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Ge on Si Feasibility Executive Summary

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The focus of study is to see if it is possible to build near-infrared (NIR) capability onto silicon CCDs (Charge Coupled Devices) for Time-Delay-Integration (TDI) applications, with the main driving force being the ability to do charge domain summation at wavelengths beyond 1µm. TDI is where devices pass collected charge, without loss or addition of noise, along the length of the detector, in the opposite direction to the motion of the spacecraft, allowing multiple integrations of the same signal prior to readout. This technique is currently used on the Gaia mission, which revolves at the same speed as the charge is transferred from pixel to pixel. No product exists that can do this in the NIR waveband. Current NIR sensitive devices have to sum individual pixel values post-conversion (either to voltage or digital values), usually off-chip, leading to an increase in noise and signal.

The activity investigates the feasibility of producing a germanium on silicon CCD to be used as a NIR sensitive TDI device for future missions and applications, including the proposed GaiaNIR mission. The requirements for this mission have been summarised and germanium on silicon CCD and other competing technologies have been considered.

Silicon CCDs are a well-established technology which, whilst being an “old” technology, are still world leading in certain applications up to a wavelength of ~1µm. Silicon CCDs supplied by Teledyne e2v are a key component on the ESA Gaia mission and there is desire for similar detectors that are sensitive in the NIR for a potential future GaiaNIR mission.

Germanium has been chosen to be the candidate photodiode material for this work due to several reasons. The first and most important is that it is sensitive in the NIR range, and with the addition of tin (to make germanium-tin) has a sensitivity up to 1.9µm, the cut-off of the detector currently baselined for the GaiaNIR mission. The second is that high quality germanium can be grown on silicon, with this being done already for other types of devices. Finally, the semiconductor physics of the silicon-germanium junction allows electrons to flow from germanium into silicon with little or no barrier. The band-structure of other IR materials and silicon typically result in an energy barrier so good transfer across the junction is not possible.

Analysis suggests that the growth of 2µm thickness of germanium on top of the active Si part of a CCD should allow the detection of photons out to about 1450nm wavelength at a temperature of 125K and with an absorption efficiency of ~70%. The efficiency can be increased by increasing the germanium thickness, raising the operating temperature or by incorporating tin into the germanium (although this will increase dark current due to the reduction in band gap).

Due to the lattice mismatch of germanium and silicon there will be defects in the deposited germanium and dislocations may also be produced in the underlying silicon. These will not be in the CCD buried channel and as such, they will not affect the charge transfer of the CCD. The defects will affect however, the transfer of charge from the photodiode to the CCD, resulting in a tail of signal following a bright object.

The one area that is most difficult to predict until devices are produced is the dark current. The dark current of germanium is several orders of magnitude higher than that of silicon for a given operating temperature (due to the narrower band-gap and significantly lower electron effective mass). There are methods that can improve the dark current but the reality is that devices will have to be made to determine the magnitude as it will be strongly dependent on the design and fabrication processes.

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The key to the successful operation of a germanium on silicon CCD for a TDI mission may be finding an operating temperature where the germanium (or more preferably germanium-tin) photodiode dark current is low enough but operated at a high enough temperature such that the performance of the silicon CCD does not degrade. Silicon CCD performance could be limited by an effect called carrier freeze out (where the transfer of electrons becomes more difficult at low temperatures) or by the introduction of defects by radiation. Potential effects at very low temperatures in CCDs have not been the subject of much study due to their limited effect at the higher temperatures generally used.

Alternative technologies have been considered with germanium CCDs being of particular interest. For CCDs fabricated completely in germanium the carrier freeze out temperature is lower than for a silicon CCD, allowing the germanium CCD to be cooled to a lower temperature and so reduce the dark current. A fully germanium composition also means that there are no defects resulting from lattice mismatch. However, there are two disadvantages of germanium CCDs over the germanium on silicon approach. Firstly, it is a very new technology, the TRL (Technology Readiness Level) is very low when compared to that of silicon CCDs which have flown on space missions for several decades, and the understanding of the performances and limitations of such detectors is still in the very early stages. Secondly, there is a potential limitation on the cut-off wavelength. Since germanium CCDs are built on single crystal, the availability of germanium-tin may be limited as it is likely that the high temperature processing steps that would be required following a front-end germanium-tin deposition would cause precipitation of the tin and so severely affect performance. This is not an issue for germanium on silicon CCDs as the high temperature processing steps will have already been performed before the deposition of germanium/germanium-tin.

The next steps for this technology should include engaging with the authors of the GaiaNIR study report and other potential users to provide further input into the possible use of a TDI device with low noise but higher dark current, as this is the most likely product that would come from any efforts to manufacture a germanium on silicon CCD. If it is considered that this type of device could be suitable then there are two key further subjects of study. Firstly, the design, manufacture and characterisation of germanium photodiode test structures to assess the technical viability. Secondly and perhaps just as important, is the study of silicon CCDs at lower temperatures to understand the operational limits that could impact the performance of potential future Ge-on-Si CCD detectors.

In summary, the study investigated the feasibility of building germanium photodiodes into already existing silicon CCD technology (including existing industrial processes). It was found that, with further development, this could potentially be a very good candidate for the proposed GaiaNIR mission and other extended waveband TDI applications, being both sensitive in the NIR up to 1800nm and able to operate in TDI mode, a combination which is not possible with any currently available technology.