Realization and application of a 111 million pixel backside-illuminated detector and camera

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ABSTRACT

A full-wafer, 10,580 × 10,560 pixel (95 × 95 mm) CCD was designed and tested at Semiconductor Technology Associates (STA) with 9 μm square pixels and 16 outputs. The chip was successfully fabricated in 2006 at DALSA and some performance results are presented here. This program was funded by the Office of Naval Research through a Small Business Innovation in Research (SBIR) program requested by the U.S. Naval Observatory for its next generation astrometric sky survey programs. Using Leach electronics, low read-noise output of the 111 million pixels requires 16 seconds at 0.9 MHz. Alternative electronics developed at STA allow readout at 20 MHz. Some modifications of the design to include anti-blooming features, a larger number of outputs, and use of p-channel material for space applications are discussed.

Keywords: Astrometry, large-format CCD, all-sky-survey, star tracker, Space Situational Awareness

1. INTRODUCTION

This paper descibes the motivations and requirements which led to the development of the world's largest-format CCD detector. The history and realization of the entire camera around this device for the U.S. Naval Observatory (USNO) is presented. Some performance results obtained from a thinned, backside-illuminated detector of this kind are given. The paper concludes with plans for the future and explains applications in ground-based and space-based programs.

2. REQUIREMENTS

In recent years the requirements for ever larger focal plane assemblies at astronomical telescopes have mostly been satisfied by assembling numerous smaller devices into large focal plane mosaics. The advantage of this mosaic approach is a larger yield in producing high quality detectors, which results in cost savings for the instrument development. Although larger, monolithic detectors are desirable, there has not been a real driver requiring the bold step to go beyond the current typical 2k × 4k scale devices.

2.1 Astrometry

In planning projects beyond the successful USNO CCD Astrograph Catalog (UCAC) program[1] it was realized that a large-format detector is needed. Using the technique of photographic astrometry the positions of stars are determined with respect to several reference stars with known positions by direct imaging of the sky using dedicated telescopes. The large-format photographic plates (up to about 17 inches on a side) traditionally used were later replaced by CCD detectors, providing higher quantum efficiency and more accurate centroiding results as compared to the photographic process. Unfortunately, CCD detectors are very small compared to photographic plates. For high accuracy astrometric measurements many reference stars need to be on the same detector or at least many well exposed anonymous stars are required to tile together overlapping fields with as few mapping parameters as possible. We needed to advance beyond the existing CCD formats in order to make

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Figure 1. The U.S. Naval Observatory Twin Astrograph, currently at the Flagstaff Station, with 10k camera dewar attached to the "red lens." This setup will be used for astrometric test observations on the sky in preparation for the URAT program.

significant progress[3] in this area and to fully utilize the existing large focal plane of our astrograph as well as those of future dedicated astrometric telescopes.

At that same meeting[3] where the need for larger-format CCD detectors for astrometric mapping was presented, we learned that designers of a Large Binocular Telescope spectroscopic instrument were also looking at similar types of CCD detectors to improve calibrations and lower systematic errors. Following discussions, both groups agreed to share risks in development of a large-format detector which could be used for both projects. A pixel size of 9 μm was agreed upon, but independent funding avenues had to be pursued.

Of particular importance for astrometric applications are a high charge transfer efficiency and relatively fast readout, with a goal of about 10 sec for the full frame. This required the use of a large number of parallel outputs. Standard high-quality materials and designs used for science grade CCD detectors were sufficient to satisfy all other requirements, providing the yield issue could be addressed successfully.

2.2 USNO Telescopes

Figure 1 shows the USNO Twin Astrograph, which was used for the UCAC program (1997 to 2004) and before that for astrometry using photographic plates (24 cm square and 8 × 10 inch). The original "blue" lens was replaced by a 5-lens "red lens" objective[2] of extremely high astrometric performance, which has been in operation since 1990. The new 10k camera dewar is attached to the red lens now, while the second telescope tube features a visual bandpass corrected lens which is used for guiding.

The following table presents the main characteristics of the existing USNO astrograph and the planned USNO Robotic Astrometric Telescope (URAT).[4,5] Both feature an available focal plane area of about 30 cm in diameter. Design work on the URAT began in 2000 and concluded in 2005. A contract was signed with EOST to produce the primary mirror which will be delivered by the end of 2007. Funding of the URAT telescope is uncertain beyond that time. However, the focal plane development is progressing well with major purchases anticipated in 2008.

Table 1. Comparison of the existing USNO Twin astrograph (red lens) telescope with the planned USNO Robotic Astrometric Telescope (URAT).

property	astrograph	URAT
aperture [meter]	0.20	0.85
focal length [meter]	2.00	3.60
scale [arcsec/pixel]	0.90	0.50
diameter field of view [degree]	9.00	4.50
diameter focal plane [mm]	320	283
bandpass [nm]	550−750	600−800

The astrograph will serve as a testbed for any future URAT focal plane assemblies, and might even be used for a new all-sky survey (see below). An upgrade of its control interface with integration into the new camera system is in progress.

3. REALIZATION

3.1 Research Program

A sponsor for the development of a general, large-format, monolithic detector was found at the Office of Naval Research. A Small Business Innovation in Research (SBIR) topic proposed by the USNO Astometry Department was accepted for a phase I study in 2004. Originally an 8-inch full-wafer CMOS or CMOS/hybrid device was considered, but this was quickly rejected as unrealistic at the time. Instead, 2 companies were funded in phase I to develop a 6-inch wafer full-frame CCD detector. In 2005 the main research phase II funding was awarded to one of the phase I participants, Semiconductor Technology Associates (STA), of San Juan Capistrano, CA.

3.2 Chip Design

This 10,580 × 10,560 pixel array was designed and developed at STA. A combination of new features went into the CCD design to increase yield and lower risk and costs.

To achieve high frame rates it is necessary to clock both the parallel and serial clocks at high rates. Existing bussing for the serial registers is satisfactory for transfers at rates in excess of 40 MHz. A parallel clock gate is normally bussed from the left and right sides with aluminum straps. Resistance across the gate is usually only several thousand ohms, with a distributed capacitance of several picofarads. It is normally possible to clock these structures at several hundred kilohertz. However, the very large size of the STA1600 yields parallel gates that are over 95 mm long, with a resistance close to 790K ohms. This permits only very slow parallel clocking. To reduce the effective gate resistance a metal grid is placed over the image area. Three micron metal lines run vertically and horizontally over the polysilicon gates. Periodic contacts connect to the polysilicon, lowering its resistance. The small metal lines require contacts smaller than is possible with the 1x masks used for the CCD manufacture. To obtain the required 1 micron contacts we used a second contact mask solely for this strapping. These contacts are printed with a photostepper and a 5x mask plate. This mixed mask approach is simpler and more cost effective for creating such a large device. Using only a stepper alone for manufacturing a CCD of this size would require many additional masks and be much more costly.

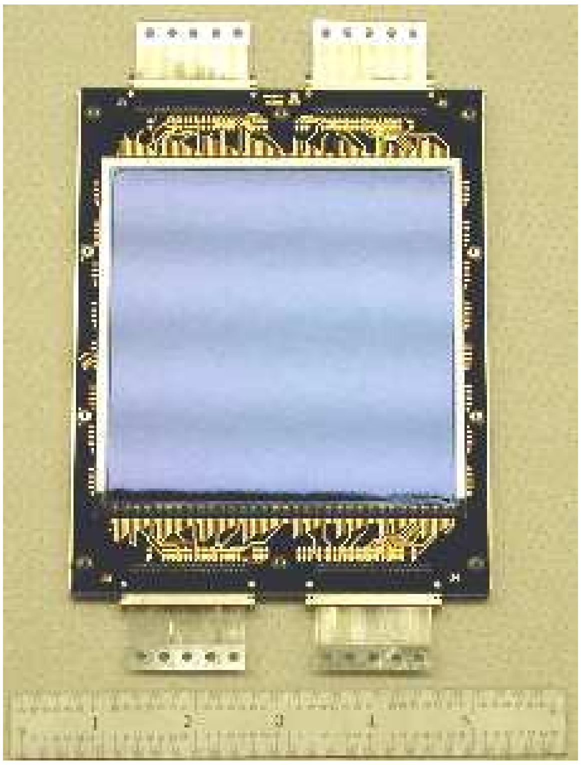

Figure 2. The STA1600 chip after packaging. The top and bottom areas connect to 8 outputs each. The photo-sensitive area is 95 mm × 95 mm.

3.3 CCD Fabrication

The STA1600 full-frame detector was successfully manufactured by DALSA in June 2006 (see press release). The yield was sufficient to produce several engineering and science grade chips. Initial characterization by STA of the full-wafer device confirms acceptable parameters.[6] Figure 2 shows the packaged device with 4 connectors for 4 outputs each.

3.4 Thinning

The backside processing of the 10k CCD is similar to processing smaller devices.[7] The wafers are first mechanically lapped to 250 μm. Gold stub bumps are applied to each bond pad and then the wafer is diced. The die is hybridized to a 1.4 mm thick silicon substrate with indium bumps matching the CCD bond pads. Epoxy is used as an underfill material. Backside thinning is accomplished in a selective etch which stops at the epitaxial layer. A final etch polishes the surface. Backside coatings are applied using the University of Arizona Chemisorption Charging process.[8] A custom invar package and circuit board set has been designed and fabricated for the backside parts. After packaging and wire bonding the device is ready for testing.[9] A mechanical flattness is achieved to support an f/4.5 beam of the URAT instrument.

4. CAMERA AND PERFORMANCE

In addition to the thinned, backside-illuminated, science-grade STA1600 CCD detector, the 10k camera consist of a custom dewar, filter, shutter, electronics and required interfaces. The filter, made by Andover Corporation, is 12 mm thick, ultra-flat, and has a diameter of 160 mm for a 683 to 747 nm bandpass. The bandpass has been chosen to be as red as the astrograph lens supports but to exclude the H_α region of the spectrum, in order to avoid photons from emission nebulae on exposures taken for high accuracy centroiding of stellar images. The filter is fixed mounted as dewar window and the separation of the backside of the filter to the focal plane is

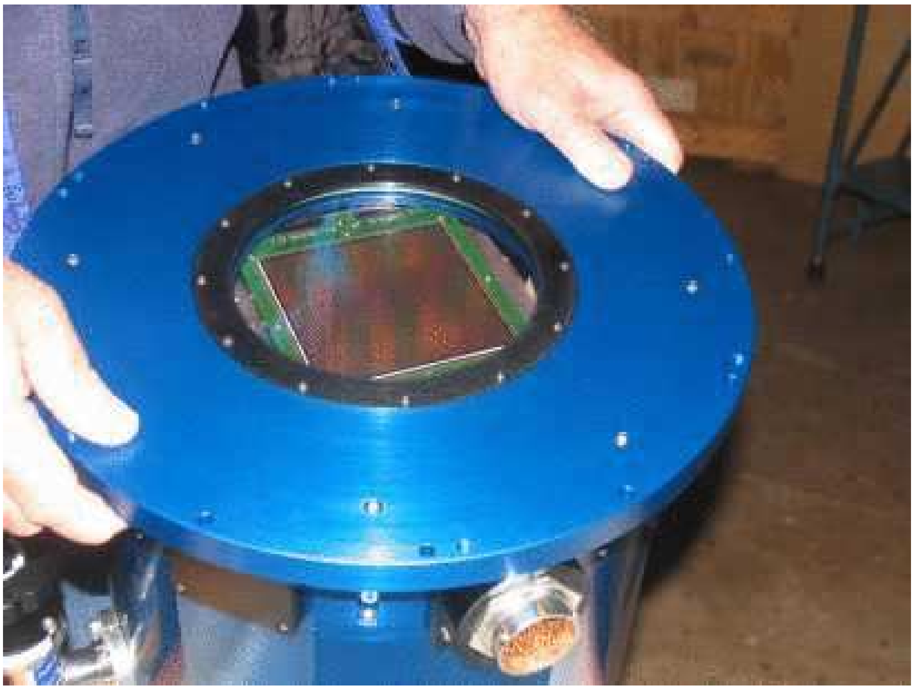

Figure 3. The STA1600 chip inside the 10k camera dewar. Here an operational front-side chip is used.

only 5 mm. In addition to the interference layers and coatings of that filter a small (1.2 mm diameter) neutral density spot with a factor of about 200 attenuation has been added near the center of the filter. This will allow astrometric observations of bright stars in reference to much fainter stars in the same field of view.

Figure 3 shows the dewar with an engineering grade STA1600 chip and a clear glass window for testing. This 10k camera is currently limited by the Leach electronics. A complete readout of the full 111 megapixel image requires 16 seconds. We are using an Astronomical Research GenIII camera with 2 ARC48 8-channel A-D boards. The camera is running the CCD with a 912 kHz serial clock and a 30 kHz parallel clock. An ARC42 fiber optic timing board relays output data from the ARC controller to the PC. We are digitizing 16 bits for each of the 16 outputs. This data rate of 912 kHz is limited by the capacity of the current fiber optic card. At 912 kHz we achieve a read noise of 6 electrons RMS on a thinned STA1600 CCD. Alternative electronics has been developed at STA and a readout at 20 MHz has been demonstrated on a frontside device.

A 150 mm aperture shutter was custom built for the 10k camera by the Bonn instrumentation group[10] (Fig. 4). The camera is run by a Linux PC. Operation of the shutter has been integrated and a completely new interface to an upgraded astrograph is in preparation, all controlled by the same PC from a command-line interface suitable for robotic operation. Image data files will be stored in a compressed FITS format, about 120 MB per full-frame.

5. APPLICATIONS

5.1 Ground-based Star Catalogs

The main application for this detector and camera is to support DoD needs and requirements for star positions. This will also serve the general astronomical community by providing highly accurate positions and proper motions of millions of stars.

For star tracker applications (bright stars) the goal is to improve upon the Hipparcos Catalog[11] positions, which have steadily degraded due to accumulation of proper motion errors since their mean observing epoch in 1991. This improvement can be accomplished by observing bright targets with the USNO astrograph and the

Figure 4. The "Bonn" shutter system for the 10k camera. This custom made shutter (black device) comes with control electronics to fit into a standard rack.

new 10k camera through the neutral density spot on its filter. Tycho-2 stars in the same 2.5 by 2.5 degree field of view will serve as reference frame.

For Space Situational Awareness research the 10k camera can be used at either the astrograph or the URAT to determine accurate positions of faint stars (down to R magnitude 18 and 21, respectively). For this application maximal sky coverage per exposure is needed. Figure 5 shows a focal plane layout with 4 of the 10k CCD detectors in their current packaging. The circle is 333 mm in diameter, close to the limit of the astrograph focal plane area. Attached to the astrograph this would provide 27 square degrees sky coverage in a single exposure. This layout would need to be modified to be able to mount the 10k chips closer together for the slightly smaller URAT focal plane.

We plan to purchase such a "4-shooter" camera in 2008. This would allow us to construct a URAT focal plane and use it at the astrograph. After only 2 years of observing time from the Cerro Tololo Inter-American Observatory (CTIO), positions and parallaxes of stars in the 11 to 16 mag range on the 5 to 10 mas level could be produced, significantly improving current star catalog data.

If the USNO-lead Milli-Arcsecond Pathfinder Survey (MAPS) mission[12, 13] is approved, the tie of the resulting new celestial reference frame to fixed, extragalactic sources would be performed by URAT, and funding is expected for the new, dedicated, ground-based telescope utilizing the 4-shooter camera based on an anti-blooming modified version of the STA1600 chip.

5.2 In Space

The initial design for the STA1600 called for 16 2-stage outputs that could run at up to 15 MHz, resulting in a maximum frame rate of approximately 2 frames per second (fps) with a resultant post-CDS read noise of 40 to 50 e^- RMS. Because it was designed to be operated at ground-based observatories, the current design has no built-in radiation mitigation capabilities.

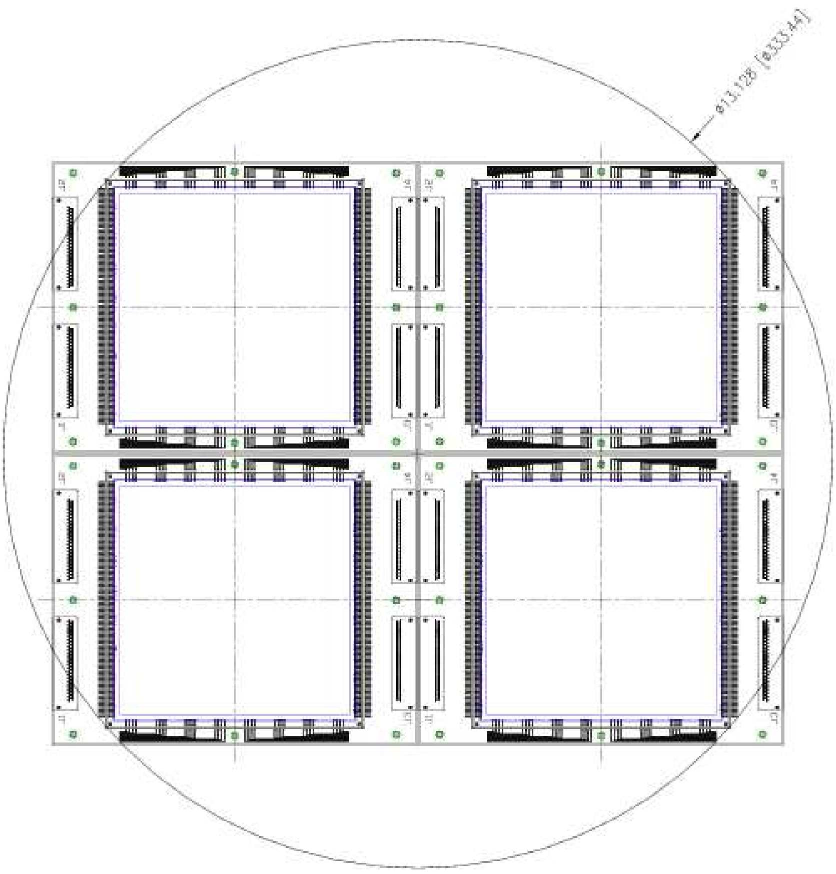

Figure 5. Layout of a 4-shooter focal plane based on the existing STA1600 chip design. This design would barely fit the astrograph field of view and is slightly too large for the URAT focal plane. A modification of the packaging is planned.

A space-based implementation of this CCD could include an increase in the frame rate and improved radiation hardening. In order to increase frame rate, the number of readout amplifiers would be increased to 32 and 3-stage amps would be used rather than 2, increasing the speed to 40 MHz per channel. This approach would allow the frame rate to be increased from 2 to 10 fps, with an increase in read noise to around 60 e^- RMS. In order to improve radiation hardness, perhaps the most straightforward approach would be to use p-channel rather than n-channel material. Numerous results[14] have shown an increase of approximately an order of magnitude in hardness vs. displacement damage is achieved when using p-channel material. Other solutions, such as active circuitry, could also be considered, although these methods are less attractive due to their added complexity and potential negative impact on yield.

6. DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, the USNO does not endorse any commercial product nor does the USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

ACKNOWLEDGMENTS

We wish to thank the Office of Naval Research (ONR) for funding this large, monolithic detector research program through a Navy SBIR program and Sean Urban, Head of the Nautical Almanac Office, for finding that sponsor.

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