[Invited] CCD image sensor for astronomical applications

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Abstract We introduce our CCD image sensors for astronomical applications. We developed the fully-depleted thick back-illuminated CCD fabricated on the ultra-high resistivity n-type silicon wafer in collaboration with National Astronomical Observatory of Japan (NAOJ) for a new generation instrument for Subaru Telescope on Mt. Mauna Kea in Hawaii: a very wide-field CCD camera which named Hyper Suprime-Cam (HSC). The CCD format is 4-side buttable, 2k×4k 15μm square pixels with 4 low noise output amplifiers.

Keywords: fully-depleted thick back-illuminated CCD, 4-side buttable, Subaru Telescope

1. Introduction

For many years, Hamamatsu has developed image sensors for the measurement in broad wavelength and energy regions from infrared to visible light, to ultraviolet, vacuum ultraviolet, soft X-rays, and hard X-rays [1]. Back-thinned CCD area image sensors [2] are suitable for the low light-level detection because of their high UV sensitivity, high S/N, and wide dynamic range.

The sensors are extensively used in the biological, scientific and industrial fields such as the DNA analysis, spectrophotometry, and semiconductor inspection systems, as well as in the medical fields. Front-illuminated CCD area image sensors are used in the imaging and measurement in the visible and near infrared region. In addition to CCD image sensor, Hamamatsu provides CMOS image sensor, InGaAs image sensor and photodiode arrays to various fields.

2. CCDs for astronomical applications

Since 1990s we have been developing CCD image sensors in collaboration with NAOJ for the Subaru optical infrared telescope, with Osaka University and Kyoto University for X-ray astronomy application. The fluorescent X-ray spectrometer on board HAYABUSA (asteroid exploration), KAGUYA (lunar exploration) and MAXI (Monitor of All-sky X-ray Image onboard ISS) used CCD image sensors were supplied by Hamamatsu.

A group at Lawrence Berkeley National Laboratory (LBNL) developed a p-channel CCD on the high resistivity n-type silicon wafer [3]. Stimulated by the LBNL development and realizing the scientific importance of this type of detectors, we have developed an independent development project to build the same type of CCDs [4][5]. This kind of CCD is called as the fully-depleted thick back-illuminated CCD which achieves the higher quantum efficiency for visible, near-infrared and soft X-ray.

3. Key technology for high NIR sensitivity

The thick silicon is required for high sensitivity at near infrared and soft X-ray. For example silicon absorption length of λ=1000nm is around 90μm at room temperature. The thick depletion depth is required to reduce charge diffusion. In those sense, n-type high resistivity silicon is better than p-type silicon, because n-type silicon has lower impurity concentration than p-type silicon, and the depletion depth is proportional to the inverse square root of the impurity concentration. Also the depletion depth increases nearly with square root of bias voltage. The substrate back biasing is the effective technique for this full depletion.

Generally the ultra-high resistivity silicon generates some lattice defects and then image cosmetics become poor. Actually cosmetics of our prototype device were bad because the wafer material had some lattice defects which were oxide stacking faults. Finally the fabrication process and the excellent wafer material were successfully completed and we could get dark images with good cosmetics.

4. 4-side buttable, 2k×4k CCD image sensors

The CCD format (Photo.1, Table.2) is 4-side buttable, 2k×4k 15μm square pixels with 4 low noise output amplifiers. The optimization process was successfully completed. The CCD has the performance of the charge transfer efficiency (>0.999995), the full-well capacity (>150ke-), the charge conversion efficiency (5μV/e-), the low dark (<5e-/pixel/hour at -100°C), the low noise (<5e- at 130kHz readout, -100°C), high near-infrared QE (40% at λ=1000nm) and good surface flatness (+/-7.5μm).

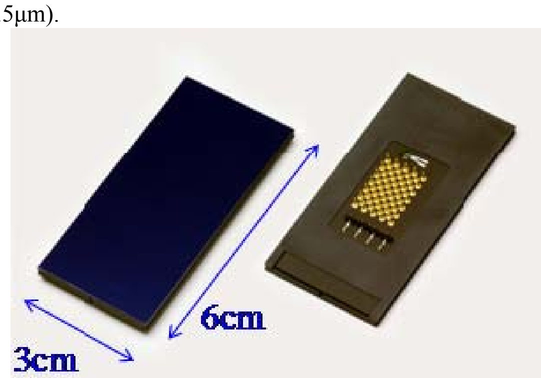

Photo.1 Hamamatsu CCD image sensor S10892-02

Parameters	Specification at -100 °C
CCD Structure	Full Frame Transfer
Pixel size	15um square
Number of active pixels	2048(H)x4096(V)
Vertical clock phase	3phases
Horizontal clock phase	2phases or 4phases
Output	One stage MOSFET SF 4ch
Package	Aluminum Nitride
CTE	>0.999995
Full well capacity	>150ke-
Dark	<5e-/pixel/hour
CCE	5μV/e-
Readout noise	<5e- at 130kHz
Quantum efficiency	40% at λ=400nm 90% at λ=650nm 40% at λ=1000nm

Table.2 The specifications of S10892-02

5. 4-side buttable assembly technology

We developed 4-side buttable CCD package for easy installation and maintenance. The CCD chip is glued to an aluminum nitride ceramic plate and the wires were pulled out to the back side of the package and connected to the connector located at the center of the package through J-FET amplifiers which is also located at the back side of the package (Photo.1).

The result shows the good flatness of +/-7.5μm. The parallelism is +/-7.5μm. The position accuracy from reference position is +/-15μm. The height variation between chips is 15~20μm. The dead space is 435μm for 3-side and 5000μm for 1-side.

6. Hyper Suprime-Cam Project for Subaru

Hyper Suprime-Cam (HSC) is a gigantic digital still camera for 8.2m Subaru Telescope which is built by NAOJ. One of the unique features of Subaru Telescope is the wide-field prime focus which makes the telescope outstanding among 8~10m class telescopes. NAOJ had a plan for a next generation instrument for Subaru Telescope: a very wide-field (1.5^{o}) CCD camera. To fill the 1.5^{o} focal plane, 116 CCDs are required. Total number of pixel is around 8.7G pixels.

The CCD was newly developed in collaboration with NAOJ and Hamamatsu. The focal plane (60 cm in diameter) is paved with 116 CCDs (Photo.3, [6]). HSC's scientific goals are surveying the parameters and properties of dark matter and dark energy in the Universe as well as exploring the causes of the accelerating expansion of the Universe. Last year 2013, HSC's first beautiful image of M31 was released (Photo.4, [7]]. This image demonstrates HSC's capability to fulfill Subaru Telescope's intention of producing a large-scale survey of the Universe.

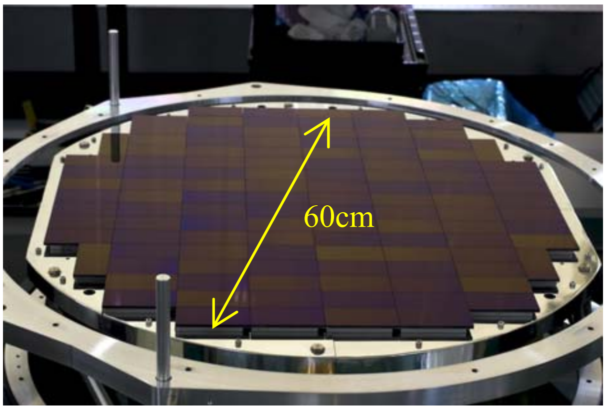

Photo.3 The focal plane of Hyper Suprime-Cam

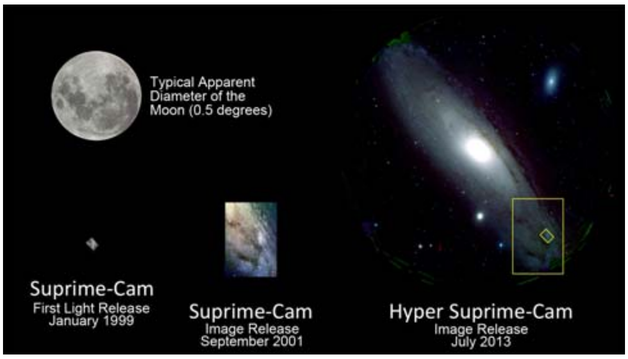

Photo.4 The beautiful image of M31

7. Soft X-ray Imager for ASTRO-H

CCDs are widely used in X-ray astronomy for imaging as well as for spectroscopy. Thick CCDs can provide high detection efficiency especially in the energy band higher than 10keV.

Recently Hamamatsu has supplied X-ray CCD image sensors especially optimized for the Soft X-ray Imager (Photo.6, [8]] on board the X-ray observation satellite ASTRO-H (Fig.5), which will be launched on 2015.

Fig.5 X-ray Astronomy satellite ASTRO-H

Photo.6 Soft X-ray Imager for ASTRO-H

8. Conclusion

We introduced our CCD image sensors for astronomical applications. We developed the fully-depleted thick back-illuminated CCDs fabricated on the ultra-high resistivity n-type silicon wafer in collaboration with NAOJ for a new generation instrument for Subaru Telescope, and with Osaka University and Kyoto University for X-ray astronomy satellite ASTRO-H.

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