CMOS ANALOG IC X-RAY IMAGE SENSOR ARRAY

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ABSTRACT

A CMOS-based digital radiographic x-ray image sensor array is being developed for nondestructive testing and medical applications in a collaboration between researchers at General Imaging Corporation and the University of Florida. The x-ray imaging sensor is the analog equivalent of a DRAM, consisting of an array of randomly accessible MOS capacitors, address circuitry and amplifiers. In developing the x-ray image sensor array, ten CMOS prototype ICs have been submitted to the MOSIS IC fabrication service in both the 3 μm and the 2 μm CMOS double-poly processes. Design strategies and specifications for x-ray imaging sensors will be reported.

SUMMARY

A CMOS x-ray image sensor is being developed for incorporation into a digital radiography system. The x-ray imaging array has the potential to replace radiographic film for non-destructive testing, dental and medical applications. The development is being performed in a collaboration between General Imaging Corporation and the University of Florida. The digital radiography system permits realtime interpretation, digital image enhancement, and a simple interface to medical picture archiving and communication systems (PACS).

Radiography involves passing penetrating radiation (typically x-rays) through an object and measuring the emerging spatial intensity variations. Acquiring a radiographic image with a solid-state sensor is a two-step process. The first step is conversion of x-ray photons incident on each sensor element into a stored parcel of electrons or holes. The second step is to scan the pixels and read the stored charge in each pixel, amplify it, digitize it, and transmit it to an imaging workstation.

The MOS capacitor was selected as the basic radiographic sensor element because it is compatible with standard VLSI processes and integration levels. Silicon is virtually

* Dr. Cox is with General Imaging Corp., Gainesville, FL 32604. This work is supported by the U.S. Air Force Wright Research and Development Materials Lab and the Wright-Patterson Air Force Base Contract #F33615-88-C-5513.

transparent to high-energy x-ray photons, so x-rays produce relatively little response in silicon. However, light-emitting phosphors similar to those used with medical radiographic film can be evaporated directly on the silicon wafer to enhance sensitivity. This increased sensitivity is essential for medical radiography, which presents stringent requirements for low dose levels and high signal/noise ratios, with good spatial resolution.

The light spreads as it passes through the intensifying phosphor layer, which limits the spatial resolution in the optical image. However, thicker phosphor layers absorb more x-ray photons. Therefore, the phosphor thickness controls the tradeoff between sensitivity and spatial resolution. Medical radiography requires a spatial resolution of 5 lp/mm, with an average sensor exposure of 500 μR. Ideally, contrast resolution (number of resolvable gray levels) is limited by the variance in the number of x-ray photons detected by each pixel. To achieve 5 lp/mm, the maximum sensor element size is 100 x 100 μm^2. Assuming a typical contrast level of 100 to 1 for a human body and 40 keV radiation, these requirements mean that between 22 and 2200 photons will be incident on each pixel. The large variance which results from the small size of these numbers could be interpreted to mean that there is no need to resolve individual photons. However, exposure differences which would not be statistically significant in a single pixel can provide significant image information when considered in context with other pixels. Therefore, every x-ray photon captured must be electronically resolvable.

In calculating the efficiency of a MOS capacitor as a sense element, we estimate a fill factor of no more than 75% and thus 25% of the incident photons will be lost. Using a Kodak Lanex - Regular Screen [1], a phosphor-imager system, 49% of the x-ray photons are captured by the screen and an average of 1195 optical photons will be incident on each pixel for each x-ray photon. This performance may be raised if the phosphor film is deposited directly on the x-ray sensor. If it is assumed that the equivalent input noise of the sense circuits is equivalent to less than 400 stored electrons or holes, then the required efficiency for the conversion from optical photons to electrons is 33%. Since conversion efficiencies for MOS capacitors used in CCDs typically approach 60%, it is clear that the required sensitivity is achievable with this sensor.

ICs fabricated through MOSIS were used to evaluate the MOS capacitor performance and to develop the associated sense circuits. The x-ray imaging sensor is the analog equivalent of a DRAM, consisting of an array of randomly accessible MOS capacitors, address circuitry and amplifiers. In developing the x-ray image sensor, ten CMOS prototype ICs have been submitted to MOSIS for the 3 μm CMOS and 2 μm CMOS double-poly processes.

Numerous measurements of MOSIS test structures have been performed. These include: 1) transistor characterization, 2) MOS capacitor dark current and doping profile measurements, 3) a study of charge generation mechanisms, 4) x–ray and visible light sensitivity measurements, 5) spectral sensitivity measurements, and 6) quantification of the effects of x-ray dose on circuit and sensor performance. Working analog amplifiers and x-ray sensor cells have been demonstrated.

P-type and n-type MOS capacitors fabricated using the MOSIS p-well process have been examined closely. Through C-V and C-t measurements, the doping profile and thermal charge generation characteristics of these MOS capacitors were measured [2]. After being placed in deep depletion by an 8 V bias, the non-illuminated substrate device took 50 minutes to discharge and the p-well device took over 130 minutes at room temperature. Thus the p-well capacitor has significantly lower dark current. By exposing the MOS capacitors to light and measuring the C-t transient, the quantum efficiency was calculated and corrected for thermal generation using the equation below [3].

$$K = \frac{qK_s\epsilon_o}{\phi A_g}\left(\frac{1dC}{C^3dt} - \frac{n_i}{\tau_g}\frac{1}{C}\right) + \frac{qn_i}{\phi A_g}\left(\frac{K_s\epsilon_o}{\tau_g C_f} - s'\right)$$

This procedure was used to calculate the variation of the relative quantum efficiency with accumulated exposure. The quantum efficiency of the n-type MOS capacitor was twice that of the p-well capacitor (see Figs. 1 and 2). Under illumination of 550 nm (the peak emission wavelength of the $Gd_2O_2S(Tb)$ phosphor) the flux was measured and an absolute quantum conversion efficiency was obtained. This was calculated as 8%. This relatively low efficiency may be due to the opacity of the polysilicon gates used for these capacitors.

There are several ways in which the performance of this sensor could be improved. The fraction of the incident x-ray flux detected can be improved using phosphors such as the specially modified CsI(Tl) phosphors produced by Phillips Medical Systems, which can be placed in intimate contact with the MOS capacitor. The MOS capacitor can be built with optically transparent gates to avoid the optical absorption of the polysilicon.

REFERENCES

1. H. H. Barret and W. Swindell, Radiological Imaging, Volume 1, Academic Press, NY, NY, 1981, 227–259.

2. D. K. Schroder, "Modular Series on Solid State Devices: Advanced MOS Devices," Addison-Wesley, MA 1987.

3. R. P. King, "The Metal-Oxide-Semiconductor Capacitor as the Fundamental Sensor Element of a Digital Radiography System," master's thesis in preparation.

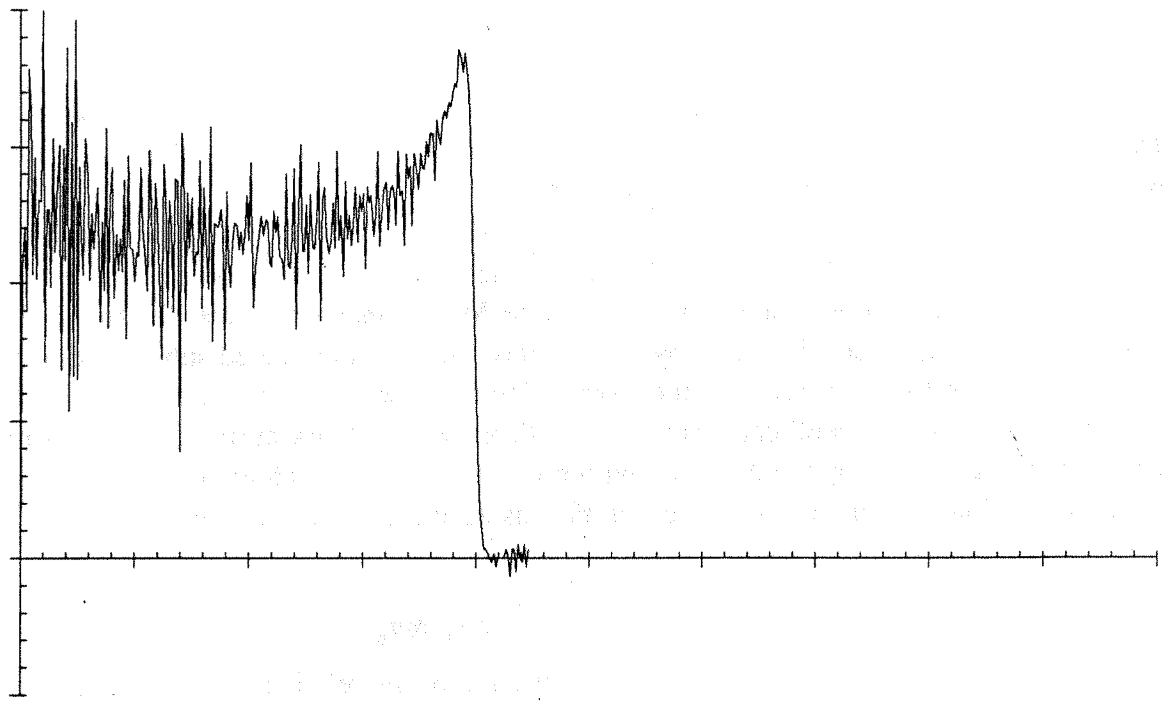

Figure 1: Relative Quantum Conversion Efficiency versus Relative Energy Fluence Measured During a Single Exposure for an N Type MOS Capacitor. Note that Figure 1 and Figure 2 are on the same scale.

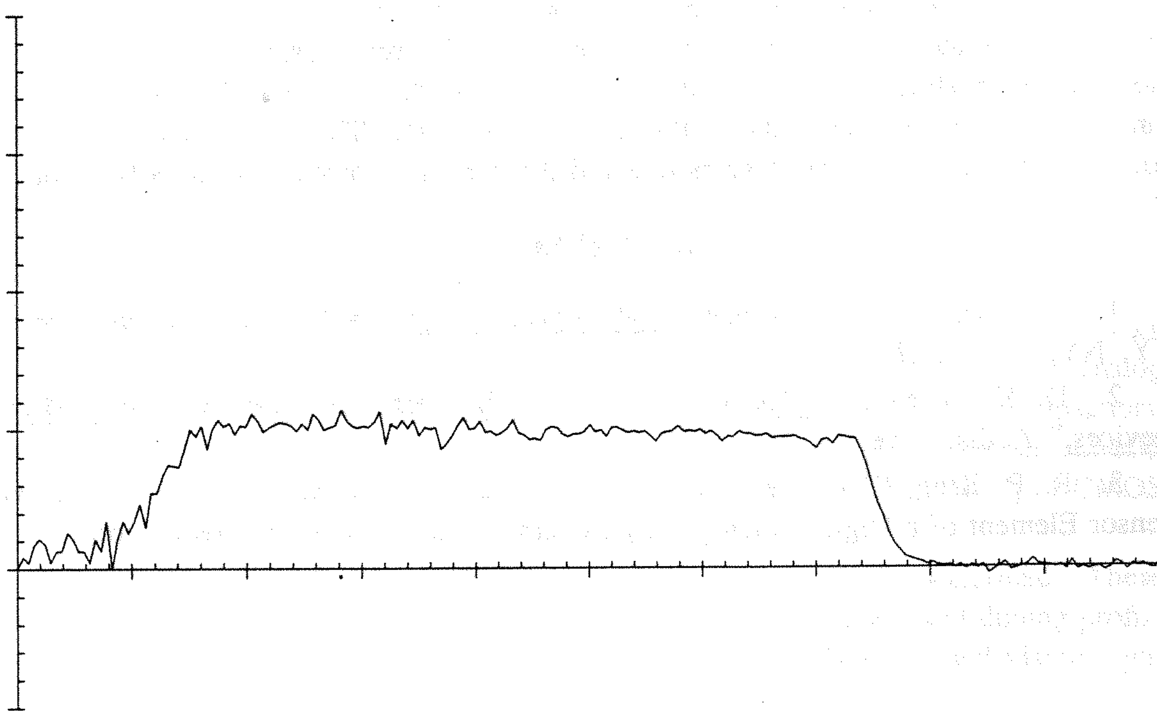

Figure 2: Relative Quantum Conversion Efficiency versus Relative Energy Fluence Measured During a Single Exposure for a P Type MOS Capacitor. Note that Figure 1 and Figure 2 are on the same scale.

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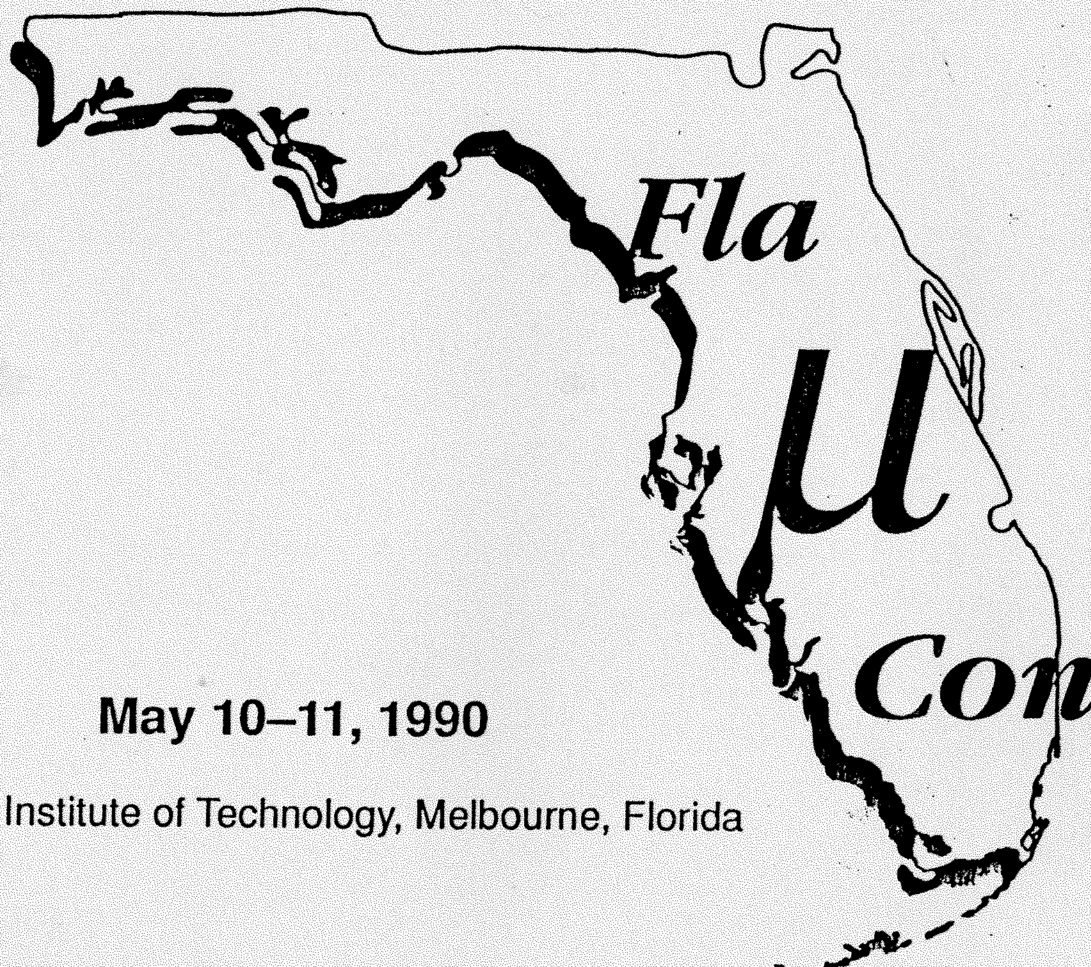

May 10–11, 1990

Florida Institute of Technology, Melbourne, Florida

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