CMOS-Based Image Sensors

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Abstract

CMOS-based image sensors have recently emerged as strongest counterparts to CCDs (Charge Coupled Devices) thanks to great improvements in image quality. The CMOS-based image sensors are generally featured by (1) fast parallel readout, (2) low power consumption and (3) on-chip peripheral circuit capability. Also, for D-SLR (Digital-Single Lens Reflex) cameras, "stitching technology" allows only CMOS-based image sensors to provide practical 35mm-format imagers. The CMOS-based image sensors are starting to contend with CCDs in small pixels such as less than 3um. Different pixel shrinkage schemes have been proposed along with process design rule miniaturization. Market demands and intense competition will continue to be the main factors to drive the technologies of CMOS-based image sensors.

Introduction

The importance of CMOS-based image sensors has never become higher than recent years: great improvement in image quality has raised their status and widened their area of applications. In this paper, the history and the overview of CMOS-based image sensors are described. Their features are explained by referencing conventional CCD image sensors. Technologies are updated for pixel shrinkage in CMOS-based image sensors.

The History

Today's CMOS-based image sensors first became known in 1993[1] when "active-type" pixel were invented. The "active-type" means that there is a signal amplifying transistor in the pixel. Linear sensors had already been in the facsimile image pickup market in '90s.

The first application of the CMOS-based image sensors was so-called "Artificial Retina Sensor" supplied by Mitsubishi. This sensor was sold as an optional module for mobile game gear. In 2000, a "sensor module" that integrated sensors, the driving circuits and optics appeared. The module was designed to be easily assembled for the mobile phones.

A milestone for the CMOS-based image sensors was the announcement of D-SLR camera "D30" by Canon. The CMOS-based image sensor adopted in this camera had relatively large pixel size of 10.5um square, but comprised a new pixel circuit and a noise reduction circuit to obtain high signal-to-noise ratio, thus high image quality[2]. The adoption of CMOS-based image sensors in high-quality demanding application raised their reputation and people started to believe in the CMOS-based image sensors.

The pixel circuit comprising 4 transistors (Fig. 1) has basically become standard for CMOS-based image sensors discussed nowadays, although there are some exceptions.

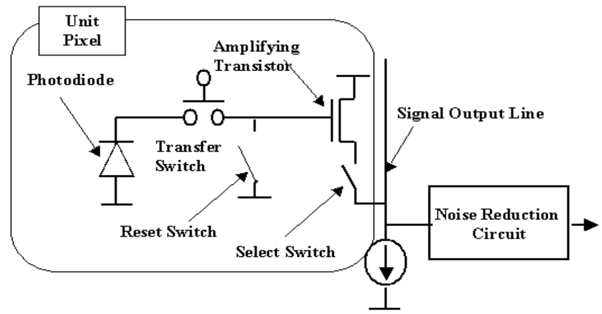

Figure 1. 4-Transistor pixel configuration. A standard pixel circuit for CMOS-based image sensors.

Features of CMOS-Based Image Sensors

It is important to clarify the features of the CMOS-based image sensors with comparison to CCDs since CCDs are most often the forerunners and there must be a good-enough reason for the system designers to use CMOS-based image sensors rather than CCDs. Three major features for of CMOS-based image sensors are: (1) fast readout, (2) low power consumption and (3) on-chip circuit capability.

Fast Readout

CMOS-based image sensors can be designed with multi-channel readout scheme (Fig. 2). Eight-channel readout with total of 100MHz and faster readout is realized without increasing the noise component. It is practically difficult to realize multi-channel CCDs, since in CCDs, charge-transfer channels can only be divided with much lower space frequency than CMOS-based image sensors, therefore difference in the signal gains between channels are much easier to be conceived by human eyes.

Low Power Consumption

The major cause of the high power consumption in CCDs is their high driving voltage to create potential barrier structure inside silicon. On the other hand, in CMOS-based image sensor, circuit operation voltage can be reduced according to the design rules. The low power consumption feature has enabled CMOS-based image sensors to allow for use in mobile tools. It should be noticed that the drop of operation voltage requires more sophisticated design for photodiodes in the pixels to have comparable dynamic range with CCDs. In fact, in D-SLR CMOS image sensors, still 5-volts is used for the power supply to have enough dynamic range.

On-chip Peripheral Circuit Operation:

Shift registors and readout circuits are basically CMOS circuits. Almost any kind of digital and analog circuits can be integrated in the same silicon, as opposed to CCDs that requires very specific fabrication processes. Timing generators, amplifiers, Analog-to-

Digital Converters (ADCs) and sometimes Digital Signal Processors (DSPs) are integrated. The level of the integration is determined by considering the size of the chip and the circuit performance: it should be noticed that the pixel performance often conflicts with MOS transistor shrinkage. An ideal "one-chip camera solution" is often replaced by more-than-two-chip solution in reality.

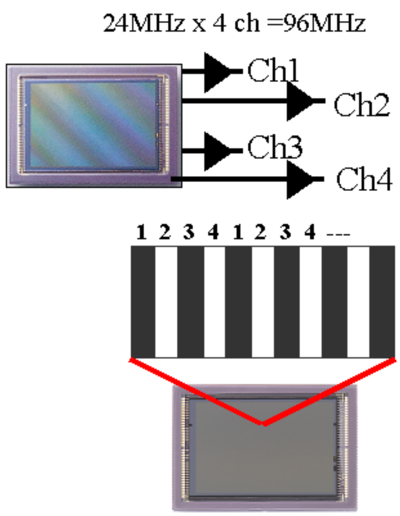

Figure 2. Multi-channel readout scheme for CMOS-based image sensors. This shows the example of 4-channel x 24 MHz/channel architecture.

To add to the features explained above, CMOS-based image sensors are more suited for 35mm film-size sensors than CCDs. To fabricate semiconductor chips larger than 25mm square, one must use "stitching technology" for semiconductor photo-exposure process. In CCDs, stitching of the charge transfer channel often cause trouble, whereas in CMOS-based image sensors, metal wires that carries voltage signal can be easily stitched together with almost no adverse effects.

Pixel Shrinkage

It has been a challenge for CMOS-based image sensors to have small pixels as in CCDs. Recent trends show that the pixel shrinkage is progressing very rapid speed that might catch up CCDs (Fig. 3).

The pixel shrinkage schemes in CMOS-based image sensors are design rule shrinkage and the pixel transistor communization. CMOS-based image sensors can take direct advantage of process technology advancements. The number of transistors per pixel has been reduced from 4 to 2.5 and 1.5 [3,4]. In these pixels, amplifying transistors, reset transistors and select transistors are common among two or more pixels (Fig.4). These new technologies have now enabled CMOS-image sensors to go down to pixel size as small as 1.75um[5].

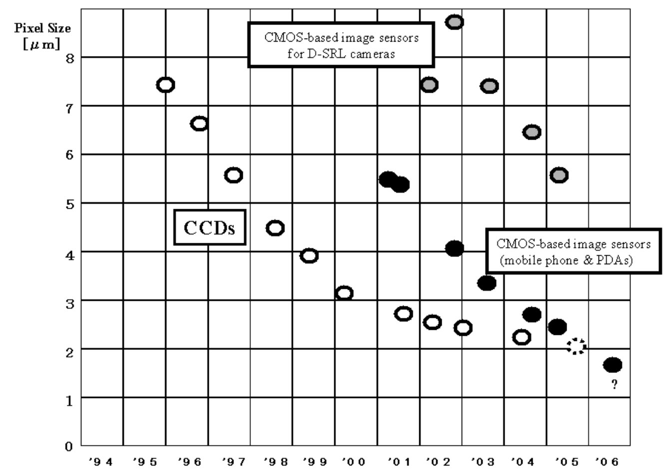

Figure 3. Trend of pixel shrinkage for CCDs and CMOS-based image sensors.

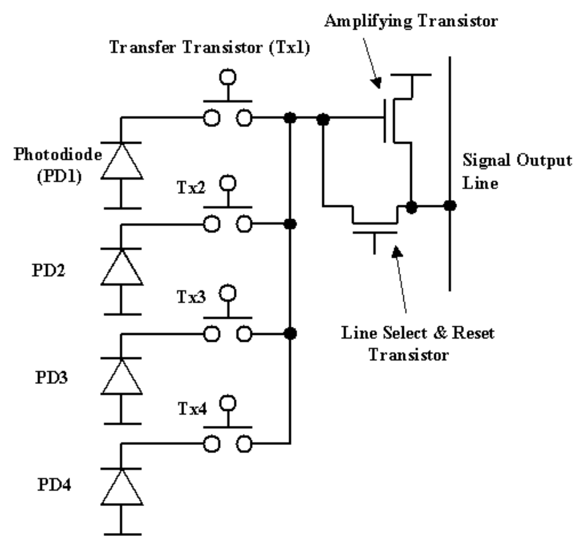

Figure 4. 1.5 Transistors/pixel cell

The pixel shrinkage should always be accompanied by increase in numbers of sensitivity and saturation per unit pixel area and reduction in numbers of noise and dark current per pixel area. Not much has been reported on device technologies to obtain better numbers in the above-mentioned characteristics. This is probably due to the fact that many of the technologies developed by CCDs are directly applicable to CMOS-based image sensors.

Continuing Issues

The author would like to mention two longtime-argued issues of CMOS-based image sensors.

The first one is "Electronic shutter". So far, no CMOS-based image sensors have achieved a completely simultaneous exposure in electronic manner. The "Electronic shutter" can be realized with CCDs and the system designers do not want any loose features because of imagers. So far and as far as the author think, there is no way to do exactly the same "electronic shutter" as in CCDs in small pixels. One good way to simulate it is to do readout operation as fast as CMOS can. Would people really still care about the "electronic shutter" issue, now?

The second one is 'one chip camera solution' issue. Already, there are CMOS-based image sensors with ADC and DSP in one silicon chip, but I do not see anything that can replace widely-sold digital camera imagers and chipset solution. Having good imager sensors and having good DSP often conflict in technology wise. At this point of time, one chip camera solution is still limited to applications that do not require high image quality. For this second issue, however, I am not going to draw any conclusion now. I will wait for the time to come when 'real one-chip camera' is realized by the CMOS-based image sensors.

Conclusion

CMOS-based image sensors have now become the real contenders of conventional CCDs. Pixel shrinkage technologies have greatly advanced in recent years and thus the features are becoming more important than the drawbacks compared with CCDs in many applications. A "One-chip camera solution" is yet to come, but the progress is strong and the market is large.

References

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Author Biography

Shunsuke Inoue has M.S. degree in electrical engineering from Stanford University, Stanford, C.A. in 1989. He joined Canon Inc., Kanagawa, Japan, where he has been engaged in research and development of solid-state imaging devices and display devices. He is now General Manager of the Device Development Department and the Semiconductor Design Department at the Semiconductor Device Development Center, Canon Inc..