A CMD Image Sensor
-An Approach to High-Resolution Imaging-

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1. Introduction

Recently, an HDTV camera and a high-speed camera using Charge Modulation Device (CMD) imagers have become available. In this paper, we review high-resolution and high-speed image capturing with CMD imagers. Moreover, we describe our future prospects of CMD image sensors. We ascertain the validity of active pixel sensors (APS) through these applications.

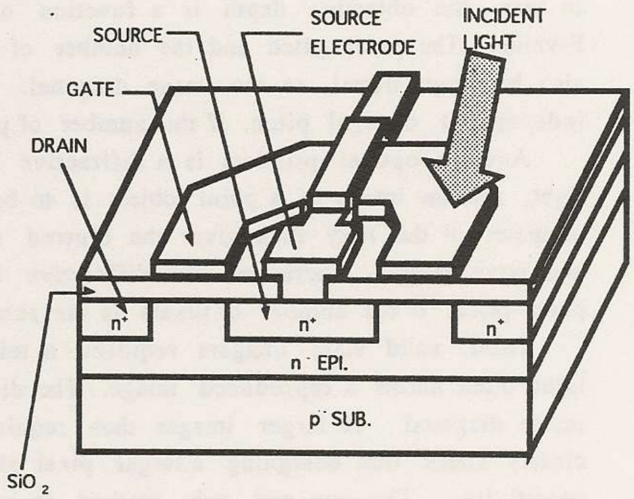

Fig. 1 Pixel structure of the CMD imager

2. Principle of CMD

In this section, we give an outline of the CMD to explain characteristic features of CMD imagers and to lay down the guidelines on its future prospects. Figure 1 presents the pixel architecture of standard CMD imagers. An annular gate acts as an MOS photo diode. Although the CMD has the cross sectional structure similar to that of the conventional *n*-channel MOSFETs, its channel region consists of an n^- epitaxial layer instead of a *p*-type layer. Photo-generated holes are stored at the Si/SiO_2-interface beneath the gate. The signal electron current corresponding to those holes flows from the source terminal to the drain. A functional block diagram of an imager is shown in Fig. 2. Each source of CMDs in a column is joined to the horizontal video line through the switching MOS transistor driven by the horizontal scanner. Each gate of CMDs in a row is connected to the vertical scanner, which selects a row to read out signal current and to refresh a pixel storage. In

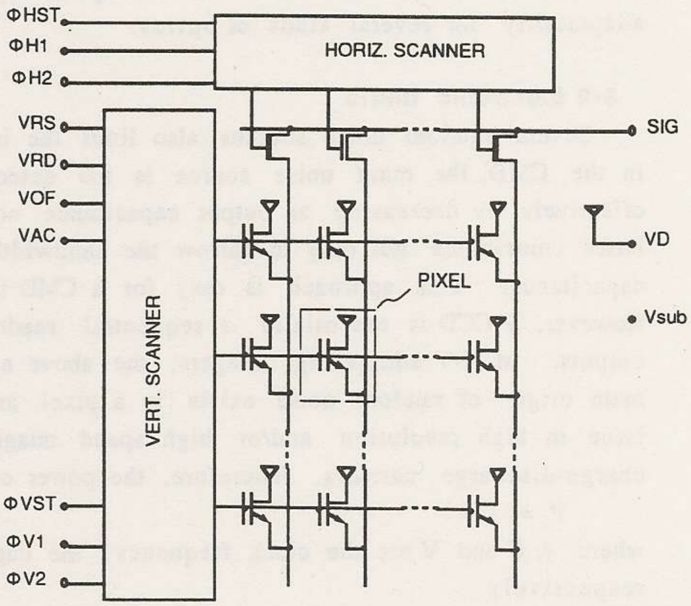

Fig. 2 Block diagram of the CMD imager

comparison with the conventional CCDs, the CMD imager has inherent features as follows,

(1) Only one active transistor is located within each pixel to buffer the signal.

(2) In all operation modes of CMD transistors, the signal carriers are controlled by electric field.

(3) CMOS X-Y shift registers scan the pixel array.

(1) realizes a low smear level and high resolution. (2) produces a kTC-noise free performance and no image lag. Besides this, the third characteristic enables a CMD imager to be operated in a high speed.

3. Performance limits of CMD and other imagers.

3-1 Optical limits

In general, high resolution images are required to maintain the same angle of view and the same objective depth as that of a conventional image. The angle of view is defined by focal length. It is proportional to an image diagonal, that is the product of a pixel pitch and a number of pixel. In turn, the objective depth is a function of focal length, permissible circle of confusion and F-value. The pixel pitch and the number of pixels define the former two, then the F-value must also be proportional to the image diagonal. Therefore, the incident energy is the same and is independent of pixel pitch, if the number of pixels is the same.

Another optical problem is a diffractive limit. An iris of a taking lens diffracts an incident light, and an image of a point object is to become blurred on the focal plane (Airy disk). The diameter of the Airy disk gives the blurred degree and is proportional to the product of F-value and wave length. Therefore, the diffractive limit of the focusing system is also independent of pixel pitch, if the number of pixels is the same.

Third, solid state imagers requires a telecentric lens system, because an inclined incident light often harms a reproduced image. The diameter of a telecentric lens has to be larger than the image diagonal. A larger imager thus requires a larger optical system. The above discussion clearly states that designing a larger pixel size is not a fundamental method for obtaining higher sensitivity. The one and only method to enlarge a signal quantity is to improve a quantum efficiency. We are now developing on-chip-micro-lens technology applicable to the CMD. The problems to be solved are F-value dependency of lens effect, chromatic aberration and adaptability for several kinds of optics.

3-2 Electronic limits

Several random noise sources also limit the imager performance in high resolution imaging. In the CMD, the main noise source is the detection noise. This noise level can be lowered effectively by decreasing an output capacitance or by employing multi-channel output ports. The latter contributes not only to narrow the bandwidth of the detector but also to decrease an output capacitance. This approach is easy for a CMD imager because of its X-Y addressing scheme. However, a CCD is essentially a sequential readout device and does not suit to multi-channel outputs. In X-Y addressing imagers, the above approach is not effective for imagers where the main origin of random noise exists in a pixel array. Power consumption is another important issue in high resolution and/or high speed imaging. In solid-state imagers, it is necessary to charge-discharge carriers. Therefore, the power consumption (P_s) is expressed as:

$$P_s = f\,C\,V^2$$

where f, C and V are the clock frequency, the capacitance to be driven and the clock amplitude, respectively.

The power consumption increases the imager temperature, thus large dark current are generated. Because (normal) high resolution imaging accompanies the increases of a clocking frequency and of a driving capacitance, a counter-plan should be prepared. Lowering the data rate to avoid these problems decreases the frame rate and extends the exposure time and/or the readout period. Even if a shutter operation is introduced to avoid a motion blur, generated dark current during the long readout period also deteriorate picture quality. Therefore, it is necessary to reduce power consumption without lowering the frame rate. In CMD imagers, three methods are available for reducing the power consumption. The first is a parallel readout method, which lowers effective frequency without lowering the total data rate. The second is to minimize a capacitance. The driven capacitors of the CMD imager exist at the pixel array and the horizontal scanner. The scanner is a digital circuit, so that it is easy to decrease its capacitance. On the other hand, CCDs have large capacitance and it is difficult to decrease their capacitance with maintaining their analog performance. Especially, extra storage gates of the FT-CCD and the FIT-CCD prevent decreasing capacitance. The third is to lower the driving voltage. This is a generic method for all types of imagers. However, the analog features of CCDs have some difficulties in comparison with CMDs.

4. Example of CMD Imaging

4-1. CMD Cameras

Two types of CMD imagers have been developed for special high-resolution imaging. One has 2 M pixels with 1-inch format for HDTV (BTA-S001) use. The other was designed for high speed image capturing.

First, the specifications and performance of the HDTV imagers are listed in Table I. To diminish dark current generation, it is necessary to lower the power consumption of the imager. For this reason, the operation voltage of the horizontal scanner was lowered to 3.0V and the architecture of two read-out ports was adopted. The CMD characteristics described in section 2 reflect its low smear level and its low power consumption. Figure 3 presents the HDTV camera configuration using the CMD imager described above. This camera was designed for optical microscopy, which requires, at least, a base band HDTV resolution. A single B/W CMD imager is located on the focal plane. Between the taking lens and the imager, there exists a rotational color filter (Red, Green, Blue and Black). The filter rotates 3.75 frames-per-second. Each

Table I Specifications and performance of the 2M imager

Pixel Size	7.3 μm(H)×7.6 μm(V)
Number of effective pixels	1920(H)×1036(V)
Die size	16.6 mm(H)×10.7 mm(V)
Optical aperture ratio	34%
Signal output	2 lines mixture
Face plate saturation	76 lx
Saturation signal	28 μA/pixel
Power dissipation	206 mW
Smear level	-123dB
Image lag	<0.1%

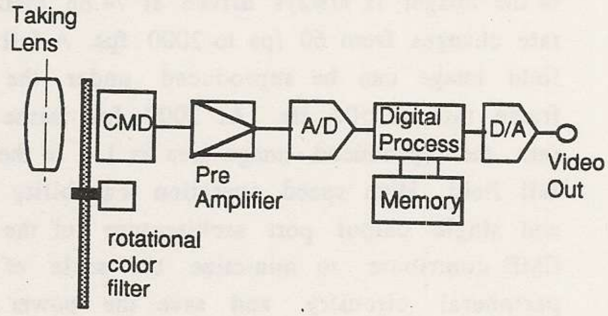

Fig. 3 HDTV camera configuration

Table II Performance of HDTV camera

Imaging device	1 inch 2M pixel CMD
Output signal	BTA-S001
Sensitivity	F4 / 2000 lx
S/N	46 dB
Horizontal Resolution	1000 TV lines

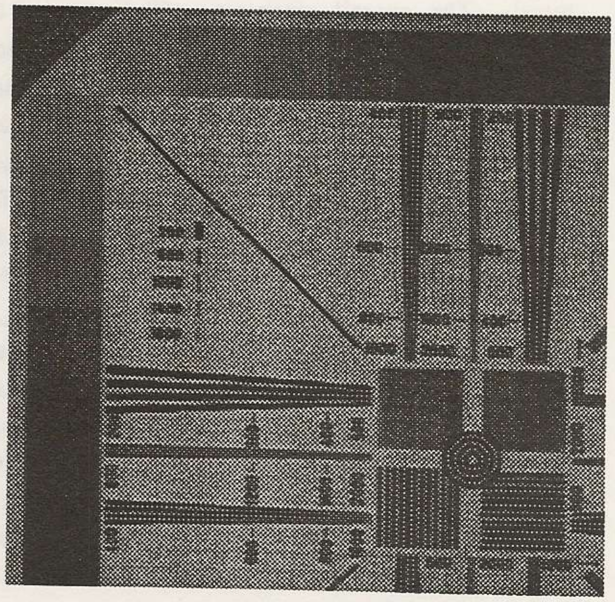

Fig. 4 Enlarged reproduced image of the HDTV camera

focused image on the CMD for red, green and blue exposures is readout sequentially. The CMD signal from the pre-amplifier is fed to an A/D converter. Each signal which corresponds to particular color is stored in the frame memory and digitally processed and synchronized. The camera outputs are analog R/G/B and $Y/P_R/P_B$. The digital outputs such as SCSI are also available. The camera performance is summarized in Table II, and Figure 4 represents a reproduced image by the HDTV camera.

Table III lists the specifications of the high speed video camera and its 330k-pixel CMD imager. This video camera developed by NAC, inc. (Japan) is characterized as a fully self-contained, color, high speed, high resolution type with an internal digital, solid state memory. It uses a single chip of the color CMD imager listed in Table III. The horizontal scanner of the imager is always driven at 74.88 MHz. By devising its clock operation, the video recording rate changes from 60 fps to 2000 fps. A full field image can be reproduced under the frame rate of 500 Hz. At 2000 fps frame rate, the reproduced image area is 1/4 of the full field. High speed operation capability and single output port architecture of the CMD contribute to minimize the scale of peripheral circuitry and save the power consumption, so that the handy high speed video camera has been built.

Table III Specifications of the high speed video camera

Imaging device	1/2 inch CMD, Single chip, color
Sensitivity	F4 / 24000 lx (@gain 0 dB and 500 pps)
S/N	46 dB
Horizontal resolution	>350 TV lines (up tp 500 pps)
Recording speeds	100, 250, 500, 1000, 2000 pps
Sensing areas	Full 580 x 434 pixels
	Half 408 x 300 pixels
	Qtr 260 x 234 pixels

4-2 CMD Imagers

The CMD performance is responsible for some of the specifications described above. The principal subject is the sensitivity. One of the restrictions of the quantum efficiency of CMD imagers is its aperture ratio. The optical aperture ratio is 30 - 40 % without on-chip-micro-lenses. The gate structure for obtaining the desirable I-V characteristics of the CMD transistor trades its optical aperture. The other restrictions are the reflection and the absorption by the gate structure.

In CMD imagers, the thickness of the gate poly-silicon is optically optimized independently of its sheet resistance, because the gate electrodes are interconnected to the vertical scanner with metal. The overall quantum efficiency of CMD imagers is about 20 % without micro-lenses. Random noise sources of CMD imagers include CMD transistor noise, dark current shot noise and detection amplifier noise. Figure 5 shows the noise characteristics of the 330k pixel CMD imager with the pixel size of 7 μ m. To eliminate the effect of the detection noise, the clock frequency of 6 MHz and the bandwidth of 3 MHz were selected. The detection noise of the system was estimated to 0.38 nA_{rms}, which is sufficiently small to be neglected. At high temperature, a dark current shot noise dominates. The main cause of the dark current is classified into two groups. One is the surface current generation via the Si/SiO_2 interface states. It originates in the generation center caused by the Si-dangling bonds. The other is multiplication of the dark current by the electric field between the drain and the gate. The newly developed processes terminate the Si-dangling bonds and form the gate structure that reduces the electric field. The dark current decreased

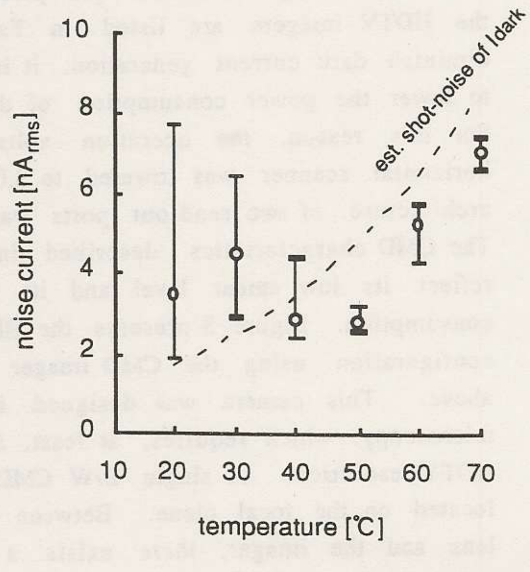

Fig. 5 Noise characteristics of the CMD imager

down to 0.5 nA/cm^2 at room temperature. The detection noise is caused by the output capacitance of an imager and a feedback type I-V conversion amplifier. This noise power is denoted by

$$(I_n)^2 = 4\, k\, T\, B^3\, (4/3)\quad \pi^2\, C^2\, R_{eq}$$

where, B, k, T, C, and R_{eq} are the bandwidth, Boltzmann's constant, the absolute temperature, the input capacitance of the amplifier and the equivalent noise resistance of the input transistor. A high speed and/or high resolution movie demands a wide bandwidth. Increased number of pixels for high resolution imaging increases output capacitance of the imager besides the bandwidth. Therefore, this detection noise becomes quite serious problem for high quality image capturing. Fundamentally, the output capacitance must be reduced to suppress the detection noise. The newly developed processes optimize the switching MOS-FET parameters and the interconnection of the signal output. The output capacitance of the HDTV imager decreases down to 20 fF/ (pixel column) including the stray capacitance of a bonding wire and a package lead. Noise sources in a CMD transistor are now under investigation.

5. Conclusion

Examples of CMD high resolution cameras are introduced and factors which limit the CMD performance are analyzed. The necessary conditions for achieving higher resolution are explained. To make the quantum efficiency near unity is the one and only method to improve the optical performance. In electronics, the main subjects are the noise suppression and the power saving. It is concluded that CMDs and some APSs are superior to CCD family in the viewpoint of wide band-width and power consumption.

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