What Should You Know About ITO?

New Technology Improves Blue/Green Sensitivity of Frontside-Illuminated CCDs

Among the most important measurable characteristics associated with charge-coupled devices (CCDs) is *quantum efficiency*. Quantum efficiency (QE), often expressed as a percentage, indicates the effectiveness of an imager to produce electronic charge from incident photons. The greater the QE at a given wavelength, the more efficient the imager at that wavelength.

In an effort to boost the sensitivity of frontside-illuminated CCDs in the blue/green region of the spectrum, the Eastman Kodak Company has pioneered a new gate structure based on indium tin oxide (ITO). Indium tin oxide was a logical candidate for a new gate material, as it has been used for many years to provide a clear conductive coating in a wide variety of applications. Before discussing the latest wrinkle in ITO technology and its impact on certain imaging applications, it is useful to first review the blue/green sensitivity issue.

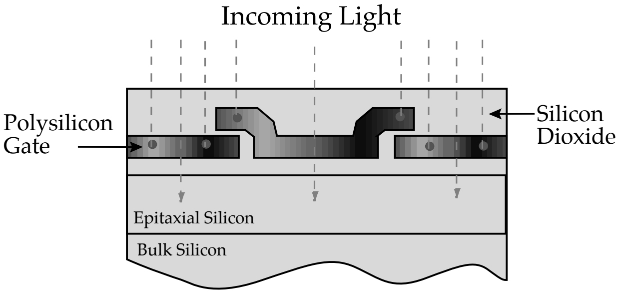

Figure 1. *Light passes through the polysilicon gates of a standard frontside-illuminated CCD in order to reach the device's photoconversion layer.*

The majority of commercially available CCDs are frontside-illuminated devices made from silicon. In a frontside-illuminated CCD, light passes through the polysilicon gates that define a charge well at each pixel **(see Figure 1)**. While the gates transmit a number of the incident photons to the CCD's photoconversion layer, they will also reflect and absorb a fraction of photons, thereby preventing some light from reaching the pixel's photosensitive region. For gates made from polysilicon, the transmission starts to drop at wavelengths shorter than 540 nm and is essentially zero below 400 nm. Therefore, frontside-illuminated sensors have a particularly low QE in the blue/green region of the spectrum **(see Figure 2a)**.

One approach to resolving the blue/green sensitivity issue is to use a thinned, backside-illuminated CCD instead of a frontside-illuminated device **(see Figure 3)**. Employing acid-etching techniques, it is possible to uniformly thin a CCD to a thickness of approximately 10 µm and focus an image on the backside of the CCD register, where there is no gate structure. Compared to conventional frontside-illuminated CCDs, thinned devices have a higher QE across the entire visible spectrum (400 - 700 nm), including far superior sensitivity in the blue/green region **(see Figure 2b)**.

There are drawbacks associated with thinned, backside-illuminated CCDs. First, commercial availability can be a concern. The "off-the-shelf" selection of thinned devices is much narrower than that of frontside-illuminated CCDs. When matching application requirements to specific format design variables, such as speed, bandwidth, full well, and array size, the lack of thinned device options can be restrictive. Price may also be a consideration. Backside-illuminated CCDs cost substantially more than their frontside-illuminated counterparts.

A second approach to the blue/green sensitivity issue is to incorporate on-chip microlenses into an interline-transfer CCD. An interline-transfer CCD's gates are aligned with its inactive, masked regions. By attaching microlenses to an interline-transfer CCD in precise register with the active areas of the detector, incident light can be directed away from the device's gates to the photosensitive

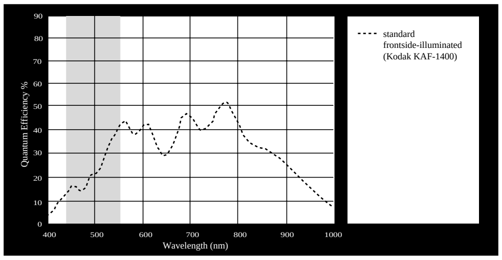

Figure 2a.
A standard frontside-illuminated CCD's QE in the blue/green region of the spectrum is relatively poor. (Kodak KAF-1400)

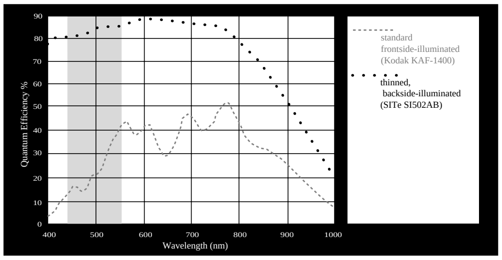

Figure 2b.
A thinned, backside-illuminated CCD's QE is much higher across the entire visible spectrum. (SITe SI502AB)

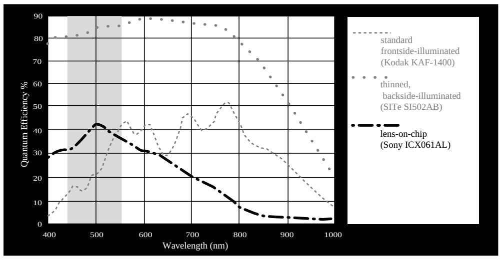

Figure 2c.
Lens-on-chip formats provide improved QE in the blue/green for frontside-illuminated CCDs. (Sony ICX061AL)

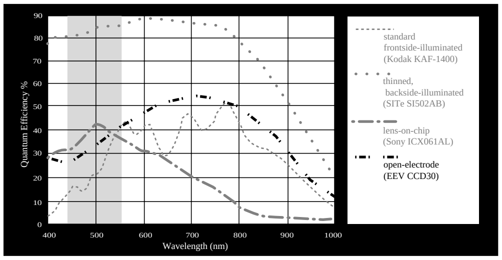

Figure 2d.
Open-electrode designs also raise the QE of frontside-illuminated CCDs. (EEV CCD30)

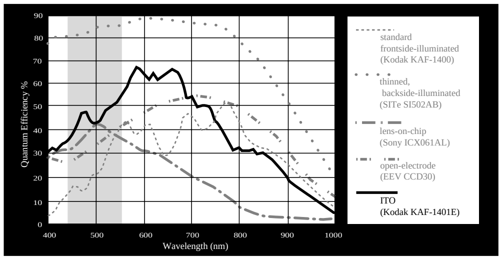

Figure 2e.
ITO technology boosts the QE of frontside-illuminated CCDs without the potential drawbacks associated with other QE-enhancing options. (Kodak KAF-1401E)

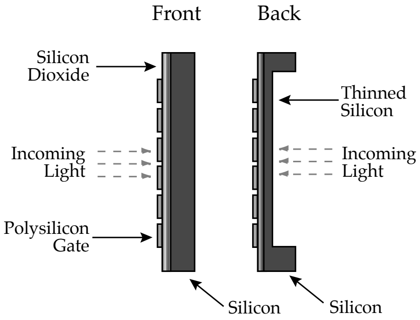

Figure 3.
Light enters the backside of a thinned device, where there is no gate structure.

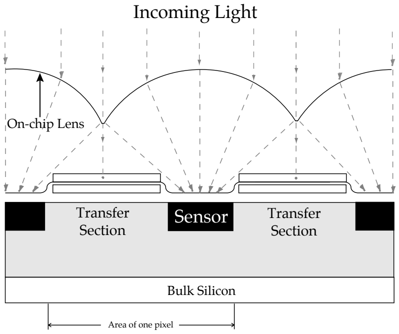

Figure 4.
A lens-on-chip design directs light away from an interline-transfer CCD's gates to its active array.

areas of the CCD **(see Figure 4).** As a result, lens-on-chip formats improve the frontside-illuminated device's QE in the blue/green, though not as dramatically as thinned, backside-illuminated devices **(see Figure 2c).** It should be noted that microlenses are more effective when parallel light is normal to the surface of the imager; the QE of lens-on-chip devices declines as the incident angle of light increases.

The primary trade-off that needs to be examined when evaluating on-chip microlens technology as an option to boost QE in the blue/green involves dynamic range — the ratio of CCD saturation to the device's read noise. This concern stems from the fact that interline-transfer CCD technology has been primarily driven by the video market, which favors smaller devices. While the use of microlenses successfully raises QE by redirecting more incident light to the active areas of the array, most available interline-transfer CCDs have small pixel geometries with limited full-well capacity, which diminishes the imager's dynamic range and precision. Therefore, this technology may not be an appropriate choice for applications that require either quantitative detection of very dim and very bright pixels within a single image (intrascene dynamic range) or place a high premium on the ability to detect and quantify individual pixel brightnesses (precision).

A common question regarding the use of interline-transfer CCDs is resolution. Due to the masked areas of the pixel array, conventional interline-transfer devices tend to be more prone than full-frame devices to aliasing — a sampling effect that has the potential to diminish image contrast and therefore general image resolution. However, microlenses help reduce this effect. Aliasing in lens-on-chip devices is not typically a significant factor.

Another approach to the blue/green sensitivity issue is to use an open-electrode architecture. In this frontside-illuminated design, some of the polysilicon gate structure is removed so that a portion of the pixel area is left uncovered **(see Figure 5)**. As with lens-on-chip devices, the QE of open-electrode imagers is significantly better than that of conventional frontside-illuminated CCDs, but not as good as the quantum efficiency of thinned, backside-illuminated CCDs **(see Figure 2d)**. Note that open-electrode technology is only available in imagers with large pixels (roughly 20 µm and greater). Also, open-electrode CCDs tend to suffer from a drop in full-well capacity due to a reduction of the potential-well depth in the uncovered regions. Another minor drawback of open-electrode devices is the considerable intrapixel variation of response between open and polysilicon-covered areas.

The aforementioned solutions (thinned devices, on-chip microlenses, and open-electrode CCDs) achieve higher QE levels in large part by directing incident light in such a manner as to avoid the CCD gates. However, the blue/green sensitivity issue can also be approached by altering the composition of the gates. Kodak's Microelectronics Technology Division has developed a new fabrication process that produces gates that are more transparent to light. Based on indium tin oxide, these gates provide higher light throughput into the photoconversion layer of the CCD **(see Figure 6)**. The resultant imaging devices have higher QE levels than those attainable with conventional frontside-illuminated CCDs. This improvement extends across the visible spectrum, including the blue/green region.

The quantum efficiency of ITO imagers in the blue/green region exceeds the QE performance generally seen in lens-on-chip and open-electrode designs **(see Figure 2e)**. Furthermore, ITO devices have no inherent reduction of dynamic range and carry a fairly comparable price tag. All three of these designs are outperformed by backside-illuminated CCDs in terms of quantum efficiency, but as was pointed out earlier, price and availability may be the largest issues when considering thinned devices. Overall, ITO technology represents an excellent "price and performance" option for many low-light-level applications that require imaging in the blue/green, including green fluorescent protein (GFP) imaging, chemiluminescent imaging, and fluorescence *in situ* hybridization (FISH).

For instance, in green fluorescent protein imaging a naturally fluorescent molecule linked to a biochemical process in a living organism is examined. The longer the specimen is exposed to light, the greater the chance that phototoxicity or bleaching will skew the results of the experiment. Using a conventional frontside-illuminated imager for GFP applications usually necessitates fairly lengthy integration times due to the CCD's relatively low QE in the blue/green region. However, the improved blue/green sensitivity provided by an ITO device allows shorter exposure times, since a greater amount of incident light reaches the CCD's photosensitive layer. Therefore, the light dosage to the specimen is decreased.

Chemiluminescent imaging, meanwhile, generally uses electrophoretic gels or microtiter plates for assay detection applications in which the presence of DNA and proteins is ascertained and quantified. The higher blue/green quantum efficiency offered by ITO devices lowers the assays' minimum detection levels (many assays emit in the 450-540 nm range) and required exposure times, resulting in more-sensitive detection capabilities as well as higher throughput. The ability of ITO technology to provide higher QE without sacrificing dynamic range is also valuable to chemiluminescent imaging as it allows for precise quantification.

In multispectral fluorescence *in situ* hybridization (mFISH), which is used in procedures such as the examination of chromosomes for early cancer detection, a number of individual reference points — each located within a distinct band of the visible spectrum — are sampled sequentially. Higher quantum efficiency performance is extremely beneficial to mFISH, as it shortens the acceptable minimum exposure times for the entire series of reference points. As discussed earlier, frontside-illuminated ITO devices offer improved quantum efficiency across the entire visible spectrum with the most-dramatic differences coming in the blue/green range, effectively raising and leveling the QE curve for mFISH and improving the efficacy of the experiment.

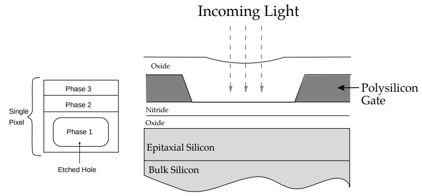

Figure 5.
In an open-electrode CCD, some of the polysilicon gate structure is removed, leaving a portion of the pixel area uncovered.

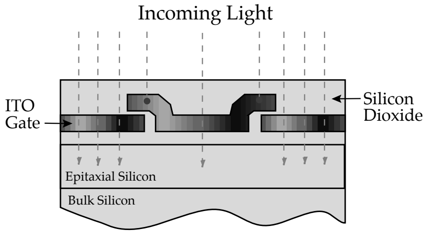

Figure 6.
An ITO device uses a conventional double polysilicon gate structure, but replaces one of the electrodes with a "transparent" version allowing more light to reach the detector's photoconversion layer.

The aim of this brief discussion has been to provide a contextual overview of CCDs that employ an indium tin oxide gate architecture. As ITO gate structure designs continue to develop and improve, we can expect to see this technology have an increasingly significant impact on a broader range of digital imaging applications.

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