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Selection of amplifier for optimized charge transfer in active pixel CMOS time of flight (TOF) image sensors

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Abstract: Although CMOS Time-of-Flight Range Image Sensors have been recently realized, the fabrication process is modified by inserting an extra mask layer to allow efficient TOF dependent charge transfer. This work focuses on the selection procedure of amplifiers to be used in the design of the TOF pixel using the standard CMOS process. From our analysis, it is found that the Cascode amplifier is the best amplifier to be used when compared to three other amplifiers. Simulation results show that the Cascode amplifier has a Charge Transfer Efficiency of 95.08% and power dissipation of 1.32 μW, which enables the same charge transfer mechanism required for TOF imaging.

Keywords: Time-of-Flight (TOF), Charge Transfer Efficiency (CTE), CMOS Amplifiers, TOF Pixels, Cascode Amplifier

Classification: Integrated circuits

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1 Introduction

Time-of-Flight (TOF) range imaging is a very cost effective method for capturing range images when compared to triangulation and interferometery due to its simple setup [1, 2, 3, 4]. An array of TOF sensors detect the travel time a light signal travels from an active illumination light source to objects in a scene and back to the sensor array that is situated at the same plane with the light source. This measured time, also known as the delay time, $\mathrm{T_D}$ is used to calculate the distance of objects, L in the scene and is given as:

$$\mathrm{L} = \frac{1}{2}\mathrm{cT_D} \tag{1}$$

where c is the speed of light constant which is 3×10^8 m/s [1]. Variations of TOF sensors using CMOS, CCD and hybrid CCD CMOS technology has been realized by transmitting pulses or sine wave light signals [5, 6, 7].

In CMOS technology, the Gates On Field Oxide structure have been shown to produce range images using light pulses with a duty cycle of 10%. Two transfer gates in the pixel separate charge into two output nodes according to $\mathrm{T_D}$. However fabrication of the sensor requires insertion of an extra mask layer to form an epitaxial layer within each pixel thus increasing fabrication cost [5]. A solution to this is to use CMOS amplifiers to transfer time delay dependent photo charge between two capacitors where the ratio of the photo charge is related to the TOF [1, 8]. This will eliminate the need for an extra mask layer to fabricate the TOF sensor. This paper explains how the most appropriate amplifier is chosen for the design of a TOF image sensor using a 0.18 μm standard CMOS process.

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2 TOF Pixel functionality and charge transfer efficiency

Charge Transfer Efficiency (CTE) is defined as the ability of an amplifier to transfer charge between its input node to its output node. Fig. 1 (a) shows the schematic of the Active Pixel TOF Sensor. The time delay dependent photo charge generated in the photodiode, PD is transferred to the feedback capacitors C_1 and C_2 during TOF light signal accumulation using a 10% duty cycle 1 MHz light pulse. The signals used to control the light TOF dependent photo charge transfer (ϕ_1 and ϕ_2) is shown in Fig. 1 (c). Signal ϕ_R is used to reset the pixel at the beginning of the accumulation time. If the Received Light Pulse (RLP) is delayed by T_D seconds then range, L is given by:

$$L = \frac{cV_2T_0}{2(V_1 + V_2)} \tag{2}$$

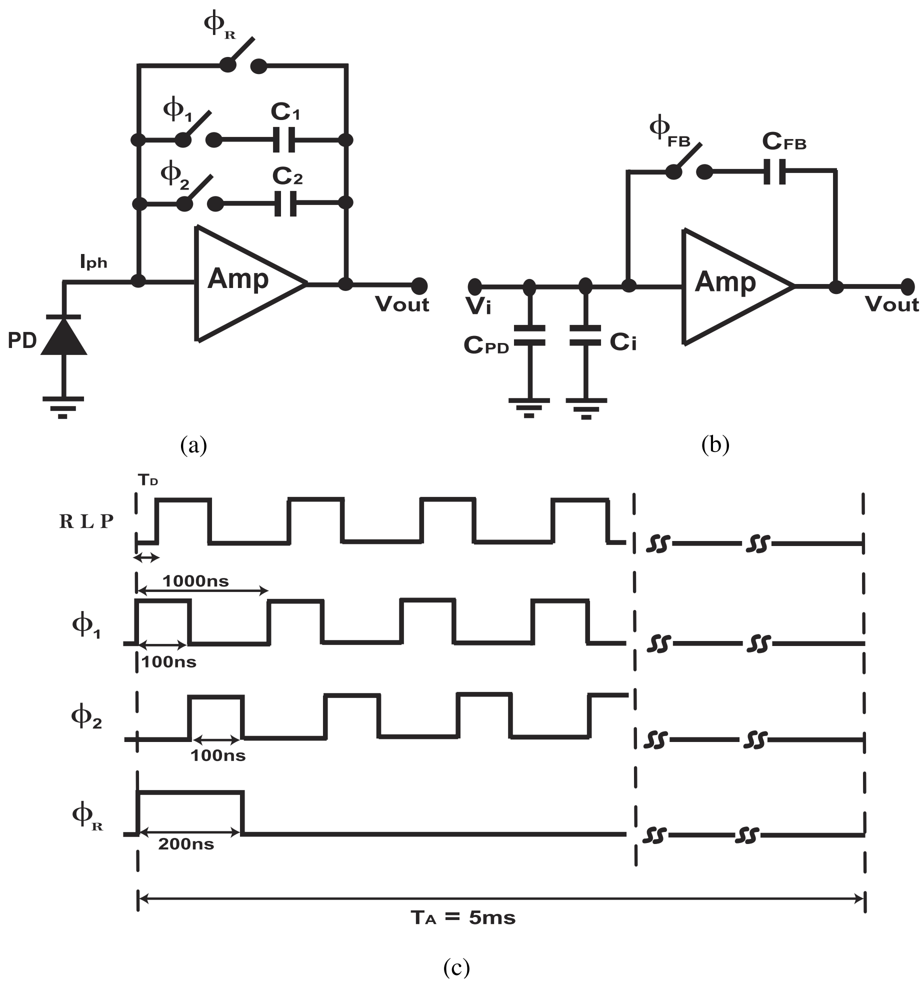

Fig. 1. Active Pixel TOF Sensor. (a) Pixel Schematic. (b) Charge Transfer Efficiency Equivalent Circuit. (c) Pixel Control Signals.

Since only one feedback capacitor is connected between the feedback loop at any given time, the equivalent circuit to analyze the CTE is shown in Fig. 1 (b) [1]. CTE of the pixel is given as the ratio of output charge in the

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feedback capacitor to the input charge generated in PD and is written as:

$$\mathrm{CTE} = \frac{Q_{FB}}{Q_{PD}} = \frac{1 + AC_{FB}}{C_{PD} + C_i + (1 + A)C_{FB}} \tag{3}$$

Fig. 1 (c) shows the control signals associated with the active TOF pixel during its operation. Eq. (3) suggests that an amplifier with a gain of 10,000 will boost CTE to 99.4% [8]. The next section explains CTE analysis done on four amplifiers in order to propose the best amplifier for the Active Pixel TOF CMOS Sensor.

3 Amplifier selection

There are several amplifier specifications that are taken into consideration when choosing the best amplifier to be used for the TOF pixel. Initially, comparing amplifiers according to their gain and CTE is carried out. Eq. (3) is used to calculate the CTE while simulation of the CTE is executed to confirm the Eq. (3). Above all, the power dissipation and numbers of transistors are also taken into consideration when selecting a suitable amplifier for the TOF pixel.

3.1 CTE Analysis for amplifier selection

Four different architectures of CMOS amplifiers are considered. The amplifiers are the 2-Stage Operational Amplifier, Folded Cascode Amplifier, Telescopic Amplifier and the Cascode Amplifier [9, 10]. Fig. 2 (a) shows the CTE plot calculated using Eq. (3). The value of the capacitors C_{PD}, C_i and C_{FB} associated with the pixel are 20 fF, 10 fF and 5 fF, respectively.

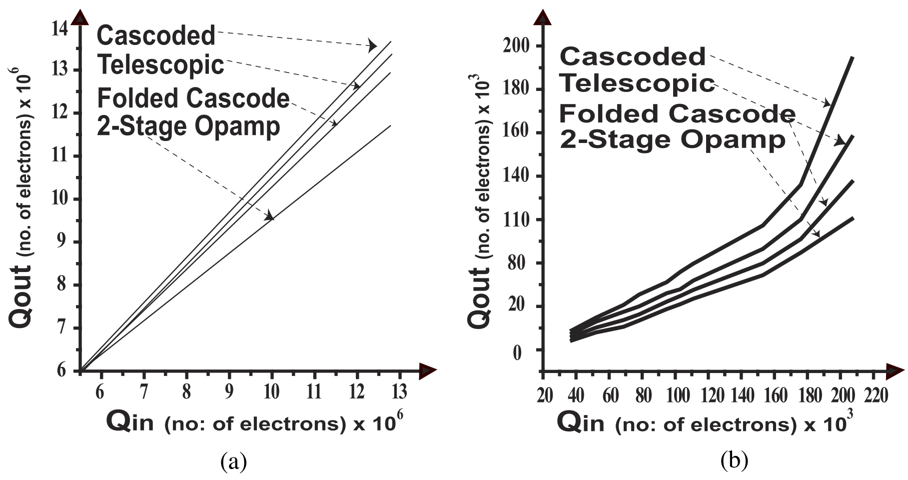

Fig. 2. Input Charge versus Output Charge (a) Calculated. (b) Simulated.

Fig. 2 (b) shows the simulated CTE for the four amplifiers. The simulation was carried out using the schematic in Fig. 1 (b) for a 10% duty cycle, 1 MHz pulsed input photo-current of 1 pA for an integration time of 5 ms. Switch ϕ_{FB} is pulsed exactly in phase as the photo-current. The resulting

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plot in Fig. 2 (b) shows that the Cascode, Telescopic, Folded Cascode and the 2-Stage Op-Amp has a CTE of 95.08%, 81.1%, 67.5% and 55.7%, respectively. Interestingly the gains of the amplifiers are 131.23 dB, 106.73 dB, 87.26 dB and 69.94 dB, respectively. This confirms that as gain increases, CTE increases. Simple analysis shows that an average increase of 20 dB in amplifier gain results in an 11.25% increase in CTE. Thus it is predicted that a 150 dB gain can yield almost 100% CTE.

The maximum gain attainable through design for this work is only 131.23 dB using the Cascode amplifier which dissipates only 1.32 μW of power per pixel. This amplifier is considered in the design of the TOF pixel. The plot also reveals that the Folded Cascode amplifier exhibits a moderate CTE of 67.5%. However, its power dissipation is only 2.64 μW, thus it is considered for the design of the TOF pixel. On the other hand, the 2-Stage Operational Amplifier has a small gain of only 69.4 dB and exhibits the lowest CTE, thus it is eliminated. Although the Telescopic amplifier looks promising, it consumes the highest amount of power which is approximately 3.3 μW. Moreover, it also has the most number of transistors (13 transistors), thus would be difficult to be used in the layout of the TOF pixel, thus it is also eliminated.

3.2 Pixel functionality for amplifier selection

Two TOF pixels as in Fig. 1 (a) were designed. The first pixel utilizes the Cascode amplifier while the second pixel uses the Folded Cascode amplifier. The feedback capacitors values are 10 pF each. Each pixel was simulated with an input RLP of 1 pA running at 1 MHz at a 10% duty cycle as shown in Fig. 1 (b). This results in a pulse width of 100 ns. According to Eq. (1), the measurable maximum distance is 15 m. The time delay, T_D of the RLP is increased (0, 20 ns, 30 ns, 50 ns, 70 ns, 80 ns and 100 ns) in order to simulate different return times of the RLP due to objects at increasing distance. For example, $T_D = 20$ ns is used to simulate an object at 3 m from the sensor while $T_D = 50$ ns simulates an object at 7.5 m. When $T_D = 0$, the RLP is perfectly in phase with ϕ_1 and all of the induced photo charge will be transferred to capacitor C_1, resulting in a larger voltage across C_1 which is denoted as V_1. On the other hand, when $T_D = 100$ ns, the RLP is perfectly in phase with ϕ_2 and all of the induced photo charge will result in a signal voltage V_2 across C_2. However, when $T_D = 50$ ns, the reflected light pulse lies equally between ϕ_1 and ϕ_2 which ideally results in equal charge transfer to both capacitors, hence V_1 is expected to be equal to V_2. Thus the difference between V_1 and V_2 for increasing T_D values are expected to move down if the pixel's delay dependant charge separation mechanism is functioning perfectly and linearly.

Fig. 3 (a) shows the plot of the output voltage difference (V_1-V_2) versus an accumulation of 5 ms for the Cascode amplifier pixel for different T_D values. For $T_D = 50$ ns, equal amounts of photo-charge are transferred into C_1 and C_2 hence the two outputs V_1 and V_2 are equal resulting in a zero difference between the two output voltage signals. As T_D increases from 50 ns ($T_D = 70$ ns, 80 ns and 100 ns), the amount of charge transferred to

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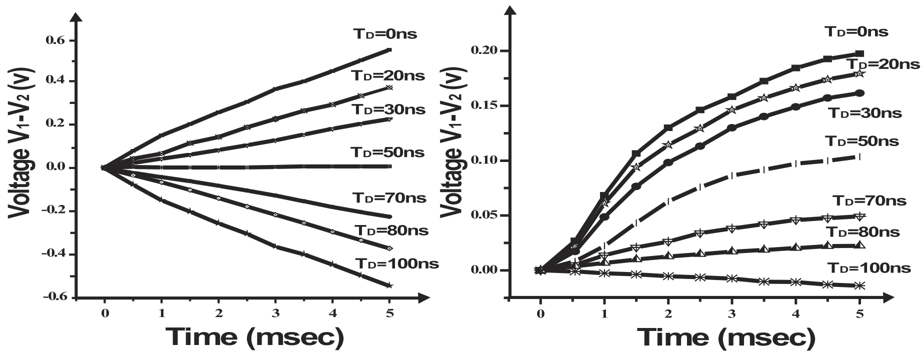

(a) (b)

Fig. 3. (V_1-V_2) versus Accumulation Time for the (a) Cascode Amplifier TOF Pixel. (b) Folded Cascode Amplifier TOF Pixel.

C_2 is more than the amount of charge transferred to C_1, thus shifting the plot downwards. As T_D decreases from 50 ns (T_D = 30 ns, 20 ns and 0 ns), the amount of charge transferred to C_1 is more than the amount of charge transferred to C_2 decreases, thus shifting the plot upwards. This plot confirms the functionality of the Cascode Amplifier TOF pixel. It is concluded that a 95.08% CTE is sufficient to obtain linear output voltages as a function of time delay.

Fig. 3 (b) shows the output difference (V_1-V_2) versus an accumulation of 5 ms for the Folded Cascode amplifier pixel. Since CTE is approximately 67.5%, the output is nonlinear. This is caused by imperfect charge transfer between C_1 and C_2 due to low amplifier gain. When a low gain amplifier is used, imperfect charge transfer occurs resulting in non-linear output voltages. For example, at T_D = 50 ns an equal amount of photo charge should be transferred equally between C_1 and C_2. However, when switch ϕ_1 initially opens, a small amount of photo-charge is trapped in PD due to low amplifier gain. Once ϕ_2 is closed, the same phenomena occurs resulting in a lesser amount of charge transferred to C_2. The results suggest that as accumulation time increases, the amount of trapped charge in PD is mostly transferred to C_1 once ϕ_1 is turned on again in the next transfer cycle. This can be observed in Fig. 3 (b) where at T_D = 50 ns, the voltage difference is a positive value which is approximately 0.113 V due to a larger value of V_1 than V_2. Moreover, the output difference starts to saturate after 5 ms. Again, this is due to the low gain of the amplifier which results in imperfect charge transfer which leads to increased charge trapping in PD and undesirable saturating output voltages.

4 Conclusion

Four different types of CMOS amplifiers which are the 2-Stage Operational amplifier, Cascode amplifier, Folded Cascode amplifier and Telescopic amplifier were designed and analyzed for possibilities to be used in the design of an Active Pixel CMOS TOF Range Image Sensor.

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Preliminary results eliminate the 2-Stage Op-Amp from the pixel design as it has a low gain of only 69.4 dB. Although the Telescopic amplifier has an exceptional gain of 106.73 dB, it is also eliminated as it has the highest power consumption of 3.3 μW and complicated to layout due to the large number of transistors required for its design. The Folded Cascode amplifier is also eliminated because when integrated into the TOF pixel, the output exhibits non-linearity as CTE is low. The results suggest that the Cascode amplifier is the most suitable amplifier in designing the CMOS TOF pixel. The results also show that when a low CTE amplifier is used, the delay dependent charge separation mechanism does not work perfectly. For best linearity, a CTE of at least 95% should be met.

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