Highlights of "Scientific Detectors Workshop 2002" The workshop of (in)famous characters in the detector community

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ABSTRACT

This paper provides an overview of the "Scientific Detectors Workshop 2002", a 5 day meeting held on the Big Island of Hawaii in June 2002. The purpose of this workshop, which is held every 3 years, is to bring together the leading scientists and engineers working in the field of optical and infrared detectors. The 125 participants came from 14 countries on 6 continents and included representation from every major detector designer / manufacturer and 27 astronomical observatories.

This paper is a synthesis of the information presented at the workshop. In order to provide context, we begin with an introduction to the use of optical / IR detectors in astronomy and the basic steps in light detection. We then present the major developments in optical and infrared detectors. We conclude with information about the 2002 workshop format and give advance notice of the next workshop, scheduled for 2005.

1. HISTORY OF THE WORKSHOP

This workshop started in 1991 when scientists and astronomers gathered at the European Southern Observatory (ESO) to discuss the state-of-the-art of CCD detectors for astronomy. The workshop re-convened in Garching in 1993, 1996 and 1999. The 1991-99 workshops have been given the moniker the "ESO CCD workshops".

Since 1999, the communities that work with optical and infrared detectors have become increasingly intertwined. Thus, the 2002 workshop was expanded to include all focal plane arrays that detect radiation from the ultraviolet (0.3 μm) to the mid-infrared (20 μm). The name of the workshop has changed accordingly – it is now called the "Scientific Detectors Workshop" [1]. The 2002 workshop also moved its location to Hawaii, where a great variety of informal activities kept the meeting attendees energized and interested.

The next workshop will take place in 2005, at a location that will be determined in mid-2003. No matter where the workshop is held, we plan to continue the tradition of providing an excellent environment for the leaders in detector technology to exchange information and enjoy each other's company.

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Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, Masanori Iye, Alan F. M. Moorwood, Editors, Proceedings of SPIE Vol. 4841 (2003)

2. INTRODUCTION TO THE USE OF OPTICAL AND INFRARED DETECTORS IN ASTRONOMY

Detectors are a critical technology in astronomy, since most astronomical information comes from the detection of light. A majority of astronomical science is done with optical and infrared light which, for ground-based observations, extends from 0.3 μm to 20 μm.

Optical and infrared detectors have become nearly perfect detectors of electromagnetic radiation, with over 90% quantum efficiency and very low detector noise. In addition, in the past decade, there have been great advances in the ability to produce large focal plane arrays.

To understand the role of detectors in astronomy, we divide an astronomical observatory into four major parts as shown in Fig. 1.

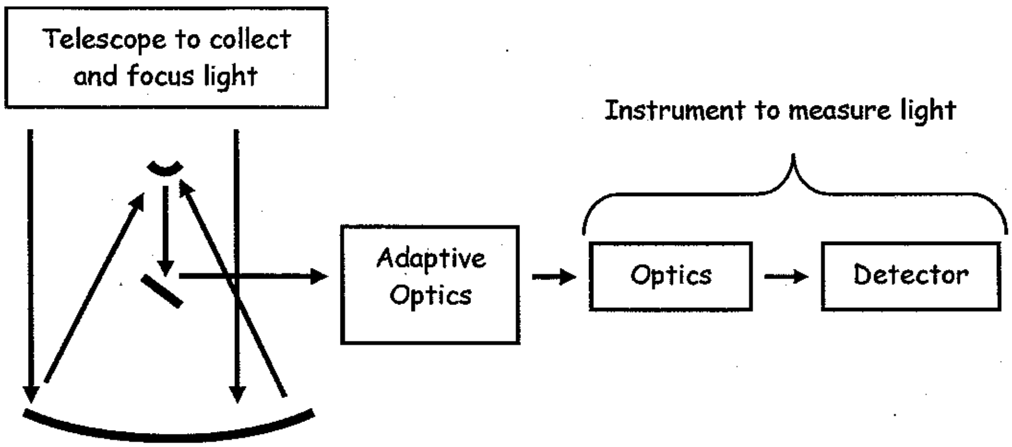


Fig. 1: A ground-based astronomical observatory can be depicted as having four major parts: telescope, adaptive optics (optional), instrument optics, and most importantly, the detector.

The telescope collects and focuses the light. For a ground-based telescope, the image is always distorted, even on good nights, by the Earth's atmosphere. For a large telescope, the atmospheric blurring (or "seeing") can spread the light over an area that is up to 1000 times larger than the diffraction-limited spot. Adaptive optics is now used at many ground-based telescopes to reduce the seeing, although the technology is presently limited to providing good results in the infrared for relatively bright objects, and the correction is only effective over relatively small fields of view (~1 arc min).

The instrument, which is placed at the telescope focal plane, consists of optics and a detector to measure the light. As depicted in Fig. 2, the instrument attempts to measure a three-dimensional data cube – intensity as a function of wavelength and two spatial dimensions on the sky (right ascension and declination).

A major challenge for instrumentation comes from detectors being "colorblind". All optical and infrared detector arrays, from the human eye and photographic film to the state-of-the-art used on astronomical telescopes, can only measure intensity and not color. Thus, a focal plane array is only able to measure a two-dimensional slice of the three-dimensional data cube shown in Fig. 2. The most significant challenge for an instrument designer is figuring out how to most efficiently sample a 2-D portion of the 3-D data cube. There are several ways to select a 2-D portion, such as:

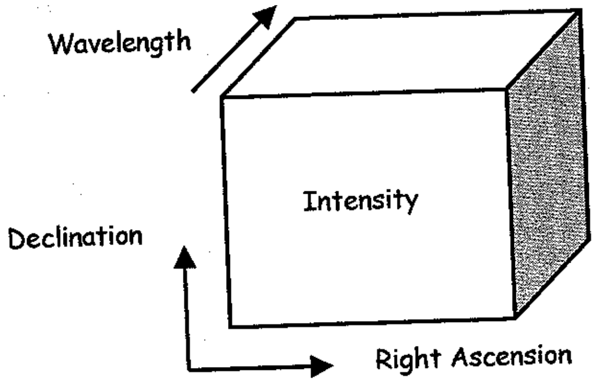


Fig. 2: Three-D data cube that is probed by an astronomical instrument.

1. a filter, which takes an image in a limited wavelength band,
2. a slit spectrograph, which takes a 1-D slice of the sky and disperses the spectrum in the orthogonal direction,
3. a multi-object spectrograph, which spatially filters the image with slits in the image plane and disperses the spectra in the orthogonal direction (in general, none of the slits can overlap in the spatial direction),
4. an integral field spectrograph, which samples a contiguous array of spatial pixels and uses lenses, fibers or mirrors to feed the light to a spectrograph.

3. THE IDEAL DETECTOR, DETECTOR ZOOLOGY & FIVE STEPS OF PHOTON DETECTION

The attributes of an ideal detector and the performance achieved by today's technology are given in Table 1.

Attributes of an ideal detector	Performance achieved by the state-of-the-art
Detect 100% of photons	✓ Up to 99% quantum efficiency
Each photon detected as a delta function	✓ One electron for each photon
Large number of pixels	✓ Over 377 million pixels
Time tag for each photon	☒ No - framing detectors
Measure photon wavelength	☒ No - defined by filter
Measure photon polarization	☒ No - defined by filter
No detector noise	☒ Readout noise and dark current

Table 1: Attributes of an ideal detector and performance achieved by the state-of-the-art detectors in astronomy.

Optical and infrared detectors are nearly ideal in several ways:

- Quantum efficiency - The peak q.e. of a detector can be nearly perfect, with 99% q.e. achieved at the wavelength for which the anti-reflection coating is tuned.
- Delta function response - Over most of the wavelengths of interest, optical and infrared detectors produce one photoelectron for every detected photon, which provides a one-to-one correspondence between detected photons and photoelectrons.

- Large number of pixels - The largest number of pixels placed in a single detector plane in astronomy is the mosaic of 40 CCDs with 377 million pixels in the wide field of view imager, Megacam, at the Canadian-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii.

However, there are several ways that optical and infrared detectors fall short of being ideal:

- Limited temporal resolution - The focal plane arrays all are inherently framing detectors and accuracy of knowledge of the arrival time of photons is limited to the frame time of the detector. While the frame time can be quite short for adaptive optics detectors (~1 msec), in most astronomical instruments, the frame time is on the order of seconds or minutes, usually adequate for most astronomical science, but not all.
- Colorblind - As stated above, the focal plane arrays in use today can only detect intensity, and wavelength must be defined by a filter or the optics of the instrument.
- Polarization blind - Polarization cannot be detected, but must be defined by a filter.
- Detector noise - The two most significant noise sources of a detector are readout noise and dark current.
    - Readout noise can be as low as 2 electrons (e^-) rms for CCDs at slow readout rate (50 kHz). For infrared detectors, the single read noise is 15 e^- for the best detectors, but this noise can be reduced to 3-5 e^- with multiple (or Fowler) sampling since IR detectors have non-destructive readout structures. In general, the readout noise of most detectors increases with faster readout.
    - Dark current for a detector depends on the maximum wavelength sensitivity, the temperature of the device, the size of a pixel, and quality of materials. For devices with longer wavelength cutoff, the smaller "energy gap" results in higher dark current at a given temperature. The higher dark current can be reduced with cooling. CCDs, which are made of silicon, are typically cooled to −110 or −120 °C, reducing the dark current to <2 e^-/pix/hr, low enough to be negligible. For HgCdTe IR detectors that are sensitive to 2.4 μm, cooling to liquid nitrogen temperature (−196 °C) will reduce the dark current to as low as 15 e^-/pix/hr.
- Other detector imperfections - Detectors also exhibit a wide range of other "features" that make these devices less than perfect. A major attribute that describes performance is cosmetic quality. Due to defects in the material or fabrication errors, some pixels of an array can exhibit lower quantum efficiency, and in the worst case, be completely dead. Also, some pixels will exhibit excessively high dark current. In a CCD, an extremely bad pixel can make an entire column useless, and thus, the primary cosmetic measure for a CCD is the number of bad columns. Other deleterious features include fringing, charge diffusion (which blurs the point spread function) and for infrared detectors, amplifier glow.

Emphasis of this paper

In this paper we do not discuss all of the attributes of optical and infrared detectors. Instead, we will concentrate on the three areas where optical and infrared detectors have made the greatest advancements in the three years since the last detector workshop:

- Quantum efficiency (q.e.)
- Number of pixels in a single detector or mosaic of detectors
- New detector architectures and materials

Detector zoology

The optical and infrared detectors discussed at the scientific detector workshop can be organized into a zoology that is presented in Fig. 3. The wavelength regions included in the graph are x-ray, optical (0.3 – 1.1 μm), near infrared (NIR, 1-5 μm) and mid-infrared (MIR, 5-20 μm). *(The wavelength assignment of these regions is not sacrosanct and may be stated differently by other authors.)* For the optical devices, silicon CCDs and CMOS, there are several designers and manufacturers. In the infrared regime of HgCdTe and InSb devices, only Raytheon and Rockwell Scientific have a significant presence.

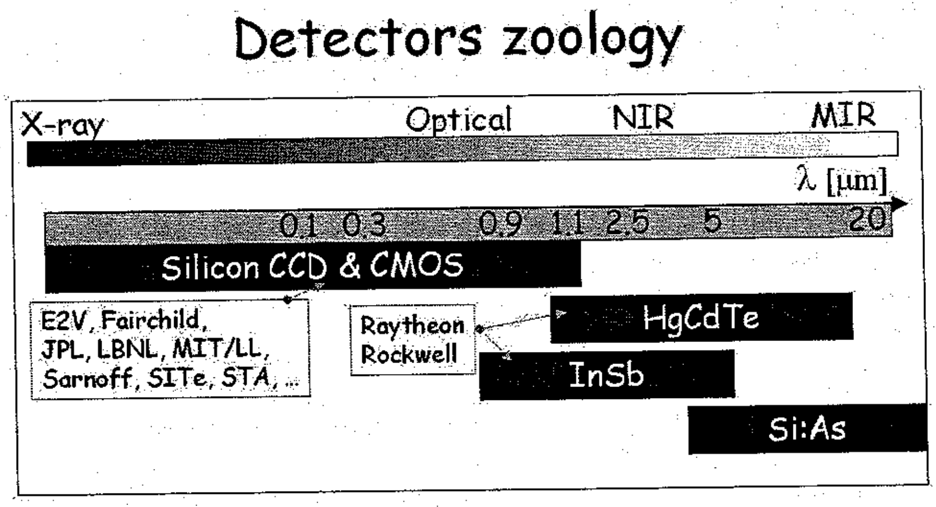


Fig. 3: Optical and infrared detector "zoology". The wavelength region is stated on the first row, with corresponding wavelength in microns shown on the second row. The type of detector and associated manufacturers are shown in the boxes below, which also depict the wavelength coverage possible with each type of device.

Basic steps of photon detection

In order to appreciate the advances made in detectors, it is important to understand the five basic steps in optical/IR photon detection. This delineation follows the framework taught by James Janesick [2]:

1) Get light into the detector (anti-reflection coating).
2) Charge generation (most popular materials: silicon, HgCdTe, InSb).
3) Charge collection (electric fields in the material collect photoelectrons into pixels).
4) Charge transfer (in the infrared, no charge transfer is required / for a CCD, move the photoelectrons to the edge of the detector where the amplifiers are located).
5) Charge amplification & digitization (a noisy process for which CCD amplifiers have the lowest noise / CMOS and IR amplifiers have higher noise).

The first two steps, getting light into the detector and charge generation, are the ones that most affect q.e.. The point spread function (PSF) of a detector is affected by the 3rd and 4th steps (charge collection and charge transfer). Unless proper attention is paid to the PSF of a detector, it can negate the heroic efforts of optical designers who strive to maintain a tight PSF through instrument optics. All five steps affect the sensitivity of a detector, with different steps dominating the sensitivity at different light levels.

4. NEW DEVELOPMENTS IN OPTICAL DETECTOR TECHNOLOGY

In this section, we discuss the advances that have been made in optical detectors in three areas:

1. Quantum efficiency
2. Number of pixels in the focal plane
3. New developments in detector architecture

The optical detectors discussed here are all similar in that they use silicon as the photosensitive material. Silicon processing has been optimized by the semiconductor industry - extremely high quality silicon is mass produced and the equipment for processing silicon wafers is better than required for producing the detectors desired by astronomy. However, standard silicon processing is not concerned with the highest q.e. and lowest noise that is highly prized by astronomy. Since astronomy is a relatively small market, observatories must push industry to address our special needs, resulting in a procurement process that is uncertain and expensive.

Quantum efficiency

Quantum efficiency is the most important attribute of a detector. Quantum efficiency is defined as the percentage of incidents photons that are detected. The factors that lead to less than 100% q.e. are:

- Reflection at the detector surface
- Transmission through the detector without absorption
- Absorption in part of the detector where photoelectrons are not collected (e.g. polysilicon gates of a CCD)
- Loss of photoelectrons to traps or dangling bonds

Silicon is an excellent material for the detection of optical light; all absorbed photons will be converted into photoelectrons, with a one-to-one correspondence over the 0.3-1.1 μm band. However, silicon presents a special challenge in that the absorption depth of photons changes tremendously over the wavelength region of interest. The absorption depth is the length of material that will absorb 63.2% of the radiation (1/e of the energy is not absorbed). After two absorption depths, 87% of the light has been absorbed, and after 3 absorption depths, 95% has been absorbed. The absorption depth of silicon is presented in Fig. 4. Note that the horizontal (wavelength) scale is linear and the vertical (absorption depth) scale is logarithmic. The absorption depth varies from less than 10 nm in the UV (0.3 μm) to over 100 μm in the far-red (>1 μm) – over a factor of 10,000 variation in absorption depth! In addition, the index of refraction varies significantly for wavelengths shorter than 450 nm, making it difficult to optimize anti-reflection coatings for broad bandpass.

The short penetration depth of UV/blue photons is the reason that "frontside" CCD detectors have very poor q.e. at the blue end of the spectrum. The frontside of a CCD is the side upon which are deposited the polysilicon wires that control charge collection and transfer. These wires are 0.25 to 0.5 μm thick and they will absorb all UV/blue photons before these photons reach the photosensitive volume of the CCD. For good UV/blue sensitivity, a silicon detector must allow direct penetration of photons into the photosensitive volume. This is typically done by turning the CCD over and thinning the backside until the photosensitive region (the epitaxial layer) is exposed to incoming radiation. A thinned CCD will naturally build up an internal electric field that will pull electrons to the back surface with subsequent loss of photoelectrons. In order to overcome this natural electric field, a "backside passivation" process must be used.

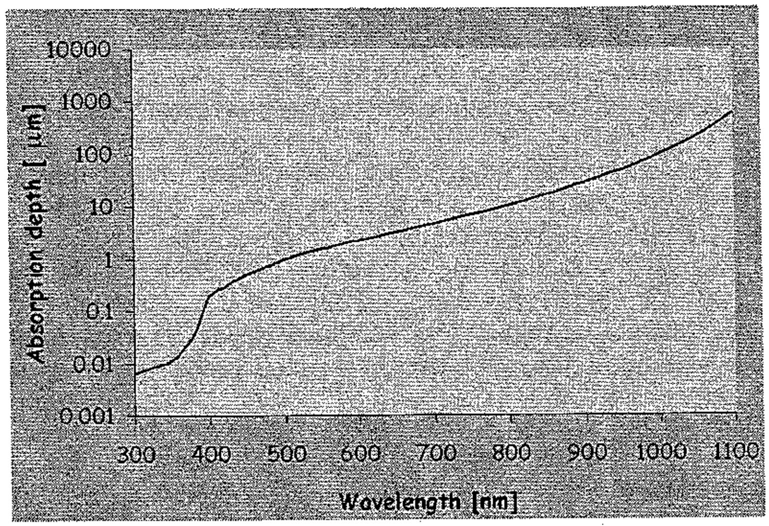


Fig. 4: Absorption depth of photons in silicon.

There are a number of ways to passivate the backside, and three processes were presented at the detector workshop. A relatively old technology is a boron implant followed by laser anneal. In this process, boron atoms are accelerated into the backside of the CCD followed by a laser beam anneal. The annealing process is not perfect since variation in the depth of melt can cause a reduction in UV/blue q.e. and a large variation in q.e. across pixels. This effect is demonstrated in the "flat field" images taken in the UV and blue with the E2V and MIT Lincoln Laboratory (MIT/LL) 2Kx4K devices (see Fig. 5).

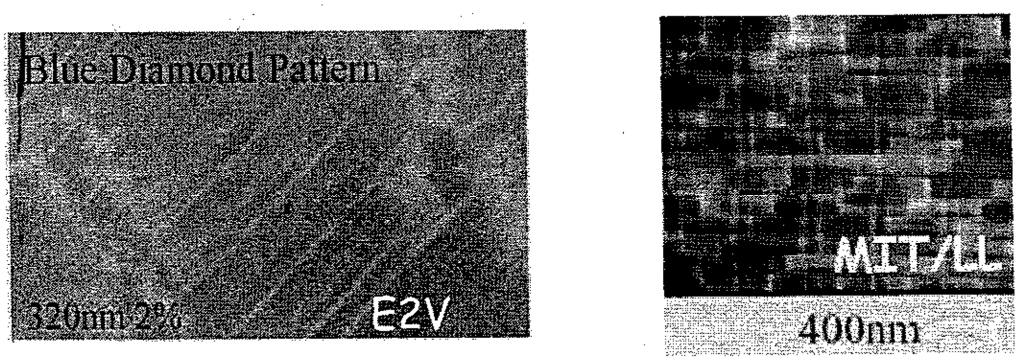


Fig. 5: Flat field images taken at 320 and 400 nm on the E2V and MIT/LL devices. Only a portion of the 2Kx4K detectors is shown. Data provided by Cyril Cavadore (ESO).

A more recently developed passivation process is one that was originally demonstrated at JPL and further developed by Mike Lesser and his colleagues at the University of Arizona. In this process, a special coating is placed on the back surface of the CCD. Years ago, this coating required special handling to "charge" the backside, but the U. Arizona has developed new coatings that do not require special handling or protection. Since this coating does not penetrate the silicon surface, it provides a passivation layer that is effectively zero thickness and thus, with proper anti-reflection coating, will produce extremely high q.e. in the UV. This so-called "Lesser process" has been licensed by Fairchild and SITe and has been demonstrated to give very high q.e. as shown in Fig. 6.

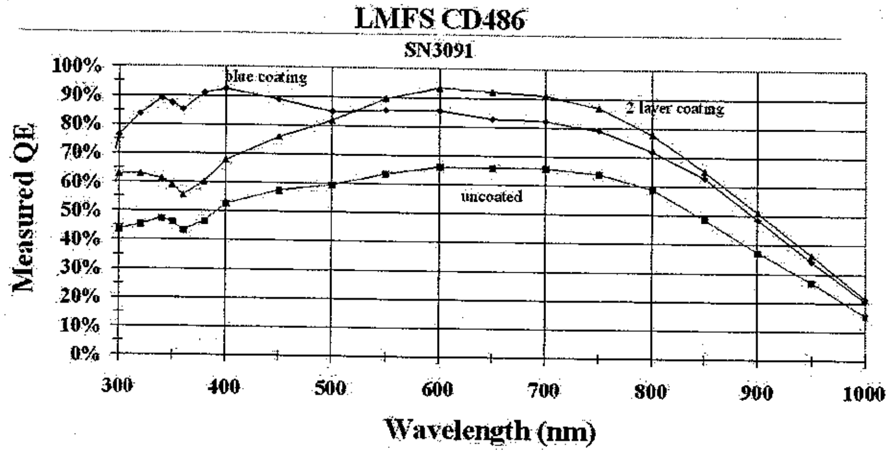


Fig. 6: Quantum efficiency of a Fairchild Imaging CCD, with "Lesser" process - no AR coating and coatings optimized for UV and broadband (Mike Lesser, U. Arizona).

The Lesser process is used to backside passivate n-channel CCDs, which collect photoelectrons into pixels. There are also p-channel CCDs that collect and move holes (as opposed to electrons). In these devices, the backside must be positively charged to push the holes toward the collection wells in the pixels. A process analogous to the Lesser process is used to produce a charged region at the backside of the CCD, however in this case a relatively large potential (~40 volts) must be used to provide the positive voltage at the backside.

The most recently developed process for backside passivation is the growth of a very thin layer of silicon with boron on the backside of the CCD, using molecular beam epitaxy (MBE). Originally pioneered by a group at JPL, a similar approach has been refined by MIT/LL. The MBE layer, which can be only a few nm thick (about 20 atomic layers), can produce high q.e. in the UV region, as shown in Fig. 7.

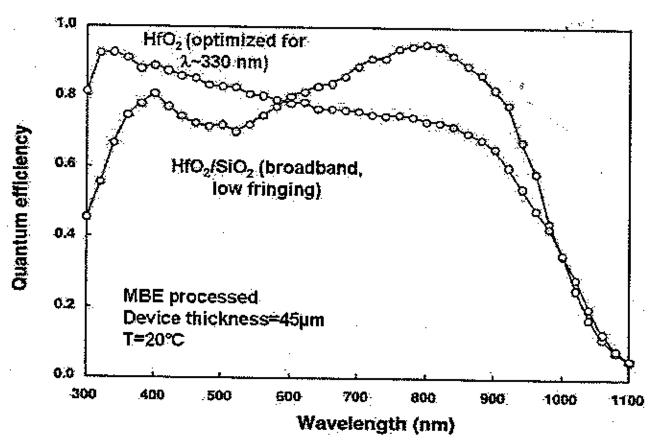


Fig. 7: Quantum efficiency of MIT/LL CCDs, with the MBE backside passivation process and AR coatings optimized for UV and broadband (Barry Burke, MIT/LL).

The advantage of the thin layer processes (Lesser, p-channel and MBE) is that they can produce extremely high q.e. in the UV and also very uniform flat fields in the UV/blue. To the best of our knowledge, the backside passivation processes used by various manufacturers is shown in Table 2.

	Backside Passivation Process		
CCD manufacturer	Boron implant & laser anneal	"Lesser" or similar process	MBE
E2V	X		
SITe		X	
Fairchild Imaging		X	
Sarnoff	X		
MIT/LL	X	X	X
JPL	X	X	X
STA (Bredthauer)		X	
LBNL (p-channel)		X - p-channel	
Max Planck (p-channel)		X - p-channel	

Table 2: Backside passivation processes used at various CCD manufacturers. (Any error is this table is solely attributable to the authors.)

It became evident at this detector workshop that a large number of CCD manufacturers are using the Lesser or similar process. This is a significant and quiet change in the technology of this community. However, we would remiss if we did not note that E2V, the largest producer of scientific CCDs for the astronomical community, still retains the boron implant and laser anneal process, with excellent q.e. performance in the UV. An E2V CCD recently delivered to the Keck Observatory has 63% q.e. at 350 nm and 77% q.e. at 400 nm, with photo-response non-uniformity of only 1.3% at 400 nm. The AR coating on this device is single layer hafnium oxide (HfO_2), and we estimate that the coating is 30 to 40 nm thick.

The backside passivation processes presented above are targeted at high q.e. in UV and blue wavelengths. In the middle of the optical band, the penetration depth of photons is a few microns and it is relatively easy to obtain high q.e. – the photons penetrate beyond the depth of polysilicon wires and backside passivation layers, but do not pass all the way through the CCD. CCDs have been typically made with thickness of about 15 microns, so that photons with wavelengths of 0.5 to 0.7 μm can be detected with high efficiency. However, at the red end of the optical spectrum, the photon absorption depth can quickly exceed the thickness of the CCD. The absorption depth at 800, 900 and 1000 nm is respectively 11, 29 and 94 microns.

In order to provide higher q.e. at the red end of the spectrum, two approaches have been taken. One approach is to produce a very thick n-channel device. In order to do this, the resistivity of the silicon must be made relatively high, about 5,000 to 10,000 Ω-cm (as opposed to the 20-100 Ω-cm material used in "standard" n-channel CCDs). The higher resistivity is required for greater penetration depth of the fields produced by the frontside polysilicon wires (penetration depth is proportional to the square root of the resistivity). These "thick" high resistivity CCDs have been developed for detection of soft x-rays with space satellites and can be procured from E2V and MIT/LL. A demonstration of the red q.e. possible with 45 μm thick "high-ρ" CCD is shown in Fig. 7.

A second approach to high q.e. in the far-red is the p-channel device. Development of this type of detector is led by Steve Holland and his colleagues at Lawrence Berkeley National Laboratory (LBNL). P-channel devices collect and move holes instead of electrons. These p-channel devices are 300 μm thick with 15 μm square pixels, each pixel is the shape of a "skyscraper". Amazingly, the PSF of these devices is as good as 15 μm thick n-channel devices, due to the steep voltage gradient produced by a backside charge of 40 volts. The p-channel devices produce very high q.e. at the red end of the optical region, with 90% or higher q.e. for 700-900 nm and 60% q.e. at 1000 nm. The best demonstration of the performance of these CCDs was done by NOAO at the Kitt Peak 4-meter RC spectrograph. Comparing images of the Dumbbell Nebula taken with the LBNL device with those taken by ESO's FORS I spectrograph (with a Tektronix CCD) is similar to comparing infrared and optical imagery - the LBNL device is able to "see" through the dust shell at the longer wavelengths. The images cannot be reproduced in these proceedings with sufficient quality. To view them, we direct you to the September 2001 NOAO newsletter (http://www.noao.edu/noao/noaonews/sep01/pdf/) and the LBNL CCD Web site (http://www-ccd.lbl.gov/).

The p-channel devices do suffer from one significant drawback. Due to their 300 μm thickness, the devices are great detectors of many types of radiation, including cosmic rays and radiation created by terrestrial sources. In fact, a dark image can look like an image from a particle physics experiment (see Fig. 8). Efforts are underway to find the best way to shield the detector from terrestrial radiation and to most efficiently remove the unwanted radiation events from the data. In addition, the LBNL team is working to "commercialize" the production process, so as to be able to fabricate the large number of detectors, half billion pixels total, which may be needed by the SuperNova Acceleration Probe (SNAP) satellite. SNAP is a proposed space mission with a wide field of view optical/IR imager to detect type Ia supernovae and measure the effect of dark energy on the acceleration of the universe.

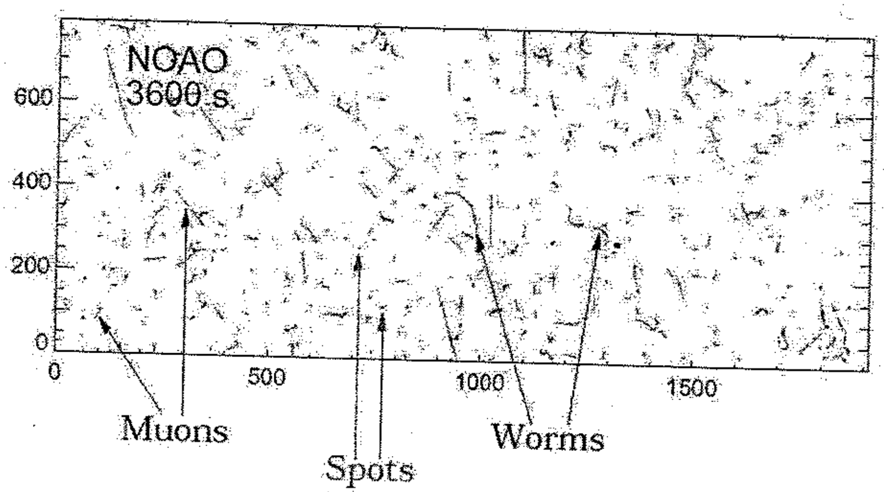


Fig. 8: One hour dark image from LBNL p-channel CCD with host of radiation events. Figure provided by Don Groom (LBNL).

The challenges of achieving high q.e. over the 0.3-1.1 μm band is summarized in Fig. 9, which shows the optical absorption depth of photons in silicon with the range of thickness of different regions of a CCD. Figure 9 captures all of the information needed for understanding the q.e. of silicon CCDs. We call it "the beautiful plot".

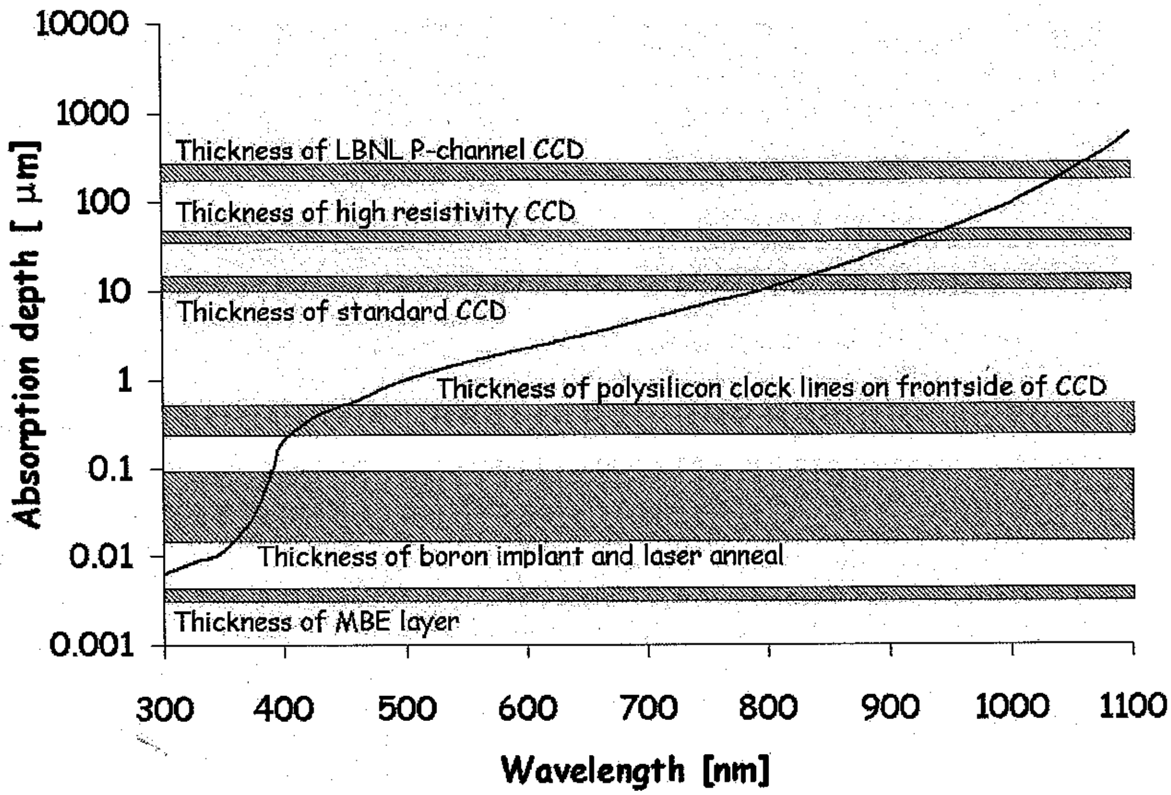
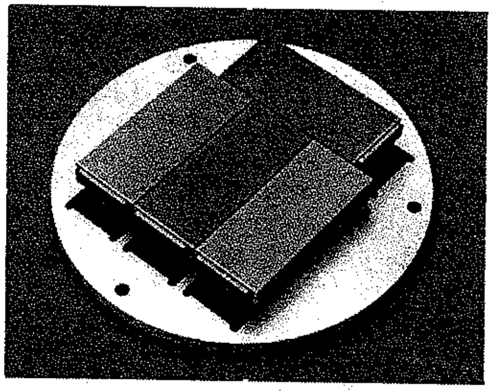


Fig. 9: Optical absorption depth of photons in silicon with the thickness of different regions of a CCD overlaid.

Large number of pixels in the optical focal plane

There is always a trade-off between producing large CCD devices and mosaicking these devices to produce a larger focal plane. The larger a CCD that is produced, the lower the yield of the production process. Several CCD producers have settled on a 2Kx4K, 15 μm pixel device as the "standard" size for their production, including E2V, SITe and MIT/LL. *(Note that the first dimension in the CCD size denotes the length of the serial register.)* E2V also produces a 2Kx4.5K, 13.5 μm pixel device as a "standard" size. The motivation behind the 13.5 μm pixel dimension is that 2Kx13.5 μm is the largest width of photomask that can be exposed with the E2V production equipment. For larger arrays of pixels, all three manufacturers have 4-side buttable packages that can be combined into large mosaics of pixels. In Fig. 10, the E2V devices are shown in 4-chip and 40-chip mosaics. The latter is the largest astronomical array ever developed, the 377-million-pixel Megacam prime focus imager at the CFHT.

Eventually, the CFHT Megacam will be dwarfed by the Large Synoptic Survey Telescope (LSST) focal plane. This 8.4-meter telescope, which aims to image the entire visible sky every 3-4 clear nights, has a focal plane of 7 square degrees with 2100 1Kx1K devices - over 2 billion pixels in a single array, which will be read out in 2 seconds.



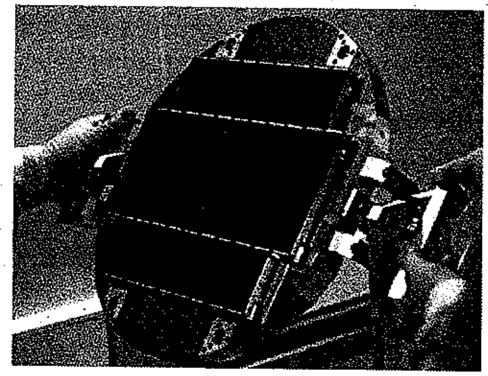
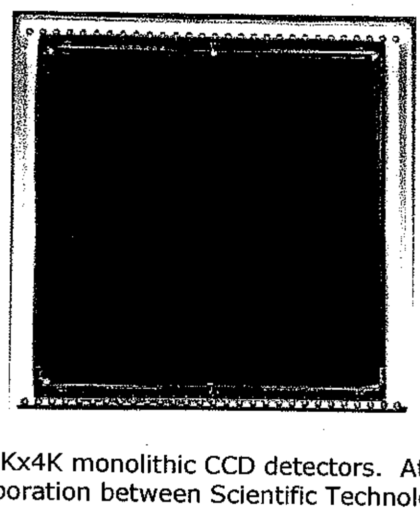


Fig 10: E2V 2Kx4K, 15 µm devices in a 4-chip mosaic for the Large Binocular Telescope (LBT) and E2V 2Kx4.5K, 13.5 µm devices in a 40-chip mosaic for CFHT (Paul Jorden, E2V).

The primary disadvantage of a mosaic is the dead region between detectors, which can be as few as 20 pixels to as many as 100 pixels wide, depending on the skill and nerve of the mosaic integrator. For an imager, this is not a significant drawback, since multiple images must be taken with telescope dither to compensate for the dead columns of the CCDs. However, for a spectrograph this is not desirable, especially for a spectrograph with a 4Kx4K image plane. There are many instruments where a 4Kx4K detector would be ideal – examples are the low resolution spectrograph / imagers on the Keck and VLT telescopes (LRIS and FORS, respectively) and the high resolution spectrograph of the VLT (UVES). After years of requests from the major observatories for a 4Kx4K device, Fairchild Imaging presented data from such a device at the workshop. The CCD485 package, shown in Fig. 11 is the result of this development. In parallel, Semiconductor Technology Associates (Bredthauer) and the University of Arizona have collaborated to design a wafer with two 4Kx4K devices on a single wafer (see Fig. 11). These devices, which have yet to be installed in a facility instrument at an observatory, should become popular once they have been fully demonstrated, especially if they deliver the q.e. that is associated with the Lesser process.



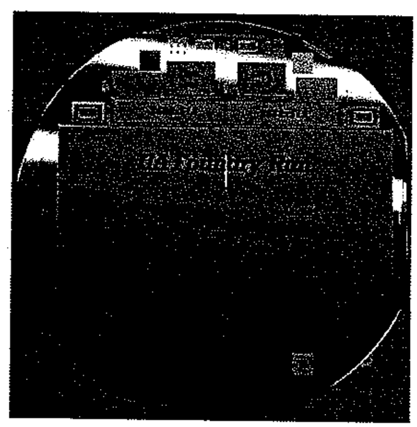


Fig 11: 4Kx4K monolithic CCD detectors. At left is the Fairchild Imaging device, and at right is the result of a collaboration between Scientific Technology Associates and the U. Arizona (Mike Lesser, U. Arizona).

Fairchild Imaging has gone far beyond a 4Kx4K device and has produced the largest monolithic detector in the world, a 9Kx9K, 8.75 µm pixel imager that is used for surveillance applications.

This device, shown in Fig. 12, has an 80.6 mm square image area and can be read out in 1 sec with 25 e⁻ noise (8 port, each read at 25 MHz). Unfortunately for astronomers, this device only comes in a front-illuminated version with q.e. limited to 30% over the 0.5-0.8 μm band.

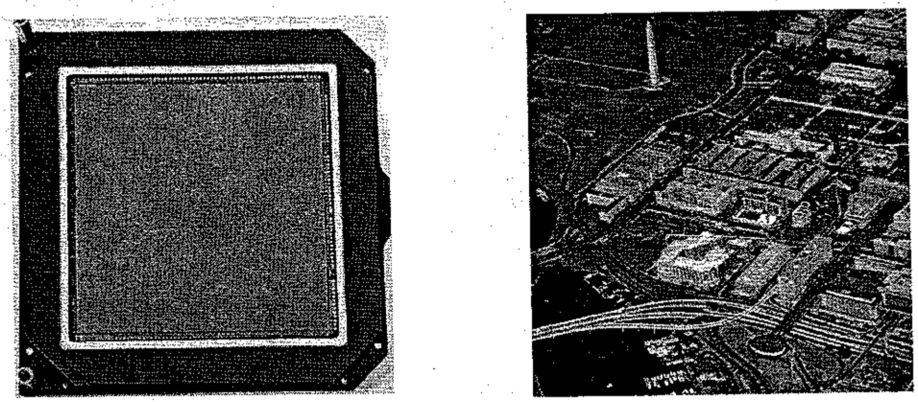
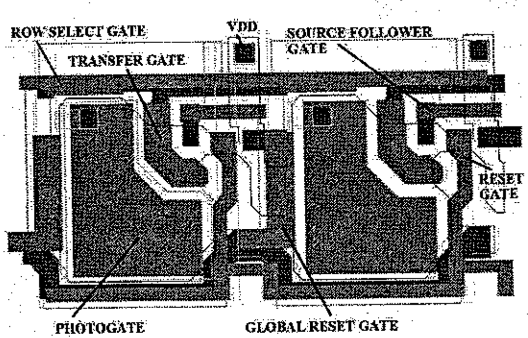


Fig. 12: Fairchild 9Kx9K monolithic CCD focal plane array, on left, with example image at the right. Sadly, this device only comes in a frontside illuminated version. Paul Vu (Fairchild Imaging).

New developments in optical detector architecture

The CCD has had a nice run, but a war of the worlds is beginning with CMOS devices. CMOS stands for "Complimentary Metal Oxide Semiconductor", which is the same technology used for the fabrication of the multiplexers used in infrared focal plane arrays (to be discussed in the next section). In a "standard" optical CMOS detector, the CMOS structure contains the photosensitive area; every pixel has both a photogate and the circuitry associated with the pixel readout. Since each CMOS pixel requires a minimum of three MOSFETs (metal-oxide-semiconductor field effect transistors), as shown in Fig. 13, and the MOSFETs are optically dead, the q.e. of a CMOS device is inherently less than a CCD. In addition, lower readout noise requires additional MOSFETs, which further reduces fill factor.



6T PHOTO GATE CMOS 10 um PIXEL

Fig. 13: Geometry of a CMOS pixel. The MOSFETs required for pixel operation are dead areas that are not sensitive to light, decreasing quantum efficiency. Courtesy of James Janesick (Sarnoff).

However, improvements are being made to CMOS detectors and it is important for the astronomical community to pay attention to this rapidly developing technology. At the detector workshop, James Janesick, who has turned his attention from CCDs to CMOS, gave this assessment of the merits of CCDs and CMOS:

- The two technologies will coexist.
- CCDs presently deliver the best performance in most areas, including q.e., pixel crosstalk, dark current, read noise, linearity and dynamic range.
- CMOS is a much easier device to operate, since it can have fully integrated control electronics on-chip, including analog-to-digital (A/D) conversion.
- CMOS is superior to the CCD in high-speed applications and radiation hardness.
- For CMOS to compete scientifically, major developments are required.
- Hybrid sensors that combine CMOS and CCD are ramping up quickly.

Vyshnavi Suntharalingam of MIT/LL presented CMOS/CCD technology that is being developed at MIT/LL. As shown in Fig. 14, the back-illuminated SOI-based imager (silicon-on-insulator), combines CCD backside illumination with 100% fill factor with a single-pixel CCD type transfer to a CMOS structure at the frontside of the device. MIT/LL has tested a 128x128 pixel device and is developing a 640x960 device that will include on-chip timing, clock drivers and A/D converter.

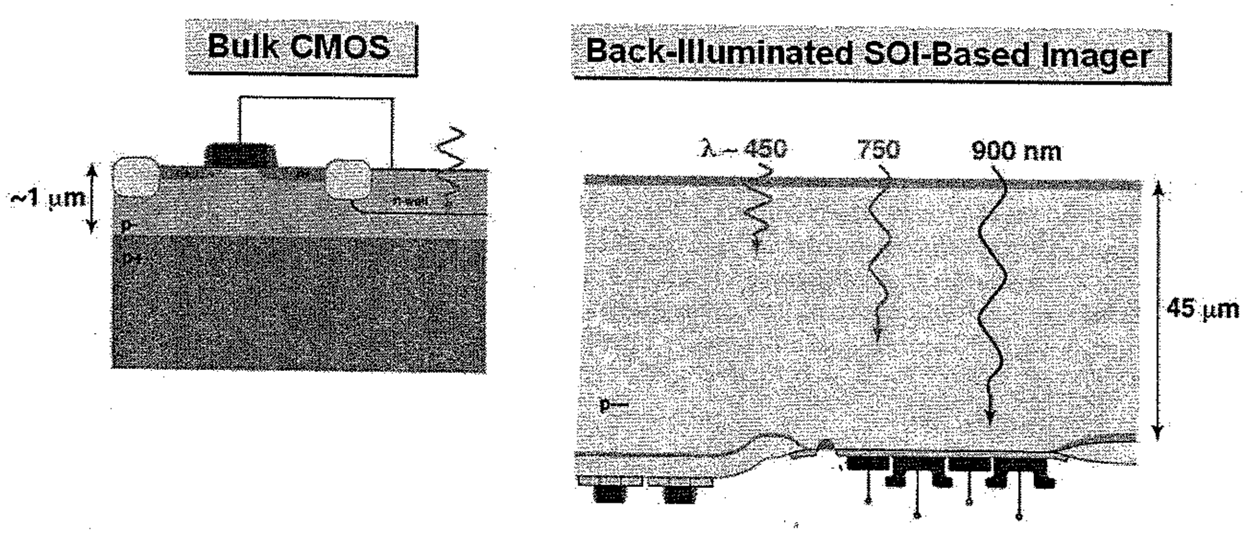


Fig. 14: Structure of a SOI-based imager pixel compared to a standard CMOS pixel.
Figure provided by Vyshnavi Suntharalingam (MIT/LL).

Another major development in optical detectors is being pursued by Rockwell Scientific. Lester Kozlowski and colleagues are using the same hybrid detector technology used for IR arrays to mate silicon multiplexers with a silicon photosensitive material. This hybrid silicon detector, entitled "HyViSI" (Hybrid Visible Silicon Imager) by Rockwell, combines the best features of CCDs with CMOS, without the differential temperature effects that plague IR arrays. Rockwell has demonstrated peak q.e. of 86% with excellent far-red response and 3 electrons readout noise on a 2Kx2K device. This technology may advance rapidly and the astronomical community should pay attention to developments in this area. The HyViSI Web site (http://www.rockwellscientific.com/imaging/hyvisi/index.html) should be consulted for the latest information.

Compared to CMOS, SOI-based imagers and HyViSI, modifications to CCD architecture may seem trite, but there is one very significant development presented at the detector workshop that should be highlighted. John Tonry, of the Institute for Astronomy (U. Hawaii), presented an excellent paper on the orthogonal transfer CCD (OTCCD) that can be used to provide "on-chip" tip/tilt correction. The OTCCD, developed by MIT/LL, allows charge to be moved in two orthogonal directions on the CCD – it is not limited to movement in one-dimension as for other CCDs. For moderate-sized telescopes, atmospheric tip/tilt can significantly degrade image quality. John Tonry presented results where the OTCCD was used to improve seeing from 0.59 arc sec to 0.45 arc sec with a 7 Hz update rate. The optimum tip/tilt correction will vary across the sky so John Tonry and his colleagues are working with Barry Burke of MIT/LL to produce a 4Kx4K OTCCD with independently controlled 512x512 pixel regions, shown in Fig. 15.

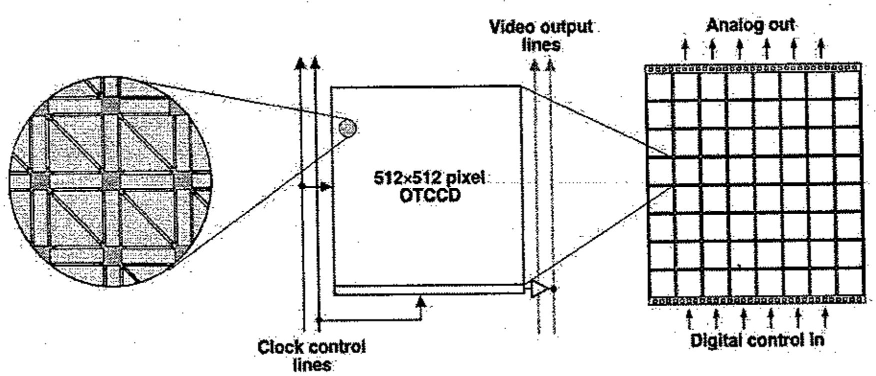


Fig. 15: Architecture for a 4Kx4K OTCCD with independently controlled 512x512 pixel regions. Figure Courtesy of the Pan-STARRS project (IfA, U. Hawaii).

The project that will use these detectors is called Pan-STARRS and more information can be found at (http://www.ifa.hawaii.edu/pan-starrs/). The complete system is planned to be four 1.8- to 2-meter telescopes, each with a mosaic of 64 4Kx4K OTCCDs, totaling more than 4 billion pixels. Each array is to be read out in 2 seconds with 3 electrons read noise, a data rate exceeding that planned for the LSST.

5. NEW DEVELOPMENTS IN INFRARED DETECTOR TECHNOLOGY

Please refer to the associated paper by Finger and Beletic [3] for more information on infrared detectors discussed at the workshop.

The recent developments in infrared detectors are primarily in the areas of:

- Variation of wavelength cutoff for HgCdTe
- Large number of pixels in the focal plane
- Electronic developments - on-chip guiding, application specific integrated circuit

Before we begin discussing infrared detector technology, let's remind ourselves of the architecture of IR focal plane arrays. Figure 16, from Ian McLean [4], presents the structure of scientific IR arrays used in astronomy. The photosensitive material is bonded to a silicon multiplexer (CMOS) by an array of indium bump bonds. The choice of photosensitive material defines the wavelength sensitivity of the detector. With modern silicon processing, it is possible to make fully tested CMOS arrays of whatever size is desired. The limit to the size of an IR detector is set by the availability of substrate material and the fabrication process c mating the photosensitive substrate to the multiplexer.

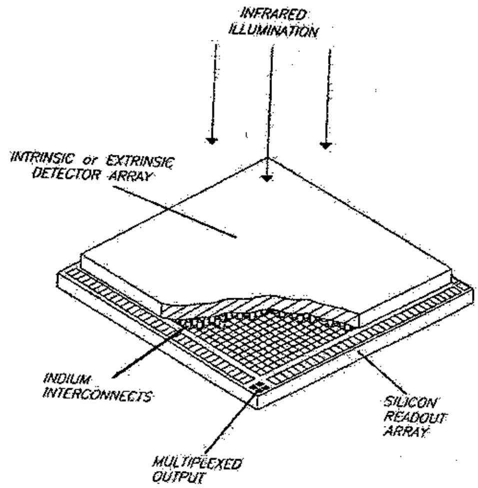


Fig. 16: Schematic of the architecture of IR focal plane arrays used in astronomy (Ian McLean, UCLA).

In the previous section on optical detectors, a significant amount of discussion concentrated on the challenges and progress in producing high q.e. across the wavelength range of 0.3 to 1.1 µm. The difficulty is due to the large variation in photon absorption depth in silicon and also the rapid variation of index of refraction for wavelengths shorter than 450 nm. In the infrared, life is much easier. Essentially all photons are absorbed within the first 10 microns of material and the index of refraction is relatively constant across the wavelengths of interest. An example of this is presented in Fig. 17, which shows the relatively constant q.e. across the 1-2.5 µm wavelength region, with peak q.e. of 84% in the K-band.

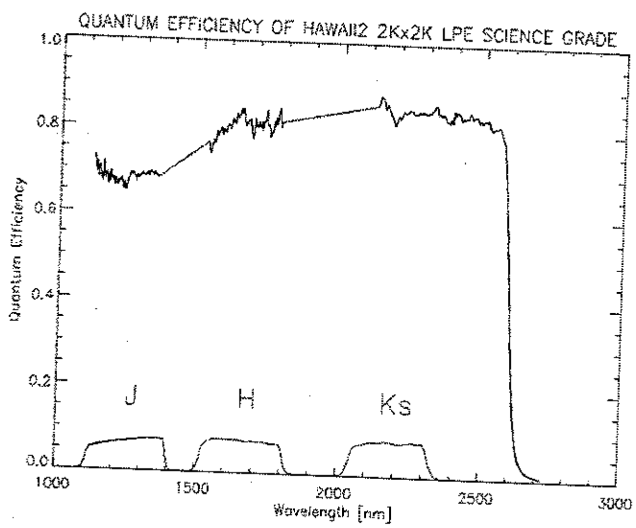


Fig. 17: Quantum efficiency of the Hawaii-2 2Kx2K array, science grade with AR coating.

Figure presented by Rockwell Scientific, data provided by Gert Finger (ESO).

Not all infrared arrays are delivered with anti-reflection coatings. Typically, the q.e. is 60% without AR coating and about 80% with AR coating.

The two materials used most often for scientific detectors in the near-infrared (to 5 μm) are Mercury-Cadmium-Telluride (HgCdTe) or "Mer-Cad-Tel" and Indium Antimonide (InSb) or "Ins-B". For longer wavelengths, arsenic doped silicon (Si:As) is the material of choice. The primary material property is the energy gap (E_g) between the valence band and the conduction band. For an electron to be excited by incident radiation, the photon energy must be greater than the energy gap, which is usually expressed in electron-volts. The energy gap also corresponds to a cutoff wavelength (λ_c), which is the longest wavelength with enough energy to excite electrons across the energy gap. The energy gap and cutoff wavelengths for the materials discussed in this paper are listed in Table 3.

Material Name	Symbol	E_g (eV)	λc (μm)
Silicon	Si	1.12	1.1
Mer-Cad-Tel	HgCdTe	1.00 - 0.09	1.24 - 14
Indium Antimonide	InSb	0.23	5.9
Arsenic doped Silicon	Si:As	0.05	24

Table 3: Optical / IR detector materials, symbols, energy gap and cutoff wavelength.

It is possible to customize the cutoff wavelength of $Hg_{1-x}Cd_xTe$ by varying the ratio of Mercury and Cadmium. For instance, if a user only wishes to detect light out to a wavelength of 1.6 μm (through the J band, see Fig. 17), it is much easier to build an instrument and detector system if longer wavelength photons cannot be detected. This allows the instrument to be operated warmer. Conversely, it may be desirable to detect photons out to a wavelength longer than the 5.9 μm cutoff of InSb material. At the detector workshop, Rockwell Scientific presented data on their experiments with modification of the band gap of HgCdTe.

In parallel, Raytheon Infrared Operations (RIO) presented data on their extensive experience with HgCdTe. RIO, which formerly was SBRC (Santa Barbara Research Center), is sometimes mistakenly associated as only having InSb experience, a mistake that should not be made by the astronomical community as a whole.

<u>Large number of pixels in the infrared focal plane</u>

Both Raytheon and Rockwell have been focusing on efforts to produce larger monolithic devices and being able to mount these devices on 3- and 4-side buttable packages. Both companies presented 2Kx2K devices that will soon complete development and commence production.

The Rockwell HgCdTe 2Kx2K originally was produced in 1998 as the Hawaii-2. A more recent version is named Hawaii-2RG: the "R" denotes special circuitry on that enables the user to do a better job of bias subtraction, and the "G" means "guide mode" due to the ability to rapidly readout sub-arrays of the chip for the guiding function.

The Raytheon HgCdTe 2Kx2K device is called Virgo and Raytheon's InSb 2Kx2K device is called Orion. Virgo is mounted in a 3-side buttable package (enabling a 4Kx2nK mosaic), while Orion was presented in a 2-side buttable package (enabling a 4Kx4K mosaic). Raytheon projected that the limit to monolithic devices will be set by the availability of detector substrate. They do not foresee individual detectors larger than the 4Kx4K HgCdTe and InSb devices they expect to produce in 2004.

At present, to make IR arrays larger than 2Kx2K, the user needs to mosaic detectors as is done for optical arrays. Several observatories presented plans for 4Kx4K infrared focal plane arrays using this approach.

For detection of mid-infrared light, out to 20 μm, Raytheon produces a 1Kx1K Si:As (arsenic doped silicon) impurity band conductor that is sensitive from 2 to 26 μm.

Electronic advancements – on-chip guiding and ASICs

Rockwell presented two significant developments in electronics for IR arrays.

The "guide mode" enables the user to read out a sub-array as many times as desired while integrating light on the rest of the array. This will be useful for imaging a bright field star to operate a tip/tilt mirror system to stabilize the image on the array. Incorporating this feature in the science path simplifies the design of instruments and avoids non-common path errors between a guide camera and the science array. Rockwell presented images that demonstrated that the guide mode does not produce electronic artifacts in the long exposure data.

A second development presented by Rockwell at the detector workshop is an Application Specific Integrated Circuit (ASIC) that is designed specially for the Hawaii-2RG. As shown in Fig. 18, the ASIC, which mounts below the IR array, will incorporate all of the functions that are usually associated with "detector head electronics". When this advance becomes fully functional, a focal plane array will become a "digital detector" with a simple "take frame" signal in with digital data out. The same could be done for optical detectors in the future.

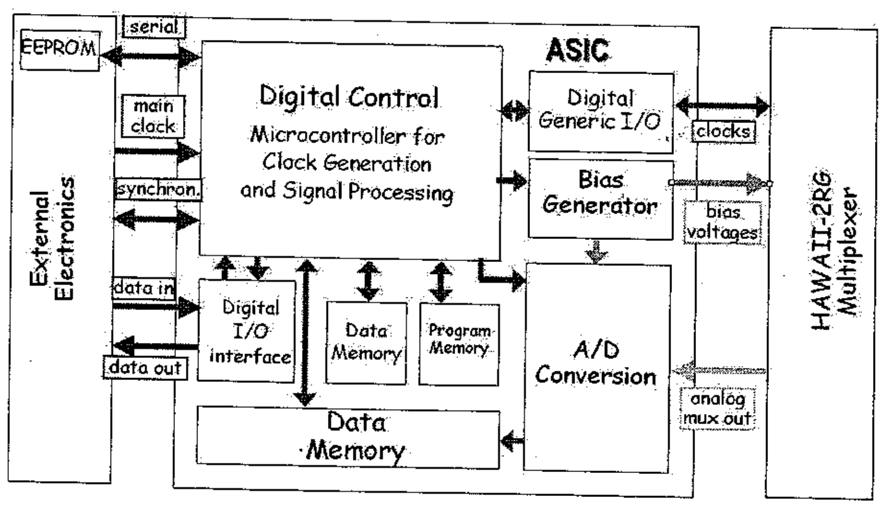


Fig. 18: Schematic layout of the Rockwell Scientific ASIC for optical / IR hybrid arrays. Diagram courtesy of Lester Kozlowski (Rockwell Scientific).

6. SUMMARY OF STATE-OF-THE-ART OF OPTICAL / INFRARED DETECTORS

The previous sections gave a broad overview of the state-of-the-art of optical and infrared detectors. In our view, the major news from the scientific detector workshop is as follows:

- There are several possible sources for optical focal plane arrays, but only two major sources for scientific infrared arrays (Rockwell and Raytheon).

Optical

- Backside passivation of CCDs is gradually being done by more groups with the so-called "Lesser method" – both SITe and Fairchild Imaging have licensed the process and MIT/LL is experimenting with a variation of the approach. This is a significant change in direction of the community.
- The MBE process has been demonstrated by MIT/LL to produce an extremely thin passivation layer that provides exceptionally high UV q.e. The community is waiting to see how MIT/LL proceeds with this technology development.
- The p-channel device from LBNL produced impressive results at the Kitt Peak National Observatory. This "very thick" CCD gives very high red q.e. at the expense of increased dark current and increased sensitivity to radiation.
- CCD mosaics are rapidly growing in size (present record is 377 million pixels), with larger arrays expected in the next several years: LSST – 2 billion pixels, Pan-STARRS – 4 arrays of 1 billion pixels each.
- Fairchild has produced a monolithic 4Kx4K, 15 μm detector that is thinned and ready for use in an astronomical instrument. Fairchild has also produced the world's largest monolithic device, a 9Kx9K, 8.75 μm detector than can be read at 1 frame/sec with 25 electrons noise – unfortunately this device is only frontside illuminated with maximum q.e. of 30%.
- There are three types of optical detectors that astronomers should follow for potential use: CMOS is rapidly being improved, with experts like James Janesick now working full-time on CMOS development, (2) SOI-based imagers, which combine the best of CCDs and CMOS, are being developed by MIT/LL, and (3) the hybrid devices being produced by Rockwell – similar in architecture to IR arrays, but with a silicon substrate as the detector material.

Infrared

- In the infrared, both Raytheon and Rockwell are offering 2Kx2K HgCdTe devices and Raytheon is offering a 2Kx2K InSb device. Both companies are making these devices in 2-side and 3-side buttable packages.
- Raytheon is also producing a 1Kx1K silicon doped arsenic (Si:As) impurity conduction band array for detection of radiation at wavelengths to 26 μm.
- Raytheon predicts monolithic IR detectors of 4Kx4K, in both InSb and HgCdTe.
- Rockwell is developing several new advances in the electronics of IR focal plane arrays: (1) a series of extra gates are built into the Hawaii-2RG devices so that the user can do a better job of bias compensation, (2) a guide mode feature is being implemented in the RG devices to allow on-chip tracking of guide stars while integrating the signal of fainter objects, and (3) special purpose ASICs are being developed to mate directly to the detector multiplexers to eliminate the need for detector head electronics.

7. OVERVIEW AND HIGHLIGHTS OF THE WORKSHOP

The "Scientific Detectors Workshop 2002" (SDW2002) was held in Waimea, Hawaii during June 16–22, 2002. Most of 125 participants and their 25 guests were housed in the dormitories of the Hawaii Preparatory Academy, which provided meals, meeting rooms and recreational facilities. Keeping participants together on campus and eliminating the need for travel to/from lodging promoted a relaxed atmosphere with many opportunities for informal discussion.

The participants, who work with optical and infrared detectors, included scientists, engineers, technicians, astronomers and a physical chemist. There was a great wealth of experience present, with some of the participants active in the field for several decades. Participants came from 6 continents, 14 countries, 11 U.S. states, 27 astronomical observatories and every major designer / manufacturer of scientific optical and/or infrared arrays.

The format of the workshop encouraged both formal and informal interaction, combined with other social activities to keep the participants refreshed, energized and engaged. The "formal" sessions included three major activities: oral presentations, poster sessions and roundtable discussions. These presentations and discussions were organized into several general areas:

- detector manufacturers
- observatory status / plans
- instrumentation
- electronics
- detector testing and characterization
- focal plane mosaics
- space missions
- sub-electron noise

There were no parallel sessions and all poster papers were given a 2 minute period to present a summary to the entire group. Poster papers remained on display for the entire week.

Formal sessions were scheduled over 2 full days (Monday and Friday) and 3 half-days. The afternoons of the three half days were used for the following activities: 1) trip to the summit of Mauna Kea with tours of the Keck, Subaru, Gemini and CFHT observatories; 2) sports afternoon with choice of basketball, horse riding, hiking or a trip to the beach; 3) trip to the best snorkeling spot on the Big Island (Kealakekua Bay), followed by paddling in outrigger canoes, volleyball, Frisbee and a beach barbeque.

On three of the evenings during the week, we traveled off-site for dinner. The Paniolo (cowboy) night tested the participants' coordination with mechanical bull riding and line dancing. The formal conference dinner was outdoors at the beach of the Mauna Kea Beach Hotel where we were graced by the presence of talented local hula dancers.

The workshop began on Sunday with a welcoming reception and ended on Saturday. About 35 participants stayed for an extra day, traveling to the Volcano National Park for a guided tour by a local geologist, followed by up close viewing of the lava flowing at night .

While this format may seem like a boondoggle from a distance, it actually is very successful in producing an atmosphere that maximizes exchange of technical information. To be honest, the average participant is a relatively hard core nerd who will continue to discuss detector technology even while on a snorkeling trip or toasting mai-tais to a lovely Hawaiian sunset. Providing breaks from a constant barrage of formal sessions kept the participants energized and engaged with each other. The common experiences shared during the informal activities formed bonds that strengthen professional relationships. This format proved to be very successful in 1999 and even more so this year, so we plan to continue it in future years.

The "nerd" aspect was encapsulated in the workshop theme. Playing upon the recent release of the film based on Tolkien's novels, the workshop theme was "Lords of the chips" with sub-title "Fellowship of the nerds".

The next "Scientific Detectors Workshop" will be held in 2005. The location of the workshop has not yet been decided, since several countries have volunteered to help host it. Amongst the candidate locations are China, Australia, Chile, the Canary Islands, France (Corsica), Italy (Sicily), Germany (Garching), Scotland and Hawaii. "Bids" are welcomed and we will do our best to visit your site personally for a more informed selection ;-)

ACKNOWLEDGMENTS

This workshop was a joint effort of four of the observatories on the island of Hawaii. The Keck Observatory undertook overall coordination with Subaru, Gemini and CFHT providing significant sponsorship. We also thank the Hawaii Preparatory Academy for providing excellent accommodations and service.

The scientific organizing committee (SOC) provided guidance to the program and is reviewing papers for the published proceedings. Our hats go off to this group who also assisted with chairing sessions and selecting award recipients. The members of the SOC are: Paola Amico (Keck), Bruce Atwood (OSU), James Beletic (Keck), Randy Campbell (Keck), Cyril Cavadore (ESO), Mark Clampin (STScI), Jean-Charles Cuillandre (CFHT), Bob Goodrich (Keck), Gert Finger (ESO), John Geary (CfA), Derek Ives (ROE), Klaus Hodapp (IfA), Gerry Luppino (IfA), Ian McLean (UCLA), Tetsuo Nishimura (Subaru), Doug Simons (Gemini), Roger Smith (Caltech), Barry Starr (NOAO), Richard Stover (UCSC) and Lothar Strueder (MP Semiconductor Laboratory).

Many Keck Observatory staff contributed to making this workshop a success and we can not list all here. However, special thanks should be given to Gale Kihoi, who worked long hours before and during the workshop.

We thank the following workshop participants who contributed figures or photographs to this paper: Ken Ando, Barry Burke, Cyril Cavadore, Mark Downing, Don Groom, Olaf Iwert, James Janesick, Paul Jorden, Lester Kozlowski, Mike Lesser, Ian McLean, Peter Sinclaire, Vyshnavi Suntharalingam, John Tonry and Paul Vu.

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