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Direct charged particle imaging sensors

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Abstract

CMOS image sensors optimized for charged particle imaging applications, such as electron microscopy and particle physics, have been designed and characterized. These directly image charged particles without reliance on performance-degrading hybrid technologies such as the use of scintillating materials. Based on standard CMOS active pixel sensor (APS) technology, the sensor arrays uses an 8–20 μm epitaxial layer that acts as a thicker sensitive region for the generation and collection of ionization electrons resulting from impinging high-energy particles. This results in a 100% fill factor and a far larger signal per incident electron than a standard CMOS photodiode could provide. A 512×550 pixels prototype has been fabricated and used extensively in an electron microscope, including having been used to take sample images. Temporal noise was measured to be 0.9 mV RMS, and the dynamic range was 60 dB. Power consumption at 70 frames/s is 20 mW. The full-width half-maximum of the collected ionization electron distribution was found to be 5.5 μm, yielding a spatial resolution of approximately 2.3 μm for individual incident electrons, and the modulation transfer function of the sensor at the Nyquist limit is to be 32%.

Keywords: Active pixel sensors; CMOS APS; Charged particle imaging; Electron microscopy

1. Introduction

New high resolution and high-speed charged particle imaging systems, for such applications as determining the three-dimensional structure of proteins and viruses [1], are needed in chemistry, structural biology and physics. Techniques such as cryogenic electron microscopy [2] can require thousands or millions of frames of data to be acquired. Film is therefore far from optimal due to cumbersome chemical processing and post-development digitization. Currently available charged-coupled-device (CCD) cameras for electron microscopy applications requires the use of a scintillation screen and optical relays such as lenses or optical fibers, leading to spatial distortion and non-uniformity and the reduction of signal-to-noise ratio (*SNR*), quantum efficiency and resolution. To overcome these difficulties, we have developed a direct electron image sensor based on CMOS active pixel sensor (APS) technology [3–5].

While visible light can generate no more than one electron per photon in the conduction band of silicon, an X-ray or incident energetic charged particle liberates multiple ionization electron–hole pairs [6]. For instance, ^{55}Fe (5.9 keV) X-rays result in an average of 1639 ionization electrons per photon, and 200 keV electrons can each yield about 140 ionization electrons per micrometer in silicon [4]. In order to obtain *SNR* that is high enough to resolve individual incident electrons, at least several micrometers of silicon cross-section is necessary.

Fig. 1 shows a diagram of an APS pixel as used in charged particle detection, including the standard three transistors for reset, buffering and multiplexing, and an n-well/p-silicon diode [7]. Because the number of ionization electrons (Fig. 2) generated by incident high-energy electrons depends on the thickness of the sensitive region through which they penetrate (8 μm is used in the prototype discussed in this paper), a thicker epitaxial-silicon layer is used as the sensitive region. This field-free region is sandwiched between p-well and p-substrate regions, which are more heavily doped than the epitaxial layer, and thus create potential barriers that reflect and confine the diffusing electrons. Given that the epitaxial region is very

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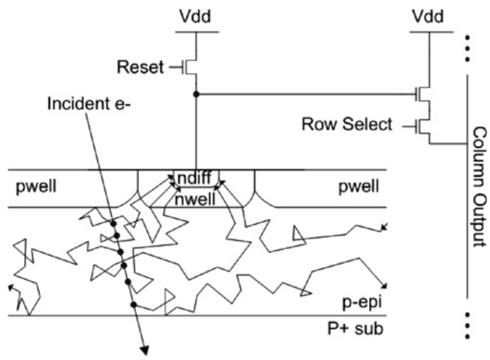

Fig. 1. Pixel cross-section showing charge diffusion in p-epi region, collection diode, and APS readout schematic.

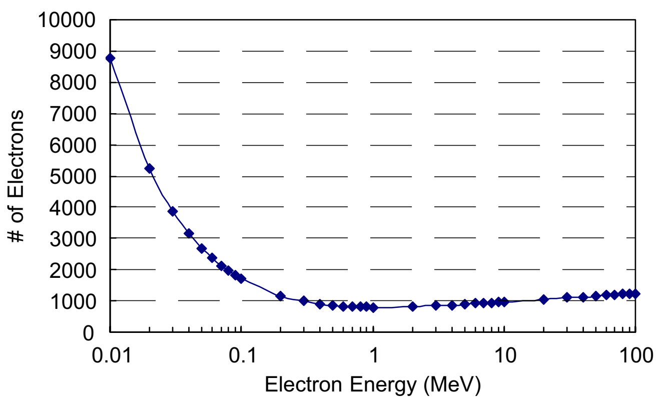

Fig. 2. No. of electrons ionized in 8 μm of Si versus incident electron energy.

lightly doped, the lifetime of diffusing electrons is sufficiently long that there is a high probability that they will eventually be collected by pixel diodes. The epitaxial silicon is continuous and hence provides 100% sensor coverage ("fill-factor") [8] to incident energetic electrons.

2. Pixel geometry considerations

A serious concern in this application the small amount of ionization charge liberated per incident charged particle. Therefore, the pixel's collection diode node must have a small capacitance in order to obtain sufficiently high charge-to-voltage conversion gain. On the other hand, a small photodiode would pick up a smaller fraction of the locally liberated charge, allowing the rest to diffuse to neighboring pixels or recombine—a contradictory trade-off. In practice, we found that using very small diodes (e.g., $2.5 \times 2.5\,\mu m$) resulted in the best *SNR* ratio. In using small diodes, however, we found that recombination at room temperature becomes measurable above about a $10\,\mu m$ pixel pitch.

The thickness of the epitaxial silicon is also a variable of interest, since a thicker epi will yield a greater number of ionization electrons for collection, and hence offers the possibility of a higher *SNR* ratio. Unfortunately, standard fabrication processes do not typically offer a choice of epi thickness, and hence opportunities for systematic experimentation are limited. By simulation, it was found that thicker epi does initially gives rise to a higher total signal and better performance, until a plateau in total signal is reached due to recombination. Furthermore, lateral diffusion to neighboring pixels eventually becomes more pronounced and hence spatial resolution drops, and overall performance decreases. From these simulations, it appears that an epi thickness that is about the same as the pixel pitch is close to optimum in terms of *SNR* and spatial resolution, etc.

Finally, with a conventionally thick silicon substrate, back scattering of the incident electrons can become an issue; electrons may re-enter the epi from behind, a very undesirable result that causes pixels to acquire large false signals [9]. This problem can be mitigated by thinning the chip and suspending it in an open frame.

3. A complete charged particle camera

A prototype direct-imaging camera consisting of a 512×550-pixel array was designed and fabricated (Fig. 3). The pixel pitch is $5 \times 5\,\mu m$ and the diode is $2.5 \times 2.5\,\mu m$ in an $8\,\mu m$ epitaxial silicon. Reads are fully independent of resets, thereby permitting multiple reads per reset and hence true correlated double sampling (CDS) is possible with the use of off-chip frame storage and subtraction. Four analog outputs were used to increase throughput and achieve over 70 frame/s performance.

3.1. Performance measurements

Devices were tested using ^{55}Fe X-rays as a calibrated signal source. Fig. 4 shows the measured average charge distribution, resulting from individual ^{55}Fe X-rays, acquired in a 5×5-pixel region of pixels. As expected,

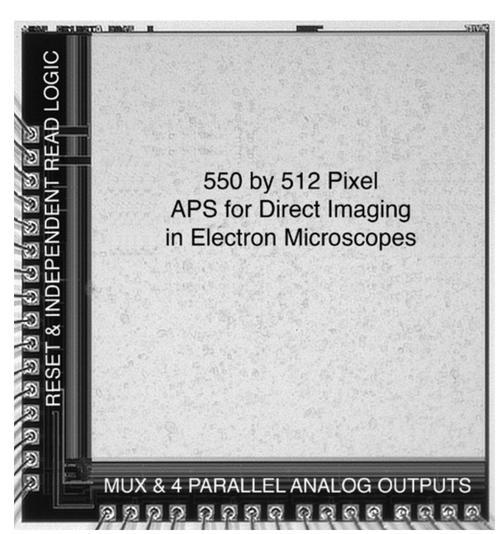

Fig. 3. Direct electron imaging sensor die photograph.