Front-illuminated full-frame charge-coupled device image sensor achieves 85% peak quantum efficiency

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ABSTRACT

A high sensitivity front-illuminated charge-coupled device (CCD) technology has been developed by combining the transparent gate technology introduced by Kodak in 1999 with the microlens technology usually employed on interline CCDs. In this new architecture, the microlens is used to focus the incoming light onto the more transparent of the two electrodes. The new sensors offer significant increases in quantum efficiency while maintaining the performance advantages of front-illuminated full-frame CCDs including 3 pA/cm^2 typical dark current at 25ºC, and 55 ke full well in a 6.8 µm pixel.

1. INTRODUCTION

Kodak introduced the world's first commercially available megapixel full-frame CCD in 1986 and today has a full-frame CCD product portfolio that ranges in pixel size from 6.8 µm to 24 µm and in resolutions from 512 x 512 pixels to 4096 x 4096 pixels. All of Kodak's full-frame CCDs are based on a true 2-phase buried channel CCD architecture. They are manufactured both with and without color filter arrays and lateral overflow drains (LODs) for antiblooming protection.

Full-frame sensors are usually selected for high-performance imaging applications where high sensitivity, low dark current, and low noise are critical. Sensitivity may be improved by reducing the amount of light that is absorbed in the gate electrodes lying on top of each pixel. There are two basic strategies for minimizing that absorption. One is to thin the sensor substrate and illuminate the pixels from the backside. This results in very high quantum efficiency from the ultraviolet to the near infrared. The penalties are reduced manufacturing yield and higher dark current. The second strategy, adopted by Kodak, is to make the gate electrodes more transmissive.

Work started in the early 1990s to replace one of the two polysilicon gate electrodes with the more transmissive indium tin oxide (ITO). The ITO also provides better index matching with the silicon below, reducing reflection losses. In 1999, Kodak announced products using this new technology, and today over a dozen different full-frame image sensors that exploit it are available. With this approach, high manufacturing yields and low dark current were maintained as sensitivity was improved.

To further increase sensitivity, a microlens has been added to the pixel. The microlens directs light preferentially toward the ITO gate, to take full advantage of its increased transmissivity. The result is a full-frame pixel that achieves a peak quantum efficiency in excess of 85%.

2. PIXEL ARCHITECTURE

An example of a two-phase full-frame pixel with ITO is shown in Figure 1. The ITO is the lighter of the two gate materials shown. Although both sides of the pixel are light sensitive, more light will be transmitted through the ITO gate.

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Figure 1. The lighter material is the ITO in this scanning electron microscope (SEM) image of a cross section of a 2-phase CCD pixel.

Microlenses have recently been added to this architecture to further increase sensitivity. Microlenses are usually associated with interline CCD technology, where only a portion of the pixel is light sensitive, and a microlens is used to offset the loss in fill factor by focusing light onto the photodiode. In the case of a full-frame CCD with one ITO phase (although the whole pixel is sensitive to light), the ITO gate is more transmissive than the conventional polysilicon gate, so an increase in sensitivity can be realized by using a microlens to focus more of the incident light through the ITO gate.

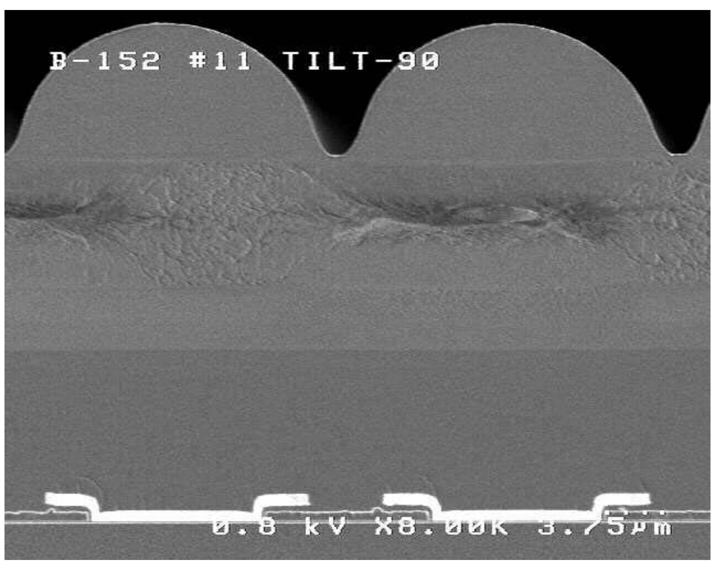

Figure 2. Microlenses are used to focus incident light through the ITO gate, which is more transmissive than the polysilicon gate.

For monochrome devices, cylindrical lenses are typically used. Figure 3 shows a top view of the Kodak KAF-3200ME image sensor employing the cylindrical lens. The bright horizontal lines are polysilicon showing through the lens gaps. The vertical lines are the channel stops.

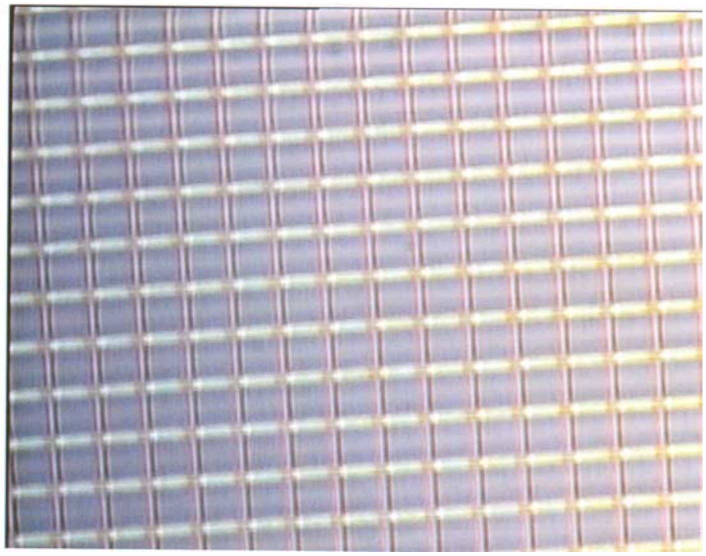

Figure 3. Cylindrical microlenses are used to focus light through the ITO electrode.

The architecture for color devices is slightly different and is shown in Figure 4. The cylindrical lenses are not used on color devices because light piping along axis in the microlens can contribute to color crosstalk, so traditional lenses are used instead. To further mitigate color crosstalk, a metal aperture is used, opening only over the ITO electrode. In Figure 4, the rectangles over the polysilicon are the sides of the metal aperture. The color filters can be seen between two spacer layers under the lens.

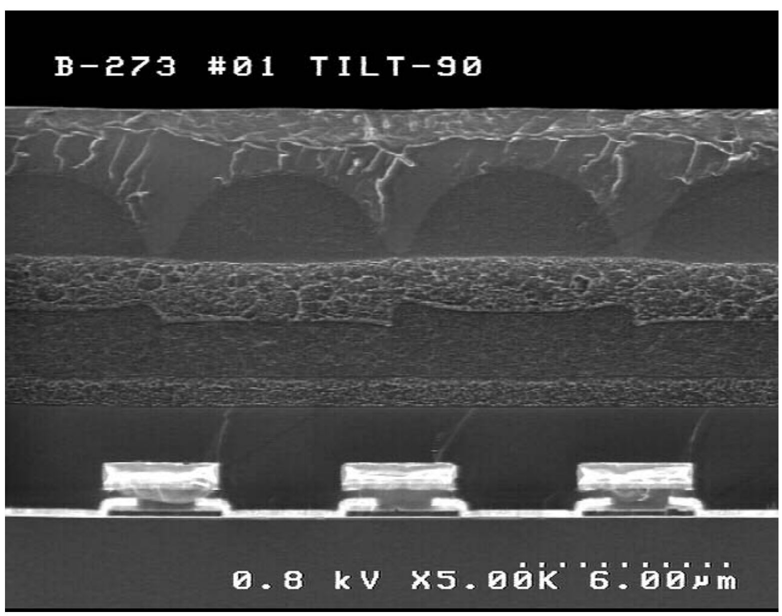

Figure 4. For color devices like the Kodak KAF-5101CE image sensor shown here, a metal aperture and traditional lenses are used to reduce color crosstalk. The layer above the microlenses in this image is for protection during dicing.

3. PERFORMANCE

Figure 5 shows the progression of the full-frame technology at Kodak over the last 10 years. The ‘poly’ curve shows the quantum efficiency of a pixel in which both gate electrodes of the 2-phase pixel are polysilicon. The ‘ITO’ curve shows the quantum efficiency when one of the polysilicon gate electrodes is replaced with the more transmissive ITO. The ‘ITO w/ ulens’ curve shows the result when the microlens is added to focus light onto the ITO electrode. All of the data refers to a 6.8-µm, 2-phase pixel. The improvements have been most dramatic in the blue portion of the spectrum, where the absorption of incident photons by the polysilicon gate material accounted for most of the loss in the all-poly pixel. At 400 nm, the quantum efficiency has increased from less than 5% to just under 60%. Between 500 nm and 550 nm, the portion of the spectrum of interest to applications looking at light from a phosphor screen or green fluorescent protein, the quantum efficiency has increased from 43–55% to 67–82%. The quantum efficiencies shown in Figure 5 are for pixels without lateral overflow drains.

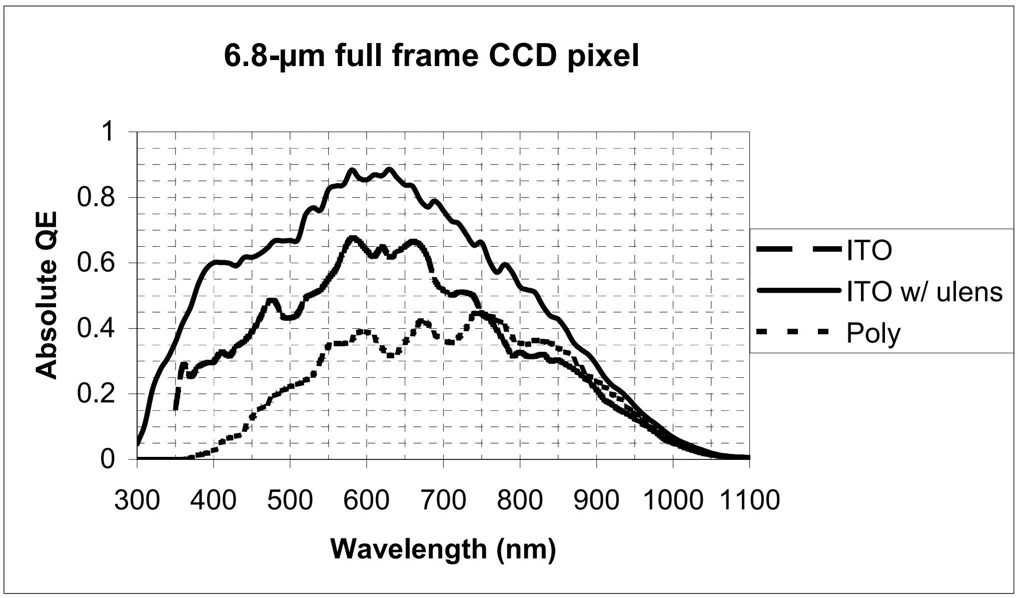

Figure 5. Absolute quantum efficiency of a Kodak 6.8-µm full-frame pixel without coverglass.

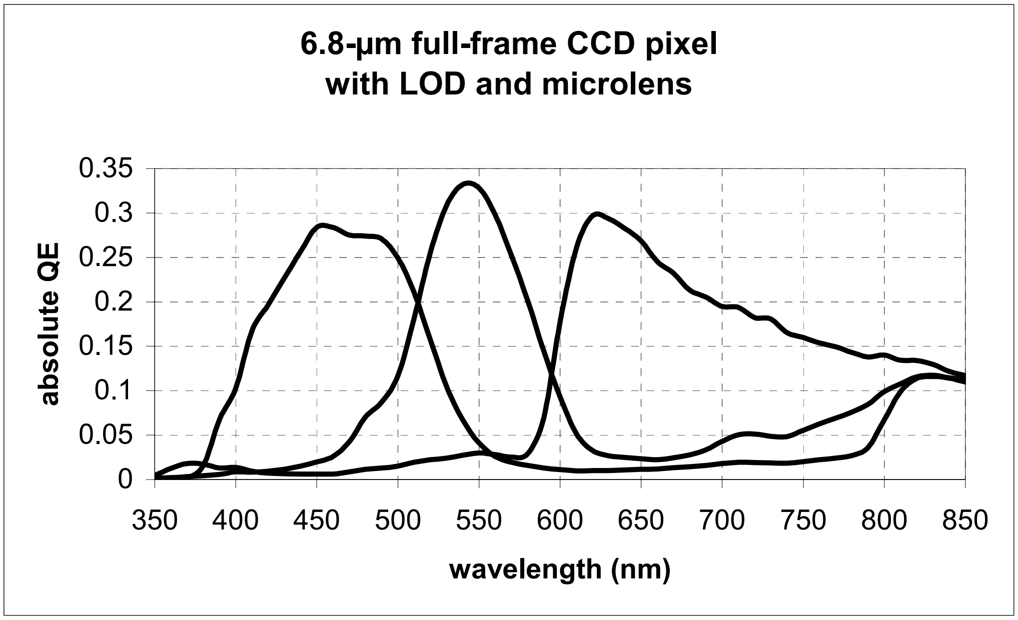

Figure 6. Absolute quantum efficiency of a 6.8-µm pixel full frame CCD with color filters and microlens. Measurements were taken with clear (no anti-reflection coating) cover glass in place.

Figure 6 shows the quantum efficiency of the color device whose architecture was shown in Figure 4. This pixel is also 6.8-µm, but includes a lateral overflow drain for antiblooming protection. The quantum efficiency measurement was performed with the package's clear cover glass in place, but no infrared cut-off filter.

A wide variety of output amplifier designs are employed on Kodak full-frame sensors. The 2-stage amplifier on the KAF-3200ME sensor, shown in Figure 7, has a low-capacitance sense node achieving 20 µV/e- and 6 electrons total system noise at a 1 MHz pixel rate in a test camera. At this pixel rate the chip delivers 12 bits of dynamic range; 14 bits with 2 x 2 binning. The maximum speed for this output structure is around 12 MHz, above which linearity begins to degrade. The total system noise in the test camera at the maximum pixel rate is around 20 electrons. The 3-stage amplifier on the KAF-5101CE sensor is designed to operate at 28 MHz, where to the total system noise is 21 electrons measured on a Kodak evaluation board using an analog front end (AFE) chip from Analog Devices. This design has a charge-to-voltage conversion of 18 µV/e-.

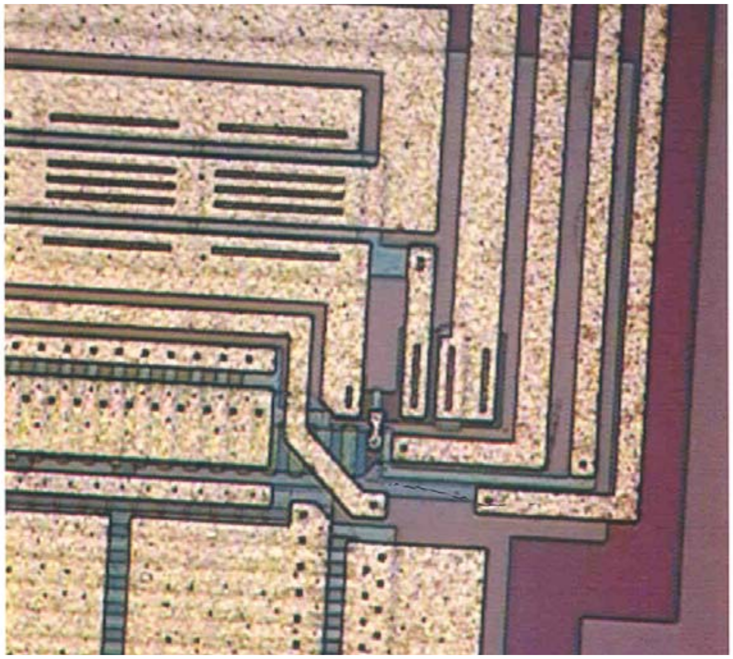

Figure 7. The output structure of the KAF-3200ME sensor contains a dual-stage amplifier. In this image, charge is transferred to the right along the horizontal CCD.

The low dark current shown in Figure 8 is typical for front-illuminated full-frame image sensors, and is one of their main advantages over other imaging architectures. This low dark current is achieved in part by operating the sensor in multiple pinned phase (MPP) mode, also referred to as accumulation mode. In this clocking mode, the gate electrodes are held at a voltage that accumulates the silicon-silicon dioxide interface with holes, decreasing the rate of dark current generation. A dark current around 3 pA/cm^2 at 25ºC is typical for Kodak full-frame CCDs, and dark current levels vary from lot to lot by around a factor of 2.

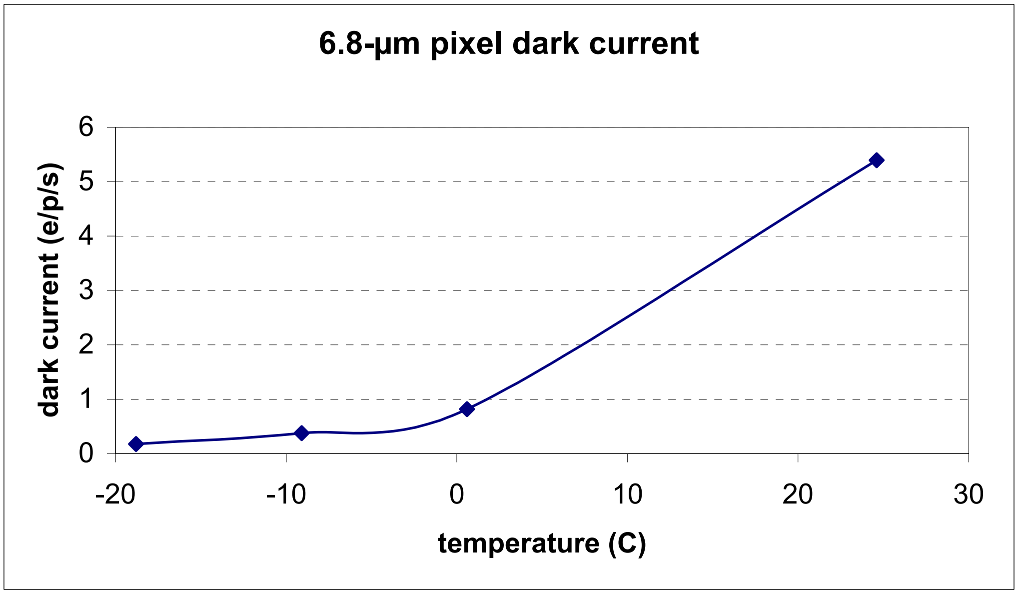

Figure 8. This measurement shows a typical dark current of 5.4 e/p/s at 25ºC, corresponding to 1.9 pA/cm^2 for the 6.8-µm pixel.

4. APPLICATIONS

Many of the applications that will benefit most from the monochrome full-frame with microlens technology are in the medical and biological markets. In medical x-ray, where higher quantum efficiency translates to lower x-ray dose for the patient, higher sensitivity is always beneficial. Because x-ray systems use a phosphor screen, the high quantum efficiency is only needed around 550 nm, where this technology achieves nearly 85%. Other applications that will benefit from this technology include gel electrophoresis, chemiluminescence, fluorescence, DNA sequencing, micro-titre plate reading for drug discovery, and astronomy. In the biological applications cells are usually stimulated by UV radiation and then fluoresce in the visible, but there is a desire to move toward tags that are stimulated with visible light and fluoresce in the near infrared (NIR), since the visible light is less damaging to the cell samples. In those applications NIR sensitivity is of great interest, and with a QE of over 50% at 800 nm, this full-frame architecture is a good match. This technology will also be used in film scanning minilabs, where images are color-sequential and the increased sensitivity will translate into higher throughput.

For low light level applications, where long exposures are required, dark current is a critical parameter. The shot noise component of the dark current often determines the noise floor of the camera system in these cases. These applications will benefit from the low dark current found on all Kodak full-frame sensors, including those with microlenses. When the sensor's dark current is very low, long integrations without active cooling are possible.

While the color version of the new pixel was designed primarily for the digital still camera market, any application in which the goal is to get a high-quality color image from a single snapshot will benefit from this advance.

The microlens will be incorporated, as on option, into the Kodak full-frame product line over the next couple of years.

5. CONCLUSION

By mixing and matching technologies from disparate imaging architectures, Kodak has created a front-illuminated full-frame CCD technology with peak quantum efficiency over 85%. The sensors can be used to improve the signal-to-noise ratio or to reduce the integration time for low-light applications.

6. ACKNOWLEDGEMENTS

The authors would like to thank everyone at Kodak's Image Sensor Solutions for the process development, fabrication, and testing of these sensors.

7. REFERENCES

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