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A Study of Stray Minority Carrier Diffusion in CMOS Image Sensors

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The complementary metal-oxide-semiconductor (CMOS) and charge-coupled device (CCD) are two important image sensing techniques. The disadvantages of the CMOS image sensors were low resolution and dynamic range, which make CCD image sensor dominate the market of the high-level image sensors for a long time [1].

Due to the scale-down and progression in CMOS technique, the CMOS image sensor is adopted gradually for more and more high-level image applications. The high resolution is achievable for the advanced CMOS processes [2], and the high dynamic range can also be achieved by different read-out circuits [3]. Furthermore, the high circuit integration and the low power consumption make the CMOS image sensor more attractive.

Fig. 1 illustrates the operation of an nMOS. When the transistor is turned on, the carriers will be induced and an ionic channel is formed; when the transistor is turned off, those induced carriers will be absorbed by the drain or source. At the same time, some carriers will be pushed and diffused into the substrate in every direction. These carriers may be recombined with the majority carriers after a long-distance diffusion. At a low operating frequency, most of the minority carriers will be absorbed or recombined around the transistor. However, when the transistor is operated at a high frequency, the huge number of the minority carriers will be generated, and some unabsorbed carriers will be diffused to substrate. Once the diffused carriers are absorbed in the photo sensing area, the caught carriers will become part of the photo current. This mechanism led to a distorted image or a saturated image, depending on the number of absorbed stray minority carriers.

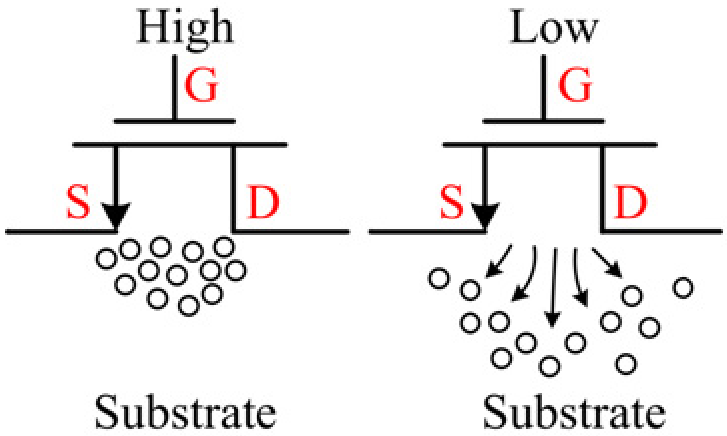

Fig. 1 Illustration of carrier diffusion for a switching transistor

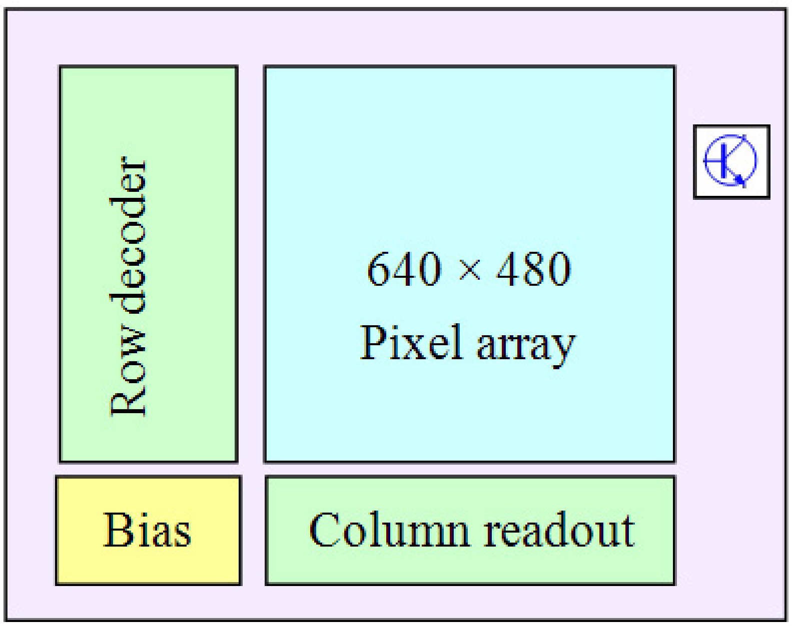

Fig. 2 The floorplan of the testchip

In the standard CMOS process, the light doping P-type epi-wafer is used as the substrate, and the light doping substrate permits the carriers to be diffused for a long distance. So, the high-frequency operation and light-doping substrate make the effect of the stray minority carriers worse. Generally, this noise mechanism is prevented by a guard-ring. This research proposes a method to quantify the area influenced by the stray minority carrier in a CMOS image sensor. Moreover, a guideline for choosing the width of the guard-ring is proposed, according to our measured results.

A CMOS image sensor chip is fabricated with the TSMC 0.13 μm CMOS image sensor process. The imager contains a 640×480 pixel array and a set of readout circuitry in each column. The area of each pixel is 3.3 × 3.3 μm^2. To simplify the noise analysis, only the row decoder, bias circuit, and readout circuit were designed in this chip. All control signals are generated by an off-chip CPLD. The floorplan of the chip is shown in Fig. 2, and the detail specifications are listed in Table 1. A transistor with 4 μm in length and 10 μm in width is used to generate the stray minority noise. The transistor was located at 10 μm from the right edge of the sensor array and one quarter of the way down from the top of the chip.

Table 1 The specifications of the imager

Technology	TSMC 0.13 1P3M CIS
Fill Factor	20%
Num. of Pixels	640*480
Pixel Size	3.3×3.3 μm^2
Chip size	3880×3350 μm^2
Readout Speed	30 frames/sec
Dark Current	0.0891 nA/cm^2
Sensitivity	0.747 V/lux-s
Dynamic Range	66.84 dB
FPN	1.11 mV (0.23% of sat. level)
Random Noise	0.21 mV
Conversion Gain	27.09 μV/e-

A picture taken with this test chip is displayed in Fig. 3. Fig. 3(a) shows the image under normal operation, and Fig. 3(b) reveals the influenced image with a noisy transistor operating at 10 MHz. The influenced area marked in the right upper corner of Fig. 3(b) is a bright triangle zone. The pixels in the bright zone are saturated because of the stray minority carrier mechanism. The number of the influenced pixels will increase with the operating frequency of the noisy transistor. The saturated pixels in the peripheral of the taken image are due to a different reason — dummy pixels designed for matching. These dummy pixels will form a fixed pattern noise (FPN) and can be eliminated with a correlate double sampling technique.

Fig. 3(a) The image taken in normal mode, (b) the image taken with a noisy transistor operating at 10 MHz.

In order to focus on the noise issue, all pictures were taken in a dark box. The dark current and the FPN in the image are eliminated with CDS technique. Then, a binary image that distinguishes the affected region from the unaffected region is obtained and shown in Fig. 4(a). Two indexes are defined: the depth of the effected region (DER) is defined as the maximum effected pixel number along the rows; the width of the effected region (WER) is defined as the row number between the two points, where their corresponding effected pixel numbers is half of the maximum value. Both indexes is illustrated in Fig. 4

(b)

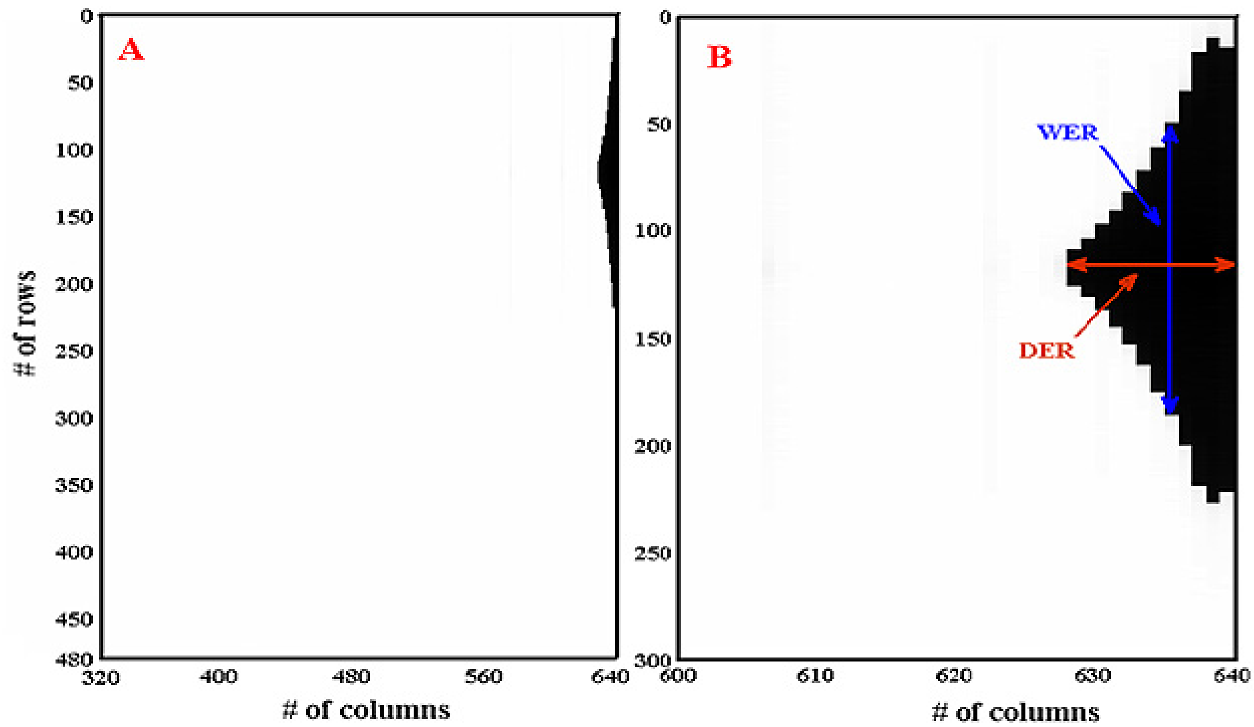

Fig. 4(a) The binary image, (b) The effected region with marked DER and WER indexes.

The relationship between the indexes and frequency can be acquired by changing the operating frequency of the noisy transistor, and is shown in Fig. 5. Both indexes increase with the increasing frequency. However, WER grows faster than DER.

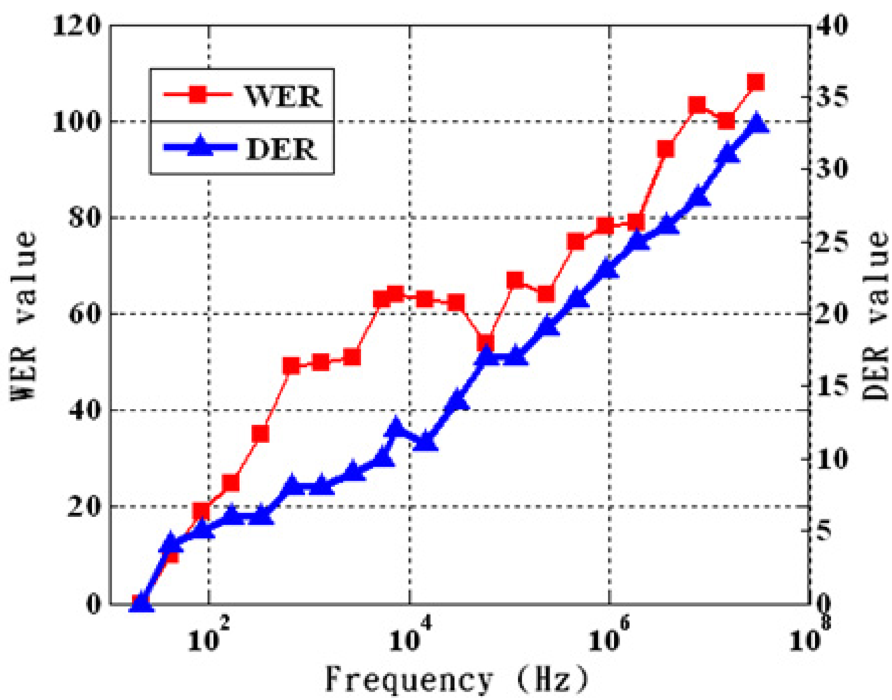

Fig. 5 The relationship between the DER, WER and frequency

In this experiment, the influence of stray minority carriers in an imager is examined. Fig. 5 shows that the horizontal diffusion path is shorter than the vertical path. The light doping substrate cause the most carriers absorbed in the pixel. When the outside pixels are saturated, the carriers can go deeper into the pixel array. However, most carriers are absorbed by the outside pixels, which lead the penetration width to increase at a rate faster than the penetration depth. To prevent this minority carrier effect, designers can place the high-speed circuits apart from the pixel array, or place a (DER × 3.3) μm width N-type guard-ring surrounding the pixel array. Using the appropriate guard-ring, the image quality can be improved.

This work studies the impact of stray minority carrier diffusion upon image quality. The significant influence of the stray minority carriers was observed in Fig. 3(b). Fig. 5 reveals that the effected region expands as the switching frequency of the noisy transistor increases. The results show that this noise mechanism would deteriorate the image quality significantly if no proper protection were taken. Fig. 5 provides the information of the required guard-ring widths to eliminate the excess minority carrier diffusion effect. This effect should be considered during image sensor design phase.

Reference

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