Current status of CCDs for astronomical observations and a development of a large mosaic camera

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1 CCDs for Astronomy

Since early 1980's, CCDs have been used for astronomical observation replacing the conventional photographic plates. The advantage of CCDs includes high quantum efficiency (QE) and the good linear response against the light input. It enabled to explore strikingly deep universe [1]. Drawback was its relatively small size of the imaging area. Focal plane of the telescope is usually 10∼50 cm across and specially ordered photographic plates were used. Meanwhile, the size of early phase CCDs were $<\sim$ 1 cm and thus constrained the FOV significantly.

Synchronized with the rapid improvement of semiconductor technologies to manufacture CPUs and memories, the performance of CCD improved dramatically in many aspects such as the readout noise, the dark current level, charge transfer efficiency (CTE) and the cosmetics. Although CCDs became popular in commercail products such as camcoders, the direction of the developments were toward even smaller imaging area and finer pixel size to make the optics system of the products as compact as possible. This was completely opposite to the direction that astronomers wanted to pursue.

Thus, there appeared a astronomer's group who actually designed ideal CCDs for astronomy by themselves. Geary et al. [2] designed 2048 × 2048 (2k2k) with 15 μm pixel using a 'AutoCad' software running on a PC clone and asked the 22 wafers foundry run at Ford Aerospace. The type of the device is called 'Frame Transfer (FT)' where all of the pixel area is used both for the charge integration and the transfer. The pixel structure of FT CCD is simpler than other types like 'Interlace' where the integration and transfer area is separated by the transfer gate. Out of the 88 devices, 26 (30 %) devices were unshorted and showed excellent cosmetics with good CTE over > 0.999997. Although the readout noise level was not shown, the results were quite encouraging for astronomers. They, then, developed 2k2k 'Edge-Buttable' CCD where bonding pads were placed only along two sides and the pixels were placed very close to the other two sides. The final variant of this family was 2k4k three edge buttable CCDs [3] with 15 μm pixel that was manufactured by Loral. This format became a defacto standard of CCDs for astronomy over the decades.

1.1 Back illuminated CCDs

One of the biggest reason to build large telescopes is to increase the photon collecting power. Considering the costs to build and operate large telescopes, the demands on the QE of CCD detector is high. On the conventional front-illuminated (FI) CCD, most of the incident photons especially in the shorter wavelength (< 450 nm) are absorbed or reflected at the poly-silicon gate that covers front side the frame transfer CCD. Photographic plate, on the other hand, have the sensitivity up to this short wavelength. In order to compare with the legacy data accumulated by plates, the sensitivity in the short wavelength was highly required on CCD detectors. To avoid the absorption one flips the detector and makes the photon incident from the backside. This is called back-illuminated (BI) CCD. Stewart Observatory, University of Arizona, has a CCD detector laboratory where Lesser et al. pioneered the BI process for astronomical application and has been long serving to the community by providing small number but high quality devices [4].

1.2 Deeply and Fully depleted CCDs

QE in shorter wavelength is dramatically improved by the BI processing. The QE in red, on the other hand, drops because CCD membrane is transparent for longer wavelength photons. To improve it, required is thicker depletion layer where the lateral electric field exists for photocharge collection. Barry Burke at MIT/LL employed high resistivity p-type silicon and realized 40 μm thickness on

2k4k 15 μm device (CCID-20) [5] which is significantly thicker than conventional devices whose typical thickness of the depletion layer was < 20 μm. The device, CCID-20, was jointly developed by an astronomer's consortium led by Gerry Luppino, University of Hawaii and used in the various instruments for large telescopes; eg. Supreme-Cam on Subaru Telescope, DEIMOS on Keck telescope and CFHT12K Camera on CFHT. The device also features high responsivity amplifiers (15 μV/e) which enabled low noise readout (2-3 e) for slow rate (50 kHz).

Steve Holland at Lawrence Berkeley National Laboratory first fabricated CCDs on even higher resistivity (> 10 kΩ·cm) silicon [6, 7]. The n-type silicon wafer is used because it is easier to obtain high resistivity material. In this device the signal carriers are not conventional electrons but holes whose mobility is worse than electrons. This does not matter so much because the large format device of this type is typically read out very slowly ($\sim$ 150 kHz readout). They realized 300 μm thickness that improved the red response dramatically. This also suppressed the level of interference fringing due to the multiple reflection inside the silicon membrane.

Simulated by the pioneering works, Hamamatsu Photonics developed fully developed CCDs of 2k4k format with 15 μm pixel for Subaru telescope [8, 9]. In order to fully deplete the silicon across the 200 μm thickness, bias voltage of 50 V is applied which minimized the charge diffusion (rms) as well down to half a pixel size. When one chooses the thickness of devices one must consider the focal ratio (F) of the optics. Faster cone beams, which has wider opening angle, tends to have more dilute images in thicker device especially in the longer wavelength. In the case of Subaru prime focus, because the F/ratio of 2.0 is faster than that of other 4 m class telescope, moderate thickness of 200 μm was chosen by balancing the image size and QE.

2 Mosaic Imagers

As the telescope becomes larger, the focal plane becomes larger compared with the typical dimensions of CCD detectors. Therefore, CCDs have been configured in mosaics to cover the large focal plane.

SDSS photometric camera employed 30 of TK2048Bs whose field of view reaches up to 6 deg^2 mounted on the modified Ritchey-Chrétien SDSS telescope. Five different filters (u, g, r, i, z) are fixed just in front of CCDs and TDI operation are made across six CCDs with the same filter. The device has notorious convex curvature ($\sim$ 200 μm) toward incoming light and they coped with it by cementing a have Kovar stiffener on the back [10].

Subaru telescope uniquely features a wide field prime focus on large telescope (D >8 m). Suprime-Cam [11] was built using ten CCID-20. Coupled with the compact corrector with lateral shift ADC, the camera realized seeing limited imaging at Mauna Kea over 0.5 deg FOV. Thanks to the high QE in longer wavelength given by the high resistivity version of CCID-20, Suprime-Cam has been good at hunting high redshift galaxies in 2000's by using very narrow band filters tuned to the wavelength where OH emissions from the sky are low. Hyper Suprime-Cam (HSC) is a successor of Suprime-Cam which also features seeing limited imaging over ϕ 1.5 deg FOV . HSC adopts Hamamatsu's fully depleted (FD) CCDs (2k4k four-edge-buttable) whose thickness (200 μm) doubles the QE at 1 micron compared with CCID-20 (Figure 1). PAUCam also adopts Hamamatsu's fully depleted CCDs[12].

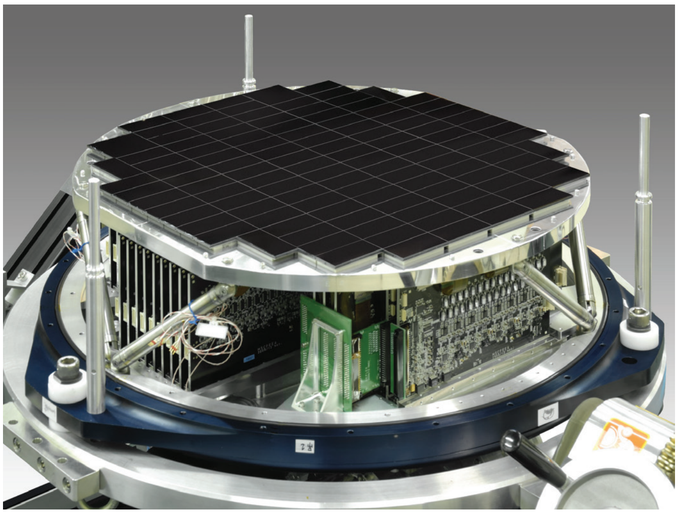

Figure 1. 500 mm diamter focal plane of Hyper Suprime-Cam paved by 116 four side buttable HPK CCDs

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