

UV-Optical CCDs

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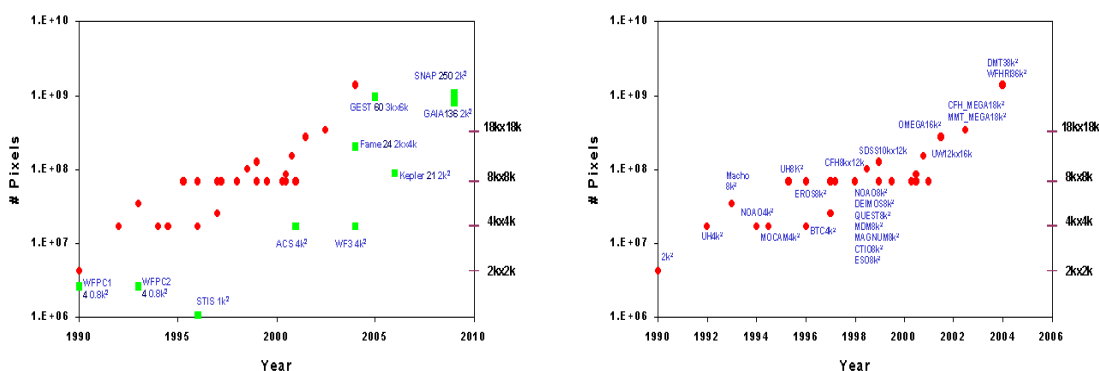
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ABSTRACT

We review the performance of large format CCDs currently planned for instruments in space science missions to be flown the coming decade. With focal planes of up to a billion pixels, we review technical challenges in transferring this technology from ground-based to space imagers and identify areas for future development to facilitate these missions. The current capabilities of CCDs for UV imaging are also summarized and future directions for the development of CCDs suitable for wide field UV imaging are highlighted.

1. INTRODUCTION

The last decade saw an exponential increase in the size of CCD focal plane arrays for ground-based astronomy as shown in [Figure 1](#) adapted from Luppino et al. 1998. Focal planes at the start of the decade were typically assembled with 2048x2048 CCDs, but the advent of a three-edge buttable 2048x4096 (2kx4k) format in the mid-nineties led to almost universal adoption of this format for the construction of focal plane mosaics. Current plans for the next generation of astronomical instrumentation require focal plane arrays based on 2kx4k CCDs with up to a billion pixels by the middle of this decade. Luppino et al. (1998) first noted the exponential growth rate in pixel density and predicted that it would flatten out as CCD focal plane arrays fully sampled the working field of view of 8-10 meter telescopes. However, plans for 25 meter (Nelson and Mast 1999) to 100 meter aperture (Gilmozzi 2000) optical telescopes, wide field optimized 8m telescopes (Tyson), and new, high-angular resolution cameras Kaiser et al. 2000) have provided new impetus to drive for even larger focal plane arrays.



[Figure 1.](#)

Plans for space astronomy missions in the new millennium include a number of missions which require large format imaging capabilities in the UV and optical, and are discussed by Morse in

these proceedings. In Table 1 I have identified a selection of missions planned by NASA (Morse 2000), ESA and other missions under development by individual groups which are likely to require CCD imaging.

Table 1. A selection of NASA, ESA and University missions, or concepts which are likely to require CCD imagers for UV or visible imaging applications.

Mission	Format	BandPass	Instrument	Reference
Hubble Space Telescope/NASA	1 x 4kx4k	Visible	Wide Field Imager	Ford et al. 1998
Hubble Space Telescope/NASA	1 x 4kx4k	NUV/Visible	Wide Field Imager	Cheng et al. 2000
Fame/USNO	24 x 2kx2k	Visible	Astrometric Imager	Horner et al. 2000
Score/NASA-TBD	TBD	Visible	Coronagraphic Imager	See Morse 2000
Kepler/JPL	21 x 2kx2k	Visible	Planetary Transit Imager	Koch et al. 1998
GEST/Univ. Notre Dame	60 x 3kx6k	Visible	Micro-lensing/KBO Survey	Bennett, 2000
SNAP/LBL	250 x 2kx2k	Visible	High-Z Supernova Survey	Deustua et al. 2000
Legacy-1/NASA	~16kx16k	UV		See Morse 2000
PBD-8/NASA	TBD	Visible	Earth-like planet detection	See Morse 2000
COROT/ESA-	4 2kx2k	Visible	Planetary transit/astrometer	Weiss et al. 2000

GAIA/ESA	136 x 2kx2k	Visible		Gilmore et al. 2000
Solar B	TBD	UV	High latitude Solar Imager	NASA's Sun-Earth Connection Roadmap
Jupiter Polar Orbiter	TBD	UV	Polar Orbit imaging of Jupiter	NASA's Sun-Earth Connection Roadmap

Progress in CCDs for UV/Optical applications in space science has not matched ground-based astronomy, despite the early leadership in this field provided by the Hubble Space Telescope's Wide Field Planetary Camera program (Westphal 1982, Blouke 1981). In [Figure 2](#) we show the evolution of space-based UV/Optical CCD focal plane arrays, primarily for the Hubble Space Telescope Instruments. It shows that state of the art for flight arrays lags ground-based astronomy by about three to five years, probably due to the schedule risk associated with flight systems, which often precludes selection of new technology. While the current state of the art in

UV/Optical CCDs is the 4096x4096 mosaic scheduled to fly in the Advanced Camera for Surveys (ACS), a number of future missions plan to fly focal plane arrays matching those planned for ground-based instruments in the new decade. Since flight focal plane arrays lag ground-based astronomy we will address the current status of CCDs for UV/Optical flight applications and highlight issues which will have to be addressed if the next generations of flight CCD focal plane arrays are to catch up with ground-based astronomy.

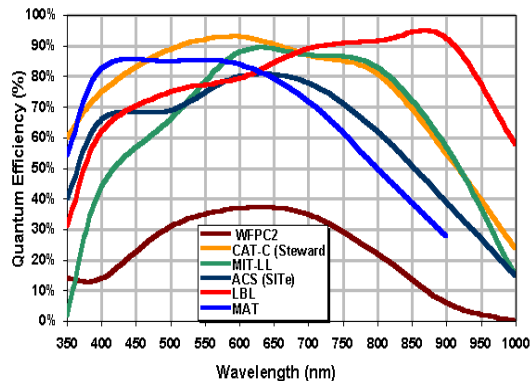


Figure 2.

2. CCD Performance OVERVIEW

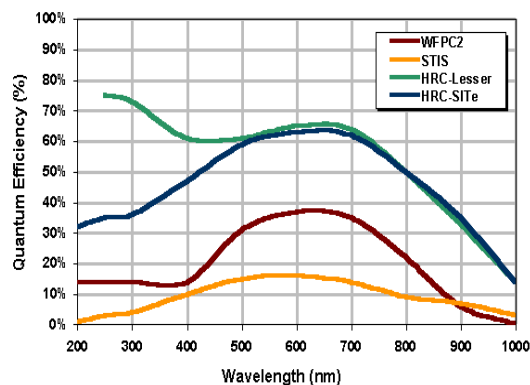
It could be argued that the current performance of CCDs intended for ground-based astronomy are close to state of the art and unlikely to improve significantly. Quantum efficiency (QE) is close to unity in the visible, dark current is negligible, charge transfer efficiencies (CTE) ³ 0.999999, full well ³ $10^5 K e^-$, and read noise ranges from $2 e^-$ to $5 e^-$ RMS depending upon the readout rate. However, for UV/Optical space instrumentation CCD performance still has considerable room for improvement, since the operational environment opens up the UV bandpass for imaging and has significant impact on CCD performance parameters such as dark current, full well and CTE, to the extent that unique tradeoffs based on scientific merit are often required during device design.

The three phase CCD architecture is the standard for UV/Optical space instrumentation and ground-based astronomy, although some missions have previously flown alternative device architectures such as the virtual phase imager on Galileo (Janesick et al. 1981). CCDs for space applications often feature multi-phased pinned (MPP) or, inverted operation, which provides significant reduction in dark current. CCD dark current originates from two sources, Si-SiO interface states at the CCD backside surface and a lesser contribution from the bulk material. MPP operation passivates the backside surface states and allows the device to operate at relatively high temperatures compared to ground-based CCDs. For example at operating temperatures of -110°C to -130°C typical dark currents for non-MPP CCDs are in the range $1 - 4 e^- \text{ pixel}^{-1} \text{ hr}^{-1}$ (Jordan et al 1998; Stover et al. 1998), compared to $5 e^- \text{ pixel}^{-1} \text{ hr}^{-1}$ for a MPP CCD operating at -83°C (Clampin 2000). In space instruments CCD array's are generally cooled by Peltier cooler stacks, so the use of MPP can provide both margin and design relief on spacecraft power and thermal budgets. MPP requires additional implants during CCD fabrication and carries the [Figure 1](#) : Plot showing the growth of focal plane arrays (total number of pixels), as a function of time. Beyond the year 2000, the cameras shown are planned for 8-10 meter telescope instruments.

In order to achieve optimum sensitivity CCDs are generally thinned and backside-illuminated. Frontside illuminated CCDs, such as the Wide Field and Planetary Camera 2 (WFPC2) CCDs built for HST, carry the penalty of low QE, especially at shorter wavelengths, due to the polysilicon electrode on the chip. Backside processing of CCDs to achieve high, stable quantum efficiency involves thinning the substrate to the epitaxial layer, backside surface passivation by charging, ion implantation or molecular beam epitaxy (MBE), and the deposition of an anti-reflection coating optimized for the science application.

The ACS 4kx2k detectors are manufactured by Scientific Imaging Technology (SITE) and are processed with a proprietary backside procedure, and anti-reflection coated with the SITE “VIS-AR” coating. Typical QE for a SITE “VIS-AR” device is shown in [Figure 3](#), which contrasts the reported sensitivities of CCDs summarized in Table 1. The ACS devices are thinned to $\sim 13 \mu\text{m}$, which provides a good compromise between long wavelength QE and modulation transfer function (MTF). SITE CCDs are fabricated with silicon resistivity $\sim 20\text{-}40 \Omega\text{-cm}$, so charge diffusion in the field free region becomes a significant problem if the epitaxial layer thickness exceeds $\sim 15 \mu\text{m}$. This is an important consideration for the both the ACS Wide Field Camera (WFC) and many planned missions, which do not fully sample the point spread function at all wavelengths. In contrast to SITE’s commercial 2kx4k CCD design the ACS CCDs are 4kx2k to reduce the number of parallel shifts to 2048. With the onset of radiation damage CTE degrades and it is advantageous to have the minimum possible number of parallel shifts. SITE has produced the commercial 2kx4k devices for several large CCD focal plane arrays, including the NOAO and CTIO 8kx8k imagers (Wolfe et al. 1998).

The Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) is also producing 2kx4k CCDs in large numbers for ground-based astronomy. The MIT-LL devices are built for a consortium of observatories (Burke et al. 1996, Luppino et al. 1998, Wei et al. 1998) including the University of Hawaii and the European Southern Observatory. The CCDs are thick ($\sim 40 \mu\text{m}$) epitaxial thickness devices yielding enhanced long wavelength QE (see [Figure 3](#)).



[Figure 3.](#)

In order to ensure that significant charge is not lost to adjacent pixels due to drift

in the field free zone, these devices are fabricated with high resistivity silicon

($r \sim 10^3 \text{ W } \text{cm}^{-2}$). Backside processing is achieved by a process of ion implantation with laser annealing. The MIT-LL CCDs have low read noises in the range of 2 e^- RMS and can be read out at Mhz rates. The CCD design employed in the ground-based arrays does not have MPP implants since it is typically operated at -120°C , where dark current is $\sim 2 \text{ e}^- \text{ pixel}^{-1}\text{hr}^{-1}$. MIT-LL also produces 2kx4k CCDs with a new CCD architecture known as the orthogonal transfer (OT) CCD (Tonry et al. 1997), which permits interpixel charge shifting during integration. The OTCCD is primarily intended for compensation of wavefront tilt (image motion) in real time at large ground-based observatories, but is also suitable for specialized applications in spacebased missions.

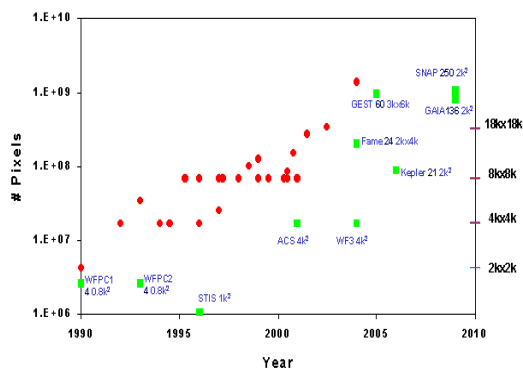
Marconi Applied Technology (MAT) also manufactures 2kx4k CCDs for astronomical applications (Pool 1996) and have recently populated the focal planes of several large telescopes including the CFHT. Marconi offers a significant degree of customization of their 2kx4k CCDs, including 13.5 mm or 15 mm pixel sizes, and the option of 40 mm thick devices for high long wavelength QE as shown, or blue optimized devices as shown in [Figure 3](#). Marconi have also recently introduced a package that permits four side abutment of 2x4k CCDs with the minimum loss of active area yielding $\sim 90\%$ focal plane coverage in a large mosaic.

Lockheed/Fairchild are now manufacturing 2kx2k, 2kx4k and also a single 4kx4k CCD with four amplifier readout for astronomical imaging. These devices are currently being thinned and backside processed by Dr Michael Lesser using his CAT chemisorption process, which yields the typical QE shown in [Figure 3](#).

Lockheed/Fairchild plan to thin devices in-house using the Lesser backside process and have recently delivered an NUV optimized CCD for the Triana mission.

An alternative to CCD thinning is to fabricate a CCD on a thick substrate of very high resistivity silicon ($10,000 \text{ W } \text{cm}^{-1}$) and to operate the device with the entire 300 mm substrate fully depleted (Holland et al. 1996). This approach has the benefit that CCD thinning is not required, thus, improving device yields and reducing processing costs. "Deep depletion" CCDs can be illuminated from the backside to preserve blue spectral response and yield excellent long-wavelength performance, as shown by the measurements of Stover et al. (1998) in [Figure 4](#).

Long wavelength fringing due to interference found in thinned, 13-25 mm epitaxial thickness CCDs is also avoided with this approach to CCD architecture. These devices are now being fabricated in formats as large as 2kx4k and are planned for use in the SNAP mission. The relative thickness of these devices does result in high bulk dark current rates of $12 \text{ e}^- \text{ pixel}^{-1}\text{hr}^{-1}$ at -130°C , however, LBL plans to reduce the substrate thickness to 200 mm to help reduce the dark current.



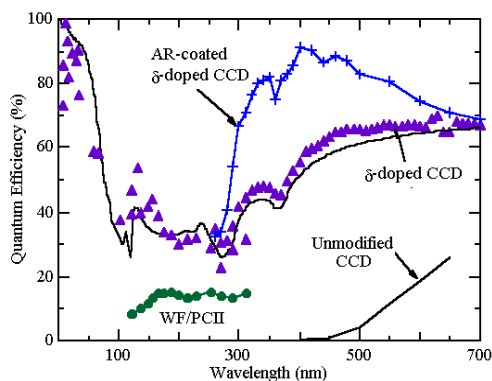
[Figure 4.](#)

Clearly, the optical QE performance of CCDs is close to reaching its limits, however, there is considerable scope for improvement in their near-UV (200 nm – 400 nm) and far-UV (100 nm – 200 nm) performance. Photon

counters have traditionally dominated UV imaging and spectroscopy, since the combination of low UV to optical flux ratios in astronomy combined with their high visible QE places CCDs at a disadvantage. However, photon counting detectors have their own limitations. Large format, photon-counting UV detectors are available (Siegmond et al. 1992; Kimble et al. 1997), but can be easily damaged if their modest local, or global count rate limits are exceeded. For wide field imaging this can result in significant costs to safely operate these detectors. Improvements in CCD read noise performance, combined with significantly improved UV spectral response has made CCDs competitive for some UV applications. There are two approaches to making UV sensitive CCDs, downconverting phosphors, and backside processing. UV sensitive phosphors such as those employed on WFPC and WFPC2 have achieved UV QEs of 14% at wavelengths from 120-400 nm. Phosphors are not stable in vacuum, and require passivation by an inert gas which can provide a conduction path from the CCD to the dewar window, creating a cold-trap for molecular contaminants (Clampin 1992). UV photons have a relatively short absorption length in silicon, so detecting UV photons with a thinned CCD requires careful passivation of the CCD backside by ion implantation or backside charging techniques such as UV flooding, flashgate or chemisorption, to achieve stable UV QE. The Space Telescope Imaging Spectrograph (STIS) successfully developed and flew a 1kx1k CCD with a SITE near-UV backside process enhanced for 200-400 nm (Kimble et al. 1994), as shown in the comparison of near-UV CCDs in [Figure 4](#). SITE improved this backside process for ACS to achieve the near-UV performance also shown in [Figure 5](#). For the ACS near-UV camera, Lesser and Iyer (1998) have combined their CAT chemisorption charging process with a HfO₂ anti-reflection coating to produce a device which offers high QE in the near-UV and good QE in the optical. The chemisorption process derives from the passivated platinum flashgate (PPTF) technique first demonstrated by Janesick et al. (1987), and subsequently adapted by Lesser (1994). The results of the CAT chemisorption process are presented in [Figure 4](#) for the ACS flight near-UV detector, a SITE 1kx1k STIS CCD. MAT also offer a near-UV sensitive CCD backside treatment for their CCDs which is also shown in [Figure 4](#).

The primary technical problems in UV imaging with CCDs are their high QE in the

visible, low UV flux levels and low sky backgrounds. While near-UV filters can be designed with effective red blocking, the problem for far-UV imaging remains a challenge. Filters with visible light suppression factors of at least $\sim 10^6$ are required for effective far-UV imaging. Woods filters can achieve these suppression levels, but at the cost of relatively low far-UV throughput. More work is required to develop technologies for efficient visible-light rejection technologies such as Wood's filters, made with Sodium and also lithium and potassium (see McCandless et al. 1998). Currently, the most effective backside process for far-UV CCD imaging is "Delta-Doping" which uses molecular beam epitaxy (MBE) to passivate the backside (McCandless 1999; Nikzad et al. 1994). Typical quantum efficiencies obtained by Nikzad with Delta Doped CCDs are shown in [Figure 5](#). It should be noted that quantum yield which becomes important at wavelengths less than 350 nm, with ~ 2.8 electrons being produced per photon at 122 nm.



[Figure 5.](#)

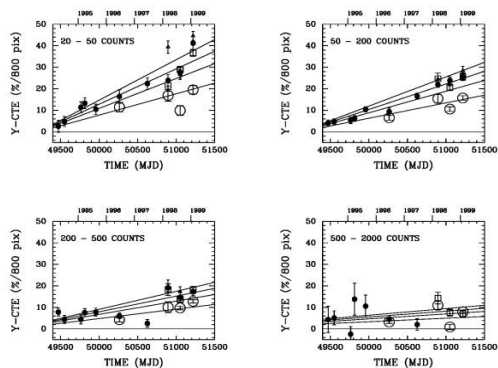
Low UV flux levels and sky backgrounds mandate low read noise and dark current

values. Typical read noise values are currently as low as $2 e^-$ RMS on the MAT and MIT-LL devices. Sub-electron noise performance could be useful in the far-UV and is possible by employing the Skipper amplifier design (Janesick 1990). Dark currents on par with photon counting devices require CCD operating temperatures of $<100^\circ\text{C}$, combined with MPP device architecture.

3. Challenges

CCDs are beginning to face competition from technologies that offer new capabilities such as radiation hardness, low power consumption and integrated camera systems. These technologies include Active Pixel Sensors (Pain 2000) and Hybrid CMOS focal plane arrays (Vural 2000) and have yet to attain the low noise performance and scalability of CCDs. However, they clearly pose a number of challenges that need to be addressed by development of CCD technologies with a focus on the needs of future space applications. **Radiation Tolerance** The space environment confronts CCDs with a spectrum of high energy charged particles which can cause both ionization damage, leading to flat band shifts, and bulk damage which manifests itself as traps caused by the displacement of Si atoms in the lattice and dark current spikes. The particular environment seen by a CCD camera will depend on the mission's orbital profile and the solar cycle. CCDs for flight applications are typically shielded by dewars made of tantalum, molybdenum

or Alloy 42, however, the dewar wall thickness is usually a tradeoff between damage from primary high-energy protons, and secondaries produced in the dewar walls. Large flight arrays will incur a significant mass penalty to shield the CCDs. In practical terms, the production of traps causes long term degradation in CTE (Janesick et al. 1989; Dale et al. 1993). The characteristics of CTE degradation have been recently discussed by Whitmore et al. (1999) for the case of WFPC2, which has been installed in HST in 1993. By late 1999, parallel CTE in WFPC2 at small signal levels had degraded to between 15% - 40% across 800 rows, depending upon the sky background level as is shown in [Figure 6](#). In practical terms this means that the most scientifically important observations, at low signal levels, are those which are impacted first.



[Figure 6.](#)

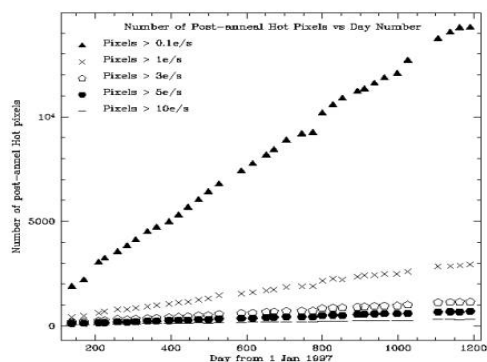
There are a number of methods to combat the effects of radiation damage

on CCDs, the simplest of which is to minimize the number of parallel readouts. An example of this approach is the ACS 4kx2k CCD, where the standard SITE commercial 2kx4k design was modified to reduce the number of parallel shifts from 4k to 2k by moving the serial register and increasing its size to 4k pixels. Mosaicing a larger number of smaller chips is also an option, especially with the arrival of 4 side buttable packages, such as those offered by MAT. A technology which has been available for some time is the notch, or supplementary buried channel (SBC), which restricts small charge packets to a smaller cross section within the pixel, thus reducing the number of traps seen by the signal. The use of smaller pixels can also provide a similar benefit. Robbins (2000) has done a number of simulations which suggests that a 3 mm mini-channel could be expected to produce a factor of two improvement in Charge Transfer Inefficiency (CTI) at low signal levels, where $CTI = (1 - CTE)$. However, work is required to demonstrate the true performance of SBCs for low signal level imaging, and understand their interaction with other device architectures such as MPP.

P channel CCDs are another option for increasing the radiation tolerance of CCDs. The P channel design prevents the formation of silicon-E centers, the primary cause of trapping (following 10^{10} 10 MeV protons cm^2 there will be $\sim 2 \cdot 10^1$ silicon-E centers cm^{-3}). Hopkinson (1999) recently demonstrated a reduction in CTI by at least a factor three in a prototype device fabricated at MAT. Several other groups are now fabricating P channel CCDs to evaluate their radiation tolerance, including GSFC, and the LBL who are fabricating fully depleted P channel devices.

For specialized programs charge can be injected into the parallel register to improve CTE during readout. The method can be optimized for different observations, for instance a sequence of charge filled rows can be placed in front of several targets, so that these rows are clocked out ahead of the targets to fill traps without an increase in shot noise for the targets. The effectiveness is a function of the trap's emission time constant. This method has been employed effectively for X-Ray missions, and should prove especially useful in forthcoming imaging astrometry programs such as FAME and GAIA. The more traditional way to fill traps prior to an observation is to preflash the CCD with a calibration lamp, however, this carries a penalty in lost sensitivity due to increased shot noise in observations.

Hot pixels are dark current spikes caused by field enhanced emission from defects in high field regions. [Figure 7](#) shows the growth of different hot pixel populations in the Space Telescope Imaging Spectrograph's (STIS) 1kx1k CCD. Hot pixels are likely to be a feature of competing technologies to CCDs as well. Experience with HST's CCD cameras has shown that annealing monthly at temperatures of 0°C – 20°C can significantly curtail the growth rate of hot pixels. More research is required to determine an optimum practical temperature for annealing CCDs during flight operations.

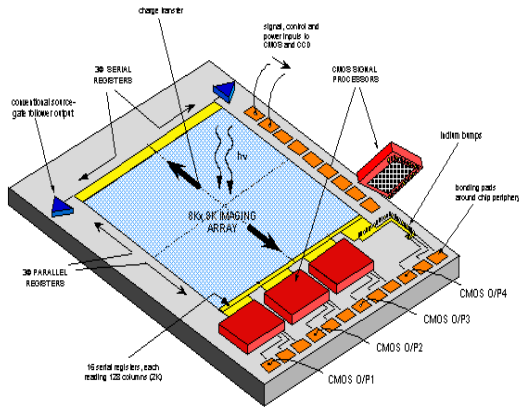


[Figure 7.](#)

CCD Controllers

APS and CMOS imagers are particularly attractive because of their relatively simple and compact controller requirements. The growth in large format CCD mosaics for ground-based astronomy has been accompanied by the development of increasingly sophisticated CCD controller systems able to handle multiple readout channels, such as the ESO Fiera controller (D' Odorico et al. 1998), and the SAO Megacam (Geary and Amato 1998). The extension of these technologies to large format CCD arrays for future space astronomy missions will present significant challenges in controlling power consumption, heat dissipation and instrument cost. This point is illustrated by the case of ACS where the WFC dissipates up to 27 Watts, and the support electronics for both CCD cameras dissipates 197 Watts (Rafal 1998). French et al. (1998) have addressed this issue by developing an Application Specific Integrated Circuit (ASIC) which can perform the tasks of waveform generation and sequencing on a single chip for space-based CCD applications (Waltham et al. 1995). This ASIC controller is currently being ported to a radiation-hard CMOS process and will offer a significant gain in reduced mass, power consumption and heat dissipation. Single chip controllers also offer improved reliability and protection from single component failures, since they are easily implemented in redundant configurations for very low cost. Hybrid imaging technologies (HIT) offer similar benefits with an approach that merges the best features of CCD and CMOS technologies. HIT uses bump-bonding to couple CMOS circuitry to a CCD-based imaging array and is illustrated in

[Figure 8](#) which shows a device being developed in a program led by Wadsworth at the Jet Propulsion Laboratory (JPL). A similar concept is being developed by MIT-LL and is discussed in these proceeding by Bautz. The development of these techniques is vitally important in order to support the next generation of billion pixel CCD mosaics in space.



[Figure 8.](#)

Alternate materials

In the past few years, the quality of wide band gap materials has significantly improved and the development of optimized UV sensitive CCDs is now a possibility. The poor quality of wide band gap materials to date has resulted in unacceptable trap densities, resulting in poor CTE. In addition to the possibility of “solar blind” UV imaging, these devices should also provide excellent radiation tolerance. CCDs have already been fabricated from SiC (Sheppard et al. 1996), and Mott (2000) has initiated a program at the GSFC to develop a GaN CCD. As the commercial market for SiC and GaN semiconductors develops, opportunities for fabricating wide band gap CCDs should be pursued.

4. Summary

Several vendors are currently producing 2kx2k, 2kx4k and 4x4k CCDs suitable for the next generation of missions featuring large format CCD arrays. The practical requirements for flight science operations of CCDs suggest that further development is, however, required to address some of the issues we have addressed in this review.

Radiation tolerance is still *the major hurdle* facing billion pixel imagers for flight applications. Further work is required to determine the optimum application of SBCs (notches), evaluate the utility of p channel CCD architectures, and new radiation tolerant materials such as SiC. Large format CCD focal planes might be better built from larger numbers of smaller devices (e.g. 2kx2k). New 4 side buttable packaging concepts should be further developed to facilitate high density arrays of smaller format CCDs. Devices with smaller pixels sizes will also help address the radiation tolerance issue by reducing pixel cross section. Given the large number of programs planning to use similar CCDs in the next generation of missions, the development of a standard flight package concept for 2kx2k and 2kx4k CCDs would also help reduce mission costs across programs.

The practical problems of operating large arrays of CCDs for flight has not yet been addressed. There is an immediate need for hybrid CCD/CMOS technologies and “single-chip” controllers to be developed for future missions in order to contain their costs.

Access to vendors able to fabricate flight CCDs is a concern first raised in the FOSI report (1993). The next generation of billion pixel missions will need access to vendors who can meet large volume CCD fabrication schedules, possibly on P type architectures, at a time when the traditional scientific CCD market may be under attack from alternative technologies such as CMOS imagers.

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