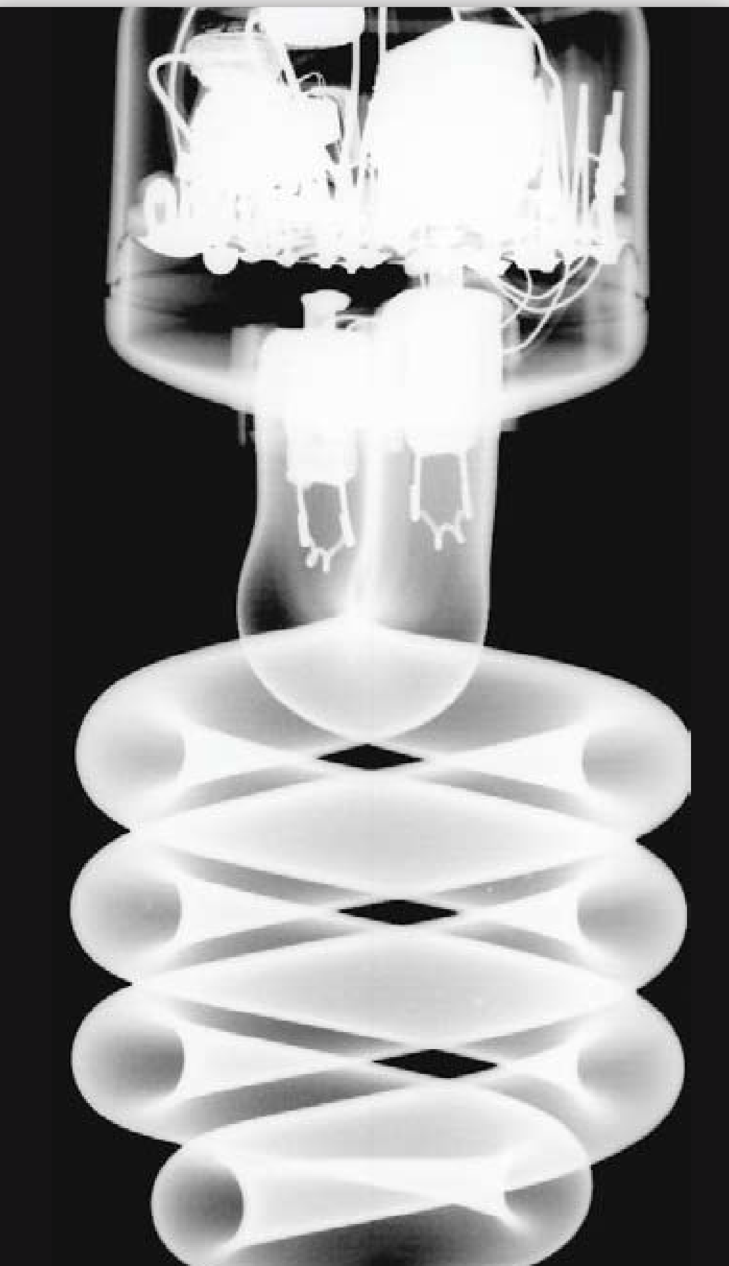
Digital Radiography Revealed



An inverted image of a modern low-power light bulb is shown here. Sensor resolution is 5 lp/mm and the image was taken using a 50kV X-ray source at 1 second integration time. *Source: Rad-icon Imaging Corp.*

Discover the advances in X-ray image sensors for digital radiography.

By Michael G. Farrier, Gene P. Weckler and Thorsten Achterkirchen

The digital imaging market spaces are mostly serviced by charge-coupled device (CCD), complementary metal-oxide semiconductor (CMOS), and flat panel image sensor technologies. Each technology serves specific markets with certain advantages. CCD technology, despite being expensive, dominated the visible imaging markets for two decades because of its high-quality, low-noise imaging performance. Large panel digital radiography markets have been well served by thin film transistor (TFT) technologies due to the manufacturability of large arrays of the relatively simple single transistor passive pixel circuits. CMOS Active Pixel Sensor (APS) technology has emerged recently to offer a cost and performance advantage over both CCD and TFT technologies in many radiography applications.

The uniqueness of X-ray imaging systems for nondestructive testing (NDT), medical, dental and other applications is due to the penetrating radiation that forms "shadow" images, with signal levels proportional to the density of material being penetrated. Penetrating radiation systems generally do not use focusing optics. Thus, the detection focal plane must be as large as the object under study. Clearly, coverage of large area objects such as the human chest or large circuit boards require large area detectors, which has been a challenge for CMOS and CCD technologies.

Standard foundry CMOS integrated circuit technology has been optimized for manufacture of hundreds of small devices on a round wafer, with reasonable tolerance for a few defective die. Filling a single wafer with one or two very large CMOS die can present significant challenges and special design features are required to minimize the effects of defects on the sensor circuits. Fortunately, strategies such as device tiling enable large focal planes to be constructed from smaller format image sensors.

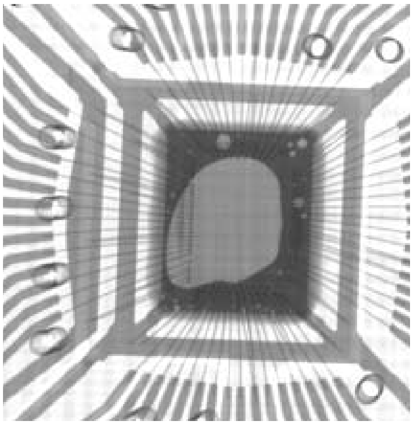
Fundamental design considerations for CMOS X-ray image sensor technologies include the concept that image resolution is not a direct function of the pixel size. Furthermore, the signal value of each CMOS pixel is mostly independent of the pixel aperture. X-ray sensors require conversion of X-ray energy into visible light using an X-ray scintillator material such as gadolinium oxysulfide (GadOx), cesium iodide or other compounds. The visible light output is proportional to the intensity of the X-ray beam that penetrates the object of interest and the CMOS detector converts the signal electrons generated in a silicon photodiode into a voltage using a voltage conversion amplifier called a source-follower.

A CMOS pixel, consisting of three or more transistors that perform a voltage conversion proportional to the photo-generated signal, is known as an Active Pixel Sensor (APS). By contrast, the typical large panel X-ray image sensor uses TFT circuits with amorphous silicon thin film technology and a single transistor per pixel.

The TFT pixel is know as having a "passive pixel" circuit design and has no buffering from noise sources within the pixel or on the bus lines connecting the pixels. As the size of the array increases the noise signal increases, which reduces the effective dynamic range of the TFT sensor. The CCD image sensor has pixel architecture with no transistors or amplifiers in the pixel. Signal charge from the visible light is generated in a gated capacitor and transferred in a serial/ parallel readout scheme, usually through a single charge conversion amplifier operating at high speed. Because the signal charge is transferred without conversion to voltage until exiting the sensor, fewer noise sources are introduced into the signal.

CCD technology, however, remains expensive to fabricate, particularly in large areas, and is less serviceable for close tiling. Often CCD detectors are used with minifying fiber optic couplers such that the image plane can be larger than the detector area. Minifying optics are expensive and awkward to use, however.

CMOS APS pixel design enables the cancellation of voltage offsets and reduction of random noise from the sensor output by sampling and subtracting background signal from imaged signal. Lower noise content allows for a wider dynamic range and better small-signal performance than that of the TFT technology for comparably sized arrays. Additionally, the X-Y addressability of the CMOS APS arrays allows for digital substitution of signal from neighboring



This is a detailed image of an advanced IC package using a microfocus source and a 1k x 1k CMOS image sensor. Voids in die attach epoxy and very fine bond wires are clearly visible. *Source: Rad-icon Imaging Corp.*

pixels when the inevitable pixel defects occur.

Unlike sensor technologies such as CCD, which fails catastrophically from shorting defects, shorts in a CMOS APS sensor generally result in the loss of a few pixels or a row or column of pixels, which can be "corrected" using gain and pixel mapping corrections. Correctable defects allows for better yield and lower cost per device.

X-ray sources generally are rated by their spot size, peak voltage and power output. Small spot sizes are achieved using lower power sources and target materials optimized for small spot sizes. Both the spot size of the X-ray beam and the desired magnification of the image largely define the resolving power of the source-detector system. Large spot size X-ray sources (1 millimeter diameter or more) require only low-resolution image sensors with large pixel pitch because there is no resolution gain possible even if a small pixel pitch sensor is used.

Fine focus X-ray sources generate spot sizes that can take advantage of sensor pixel dimensions in the range of 50 microns. Microfocus X-ray sources can produce spot sizes at one micron at reduced power and are increasingly used in NDT applications for small defect detection. Lately nano-focus sources have been reported with capability to produce sub-micron spot sizes at low power.

X-ray radiography also relies on the energy of the source (in peak kilovoltage, or kVp) to penetrate dense or thick materials. As a reference, NDT applications for circuit board inspection favor source energies of 50 to 70 kVp, while intra-oral dental radiography requires 60 to 70 kVp to produce high contrast imagery. Dense metals of 5 to 10 millimeters thickness require relatively high X-ray energies of 120 to 160 kVp to reveal fine structure.

As image sensors are both sensitive to X-ray radiation and are damaged by X-rays, there are often elements such as fiber optic faceplates (FOFP) attached to the sensor surface. Light from the scintillator is coupled through the faceplate to the pixels below. A few millimeters of FOFP thickness are necessary as a shield for high-energy X-ray imaging (greater than 50 kVp) and for general reduction of radiation damage at all beam energies.

CMOS image sensors are commercially fabricated with pixel sizes ranging from 1 micron to a few hundred microns in dimension. Sensors with very small pixels—less than 5 microns—require state-of-the-art CMOS fabrication technologies and are used in consumer applications such as cell phone cameras.

In contrast, the typical NDT inspection application will use sensors with relatively large pixels, in conjunction with an X-ray source rated to penetrate objects, produce adequate image contrast, and ensure some moderate rate of throughput in a manufacturing, quality assurance or other potentially automated test environment. Small objects, such as fine bond wires and small solder voids, are easily detected using fine focus or microfocus sources and pixels in the 40- to 50-micron size range.

CMOS sensors with smaller pixel pitch, approximately 20 microns, also are found in intra-oral dental sensors. While better resolution can be obtained from the smaller pixels, measured resolution in digital dental radiographs is approximately 12 to 14 line pairs per millimeter and is limited by system parameters such as the X-ray source spot size.

Since the late 1990s CMOS radiographic sensor and camera technologies have been steadily progressing from tileable sensors measuring 2.5 by 5 centimeters with 48-micron pixel pitch to a

Eight tiled CMOS image sensors configured for use in a CT imaging application. The sensor resolution is 4k x 1k pixels at 48-micron pixel pitch. *Source: Rad-icon Imaging Corp.*

second generation of tileable very large area (VLA) sensors measuring 5 by 10 centimeters with 96-micron pixel pitch. The early CMOS sensor technology perfected the construction of tiled arrays with active sensor area as large as 10 by 10 centimeters or 5 by 20 centimeters.

In contrast, TFT panel technology can produce active sensor areas greater than 40 by 40 centimeters at pixel sizes ranging from 125 to 400 microns. The TFT technology does not rely on tiling to create large arrays; however, manufacturing costs are impacted by yield loss due to defects and expensive large area patterning process costs.

Many NDT applications are adequately serviced by sensors with active area of 5 by 5 centimeters to 10 by 10 centimeters. The next generation of tileable CMOS sensor will be used to create panels of 20 by 20 centimeters to 20 by 30 centimeters and larger. With larger active areas, the VLA CMOS radiographic sensors will be able to extend the range of object sizes that can be usefully imaged as well as service applications currently only accommodated by the TFT and other passive pixel technologies. CCD image sensor technology is not considered viable for competing in the large area sensor markets because of sensitivity to defects, limited on-chip circuit options and high cost of manufacture.

It is projected that the CMOS APS radiographic sensor technology will offer improved dynamic range, resolution and signal to noise performance over competing large area X-ray sensor technologies at a better price per centimeter squared of detector area. **NDT**

Gene P. Weckler is president of Rad-icon Imaging Corp. (Santa Clara, CA), Thorsten Achterkirchen is General Manager, and Michael Farrier is senior engineer. For more information, e-mail mfarrier@rad-icon.com, call (408) 486-0886 ext. 6 or visit www.rad-icon.com.