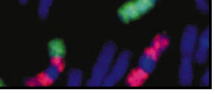


CCDs Make the Most of Every Photon

Innovative gate materials and microlenses help large-format, full-frame CCDs perform comparably to back-thinned imagers in low-light applications.

by William Des Jardin

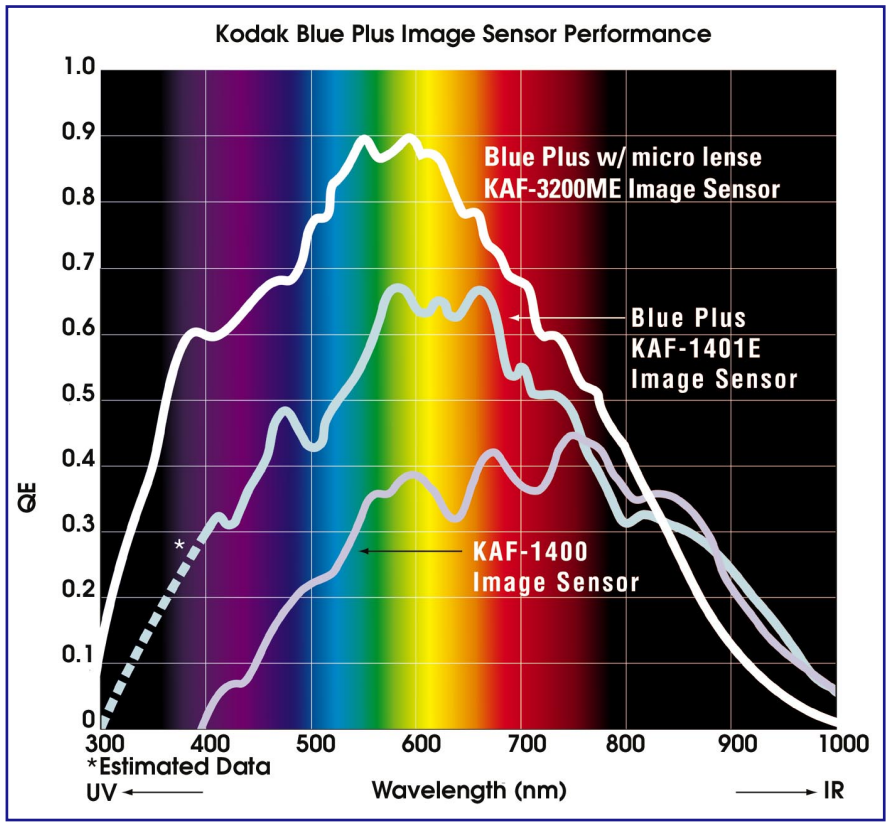
CCDs that can capture more photons enable faster or more sensitive imaging systems for low-light applications in biomedicine, microscopy, commercial photography and astronomy.

Large-format, front-illuminated, full-frame and frame-transfer-style CCD image sensors accommodate long exposure times. Because they offer the lowest dark current of available sensor technologies, they produce the best signal-to-noise ratios in low-light conditions. Their high sensitivity, high charge capacity and low dark current also deliver a very large dynamic range.

However, because 100 percent of the surface in these CCDs is photosensitive, gates are placed over the sensing region. The gates typically are composed of semitransparent polysilicon that absorbs or reflects incident light at wavelengths below 500 nm. Therefore, the trade-off for large sensing areas has been reduced sensitivity at shorter wavelengths.

A number of options attempt to compensate for this lower efficiency, including UV-sensitive phosphor overlays, virtual phase technologies and thinning the back side of CCD chips to allow light to enter through the substrate. But each option either increases the cost and complexity of the sensor or compromises other aspects of its performance.

The gates for full-frame CCDs are placed over the photosensitive area, so changes that allow more light through the gates improve overall efficiency. By mixing and matching technologies from disparate imaging architectures, Eastman Kodak Co. created a full-frame CCD sensor, the Blue Plus KAF-3200ME, with quantum efficiencies as high as 85 percent. The sensor can either help improve signal-to-noise ratio or reduce the integration time for a number of low-light applications that require front-illuminated, full-frame CCDs.

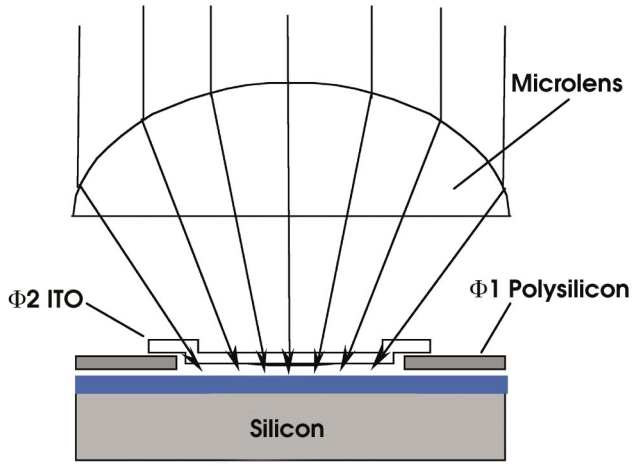


Quantum efficiency (QE) in typical full-frame CCD imagers is inhibited at wavelengths below 700 nm by polysilicon gates. Replacing one gate with indium-tin-oxide material enables imagers such as Kodak's Blue Plus to significantly improve efficiency in the blue wavelength range. Adding microlenses also improves quantum efficiency, from about 350 nm to about 1 µm.

Two changes helped to increase the amount of light that arrives at the sensing area: the use of indium tin oxide and microlenses.

ITO is commonly employed as an electrode in flat panel displays. It is more transparent than polysilicon at short wavelengths, so it allows more short-wavelength light to reach the sensing area, dramatically improving sensitivity below 750 nm while retaining it from 750 to 1100 nm. ITO

Reprinted from the August 2002 issue of PHOTONICS SPECTRA © **Laurin Publishing**



A microlens above each pixel directs light through an indium-tin-oxide gate, which is more transparent than conventional polysilicon gates. This increases the number of photons that reach the sensing area and raises the quantum efficiency of the sensor.

also opens up the spectral area from 300 to 400 nm. The Blue Plus sensor's efficiency rose to 30 percent at 400 nm. Peak quantum efficiency, which occurs from 575 to 675 nm, rose to 63 percent.

This approach does not sacrifice other performance parameters such as charge capacity, noise floor or dark current. Nor is manufacturability sacrificed. The change in gate materials is a straightforward modification. Ideally, both gates would use ITO rather than polysilicon.

Microlenses can also help to raise efficiency. Interline CCDs commonly rely on microlens arrays to direct light to photosensitive areas. The same approach works for directing light through the ITO gate and further reduces the amount of light lost to the polysilicon gate.

These combined changes raised the peak quantum efficiency to 85 percent, a level previously possible only by thinning the wafer and illuminating the image sensor from the back side — an expensive process. They also improved quantum efficiency for blue wavelengths around 400 nm from 0.3 to more than 0.6 percent, which is a signal increase of more than 100 percent, or an improvement of 30 percent in absolute quantum efficiency units.

In the IR region around 750 nm, quantum efficiency improved from 0.44 to more than 0.66, which increased the signal by 50 percent, which amounts to an improvement of 22 percent in absolute units.

Neither ITO nor microlenses represent new technologies. What is novel, however, is their combined application to large-format, full-frame and frame-transfer CCD image sensors. The improved efficiency has a marked effect.

Low-light applications

Many low-light visible microscopy applications in the life sciences use cameras in conjunction with fluorescence imaging techniques to observe living cells. Objects of interest are tagged with fluorophores that, when illuminated, give off light at longer wavelengths. By imaging this signal, scientists are able to visualize and measure what is going on inside the cell.

Fluorophores, however, present challenges to imaging technologies:

- Light can be toxic to the cells, so illumination levels must be minimized.
- Extended exposure can bleach fluorophores, eliminating their ability to fluoresce.
- Exposure times are often short so that changes in behavior can be followed.
- Cells can take in only so many fluorophores before they are damaged or altered.

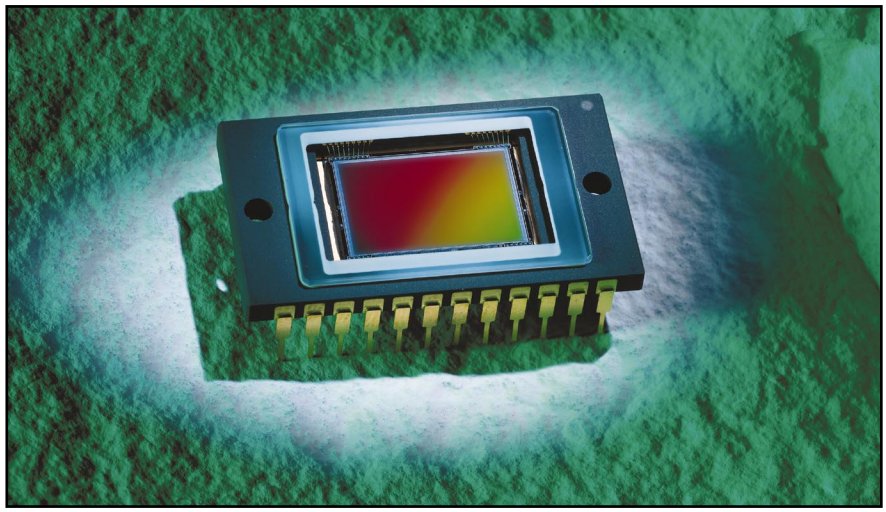
These limitations mean that anything improving camera sensitivity — including its quantum efficiency — aids users.

In the past, the most demanding fluorescent imaging applications used costly back-illuminated CCDs, which have quantum efficiencies higher than 90 percent. With peak efficiencies at 45 percent, standard front-side, full-face CCDs could not compete.

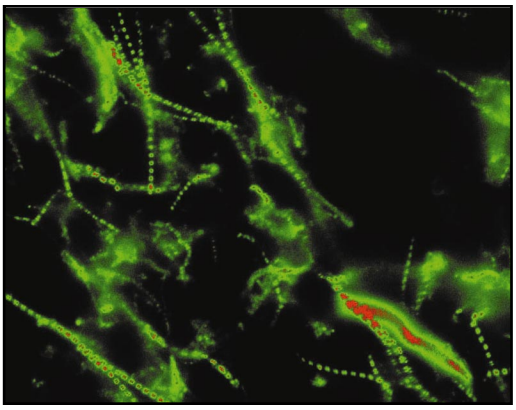
Back-illuminated CCDs are expensive because they are difficult to make and so are produced in low volumes. They also have large pixel sizes, which limits spatial resolution. Pixel sizes smaller than 13 μm^2 are rare among commercially available back-illuminated CCDs. The devices' dark current is higher as well.

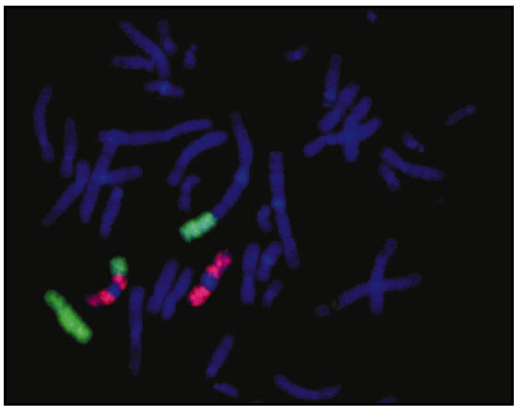
A full-frame CCD sensor with quantum efficiencies as high as 85 percent can compete with them. It also provides other benefits, including pixels measuring 6.8 μm^2.

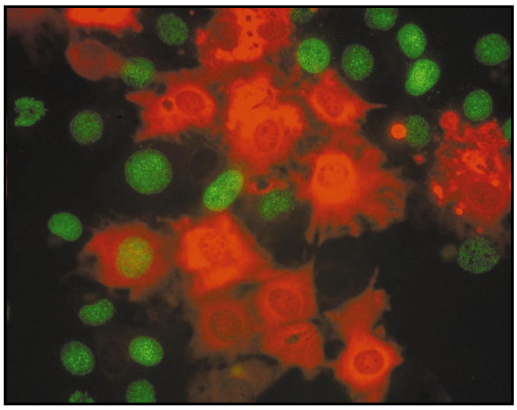
The goal of proteomics is to un-

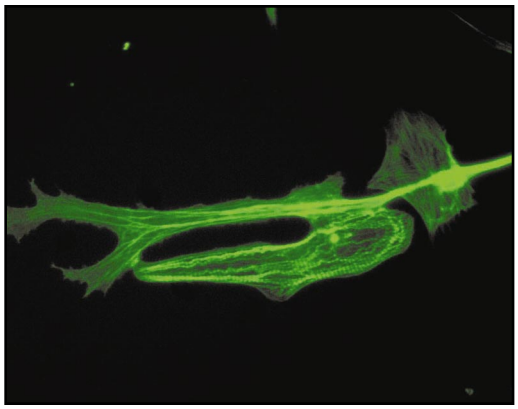


Two common technologies are combined in the full-frame CCD to provide efficiencies up to 85 percent, while still allowing front-side illumination. This enables users to replace less efficient sensors without redesigning the camera.









derstand protein expression at the cellular level and to apply this information to scientific and medical problems. It is a technique that is widely used in drug discovery and, therefore, has attracted much interest and funding from biotechnological and pharmaceutical companies.

PerkinElmer Inc. manufactures a color camera for capturing fluorescent images of proteins in two-dimensional electrophoresis. Fluorescently tagged proteins, placed on a gel, move when an electric field is applied across the gel's surface. The speed at which individual proteins move depends on their electrical charge, weight and cross section. Using cameras to track their movement and speed, scientists can learn about the weight and structure of each.

The fluorescence is very faint — three or four orders of magnitude lower than the unaided eye can see. This requires imagers with high sensitivity.

Tieer Gu, the director of engineering for digital imaging at PerkinElmer, said that the technology in the KAF-3200ME "increases overall performance and light sensitivity, allowing scientists to more accurately collect biological data, which translates to fewer failed experiments and improved productivity."

The technique also requires an imager with low noise — so that the signal isn't overwhelmed — and high dynamic range. The camera incorporating Kodak's sensor achieves a readout noise of only about 5 electrons running at 250 kHz and has dark current of about 0.02 electrons per pixel per second when cooled to −35 °C.

The new sensor's 85 percent peak quantum efficiency replaces a device with a peak of 55 percent. "If we could sense 10 photons before and the sensor improves by 20 percent, then we can now count eight photons," explained Jaime Ku, project manager. "In an application like this, every photon counts." □

Meet the author

William Des Jardin is a product engineer at Eastman Kodak Co. in Rochester, N.Y.

A full-frame CCD can image fluorescently tagged structures and processes inside living cells. But the imager must have high sensitivity and quantum efficiency on the order of 85 percent. Courtesy of Roper Scientific.