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Introduction to detectors: possible status in 2010–2020

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Abstract. Both optical CCD detectors and infrared detector arrays have steadily evolved over the past 5 years, and have reached very satisfactory levels of quantum efficiency and dark current. Optical CMOS detector arrays have rapidly improved and are beginning to compete with CCD detectors. A new development of great relevance for future instrumentation is the integration of the readout electronics into an integrated circuit in close proximity to the detector, or, in the future, its vertical integration with the detector array and multiplexer. This paper reviews the present status of these technologies and identifies opportunities and risks for the next decade.

Keywords. Instrumentation: Detectors.

1. Introduction: the current market for astronomical detector arrays

A recent survey conducted by Simons & Amico (2005) of the instruments currently in use at major observatories, as well as of instruments in the design process gave an interesting snapshot of the current use of detector arrays.

At present, the majority of astronomical instruments are optical devices, while the total count of infrared (IR) instruments is about half that of the optical ones. Of the infrared instruments, the vast majority are near-infrared (1–5 μm) systems. The total number of mid-infrared (10–20 μm) instruments is an order of magnitude lower.

However, among the instruments under design and construction, the numbers of infrared and optical instruments are almost equal, a testament to the growing maturity of infrared technology and to the high scientific interest in these longer wavelengths. Mid-infrared instruments are still small in number and clearly represent a niche market, reflecting the technical and observational difficulties of ground-based Mid-IR observations.

The most popular format in existing optical instruments is the $2\,\mathrm{k} \times 4\,\mathrm{k}$ (15 μm) Charge Coupled Device (CCD), which is commonly used as the building block of larger mosaic focal planes. For future instruments, individual CCDs in $4\,\mathrm{k} \times 4\,\mathrm{k}$ format and various pixel sizes are gaining in popularity, being used about as often as the $2\,\mathrm{k} \times 4\,\mathrm{k}$ CCD building block. In near-infrared instruments, the $1\,\mathrm{k} \times 1\,\mathrm{k}$ devices dominate in existing instruments with pixels being 27 μm (Aladdin) or 18.5 μm (HAWAII-1) in size, while only a small number already use the newer $2\,\mathrm{k} \times 2\,\mathrm{k}$ devices. For future instruments, the $2\,\mathrm{k} \times 2\,\mathrm{k}$ format dominates and mosaics are becoming increasingly popular, mirroring the trend in optical imagers with about a decade delay. Common pixel sizes for large format infrared arrays are 18 μm and 20 μm.

Today, E2V has the largest market share for astronomical CCDs, while Rockwell provides most infrared detector arrays. However, a number of other manufacturers also have significant market shares. For instruments currently under design, a trend toward further concentration on E2V and Rockwell is evident.

2. Optical CCDs

2.1. *Deep Depletion CCDs*

The design of CCDs, and indeed of any Silicon photodiode, is a struggle with the pronounced wavelength dependence of the photon absorption cross section in Si, a consequence of the bandgap structure of Si, where photon absorption over most of the visible spectral range is an indirect process. Simple, thick CCDs with a thin depletion region are mostly sensitive in the red part of the spectrum while most blue photons get absorbed outside of the depletion region and the charge they generate does not get collected. On the other hand, most far-optical (0.8–1.1 μm) photons don't get absorbed at all. The blue sensitivity problem was solved two decades ago by thinning and backside illumination of the CCDs. However, while these thinned CCDs performed well at short wavelengths, their quantum efficiency at long optical wavelength was still unsatisfactory. In combination with the quantum efficiency problem of most early infrared detectors at short IR wavelengths (1.1–1.4 μm), this led, in effect, to a sensitivity gap of astronomical observations around a wavelength of 1 μm.

In recent years, great progress has been made in fabricating CCDs out of highly pure Silicon so that a deep depletion zone can be generated as described by Kolbe (2005), Bebek *et al.* (2004) and Kamata *et al.* (2004). In such devices, far-optical photons have a high probability of absorption, leading to much improved quantum efficiency at the long wavelength end of the silicon sensitivity range. Blue photons still get absorbed very close to the backside, but even there the electrical field in the depleted region is strong enough to efficiently collect the electrons to the electrodes. Today's deep depletion devices, with typical thickness of 200 μm come close to the ideal detector for optical radiation. Their peak quantum efficiency reaches 90% in the red, and they have sufficient quantum efficiency at around 1 μm to overlap well with the quantum efficiency of today's improved infrared detector materials, so that the one-micron gap in instrument capabilities has now vanished. Pixels in deep depletion devices are much taller (up to 200 μm) than wide (typically 15 μm) and therefore, lateral diffusion of the photo-generated charge on its way to the collection electrodes is a concern. This has been overcome by applying a high voltages, up to 200 V, to the detector substrate, thereby generating a sufficiently high field to direct the electrons to the electrode nearest to the point of photon absorption.

2.2. *CCD size*

The most common size of scientific CCDs today is the $2\,\mathrm{k} \times 4\mathrm{k}$, 15 μm pixel device that forms the building block of most mosaic CCD cameras. This particular size was chosen as a compromise between fabrication yield, which favors smaller building blocks, and integration complexity for mosaics, which favors larger blocks. For the Pan-STARRS project, where ultimately four gigapixel (1.4 Gpixel each) focal planes will be built, the size of the orthogonal transfer array (OTA) (see section 2.5) building block was chosen at $4\,\mathrm{k} \times 4\mathrm{k}$, primarily based on the need to reduce the cost per pixel by an order of magnitude compared to previous large focal planes, and consequently the need to increase the yield of acceptable devices during fabrication.

Some physically larger CCDs are being fabricated, such as the Fairchild Imaging $4\,\mathrm{k} \times 4\,\mathrm{k}$ CCDs with dimensions of about 6 cm × 6 cm, and even $9\,\mathrm{k} \times 9\,\mathrm{k}$ devices with 81 mm × 81 mm physical size, and 8.75 μm pixels have been reported by Vu, Onishi & Potter (2004), Lesser (2004), and Bredthauer & Lesser (2005). For most manufacturers, the limitation to the maximum physical size of CCDs is set by the size of Si wafers that they process, typically 100 mm or 150 mm diameter. However, the yield for the fabrication of physically large CCDs is much smaller than for smaller devices, so that the fabrication of large cameras from large unit CCDs is not practical. For most large-format mosaic CCD cameras currently in the design stage, both 2 k × 4 k and 4 k × 4 k building blocks are being used.

2.3. *CCD noise*

The noise performance of CCD readouts strongly depends on the readout speed and is dominated by white amplifier noise. For the typical readout speed of 50 kHz pixel rate, typical detector systems in practical use have noise values $\approx$5 e^-rms, and laboratory noise values as low as 2 e^- have been reported. Readings CCDs at high speeds, for example for wavefront sensing purposes, involves a severe noise penalty.

2.4. *Electron Multiplication CCDs*

It is possible to boost the signal of a CCD by amplifying the collected charge package before transferring it to the output amplifier. The first company to market such devices was E2V Technologies in England. Details of the operation of such Low Light Level CCDs (L3CCD) (or EMCCD for electron multiplication CCD) devices were discussed by Mackay, Basden, & Bridgeland (2004), Smith *et al.* (2004), and Burke, Jorden & Vu (2005). Their basic principle is the addition of a several hundred high voltage electrodes to the output serial register. With electrode voltages in the range of 30V–40V, electrons are not simply transferred from one electrode to the next, but are accelerated to the point where each electron has a small probability of producing a second electron by impact ionization. After many of these steps, the charge package leaving this multiplication register is amplified by typically a factor of 100 before reaching the output amplifier. Therefore, a single electron is converted into a package of charge that is many times larger than the read noise of the output amplifier and can therefore be recorded individually. The statistical nature of the charge multiplication process leads to an additional noise source, however, that increases the noise for large signals. Due to this fundamental limitation, L3CCD are best operated in fast readout, near photon counting mode, where each pixel will record only a small number of photons per integration time. Typical applications are fast reading wavefront sensing detectors or techniques such as “lucky” imaging, described by Tulloch (2005), where huge numbers of short-integration-time frames are recorded, and only the few frames with the best image quality get added up into the final image. A limitation of L3CCDs is the clock-induced charge, where spurious charges get injected into the CCD by the operation of the clocks, leading to a false count rate that competes with true photon counting. This can be minimized by reducing the voltage swing of the non-multiplying clocks, and by slowing the clock edges as much as practical, a strategy partly conflicting with the desire to read fast to achieve true photon counting.

2.5. *OTCCDs*

A recent development in CCD architecture is the Orthogonal Transfer CCD, described by Burke *et al.* (2004) and Tonry (2005), that replaces the fixed channel stop implants in conventional CCDs by electrodes, and thereby allows the shifting of the charge packages in two orthogonal directions. In the implementation developed for the Pan-STARRS project, an 8 × 8 grid of such OTCCDs, each independently clocked, forms an orthogonal transfer array (OTA). In direct imaging applications, individual OTCCDs (cells) containing bright stars can be used to measure the centroid position of that star, thereby measuring any image motion, whether from telescope shake or atmospheric effects. By interpolation between the motions measured for a set of stars, the neighbouring cells can then be clocked to shift the accumulated charge package of any object to a position under its incoming photon stream. By its ability to compensate for image motion, OTAs can significantly sharpen the image on small telescopes, where the speckle pattern is still dominated by a single brightest pixel. For larger telescopes (>2 m) the benefits of image motion correction at visible wavelengths are rapidly diminishing.

3. Optical CMOS imagers

Optical CMOS (Complementary Metal Oxyde Semiconductor) imagers were developed out of the multiplexers that have been used in hybrid infrared arrays for the past two decades. These multiplexers always had some spurious sensitivity to optical wavelengths, but this feature was only used for the early, ambient temperature testing of infrared array readout electronics.

In their simple form, CMOS imagers include the light-sensitive photodiode on the same integrated circuit as the multiplexer, forming a monolithic device. The continuing trend toward finer design rules for the fabrication of CMOS circuits enables the fabrication of monolithic CMOS detectors with light sensitive areas covering 60% to 70% of the pixel area. Since CMOS devices do not require a mechanical shutter and integrate easily with low-voltage CMOS readout electronics, either on-chip or on separate readout electronics, monolithic CMOS imaging devices are now taking over the market for consumer imaging products. Since these simple monolithic CMOS devices are built on standard silicon wafers, they perform well in the middle of the Silicon wavelength range, which is sufficient for most consumer imaging products, but they fall short of the performance required for astronomy. Due to the area required for readout circuitry, the geometric size of the light sensitive area limits the effective quantum efficiency of monolithic CMOS sensors to about 50%–60%, and at these values, they are not competitive with backside illuminated CCDs. Further increase in the relative size of the photodiode relative to the pixel might make these monolithic devices interesting at least for small telescopes with very limited instrument budgets.

However, the same hybridization technology developed for infrared detector arrays can be used to fabricate hybrid CMOS devices with very high fill factor, as described by Bai *et al.* (2004). The hybridization process achieves very high yields, and since this is a Si-on-Si hybrid, Charge Transfer Efficiency (CTE) mismatch problems do not limit the hybrid reliability. The Si photodiodes, typically PIN diodes, are fabricated separately from the CMOS multiplexer, and can therefore be optimized for high quantum efficiency. Hybrid PIN diode arrays achieve essentially the same performance as the best deep depletion CCDs. Also, PIN photodiodes implanted in Si tend to have only about half the diode capacitance of similarly sized diodes in infrared materials, so that the resulting hybrids have a higher gain and consequently lower read-noise, but also lower well capacity. Since read-noise of about 3.5 e^- has been achieved in infrared detector arrays, noise levels of ≈ 2 e^- can ultimately be expected from hybrid PIN-CMOS arrays, albeit with the use of rather elaborate signal sampling techniques.

Advantages of CMOS detectors over CCDs are their relatively simple operation without the need to fine-tune clocking voltages to the characteristics of individual devices, a great flexibility in readout modes, from fast reading to low-noise slow reading, the possibility to guide on brighter stars in the field, and the ability to achieve, in up-the-ramp sampling, very high dynamic range and the rejection of cosmic ray events during the integration. For space applications, the better radiation hardness of CMOS devices is another important advantage. For instruments where the operating temperature of the detectors is low, for example combined optical and infrared instruments, CMOS devices offer the advantage of operating down to about 30 K without problems. When coupled with the newly developed ASIC readout chips, very compact systems will be possible that are highly scalable.

4. Infrared arrays

Infrared detector arrays are hybrid devices consisting of a photodiode array implanted in an infrared sensitive material (HgCdTe, InSb, and Si:As), then bump-bonded to a silicon multiplexer. Various designs and fabrication processes for the multiplexer have been used over the past two decades. Today's large format astronomical arrays all use CMOS multiplexers with a source follower circuit in each pixel. The emission of photons is an essentially unavoidable byproduct of the operation of a CMOS device, and manifests itself as multiplexer glow, with the high-current output amplifiers being the single most important source of glow. Due to improvements in multiplexer design, in particular the use of blocking metal layers, amplifier glow can now be controlled very well and no longer poses a limitation to the use of large number of reads, either in Fowler sampling or up-the-ramp sampling. Noise values of $\approx$5 e^- rms are being achieved by using about 8 Fowler sampling points and noise values as low as 3 e^- have been demonstrated with up to 32 Fowler samples. The basic source-follower-per-pixel architecture that is working well for the basic astronomy arrays from both main manufacturers is likely to be maintained. Incremental progress toward slightly lower noise can be expected, in particular if the pixel size is further reduced.

Rockwell is ready to take the next step in detector size, having developed full confidence in the process of stitching together physically large CMOS devices from multiple masks that was successfully used for the HAWAII-2RG multiplexer. Hybridization of increasingly large devices always involves an incremental learning process, but there do not appear to be fundamental limitations to the hybrid size, if the detector material is substrate removed and the detector array therefore complies with the thermal expansion of the multiplexer.

In the following, we will discuss the current status of different detector materials individually.

4.1. *HgCdTe*

A major step forward in the quality of HgCdTe devices for astronomical applications was made in the late 1990's with the introduction of detector material growth by molecular beam epitaxy on CdZnTe substrates. With this technique, the HgCdTe material is lattice matched to the substrate. Rockwell Scientific had many years of experience with this technique for other applications, but has only recently utilized it for astronomical devices. For the past 25 years, the standard HgCdTe crystal growth technique for astronomical detector arrays had been PACE-1 (Rockwell), which stood for "producible alternative to CdZnTe for epitaxy", and was a liquid-phase epitaxy technology on sapphire substrates. The name indicates that it was well known that the right technology would be to grow the HgCdTe on a crystal lattice matched substrate like CdZnTe, but such substrates were not available in the required sizes. As the result of growing on a mismatched substrate, PACE-1 HgCdTe had a relatively high density of defects that manifested themselves as excess dark current, low quantum efficiency at short wavelengths, low quantum efficiency at low operating temperatures, and poorly controllable residual leakage current after prior exposure of a pixel. Despite these nagging problems, PACE-1 detector arrays in the 2.5 μm cutoff variety have dominated the near-infrared detector market and have produced an impressive amount of scientific results. On the other hand, PACE-1 detectors with 5 μm cutoff wavelength have always been inferior to InSb detectors.

The competition between InSb (Raytheon) and HgCdTe (Rockwell) for the detector contract for the JWST provided the motivation to develop improved material growth technology for HgCdTe. This major improvement in material quality was achieved when sufficiently large CdZnTe substrates finally became available and precisely controllable molecular beam epitaxy techniques were developed by Garnett *et al.* (2004). The resulting material shows greatly improved crystal structure, and consequently, the problems associated with PACE-1 material have disappeared.

Dark currents in the range of a few electrons per pixel in 1000 s integration time at a temperature of 37 K have been demonstrated by both Hall *et al.* (2004) and Finger *et al.* (2004), both on 2.5 μm material and 5 μm cutoff material. Quantum efficiency at the short wavelength end (0.6–1.4 μm) is now above 60% for science grade devices, and is largely temperature independent. Residual leakage current problems (persistence) has been reduced substantially. It can still be detected after strong overexposure of a pixel, but both the magnitude of the effect and its decay time are orders of magnitude better than previously in PACE-1 material.

With the HAWAII-2RG multiplexers from Rockwell for JWST, infrared detector arrays have achieved a high degree of versatility in readout speed, readout modes, and the ability to compensate for instabilities in the operating conditions by using reference pixels.

Alternatively, Raytheon Vision Systems has produced 2.5 μm HgCdTe by liquid phase epitaxy (LPE) on CdZnTe substrates for the ESO VISTA project as reported by Love *et al.* (2004). For this ground-based imaging survey project, the dark current requirements were not as stringent as for JWST, and the VIRGO LPE detectors gave acceptable performance, as reported by Bezawada, Ives & Woodhouse (2004). Tests of one VIRGO engineering array by Smith, Bonati & Guzman (2004) under low background conditions demonstrated dark currents as low as $0.025\mathrm{e}^-$/s/pix, suggesting that this detector material is also suitable for low-background applications.

The next limiting factor in the increase in detector size is the availability of CdZnTe substrates, currently limited to 7 cm × 7 cm, sufficient for a 4 k × 4 K (15 μm) detector array. It is technically feasible to grow larger substrates, but only with a major investment in fabrication equipment. This investment will not happen unless there is a profitable market for very large infrared detector arrays, and the only likely market for such large devices will be astronomy. Both Raytheon, who grow their own CdZnTe substrates, as well as Rockwell, who import theirs, see basically the same limitation.

To overcome the detector material substrate limitations, experiments are under way at both main detector manufacturers to grow HgCdTe layers on Si substrates, where commercially available single-crystal wafers would allow the fabrication of huge diode arrays. The problem is the less than perfect crystal lattice match between Si and HgCdTe, which potentially will re-introduce the type of lattice defects that the older PACE-1 process was limited by. Rockwell is optimistic that with proper design and fabrication control of interface layers between the Si and the HgCdTe, and with the ultimate removal of the Si and the interface layers, diode arrays of acceptable performance will be produced.

4.2. *InSb*

InSb has been used as a high-quality detector material for several decades, beginning with single detector elements. Today, InSb arrays in 2 k × 2 k format are being produced by Raytheon Vision Systems, the main supplier of astronomical InSb devices, as recently summarized by Hoffman *et al.* (2004). In contrast to the liquid phase epitaxy or molecular beam epitaxy growth process for HgCdTe, InSb detector arrays are fabricated from large, monocrystalline boules of InSb material. The material is mechanically cut into thin slices that get polished and surface treated before implanting the diode array. After hybridization to the multiplexer and epoxy backfill, the InSb material in excess of the diode implant area is thinned away, usually by mechanical diamond milling or etching. The resulting thin layer of InSb is mechanically much weaker than the multiplexer that it is bump-bonded to, and therefore complies with the multiplexer's thermal expansion. This hybridization and thinning process is well developed and thermally very reliable hybrid arrays are being produced.

InSb was one of the two materials evaluated for use in the JWST NIRCam instrument. The InSb detectors from Raytheon performed very well, but achieved the required dark current at a slightly lower temperature than the competing $5.3\,\mu$m HgCdTe devices. This characteristic would have increased the risk associated with the thermal design of JWST and was the main reason why InSb was not selected.

InSb is currently available in boules of up to 100 mm diameter, setting essentially the same limit on detector size as the availability of CdZnTe substrates. Raytheon is optimistic, however, that this limitation can be overcome in the foreseeable future.

4.3. *Si:As*

Doping Si with other materials creates loosely bound electrons in the crystal lattice that can be excited into the conduction band by the absorption of long-wavelength photons. Of the many possible dopants, Si:As is the only technology currently being used and produces infrared detector arrays with a sensitivity out to $28\,\mu$m, covering the atmospheric N and Q bands. Si:As detectors are usually designed as BIB (blocked impurity band) photoconductors that show a substantially reduced dark current compared to simple photoconductors.

Fabrication of doped Si devices is relatively easy and very large Si substrate wafers are available. Also, there are no thermal expansion mismatch issues between the detector array and the multiplexer. For the JWST MIRI instrument, Raytheon has developed a Si:As detector array in $1\,\mathrm{k} \times 1\,\mathrm{k}$ format as reported by Love *et al.* (2004).

The challenge for Si:As devices is the design and fabrication of the multiplexer. For ground-based imaging, the thermal backgrounds in the N and Q windows are huge, and multiplexers with high charge capacity and very fast readouts must be designed. The other challenge is the operating temperature of about 10 K required to achieve low dark currents in Si:As. This temperature is outside of the range where standard commercial CMOS devices work. It is possible to vary the standard CMOS design recipes (doping level etc.) so that devices can work at deep cryo temperatures. This, however, is usually not done at major commercial CMOS foundries, but is the niche of smaller, specialty fabrication houses.

Another problem pointed out by the manufacturers of Si:As (Raytheon) is that the market for astronomical Si:As devices is so small that there is no continuity between individual fabrication contracts, leading to a feast-and-famine cycle for the small groups maintaining this technology. The risk is that these small groups will dissolve or be assigned to other tasks unless a reasonably continuous stream of business can be established.

4.4. *General trends*

High quality large ($2\,\mathrm{k} \times 2\mathrm{k}$) infrared detector arrays are very costly, currently ≈$ 0.5 million for science-grade Rockwell HAWAII-2RG and somewhat less for Raytheon arrays. The key to lowering the cost is mass production and the automation of several, still largely manual, production steps, as well as of the various testing procedures. Further, different detector substrate materials with the potential for lower cost are being developed. For mass purchases of detector arrays for the next generation of large instruments, it may be possible to keep the price of a future $4\,\mathrm{k} \times 4\,\mathrm{k}$ array at the level of todays $2\,\mathrm{k} \times 2\,\mathrm{k}$ devices.

5. Integrated readout electronics

Astronomical detector systems have traditionally relied on external readout electronics, often custom designed for specific applications. Readout electronics systems have also been available commercially. The study by Simons & Amico (2005) showed that the market leader is the "Leach" San Diego State University controller described by Leach & Low (2000). In recent years, the manufacturers of detector systems for commercial mass markets have begun integrating the clocking and signal processing functions directly into their detectors, thereby achieving a substantial simplification and reductions in size, weight, and cost of consumer cameras.

The same basic idea led to the development by Loose (2005) of the Rockwell "Sidecar" ASIC (Application Specific Integrated Circuit) to operate the HAWAII-2RG and potentially other future detector arrays. Rather than integrating the readout functions directly into the multiplexer, which would have been technically possible, the ASIC was designed as a separate device that could be operated in the same environment as the HAWAII-2RG detector arrays. This approach was chosen so that possible problems during the development of the ASIC would not impact the testing of the multiplexers. The use of the ASIC dramatically simplifies the design of astronomical instruments and will potentially even lead to better performance than external readout electronics, in particular when detectors work over long cable lengths and in RFI-rich environments. For these reasons, NASA has adopted the ASIC for all three NIR instruments (NIRCam, NIRSpec, and the FGS-TF) on JWST.

The capabilities of the Rockwell ASIC surpass the requirements for JWST and offer interesting possibilities for fast reading ground-based instruments. In particular, the ASIC contains 36 A/D converters with 16 bit resolution and a maximum speed of 5μs per sample for low-noise applications, and another 36 A/D converters with 12 bit resolution and sample times as fast as 100ns for high-background, very fast reading instruments. It also has enough memory and processing power for limited data processing, but not for full frame storage and processing. All HAWAII-2RG multiplexer functions, e. g., sub-array reads, reference pixels etc. are supported by the ASIC. The first Sidecar ASIC prototypes from Rockwell were tested in the KSPEC test system at University of Hawaii. In a direct comparison under otherwise identical conditions the ASIC slightly outperformed the carefully tuned external SDSU detector controller system that is normally used for detector characterization in KSPEC.

Even though the initial investment of time in the development of ASIC control code will be substantial, this technology will make the design of multi-detector focal planes or instruments with large numbers of distributed detectors much more feasible and their operation more reliable. It should be noted, however, that the new Rockwell Sidecar ASIC is built using the state-of-the-art 3.3V CMOS process and therefore cannot be used to operate older infrared arrays with multiplexers requiring 5V control signals such as the NICMOS, PICNIC, HAWAII-1 and 2, and the devices from Raytheon, unless additional interface electronics is used. While it is easiest to match an ASIC to a CMOS multiplexer built with the same process, it is possible to design ASIC readout electronics for CCDs. For example, an integrated CCD controller is being developed by Karcher (2005) for the Supernova Anisotropy Probe (SNAP) CCDs.

The future holds great promise for further, vertical integration of detector arrays with multiplexers and readout ASICs. For some commercial applications, prototype systems have been built that consist of Avalanche Photo-Diodes (APD) arrays, signal amplification and pulse height discriminators, and counters, all in a vertically integrated package that, in principle, can be abutted to form focal planes of arbitrary size. The data output of each pixel is then simply the number of photons detected since the last reset.

6. Risks and opportunities

All manufacturers of detector arrays, both CCD and CMOS-based, are subject to market forces that astronomers can help influence, but not fully control. It appears that the market for consumer imaging products will move from CCD technology to CMOS-based imagers. This move is already almost complete on the low-cost end, but even high-end digital photography is now moving to this technology. As a consequence, the market for CCDs will get smaller and commercial CCD manufacturers may face problems. A similar situation is faced by smaller, specialty CMOS fabrication houses. Fabrication lines for the older 5V CMOS process, and special CMOS processes suitable for deep cryo applications ($T \approx 10$ K) may be forced out of the market.

On the positive side, the technology is now available to build detector arrays with up to a few hundred transistors per pixel, allowing to design sophisticated electronic systems in each pixel, such as photon counters. Larger CMOS multiplexers are definitely possible using the now mature technology of stitching together large devices from multiple masks. A challenge is the supply of large detector substrates (CdZnTe and InSb), but with the prospect of large purchases from the astronomical community, the equipment required for their fabrication could be established.

There is no space mission beyond JWST on the drawing board that will likely fund major new technology for optical or infrared detectors before the extremely large telescopes (ELTs) need their detectors. It will therefore largely be up to the ground-based astronomical community to fund any development that they need for the ELTs. The most promising areas are the increasing integration of sophisticated readout electronics into the sensor chip assemblies, and the development of photon counting detector arrays. The feedback from the detector manufacturers is that a steady stream of research and development funding at a fairly moderate level will ensure that developments outside of astronomy will get fed into astronomically useful devices. This will allow a better assessment of development risks and cost for future ELT instruments and will make sure that, when the time for large detector purchases comes, the required technology will be available without undue risk or delays.

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Discussion

DENNEFELD: You did not mention Superconductive Tunnel Junctions. What are the prospects in that direction?

HODAPP: Sorry, I am not an expert in this technology and therefore cannot comment on its prospects.

DRAVINS: The present generation of detectors is yet far from 'ultimate', even with individual photon-counting, there remains the need for wavelength-, and polarization resolution. And, at least in principle, also for quantum-optical properties such as photon orbital angular momentum.

HODAPP: This is a very good point. Today's photodiode arrays are coming close to perfect quantum efficiency and will evolve to photon-counting capability, but they will not provide energy resolution nor sensitivity to polarization. Bolometric detectors based on transition-edge devices have the potential to provide useful energy resolution. At this time, this technology has been demonstrated, but is far from becoming available in large-format arrays.

ZINNECKER: What do you estimate will be the cost of the $4\,\mathrm{k} \times 4\,\mathrm{k}$ IR arrays that you mentioned will be available in the near future?

HODAPP: The price of new infrared arrays depends on the number and difficulty of fabrication steps and the fabrication yield. Progress is being made to improve all these factors. As a result, the cost of infrared arrays has historically increased slightly slower than the linear size of the detectors. The manufacturers realize that this is quite costly and they will try to develop detector materials, such as HgCdTe grown on Si, that are cheaper to produce but may not have JWST-style quality.

HERBST: How well do the ASICs operate cold? Can you place them at 30 K right next to the detector?

HODAPP: The ASICs are specifically designed to work in the same environment as the detectors. They work fine at the JWST temperature of 37K, in fact somewhat better than at room temperature.

BALEGA: What about the temperature stability of the ASIC devices?

HODAPP: In our tests, the ASICs are temperature stabilized at cryogenic temperature, which is very easy to do. The detectors are stabilized to ± 1 mK, and at this level, no noise contribution from temperature fluctuations is observed. By proper calibration and the use of the reference pixels, effects of temperature fluctuations as high as ± 50 mK (the JWST ISIM specification) can be fully corrected.

KÄUFL: How do you rate the potential of InGaAs detectors as general imaging material?

HODAPP: InGaAs has potential as a near-infrared high-operating-temperature material, and some manufacturers are willing to try and develop this material for astronomy. Of particular interest is the use of InGaAs for APD photon counting detectors. However, InGaAs competes directly with short-wavelength HgCdTe, and astronomers have, so far, preferred the latter material.

HOUGH: Do the devices employing internal gain, e.g., APD-type, suffer from the usual excess noise over and above photon shot noise, or are gains sufficiently low that the excess noise is low?

HODAPP: Avalanche charge multiplication is a statistical process and does indeed introduce additional noise. For large number of detected photons, this multiplication noise dominates over the read-noise and photon shot noise and makes APD devices inferior to conventional (non APD) detectors. The strength of APD-type detectors is in the detection of small numbers (<20) of electrons, and they are the technology closest to achieving true photon counting in low flux situations.