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LARGE FORMATTED AND HIGH RESOLUTION CMOS FLAT PANEL SENSORS FOR X-RAY

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ABSTRACT

The CMOS panel sensors developed for detecting high quality X-ray images, feature large formatted active area and high resolution. The purpose of this study was to assess the performances of imager have a diagonal size of 6.9 inches (non-tiled monolithic chip) and made of monocrystalline silicon optimized for use in digital radiography associated with two kind of thallium doped cesium iodide scintillator. The C7942CA-02 has 50 um pixels, 2400 × 2400 pixel array (5,760,000 pixels) features high resolution of 8 lp/mm with single pixel drive. The C7943CA-02 has 100 um pixels, 1248 × 1248 pixel array delivers in a high frame rate of 30 frames/sec achieved by means of 4×4 binning readout. Both sensors utilize an FSP (flipped scintillator plate) made from high resolution, high luminance CsI crystals grown into a needle structure and coupled to a photodiode array for indirect detection of X-ray images. Furthermore, needle structure CsI was directly deposited upon the sensor chip to accomplish optimum resolution. The CsI scintillation spectrum well matches the spectral response range of the large formatted photodiode array. These image sensors are manufactured in a standard CMOS process rule allowing a high fill factor of 79 % for the C7942CA-02 and 87 % for the C7943CA-02. The monolithic amplifier blocks have 2400 channels of charge amplifiers with internal CDS (correlated double sampling) circuit has an optimal design, yielding a high gain of 1.07 uV per electron and a data transfer speed of 23 M bytes per second in sufficient low noise.

Keywords: CMOS flat panel sensors, X-ray

1. Introduction

Over the last 10 years, research and development into various methods for capturing X-ray image with solid-state image sensors have been carried out, and some remarkable results have been recently achieved. Solid-state image sensors are expected to replace conventional image acquisition methods based on ortho film or imaging tubes, also ideal for digital imaging. Outdated X-ray image intensifiers have a photoelectric conversion and amplification section for converting X-rays into photoelectrons and then accelerating the electrons to allow high sensitivity and measurement of moving images. However, since these are vacuum tube devices, their structure is fragile and bulky, performance variations tend to occur, image distortion appears, has an effect on magnetic field. Moreover, their dynamic range is narrow and the detector downsizing (especially for thin unit structures) is not possible. Meanwhile, investment of large sums of fund has led to development of solid-state image sensors using amorphous silicon material [1]-[3] and an array device with the large active area required [4], [5]. The current process technology used for amorphous silicon unfortunately exhibits an extremely long signal decay time. This is because a high-concentration metastable level is present between the conduction band and forbidden band, consequently the decay (after image or image lag) often lasts from several hundred microseconds to few seconds. This prevents amorphous silicon devices from delivering images with a high resolution and high frame rate. Another drawback is that fill factor is poor because of the wide electrode width and switch size, so extremely small pixels cannot be archived. Amorphous silicon devices have a pixel size of about 150 um and a fill factor of 50 to 60 %. On the other hand, direct conversion types using materials such as a-Se [6], [7] and CZT [8] are not subject to light diffusion from the phosphor material so that high resolution image sensors can be developed. However, these direct conversion types require bump bonding with TFTs, making it nearly impossible to fabricate megapixel image sensors having a pixel size of several tens of microns yet small defective pixels.

In recent years, large formatted CMOS solid state image sensors of monocrystalline material have become available for digital radiography and dynamic imaging. Authors have developed two types of flat panel sensors that show the tremendous potential offered by large size image sensor devices implemented in a 0.6 micron standard CMOS process. The C7942CA-02 is a high-resolution type flat panel sensor with a pixel size of 50 um in a 2400×2400 pixel array. The C7943CA-02 has a 1248×1248 pixel array with a pixel size of 100 um, realized high speed of 30 frames per second by means of 4x4 binning operation. These devices have an anti-blooming facility (overflow drain), a correlative double sampling (CDS) circuit, external frame start, binning functions and 12-bit digital data transfer at high speeds of 23 MHz. The devices are externally comprised of a thin flat panel of 28 mm.

2. Structure

2.1 Sensor

When the high-sensitivity photodiode matrix receives scintillation light from the newly developed FSP (flipped scintillator plate), it generates carriers and accumulates them in the junction capacitance of each pixel. All pixels have an overflow drain function so that blooming in adjacent pixels is suppressed even when a portion of the pixel saturate. Our standard CMOS process implemented with a photodiode matrix with 2×2 and 4×4 binning functions achieves a high ratio of fill factor of 79 % for 50×50 um pixels and 87 % for 100 um pixels (See Fig. 1.) Supplied shift pulses by the vertical scanning shift resistor for sequential scanning, one line of photodiodes flows the carrier into each data line. The on-chip 2400 channels and 1248 channels of extremely low noise charge amplifier array for 50 um and 100um pixel with CDS circuit is somewhat complicated in terms of structure and operation, however the offset components can be cancelled out by finding the differential between the accumulated charge and zero level. This makes a huge improvement in image output uniformity. Generally, some kinds of corrections are made to an acquired image before it is displayed, but the flat panel sensor was designed to have a high level of image quality before making those corrections. The output noise is mainly determined by the charge amplifier itself and the data line capacitance. The ENC (total equivalent noise charge) is given by the following equations.

$$ENC = 8kT/(3g_m) \times c_t^2 \tag{1}$$

$$C_t = C_d + C_p + C_f \tag{2}$$

$$V_{out} = (ENC + Q)/C_f \tag{3}$$

where: C_d - junction capacitance of photodiode, C_p - data line capacitance, C_f - feedback capacitance of the charge amplifier, K - Boltzmann's constant 1.3806×10-23, T - absolute temperature, V_{out}: output voltage and Q - signal charge.

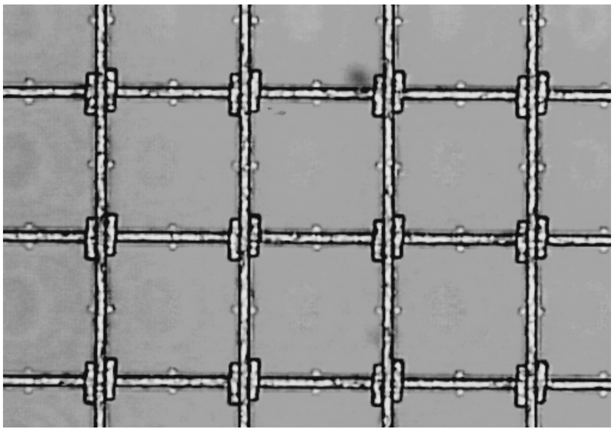

Fig. 1: Photodiode matrix.

Reducing the noise here requires increasing the FET conductance (gm) at the input stage of the charge amplifier and lowering the Ct. The noise at a pixel size of 100×100 um is approximately 1,000 electrons.

2.2 Scintillator

One major application of the large formatted image sensor is in the X-ray imaging field. There are two methods for to design X-ray devices from monocrystalline silicon. In the direct detection method, an electron-hole pair is obtained upon absorbing an X-ray energy of approximately 3.6 eV. Silicon with a thickness of 6.5 mm would be required to absorb for example 50 % of an X-ray energy of 50 keV. However, not only a thickness of 6.5 mm is impossible to obtain using standard CMOS processes and materials but such a device would tend to have a high cost and poor performance characteristics.

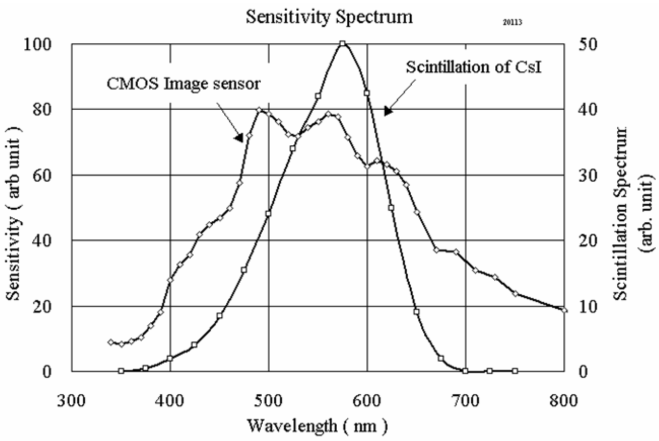

Fig. 2: CsI emission spectrum and photodiode spectral response.

The other method is the indirect method utilizing a scintillator. A spectral response characteristic that matches the peak wavelength and spectral range of the scintillator emission is a critical factor in the photodiode matrix design. (See Fig. 2.) By controlling the impurity profile and anti-reflection layer, we have successively developed an optimal, high-sensitivity X-ray device that is ideal for indirect X-ray detection. The needle-like crystal morphology of CsI:Tl (See Fig. 3.)

mounted on the large formatted photodiode array allows to channel the scintillation light through the fiber-like crystals. This structure offers advantages in light propagation over other scintillators having grainy crystalline structure. The FSP (flipped scintillator plate) formed on the photodiode active area also provides higher intensity and better resolution compared to Gd2OsS:Tb used for medical diagnosis screens.

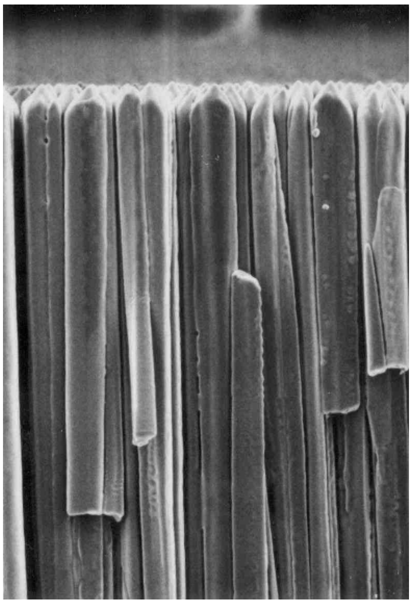

Fig. 3: Newly developed CsI FSP with needle structure.

3. Measurements

3.1 Dynamic Range

A design achieves low noise amplifier and in particular lowers input capacitance as much as possible in the initial stage of the charge amplifier is essential for attaining a wide dynamic range at the 12 bit, 4096 gray level. A wide dynamic range is obtained by keeping the output swing width of the amplifier within the range of the 5 V supply used in the standard CMOS rule and by optimizing the saturation voltage for the photodiode array. However, improving the gain in the initial stage of amplifier matched to the fine pixels means reducing the charge amplifier feedback capacitance Cf. A one line portion of gate switch drain capacitance is also added on the data line capacitance, along a large active area making up large input capacitance Ct. X-ray image sensors usually require a large active area, however the value for Ct in formula (2) then becomes too large so that a format with a large active area and extraordinary small pixels has drawbacks in terms of noise. However by optimizing the gm of the initial amplifier stage, and using patterning that miniaturizes the data lines and reduces stray capacitance, the C7942CA-02 and the C7943CA-02 achieved respective wide dynamic ranges of 2100 and 4300. Since a highly stable X-ray source is not obtained for measurements, a simulated light system emits a light spectrum nearly close to the CsI emission spectrum was used. The scintillator was then removed from the flat panel sensor and placed in a dark box facing the light source. After setting the light source on a fixed light intensity with a neutral density filter, the distance between the light source and flat panel were adjusted and the linearity was measured. (See Fig. 4)

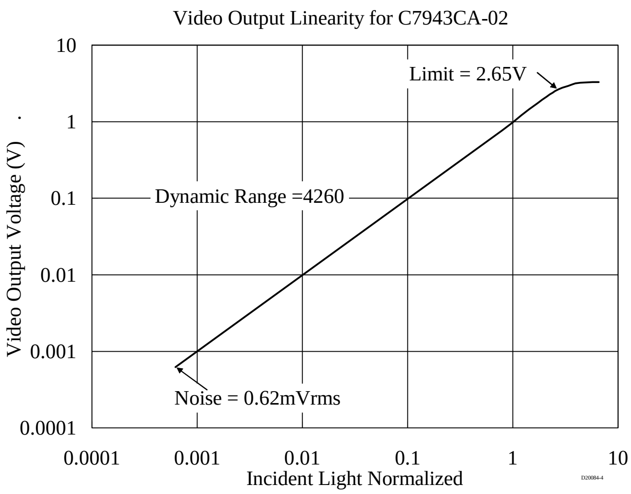

Fig. 4: Linearity data of C7943CA-02.

An analog video signal before being inputed to the AD converter was measured on a Hewlett Packard 54845A oscilloscope. The 100 micron C7943CA-02 has over 4200 dynamic range is good agreement with calculated noise level and simulated saturation voltages of the charge amplifiers.

3.2 Resolution

The CTF characteristics of the C7942CA-02 was measured using a resolution target (Nuclear Associates #07-553 lead-thickness 0.05 mm, 07-525 lead thickness 0.03 mm), a micro focus X-ray source (Hamamatsu Photonics L6731-02) and an image grabber card (National Instruments PCI-1424) at x-ray tube voltages of 40 kVp. After correction between the resolution target image data and the dark current image data, the shading was normalized under light field image data. One line of data was extracted from the final image and CTF (contrast transfer function) was calculated from the contrast ratio.

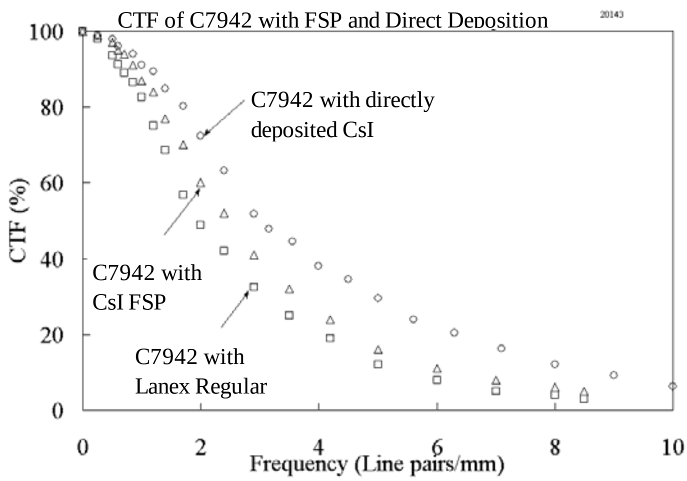

Fig. 5: Resolution curve of FSP and Direct deposition.

The FSP (flipped scintillator plate) used for the panel sensors is manufactured by growing needle-shaped CsI crystals on a glass substrate with an aluminum reflective film in a resistor heated vacuum furnace. The furnace well suited to the compound deposition, provide accurate temperature control to achieve high polycrystalline structure. Thanks to the appropriate rotation of the substrate and revolution of the fixtures provided uniform and fine morphology of 5-micron

diameter, needle height equal to the layer thickness. Three types of the C7942 sensor chip, First coupled with a Lanex regular screen, second coupled to the FSP, where CsI thickness is 200um, and the last, CsI was directly deposited on the photodiode array in 300um thickness were measured to compare their resolution performance. (See Fig. 5.)
In the 0 to 8.5 line pair range, the newly developed FSP achieves a higher CTF than Lanex regular. The experimental data on the directly deposited CsI sample showed highest resolution of 12% at 8 lines / mm. The resolution and emission output obtained from the scintillator generally have a trade-off relationship with each other along the scintillator thickness. However, the FSP mounted in the C7942CA-02 while showing high resolution also succeeded in producing emission 10 % higher than the Lanex regular screen and furthermore, direct deposition showed sensitivity of 65% higher than Lanex to achieve both high resolution and high luminance.

3.3 Imaging Speed

The C7943CA-02 while capturing static images with high resolution, also utilizes a binning mode matching the dynamic image by dividing the active area and low noise amplifier cluster into 8 blocks to achieve high-speed parallel drive. High resolution is generally not demanded in moving images. In a binning operation for 4×4 pixels, the charge from 1×4 pixels is pumped up four times in 4×4 mode.

$$\left(T_h + 1/f_a \times 1248/8\right) \times 1248/4 = 1/30\,s \qquad (4)$$

where T_h - accumulated charge hold time of approximately 20e-6 s and f_a - amplifier operating frequency.
According to (4), if the operating frequency of the final output stage amplifier is at least 1.8 MHz, then images are obtainable at 30 frames per second. Since a dummy horizontal line is required before and after the image output in order to synchronize with the video signal, the actual operating frequency is set at 1.9 MHz. The rise time and fall time of the analog video output waveform have times of 169 ns and 105 ns respectively as shown in Fig. 6. Separate blocks of 12 bit A/D converters and memories are connected to the final amplifier stage, and a high data rate of 23 MB per second is obtained by driving these 8 blocks of charge amplifiers in parallel. (See Table I and Fig. 6.)

Table 1: Specifications (Typ.)

Parameters	Symbol	C7942CA-02	C7943CA-02	Units
Pixel size	-	50	100	um
Active area	-	120	124.8	mm
Number of pixels	-	5.76	1.56	M pixels
Frame speed (single)	Sf(int)	2	7	frame/s
Frame speed (2x2 binning)	-	4	15	frame/s
Frame speed (2x2 binning)	-	9	30	frame/s
Frame speed external (single)	Sf(ext)	Sf(int) to 0.1	Sf(int) to 0.1	frame/s
Noise(r.m.s.)	N(r.m.s.)	1100	2300	electrons
Saturation charge	Csat	2.2	10	M electrons
Resolution	Reso	8	5	LP/mm
Dynamic range	-	2000	4300	-
Number of pixels	-	2400 x 2400	1248 x 1248	-
Number of effective pixels	-	2240 x 2368	1216 x 1232	-

3.4 Radiation Hardness

Sensitivity and increase of dark current was investigated under 80kVp x-ray source beyond 1,000,000 roentgens. To a level of less than 3% of the full dynamic range, slightly increase of the dark current was observed. In a study of sensitivity behavior within 200,000 roentgen, 25% decrease in the sensitivity was evaluated (Fig. 7). This sensitivity decline is in good agreement with data related in the scintillation reduction of the CsI. After removing scintillator plate, to a level of 3%, no change was obserbed in the light sensitivity in the photodiode array.

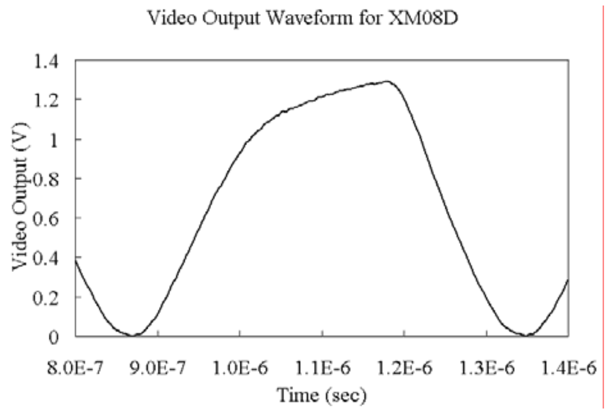

Fig. 6: Internal video signal waveform.

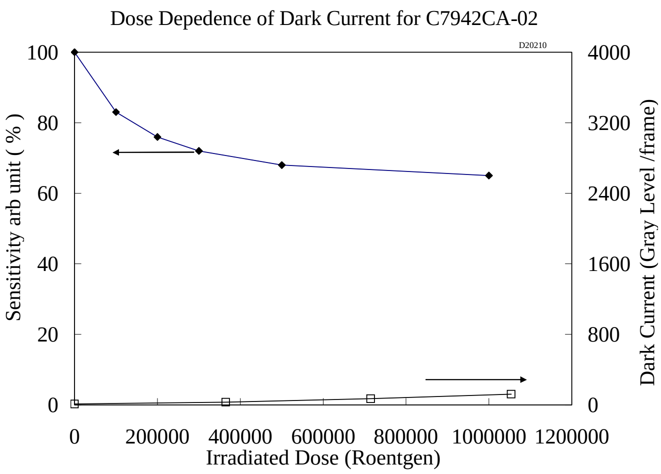

Fig. 7: Result of radiation test.

4. Conclusions

Flat panel sensors were developed with the objective of driving a high resolution image sensor having a massive number of pixels and large active area, at a high frame rate and over a wide dynamic range. Achieving this objective required using a single chip of non-tiled monocrystalline material, rather than a-Si or direct-converting material. This paper described the design and device characteristics meet those requirements.

Handling all the various applications with just one device was impossible, so we presented designs for two devices. One device was the high resolution C7942CA-02 and the other the dynamic imaging speed C7943CA-02 that together cover a wide range of needs. (See Table I) The devices we introduced in this paper utilize a standard CMOS manufacturing process and, compared to a-Si and CCD lines, are ideal for extremely fine patterns to accommodate rapid technical innovations.

The effort to design a high performance CMOS amplifiers, photodiode matrix and scintillator and achieve an even larger surface area to optimize the device characteristics of these flat panel sensors, has spurred innovations in process and design technology that will allow developing a diverse range of flat panel sensors for future use.

5. References

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