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Scientific CCD Technology at JPL

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Introduction

Charge-coupled devices (CCDs) were recognized for their potential as an imaging technology almost immediately following their conception in 1970. Twenty years later, they are firmly established as the technology of choice for visible imaging. While consumer applications of CCDs, especially the emerging home video camera market, dominate manufacturing activity, the scientific market for CCD imagers has become significant. This paper describes activity of JPL and its industrial partners in the area of CCD imagers for space scientific instruments. Requirements for scientific imagers are significantly different from those needed for home video cameras, and are described below. An imager for an instrument on the CRAF/Cassini mission is described in detail to highlight achieved levels of performance.

A charge-coupled device can be thought of as an electronic conveyor belt, that collects electrons generated by incident light, and shifts them toward an output amplifier. The charge is confined by voltages applied to electrodes separated from the semiconductor by a thin insulating layer. As the voltages on adjacent electrodes are changed, the charge in the semiconductor is pulled along (See Fig. 1). By using hundreds or thousands of electrodes, a packet of a few thousand electrons can be transferred over a centimeter or more of distance. A major issue in CCDs is the charge transfer efficiency (CTE) which is defined as the fraction of charge successfully transferred from electrode to electrode (though sometimes defined per pixel). While a CTE of 0.999 might appear to be rather good (losing only 1 electron in a thousand), if the packet undergoes 500 transfers, the net efficiency is $0.999^{500} = 0.61$ representing an unacceptable deterioration of the signal. Scientific CCDs routinely achieve CTEs greater than 0.99999.

To build an imaging device, the imaging area is divided into picture elements or pixels. The image is focussed onto this region, and photons penetrate through the electrodes (made from thin silicon) and the insulator into the semiconductor. Each photon generates an electron-hole pair. The hole is repulsed, and the electron is captured due to the voltage applied to the electrode. To prevent electrons in adjacent pixels from mixing and consequently blurring the image, several electrodes are used in each pixel. At least one electrode is biased to prevent electrons from escaping into neighboring pixels. The pixels are also divided in the columnar direction by physical structures called channel stops that block the horizontal movement of electrons. The electrons are collected during an integration or exposure period that may last many minutes in the case of faint objects. Following the integration period, the CCD is now operated in the transfer manner. Referring to Fig. 2, all columns are shifted down in parallel. Upon reaching the bottom of the column, a row of charges is shifted into the horizontal register. The horizontal register is then shifted to the right to an amplifier which converts the charge signal into a voltage signal. This step often introduces the most noise into the image from the CCD. The voltage then leaves the chip and goes into subsequent amplifiers and an analog-to-digital converter. (From then on, the image is computer-compatible and can be directly loaded onto magnetic disk for later display and processing.) As each row is read out, the next row is shifted into the horizontal register. This process continues until the entire image is read out from the CCD.

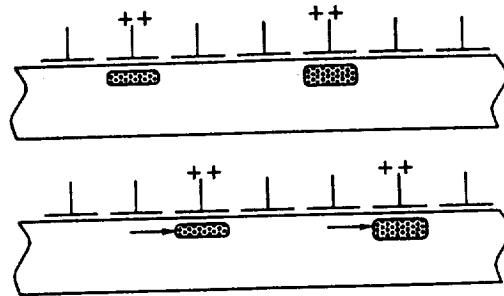


Figure 1. Simplified illustration of CCD charge transfer for a three-phase device. Changing position of positive electrode bias causes electrons in semiconductor to shift to the right.

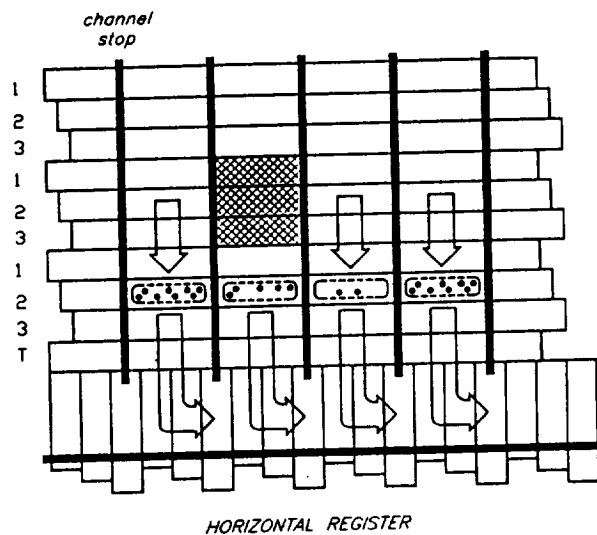


Figure 2. Schematic illustration of a portion of three-phase imager. Hatched area corresponds to one pixel. Heavy lines are channel stop structures. Arrows show path of charge transfer. Signal charge is shown confined under electrode 2.

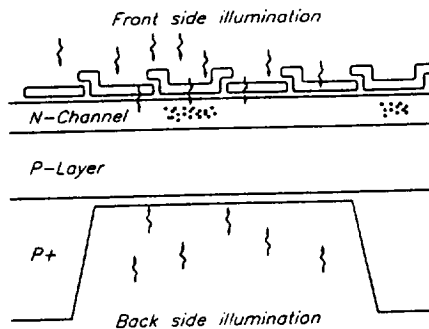


Figure 3. Cross section through a scientific imager showing three-phase polysilicon electrodes, n-channel layer (typically $0.5\mu\text{m}$ thick and doped at $2 \times 10^{16}/\text{cm}^3$), epitaxial p-layer ($10\text{-}12\mu\text{m}$ thick), and p+ substrate. Thinned structure illustrates back side illumination. Dots in n-channel represent collected signal electrons.

Requirements for Scientific CCDs

The requirements for a scientific CCD are significantly different from those for home video cameras. The major differences are (1) array size, (2) frame rate, (3) dark current, (4) read noise, (5) spectral range and (6) radiation hardness. In structure, scientific CCDs are simpler than consumer CCDs since issues such as anti-blooming, color separation, and read-out rate are relaxed for the scientific CCD. In addition, cosmetic blemishes are often accepted in non-space scientific applications but are unacceptable in the consumer arena. Nevertheless, the large volume production and smaller format of the consumer CCD have pushed its unit price to a level several orders of magnitude lower than that of a scientific CCD.

Array Size - Frame Rate

The array size of a scientific CCD is almost routinely 1024x1024, with sizes up to 4096x4096 demonstrated by Ford Aerospace. With a pixel pitch of 12 μ m, a 2048x2048 imager is nearly an inch square, with only a few chips produced on a 4 inch diameter wafer. The 4 million pixels in a single image frame read out at 50 kpixels/sec, and digitized to 16 bits require over a minute to read out and 8 Mbytes of computer memory to store. A 4096x4096 image requires 32 Mbytes - the size of personal computer hard drive disk.

Dark Current

Normally, signal electrons are generated when incident photons generate an electron-hole pair. However, thermal excitation can also result in electron-hole pair generation. Since this occurs without optical input, it is referred to as dark current. Dark current depends both on temperature, and on defect-induced energy levels (called traps) within the semiconductor energy gap. The latter act as stepping stones for thermal excitation and can arise from starting material quality, device design, device processing, and radiation events. Dark current adds to the optically generated signal, and is noisy. In consumer video cameras, dark current is not as important due to the high TV frame rate, but in a scientific CCD using a very long exposure time (e.g. 15 min), the dark current can add up to a sizeable contribution. To avoid dark current, scientific CCDs are often cooled to -70°C or lower.

Radiation Hardness

A CCD in orbit, or travelling throughout the solar system is constantly exposed to varying amounts of radiation in the form of energetic, charged particles, and high-energy photons. This radiation can damage both the insulating layer between the electrodes and semiconductor (producing unreliable operating conditions) and damage the silicon crystal. The defects caused by the radiation degrade both the charge transfer efficiency and the dark current. Unlike digital circuits that use transistors for on/off switches and are consequently more immune to such damage, CCDs suffer a gradual reduction in performance. On the other hand, transient events that cause devastating single-event upsets in digital circuits produce only one or more bright pixels in a CCD image and are not of great consequence. Hardening of CCDs to radiation damage is an important element of scientific CCD development.

Read Noise

Images generated by photons are always intrinsically noisy. Photon shot noise varies

as the square root of the number of optically generated electrons. The CCD can add additional noise both in the transfer process and in the conversion from charge to voltage domains. In a scientific CCD with very high CTE, the transfer noise component can be ignored, and the charge-to-voltage conversion process noise dominates. Contributions come from the output transistor white and 1/f noise. A typical read noise level for a scientific CCD is of the order of 4-6 electrons, and is larger than the photon shot noise for very faint images with less than approximately 50 electrons per pixel.

Quantum Efficiency

For imaging faint objects, the fraction of incident photons converted into signal charge is an important parameter. Loosely termed quantum efficiency, it includes reflection loss at the front surface, loss by absorption in the electrodes, loss in the insulator, loss caused by recombination of carriers generated deep in the semiconductor, loss caused by surface recombination, and in the case of near-infrared radiation, lack of sufficient absorption in the semiconductor. In the ultraviolet where losses due to absorption in the polysilicon electrodes would be significant, two approaches can be taken. One is to coat the front side with a photoluminescent material such that the UV photon is absorbed and a longer wavelength photon is subsequently emitted into the CCD. Although an inefficient process, the quantum efficiency in the UV can be pushed from near zero to perhaps 15-20%. Alternatively, one can thin the semiconductor under the CCD from the backside. Illumination on the back surface need not pass through an electrode before becoming absorbed in the semiconductor (See Fig. 3). If the thinning is done carefully to avoid recombination losses at the back surface, the UV quantum efficiency can be increased further, at the expense of delicate material processing and handling. This is described further below. Quantum efficiency in scientific CCDs is typically better than 50% throughout the visible portion of the spectrum, with some fall-off in the blue due to absorption in the polysilicon electrodes and reflection.

Technologies Used in JPL CCDs

JPL and its academic and industrial partners have developed technologies which specifically address the needs of scientific imagers. Three of these technologies are described here. Backside illumination technology has allowed the improvement of quantum efficiency in the blue and ultraviolet portions of the spectrum. Inversion-mode operation of the CCD has resulted in dark current reduction by several orders of magnitude. The incorporation of signal averaging circuitry in the readout amplifier has allowed read noise to be reduced to an average level of less than one electron.

Backside Illumination

There are two components to backside illumination technology; thinning of the CCD and stabilization of the back surface. Several companies participating in thinning activities include Texas Instruments, RCA, MIT Lincoln Laboratories, Thomson-CSF, Tektronix, and EG&G Reticon. The major issues in thinning are to achieve a specularly smooth surface after etching and to stop the etch at the appropriate depth. While thinning is still far from routine, processes to produce the desired thinning have been demonstrated. Following wafer fabrication and die separation, the backside of the chip is masked except for an area directly under the imaging portion. The chip is then immersed in an acid-based etching solution. The chip is typically etched from its initial thickness of 300 μm to a thickness of 10-12 μm . At this point, the chip is thin enough to permit red light to penetrate through it. Reduction of surface stress is important to prevent the warping of the resultant thin membrane. It is also important

to minimize stress arising from packaging.

The backside surface, if not passivated, is sensitive to electrical charging effects. If it becomes positively charged, optically generated electrons are drawn to the back surface where they can recombine, reducing quantum efficiency. Ideally, the backside should be negatively charged to drive electrons toward the front surface. However, this draws positively charged holes to the backside where, if allowed to accumulate, the holes counteract the initial negative charge. Several approaches have been taken to this problem both at JPL and elsewhere. A thin layer of oxide can be used to passivate the back surface, reducing recombination sites. A very thin overlayer of metal can be used to bias the backside to maintain a constant potential. Alternatively, the shallow implantation of group III impurities can be performed to generate the required field. Optically-generated holes must still be drawn out from this structure to prevent the bleaching effect described above. The present approach for the replacement wide-field, planetary camera (WF/PC) for the Hubble Space Telescope uses the thin oxide, thin metal technology.

Inversion-Mode Operation

Dark current in CCDs can be reduced by lowering the CCD operating temperature. A second method of reducing dark current is to operate the CCD in an inversion mode. Since defect levels at the silicon-insulator interface provide stepping-stone energy levels for electron-hole pair thermal generation, it is desirable to "plug" these paths. This can be accomplished by flooding the surface with holes, thus reducing the number of electrons available for hopping to the conduction band. Such flooding by minority carriers is called inversion. While understood for some time that such a mode of operation would reduce dark current, only recently has this technology been implemented in three-phase scientific CCDs. A special implantation step must be performed to insure that pixels remain isolated during integration and charge transfer. In one device, dark current was reduced from 30,000 $e^-/\text{sec}/\text{pixel}$ to 800 $e^-/\text{sec}/\text{pixel}$ at 30°C using the inversion mode, and the ratio remained constant down to -70°C (0.3 $e^-/\text{sec}/\text{pixel}$ and 0.008 $e^-/\text{sec}/\text{pixel}$ respectively). The inversion-mode also inhibits the increase in dark current after irradiation. For example, without the inversion mode, the dark current in the same device increased by a factor of 200 after 20 krad of Co-60 radiation, but using the inversion mode, the dark current was suppressed by a factor of 1000.

Read Out Averaging

The read out process of converting from charge-to-voltage adds noise to the signal as described above. There are several components to the noise, and some can be decreased by increased sampling time. However, $1/f$ noise generated by the on-chip amplifier can increase the total noise for long sampling periods. It follows that if one could repeatedly read the signal non-destructively, one can achieve noise reduction by averaging a series of output levels corresponding to the same pixel. Such a non-destructive read out circuit was recently integrated on a Ford Aerospace imager. By non-destructively reading the signal using a floating-gate amplifier, the noise was reduced as the square-root of the number of samples taken. For example, the noise in a test pattern was reduced from 7.6 e^- rms (spatial average) to 0.97 e^- rms by averaging each pixel over 64 repeated samples.

The averaging process increases the read out time for an image in proportion to the number of samples taken for each pixel. For short exposure times, the increased readout time might be better utilized as a longer exposure time. For long exposures of faint objects, and for short exposures of once-only images, the on-chip averaging process can dramatically

improve image quality.

The CRAF/Cassini Imager

The visible spectrum science imager under development for the CRAF/CASSINI mission represents a good example of the present state of the art in scientific CCDs. Although it is not a back-side-illuminated device, it is a large format imager with high performance.

The architecture for the imager, fabricated at Ford Aerospace, is split-frame / externally-shuttered. It is implemented with a triple-polysilicon process using a buried n-channel technology and inversion-mode implants. Its format is 1024x1024 pixels with a 12 μ m square pixel size. Each pixel can hold up to 100,000 electrons. The charge transfer efficiency of fabricated devices has been measured to be better than 0.999999 at -70°C. The read out noise at a 50,000 kpixel/sec readout rate has been measured to be approximately 5 electrons rms. The dark current for the device is specified to be under 2 nA/cm² at 22°C. When operated in the inverted mode, the dark current has been measured to be 0.025 nA/cm² at 22°C. The illumination response non-linearity for the CRAF/Cassini CCD is less than one percent, and the pixel-to-pixel response non-uniformity for white light is also better than one percent. Quantum efficiency under front side illumination is better than 45% at 600 nm. The performance goals and achieved levels are shown in Table 1.

Future Directions for Scientific CCD Research and Development

There are several areas ripe for continued research and advanced development activities in scientific CCDs. For example, quantum efficiency - particularly in the blue and ultraviolet, is still low for three-phase devices. New structures which avoid the absorption of these wavelengths by the overlying electrodes can enhance imaging in these wavelengths. Back side illuminated devices continue to have stability difficulties. New techniques to stabilize the back surface are needed to achieve high quantum efficiency in the ultraviolet. Damage caused by energetic particles such as protons and neutrons remain a significant problem for CCDs. Structures and operating techniques to minimize the effect of this damage warrant further investigation.

The use of improved silicon and other materials such as GaAs and Ge offer the potential for extending the useful spectral response on the CCD. For example, x-ray imaging using high resistivity silicon has already been demonstrated. The incorporation of photo sensitive III-V layers may yield a LWIR image sensor.

The integration of additional circuitry for on-chip signal processing of the image data is another area of research. For example, investigation of parallel circuitry to perform the read out averaging so that read out rate does not suffer from the averaging process is of interest. Circuitry for performing other functions such as for sparse illumination read out might also present an avenue of investigation. Finally, the continued improvement of device processing will continue to lead to improvements in image format and array size.

The advancement of fabrication capability also presents an interesting challenge to the scientific CCD. Photodiode arrays which have traditionally had higher noise, lower fill-factors, and less uniformity than CCDs, will be able to take advantage of wafer processing improvements. These devices have higher quantum efficiency, especially at shorter wavelengths, than CCDs, and are more tolerant to radiation and processing defects. It is possible that a cross-over point will be reached for very large arrays in which photodiode arrays re-emerge as a successful competitor to CCD technology.

Table 1
CRAF/Cassini CCD Imager

Parameter	Goal	Actual
Architecture Technology	split-frame, three phase triple-poly, n-buried channel inverted operation	
Array size	1024 x 1024	
Pixel shape	square	
Pixel pitch	12 μ m	
Well capacity electrons	>50,000 electrons	100,000 electrons
Charge transfer efficiency	> 0.99999	0.999999
Dark current non-inverted	< 2 nA/cm ²	
inverted	< 0.03 nA/cm ²	0.025 nA/cm ²
Response non-linearity	< 1%	1 %
Uniformity	< 3 %	1 %
Read out rate	50,000 pixels/sec	
Read out amplifier sensitivity	>1.0V/e ⁻	1.0V/e ⁻
Read out noise	\leq 10 electrons rms	5 electrons rms