A 61mmx63mm, 16Million pixels, 40 frames per second, radiation-hard CMOS Image Sensor for Transmission Electron Microscopy

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Until now, imaging sensors in transmission electron microscopes (TEM) have been mainly film and CCD, the former used in direct detection while the latter is only used coupled to a phosphor screen, as it would be quickly damaged by the impinging electrons. Films are still widely used as they provide the best performance in terms of spatial resolution and detective quantum efficiency (DQE). Phosphor coupled CCDs provide a digital solution but they suffer from poor spatial resolution, due to the spreading of the light coming from the phosphor digital sensors. Over the last years CMOS image sensors used in direct detection, i.e. without converting the signal from the electrons into light, have appeared as a possible solution [1], promising better spatial resolution and sensitivity[2]. In this paper we present the design and experimental characterization of a 16 million pixel CMOS image sensor specifically designed for direct detection of electrons in a TEM camera.

In a transmission electron microscope, an electron beam is used to illuminate a sample. The beam of electrons is generated and then accelerated and focused by electron optics. Typical beam energies are between 100 and 1,000 keV. At these energies, the equivalent wavelength of electrons is between 0.037 and 0.0037 Å, so much smaller than visible light wavelength. Electron microscopy can thus be used to image small objects, like viruses or even atomic planes. For biological application, very low intensity beams have to be used to imagine the samples as they would otherwise alter or even destroy the sample by radiation damage. A detector for electron microscopy thus needs to have good sensitivity to single electrons. It would also need to have good spatial resolution, ideally better or equal than film. For direct detection, it would also need to be radiation resistant.

When a particle traverses silicon, it loses an amount of energy ΔE and N electron-hole pairs are generated, where $N = \Delta E[eV]/3.6$. Details of the energy loss of charged particles in silicon can be found in [3]. As a reference, for relativistic particles the most probable energy loss would generate about 80 electron-hole pairs per traversed micron. The amount of generated charge is thus proportional to the thickness of the epitaxial layer. However, as the charge collection is mainly by diffusion, the crosstalk is also proportional to the thickness, so a careful trade-off between epi thickness and pixel size has to be found in order to obtain the best performance in terms of noise and spatial resolution.

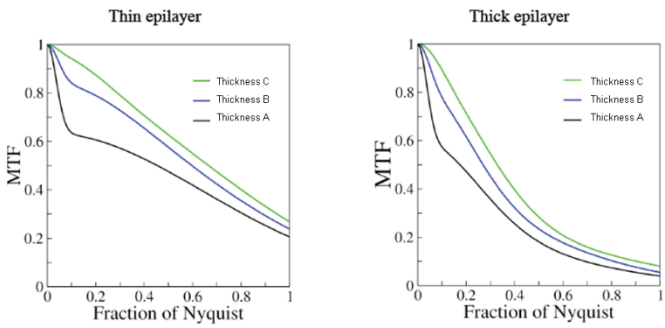

Figure 1. Dependence of MTF on thickness of the epi layer (thin epi on the left, thick epi on the right) and on the overall detector thickness, with A being the thicker and C the thinner (from [4]).

Trade-offs (Figure 1) were studied on a prototype version of the sensor, about 2cmx2cm in size. The MTF is also dependent on the overall thickness of the sensor as backscattering of electrons can spoil the spatial resolution and

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increases with increasing thickness. It is apparent that better MTF is obtained with a thinner epi and a thin detector. Different trade-offs are found for the detective quantum efficiency DQE as shown in Figure **2**.

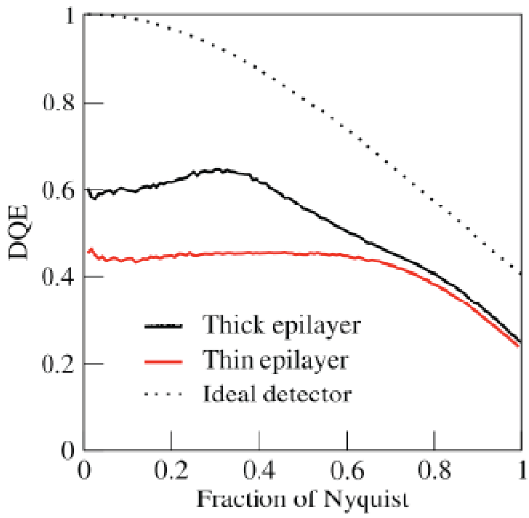

Figure 2. DQE for different thickness of the epi layer.

Radiation hardness was also studied with the prototype sensor. Variations of dark level with the irradiation to 300 keV electrons are shown in Figure 3 for two different pixel layouts. In the figure the sensor is still usable after 500 million of 300 keV electrons. This corresponds to radiation of about 20 MRad[5]. All data were collected at -20 degree C.

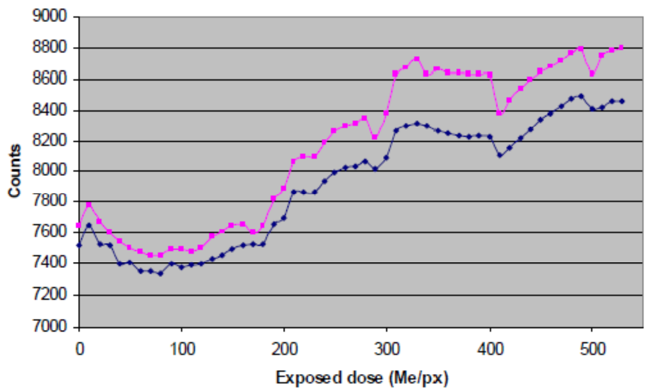

Figure 3. Variation of dark level with radiation damage for two different pixel layouts. The signal is digitized over 16 bits so that dark level changes are acceptable.

Variations in signal response are shown in Figure 4. The average signal response of a non backthinned detector is higher because of backscattered electrons. After the first 100 millions where the signal drops by a bit more than 20%, the sensor response decreases slowly with the dose. The main damage is from ionizing radiation with some minor contribution from bulk damage, the latter eventually altering the charge collection efficiency[6]. This might be the reason for a small decrease in signal at higher dose, although the response is a convolution of the charge collection together with the electronic response of the pixel. Finally, the effect of radiation on the MTF is shown in Figure 5. Little variation is seen up to 500 million 300 keV electrons and the same is true for the DQE.

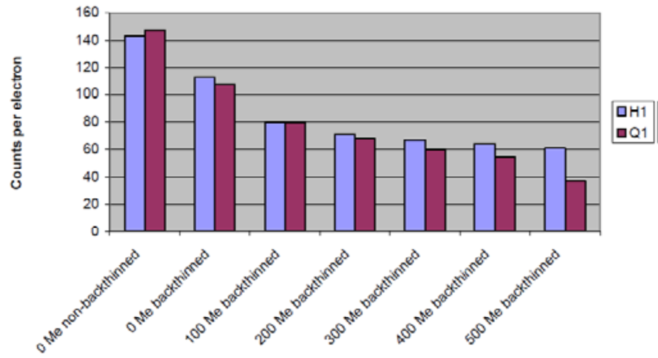

Figure 4. Response to 300 keV electrons as a function of irradiation. Despite this decrease, MTF and DQE do not show any decrease with dose (see Figure 5 below).

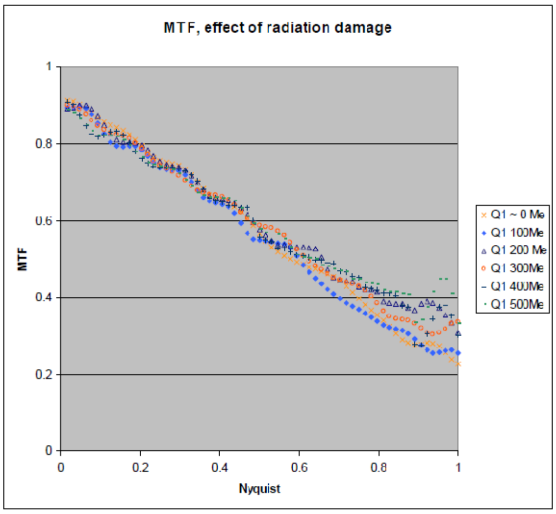

Figure 5. Effects of radiation damage on the MTF. Q1 is the name of one of the pixel layouts designed during the development phase.

For the design of a sensor a 0.35 μm CMOS technology was chosen[7]. This feature size intrinsically provides good radiation resistance[8]. Enclosed geometry transistors and guard-rings were used in the entire layout to enhance the

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[6] R. Turchetta, Nucl. Instrum. and Methods in Physics Research A 583 (2007) 131–133

[7] Plessey Semiconductor Ltd., Plessey Semiconductors Ltd., Tamerton Road, Roborough, Plymouth, Devon, United Kingdom, PL6 7BQ

[8] N.S. Saks, M.G. Ancona, J.A. Modolo, IEEE Trans. Nucl. Sci., NS-31 (6) (1984) 1249

radiation resistance of the sensor[9]. The sensor format was chosen to be 4kx4k. This is comparable with existing charge-coupled devices sensors, but, because of the enhanced spatial resolution coming from the direct detection of electrons, it corresponds to a higher resolution. The trade-off discussed above between signal size and spatial resolution set the pixel size to 14µm. A 3T architecture was chosen because of its well-known good radiation hardness[10]. Its noise performance is good enough to achieve good single electron sensitivity and can be improved by digital correlated double sampling.

The required resolution and size of the pixel mean the focal plane measures 57.3 mm in size, i.e. well beyond the size of the reticle. Stitching is then required for the manufacturing of the sensor. The reticle and the stitching plan are shown in

Figure **6**. Block A consists of a 1kx1k pixel array and is tiled four times in each direction to achieve the required resolution. Larger area detectors can be made by stitching more copies of block A.

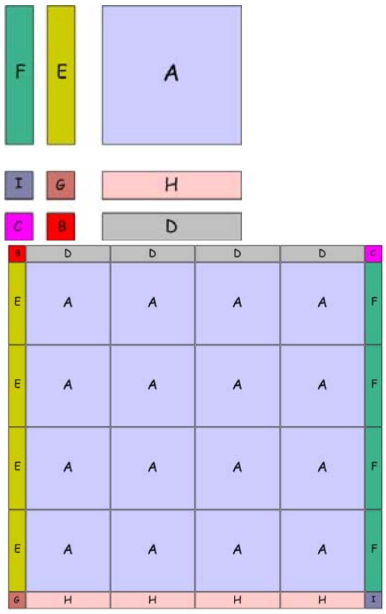

Figure 6. Schematic view of the reticle (left) and stiching plan (right).

[9] W. Snoeys, et al., IEEE J. Solid-State Circuits 35 (12) (2000) 2018
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[10] E.S. Said et al., IEEE Trans. Nucl. Sci. NS-48 (6) (2001) 1796 Part 1
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Four sensors are manufactured on a 200mm wafer (Figure **7**). In order to maximize yield, the sensor architecture was kept simple in order to maximize yield. Row addresses are generated off-chip. They are fed to a Gray-coded row decoder. Reset and select signal are also controlled off-chip and fed to the selected row. Column amplifiers send the chip voltage to a processing block that controls the binning. Each binning block is common to 4 columns and can process the signal coming from 4 rows so that x2 and x4 binning in both directions is achieved independently. The processed analogue values are passed by a 128:1 analogue multiplexer to a readout amplifier. The control of the analogue multiplexer is through a Gray-coded column decoder. The readout amplifier works at a speed in excess of 20 Mpixel/sec to achieve a design speed of 40 frames per second, equivalent to over 670 megapixels per second. To our knowledge, this is the highest pixel rate for sensors of this size, equivalent to a photographic medium format.

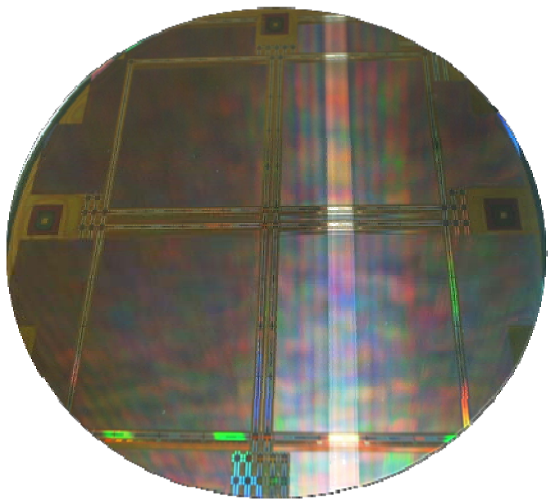

Figure 7. Photograph of the 200mm wafer with four 4kx4k sensors.

The sensor supports region of interest readout, with arbitrary size of regions depending on the off-chip controller. Because of the stitched architecture, the gain in speed is essentially proportional to the number of rows in the region, unless for small regions, i.e. contained within one amplifier block. In the sensor, biasing blocks and a temperature sensor are also integrated. In order to increase its radiation lifetime the sensor is normally operated at -20 degree C and in the vacuum of the electron microscope. Although not designed for optical measurement, the sensor is also optically sensitive, see Table 1 below.

A first example of an image recorded with the sensor is shown in Figure 8 below. The sensor used to record this image was not backthinned. The backthinned version, in preparation, will provide higher spatial resolution and DQE and is likely to displace photographic emulsion as a recording medium. Other examples of CMOS sensors used for transmission electron microscopy can be found in the literature. However, they are all prototypes to demonstrate the technology and not suitable for normal usage. The sensor presented here is the first CMOS sensor that can be directly deployed in transmission electron microscopes as a replacement for existing detectors. Because of the direct detection hence higher spatial resolution, CMOS sensors promise to become the reference sensors for TEM in the future.

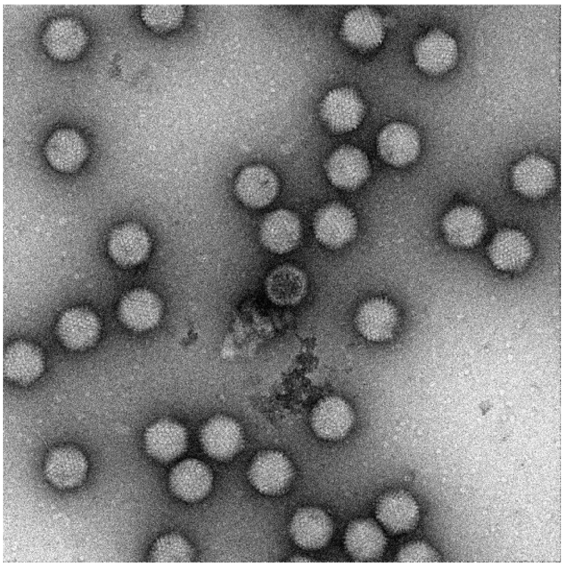

Figure 8. Picture of adenoviruses taken with the 4kx4k sensor in a transmission electron microscope (TEM). The field covered by the image is less than a 1µm.

Parameter	**Value**	**Unit**
Technology	0.35	µm
Format	4kx4k, i.e. 16Mpixel	
Pitch	14	µm
Focal plane size	57.3x57.3	mm x mm
Sensor size	61x63	mm x mm
Number of analogue ports	32	
Maximum frame rate	40	fps
Radiation hardness	>500 millions	300 keV electrons
	~20	Mrad
Region-of-interest readout	Yes	
Binning	x1,x2, x4	Both directions
Power supply	3.3	V
Power consumption	1500	mW (at full speed)
Gain	6.1	µV/e
Noise	83	e- rms (without CDS)
Full well (linear)	75,000	electrons
Full well (maximum)	120,000	electrons
Dynamic range (linear)	59	dB (without CDS)
Dynamic range (maximum)	63.2	dB (without CDS)
QE	20%	at 546 nm

Table 1. Specifications of the 4kx4k sensors designed for transmission electron microscopy.