CMD Image Sensor
- a new approach to a future smart imager

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Abstract - A charge modulation device (CMD) image sensor is grouped into the category of active pixels. It has several unique features, such as a high pixel density, a high speed operation, a low power dissipation and the flexibility for implementing various scanning modes.

In this paper, these unique features are examined. The operating principle of the CMD as a pixel element is described, followed by the description of the CMD image sensor. A 2/3-inch 2M-pixel CMD image sensor, which employs a 5.0(H)× 5.2(V) μm^2 unit pixel and operates in interlaced/progressive multi-scanning modes with an electronic shutter, is presented as a good example of the CMD approach. It is demonstrated that high speed readout is not compromised by high resolution and that low power dissipation of 160mW can be achieved with a high data rate of 74.25MHz.

The active pixel sensor has several features which will contribute to the development of a future smart imager where some additional pre-processing functions are implemented.

1. INTRODUCTION

Conceptual diagrams of the architectures of passive and active type image sensors are shown in Fig. 1. Conventional CCD and MOS imagers are grouped as passive types, where the photo-generated signal carriers at a photosite are transferred to the output amplifier through its readout channel. In active pixel sensors(APS), signal amplification or impedance conversion capabilities are implemented at the pixel. Thus, the electrical quantity (such as current or voltage), corresponding to the signal charge is handled at its on-chip readout circuit.

Now, let us consider the signal-to-noise ratio (S/N) of these two types of imagers. Here, we treat only the random noise as the noise source. The S/N of the passive type imager is represented by

$$(S/N)_{PASSIVE} = \frac{S}{\sqrt{N_{PIX}^2 + N_{RD}^2}}$$

where S, N_{PIX} and N_{RD} denote the signal, the random noise generated at the pixel and the read noise, respectively.

While in APS, assuming that the signal is amplified by the factor g, the S/N is represented by

$$(S/N)_{ACTIVE} = \frac{g \cdot S}{\sqrt{(g \cdot N_{PIX})^2 + N_{RD}^2}} = \frac{S}{\sqrt{N_{PIX}^2 + \left(\frac{1}{g} \cdot N_{RD}\right)^2}}$$

That is, the architecture of the APS leads to a relatively smaller read noise by amplifying the signal. Therefore, the APS's are superior in principle to the passive type sensors when they are utilized under conditions where the image quality is determined by the read noise.

One disadvantage of the APS is that it produces a large fixed pattern noise (FPN) caused by the electrical characteristic deviation of the active device at the pixel. At present, the image quality reproduced by APS's has not attained the level of CCDs, due to its FPN.

However, the FPN will be eliminated in principle by the improvement of semiconductor fine fabrication technology and circuit technology. Therefore, there is a possibility that APS's will be in the mainstream of fundamental imaging devices, considering the advantages mentioned above. In addition, we expect that the APS will develop into a so-called smart sensor having additional functions, because of the several features which will later be described.

In this paper, we will discuss a Charge Modulation Device (CMD) image sensor[1],[2], which is one of the APS's[3]. The operating principle of the CMD as a pixel is described in Section II, followed by the description of a 2/3" 2M-pixel CMD image sensor as an example of the CMD approach in Section III. In Section IV, concluding the report, we will explore the potential and the future of the CMD image sensor.

II. CHARGE MODULATION DEVICE

A schematic diagram of the CMD is shown in Fig. 2. The device consists of an MOS structure with an annular gate electrode. The channel region is formed in an n^--epitaxial layer with an impurity concentration of 1×10^{13} cm^{-3}. [4]-[6]. As a result, the majority carriers in the n^--epitaxial layer are depleted when the negative voltage is applied to the gate. The incident photon flux passes through the semi-transparent gate electrode and generates electron-hole pairs. Of these, the electrons are swept away to the source or the drain regions. The holes drift to the Si/SiO_2 interface under the gate. The stored holes raise the surface potential. The electron flow from the source to the drain is controlled by the saddle point potential height appearing in the channel. To hold the electron current inside the channel, the substrate should be a p-type and reverse-biased.

The operation of the CMD as an image sensor pixel (reset, photo-electric conversion, charge storage and readout) is described using the concept of potential distribution.

During the reset, the gate is positively biased and the holes stored at the Si interface are swept away to the substrate. This reset procedure is considered to be a complete reset where the carriers are completely removed from the photosite. This results in the elimination of kTC noise and an image lag. The time duration needed for the complete reset is calculated to be around 10ns.

During the charge storage period, the negative voltage is applied to the gate, forming the depletion layer in the channel region. The saddle point potential becomes high enough to make the CMD cut-off. The photo-generated holes are stored at the Si/SiO_2 interface beneath the gate electrode, while the electrons are swept away to the drain.

Potential profiles with and without illumination are shown in Fig. 3. The stored holes increase the surface potential, thus lowering the saddle potential(ϕ^*) height for electrons.

During the readout period, the gate is biased at the intermediate voltage, between the reset voltage and the accumulation voltage. The saddle point potential is lowered and the electron current flows from the source to the drain in accordance with the exposure. In other words, a light-dependent current can be obtained. The holes remain at the storage region even when the readout voltage is applied to the gate, if the quantity is below saturation level. A non-destructive readout (NDRO) can thus be possible. If the storage holes exceed the saturation level, the excess holes are swept away to the substrate. We call this operation an "overflow operation".

As is suggested by the description above, a CMD in itself possesses all the functions needed for an image sensor pixel. Therefore, it is easy to scale the pixel size down. This is essential to build a high density image sensor. Also, carriers are driven by the electric field, instead of by diffusion, due to its MOS photogate and high-resistivity channel structure. Consequently, the CMD operates at a very high speed.

III. CMD IMAGE SENSOR

A 2/3-inch 2M-pixel CMD image sensor[7] is introduced as a good example of the CMD approach. It employs a 5.0(H)×5.2(V) μm^2 unit pixel and operates in interlaced/progressive multi-scanning modes with an electronic shutter.

The architecture of the CMD image sensor is shown in Fig. 4. A pixel is selected in order by vertical and horizontal scanners. Each source of the CMDs in a column is joined to the horizontal video line through the switching MOS transistors driven by the horizontal scanner, while each gate of the CMDs in a row is connected to the vertical scanner which generates a 4-level pulse train. Each gate pulse height corresponds to the accumulation voltage, readout voltage, reset voltage and overflow voltage, respectively.

To operate both in the interlaced and the progressive scanning modes with the same chip, the vertical scanners are located on both sides of the image area and are driven by the scan controller. The scan-controller changes the vertical clock pattern which makes it suitable for either mode. The signals are read out from the two channels simultaneously to halve the drive frequency. To lower power dissipation, the pulse height of horizontal clocks is reduced to 3.0V.

A high speed operation has been achieved by building the scanning circuits with CMOS and by treating the output signal as a current. This reduces the effect of charging or discharging a parasitic capacitance of the video line.

Fig. 5 shows the timing diagrams. The reset for the CMDs in a row is performed once in a field. An overflow operation is performed during each horizontal blanking period for all of the CMDs except the CMDs being reset in a row.

A gate pulse pattern in the interlaced scanning mode is shown in Fig. 5(a). Either a readout or a reset pulse is applied to two selected gate lines, while an accumulation or an overflow pulse is applied to non-selected lines. Two selected lines are changed alternatively by each field. Consequently, a combined signal from the two vertical pixels is obtained.

A gate pulse in the progressive scanning mode is shown in Fig. 5(b). A readout or a reset pulse is supplied to only one gate line. Thus, a non-mixed signal from a pixel is obtained.

In the normal operation, a reset pulse is applied to a gate line after a readout pulse. In the shutter operation, two reset pulses are supplied in a frame. Exposure time is determined by the interval between the reset pulses.

The specification and the performance of the 2/3-inch optical format 2M-pixel CMD image sensor is summarized in Table 1.

IV. SUMMARY AND FUTURE PROSPECTS

In this paper, we have discussed several features of CMD image sensors, such as high resolution, high speed operation, low power dissipation and flexibility for implementing various scanning modes. Further, we have demonstrated, using a 2/3" 2M-pixel image sensor, that high speed readout is not compromised by high resolution and that low power dissipation of 160mW can be achieved even with a large pixel number and a high data rate of 74.25MHz.

We offer the following as an approach to the future direction of this technology:

The first is the improvement of the fundamental characteristics, which includes the improvement of quantum efficiency and the reduction of pixel noise.

The other idea is to develop a smart sensor in which some pre-image processing functions are implemented. In the system where a smart sensor is utilized, the burden of the post-processing function should be dramatically reduced and at the same time, the total performance should be superior to that of conventional systems.

The pre-processing function may require some parallel processing. Here, the features of APS shown below would become necessary:

1) Large fun-out --- large driving capability due to the active device in the pixel
2) NDRO --- can access the same pixel information several times
3) Flexibility in the readout scheme
4) Low power dissipation

Again, improving the fundamental characteristics is very important because the compensation procedure is no longer performed in the post-processing unit.

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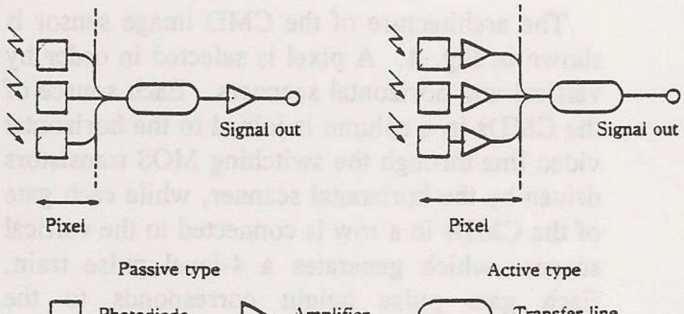


Fig. 1 Architecture of passive and active types of imagers.

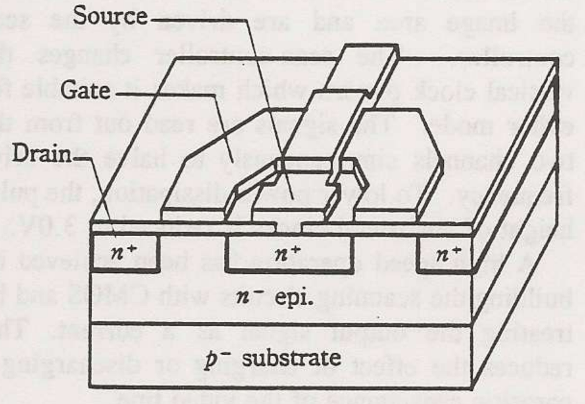
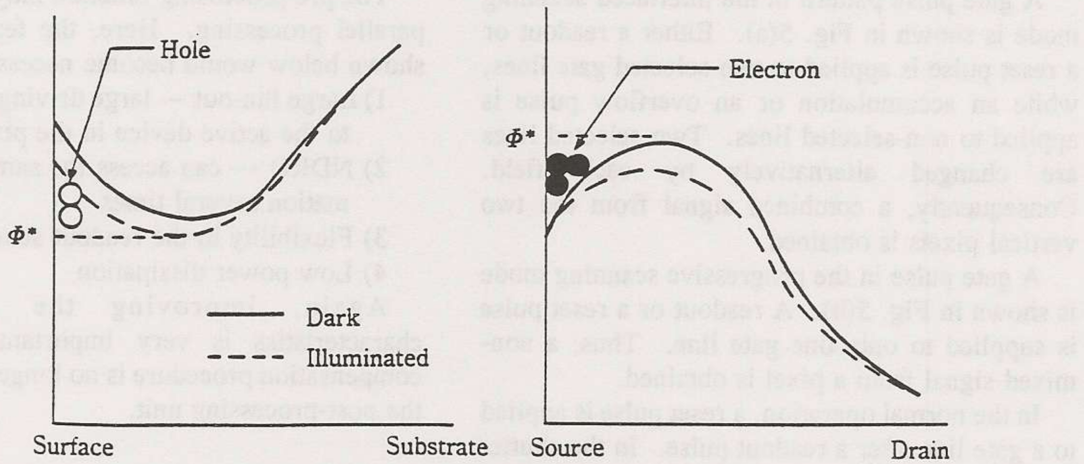


Fig. 2 Schematic diagram of the CMD.



(a) Perpendicular to the surface (b) Parallel to the surface

Fig. 3 Potential distribution profiles in the CMD. Dashed and solid lines correspond to conditions with and without illumination.

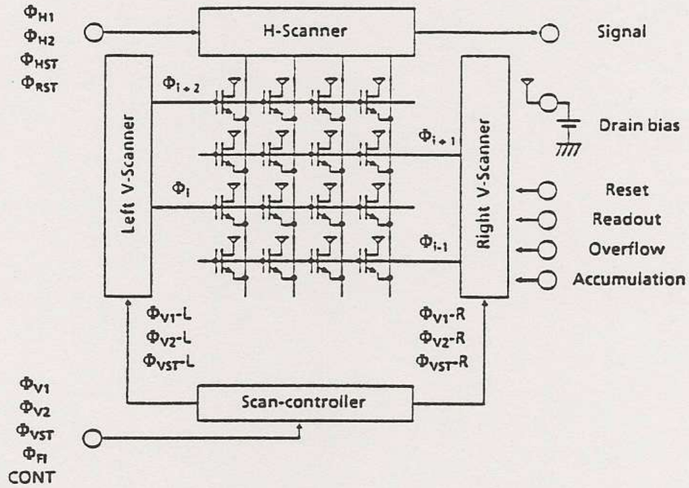


Fig. 4 Architecture of the 2/3-inch 2M-pixel CMD image sensor.

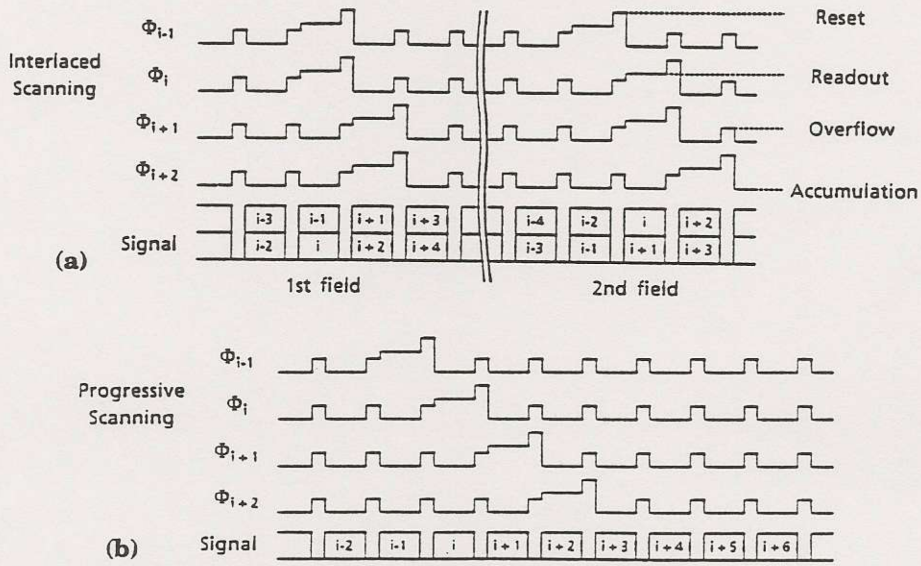


Fig. 5 Timing diagram. (a) interlaced scan mode. (b) progressive scan mode.

Table 1 Specifications and performance of the 2/3-inch 2M-pixel CMD image sensor.

Scan	Progressive	Interlaced
Optical format	2/3 inch	
Number of effective pixels	1920(H)x1036(V)	
Optical aperture ratio	34%	
Pixel size	5.0(H)x5.2(V)μm²	
Chip size	13.8(H)x9.6(V)mm²	
Saturation signal	28μA	56μA
Sensitivity	760nA/lx	
Blooming level	<-110dB (V/10 exposure)	
Image lag	<measurement sensitivity	
Power dissipation	160mW	
Fixed-pattern noise at dark	$6.0\%_{pp}$ to saturation	
H limiting resolution	1000 TV lines	
V limiting resolution	1000 TV lines	700 TV lines
Dynamic range (est.)	64dB	70dB