P4 A CMOS Image Sensor Integrating Gamma Correction and Gain Control Functions

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Abstract

A CMOS image sensor integrating gamma correction and gain control functions is presented. The proposed method is based on a fact that gain variation and level shifting in logarithmic compressed domain are equivalent to the gamma correction and the gain control, respectively, in the exponentially expanded domain. A prototype image sensor is fabricated with triple-metal double-polysilicon n-well 0.6μmCMOS technology. The measurement shows that the gamma value can be adjusted to 0.45 when the gain given in the logarithmic compressed domain is 0.74, and a gain of 20dB is obtained with every level shifting voltage of 60mV.

1 Introduction

In many imaging systems, integration of the image sensor with circuitry for performing on-chip signal processing is becoming increasingly important. CMOS image sensors have attracted much attention recently, because of the compatibility with on-chip signal processing as well as the recent improvement of the image quality by means of active pixel sensor (APS) techniques[1] [2]. In the development of solid-state image sensors so far, low-noise performance is the most important issue. Widespread application of image sensors suggests us the importance of other performance factors such as power dissipation, dynamic range, compactness of the total hardware and so on. In digital imaging systems that are becoming major products, the total image quality does not depend only on the noise performance of the sensor but also on the performance of the A/D converter used. Though resolution of 10 bits is commonly used for most of video applications, the resolution of 12 bits and more is ideal to achieve sufficient signal-to-noise ratio in the case that the gamma correction, color balancing, and aperture correction are performed in digital domain. However, such high-speed high-resolution (around 12 bits) A/D converters for video signals consumes large power and cost much. Analog implementation of video signal processing in front of the A/D converter still has a possibility of the improvement of the total performance especially in the system-on-chip solution of digital imaging systems.

This paper present a method to realize functions of gamma correction in analog domain and automatic gain control on a CMOS image sensor as well as achieving the wide dynamic range. One of attractive features of active pixel CMOS image sensors is their wide dynamic range in the case that active pixel circuits with logarithmic compression characteristics are employed[5][6][7]. The proposed method is based on a fact that the gain variation and the level shifting in logarithmic compressed domain are equivalent to the gamma correction and the gain control, respectively, in the exponential expanded domain[8]. This method allows us to realize accurate gamma correction and voltage-controlled variable gain amplification using simple interface circuits. Furthermore, if the automatic gain control is successfully implemented, we can expect wide working range due to the use of the logarithmic APS. In the conventional image sensor, to achieve high sensitivity, the signal saturation is set to relatively low illuminance level. Therefore automatic mechanical iris that increases the system costs is essential to control the incident light level to the sensor. Using the proposed approach, the sensor has always linear response to wide range of illuminance level without mechanical iris.

2 Principles of gamma correction and gain control

Figure 1 shows a conceptual schematic of the proposed CMOS image sensor. First, the input photo current signal x is converted to a voltage signal proportional to $\log x$. Then the output is amplified in

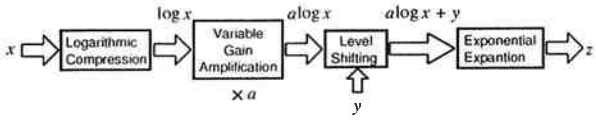

Figure 1: Conceptual schematic of proposed CMOS image sensor

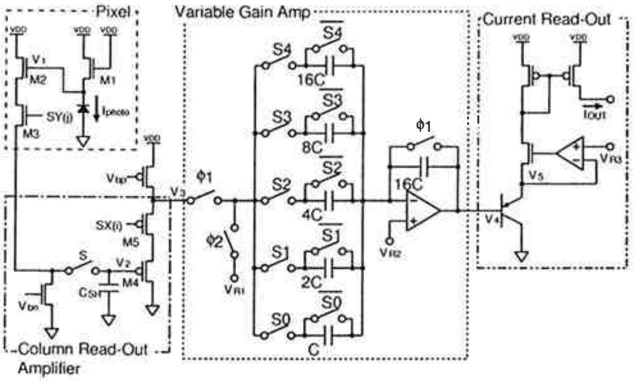

Figure 2: Total circuits configuration

variable gain amplifier (VGA) section whose gain is a. Voltage signal y is added to the amplified voltage $a \times \log x$ in the level shifter section. Finally, an exponential converter expands the logarithmic compressed signal at the output, and the resulting output signal z is given by

$$z = \exp\ (a \log x + y) = G \times x^a$$

where $G = \exp y$. Therefore, the gamma can be adjusted by the gain of the VGA section, and the total gain can be set by means of voltage control. Figure 2 shows the actual circuit configuration of the CMOS image sensor circuits with the gamma correction and the gain control functions. The pixel circuits consist of a photo diode and three n-channel MOSFETs. The n-channel MOSFET whose source terminal is connected to the cathode of the photo diode operates in sub-threshold region.[9] Since the drain and gate terminals are connected to the positive power supply, or V$_{DD}$, the source voltage, V$_1$, logarithmically responds to the photo current. V$_1$ is given by[10]

$$V_1 \quad = \quad V_{DD} - V_{Tn} - n_1 V_{th} - n_1 V_{th} \ln \left(\frac{I_{photo}}{I_{sn}} \right) \tag{1}$$

where, V_{Tn} is the threshold voltage and n_1 is the ideality factor of M1, V_{th} is the thermal voltage (kT/q). I_{sn} is given by

$$I_{sn} = \mu_{eff,n} \frac{W_1}{L_1} C_{ox} n_1 V_{th}^2 \tag{2}$$

where $\mu_{eff,n}$ is the effective mobility of n-channel MOSFET, W_1 is the channel width, L_1 is the channel length and C_{ox} is the oxide capacitance per unit area. One horizontal line of pixels to be read out is addressed by enabling vertical selection switch SY(j). Then the transistors M$_2$ and M$_4$ constitute a source follower, and the voltage variation of V_1 is read out at the output of the source follower as V$_2$. The output of the first source follower, V$_2$, is sampled onto capacitor C$_{SH}$ by enabling sample-and-hold switch S. The stored signal V$_2$ is scanned through the second set of source followers by enabling horizontal selection switch SX(i). V$_3$, the output of the second source follower, is given to a variable gain amplifier (VGA) to adjust the gamma coefficient. The gain of VGA using switched capacitor circuits can be adjusted by the ratio of the input to the feedback capacitors. The gain of the VGA can be set to the range from 1/16 to 2. The gain of the final output can be adjusted by the reference voltages V$_{R1}$ and V$_{R2}$. The output of VGA is given by

$$V_4 = G_v (V_3 - V_{R1}) + V_{R2}. \tag{3}$$

V$_4$ is provided to the base of the pnp bipolar transistor for the exponential expansion. The pnp bipolar transistor is a parasitic device of the CMOS structure whose base and collector are n-well and p-type substrate, respectively. An exponentially expanded current-mode signal with a pnp bipolar transistor is read out through the current mode amplifier using a pMOS current mirror. The output current is given by

$$I_{out} = G_c I_{sb} G_o G_R \left(\frac{I_{photo}}{I_{sn}} \right)^{\gamma} \tag{4}$$

where

$$G_R = \exp \left(\frac{V_{R3} - V_{R2}}{n_2 V_{th}} \right) \tag{5}$$

$$G_o = \exp \left[\frac{G_v (V_{R1} - V_{offset})}{n_2 V_{th}} \right] \tag{6}$$

$$\gamma = \frac{G_v \alpha_1 \alpha_2 n_1}{n_2} \tag{7}$$

V_{R3} is the reference voltage of the operational amplifier in the current-mode output section, n_2 is ideality factor of the bipolar transistor, V_{offset} is the offset voltage due to the level shift of the first and second source followers and α_1 and α_2 are the gain of the first and second source followers, respectively. Hence the gamma is set by the gain of VGA and the gain can be controlled by the reference voltage difference $V_{R3} - V_{R2}$. The gain factor G_0 of Eq. (4) is used to cancel the fixed pattern noise due to the V_{offset} variation by adjusting V_{R1} for each pixel. To do this, the output V_3 under dark condition is read out and is memorized in a frame memory after A/D conversion, then V_{R1} is generated through the D/A converter with the compensation data memorized in the frame memory.

3 Implementation and Evaluation of a Prototype Sensor

A prototype 256×256-pixel CMOS image sensor integrating the gamma correction and the gain control functions is implemented in 0.6μm double-poly triple-metal standard CMOS technology. The pixel size is $9\mu m \times 9\mu m$. Figure 3 shows the microphotograph of the chip.

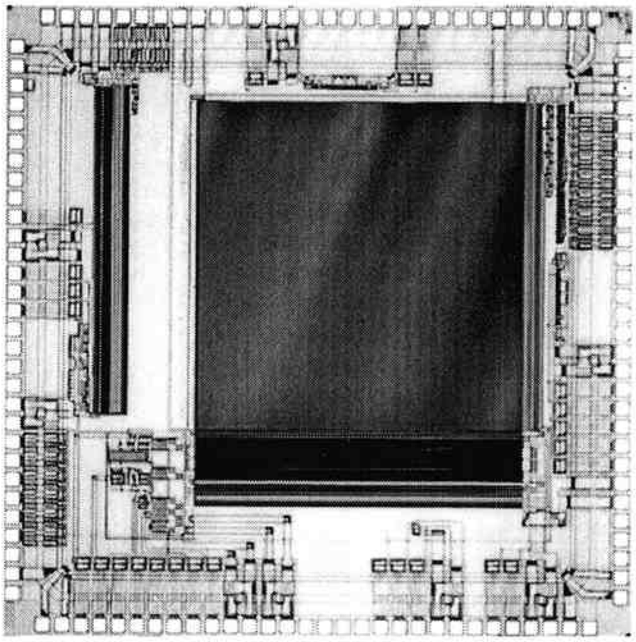

Figure 3: Microphotograph of a prototype image sensor

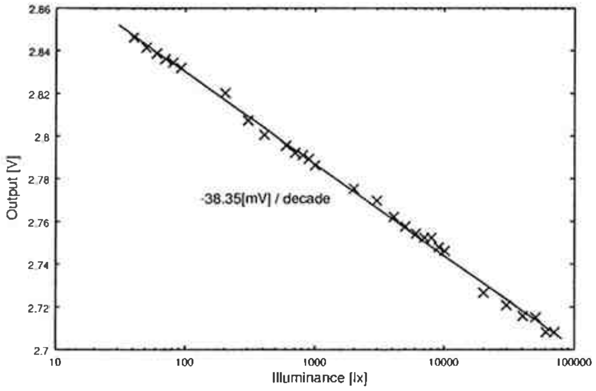

Figure 4: Photo conversion characteristic through column readout amplifier

In the present stage of evaluation, the basic DC characteristics of the sensor and the interface circuits are measured. Figure 4 shows the photo conversion characteristic through the first and the second source follower. The variation of the output of the readout amplifier is -38.35mV for the variation of 20dB of illuminance.

Using the measurement data of Figure 4 and the DC characteristics of the exponential expansion circuits, the gamma correction and the gain control behavior are estimated. Figure 5 shows the simulation results of the variation of gamma coefficient to the gain of VGA. The output current is normalized by the maximum output current that corresponds to the input photo current of $1pA$. From this result, the gamma coefficient can be adjusted to 1 and 0.4 when the gain of VGA is 1.35 and 0.55, respectively. Figure 6 shows the gamma correction characteristics estimated by the measurement data. The output current is normalized by the maximum output current when the illuminance is 1000lx. In this case, the gamma coefficient is equal to 1 and 0.45, when the gain given in logarithmic domain is 1.66, 0.741, respectively. The difference of the adjustable gain for the gamma correction compared with the case of the simulation is due to the difference of the gain in source-follower circuits.

Figure 7 shows the simulation result of the relationship between the photo current and the output current as a function of V_{R2} when γ=1. Assuming that the full scale of output current is 100μA, the total system sensitivity can be set by the reference voltage V_{R2}. The system gain is increased by 20dB as V_{R2} is increased by 60mV. Figure 8 shows the corresponding results of the measurements. Similar to the simulation, the system gain is increased by 20dB as V_{R2} is increased by 60mV.

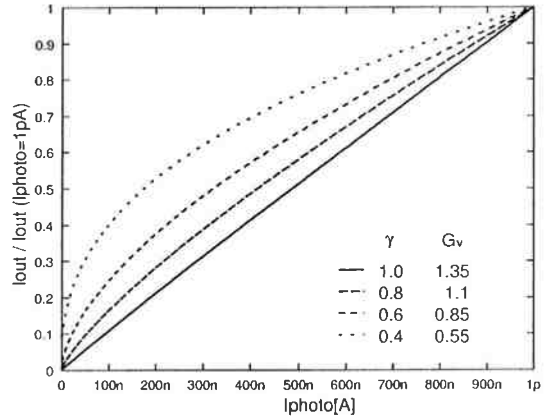

Figure 5: Simulated gamma variation to the gain of VGA

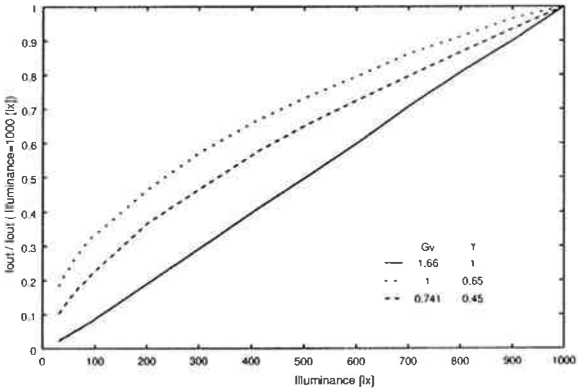

Figure 6: Measured gamma variation to the gain of VGA

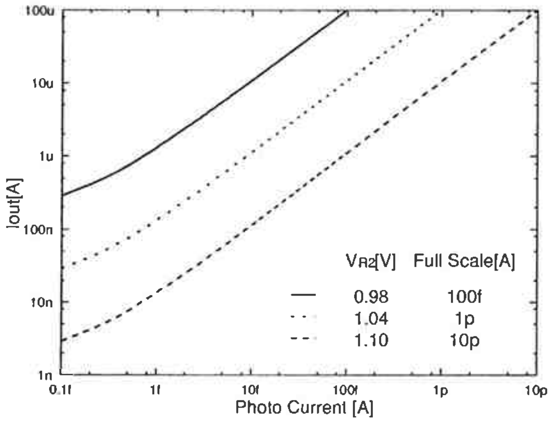

Figure 7: Simulated output current gain as a function of V_{R2}

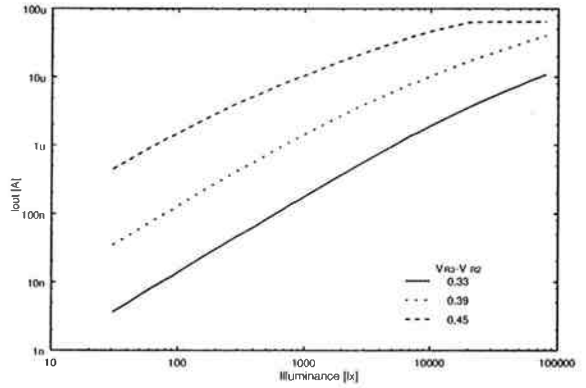

Figure 8: Measured output current gain as a function of V_{R2}

4 Conclusions

In this paper, a CMOS image sensor with the gamma correction and the gain control functions is proposed. These function is realized by the combination of the logarithmic compression in the sensor and the exponential expansion of the bipolar device. The gain is simply set by voltage control, and the gamma is set by a simple variable gain amplifier. Wide working range to the illuminance level can be expected without mechanical iris. Measurement results from a prototype sensor well agree with the simulated data, demonstrating the proposed technique is useful. The full testing and the getting image of implemented CMOS image sensor is left as a feature subject.

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