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WORKING GROUP ON DETECTORS

(GROUPE DE TRAVAIL POUR DETECTEURS)

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1. Optical Detectors

CCD manufacturers and system designers continue to push back the boundaries of what is possible with the technology. Since the last report, developments have largely been of improvement to manufacturing reliability, deployment of large (up to 10^8 pixels) mosaics to telescopes, initiation of programs to build next generation mosaics (of order 10^9 pixels), and novel variations in CCD design.

The de facto industry standard format is now a two-output-node, 2048 pixel wide by 4096 or 4608 pixel tall device, with each pixel being 15 or 13.5 μm square. Improvements in packaging design allow for four-side abutting in mosaics, although the serial-register edge inevitably accounts for larger losses than the other three. Production is dominated by E2V Technologies (formerly Marconi Applied Technologies, formerly EEV) in the UK, with further devices being obtained in the USA from SITe, Fairchild, an international consortium of observatories and universities with MIT Lincoln Labs, and a sprinkling of smaller programs. The largest production device is a thick, 9216$\times$9216, 8.75 μm pixel detector from Fairchild.

Typical specifications provide for readout rates of 10^6 pixels sec^{-1} or faster with readout noise less than 10 electrons pixel^{-1}; typical readout noise floors at slower speeds have been pushed to below 2 electrons pixel^{-1} and full well capacities to 10^5 electrons. Backside thinning technology has stabilized in general production and devices of greater than 80% QE over 200–300 nm wide ranges are unsurprising. Flat-field uniformity, particularly in the blue, and device surface flatness continue to be areas of active pursuit of improvement particularly for mosaics requiring overall flatness of a few tens of microns. Charge transfer inefficiencies of better than 10^{-5} are routine; dark current at -100°C is negligible for most applications. Ultimate production yields and quality depend on the quality of the input silicon.

Devices produced while generating this industry standard have been used to populate a number of large mosaic cameras. At the time of writing, no less than twelve cameras of 8192$\times$8192 pixels or more have been deployed as survey or common-user instruments. These are actively collecting data and, in part, constitute a first wave addressing the need to acquire targets for observation with the new generation 8–10 m aperture telescopes. A second wave is already under construction and the first of these, Megacam (3.6×10^8 pixels), is expected to go into operation late in 2002 at CFHT. Serious plans are under study for the development of cameras with up to 2×10^9 pixels (NOAO's LSST) and area up to a square meter (ESA's GAIA satellite). This rate of growth is roughly comparable with Moore's Law in the semiconductor industry at large, and likewise it shows no sign of flagging.

Controller development has had to evolve to keep pace with this growth. Many of the existing mosaics employ controllers developed primarily for the operation of single or small numbers of devices but replicated and scaled up as necessary. In the field, the most common controller is that produced by Astronomical Research Cameras, Inc. although a number of institutions large enough to develop and support their own controllers continue to do so (e.g. ESO, AAO). The next generation of mosaics will have needs not addressed by simple replication of existing controllers, nor even simple extension of existing data collection, reduction and analysis procedures. Consequently most programs (e.g. CFHT's Megacam) are producing their own fully integrated systems incorporating massively parallel readout, pipeline reduction and archiving components customized to their individual needs, some are even exploring options of developing application specific integrated circuits (ASIC) to produce the "controller on a chip". Detector development has become a large scale operation and is no longer the domain of a small group working on a shoestring.

Best-effort, wafer-run detector production programs have become rare in the face of this production reliability and standardization. The few exceptions usually represent programs to develop novel architectures or technologies, although the large scale manufacturers also engage in such ventures. Examples include:

- The orthogonal transfer CCD produced by MIT, Lincoln Labs, USA, can transfer charge in the horizontal as well as the vertical direction facilitating first order correction of image motion (Tonry, Burke, & Schechter, 1997).
- CCDs manufactured on high-resistivity, n-type silicon at Lawrence-Berkley National Laboratory, USA (Stover et al., 1997) are fully depleted and offer significantly improved QE in both red and blue but their physical thickness increases their susceptibility to cosmic ray events. The E2V catalog includes more conventional deep-depletion p-type devices, and the MIT/LL consortium has also been exploring this direction.
- The E2V catalog also includes the low light level CCD (LLLCCD) — a novel readout architecture with charge multiplication within the output register, providing photon-counting and sub-electron readout noise operating modes (Mackay et al. 2001).

Small scale efforts continue in the development of superconducting tunneling junctions in astronomy (Verhoeve 2002) but their small size ($\sim$36 pixels) and cumbersome support systems will limit their use for some time. CMOS detectors are beginning to attract attention but are still not serious contenders at the telescope — fill factor losses are significant — but various hybrid possibilities show some promise for the future.

Dewar technology also continues to develop and many sites now support clean rooms as a matter of course. Seeking to address the inconvenience of liquid nitrogen cooling, closed cycle coolers are finding their way to observatories and the Cryotiger from SHI-APD Cryogenics is particularly popular.

Clampin (2002) reviews recent CCD developments for space applications and Janesick (2002) compares the current performances of CCDs and CMOS imagers.

2. Infrared Detectors

The characteristics of optical CCDs and infrared detectors are increasingly convergent, with IR detectors now supporting quantum efficiencies greater than 65%, pixel full well greater than 10^5 electrons, dark current less than 0.1 electrons sec^{-1}, and readout noise below 15 electrons sec^{-1} with Fowler sampling.

At the time of the last report the production standard was 1024$\times$1024 pixels for primary technologies — Rockwell's HgCdTe HAWAII array and Raytheon's InSb ALADDIN. These devices are now prevalent throughout the community (more than 70 ALADDINs have been delivered) and both manufacturers are beginning delivery of 2048$\times$2048 pixel devices.

Raytheon has entered the HgCdTe arena with the VIRGO array, and is working on a 2048 $\times$ 2048 Si PIN array and a 1024 $\times$ 1024 Si:As IBC array. Rockwell have produced a larger HAWAII detector using MBE technology to move the junction from the surface and into the bulk material giving better control of bandgap and significantly improving its performance. This device also offers a "guide mode" in which a sub-array may be read out continuously at up to 5MHz while integrating on the rest of the array to provide correction data for an adaptive optics system. A direct comparison of manufacturers specifications is given below.

Device name	**ORION**	**VIRGO**	**HAWAII–2RG**
Manufacturer	Raytheon	Raytheon	Rockwell
Technology	InSb	HgCdTe	HgCdTe or Si PIN
Buttable	2-side	3-side	3-side
Pixel size	$25\mu m \times 25\mu m$	$20\mu m \times 20\mu m$	$18\mu m \times 18\mu m$
Read noise	$25e^-$	$< 15e^-$	$\leq 15e^-$
Outputs/device	64	4 or 16	1, 4, or 32
Well capacity	$\geq 3 \times 10^5 e^-$	$\geq 3 \times 10^5 e^-$	$\geq 10^5 e^-$
Dark current	$< 0.5e^- sec^{-1}$	$< 0.2e^- sec^{-1}$	$\leq 0.1e^- sec^{-1}$
Operating temp.	$30^\circ K$	$70 - 80^\circ K$	$\geq 30^\circ K$
Spectral range	$0.6 - 5.4\mu m$	$0.85 - 2.5\mu m$	$0.3 - 5.3\mu m$
Quantum Efficiency	$> 80\%$	$> 80\%$	$\geq 65\%$
Pixel rate for these properties	$655kHz$	$400kHz$	$100kHz$

A new substrate material (CdZnTe) addresses thermal expansion mismatch, a critical issue in such large devices. Wafer size for readout multiplexer production now sets the current limit on detector size. With the ability to abut these detectors, there is a clear opportunity to build mosaics and the UK survey telescope, VISTA, have already committed to building an imager incorporating 16 VIRGO arrays, the first IR 8192 × 8192 mosaic.

Similar motivations and constraints exist for the development of controllers for IR arrays as for CCDs — many existing systems use controllers originally developed for CCDs — and the future shows more possibilities for parallel developments. The Rockwell product line now includes an ASIC which will move much control and processing onto the detector assembly within the dewar.

3. Community Interaction

Regular workshops continue to foster communication and collaboration. Previously these have been held at ESO, Garching-bei-München, (in 1996 and 1999) and the latest was hosted by Keck Observatory on Hawaii, in June 2002. SPIE astronomy conferences every 2 years (March 2000 in Munich and August 2002 on Hawaii) have a broader remit but include detector presentations. The proceedings of these conferences are always useful checkpoints for current development. Ongoing discussion in the community remains supported by the email forum CCD-world (which, despite its name, addresses all varieties of optical and infrared detectors) moderated by the author. An archive and further information may be found at http://www.not.iac.es/CCD-world.

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