D3.9.1 Detailed laboratory characterisation of the LSST sensors, enabling sensor responses to be quality controlled, calibrated and modelled

WP3.9 LSST Point Spread Function, sensor characterisation and modelling

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1 Executive Summary

This deliverable consists of two reports presented as conference contributions to SPIE (The international society of optics & photonics). They are the result of experimental investigations into various performance parameters of the CCD250 sensor as used in the LSST camera focal plane, and performed in the Oxford OPMD lab. Though the title of the deliverable is very broad, we have focussed on some specific operating parameters of the sensors which have not been deeply investigated by other collaborators in the LSST project or in the LSST DESC (Dark Energy Science Collaboration). Short summaries of the content of the proceedings are provided in the this document. The intention is to submit expanded versions of these papers to be peer-reviewed and published in the journal JATIS (Journal of Astronomical Telescopes, Instruments and Systems) in 2021. The data needed for the proposed expansions is described in this document, and mostly already exists, with some small data acquisition parts having being de-scoped from WP3.9.1 (due to COVID related delays) and moved into either WP3.9.2 or WP3.9.3, as relevant.

In the first part of the deliverable ("the effect of CCD gate width on the brighter-fatter effect"), we present the results of varying the effective physical width of the CCD parallel phases, by means of using different number of parallel phases during charge integration. We analyse the size of the brighter-fatter effect in flat fields and spot projections at each gate width, and find that this parameter is important. In particular we find for high back bias that the larger experimentally accessible gate widths are preferred.

In the second part of the deliverable ("A study of the silicon divacancy defect in the E2V LSST CCD250 using the single trap pumping method"), we report the results of a study on the parallel CTI of the CCD, by means of locating and analysing the individual silicon defects present in the device. Such a study is useful for deciding on parallel transfer timings, and to make sure that there are not unexpected defects present in the ultra high resistivity silicon used to construct the device. To our knowledge, such a study has not been conducted on this type of silicon previously. We did not find evidence of the presence of new defect types, but as expected we found that the principle defect type present at LSST camera relevant operating conditions is the silicon di-vacancy trap.

2 Introduction

2.1 Purpose

The focal plane of the LSST camera consists of 189 CCD image sensors, each with with 16 400 384 square pixels of 10 μm a side. Around half of these sensors are the TE2V CCD250 model, and around half are ITL/STA 3800. In the Oxford OPMD lab we have access to an early prototype version of the CCD250, which has important process and technical differences to the final version used in the LSST focal plane, though none that we believe are salient to the studies we present in this deliverable, which depend on the bulk properties of the silicon substrate (in the case of single trap pumping), and the properties of the pixel array physics (in the case of the gate width effect), whereas to our knowledge the principle changes between prototype versions of the CCD250 and the final version were in the areas of the peripheral amplifier circuitry, the backside processing and the coatings. Hence, we present results on some experimental lab studies we conducted during Phase B to investigate particular performance parameters of interest in the CCDs.

In Section 3 we discuss the effect of changing CCD gate width on the brighter-fatter effect. The full paper should be consulted for detailed experimental details and results[1]. In Section 4 we present the analysis of single-electron trap silicon defects which cause (part of) the observed CTI in the devices. Again, fuller details and results than presented here are found in the SPIE paper[2] In section 5 some details of software tools which have been developed to assist in the acquisition and analysis of this data are presented (these are not discussed in the published technical papers at all). In Section 6 the future work connected to this deliverable are presented. Some of this future work was intended originally to be part of WP3.9.1, but were removed from this deliverable due to delays in lab work arising due to the COVID-19 pandemic. Where appropriate we have moved some of this future work to WP3.9.2 and WP3.9.3, and in most cases it fits well within those areas without substantial amendment of those sub-workpackages.

This summary document should not be regarded as the content of the Deliverable itself, but taken together with the reports referenced.

2.2 Background and Previous Work

The overall effort within both the LSST project and the Dark Energy Science Collaboration (DESC) to characterise and correct for instrument signature in general, and sensor effects in particular is large and long-running. Work on standard tests at full focal plane scale is carried out at Stanford Linear Accelerator Center (SLAC), and tests on the readout electronics is carried out in detail at Paris LPNHE. Earlier individual sensor acceptance testing was carried out at Brookhaven National Lab (BNL). In order to not duplicate effort, we focus in our work on particular examples of sensor effects or operating parameters which we believe have not had a great deal of effort applied by these two groups. The “standard” batch of tests performed on individual sensors and within the focal plane in total include (but this is not an exhaustive list):

- Camera gain via Fe-55 and photon transfer curve
- read noise and saturation (also via photon transfer curve)
- Amplifier non-linearity (via photon transfer curve)
- serial and parallel charge transfer inefficiency at 2 signal levels (via EPER method)

- Quantum Efficiency at various wavelengths from 350nm to 1000nm (via repeated flat field illuminated images at individual wavelengths)

- Pixel Response Non-Uniformity at 2 signal levels (via so-called “superflats” – flat field imaging derived from over 1000 individual exposures

For a summary of the general camera testing we refer the reader to [4] and references therein. For a fairly recent investigation in particular of the CTI issues, on which our work on trapping bear some relevance, we direct the reader to

2.3 Glossary of Acronyms

BFE – Brighter Fatter Effect

CCD – Charge Coupled Device

CTI – Charge Transfer Inefficiency

DESC – Dark Energy Science Collaboration

EPER – Extended Pixel Edge Response

ITL/STA – Imaging Technology Laboratory/ Silicon Technology Associates

LSST – Legacy Survey of Space and Time

TE2V – Teledyne - E2v

3 Gate Width Study

The adjustment of CCD gate width has an effect on the magnitude of the BFE, which causes changes in the observed shape of compact sources, which is potentially highly relevant in particular for weak lensing studies. In our investigation [1], we used both flat field and spot illumination projections at different back bias and gate width settings to investigate this.

We find that for the non back-biased operation case, there is a highly significant difference in altering the gate width between 3 micron & 7micron, with 5 micron found to reduce the BFE more effectively. However, the LSST camera will not be operating in a non back-biased situation. For a highly biased case, we find again that altering gate width has significant impact on the measured brighter-fatter effect coefficients, though in this case the advantages are less clear cut: In some settings we were able to reduce nearest neighbour brighter-fatter coefficients, whilst the overall magnitude of the brighter-fatter effect sometimes increased, due to “pushing out” the correlations to further distant pixels. In general, for the high biased case, we certainly find that gate width choices wider than the minimum available result in substantially reduced magnitudes of the BFE.

In analysing the data for this investigation, we believe to be the first published “downstream” users of the very useful analysis of the shape of photon transfer curves by Astier et al [3], which very effectively constrains and fits the non-linear shape of measured covariances to experimental data.

4 Single Trap Pumping Study

The silicon di-vacancy trap is a single electron trapping species present in all CCDs, and is part of the mechanism which causes CTI, in particular in the parallel direction but also in the serial direction. The serial direction CTI in particular is an ongoing issue in the LSST camera project at present, including discussions about both the nature and size of the effect, and mitigation strategies. It is clear that many final article CCDs in the LSST camera suffer from additional, non-trap based CTI mechanisms in the serial direction (indeed, a correction for this was needed for the study described in Section **Error! Reference source not found.**, and is thus described in detail in [1]). In our study, however, we concentrate on studying the underlying cause of the part of the CTI which is caused by trapping. This is of interest because, although it was not anticipated to highlight any particularly novel or completely unknown results, we were unable to find a prior study investigating these traps in a device of similar construction to the LSST sensors (i.e. a thick device built on high-rho bulk silicon).

We investigated the emission time constants and number of traps over a very wide temperature range (-100 to -30 celsius), and as wide an emission time range as was practicable (from <20μs to >1000μs) [2]. Because we are using an unirradiated device, the density of trapping sites is (as expected) very low, and this low density prevents a statistically useful investigation of traps in the serial register regions of the device. However, the physics of the traps themselves can be reasonably assumed to be identical in the pixel and register regions, so any parameters extracted may be useful in both cases.

We find that, as expected, the dominant trap species at LSST camera operating conditions (i.e. 95C) is the silicon di-vacancy trap. In particular we identify the emission time constant of this trap at the temperature of interest, which points towards the timings that could be used in mitigating trap based CTI as far as possible.

Though it was not used in the published report [2], we have also collected a very large “efficiency” data set, which measures the density of traps vs signal level at several different phase times and many different temperatures. We intend to use this dataset in further investigations (as part of WP3.9.2 & WP 3.9.3) as it provides an indirect volumetric probe of the charge density in the stored pixel charge packet.

5 Software Tools Development

As part of the setup of our experimental setup and analysis of data, several software packages have been developed since Phase A & continuing into Phase B. None of these are public releases yet, though we do intend eventually to release publicly some components which might be of wider use. Most of these software packages are developed internally on the Oxford Physics internal Gitlab server, which we later mirror to the LSST-UK repositories on Github.

1. **Foxtrot** – this is a simple hardware abstraction layer and networked device server written in c++, built to handle the case of needing multi-threaded access to experimental equipment from multiple client programs, though without a central co-ordinating server or database (as is the case in e.g. Tango or EPICS). It is available at https://github.com/lsst-uk/foxtrot
2. **OPMD-acq** – series of experimental acquisition scripts and framework for dumping data and metadata from camera captures on our teststand, which uses foxtrot to access hardware. Available at https://github.com/lsst-uk/OPMD_acq
3. **OPMD-eotest** – first stage reduction and analysis of image and trapping data, which ideally would be superseded by upstream LSST-DESC eotest utilities, but we have not had time to make that migration yet. Available at https://github.com/lsst-uk/OPMD_eotest

In addition to the above packages, there is some internal analysis code for both trapping and gate width analyses as presented in this deliverable, which is not yet in a state for even internal release, though we believe in particular that the code which analyses PTC curves in accordance with Astier’s formula [3], would be a useful tool to release more widely, and we are aiming to reach this goal in the coming months.

6 Future Extensions – moved to WP3.9.2 & WP3.9.3

6.1 Gate Width Study

To add to and enhance the findings of the published gate width study, we intend to run a few more short experimental runs, covering the gaps in the parameter space which we had so far not had time to do. This is simply a case of running some more runs of existing experimental setups, and in WP3.9.2 there is plenty of activity that does not require the lab setup, which means this can be done quite simply in the near future, ideally being added to the paper[1] when we attempt to expand it to a full JATIS publication.#

As part of WP3.9.2 & WP3.9.3, we aim to have physically based pixel level modelling of LSST pixels, which should then be able to corroborate the experimental results already published here.

6.2 Trapping Study

As mentioned in Section **Error! Reference source not found.**, we have available to us a large "efficiency" dataset which presents many interesting possibilities for volumetric probes of charge density. We will aim to use this dataset as part of our simulation and modelling work in WP3.9.3.

In addition, we need to demonstrate directly that our proposed timing solutions for reducing trap based CTI actually work. This would involve collecting a small subsidiary dataset using two differently selected parallel timings to observe whether the optimal timings predicted from the single trap study translate into direct CTI measurements. This type of study has been done several times by other authors for other projects, it is a fairly quick dataset to acquire, and we do not anticipate major effort being expended here, though it would be useful and a great improvement to the deliverable when we aim to publish this study in an expanded form as a full JATIS paper.

7 References

[1] Weatherill, D. P.; Wood, D.; Shipsey, I.; Plackett, R.; Loreti, A.; Metodiev, K.; Mironova, M. and Bortoletto, D. (**2020**). *Measuring the impact of CCD gate width on the brighter-fatter effect*, **https://doi.org/10.1117/12.2562730**.

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[3] Astier, P.; Antilogus, P.; Juramy, C.; Breton, R. L.; Guillou, L. L. & Sepulveda, E. The shape of the photon transfer curve of CCD sensors ***Astronomy & Astrophysics, EDP Sciences,*** 2019*, 629*, A36 **https://doi.org/10.1051/0004-6361/201935508**

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