e2v Space-Qualified CMOS Image Sensor Capability and Roadmap

A White Paper
Alice Reinheimer, Senior Applications Engineer, e2v inc.

INTRODUCTION

e2v is a leading global provider of high performance image sensors for space applications with over 100 devices flown in missions ranging from Earth observation to planetary exploration and space science. End users include all of the world's large space agencies and major satellite providers. With expertise in high sensitivity, low noise and large format sensors, e2v has provided the CCDs that enable flagship instruments such as the Wide Field Camera 3 on Hubble, the recently launched GAIA mission, and Mars Curiosity's ChemCam and Chemin instruments to "see". In addition to Space Exploration, e2v is at the heart of Earth observation missions such as SPOT II - VII and Pleiades.

e2v has extended its CMOS imaging capabilities by leveraging its extensive CCD space heritage and requirements understanding into space-qualified CMOS image sensor (CIS) products. The focus is on providing a CMOS solution into those applications that will benefit from the advantages the technology brings, e.g. applications requiring windowed readout, on-chip ADCs or inherent resistance to radiation-induced charge transfer inefficiency.

EXPERIENCE IN CMOS

e2v has over ten years of experience in the design and delivery of CMOS image sensors. Their standard product portfolio consists of 8 devices designed for high volume terrestrial applications, with a significant number of technology studies underway to improve performance in low light levels, low noise, high dynamic range, radiation tolerance, back thinning and coating technologies, very high frame rates and improved red sensitivity. The recent acquisition of Anafocus has significantly strengthened e2v's expertise in very high frame rate applications and in on-chip image processing. e2v has a number of projects under development in Space Imaging, the most noteworthy of which are the Visible Flexible Combined Imager Detector Assembly for Meteosat Third Generation and the selection of the CIS115 to fly on ESA's Jupiter's Icy moons mission in the JANUS camera.

e2v's involvement in CMOS image sensors for space started with the Geostationary Ocean Color Instrument (GOCI) which was launched on board the South Korean COMS-1 satellite. GOCI uses a 2Mp CIS that was provided to e2v. e2v's assembly, screening and qualification capabilities were utilized to package, space qualify and deliver flight models for the program.

In a similar program, e2v has provided post-processing and qualification of the VNIR multi-linear CIS for the SENTINEL 2 mission[1]. Again the CIS was provided to e2v, where post-processing, packaging and qualification were then carried out. In this program e2v implemented a new black coating deposition process on the imaging surface to minimize reflections. SENTINEL 2 is a multi-satellite earth observation mission planned for launch in 2015.

Since these early activities, e2v has completed a feasibility program to verify the performance of back-thinned CIS in a simulated space environment, including evaluation of radiation hardness. This work was based on a 2k x 1.5k 7 µm pixel prototype device. The CIS107 device was developed with a range of 3T and 4T pixel structures to assess a broad pixel parameter space. The sensor has 4 analog readout ports, and enabled verification in silicon of a range of pixel designs. Measurements showed that quantum efficiency in excess of 80% is possible for the range 450-750 nm, with peak QE over 90%, matching theoretical predictions based on back-thinned CCD QE.

A single pixel variant of the CIS107 was chosen to develop the CIS115 using internal e2v funding. It was subsequently selected for use in the JANUS instrument on ESA's JUpiter ICy moons Explorer (JUICE). A space qualification will be completed on back-illuminated devices this year.

Development of a space qualified front illuminated CIS is well underway. e2v's contract with Thales Alenia Space for the design, development and manufacture of a space qualified CMOS imaging sensor for use in the Flexible Combined Imager (FCI) instrument of the Meteosat Third Generation (MTG) has moved into the qualification phase. MTG is an ESA and EUMETSAT program aimed at delivering improved meteorological data and enhanced atmospheric composition information[2]. e2v is managing the whole of the supply chain for the detection assembly, from the in-house design of the sensors; specification and procurement of the filters and manufactured wafers; assembly and screening of the sub-assembly, to the qualification and delivery. The CIS is an unusual format with very large pixels arranged as non-square rhomboids. The main technical challenges have been the design of pixels up to 100 µm square with good charge transfer and hence low lag, and the design of a radiation tolerant CMOS architecture. Evaluation of test devices resulted in an optimized pixel design. Test of first prototypes demonstrated that the design is latch up and single event functional interrupt free up to 67.7MeV/mg/cm^2.

e2v's commercial product line of *eye-on-Si* imaging sensors have been evaluated for gamma, proton and heavy ion radiation hardness through a variety of small programs. These sensors are fabricated on the Tower (Israel) 0.18 µm CIS process and utilize a 5T pixel architecture and on-chip 10 bit column parallel ADCs, with pixel sizes from 5.8 to 4.5 µm. The "Jade" device (EV76C454) has been evaluated for gamma and/or proton radiation at Open University[3], CNES and Onera[4] and at JPL[5]. Three "Sapphire" devices (EV76C560) have been launched in 2014 in the C3D instrument on Ukube-1, a UK technology demonstrator cube-sat[6]. In support of the Ukube project, Sapphire CIS were tested for Single Event Effects (SEE) by Open University[7]. All this work has helped benchmark commercial technology and underpins e2v's understanding of the impact of radiation on CIS technology.

Other CIS are under development at e2v. These include a 2k x 4.5k, 16 µm pixel, 3-side buttable CIS with approximately 3e of read noise (rolling shutter) for high cadence astronomy use on the TAOS II telescope[8]. Although the initial use of this sensor will be in ground-based astronomy, the device has been designed for radiation tolerance in a space environment. It is being built into a set of demonstration electronics and will be subject to evaluation, including radiation test. Another CIS, a 700 frame per second 1760 x 1680, 24 µm pixel device is being developed as a wavefront sensor for large ground-based telescopes[9] where the requirement for high frame rate from such a large device with <3e noise would be impossible with a CCD. Both of these devices are being back-thinned.

CAPABILITY

e2v has over 20 staff dedicated to the design of CIS, and with the recent acquisition of Anafocus whose expertise in analog to digital conversion, and on-chip image processing is complementary to e2v's expertise in pixel design, the capability is expanding. The e2v team has built a large portfolio of silicon-proven standard blocks including 3T, 4T and 5T pixels, on-chip analog processing, on-chip ADCs, PLL and timing generation, and image processing blocks. They hold over 35 patents related to CIS design, including technology such as extended dynamic range and Time Delay and Integration CIS.

e2v has developed a very successful range of industrial sensors using their proprietary *eye-on-Si* CIS technology. These sensors incorporate 5T high efficiency global shutter pixels with on-chip ADCs and digital image processing.

Commercial devices are presently capable of 18 e- read noise in global shutter mode and less than 3.6 e- read noise in electronic rolling shutter mode They feature a high efficiency on-chip microlens and QE up to 80% with monochrome, color and sparse color filter options. Currently the commercially available formats are 838 x 640 with 5.8 µm pixels[10], 1280 x 1024 with 5.3 µm pixels[11], 1600 x 1200 with 4.5 µm pixels[12] and 1920 x 1080, also with 5.3 µm pixels[13]. The 1280 x 1024 pixel format device is also available in a version with enhanced red and NIR response, the "Ruby" CIS[14,15]. Higher resolution versions are planned in the sensor roadmap.

The CMOS processes used for image sensors typically require a fairly thin active silicon layer which in turn limits red and near-IR response. e2v has worked with their CIS foundry to develop image sensors built on thicker silicon and therefore with better red and near-IR sensitivity.

e2v specializes in back-thinning[16] of large area image sensors on an industrial scale, having delivered 130 back-illuminated flight models for the GAIA program[17]. Present processes allow thinning of up to 6" wafers, however 8" CIS wafers may be accommodated with a reduction in size. Quantum efficiency enhancements include optimization for wavelengths from soft x-ray through EUV, FUV, UV, visible to NIR, with a cutoff at around 1050 nm. Multi-layer anti-reflective coatings for high QE across a broad band in the visible and near-IR are currently under qualification for use in space.   All QE enhancement processes and anti-reflective coatings may be applied to back-illuminated CIS.

DEVELOPMENT DIRECTIONS

e2v has added to their *eye-on-Si* product line, building on the heritage already established in existing products. Introduction of a higher resolution 1600 x 1200, 4.5 µm pixel drop-in replacement for the 1280 x 1024, 5.3 µm pixel "Sapphire" CIS has occurred.   A new HDTV CIS, "Onyx HDTV", has been launched with the following features: 1980 x 1024 with 5.3 µm pixels, 8/10/12/14 bit on-chip ADC and LVDS output, 350 fps in full resolution and 10 bits, 60 fps in full resolution and 14 bits. Onyx HDTV incorporates a "digital double sampling" mode which enables global shutter capability with a read noise less than 6.5 e-.

Additional improvements to the *eye-on-Si* product line include an ongoing program to develop back-thinning of these devices.

Standard product CIS development programs in partnership with e2v's foundry are aimed at reducing read noise and improving dynamic range through improvements to transistor design. Test devices have been characterized with less than 2e- read noise in rolling shutter mode.

Improvements to radiation hardness of the analog building blocks are planned as an extension of the current activity, and development of a radiation hard digital output circuit is underway on a test chip.

An innovative TDI pixel has been demonstrated using a standard CIS process, achieving true charge transfer over 40 stages. A second design round has been evaluated with improvements in charge transfer efficiency, dark current, and dynamic range.

As mentioned above, e2v is funding development of the CIS115, a 1.5k x 2k, 7 µm, space-qualified CIS. Its key performance parameters will include 4T pixels, 4-port analog readout, less than 5 e- read noise in rolling shutter mode, pixel full well capacity of 30ke-, TID of 250 k-rads(Si) and proton irradiation test results up to $2x10^{10}$ cm^{-2} (10 MeV proton).   The device is designed for back-thinning.

SYSTEM DEVELOPMENT CONSIDERATIONS

The development of new device capability and features also provides e2v the opportunity to consider how these would impact the system integrator and the system solutions able to be offered by e2v. For a system integrator the solution they offer is primarily driven by five dominant and competing parameters.

1) Component Cost – Driven by EEE Parts Assurance
2) Power dissipation – Impacting both thermal and power management on the space craft
3) Mass – Contribution to the cost of launch and trade-offs on payload budgets
4) Performance – Noise and frame rate drivers along with other parameters
5) Export Regulations – Potential to limit markets

Device level technologies such as on chip ADCs will result in significant benefit to the system integrator as they allow a more integrated solution which reduces the cost and power of the overall system. Interconnect technology is another driving aspect at system level as traditionally low EMI solutions are preferred. The inclusion of LVDS IOs will not only reduce the EMI noise within the system, which could have an impact on performance (and potentially power too), but at the very least it reduces risk regarding EMC qualification. The introduction of LVDS IOs also enables the CIS to be located further away from the proximity electronics which drive the sensor which is of interest for satellite deployment or health monitoring cameras, or any system requiring deep cooling.

It is correct that many of the critical device requirements are based around capability, performance and radiation hardness. There are however, other system considerations which should be utilized to ensure e2v devices have a distinguishing factor within the market place. One such aspect would be the introduction of a standard CIS interface (Digital In, Digital Out). A standard interface will simplify the systems solution by potentially providing a sensor agnostic interface. A standard interface also has the ability to ease the test of the device and potentially reduce the cost of manufacture.

Conclusion

With an extensive heritage as one of the premier suppliers of space qualified image sensors, e2v is expanding their range of CIS products for space and ground based applications, building in areas where CIS and CIS systems have a natural advantage. e2v welcomes partnerships with key system stakeholders to identify and match stakeholder requirements to appropriate technical and market solutions.

[1] http://oatao.univ-toulouse.fr/4844/1/Martin-Gonthier_4844.pdf
[2] http://www.eumetsat.int/website/home/Satellites/FutureSatellites/MeteosatThirdGeneration/index.html
[3] http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1346815
[4] Radiation Effects on Optoelectronic Detectors Workshop – 28th-29th Sept. 2012 Toulouse France
[5] Unpublished report
[6] http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1267928
[7] Unpublished report
[8] http://www.e2v-us.com/shared/content/resources/File/documents/imaging-space-and-scientific-sensors/Papers/geary%20SPIE%208446-241_TAOS_CMOS_r2.pdf
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