

AMORPHOUS SILICON TFT X-RAY IMAGE SENSORS

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Abstract

This paper will review electronic device characteristics of recently developed large-area, amorphous Silicon (a-Si) TFT/photodiode x-ray image sensors, and discuss some of the imaging characteristics which such devices can achieve.

Introduction

Large-format digital x-ray image sensors are a recent development in the fields of medical imaging and non-destructive testing. Such image sensors have become practical through the emergence of large-area, amorphous Silicon (a-Si) TFT and photodiode technologies.^{1,2,3} This paper will review the fundamental requirements for such x-ray image sensors, and discuss some of the device requirements for TFTs and photodiodes which serve as the basic components in each pixel.

X-ray imaging has been used in many ways, including high resolution imaging using film, real-time video imaging using image intensifier tubes (IITs), and digital imaging for digital subtraction angiography and computer-aided tomography. Additional uses of digital x-ray imaging include bone mineral densitometry, portal imaging for radiotherapy, and many areas of materials monitoring which use x-rays for nondestructive testing. In many of these applications, a large-area flat-panel imager based on a-Si thin-film transistor (TFT) technology is an attractive component due to its light weight and small form-factor, high photosensitivity, and lack of image distortion that is present IITs.

Many of these applications can be met using a large-area array of a-Si TFTs and photodiodes. The TFTs are used as pixel switches which address each row of the array, and photodiodes at each pixel location convert incident light to charge, which is read out by charge amplifiers connected to each column of the array. The array is patterned on a large glass substrate, using technology similar to that used in fabricating active-matrix, liquid crystal displays. Gate driver and charge amplifier ICs are connected to each line on the glass using Tape-Automated-Bonding (TAB). Board and glass are mounted on an aluminum frame, forming a sensor module. An example of a 30x40 cm² active-area sensor module with 7.37 million 127 μ m pixels is shown in Fig. 1.



Fig. 1: A 30x40 cm² imager module with gate and data boards TAB bonded to the glass and mounted on an aluminum frame.

The process for fabricating the array involves deposition and patterning of various metal layers, thin film dielectrics of Silicon nitride and a-Si to form the TFT, and depositions of a-Si in the sequence *nip* to form the photodiode. Additional dielectrics for interlayer isolation and passivation are also utilized. Arrays have been made with pixels from 100 to 400 μ m in resolution, and active areas from page size to chest size. A photomicrograph of a typical 127 μ m pixels is shown in Fig. 2.

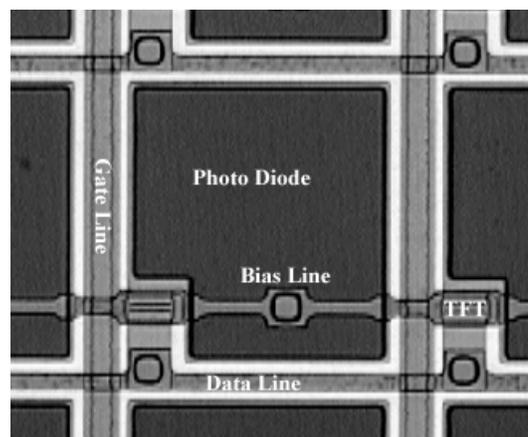


Figure 2. A photomicrograph of a 127 micron pixel sensor, showing TFT, photodiode, and interconnect.

The matrix-addressed, charge-storage method of readout is described below. Gate drivers are sequentially addressed to turn on each row of TFTs, which transfer the charges stored on their associated photodiodes each dataline. These charges are read in parallel by charge amplifiers, and multiplexed onto a small number of analog-to-digital converters (ADCs). A schematic diagram of the array matrix is shown in Fig. 3.

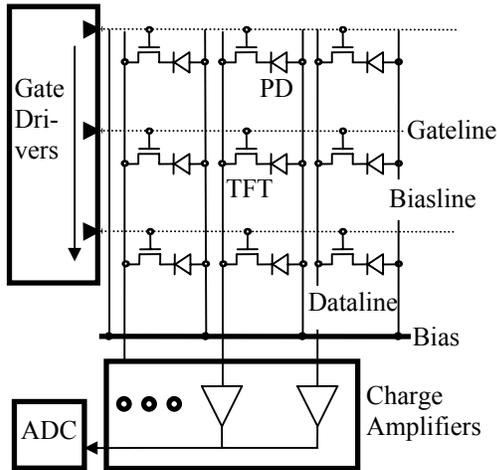


Figure 3. Schematic diagram of an a-Si 2D imaging array. Horizontal lines are sequentially addressed gatelines; vertical lines carry bias voltages on biaslines and charge signals on datalines. Datalines connect to charge amplifiers, which multiplex onto analog to digital converters.

To detect x-rays, a conversion layer that absorbs x-rays and scintillates in the visible spectrum covers the array. Efficient x-ray phosphors have peak output in the visible spectrum, and thus are well matched to the spectral response of a-Si *nip* photodiodes, shown in Fig. 4.

Quantum Efficiency vs. Wavelength

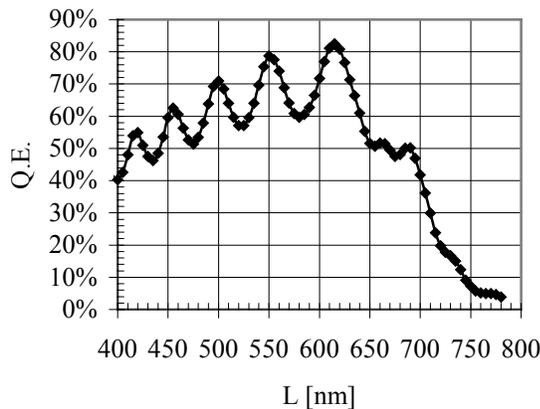


Fig. 4: Photodiode Q.E. vs. wavelength at -5 V reverse bias.

Other requirements of the photodiode are low dark current, low capacitance for improved speed and

lower noise, and fast photo response. Using an *nip* structure, one can achieve these properties, including room temperature dark currents of less than 1 pA / mm² with -5 Volts reverse bias. These low leakage currents allow imagers to operate without cooling and integrate for frame times of greater than 30 seconds, essential for low light level applications. A typical I(V) curve in the dark and under illumination is shown in Fig. 5.

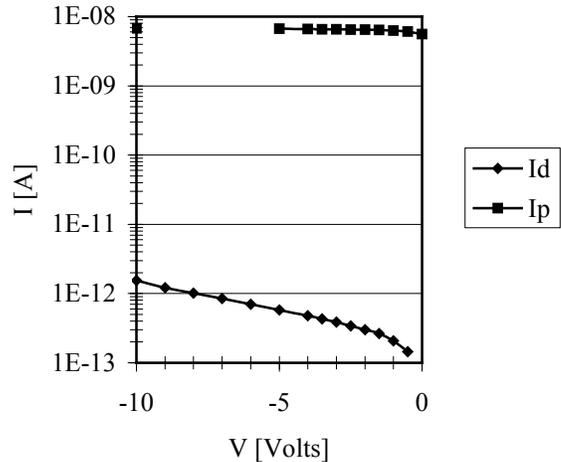


Fig. 5: I(V) curve of a 1 mm² *nip* photodiode in the dark (Id) and under 570 nm illumination (Ip).

The other important element of the array is the TFT switch. The TFT must have low enough off-current (typically a few fA) to suppress crosstalk and sufficiently low on-resistance (typically a few Mohms) to transfer the pixel charge to the dataline in a few μ sec. These characteristics are met by a-Si TFTs, as shown in Fig. 6.

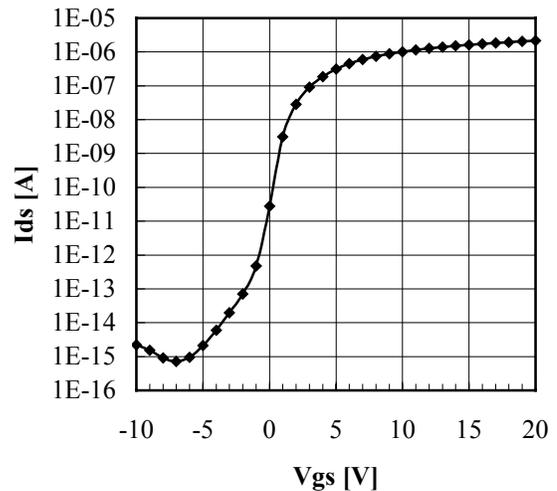


Fig. 6: Typical I(V_{gs}) characteristic of an a-Si TFT at V_{ds} = 5 V, with width W = 20 μ m and length L = 10 μ m.

Imaging Characteristics

One very important consideration in imager performance is electronic noise, as it sets the minimum signal level for detecting x-rays, and is typically in the range of 1000 to 2000 e. The minimum noise achievable in a photodiode array comes from reading the charge from a single pixel, equal to $\sqrt{2kTC_{PD}}$, where C_{PD} is the photodiode capacitance. For example, in a high resolution, 127 micron pixel, this pixel noise has been measured to be approximately 550 e.

The pixel noise is usually dominated in large-area arrays by noise arising from dataline capacitance C_{DATA} , typically 50 to 100 pF, depending on the size of the array. C_{DATA} is a parasitic element which multiplies any voltage noise developed on the dataline into a large charge noise on the output of each charge amplifier. As the dataline length increases, the effect of Johnson noise from its thermal resistance can also become important, depending on system bandwidth. Noise calculations for an assumed bandwidth of 100 kHz and typical array parameters are shown in Fig. 6.

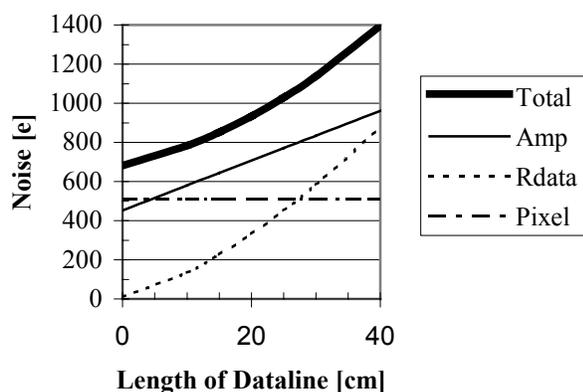


Fig. 6: Electronic noise calculated vs. dataline length, showing contributions from pixel, amplifier, and dataline resistance R_{data} .

A second important imaging characteristic is the modulation transfer function (MTF) of the sensor. The MTF measures the ability of the imager to resolve x-ray patterns of varying spatial frequency, and in the case of a high resolution, 127 μm pixel, is largely determined by the x-ray scintillation layer covering the array. $\text{Gd}_2\text{O}_2\text{S}(\text{Tb})$, a common material used in x-ray film cassettes, can serve as an efficient screen material. A Lanex® Regular screen provides a good compromise between resolution and sensitivity for many x-ray applications. An alternative approach is to coat the array with CsI(Tl) which has a columnar structure that provides a kind of light-piping effect, allowing thicker, ~ 3 x more absorptive films to be used with less light spreading than in conventional phosphor screens. MTF results for three

different Kodak-brand Lanex® screens compared with a 500 μm deposited layer of CsI(Tl) are shown in Fig. 7.

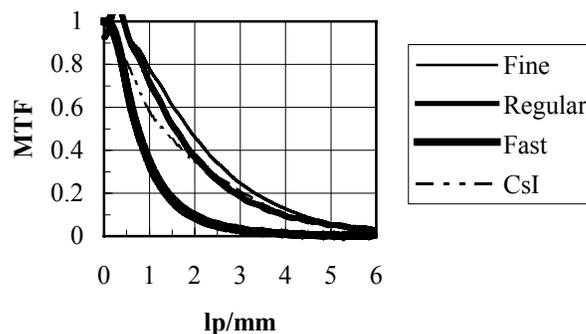


Fig. 7: Modulation transfer function (MTF) vs. spatial frequency for different x-ray phosphor screens (Lanex® Fast, Regular, and Fine) and a ~ 500 μm thick CsI layer, measured at an x-ray energy of 75 kVp.

Imaging Examples

Some examples of images taken with a large-area, 30x40 cm^2 image sensor with 127 μm pixels are below. Fig. 9a is an image of a resolution target, confirming nearly 4 lp/mm resolution. Fig. 9b is an image of a hand phantom, which at full size demonstrates fine details in the extremities obtainable with this imager.

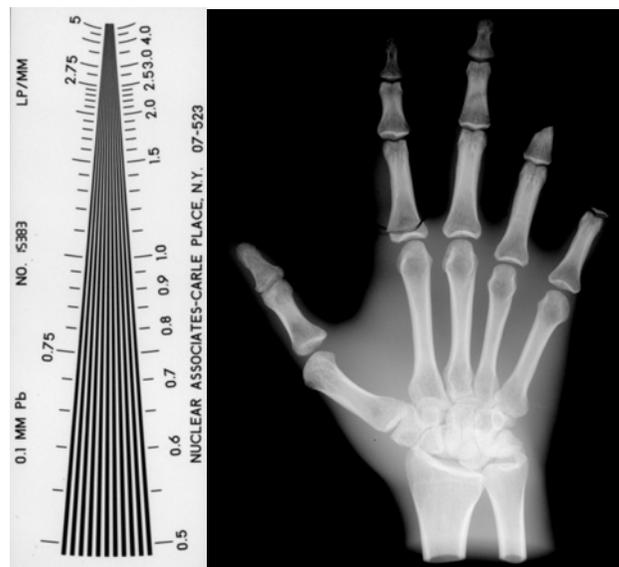


Fig. 9a: Resolution target at 77 kVp, 3 mAs; 9b: Hand phantom at 45 kVp, 12.5 mAs.

The sensor is also large enough to capture the image of a chest phantom, as shown in Fig. 10 below. In order to reduce x-ray scatter, a moving Bucky grid is used to collimate the x-rays entering the sensor. The image is displayed on a logarithmic scale in order to reveal both the details in the less dense lungs and the region behind

the spine. Unsharp masking is also used to edge enhance the final image.



Fig. 10: Image of chest phantom taken at 120 kVp, 15 mAs.

Future Considerations

One potential improvement in imager performance is sensor fill-factor, i.e., the fraction of light sensitive area in each pixel. The fill-factor in standard architectures is limited due to the photodiode being embedded within the active matrix. Fill-factor tends to be a problem for pixel sizes less than 100 μm , for example, in mammography applications. Future architectures that build the photodiode on top of the TFT matrix using a continuous sensor layer with minimally separated collection electrodes would greatly enhance fill-factor, as demonstrated in Fig. 11 below.

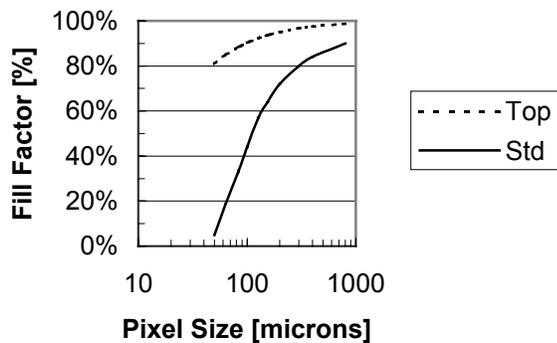


Fig. 11: Pixel fill-factor as a function of pixel size for the standard mesa photodiode (solid line) and the top photodiode structure (dotted line).

An estimate of the fundamental dynamic range for different pixel sizes can be made, based on the ratio between maximum charge capacity of the photodiode and the projected electronic noise, is shown in Fig. 12.

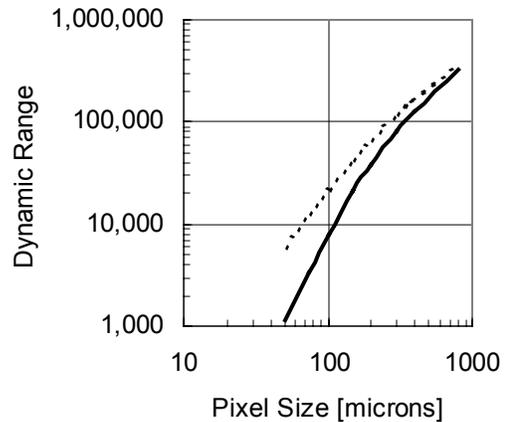


Fig. 12: Sensor dynamic range (maximum signal / electronic noise) calculated vs. pixel size. Solid line: Standard mesa photodiode structure; dotted line: top continuous photodiode structure.

Because of the enhanced fill-factor at smaller pixel sizes, the dynamic range of an imager can be increased by an order of magnitude by utilizing a higher fill-factor design. Further improvements in sensor performance can also be expected by minimizing dataline capacitance through a combination of TFT geometry, line width, crossover size, and dielectrics used. These enhancements will extend the use of large-area a-Si x-ray imagers into new, higher sensitivity areas of application.

References

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