The Principle and Design of CMOS Active Pixel Sensor

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Abstract. In today's increasingly prosperous global semiconductor development, CMOS image sensors have always been in the spotlight. The many advantages of CMOS such as lower production costs, smaller sensor sizes and lower production costs have allowed them to be used in a wide variety of devices. In this paper, the working principle of the 3-T active pixel sensor and its current applications are introduced, and the architecture and working mode of APS itself are also highlighted. The simulation software coolspice is then used to simulate the output values and timing of the circuit. In this paper, nine inputs of the same value and six pulse voltages are used to control the output sequence. The paper also describes the key technical problems of the APS itself and the solutions to these problems.

Keywords: CMOS, Active Pixel Sensor, Working principle

1. Introduction

All kinds of information to adapt and transform their environment. Human beings can obtain colourful visual information through their own visual organs, which can account for more than 80% of the total information obtained by human beings. Image sensors are the basic components of modern visual information acquisition, along with the progress of technology, because they can achieve the collection of information, transformation, and expansion of visual functions. Thus, it is possible to give a visualization of the content of colourful image information. APS is an image sensor made by the CMOS process, which mainly uses the photoelectric effect of semiconductor and the same principle as a charge-coupled device (CCD) image sensor. Since the late 1960s, CMOS image sensors and CCD image sensor research started almost simultaneously, however, because the semiconductor industry was not as advanced as it is now, the image quality, resolution, light sensitivity, and noise of the CMOS image sensors have a big gap compared to the CCD image sensors at that time. Therefore, it was not recognized by the consumer market. However, due to the development of the semiconductor industry and the level of design improvement CMOS image sensors used to have shortcomings that can now find ways to overcome, and its inherent advantages are incomparable to CCD devices, so it has once again become a hot spot for research. In the following article, the design process and principles of APS are described [1].

2. Active pixel sensor

2.1. Basic introduction to active pixel sensor

Compared to passive pixel sensors, active pixel sensors (APS) solve many of the scalability and speed problems, and APS have many advantages over charge-coupled devices (CCDs) in that they consume much less power and have lower image hysteresis than CCDs. Also, APS is smaller and less expensive to produce than CCDs. APS still has some drawbacks that make him no way to replace CCD, such as higher noise than CCD [2]. Unlike CCD, APS can be integrated into the image sensor and image processing functions, but the gap in noise, dynamic range, and responsivity has considerably narrowed for active pixel sensors. In the mobile terminal market, APS sensors have become the choice of many manufacturers due to advantages such as low production costs. APS also occupies a large share of many other growing photographic and imaging fields, and many of the world's semiconductor manufacturers produce and supply a wide range of APS, including Samsung, Toshiba, Canon, Sony and other semiconductor manufacturers. They have a large share in many production and consumer areas such as digital radiography, cell phone cameras and military image capture.

2.2. General architecture of 3T CMOS image sensor

Compared to CCD image sensors, the high degree of integration is an important feature of CMOS image sensors, which can integrate pixel arrays and various functional circuit modules on a single chip. Figure1 shows the CMOS image sensor system framework.

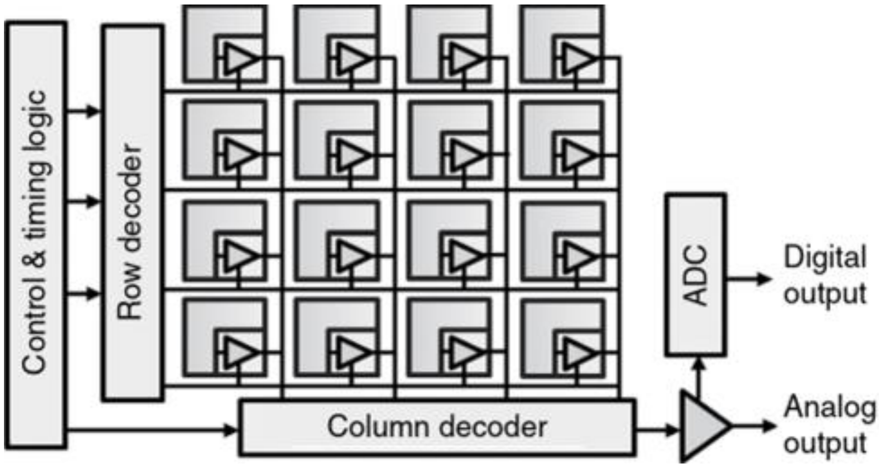

Figure 1. Layout of active pixel sensor [12]

As can be seen from Figure 1, the CMOS image sensor system is mainly composed of the following parts: line driver circuit, associated double sampling circuit, column amplifier circuit, column driver circuit and analogue-to-digital converter circuit (ADC). Depending on the level of integration on the image sensor chip, ADCs can be divided into three types: pixel-level ADCs, column-level ADCs, and chip-level ADCs, of which chip-level ADCs are simple to design and occupy a small area. The line driver circuit and the column driver circuit of the image sensor system are controlled by the external timing logic circuit to produce the line and column selection signals, and analogue electrical signals generated by the pixel array first enter the relevant double sampling circuit (CDS) to eliminate the reset (KTC) noise and fixed mode noise (FPN), then enter the column amplifier for signal amplification and finally enter the ADC in sequence. Then it enters the ADC line by line and is converted into a digital signal, which is processed by the digital signal processing unit.

2.3. Image sensor pixel circuit operation mode

Each pixel operates according to an integral mode of operation, which was proposed by Gene Weckler in 1967. In this mode, the image sensor's photoreceptor converts the incident photons into electric current. A capacitor to integrate the current can be applied and finally a voltage signal is output by the circuit. More specifically, in this mode of operation. The photodiode in the pixel will be applied a voltage to bias the photodiode and then let the photodiode receive the light. At this time, the author turn on the reset switch, and since the author can bar the photodiode as a circuit composed of a capacitor, in this equivalent circuit the photo generated carriers will decay with the increase of the integration time. After a certain time of integration, there will be a voltage difference between the two ends of the photodiode, so the author can read the voltage signal. After the reset switch is closed, the photodiode is reset to its initial value. Finally, the voltage of the light intensity by reading the voltage of the photodiode can be achieved [3].

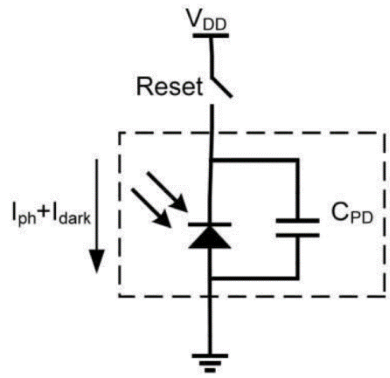

Figure 2. Active pixel working principle [13]

Figure 2 shows the schematic diagram of the image sensor pixel integration mode of operation. When the circuit is in operation, first the reset switch is in the closed position and the supply voltage V_{DD} will be connected to the photodiode, at which point the voltage of the photodiode is equal to the supply voltage. At this moment, Equation 1 can be used to calculate the charge of the equivalent capacitance on the photodiode:

$$Q_{PD} = C_{PD} V_{DD} \tag{1}$$

After the reset switch is disconnected, the capacitor CPD in the equivalent circuit starts to discharge due to the voltage difference, and the charge in the capacitor gradually decreases. In a dark environment, the photogenerated current is equal to 0. However, in this case, there is a weak value of dark current for discharge, which is caused by the characteristics of the photodiode. When the photodiode works in a light environment, the photodiode will output both light and dark currents, and since the light current is much larger than the dark current, the output current at this time will be much larger than in a dark environment. The total amount of point charge put out by the capacitor in the equivalent circuit during the integration time of the photodiode is [4]:

$$\Delta Q_{PD} = \left(I_{ph} + I_{dark}\right) t_{in} \tag{2}$$

CMOS image sensors currently have two main types of pixel structure: active pixel sensors (APS) and passive pixel sensors (PPS). The passive pixel sensor structure is simpler than the active pixel sensor, but the PPS is noisier, and the image quality is better, so the vast majority of CMOS image sensors are now made with the APS structure, which contains an active device (amplifier) that eliminates some of the noise due to the amplification and buffering function in each pixel. The active pixel sensor structure is now the dominant technology in CMOS sensors. Therefore, only the structure of active pixel sensors is analysed below [5].

The sensor element in the 3T pixel is a photodiode, which is the most widely used structure in the active pixel architecture. Figure 3 shows the schematic diagram of the structure of a 3-T active pixel and its potential well energy level, from which it can be seen that the structure consists of a photodiode to which three NMOS transistors are connected. These three NMOS transistors have different roles. The first is the Reset (RST) transistor, which, when switched on, has the same voltage as V_{DD}. The SF transistor is a source follower, the RS is a transistor used to select the output and its function is to output the value of the circuit at the right time.

$$V_{PD\_RST} = V_{DD} - V_{TH}(RST) \tag{3}$$

The threshold voltage of the RST $V_{TH}(RST)$ is represented by Vth. After the photodiode has received the light signal, the photodiode converts the light signal into an electrical signal and the current output causes V_{PD_RST} to fall slowly. The stronger the incident light, the faster V_{PD_RST} drops. The final output current is amplified by the SF. The RS transistor closes at the right time. The value in the pixel is read out [6].

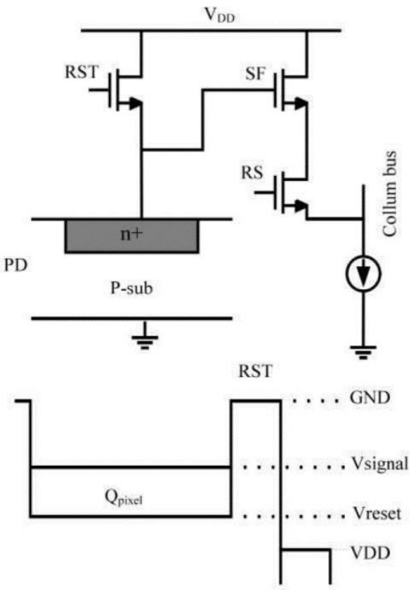

Figure 3. Active pixel and Potential well diagram [14]

3. Sections, subsections, and sub subsections

3.1. Experiment result and analysis

This experiment mainly focused on circuit design and sequence timing output. In this experiment. We first design our circuit according to Figure 4 D1 to D9 simulate the input current of the photodiode, respectively. Here the author set the same value for all input currents. Timing is very important in the APS parameters. Timing affects the correct colour sequence of the output, and a well-set timing also affects the corresponding time of the output image [7].

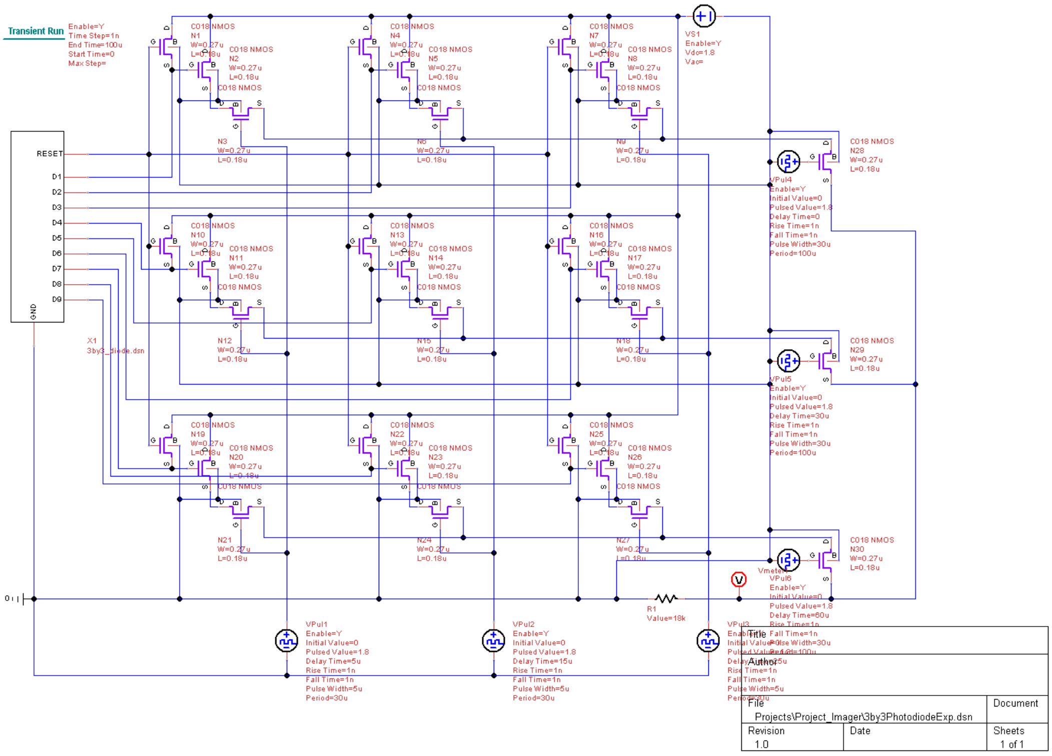

Figure 4. Layout of active pixel sensor

Here the author uses a row decoder and column decoder to control the output timing. Because if the author set up separate output timing switches for each pixel, our control logic would be much more complex. Figure 4 is the circuit made by coolspice. For example, in the circuit in Figure 4, the author uses six pulse voltage sources to control the output sequence. If the author were to control each pixel individually, the number of pulse voltage sources used in the circuit would increase to nine. Thus, the author can use a row decoder and column decoder to achieve the same effect with a simpler circuit. Figure 5 is the simulation result of the circuit in figure 4, The figure shows how this circuit outputs the value of each pixel in sequence.

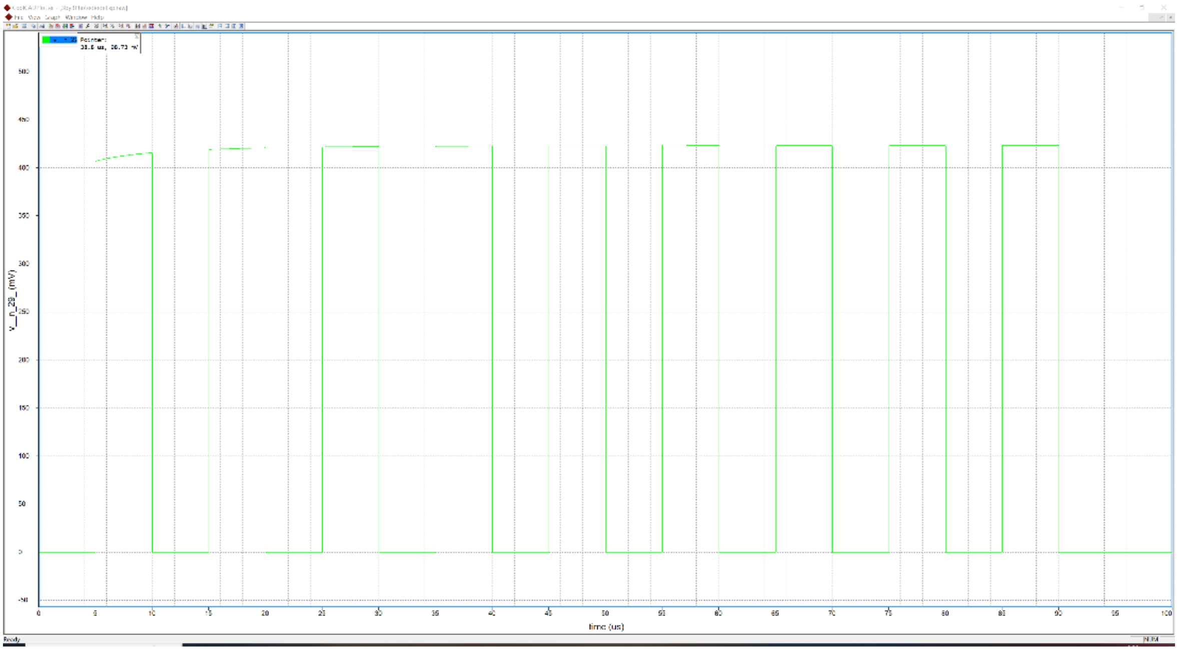

Figure 5. Layout of active pixel sensor

3.2. Key technical problems and solutions

Dark current is one of the challenges of CMOS image sensors. CMOS imaging devices have a large pixel size, therefore, within the normal range will also generate a certain amount of dark current. The dark current limits the sensitivity and dynamic range of the device. The incidence and impact of dark currents can be reduced by improving the CMOS process, lowering the temperature and compressing the junction area; at the same time, the impact of dark currents will be reduced if by measures such as increasing the frame rate and shortening the convergence time of dark currents [8].

The size of the noise directly affects the CMOS image sensor signal acquisition and processing, therefore, the signal-to-noise ratio is one of the key technologies that need to be improved in CMOS image sensors. Noise mainly includes scattering noise, thermal noise, 1/f noise, non-uniform noise and fixed mode noise. The following measures can be taken to suppress noise and improve sensitivity: a. the use of a unique circuit to reduce misalignment, using a special process for manufacturing more stable transistors; b. each image element contains an amplifier with relatively low sensitivity to various changes; c. drawing on the preparation technology of CCD image sensors, the use of relevant dual sampling circuit technology and micro-lens array technology; d. photodiode design into a needle-shaped structure or buried-shaped structure [9].

The CMOS image sensor’s fill factor is generally between 20% to 30%, while CCD image sensors are up to 80% or more, which is mainly due to the readout circuit integrated into the pixels of CMOS image sensors. Using a microlens array structure, a microlens is placed on the image element of the entire CMOS active pixel sensor to focus light on the effective area, which can substantially improve the sensitivity and fill factor [10].

Dynamic range is one of the main indicators to reflect the performance of image sensors. CMOS sensors are currently slightly weaker than CCDs in terms of noise, dynamic range, etc. However, CMOS sensors can still achieve a dynamic range of up to 140dB, which also increases the image noise, affecting the image quality to improve the dynamic range one of the methods is the use of a PECVD ultra-high vacuum system and special integrated circuit (ASIC) film technology, improve the combination of photodiode materials, to improve the sensitivity of low grey areas. Increase the sensitivity of the low grey areas to improve the dynamic range [11].

4. Conclusion

An image sensor is a semiconductor device that uses a photosensitive element such as a photodiode to capture light signals within its pixels to convert information about the incoming light intensity into electronic signals. This thesis introduces the architecture of the 3-T APS and the working principle of its internal photoreceptors and circuits, and designs and simulates the circuits with the simulation software coolspice. A simpler circuit to control the output timing was also implemented. However, there is still a lot of work to be done, on how to reduce the dark current, and how to suppress the noise and other research is not yet in-depth. The work done in this paper is only a simple design and simulation of the 3T APS, and further optimization of the pixel structure and improvement of the readout circuit are needed. The research institutions tend to make CMOS active pixel sensors with very small storage or very high resolution, and this goal involves a lot of technical challenges, which is both a challenge and an opportunity for us.

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