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The Future is Bright for CCD Sensors

CCDs will Continue to Provide a Crucial Imaging Capability for Science

Complementary metal-oxide-semiconductor (CMOS) image sensors now dominate the imaging detector market, but there are industrial and scientific imaging applications where charge-coupled device (CCD) imager sensors is still the preferred choice, from both technical and commercial perspectives.

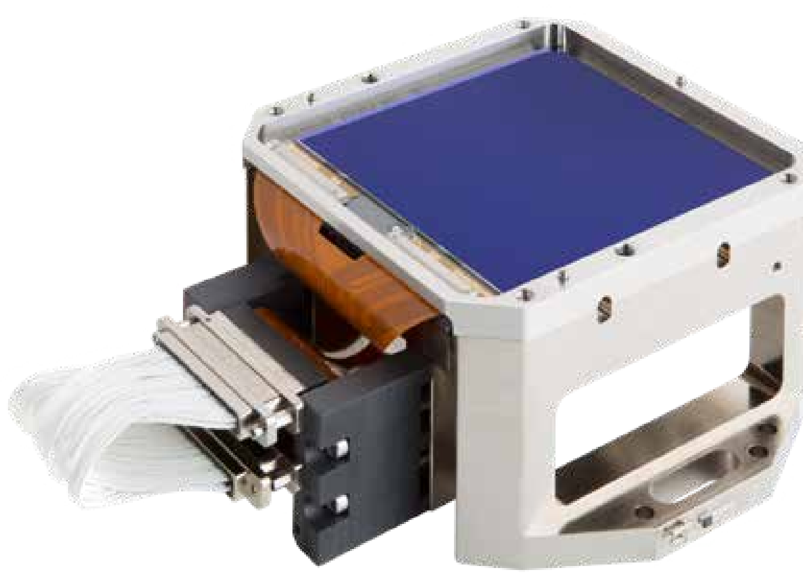
According to market research company, Research and Markets, the global image sensors market is expected to reach $23.2 billion by 2023 (as of April 2018).

Continued market growth is mainly driven by rising demand for dual-camera mobile phones, the development of low-power and compact image sensors, and the increased use of image sensing devices in biometric applications.

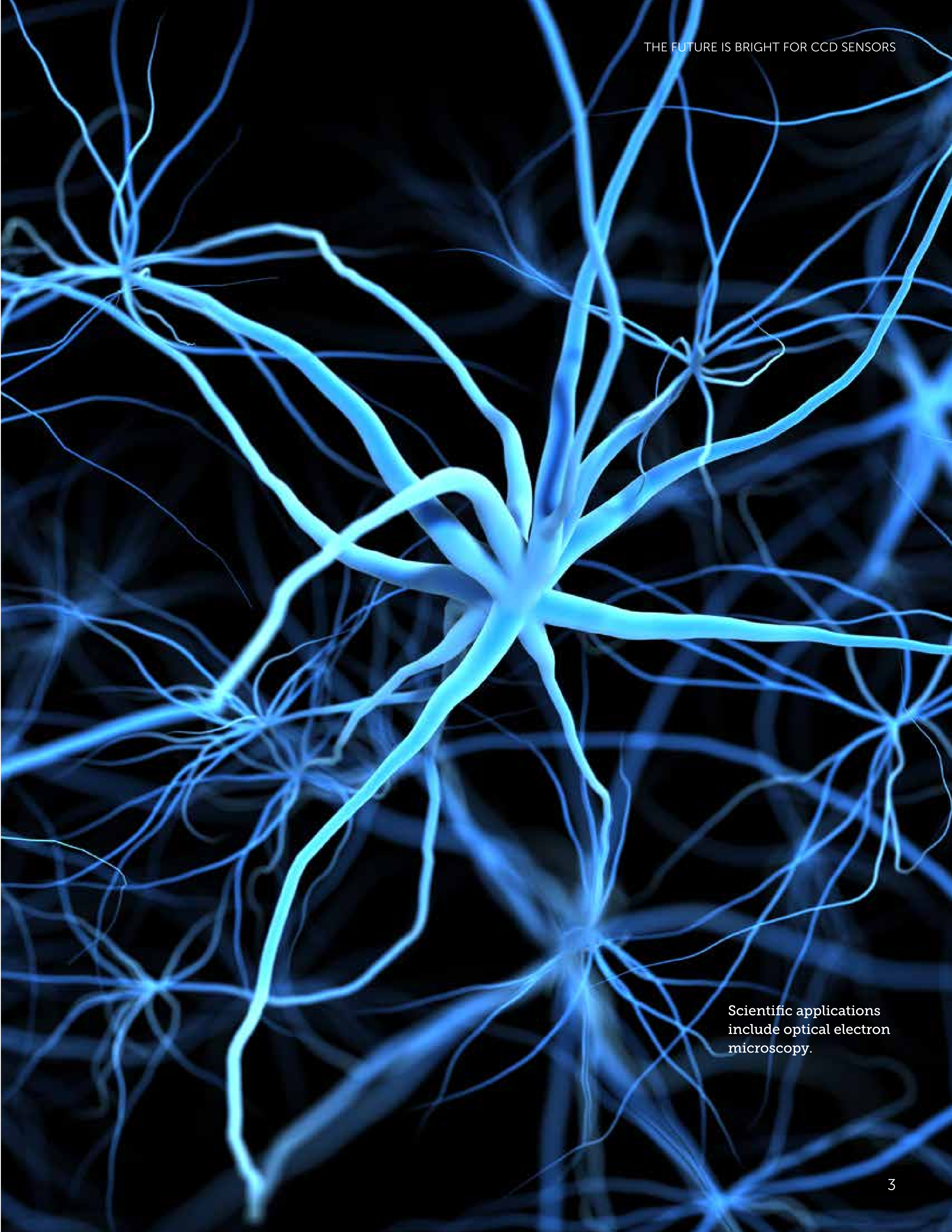
CMOS technology accounts for the majority of the visible wavelengths market, by revenue as highlighted by Yole Développement Status of the CMOS Image Sensor (CIS) Industry 2018 report.

However, while the economies of scale and sheer momentum behind CMOS sensor development are huge — predominantly in consumer applications — it is far too early to write off CCD sensors.

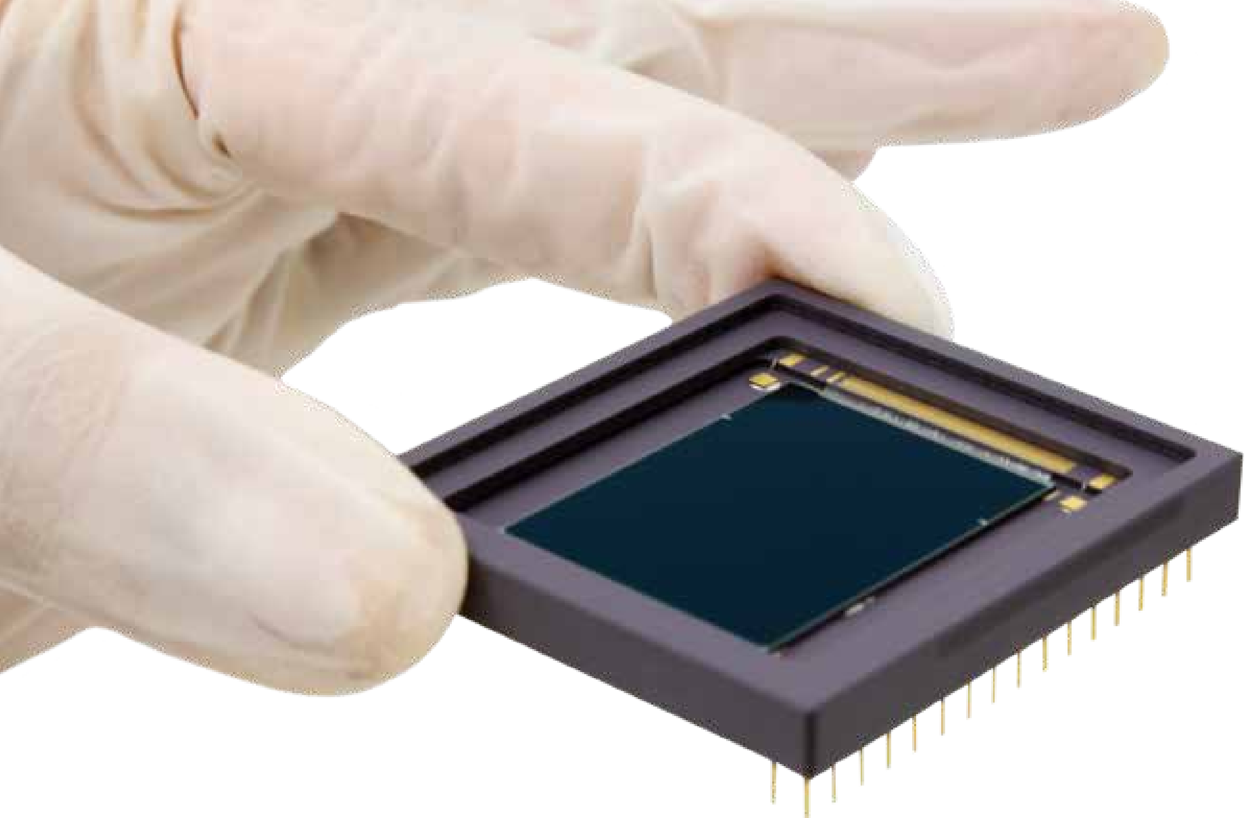
As technologies and markets evolve, what is technically feasible and what is commercially viable also evolve, and many imaging applications in spectroscopy, microscopy, medium to large ground telescopes and space science will continue to be better served by CCDs.



Teledyne e2v CCD Bruyères detector in handling jig for the ESA PLATO mission.



Scientific applications include optical electron microscopy.



Teledyne e2v CIS120 CMOS general purpose image sensor for space applications.

Invented in 1969, Charge-coupled devices where originally designed as a memory storage device in the United States at AT&T Bell Labs by Willard Boyle and George E. Smith, with their potential as imaging detectors realized shortly afterwards. Notably CCD devices became the work-horse detector in ESA and NASA missions for the last thirty years.

CCD detectors are made from silicon, which defines their spectral sensitivity. Most often used in UV, Visible or NIR applications, they can also be used for soft-X-ray detection.

Notably Teledyne e2v, in the UK, continues to maintain a vertically integrated dedicated CCD fab, make technology developments to the design and production of CCDs, and is committed to the provision of high performance and customized CCD detectors and packages on a longterm basis.

It is worth noting that the ability to customize the CCD design is one of the key enabling factors of high-performance imaging. Comparing the merits of both CMOS and CCD technology highlights that one will not satisfy all requirements over the other.

CCD AND CMOS BASICS

CCD and CMOS are both silicon based detector arrays:

- Large-format, back thinning is possible for both
- Detection efficiency is the same

CMOS have some advantages over CCDs:

- Higher readout speed and greater flexibility
- Less prone to some radiation effects
- Simpler interfacing

However, many aspects of CCDs remain superior to CMOS:

- Dynamic Range
- Longer wavelength (NIR) performance
- Time Delay and Integration (the Gaia space telescope would not be practical with CMOS)
- Electron Multiplication
- Deep understanding of performance and reliability through decades of study

Based on the above, it is clear that CMOS and CCDs have similar performance for many parameters but there will always remain critical aspects for which CCDs are the only solution.

"Teledyne is at the forefront of CMOS sensor design for scientific and space applications, and is the industry standard for CCD imaging, that is how we know when to use CCD and when to use CMOS."

Both CCD and CMOS imagers convert light energy into an electric voltage and process this into an electronic signal.

In CCD sensors, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high.

In CMOS sensors, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. With each pixel doing its own conversion, uniformity is lower, but it is also massively parallel, allowing high total bandwidth for high speed.

For Time Delay Integration (TDI) applications CMOS has developed to a level that will likely prevent future CCD TDI developments. The summing operation in Teledyne CMOS TDI sensors are now noiseless and can also have CCD type operation embedded in the CMOS chip giving cost effective charge domain operation.

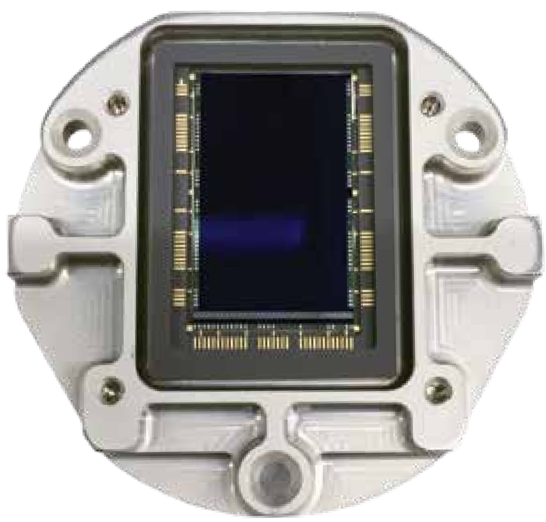
Electron multiplication CCDs (EMCCDs) multiply the signal charge packet, resulting in a net signal-to-noise ratio (SNR) gain. EMCCDs can detect signals in applications where the signal is so faint that it would not normally be above the imager noise floor. This means that EMCCDs are widely used for the very lowest signal scientific applications especially where counting of individual photons is required.

INDUSTRIAL IMAGING ADVANTAGES

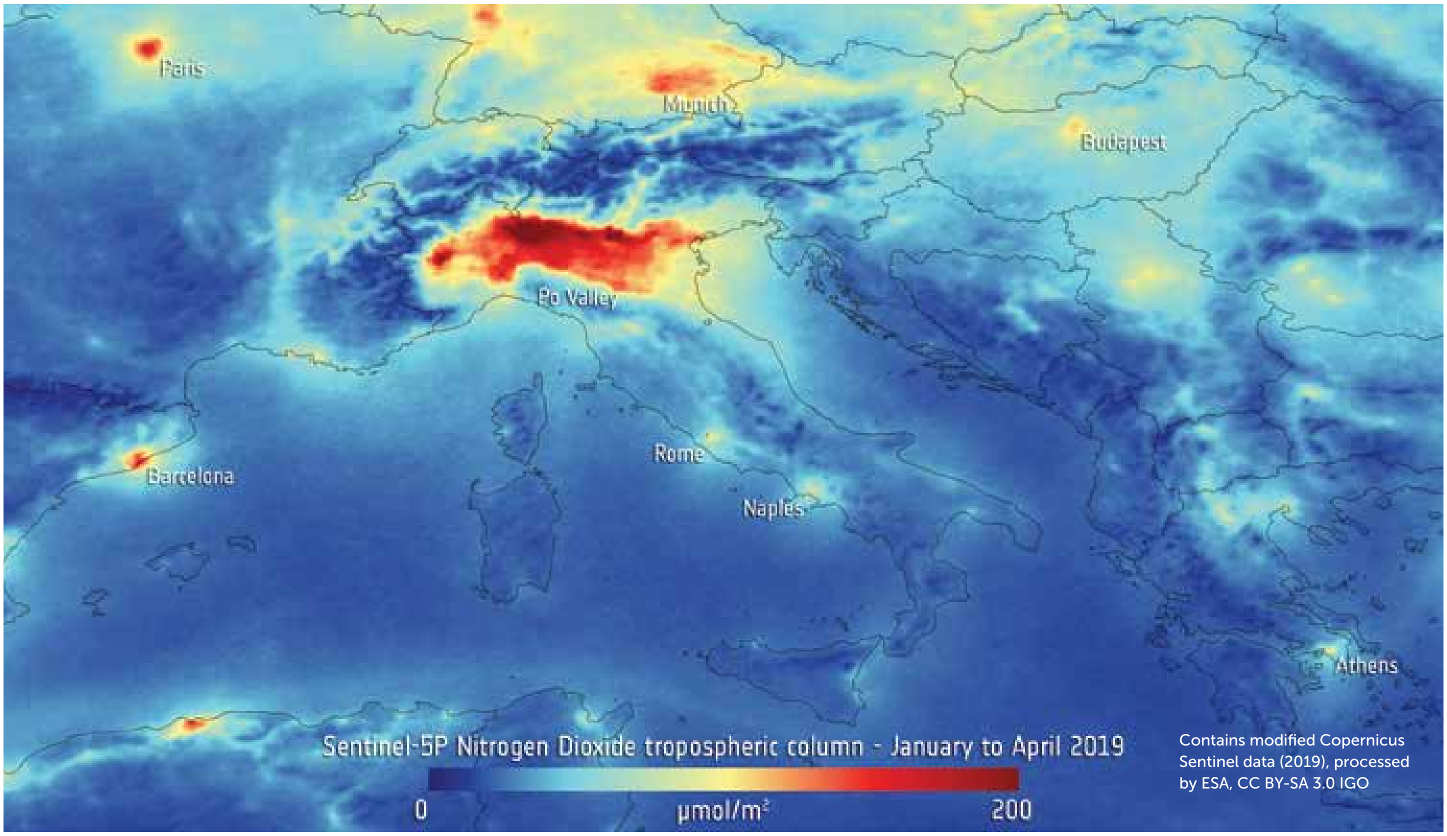
In certain industrial and scientific imaging applications CCD imagers still offer significant advantages over CMOS.

One such application is near-infrared imaging (700–1,000 nm). CCDs that are specifically designed to be highly sensitive in the near-infrared are much more sensitive than CMOS imagers.

At these wavelengths, imagers need to have a thicker photon absorption region, because infrared photons are absorbed deeper than visible photons in silicon. CCDs can be fabricated with thicker epitaxial layers, while maintaining the ability to resolve fine spatial features. In some near-infrared CCDs, this layer can be more than 100 microns thick, compared with the 5–10 micron epitaxial layer of most CMOS imagers.



CCD201 EMCCD that will be used in the Coronagraph Instrument for NASA's WFIRST mission.



Based on measurements gathered by the Copernicus Sentinel-5P mission between January and April 2019, the image shows high levels of nitrogen dioxide in the Po Valley in northern Italy. The Sentinel-5P's TROPOMI instrument uses Teledyne e2v's CCD275 detector.

SPACE IMAGING ADVANTAGES

Space imaging has several unique challenges, and typically requires highly optimized image sensors. The high cost of launching a camera into space means both performance and heritage are critical. This is why CCDs have continued to dominate the space market after they have stopped being used for most terrestrial applications.

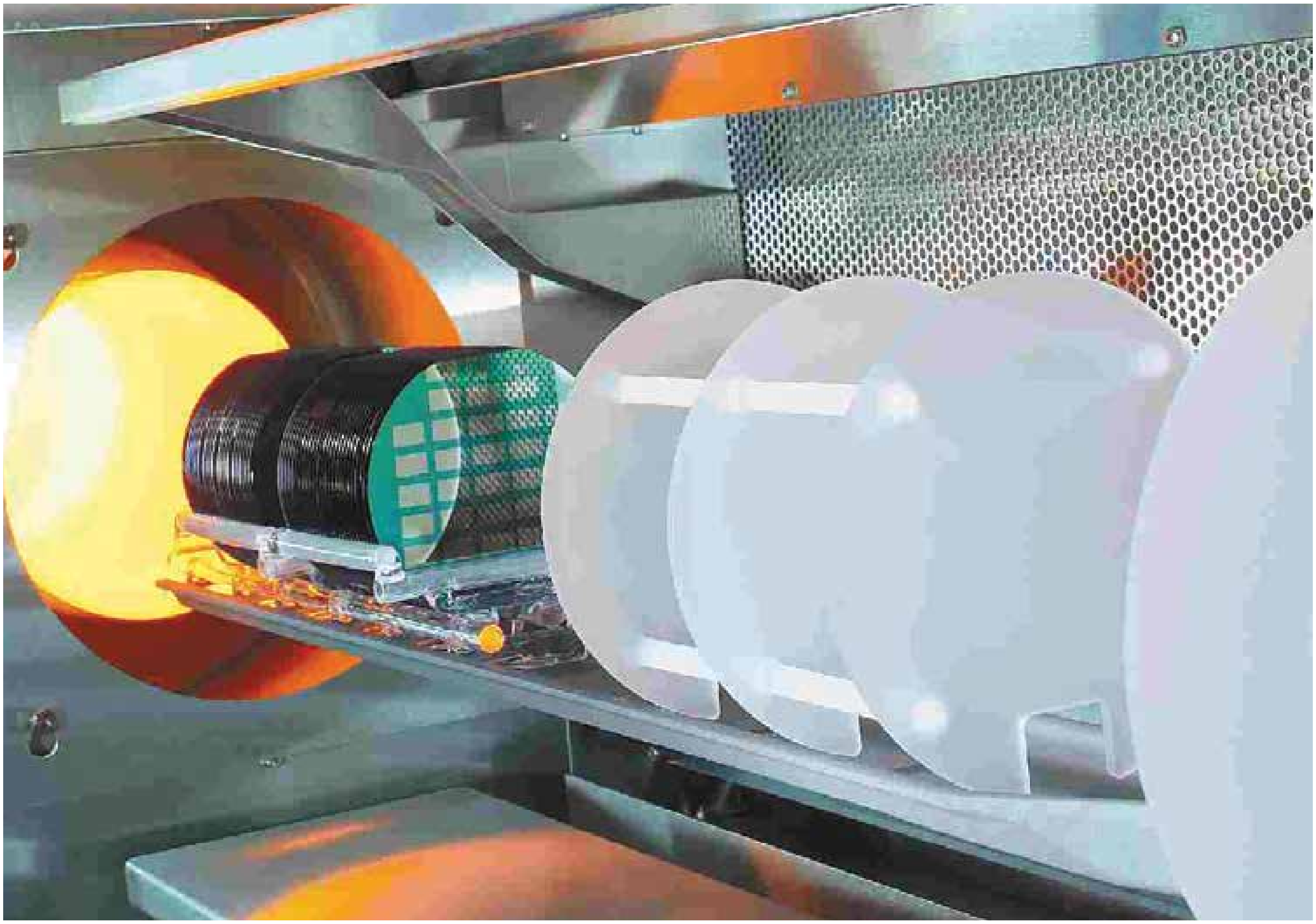
For most space applications very high electro-optical performance is critical, especially when it comes to quantum efficiency (QE), noise, dynamic range (DR), dark signal (or leakage current), uniformity and performance repeatability. Space applications also require radiation resistance, low power dissipation (CMOS typically performs better in this respect), reliability and longterm stability. It can be said for all these latter parameters CMOS meets or exceeds CCD technology.

CCD imagers offer better QE at the longest wavelengths, higher dynamic range, and better uniformity than CMOS imagers — all of which are critical for space science and hyperspectral applications.

Space-based astronomy usually requires very large, even wafer-scale, devices. Currently, only CCDs have the required image quality and TRL maturity for such missions. Although it should be noted that Teledyne is producing wafer scale CMOS sensors for a ground based X-ray applications.

Hubble Space Telescope view of Jupiter, taken on June 27, 2019. The image is a composite of separate exposures acquired by the WFC3 instrument.

Credits: NASA, ESA, A. Simon (Goddard Space Flight Center) and M.H. Wong (University of California, Berkeley)



Silicon wafers entering the furnace as part of a metalization process.

QUALITY AND PRODUCT ASSURANCE

The Teledyne e2v fab facility in the UK highlights some unique benefits over the way CMOS foundries operate. The UK facility includes the CCD semiconductor fabrication line. Silicon wafers enter at one end and a finished packaged CCD with filters and mechanical features emerges at the other. This allows Teledyne e2v to have full knowledge and control over the manufacturing processes of the detector, information that can be shared with strategic partners and constitutes an essential part of the quality assurance (QA) and product assurance (PA) aspects of using these components in space.

Detector design is also in-house and, like the manufacturing processes, both have been intimately optimized over many years. The CCD foundry is used only for CCD production, offering process stability and repeatability.

In contrast, CMOS detectors are typically designed at 'fab-less' design houses and manufactured in commercial semiconductor foundries producing many different CMOS devices. The main reason being that a modern CMOS fabrication plant constitutes a very large investment coupled to a high running cost and hence produce orders of magnitude higher volumes.

This means process and design stability is continuously evolving for CMOS and presents increased challenges for QA and PA as well as gaining insight to processing details, key requirements for space qualification activities.

Teledyne e2v CCD fab – corridor leading to multiple CCD processing clean rooms.

RADIATION HARDNESS

Image sensors in space encounter high-energy protons, electrons, and galactic cosmic rays. This causes both gradual deterioration in sensor performance and instantaneous single event effects (SEEs). The long-term effects are caused by ionization damage in the insulators (typically oxides and nitrides) and their interfaces to the active silicon, and by displacement damage to the silicon crystal lattice. Both can lead to an undesirable increase of the dark current, noise and charge transfer inefficiency.

Both CCDs and CMOS sensors are subject to radiation damage and whilst CMOS is more resistant to proton radiation, CCDs offer mitigation in this area in other ways.

Instantaneous effects include single event upsets (SEU) which can corrupt memory elements in CMOS sensors or interfere with the normal operation of their logic circuitry. Single event functional interrupt (SEFI) causes major disruption in the operation of CMOS circuitry, but is correctable via reset of power cycling. While these can be considered 'soft' transient errors, heavier particles and energetic protons can cause single event latch-ups (SELs) in CMOS circuits, which can damage an image sensor permanently.

CCDs do not suffer from SEU, SEFI or SEL because of the lack of CMOS logic circuitry and parasitic thyristors. Qualifying the radiation hardness of an image sensor is usually a time-consuming job and requires a great level of expertise in device physics and operation.

LONG-TERM AVAILABILITY

Most space science missions take decades from conception to launch. By contrast, commercial technology development timescales are much shorter. This can create concerns around the long-term availability of the preferred manufacturing processes (especially in fast-moving consumer electronics), and the longevity of the semiconductor vendor.

What's more industrial and consumer sensor technologies tend to go in contrasting directions to space and science. Space agencies and scientific organizations can take-heed that there is a longterm supply of the required sensor technologies focused on space and science needs, from Teledyne, to support them.

HERITAGE

The image sensor constitutes a critical point of failure and redundancy is generally deemed as impractical. The huge costs of building and launching spacecraft, and the risk of mission loss, mean the space industry is very conservative and risk-averse. Image sensors and cameras with problem-free flight heritage are highly valued, and may often be preferred to more capable but untested alternatives.

CCDs have tens of thousands of years of cumulative space heritage while CMOS sensors are only finding use in space in recent times. The investment required to reach reliability comparable CCD is huge.

COMMERCIAL CONSIDERATIONS

Of course, the choice of imaging sensor will never come down to just technical superiority: commercial considerations are clearly an important factor. The cost picture for imaging sensors is complicated, but there are a few important points to consider.

The **FIRST** is leverage: imagers that are already on the market will cost much less than a full custom imager, regardless of fundamental technology. Whenever customization is required, it is generally less costly to develop a custom CCD than a custom CMOS imager for all but the most insignificant adaptations. This is because CMOS imagers use more expensive deep submicron masks, and have much more on-chip circuitry.

SECOND, volume matters. Although the higher development cost of a new CMOS

imager can be recouped when production volumes are high, for small production runs, the lower development costs of CCDs can be an important factor.

THIRD, security of supply is vital: it is very costly to be left with a product that is designed around a sensor that is discontinued. Whatever the value proposition, it may be wiser to choose a sensor source that is committed to continued development and manufacture for the longterm.

For longer-term projects, the use of commercial CMOS foundries can be problematic, as the manufacturing process undergoes continual improvement to meet commercial needs. The changes may not always be visible from one manufacturing run to the next, which may be fine for projects requiring just one or two silicon batches over a short period of time. However it can become an issue if repeat runs of the same build are required several years apart; re-qualification may be needed.

CONCLUSION

The large majority of high-performance applications currently use CCDs thanks to their heritage, excellent uniformity and QE. Furthermore, the development of CMOS sensors for space imaging will continue. However, certain scientific applications, such as astronomy, spectroscopy and microscopy, will also continue to rely on CCD performance.

It is necessary for instrument designers to take note of the different detector operation requirements and not to expect CMOS as a direct replacement in all applications.

(Above and left) CCD fab inspection and process control.

Teledyne e2v ultraviolet laser detector technology, CCD69, deployed on ESA's Aeolus Satellite to profile the world's winds.

With some leading manufacturers in recent times ending or planning to end their CCD production, it will be important for industrial and scientific imaging system designers to have continued access to CCD development expertise and manufacturing capability for specialist industrial and scientific imaging applications, especially for space imaging applications.

Despite their maturity, CCDs have not reached the end of their development, and several aspects have been identified which could be of benefit for future science applications and space missions for example. Identified improvement areas include enhancements to the signal handling and noise performance, increasing the tolerance to non-ionising radiation, and changes to further increase the UV and NIR quantum efficiency and stability.

Teledyne e2v, in the UK, continues to develop a longterm, vertically integrated, dedicated CCD fab and make technology developments to the design and production of CCDs. Teledyne is committed to providing the correct standard, customized and high performance CCD and CMOS solutions, investing significantly in CCDs, CMOS and related imaging technologies.