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PRECISION ASTRONOMY WITH FULLY DEPLETED CCDs

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Properties of tree rings in LSST sensors

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ABSTRACT: Images of uniformly illuminated sensors for the Large Synoptic Survey Telescope have circular periodic patterns with an appearance similar to tree rings. These patterns are caused by circularly symmetric variations of the dopant concentration in the monocrystal silicon boule induced by the manufacturing process. Non-uniform charge density results in the parasitic electric field inside the silicon sensor, which may distort shapes of astronomical sources. In this study we analyzed data from fifteen LSST sensors produced by ITL to determine the main parameters of the tree rings: amplitude and period, and also variability across the sensors tested at Brookhaven National Laboratory. Tree ring pattern has a weak dependence on the wavelength. However the ring amplitude gets smaller as wavelength gets longer, since longer wavelengths penetrate deeper into the silicon. Tree ring amplitude gets larger as it gets closer to the outer part of the wafer, from 0.1 to 1.0%, indicating that the resistivity variation is larger for larger radii.

KEYWORDS: Detectors for UV, visible and IR photons; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Systematic effects

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1 Introduction

1.1 Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST) is a 10-year optical survey of the Universe designed to study four principal areas: Dark Matter and Dark Energy, the Solar System, the Transient Optical Sky, and the Milky Way. The telescope is under construction in Chile and will be ready to take data with its 3200-megapixel camera from 2022. It will cover 20,000 square degrees, recording images of ten billion galaxies in six bands: u , g , r , i , z , y . The focal plane of the LSST Camera consists of 21 Science Rafts, with each raft composed of nine $4k \times 4k$ CCD sensors. Therefore, more than 200 CCD sensors (including 4 corner rafts and 2 engineering test units) are needed. Most of these sensors will be tested at Brookhaven National Laboratory (BNL).

The Dark Energy Science Collaboration (DESC) will analyze the LSST data aiming to study cosmology, and SAWG (Sensor Anomalies Working Group) within DESC, is studying how these CCD sensor effects may limit the precision in the measurement of cosmological parameters made by LSST. SAWG aims to develop correction procedures and investigate the residual systematics caused by CCD sensor effects. In this work we study an important sensor effect called “tree rings”.

1.2 Origin of tree ring patterns

The manufacturing process of growing a single crystal silicon boule leads to a circularly symmetric variation of dopant concentration inside the silicon, which results in the tree-ring-like patterns visible in images taken at a uniform illumination [1–4]. Variation of the dopant concentration causes a parasitic electric field in the direction orthogonal to the drift of photoelectrons, hence the shape of sources could be distorted based on their location on the sensor. Figure 1 shows a small area (400×400 pixels) of the sensor ITL-3800C-107 in the outer part of the wafer where the tree rings are easily visible. ITL sensors are described in detail in another contribution to this workshop [5].

Figure 1. Small area, 400×400 pixels, of the sensor ITL-3800C-107 to illustrate the tree rings in two different representations.

Figure 2. Layout of the silicon wafer. Because the wafer is cut into four sensors, tree rings on each sensor will have four possible orientations.

The silicon wafer is cut into four sensors hence there are four types of tree ring orientation depending on its position on the wafer. The gap between two neighbouring sensors is 4 mm, see figure 2. The geometry is well known and the dicing process is very precise, with only a few micron uncertainty, so the tree rings from sensors on the same wafer should have a common center. This was used in the following analysis to calculate the center of the rings more accurately. A comparison of tree rings that come from different sensors originating from the same wafer will be discussed in section 3.3.

Figure 3 shows examples of flat images with tree rings from four sensor types discussed above. ITL-3800C-022 (die2, (b)) and ITL-3800C-017 (die4, (d)) originate from the same wafer.

Figure 3. Examples of flat images recorded for sensors ITL-3800C-021 (a), ITL-3800C-022 (b), ITL-3800C-032 (c) and ITL-3800C-017 (d). Red dots are the points on radius of 4400 pixels. Sensors in (b) and (d) originate from the same wafer.

2 Methods

2.1 Reduction of flat images

Each image is composed of 16 segments, corresponding to different sensor amplifiers. The data also includes an overscan region for each segment, which was used to remove the amplifier offsets. After assembling 16 segments, AstroCCD [6] code was used to emphasize tree rings in the images. The code subtracts the mean flux in each amplifier segment, and selects the high frequency patterns only to suppress other effects. After that, a contrast of the resulting image was adjusted for the best presentation.

2.2 Finding the center of the tree rings

To find the center of the ring, three points on the ring were picked by eye, then the center of the circle was calculated so the circle with that center crosses all three points. To make this calculation more precise, we repeated the process with several rings on the same sensor and also used the 4 mm gap between the sensors to drop unreasonable calculations.

2.3 Measuring amplitude and period of tree rings

The image size for each sensor is 4072 pixels by 4000 pixels and data files are composed of x , y , and flux at the position (x, y) . Based on the calculation of the ring center, we converted flux at each (x, y) point to flux at each radius r . The flux values were averaged along the rings over the same radius to improve precision and integrate out variations from other effects. This allowed for presentation of the ring amplitude as function of radius from the ring origin. In total, two thousand points were measured over the radius range from 0 to 6000 pixels.

We defined maximum peak as a center point with two lower adjacent points. The definition of minimum peak value is the opposite. Maximum and minimum peak values are measured locally period by period.

The sensor's tree ring peak-to-peak amplitude was measured by subtracting a local minimum value from an adjacent maximum value as illustrated in Figure 4. This peak-to-peak amplitude will be referred in the following simply as "amplitude". The tree ring period was defined as the distance between local maximum peaks.

Figure 4. Definition of maximum/minimum peak values and peak-to-peak amplitude.

3 Results

During the electro-optical tests at BNL, the flat (uniformly illuminated) monochromatic images are taken from 320 nm to 1100 nm with 10 nm steps. The images at 770 nm were selected to measure the amplitude of tree rings for 15 ITL sensors. Flats for the sensor ITL-3800C-017 at 320, 400, 540, 770, 850, 900, 970, and 1080 nm were used for the analysis of the wavelength dependence. Flat images with different wavelengths are shown in figure 5. Structures in the 320 nm image are explained by much shorter penetration of UV light into the sensor, which then becomes more sensitive to the surface unevenness. Fringes in IR originate from the varying thickness of the silicon wafer. In the shorter wavelength region, before fringes start to dominate, the tree rings are visible, caused by variation in the wafer resistivity as discussed before. Fringe pattern starts to dominate over tree rings around 880 nm and shows maximum impact around 970 nm.

Figure 5. Uniformly illuminated images for the sensor ITL-3800C-017 taken at different wavelengths: 320, 400, 540, 770, 850, 900, 970, and 1080 nm (from top-left to bottom-right).

3.1 Radius dependence

The tree rings become apparent around a radius of 2500 pixels, then their amplitude gets larger as it approaches the outer part of the wafer typically increasing from 0.1 to 1.0% as can be seen in figure 6. This suggests that the resistivity variation is larger for larger radii.

3.2 Wavelength dependence

Relative flux variation as a function of the tree ring radius from 4800 to 5300 pixels for the sensor ITL-3800C-017 for the wavelength of 320, 400, 540, 770, 850 and 970 nm is shown in figure 7. For the images taken at different wavelengths, the tree ring pattern does not change considerably until approximately 880 nm, where the fringe effect starts to dominate. The tree rings shows some dependence on the wavelength, with amplitude changing from 0.27% at 400 nm to 0.20% at 850 nm. The amplitude gets smaller as wavelength gets larger because photons with longer

Figure 6. Relative flux variation as function of tree ring radius for the sensor ITL-3800C-017.

wavelength convert deeper in the silicon, so the respective photoelectrons have less distance to drift and are less affected by the parasitic electric fields induced by the tree rings.

As was demonstrated in figure 5, the shorter wavelengths are more sensitive to the nonuniformity of the surface. Nonuniformity of the surface affects the 320 nm line in figure 7 causing this line to not follow the behavior of other lines. The same argument is valid for the 970 nm line where the image is dominated by the fringe patterns. If averaging the flux along the ring was not applied to the data shown in figure 6, the lines at 320 nm and 970 nm would be dominated by surface

Figure 7. Relative flux variation as function of the tree ring radius from 4800 to 5300 pixels for the sensor ITL-3800C-017 for the wavelength of 320 nm (orange), 400 nm (green), 540 nm (cyan), 770 nm (blue), 850 nm (magenta), 970 nm (dashed red).

nonuniformity and fringing, respectively. However, due to this averaging procedure it is possible to see some subtle effects due to tree rings at these two wavelengths. Because this action does not perfectly cancel out other non tree-ring effects, one can still see some discrepancies between the 320 nm and 970 nm line with the other lines shown in figure 7.

3.3 Sensors from the same wafer

Among the sensors that were received and tested at BNL, there are three pairs of sensors originating from the same wafer: ITL-3800C-022 & 017, ITL-3800C-091 & 097 and ITL-3800C-145 & 107. For the first two pairs, the sensors are immediate neighbors on the wafer, while for the latter pair they originate from diametrically opposite positions of the wafer. The tree ring patterns of the three sensor pairs are compared in figure 8. One can see a clear correlation of the patterns for the sensors from the same wafer. The disagreement between the sensor pairs originating from the same wafer could come from variability during manufacturing and uncertainty in finding the ring centers.

3.4 Variability of tree ring parameters in ITL sensors

At the time of writing, 15 ITL sensors were analyzed using the approaches described above. The distributions of the maximum tree ring amplitude over the full sensor and median tree ring amplitude in the radial range of 5000 to 5500 pixels (so in the region with the largest tree rings) are shown in figure 9. The mean values for the maximum amplitude and for the median amplitude in the above range were 0.87% and 0.16% respectively.

4 Summary

Using uniformly illuminated images of LSST sensors produced at ITL, which were taken during the electro-optical testing at Brookhaven National Laboratory, we observed tree-rings patterns for all tested wavelengths. The tree ring amplitude appears to grow with the radius, suggesting that the variation of dopant concentration is larger in the outer parts of the wafer. The tree-ring effect shows weak dependence on wavelength, with the amplitudes getting smaller for longer wavelengths, explained by the fact that the longer wavelengths penetrate deeper into the silicon. Tree ring patterns for sensors originating from the same wafer are reasonably matched to each other. At the time of writing, data for 15 ITL sensors is available with mean value of the maximum tree ring amplitude of 0.87%.

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(a)

(b)

(c)

Figure 8. Comparison of the tree rings for sensor pairs originating from the same wafer. Relative flux variation as function of the tree ring radius in the range from 4500 to 5300 pixels for (a) ITL-3800C-017 (die4, red) and 022 (die2, blue), (b) 145 (die2, red) and 107 (die3, blue), and 097 (die4, red) and 091 (die2, blue).

Figure 9. (a) Distribution of (a) maximum amplitude over whole radial range and (b) median amplitude in radial range of 5000 to 5500 pixels for the sensors received and tested at BNL. Red dashed lines show the mean values.

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