Sensor Testing & Characterisation

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Introduction

In WP 3.9, we focus on modelling and testing the sensors in the LSST camera in order to predict and optimise the performance. Many of these parameters are important, the physics of how the sensor's construction and operating parameters affect them are well known, and it's fairly obvious what they represent in terms of scientific imaging: readout noise, linearity of signal with incident flux, the quantum efficiency of the sensor across various wavelengths, dark current accumulation rate and so on. Then there are a few parameters which depend much more subtly and sometimes sensitively on sensor operation and manufacture: the diffusion broadening of the detector PSF and the charge handling capacity (often referred to as "full well") of the pixels being two examples. Whilst we do measure and think about these metrics in WP3.9, in this article I want to focus on one of the much more obscure detector performance metrics which is a current focus of research in the Oxford Physics Microstructure Detector (OPMD) laboratory. The explanations of why astronomers should care about these things are perhaps rather indirect, but I hope nonetheless readers will find it interesting why we might investigate them. We are always happy to talk about and answer any questions we can about the operation of LSST camera and the sensors in particular, please contact myself (daniel.weatherill@physics.ox.ac.uk) or Ian Shipsey, the PI of WP 3.9 (ian.shipsey@physics.ox.ac.uk), for discussion, or join us at the weekly LSST:UK hangout on Slack at 10:00 UK time. The work presented here has been greatly benefited by the involvement of my colleague Dan Wood, also at Oxford, who does not work funded by LSST:UK but is an expert in the area I'm discussing today. None of this is published yet, though we are aiming to present this work in a much more complete form as one of the two papers we present at SPIE Astronomical Telescopes and Instrumentation 2020.

Trapping

Charge Transfer Inefficiency (CTI) is perhaps the main sensor effect which is quite unique to CCDs (as opposed to other solid state imaging sensors). The CCD operates by collecting charge in pixels, and then physically moving this charge during readout to an amplifier. This design allows the CCD to maintain effectively a 100% sensitive area in the pixels, unlike an active pixel sensor (which is the type of imager that is now prevalent in digital cameras, mobile phones etc). However, the charge transfer process is not completely efficient (though in modern devices it is quite literally more than

99.999% efficient): sometimes an electron in a charge packet can be temporarily "left behind" and appear in a pixel which is behind that where it arrived when it reaches the readout amplifier.

CTI is the cause of the "trails" behind bright objects which are evident in uncorrected images from space based instruments after several mission years: in those cases, the harsh radiation environment (in this case it is particularly "displacement damage" from e.g. high energy protons) of space causes CTI to get progressively worse over time, and indeed this is the chief radiation damage mechanism which limits the lifetime of CCDs in space (see Figure 1). Of course, in the ground based environment of the LSST camera we don't expect substantial radiation damage throughout the survey lifetime, and so CTI is not in itself the most concerning performance issue for the camera. Modern devices can achieve extremely low CTI at manufacture time (orders of magnitude better than the first devices from the 60s and 70s).

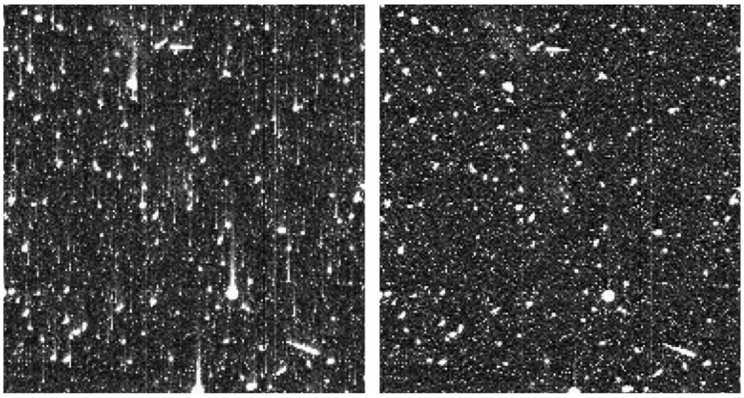

Figure 1: Figure 1: Example of a Hubble WFC image (HST-GO-11689) before (left) and after (right) CTI correction, from [Massey 2010]

However, CTI is still a concern for the LSST camera team, for two reasons

- Though the CTI of the devices is excellent, the astrometric and photometric precision required to meet the science goals of the Rubin Observatory demand it to be so, therefore we must make sure that we minimise CTI (below the requirement of 1E-5) as far as possible without negatively impacting on other more important performance parameters. Large area devices with many pixels require good CTI performance, as the charge packets must be transferred more times for readout than smaller devices (for more about the CTI requirements on LSST sensors, see [Radeka et al. 2009])
- CTI produces correlations between pixel values, similar to the "brighter-fatter effect" (BFE) which you may have heard of, and which I will likely make the subject of a future article. These correlations are produced during readout as opposed to during charge collection, so are of a different nature. Nevertheless the existence of CTI based correlations hampers somewhat our ability to accurately calibrate and correct for the correlations caused by the BFE ([Antilogus 2019])

There are actually a few well known physical mechanisms causing CTI, and the LSST CCDs in particular have a very curved register shape design which sometimes can cause electrons to "fall off" the edges whilst in transit, a major contributor to CTI (and this is being very well investigated by our colleagues at SLAC). However, the main cause of most CTI issues has long been recognised as the existence of "trapping centres" within the silicon lattice. Several species of these are known and have been studied for decades (because the same trapping centres cause other issues in other kinds of microelectronic devices). Essentially, these trapping centres all share something in common: they provide a near-band edge empty state where mobile electrons can be captured ("trapped" in place), and then sometime later the electron is thermally released back into the conduction band. At a certain temperature, a certain trap species will have a characteristic emission time, and a capture time which depends on the local electron density among other things. The capture time is generally much shorter than the emission time, and in the past it has thus been the emission time which has largely been studied in connection with CCD performance.

A method known as "trap pumping" has been used since the mid 90s (popularised originally, as seemingly every familiar test in the CCD world was, by Jim Janesick) to study these silicon defects in CCDs. In recent years the technique has evolved greatly thanks to the work of researchers at The Open University in the UK, at ESA ESTEC in Noordwijk, and at NASA Goddard in Maryland, [Hall,Murray,Holland,Gow,Clarke & Burt 2014] and is now a staple tool used in qualifying CCDs for space missions, though it's not been used to our knowledge for any ground-based project before. The technique has several subtleties and difficulties which there isn't space to cover here, but in essence it is very simple: we inject some known amount of charge into every CCD pixel, and then repeatedly transfer the charges back and forth in the CCD, with a known timing. We typically do this shuffling 50000 times per image in our testing. We see a characteristic shape of a bright pixel next to a dark pixel emerging, which shows that a silicon trap has "pumped" charge from one pixel to another – see Figure 2. By varying the rate at which we shuffle (the "phase time" as we call it), we can observe how readily a particular trap captures electrons, and thus work out the emission time parameters of the trap (see Figure 3). I should emphasize here that we believe that each of these traps are **individual** defect centres in the silicon lattice (there is very good evidence for this, but it would require another lengthy article to do justice to!). There is a lot of interesting physics in the traps themselves (relating to extracting other parameters of the device indirectly such as the size of the charge packet based on capture time) which we are also working on in OPMD and may be the subject of a future article but for now I will talk purely about the most common measurement that is done with these datasets, which is the "trap landscape". We repeat this procedure of measuring the emission times of traps over a large temperature range (indeed we believe this particular experiment is the widest temperature range ever attempted in such a measurement), which allows us to plot a graph of temperature vs trap emission time. In total, collecting this data took a couple of solid months on our LSST test stand in 2019 - see Figure 5 (we had to acquire many temperatures, over many phase times, and for technical reasons had to repeat each one 4 times due to different clocking configurations available in the e2v CCD250). With 50000 pumping cycles, at the longer phase times each image can take several minutes to obtain, even when the exposure

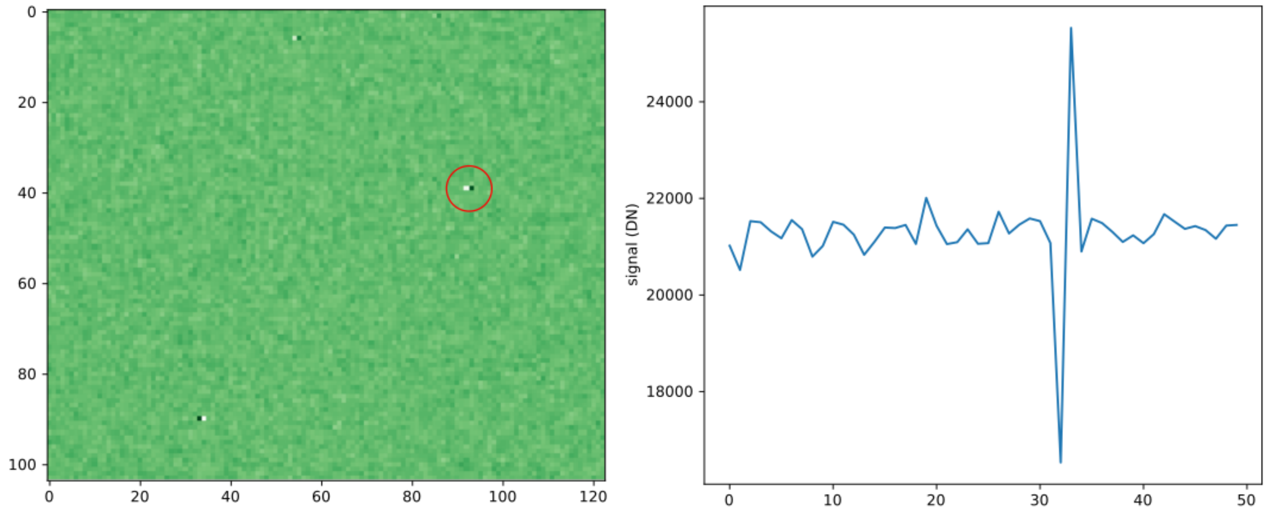

Figure 2: Example of "pumped" traps in a flat field image - taken at -95C, phase time 340 us. (Left panel)– a section of image with some pumped traps clearly visible, and one highlighted by a circle, (Right panel) – a slice through the image on row 40, the trap can clearly be seen

time to inject the charge is only 2 seconds. We repeat the exact same image several times to somewhat suppress shot noise and fixed pattern noise in the analysis by averaging. We also have to correct for several other side effects, such as the increased dark current which we incur at the longer emission times (simply due to them taking longer to obtain).

In this landscape, each type of trap shows up as a characteristic peak (Figure 1). We have thus determined that, largely as expected, at LSST camera operating temperature (of -95C) the most worrying trap species for us is the silicon di-vacancy (two “missing” silicon atoms in the lattice in neighbouring positions). It was necessary to do this experiment to make sure, and we were also concerned that nobody else seemed ever to have performed such a study on a high resistivity device

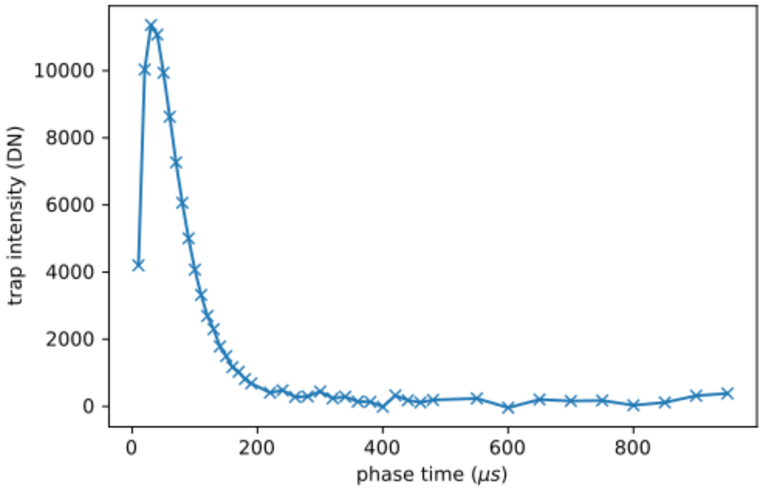

Figure 3: A plot of a particular trap at -95C across many phase times. Note the phase time is not identical to the emission time, but a curve can be fitted to determine emission time from phase time

constructed on bulk-type silicon (as used in the LSST camera), which we thought may have changed the trap species present substantially.

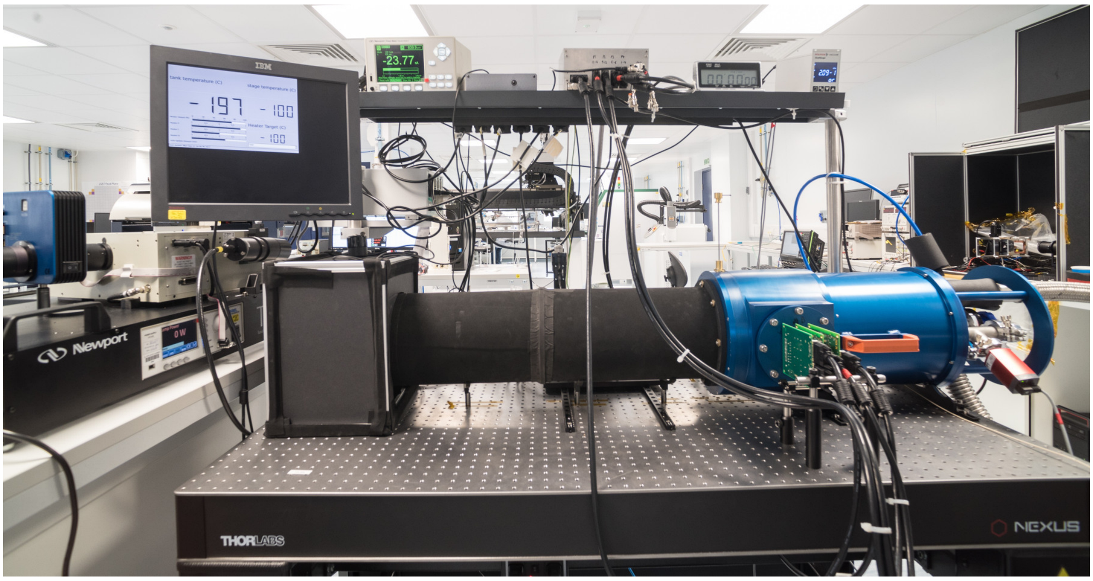

Figure 5: The LSST hardware test stand in the OPMD lab, from [Weatherill,Arndt,Plackett & Shipsey 2017]

Luckily, in the LSST camera's case, since it is on the ground and will not experience a large increase of trap centres over the mission lifetime, we believe that the CTI caused by these traps can be reduced substantially, simply by choosing a timing sequence for the camera readout which does not contain any timings which are harmonically related to the trap emission times. Such a strategy (choosing timing constants and indeed operating temperatures) is also involved in mission planning for modern space missions, e.g. EUCLID, for exactly the same reasons. In those cases, it is much more difficult, because we also have to take into account what traps will be present years down the line and attempt to shape our timing sequences to avoid them as much as possible as well. On the other hand, since EUCLID is operating at a much lower temperature than LSST, the trap species that must be mitigated against are different than those which are present in the LSST camera.

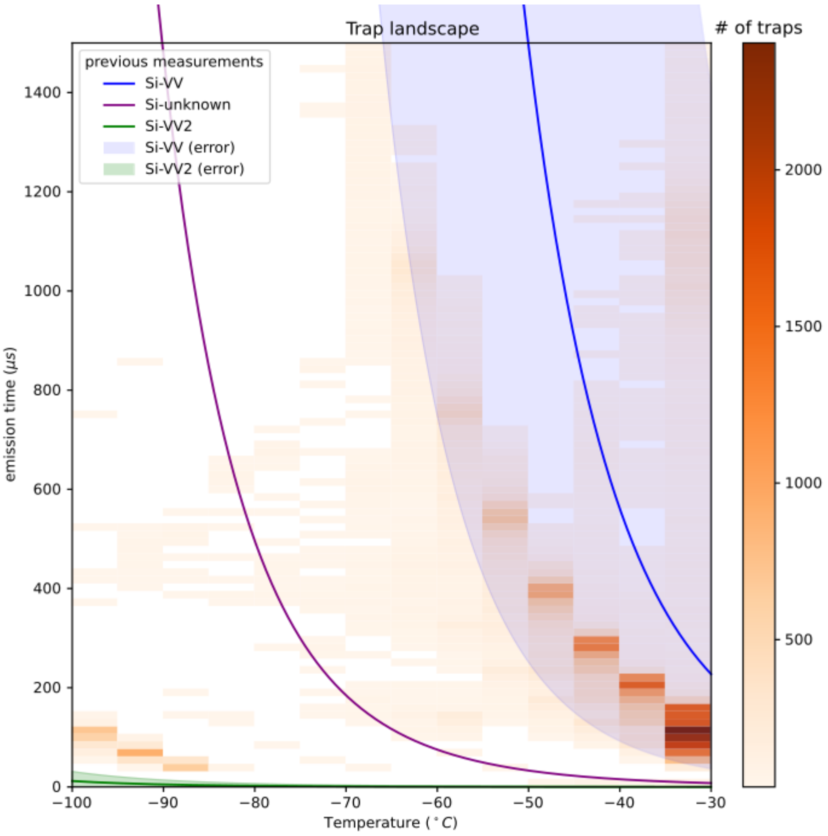

Figure 4: The trap landscape of the un-irradiated e2v CCD250 sensor

Note that we have overlaid on our trap landscape the previously published values for some known silicon traps (the one labelled “unknown” is only unknown in the sense that we have no idea what the exact solid state physics of this species is, we certainly know that it exists and have done for over 20 years). It is somewhat concerning that our measured trap lines do not closely match those previously published, but again we emphasize that most previous studies have been at very different temperature ranges, and that some of the factors (and their own temperature dependence!) that go into calculating these theoretical curves are extremely loosely constrained by previous work.

Our next steps in this area will be to carefully construct two timing sequences: one that we expect to be very “bad” for CTI given our trapping findings, and one that should be very “good”. We will run standard test sequences for spot and flat field images using these sequences and hopefully show that taking the trapping times into account will be able to improve the CTI performance of the LSST camera.

References

References

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