CMOS Active Pixel Sensor with In-Pixel Contrast Stretching

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Abstract

In this paper, we demonstrate a CMOS active pixel sensor structure for implementing in-pixel intensity mapping function. With array of in-pixel intensity transformers, we are able to perform contrast and brightness adjustments with low power, low cost and high dynamic range. In addition, with a simple design of the in-pixel transformer, easy control of the transformer is achieved, which can facilitate to adaptation of processing during integration. This paper includes a detailed design of in-pixel light intensity transformer and its analysis, along with operational performance and experimental results.

I. Introduction

The in-pixel contrast and brightness adjustment are essential components in point processing operations, particularly contrast enhancements such as contrast stretching and histogram equalization [2]. The proposed design of an intensity transformer with mapping function uses a non-linear transfer element in each pixel in order to implement a point image processing scheme with low power, reduced processing time and adaptation of environment [3] [4]. The main purpose of this study is to explore the on-chip implementation of fundamental image processing blocks and to gain a better understanding of the design issues needed for high quality contrast enhancement and automated contrast optimization.

II. The Theory of Operation

The basis of the circuit is a CMOS common source amplifier, shown in Figure 1 (a), with the source connected to input control voltage instead of ground, and an active load. The transfer function of the intensity transformer is shown in Figure 2. The transfer characteristic displays three different regions. In region I, the driving transistor M1 is off, since Vin < Vt. Nevertheless, M2 is always in the saturation region and is slightly conducting; hence the output voltage is $V_{DD} – V_{t2}$. In region II, M1 is conducting and is operating in saturation, and so the region II has linear transfer response line. Finally, in region III, M1 leaves the saturation region and enters the triode region and the curve flattens off.

The analytical derivation of equation describing the transfer curve is shown below. For the derivation, we assume that both devices (M1 and M2) have infinite output resistance (r_0) in saturation. Furthermore, the two devices will be assumed to have equal threshold voltages Vt but different physical parameter values of K (K1 and K2).

When M1 is in saturation, the current is equal to

$$I_{D1} = K_1 (V_{GS1} – V_t)^2 \qquad (1)$$

Since $I_D = I_{D1} = I_{D2}$ and $V_{GS1} = V_{in} - V_{ref}$, this equation can be rewritten as

$$I_{D1} = K_1 (V_{in} – V_{ref} – V_t)^2 \qquad (2)$$

The current of M2 is equal to

$$I_{D2} = K_2 (V_{GS2} – V_t)^2 \qquad (3)$$

Since $V_{GS2} = V_{DD} – V_{out}$, this equation can be rewritten as

$$I_{D2} = K_2 (V_{DD} – V_{out} – V_t)^2 \qquad (4)$$

Combining Equation (2) and (4) and after simplification, we obtain

$$V_{out} = (V_{DD} - V_t + sqrt[K_1/K_2]V_{ref} + sqrt[K_1/K_2]V_t) - sqrt[K_1/K_2]V_{in} \qquad (5)$$

which is a linear equation between V_{out} and V_{in}. This is obviously the equation of the straight-line portion of the transfer characteristic (region II) of Figure 2. Figure 3 shows a response of the amplifier when a photodetector is placed as an input of the amplifier.

In this particular design, a PMOS active load is used instead of enhanced mode active load to provide programmability and larger output swing, shown in Figure 1(b). For contrast adjustment, the slope of the transformer should be controllable. The enhanced mode NMOS load cannot be programmed, since the slope is determined by the physical dimensions of the transistors (see equation 5). Using a PMOS active load with the gate controlled by input bias voltage allows different slopes to be determined by the bias voltage. In addition, the enhanced mode load has an output range from V_{ref} to V_{DD} - V_t because V_{GS} should be greater than Vt in order for the transistor, M2, to stay on. The PMOS active load has an output range from Vref to V_{DD}, gaining Vt over that of the enhanced mode load.

III. In-pixel Intensity Transformer

Here, we implement contrast stretching using a simple non-linear amplifier with only 3 additional transistors per pixel. Operation of the circuit is controlled by two analog voltages, as shown in Figure 1 (b). This circuit is combined with a standard active pixel readout to form a pixel which outputs both a normal image and a contrast-enhanced image. An inverter at the base of each column serves to sharpen the voltage transition of the contrast stretch output to offer an additional binary output. A prototype chip comprising a 64 x 64 array is fabricated in standard 0.35µm CMOS technology, a die photograph of which is shown in Figure 4. Each pixel is 30µm square, with a fill factor of 66%.

The variations of photoresponse of an individual pixel with light intensity, biasing voltages, and reference voltages are shown in Figure 6. These data demonstrate that the response of the pixel to different light intensities and control voltages allows good control of the contrast stretching function. The global photoresponse of the prototype array in each of the three modes is presented in Figure 5 for uniform illumination. Images captured by the prototype sensor in the three operational modes are compared in Figure 7, along with calculated histograms showing the distribution of pixel values in the image. A normal mode image with poor contrast is shown with its narrowly distributed histogram. With an appropriate values for V_{biasp} and V_{ref}, the contrast stretched mode shows enhancement of contrast by spreading out the histogram distribution. The binary mode converts grayscale image to one bit binary image and therefore the histogram contains only two values: black and white. The contrast stretched mode enables modulation of not only the contrast of the image, but also its brightness. As shown in Figure 8, V_{biasp} changes the distribution of the histogram, retaining the original maximum and minimum values of the histogram, thereby changing the contrast of the image. In contrast, V_{ref} does not change the basic distribution of the histogram, but modulates the minimum value, thereby changing the brightness, shown in Figure 9.

IV. Conclusions

In summary, this paper reports the design of in-pixel intensity mapping function and its analysis, along with operational performance and experimental results. In-pixel processing has potential advantages of low power and local adaptation, as well as forming the basis for further in-pixel functionality. In addition, by placing the non-linear amplifiers close to the photodiodes, higher signal to noise ratio and dynamic range are expected. However, because of the limited area within the pixel, the circuit realization should be simple and use a small number of transistors.

Acknowledgements:

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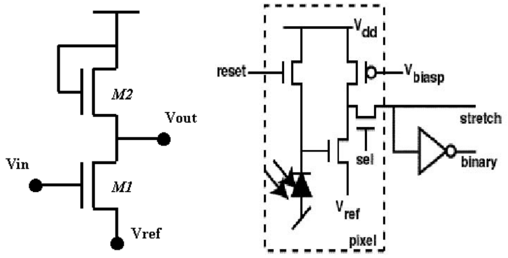


(a) (b)

Figure 1. Schematics of common source follower consists of (a) a transformer with enhanced mode NMOS active load and (b) with PMOS load for controllability and dynamic range

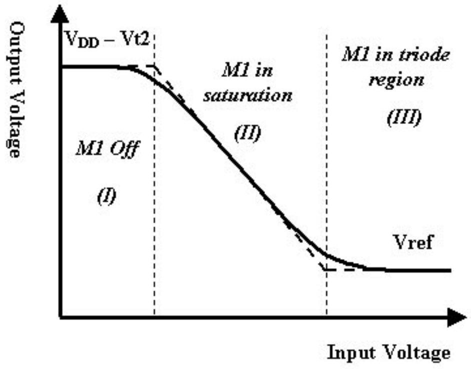


Figure 2. Voltage response of a common source amplifier with enhanced mode NMOS active load

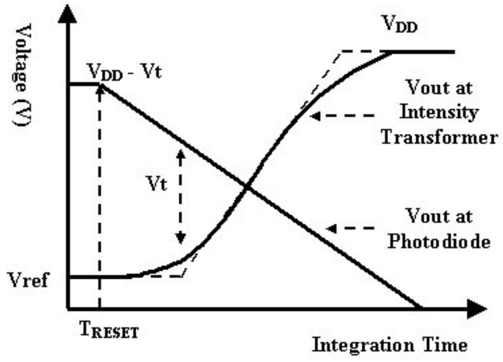


Figure 3. Response of a common source amplifier with voltage output of photodiode as its input

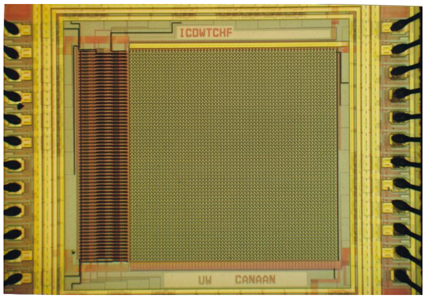


Figure 4. Die photograph of the prototype chip. Total die area is 16mm^2

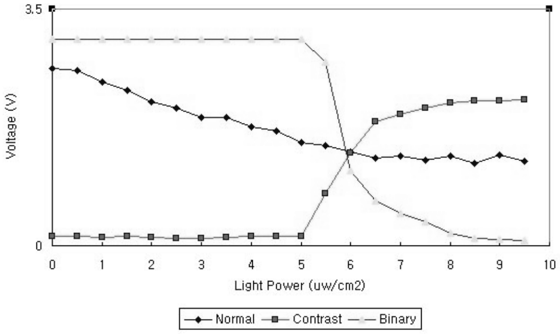
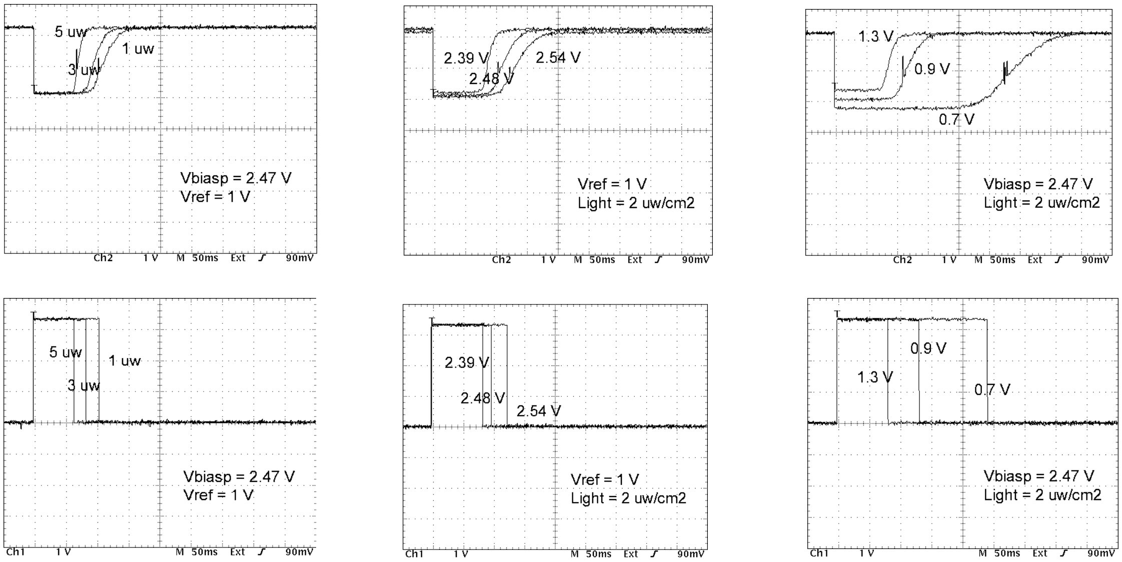
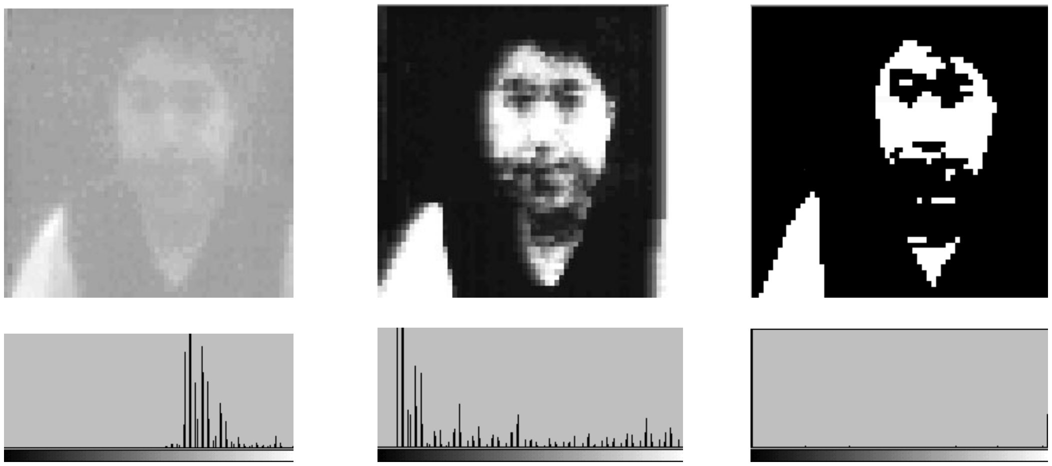


Figure 5. Photoresponse of array as a function of light intensity for each output mode; each point is the average value for the array.



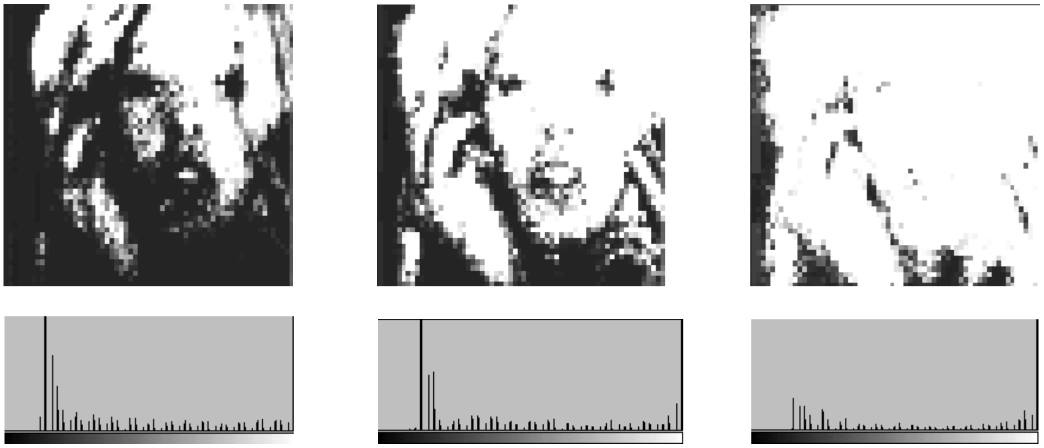
Light intensity *Vbiasp (Contrast)* *Vref (Brightness)*

Figure 6. Photoresponse from the "stretch" output (top row) and inverter output (bottom row) of a pixel with in-pixel contrast stretch at various light intensities, bias voltages and reference voltages



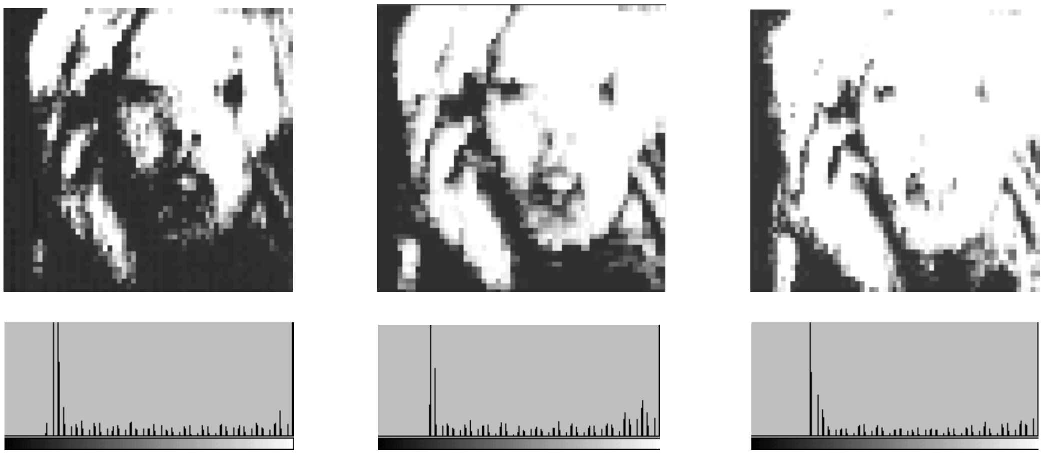
Normal mode (poor contrast) *Contrast stretched mode* *Binary mode*

Figure 7. Sample Images and histograms of three output modes



Vbiasp = 3.0 V *Vbiasp = 2.9 V* *Vbiasp = 2.8 V*

Figure 8. Effects of biasing voltage (Vbiasp). Vbiasp increases the contrast of image; while maximum and minimum of the histogram remains same, the distribution spreads out.



Vref = 1.40 V *Vref = 1.45 V* *Vref = 1.50 V*

Figure 9. Effects of reference voltage (Vref). Vref increases the brightness of image; while distribution of histogram remains same, the minimum value increases as Vref increases