Two-phase full-frame CCD with double ITO gate structure for increased sensitivity

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ABSTRACT

In 1999, Kodak introduced the first two-phase front-illuminated, full-frame charge-coupled device (CCD) in which the electrodes corresponding to one phase were composed of indium tin oxide (ITO), a material more transmissive than polysilicon. In an effort to further increase the sensitivity of front-illuminated image sensors, Kodak has developed an all-ITO electrode CCD. A 1280 x 1024 sensor with 16-μm pixels has been manufactured and characterized. The imaging performance of this device, including its sensitivity, dark current, and charge transfer efficiency, is described. The noise characteristics of the ITO-gated output amplifier, MOSFET, are also discussed.

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 up to 22 million 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 silicon, reducing reflection losses. In 1999, Kodak announced "Blue Plus" products using this new technology, and today over a dozen different full-frame image sensors that exploit it are in production. With this approach, high manufacturing yields and low dark current were maintained as sensitivity was improved.

In 2001 Kodak introduced an enhancement to this architecture. To further increase sensitivity, a microlens was 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%.

Although the microlens approach provides excellent sensitivity, it can suffer from shading at the edges of the field when imaging with a lens, although only in one dimension and to a lesser extent than is typical for an interline CCD or CMOS imager. More problematic for those working in x-ray applications, its benefits can't be exploited when bonding fiber optics to the sensor. By replacing all of the polysilicon on the device with ITO, Kodak has increased the sensitivity without introducing lens-interaction artifacts. Further, the sensitivity gained in this way is not lost with the bonding of fiber optic tapers or faceplates to the sensor surface. The result is a very robust solution to the need for a high-sensitivity full-frame CCD in applications ranging from direct digital x-ray to professional photography.

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The test vehicle used to develop the all-ITO gate technology was a 1280 x 1024 array of 16-µm pixels. The following sections review the pixel architecture and performance of this test device.

2. PIXEL ARCHITECTURE

An example of a two-phase full-frame pixel with one ITO gate introduced by Kodak in 1991 is shown in Figure 1. The ITO is the lighter of the two gate materials shown.

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.

The addition of the microlens to this architecture further increases 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, 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.

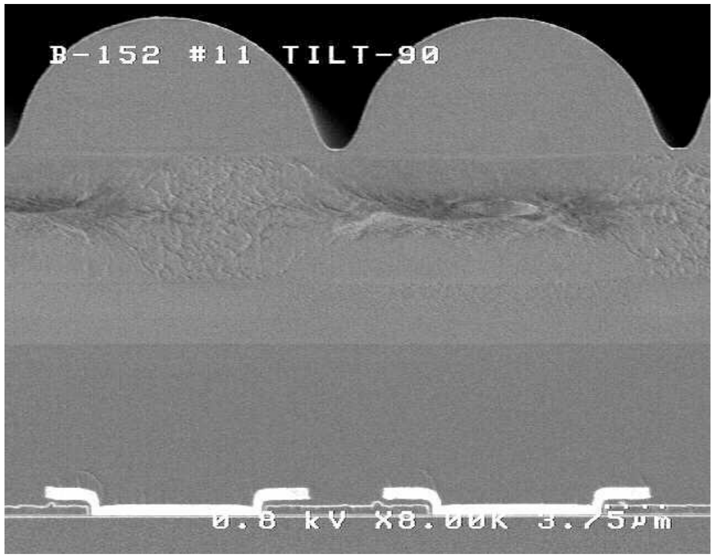


Figure 2. Microlenses are used to focus incident light through the ITO gate, which is more transmissive than the polysilicon gate.

The all-ITO gate pixel eliminates the traditional gate overlaps. The U-shaped ITO gates are separated by a 0.2-µm gap with a thermally grown SiO_2 gate separation insulator. The finished device consists of no polysilicon—even the gates of the output amplifier MOSFETs are composed of ITO. The pixel architecture is shown in the diagram of Fig. 3 and the SEM of Fig. 4.

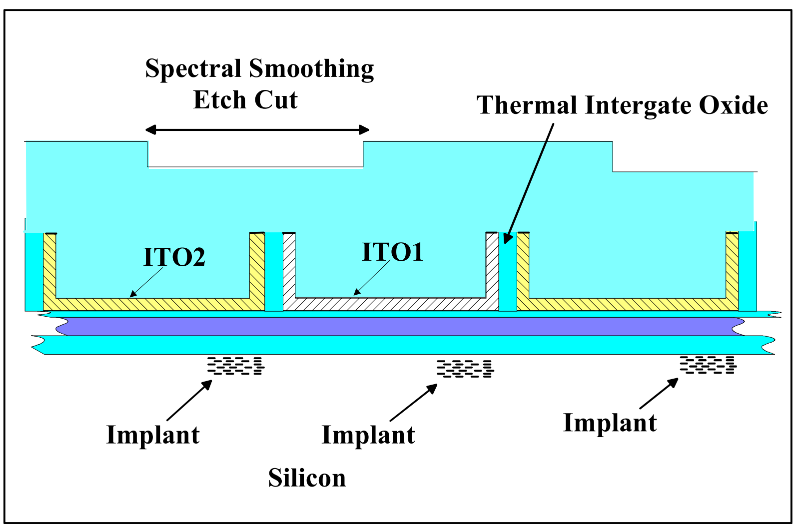


Figure 3. In the all-ITO CCD, a sidewall oxide separates U-shaped gates. A spectral smoothing etch cut averages out the problematic effects of layer thickness variations.

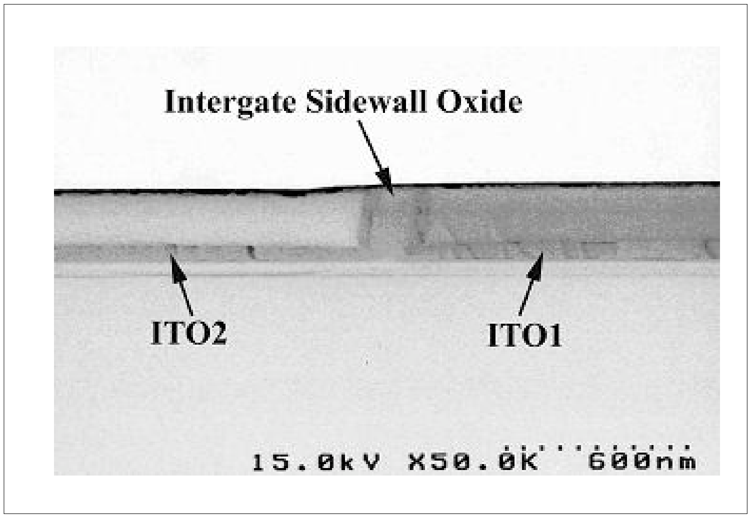


Figure 4. SEM image of a partially processed device, showing the gate structure described in Fig. 3.

Global non-uniformities in layer thicknesses can produce variations in optical interference patterns across the device and lead to variation in the optical response, both with respect to wavelength and physically across the sensor. To avoid this, a spectral smoothing etch, approximately ¼ wavelength in depth, has been incorporated into the device structure as shown in Fig. 3. At top-down view of the etch pattern is shown in Figure 5. This technique successfully minimizes QE variation with wavelength and improves the uniformity of the flat-field response as shown in Figures 6 and 7.

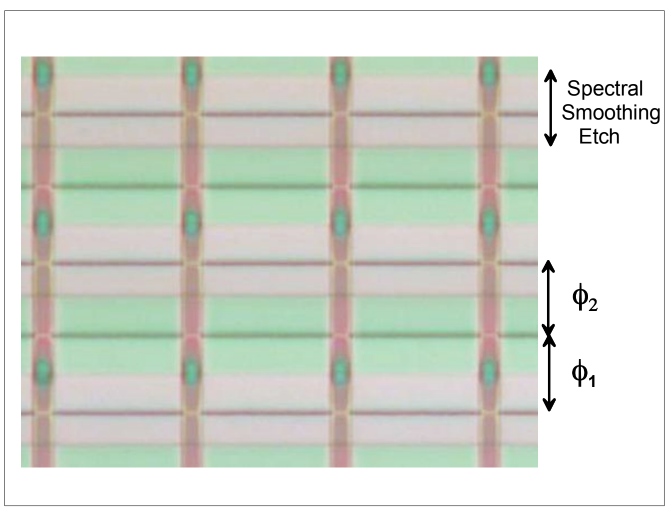
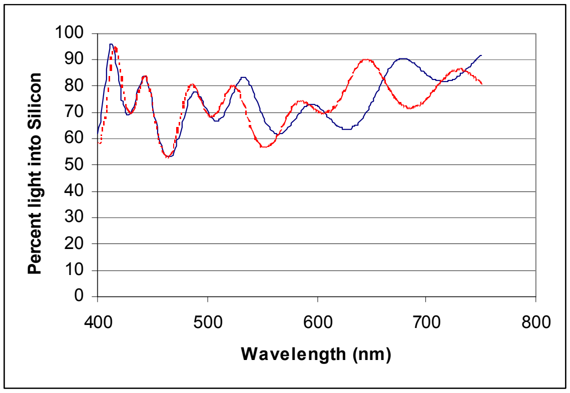


Figure 5. A top-down view of the spectral smoothing etch pattern used to minimize QE variations with wavelength and improve sensor flat-field uniformity.



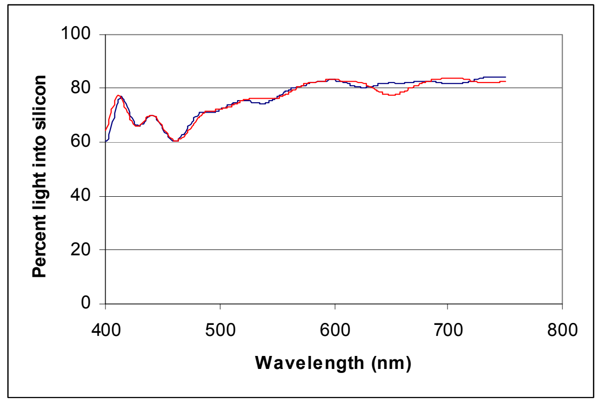
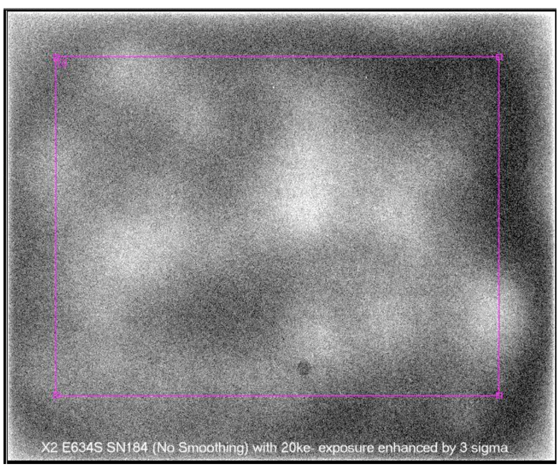


Figure 6. Quantum efficiencies without (left) and with (right) spectral smoothing.



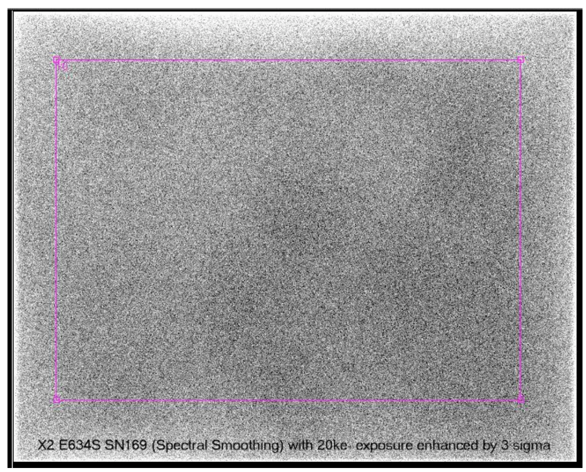


Figure 7. White light flat-field responses without (left) and with (right) spectral smoothing. Images are enhanced to exaggerate non-uniformities.

3. PERFORMANCE

The test sensor demonstrated a more than 2x improvement in quantum efficiency at shorter wavelengths, with improvements across the visible spectrum, while maintaining excellent charge transfer efficiency, dark current and read noise figures. Figure 8 shows the quantum efficiencies of several generations of Kodak full frame CCDs including an all-polysilicon gate device, a "Blue Plus" CCD employing one ITO gate and one poly gate in each pixel, and all-ITO gate devices both with and without spectral smoothing. The test sensor achieves a quantum efficiency of 20% as low as 300 nm. The QE remains high—between 60% and 70%—and relatively flat between 400 nm and 800 nm. At 900 nm, where transmission losses dominate QE performance, the test device shares a QE around 30% with previous generations of Kodak sensors.

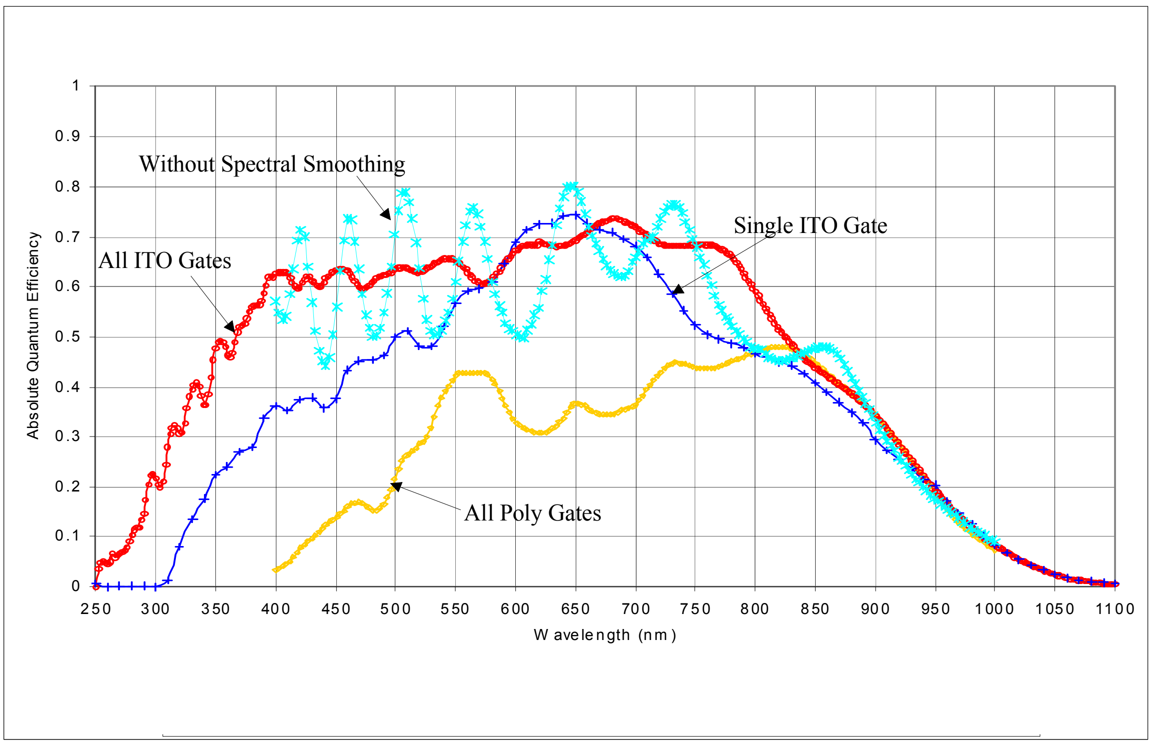


Figure 8. The test sensor demonstrates a more than 2x improvement in sensitivity at shorter wavelengths and maintains 60-70% QE from 400 nm to 800 nm.

High charge transfer efficiency is maintained by self-alignment of potential shaping implants, which allow a single gate conductor for each CCD clock phase and accumulation mode clocking for low dark current. CTE measurements taken on the test device are shown in Figure 9. Despite the gaps between electrodes the CTE is better than the previous generation technology in the same pixel size.

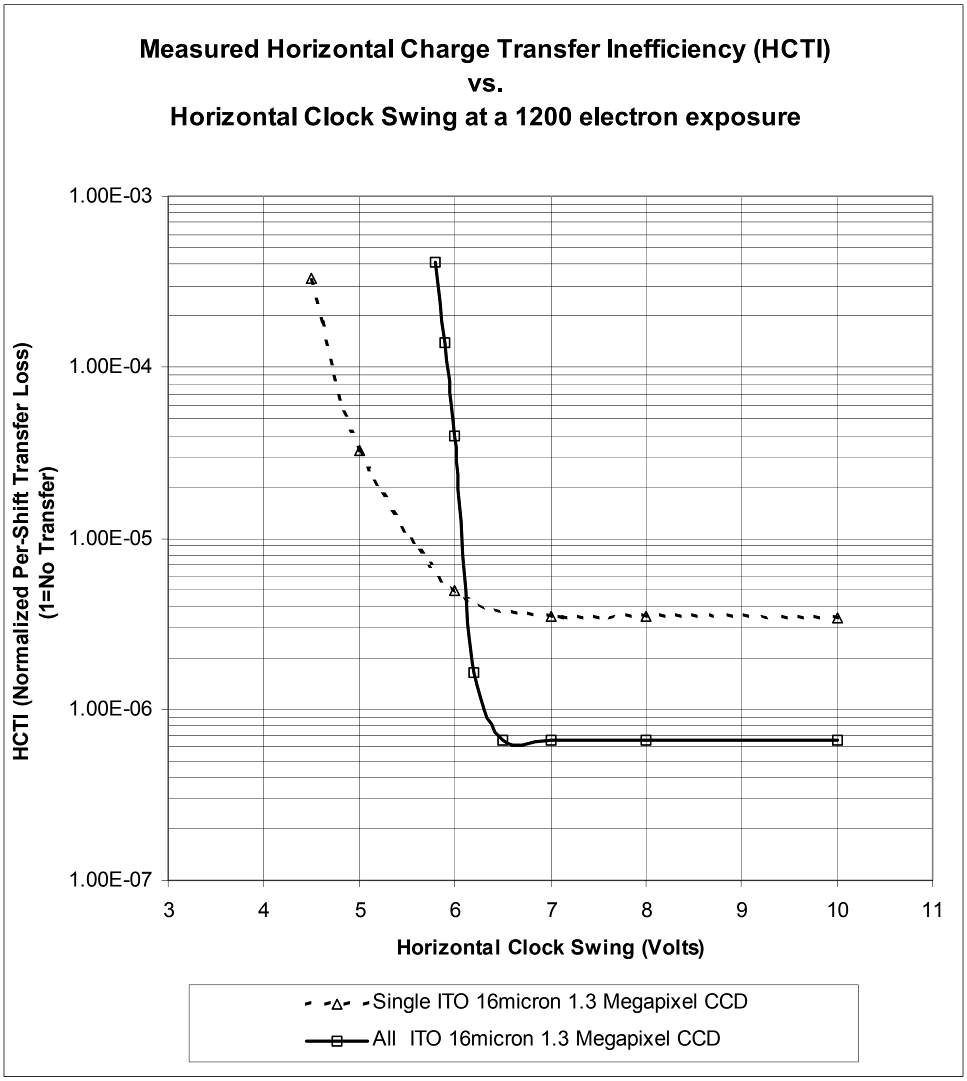


Figure 9. The charge transfer inefficiency (CTI) of the test device is lower than that of the previous technology in the same pixel size. Measurements were taken at room temperature.

Using accumulation mode clocking to suppress surface-generated charge, the dark current of the test device is 41 pA/cm^2 at 55C, in line with the low dark current characteristic of Kodak full frame CCDs.

The output amplifier of the test device is a 2-stage design incorporating ITO as the MOSFET gate electrode material. Since ITO gates in CCDs are known to generate higher levels of surface dark current than poly gates, there was some concern that this might translate into higher 1/f noise in ITO-gated MOSFETs. The noise spectrum of the drive MOSFET was measured using a spectrum analyzer and the results are shown in Fig.10. Although the ITO-gated MOSFET could be forced to demonstrate higher 1/f noise by increasing the current thru the device and driving the channel closer to the surface, under normal operating conditions the ITO-gated MOSFET didn't perform differently than a poly-gated MOSFET of similar geometry.

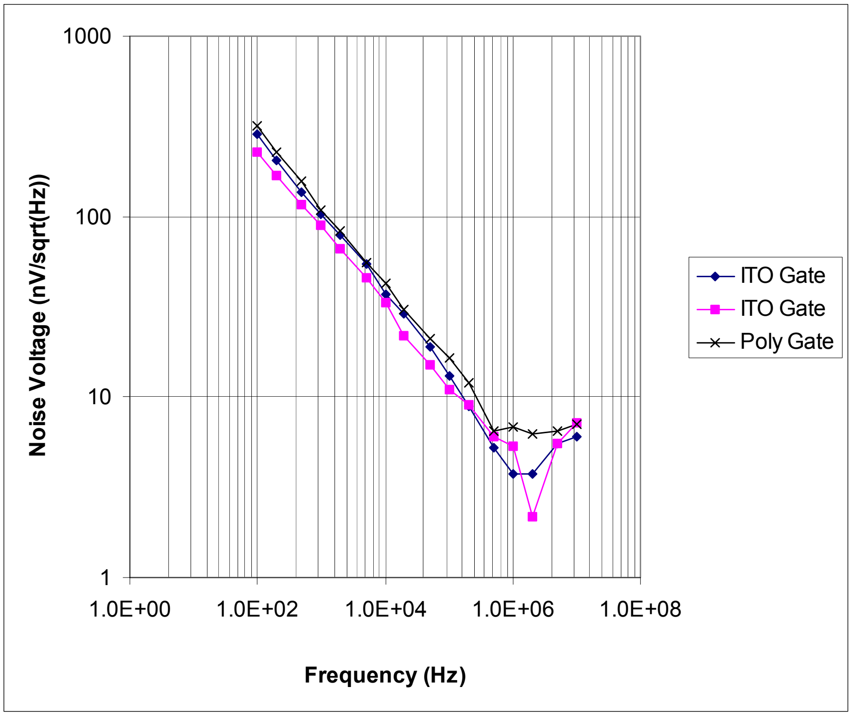


Figure 10. Under normal bias conditions the noise spectrum of the ITO-gated MOSFET was similar to a poly-gated MOSFET of similar geometry.

4. CONCLUSION

A process for the manufacture of a 2-phase all-ITO gate full-frame CCD image sensor has been demonstrated. The quantum efficiency of the 16-μm pixel test device is between 60% and 70% from 400 nm to 800 nm. This technology demonstration yielded the expected improvements in quantum efficiency while also improving on charge transfer efficiency and maintaining low dark current and read noise.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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