In Search of the Ultimate Image Sensor

Chip makers contemplate the 100-megapixel image sensor. Physics says it's possible, but is it practical or even desirable?

by Brian L. Benamati

The mainstream in image sensors for high-end studio photography has been 6-megapixel CCDs, and the market is now adopting 16.8-megapixel image sensors as the new reference standard. The semiconductor processes used to manufacture sensors can achieve increasingly smaller pixels and larger sensors for even higher-density chips. The market requirements for image quality and the practical considerations of camera systems, however, must be understood to answer the question: What will be the "ultimate" image sensor of days to come?

Marketplace dynamics will strongly drive the evolution of image sensors. It's relatively easy to conceive of imagers approaching 100 megapixels that deliver extraordinary image quality, but could such devices achieve commercial success? Chip makers face such concerns as process technology, pixel and chip size, and the number of chips per wafer. Camera makers are concerned with sensitivity (effective film speed), dynamic range, noise, compatibility with camera formats and legacy lenses, and, of course, price.

By increasing the active sensing area and the number of pixels in it, higher-resolution sensors improve image quality, but the level of sensor performance most suitable for digital imaging applications depends on the imaging market segment they serve. For the astronomy market, where scientists work with multimillion-dollar optics, there will be one answer. At the other end of the spectrum, where consumers expect to pay less than $100 for a camera for the Web, the answer is quite different.

Consider professional photographers, who traditionally rely on large-format (4 × 5 in.) and so-called "645" medium-format film cameras to achieve exceptional image quality, well beyond that of 35-mm-format cameras. Digitizing these larger-format systems demands larger-format silicon image sensors beyond the traditional 35-mm format. Photographers expect these larger image sensors to provide quality approaching that of traditional large-format photographic film, while offering the conveniences of digital image capture.

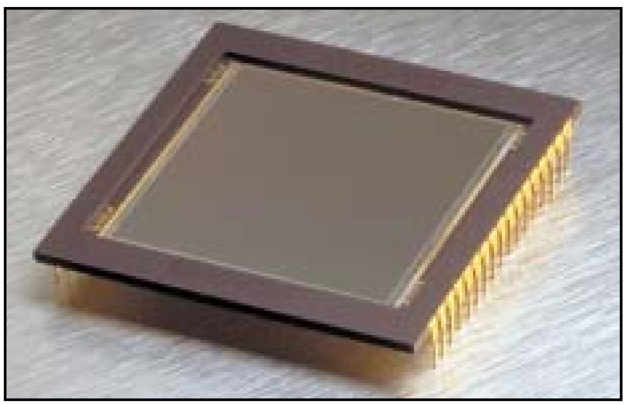

Figure 1. *A 16-megapixel, full-frame CCD image sensor is today's reference standard for commercial imagers. Physicists can easily conceive of 100-megapixel devices, but the marketplace has its own conceptions about digital imaging cost/performance trade-offs.*

The advent of digital imaging brought forth image sensor alternatives in a variety of optical formats: 1/5 in. (and smaller) to 2/3 in. for consumer cameras; 4/3 in. for so-called pro-sumer cameras; APS format for advanced amateur cameras; and 35 mm for professional cameras. Sensor formats of 48 × 36 mm and "true 645" (56 × 42 mm) may be on the horizon.

Pixel size

Today numerous companies offer digital camera backs for medium- and large-format cameras using traditional 35-mm-format CCD image sensors with 6 megapixels, based on 12-µm pixels. The cameras and lenses, however, are crying out: "More pixels!"

Most recently, the high end of the digital photography market began migrating from 6 megapixels to a higher-resolution 16.8-megapixel (4k × 4k) image sensor. This device uses a 9-µm pixel in a 36 × 36-mm (1:1 aspect ratio) optical format.

Over the next several years, image sensors will transition to 20 megapixels and even 36 megapixels. Manufacturers may offer even higher-resolution solutions, but they will appear first in niche markets. Only time and price will determine how broad the market appeal will be for large-format, ultrahigh-resolution image sensors.

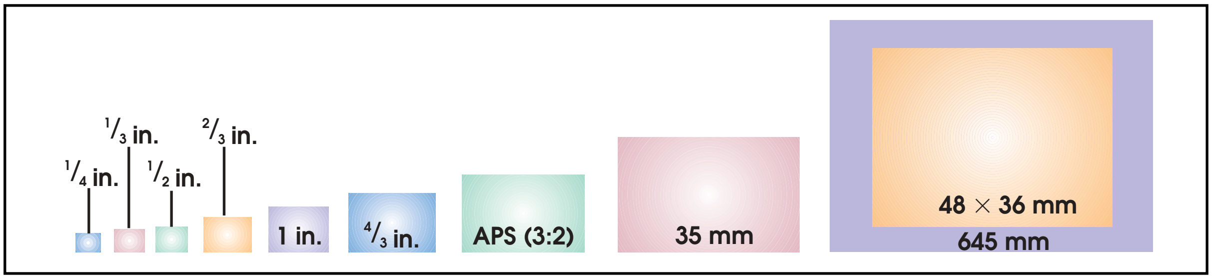

Figure 2. *Photographers want digital imagers to be compatible with traditional lenses and cameras, so manufacturers try to make the largest possible sensor to fill a camera's optical format. Smaller sensors change the effective magnification factor of the lens.*

Scaling from a 9-µm to a 6.8-µm pixel, for instance, would produce more than 36 megapixels in a 48 × 36-mm sensor. Development would not be trivial, but such an image sensor is a realistic proposition.

To take this approach a step or two further, imagine scaling to a 5-µm pixel and increasing optical format to 56 × 42 mm. This would enable nearly 100 megapixels, theoretically viable for a 645-format camera and lens system.

Tomorrow's sensor designers and manufacturing processes can generate these ultrahigh-resolution sensors, but what is really practical? Is there a point at which the reduction in pixel size runs into diminishing returns because of the fundamental limitations in sensor sensitivity, charge capacity or dynamic range?

Generally speaking, an imager's ability to gather light and to store charge at each picture element is a function of a pixel's effective area. In a simple model, a 10-µm pixel (area of 100 µm^2) should have twice the "performance" of a 7-µm pixel (area of 49 µm^2). However, chip makers use the best available technologies to improve a detector's quantum efficiency (ability to convert incident photons to electrons) and linear charge capacity (ability to correctly store the converted charge) while minimizing noise (e.g., dark current generated in the bulk silicon).

In consumer electronics, such innovations are largely responsible for today's handheld camcorders with "0-lux" performance as compared with older over-the-shoulder camcorders with "4-lux" performance. New semiconductor technologies have improved the detector's performance per nano-acre substantially.

Common Image Sensor Optical Formats

Imager Format	Aspect Ratio	Width H (mm)	Height V (mm)	Diagonal (mm)
1/4 in.	4:3	3.2	2.4	4
1/3 in.	4:3	4.8	3.6	6
1/2 in.	4:3	6.4	4.8	8
2/3 in.	4:3	8.8	6.6	11
1 in.	4:3	12.8	9.6	16
4/3 in.[1]	4:3	17.8	13.4	22.3
APS[2,3]	3:2	25.1	16.7	30.1
35 mm	3:2	36.0	24.0	43.3
48 × 36 mm	4:3	48.0	36.0	60.0
645	4:3	56.0	41.5	69.7

1. Kodak KAF-5100CE image sensor
2. Nikon D1: 23.7 (H) × 15.6 mm (V), 28.4 mm diagonal
3. Canon D30: 22.7 (H) × 15.1 mm (V), 27.3 mm diagonal

And chip makers will continue to push the envelope for pixel performance as seen in the eyes of the camera maker and professional photographer. Why should these advances cease?

In the high-volume consumer market, where the 1/2-in. optical format is the most prevalent, leading-edge resolution now ranges between 3 and 5 megapixels, with pixel size decreasing from 4 toward 3 µm. But camera users have reported that shrinking pixels sometimes compromises image quality because of the aforementioned fundamental limitations.

The system implications for increased resolution are also costly. A higher pixel count means a need for higher-capacity memory and faster signal processing to achieve comparable frame rate, for example.

In the professional market segment, trade-offs between higher resolution and frame rate are now becoming apparent. Fashion photographers, for example, develop a rhythm while working with models, and slower image capture rates from ultrahigh-resolution digital cameras could adversely affect their productivity. Image sensors beyond 16 megapixels can meet the minimum frame-rate requirement by using multiple-output sensors; however, this approach creates system-level complexities for the camera maker.

The role of tradition

Format compatibility with traditional lenses and cameras also plays an important role in the professional photography segment.

For digital imaging, it's best to have the largest-possible sensor to fill the camera's optical format, and larger sensors are the logical next step for the industry, packing more pixels into a sensor using an already proven pixel size.

Larger chips, however, present a manufacturing challenge. If doubling sensor size halves the number of sensors on a wafer, the cost to manufacture the chip essentially doubles. Managing yield for such devices to

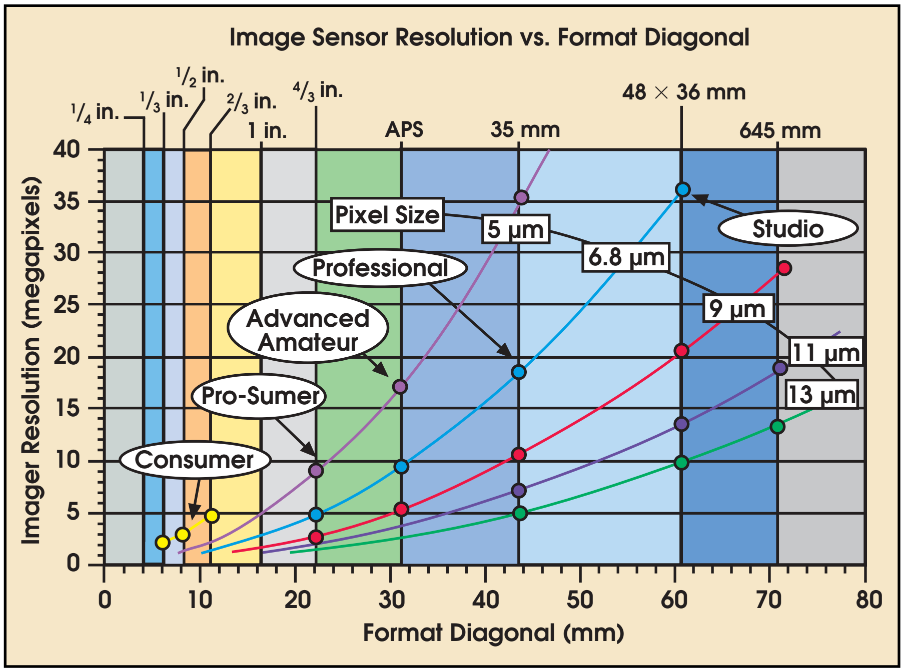

Figure 3. *Improving resolution for a given sensor format/size means shrinking pixels, which can affect the sensor's ability to gather light and store charge.*

achieve a practical price point is a major challenge.

Other challenges of creating larger sensor chips include achieving flatness and photoresponse uniformity across large dies. For the camera maker, it can be a challenge to focus such a large chip within a camera back on a traditional camera.

Larger sensors also pose a problem for conventional semiconductor manufacturing techniques. Manufacturers who use steppers for lithography, for example, are limited by the field size of the stepper, and some have been forced to use "stitching" to make larger chips. This forces the camera maker to deal with stitch boundaries and to minimize boundary errors in the final image. Newly introduced semiconductor equipment should be able to avoid these issues in manufacturing the next generation of large-format image sensors.

Smaller image sensors may seem more economically appealing, but they cause the camera maker significant optical problems. In particular, a sensor that's much smaller than the optical field presented to the focal plane of the lens changes the effective magnification factor of the lens so that what you see through the viewfinder is not what you capture.

Professional photographers will not accept large photographic magnification errors. A 35-mm-format (36 × 24 mm) sensor has a focal length magnification error of 1.62× for a true 645 (56 × 42 mm) field. A 48 × 36-mm sensor would have a 1.16× factor. A true 645 sensor (56 × 42 mm) would have "perfect" (1.00×) magnification in such a camera, but peripheral fading caused by lens roll-off near the edges of the field would be of concern.

In the future, the photographic world may be flooded with lenses designed for digital imaging. But the practical reality is that imager manufacturers must serve traditional cameras and lenses. Given that the resolving power of traditional professional lenses is about 5 µm, moving to smaller pixels — such as those in consumer sensors — will not provide an effective resolution gain and would likely pose a problem.

The ultimate sensor

As digital imaging science advances and image sensor design and processing technologies improve, the professional photography market will benefit from larger-format chips with smaller pixel sizes. Chip sizes of 48 × 36 mm and 52 × 42 mm would fulfill the optical requirements of professional photographers. And as pixel architectures migrate from 12 to 9 µm, and then toward 7 and even 5 µm, the chips will provide extraordinary resolution.

These technological advances will bring the ultimate in performance to digital cameras. The true limitation will not be the chip maker's ability to deliver image sensors, but rather the practical trade-off between image quality and price that the photographic market is willing to bear. Whatever the marketplace decides, chip makers will strive to surpass the wildest dreams of camera makers and photographers, who are all on the same quest: the search for the ultimate image sensor. ☐

Meet the author

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