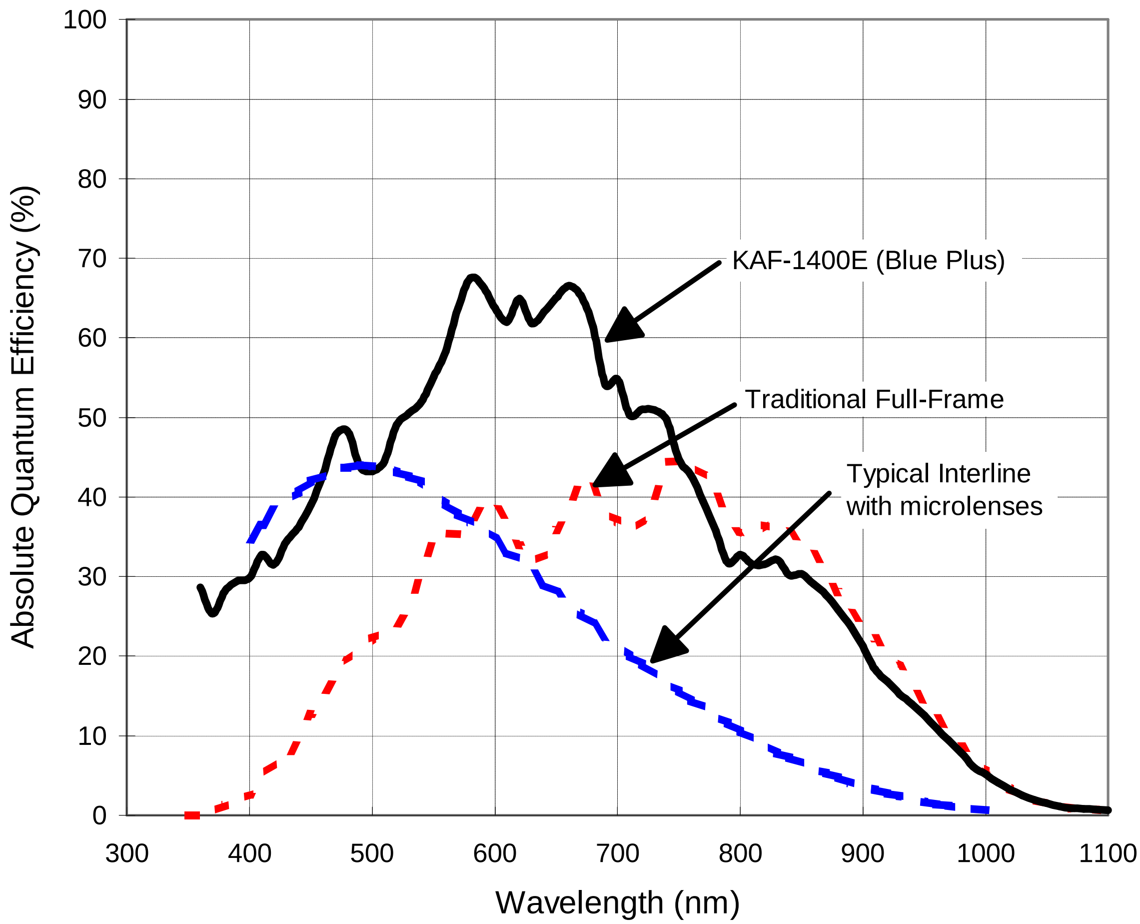

Figure 4 Spectral Response of Image Sensor Technologies

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4.2 Dark Current

The dark current of image sensors is a critical parameter. It can be a principle component of the noise floor and determines the maximum integration time used in an application. Conversely, it will determine the maximum temperature an array must be operated at in order to achieve desired performance.

The dark current of sensors produced with the transparent electrode process has been measured as a function of temperature. The results are presented in Figure 5. The measured dark current of 2.1 pA/cm^2 at 25°C is indistinguishable to that of the traditional full-frame sensor manufactured with the same true two-phase CCD process. The sensor was operated in the MPP clocking mode recommended for sensors using this technology.

The measured data is from a 6.8 micron pixel design. Pixel designs greater than 9 microns are fabricated using a higher resistivity epitaxial silicon layer to improve the transfer efficiency with the larger fringing fields that result. Dark current is proportional to the square root of the resistivity and is three times greater for larger pixel designs.

Pixel designs containing the lateral overflow antiblooming structure exhibit lower dark current per area since the overflow drain occupies up to 30 percent of the pixel area. The dark current from this area is removed through the overflow drain and does not contribute to the photo signal.

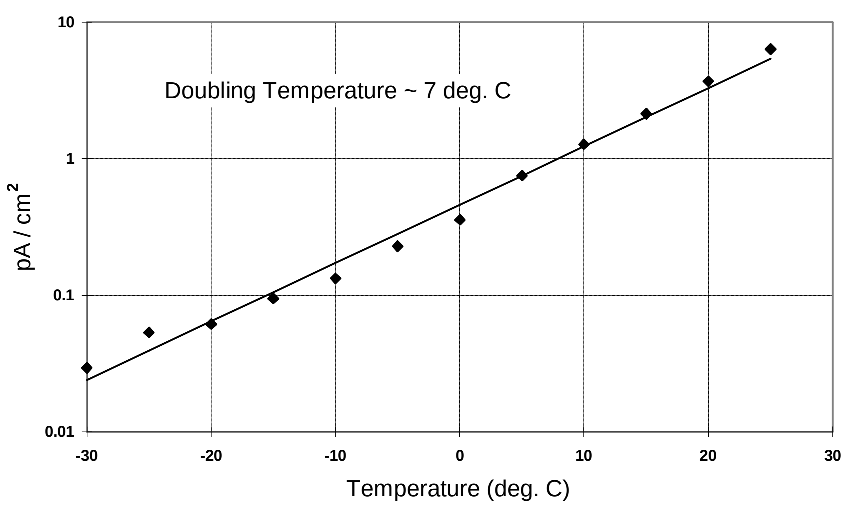

Figure 5 Dark Current of Transparent Electrode Full-Frame Sensor

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5. SENSOR FAMILY

Kodak has a family of full-frame image sensors, KODAK DIGITAL SCIENCE ™ KAF Series Image Sensors, with pixel sizes from 6.8 microns to 24 microns and resolutions from 262,000 pixels to 16.8 million pixels. All are manufactured with the same process technology and benefit from the new transparent gate technology. These sensors are summarized in Table 1.

Table 1. Summary of Available Full-Frame Designs

Kodak Sensor	Resolution	Pixel Size (μm)	Dark Current [ab] (pA/cm^2)	Noise Floor [b] (Electrons)	Charge Capacity [b]	Anti-Blooming
KAF-0261E	512 x 512	20	10	12	400,000	No
KAF-0401E	768 x 512	9	3	12	95,000	No
KAF-0401LE	768 x 512	9	2.1	12	50,000	Yes
KAF-1001E	1024 x 1024	24	10	12	650,000	No
KAF-1301LE	1280 x 1024	16	10	12	120,000	Yes
KAF-1401E	1320 x 1035	6.8	2.1	12	95,000	No
KAF-1602E	1536 x 1024	9	3	12	95,000	No
KAF-1602LE	1536 x 1024	9	2.1	12	50,000	Yes
KAF-6303E	3072 x 2048	9	3	12	95,000	No

[a] Temperature = 25°C
[b] Values listed are typical. Min./Max. specifications may differ.

6. SUMMARY

The incorporation of a transparent gate significantly improves the response of full-frame image sensors. This is a straightforward modification that preserves the performance and fabrication simplicity of these sensors. An existing family of full-frame sensor designs that use a true two-phase CCD process has been fabricated with the new process.

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