Active Pixel Sensors: Are CCD's Dinosaurs?

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ABSTRACT

Charge-coupled devices (CCD's) are presently the technology of choice for most imaging applications. In the 23 years since their invention in 1970, they have evolved to a sophisticated level of performance. However, as with all technologies, we can be certain that they will be supplanted someday. In this paper, the Active Pixel Sensor (APS) technology is explored as a possible successor to the CCD.

An active pixel is defined as a detector array technology that has at least one active transistor within the pixel unit cell. The APS eliminates the need for nearly perfect charge transfer -- the Achilles' heel of CCDs. This perfect charge transfer makes CCD's radiation "soft," difficult to use under low light conditions, difficult to manufacture in large array sizes, difficult to integrate with on-chip electronics, difficult to use at low temperatures, difficult to use at high frame rates, and difficult to manufacture in non-silicon materials that extend wavelength response. With the active pixel, the signal is driven from the pixel over metallic wires rather than being physically transported in the semiconductor.

This paper makes a case for the development of APS technology. The state of the art is reviewed and the application of APS technology to future space-based scientific sensor systems is addressed.

1. INTRODUCTION

The charge-coupled device (CCD), while presently the imager technology of choice in scientific applications, is a dinosaur doomed to extinction. The likely successor to CCD technology is the Active Pixel Sensor (APS) technology, just emerging in the most advanced imager laboratories in Japan for application to high-definition television (HDTV) and electronic still cameras. While APS technology is still in its infancy, it is easy to extrapolate to the demise of CCDs. The APS technology preserves all the desirable features of CCDs, yet circumvents the major weaknesses of CCD technology.

The Achilles' heel of CCD technology is fundamental to its operation -- the need for the perfect transfer of charge across macroscopic distances through a semiconductor. Although CCDs have become a technology of choice for present-day implementation of imaging and spectroscopic instruments due to their high sensitivity, high quantum efficiency, and large format, it is well-known that they are a particularly difficult technology to master. The need for near-perfect charge transfer efficiency makes CCDs (1) radiation "soft," (2) difficult to reproducibly manufacture in large array sizes, (3) incompatible with the on-chip electronics integration requirements of miniature instruments, (4) difficult to extend the spectral responsivity range through the use of alternative materials, and (5) limited in their readout rate. A new imaging sensor technology that preserves the positive attributes of the CCD yet eliminates the need for charge transfer could quickly eclipse the CCD.

Continued advancement in microlithography feature size reduction for the production of semiconductor circuits such as DRAMs and microprocessors since the invention of the CCD in 1970 enables the consideration of a new image sensor technology, called the Active Pixel Sensor (APS). In the new APS concept, one or more active transistors are integrated into the pixel of an imaging detector array, and buffer the photosignal as well as drive the readout lines. At any instant, only one row is active, so that power dissipation in the APS is less than that of the CCD. The physical fill-factor of the APS can be approximately 50% or higher, and the use of on-chip microlenses or binary optics can increase the effective fill-factor to over 80%. Sensitivity, read noise, and dynamic range are similar to the CCD. Thus, the APS preserves the high performance of the CCD but eliminates the need for charge transfer.

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The APS concept represents a significant revolution in scientific image acquisition. Since CCDs are used ubiquitously in imaging and spectroscopic instruments, the benefits of a technology not susceptible to the shortcomings of CCDs described above can be immense. This technology can enable a large step in the miniaturization of instrument systems by allowing a high degree of electronics integration on the focal-plane. Since the APS technology allows random-access (window-of-interest) capability, new guidance and navigation sensors can be envisioned.

This paper explores APS technology. The limitations of CCDs due to the requirement for nearly perfect charge transfer are discussed. Related technologies to APS such as photodiode arrays, charge-injection devices, and hybrid infrared focal-plane arrays are also discussed. The APS concept is then introduced. Both lateral and vertical configurations are described. The advantages of APS technology are summarized. The state of the art of APS technology development is then addressed. CMD, BCMD, SIT, and other device structures are reviewed. Finally, applications of APS technology to projected NASA mission needs are described.

2. BACKGROUND

2.1 What's wrong with CCDs

The charge-coupled device (CCD), an electronic analog shift register, was invented in 1970. In the intervening 23 years, the CCD has become the primary technology used in scientific image sensors. The details of CCD technology are complex, even for students of semiconductor device physics. It is not possible to provide a complete description of CCD operation in this paper, but the interested reader is referred to texts such as that by Yang[1] or Tompsett[2]. The virtues of the CCD include its high sensitivity, high fill-factor, and large formats. The high sensitivity arises from a high net quantum efficiency of the order of 40%, the high fidelity of reading out the CCD, and the low noise output amplifier. Typical output amplifier noise is of the order of 5 electrons r.m.s. due to the low capacitance of the output sensing node. The high fill-factor of a CCD pixel (80%-100%) is due to the fact that the MOS photodetector is also used for the readout of the signal. The large format of CCDs (typically 1024x1024, and as high as 4096x4096[3]) has been enabled by the concurrent drive of the semiconductor memory business to improve silicon wafer quality and fabrication yield.

Even as the scientific CCD has become the baseline detector technology for visible imaging and spectrometer systems, its weaknesses have also gained in importance and driven the development of alternative imaging technologies, with the high performance CCD as a benchmark.

The Achilles' heel of CCDs is fundamental to the CCD operating principle -- the need for nearly perfect charge transfer. The CCD relies on the transfer of charge (usually electrons) from under one MOS electrode to the next through sequencing of voltages on the electrodes. The electrons are transported through the bulk silicon material macroscopic distances (e.g., centimeters) before they reach the output sense node. A typical CCD has three electrodes per pixel, so that in a 1024x1024 imager, the electrons may be shifted, on the average, several thousand times. The ratio of electrons successfully transferred to number left behind per electrode is the charge transfer efficiency (CTE). The CTE needs to be as close as possible to perfect to enable scientifically acceptable performance of the CCD. If the CTE is given by η, the net fraction of signal transferred after m transfers is simply η^m. As shown in the table below, the CTE must be very high.

Table 1. CCD Fidelity vs. CTE

ARRAY SIZE	CTE	FRACTION AT OUTPUT
1024x1024	0.999	0.128
	0.9999	0.815
	0.99999	0.980
2048x2048	0.99999	0.960
4096x4096	0.99999	0.921
8192x8192	0.99999	0.849

Typical scientific CCDs have a CTE of 0.99999 and a representative number of electrons in a scientific CCD signal packet is 1,000. For a CTE of 0.99999, this means only one electron can be lost every 100 transfers! Since a single broken bond in the silicon crystal can (and usually will) capture a signal electron, the need for perfect silicon crystal quality is the major weakness of the CCD.

The need for perfect transfer efficiency has a great impact on the viability of CCDs for future space missions. The five major issues are (1) the radiation softness of CCDs, (2) a difficulty to achieve large array sizes, (3) an incompatibility of CCDs with the requirements for instrument miniaturization, (4) difficulty in increasing the spectral responsivity range of CCDs, and (5) difficulty in increasing the readout rate of CCDs. These issues are described below.

Radiation softness

CCDs suffer from both ionizing and displacement damage. Ionizing damage affects the oxide, and is not considered critical since processes that harden the oxide against ionization damage are well known. On the other hand, *displacement damage caused by high energy particles and photons is deadly to CCDs.* Particularly damaging are protons in the few hundred keV range. A single 250 keV proton causes an average of 10 silicon lattice displacements[4], though higher and lower energy protons can be less damaging. If all radiation consisted of 250 keV protons, then 1 krad corresponds to a fluence of approximately 125,000 protons/cm^2, or for a 1024x1024 CCD with 20 micron pixels, approximately 5 electron traps per pixel. Fortunately, only a fraction of the (post-shielding) protons fall in this maximum damage regime, so that the actual dose tolerance of a 1024x1024 CCD is about 10 krads. For future orbiter missions around Jupiter and Saturn, the use of CCD technology is tenuous at best. Certain earth-observing orbits can also result in high dose rates. Future spacecraft with nuclear propulsion systems are expected to generate high radiation dose rate environments. It should be noted that the radiation tolerance of a CCD gets worse as the sensor format gets larger since more transfers are required to deliver the signal electrons to the output amplifier.

Difficulty to achieve large array sizes

Since the net transfer efficiency goes exponentially with number of transfers (η^m), it is obvious that as CCD array sizes grow larger, the requirement on transfer efficiency becomes more stringent. To compensate, readout rate must be decreased, but scientific CCDs are already slow to read out (50 kpixels/sec, or 20 seconds per frame for a 1024x1024 CCD). The radiation dose tolerance decreases with increased array size as described above. *The manufacturing yield decreases as the array size grows, particularly since CCDs are highly vulnerable to single point defects that can block an entire column.* This is why only one or two 4096x4096 CCD ICs have actually been demonstrated, and they had numerous defects. The drive power requirement for CCDs also grows with array size since CCDs are capacitive in nature, and the entire CCD must be driven to achieve the output of a single pixel.

Incompatibility with miniature instrument requirements

Instrument miniaturization will require highly integrated, low-power sensor electronics. This will, in turn, require on-chip timing and driver electronics, as well as on-chip signal chains and perhaps analog-to-digital conversion for the image sensor. The CCD device structure is not easily integratable with CMOS. Furthermore, CCDs typically require high and varied voltages, also incompatible with low-power CMOS electronics. Operating on-chip devices with high voltages can cause emission of infrared radiation that is detected by the imager, contaminating the image. While it is possible that first-generation miniature instruments may utilize CCDs with off-chip electronics, the future of smart miniature imaging and spectrometry instruments will require a more tractable technology.

Extension of spectral range

Future astrophysics and planetary instruments will benefit from large, monolithic detector arrays that extend the nominal 0.4 - 1.0 micron spectral range of CCDs. Increasing the spectral responsivity range of CCDs requires the utilization of materials other than silicon, and/or the removal of structures integral to CCD operation. Blue, ultraviolet and soft x-ray response requires the elimination of overlying electrodes that absorb higher energy photons. Backside illumination has been used on the ground with some success but the long term stability of backside illuminated CCD structures for UV response has prevented their widespread use in space instruments (an exception is the WF/PC instrument in HST and it required significant modification to apply a last minute, expensive, (albeit successful) Rube Goldberg-like remedy). Low-QE, low-MTF, down-converting phosphors (lumogen) deposited on the front-side of CCDs will be used on WF/PC II. Pinned photodiode inter-line transfer CCDs have been developed by Kodak[5] and used with some success to overcome these problems. Infrared response of silicon CCDs requires integration of infrared absorbing materials such as platinum silicide[6] or SiGe junctions[7,8]. These devices suffer from very low QE and incomplete reset resulting in large kTC noise. Large format scientific CCDs in non-silicon materials (e.g., GaAs, InGaAs, Ge, diamond) are unlikely to be achieved due to the relative immaturity of these materials compared to silicon. Non-CCD structures will be required to achieve monolithic, large format, scientific performance.

Limited readout rate

For many present and future applications, the readout rate of scientific CCDs (50 kpixels/sec) is nearly too slow for practical use. Examples include star trackers and fine guidance sensors, astrophysics and material analysis instruments requiring photon position and energy information (energy is proportional to the number of photoelectrons), and imaging systems supporting microgravity materials processing experiments on Space Station Freedom. Three to five orders of magnitude improvement in detector array readout rate is required. While some high speed, large format CCDs are being developed for HDTV (1900x1120 at 70 Mpixels/s), the performance of these CCDs is inferior to the competing APS technology, and not suitable for most scientific applications. This is because charge transfer efficiency degrades rapidly with increasing transfer rate.

Other well-known problems stemming from charge-transfer in CCDs includes low temperature performance degradation due to the onset of carrier freeze-out (e.g. an on-focal plane SIRTF fine guidance sensor operating at 4K could not use a CCD, or the MIT Lincoln Laboratory infrared HIP-CCD performance limited by low temperature CCD CTE[8]), and spurious charge generation in virtual phase CCDs.

In essence then, nearly all the problems with CCDs stem from the need to efficiently transfer electrons through macroscopic distances of semiconductors. If the need to transfer the signal can be eliminated, detector array performance can be significantly be enhanced.

2.2 Related Image Sensor Technologies

Photodiode Arrays

Imaging photodiode arrays predate CCDs by a few years[9]. Pixels contain a p-n junction, an integrating capacitor (often the p-n junction itself) and MOS selection transistors. The photodiodes on a single row are typically bussed together on an output line with a column selection transistor connecting a single photodiode at a time to the bus. The photodiode array (the *reticon*) was one of the first solid-state imaging devices and had large advantages over its vacuum tube predecessors. Compared to the CCD, however, the photodiode array was more complex since selection transistors had to be fabricated within each pixel, and some on-chip multiplexer circuits had to be fabricated as well. Later, the noise of the photodiode array also became a limitation to its performance compared to the CCD since the photodiode readout bus capacitance results in an increase in noise level. Correlated double-sampling (CDS)[10] cannot be readily employed with a photodiode array without external memory.

Recently, a photodiode array configured for random accessibility with on-chip CMOS circuitry was reported[11]. This 80x80 prototype array was designed for random accessibility and included an in-pixel source-follower to minimize bus capacitance effects (making it an active pixel sensor as described below.) The pixel size using 3 μm CMOS design rules was 144 μm x 144 μm with a fill-factor of 6%. An estimated input referred noise level of approximately 250 electrons r.m.s. was reported. This noise was dominated by $(kTC)^{1/2}$ processes inherent in photodiode arrays. The architecture also is susceptible to significant fixed-pattern noise and 1/f noise since CDS cannot be readily applied.

Charge Injection Devices

The charge injection device (CID) was invented in the early 1970's, a few years after the invention of the CCD[12]. The CID, unlike the CCD, requires only a single, intra-pixel charge transfer. The charge is shifted under a floating sense gate and the induced voltage change is the output signal. Thus, CIDs are immune to the deleterious effects of imperfect charge transfer and have been used in high radiation environments. CIDs also feature random accessibility of the pixels, high fill-factor, and good blue/UV response. Unfortunately, the CID, like the photodiode and MOS imager, suffers from high bus capacitance since the sense gates of all pixels on a given row are tied in parallel. In a recent paper, a high performance 512x512 CID imager was reported to have a single-read input-referred noise level of 220 electrons r.m.s.[13]. The CID, however, can be operated in non-destructive readout mode so that multiple reads of the same signal can be performed and averaged together. Multiple sampling results in a nearly $(1/N)^{1/2}$ reduction in read-noise level where N is the number of reads so that the input-referred read-noise level after 100 reads is reported to be 26 electrons r.m.s. The drawback of multiple reads is an N-fold increase in readout time and a need to reduce dark current[14].

Hybrid IR FPAs

Hybrid infrared focal-plane arrays typically consist of a detector array chip bump-bonded to a silicon readout multiplexer[15,16]. Each detector pixel has an associated unit cell in the multiplexer that contains an integrating capacitor, selection transistors, and usually some preamplifier of varying sophistication. For example, a capacitive transimpedance amplifier (CTIA) can be integrated within the unit cell to maintain constant bias on the detector and reduce low RoA effects. The separation of detector and unit cell electronics allows for separate optimization of each, and enables detector pixels with nearly 100% fill factor. Read noise is typically in the 30-50 electron r.m.s. range, though multiple sampling can help reduce the noise level.[17] The major difficulty associated with hybrid IR FPA technology is the manufacturability of the hybrid. A second difficulty is that when the detector and readout multiplexer are made of differing materials, stress is induced by the difference in thermal expansion coefficients when the hybrid assembly is cooled. The stress can lead to reliability concerns regarding the structure's integrity.

3. ACTIVE PIXEL SENSOR CONCEPT

The active pixel sensor (APS) technology preserves the desirable attributes of CCDs such as high sensitivity, high signal fidelity and large array formats. The recent invention of the on-chip microlense or binary optics allows the nominal 50% fill-factor of the APS to approach to 80-90% fill factor of the CCD. The APS approach does not require charge-transfer across macroscopic distances and thus eliminates the five negative major issues associated with CCD detector arrays described above.

An active pixel sensor (APS) is defined as a sensor with one or more active transistors located within each pixel. The in-pixel active transistors can provide both gain and buffering functions. Twenty years ago, an active pixel sensor with a practical pixel size was not possible due to the state-of-the-art of microlithography in the early 1970's. The technological push of the semiconductor industry has driven microlithography to the sub-micron regime, and 1.25 micron CMOS is practically an industry standard. It is in the shadow of this progress that the fundamental advantage CCDs had over any other imaging technology has been eclipsed. CCDs in the 1970's were attractive because only three electrodes were required per pixel to make them operate. A 30 micron pixel was thus possible. However, pixel size is determined more by scientific imaging optics in the 1990's than by microlithography constraints. Thus, there is a new window of opportunity to take advantage of the advances in microlithography as it continues its inevitable evolution driven by the digital microelectronics industry.

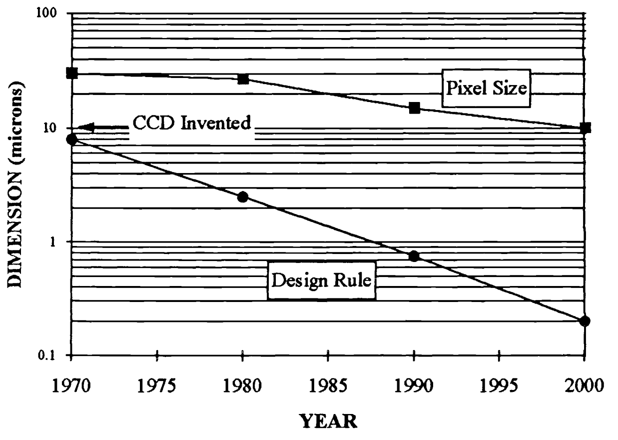

Fig. 1. Evolution of photolithographic feature size vs. pixel size.

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