Injection efficiency for direct injection model in an optical sensor

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The basic theory for direct injection model in an optical imaging sensor is discussed. Both the tranconductance of an input gate and the impedance of a photodiode are the main factors that influence the injection efficiency at a low operation frequency. In addition, the injection efficiency decreases with the increase of the frequency at high sampling frequencies. A direct injection efficiency of near 100% can be achieved by using a special current mirroring direct injection, even when the impedance of the photodiode is low. A circuit design and implementation for the current mirroring direct injection model with an InSb 64 pixel linear array have been proposed. Testing results match with the theoretical analysis.

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1. Basic theory for a direct injection model

The optical sensors include a CCD imaging, CMOS imaging and infrared focal plane array. Their injection models are subdivided into a direct injection and a gate modulation injection. The direct injection model is suitable for a photovoltaic detector and the gate modulation injection is suitable for a photoconductive one. An expression of the direct injection model was firstly reported by an American scholar Steckl in the 1970s [1], and then an accurate expression was provided by a Chinese scholar in the 1980s [2]. The two expressions were later combined and called Steckl-Yi's formula which is included in the handbook of laser and infrared technology [3].

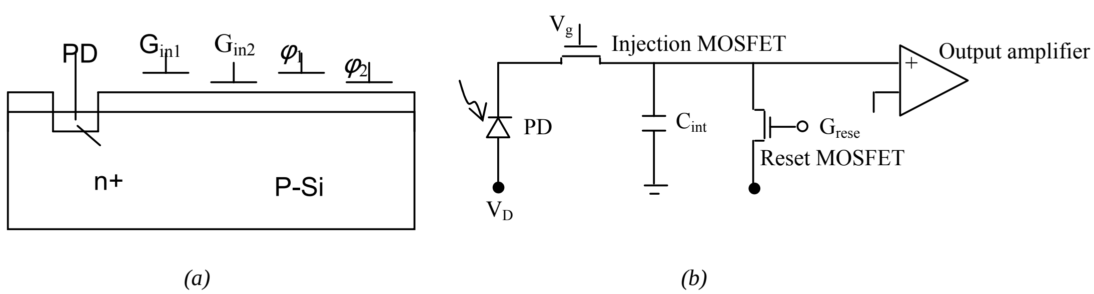

Fig.1 Basic structures for CCD and CMOS direct injection model: (a) CCD,(b)CMOS PD- photodiode , G_{in1}-injection gate , G_{in2}-injection storage gate, Φ_1、Φ_2-transit gates V_g-injection gate of injection MOSFET, C_{int}-integration capacitance.

A direct injection readout circuit is shown in Fig. 1. Fig. 1 (a) shows the direct injection circuit for CCD and IR-CCD. Fig. 1 (b) represents the direct injection model for a CMOS circuit. The expression of the direct injection model for both CCD and CMOS imaging devices is presented bellow [2].

$$\eta = \frac{g_m}{G_D + g_m} \cdot \frac{A}{1 + \omega^2 [(C_D + C_{gs}) / (G_D + g_m)]^2} \qquad (1)$$

$$A^2 = 1 + \frac{\omega^2}{(G_D + g_m)^2}\left\{\left[2C_{gs}C_D + 2C_{gs}^2\left(1 + \frac{G_D}{g_m}\right)\right] + \frac{1}{g_m^2}[C_{gs}^2 G_D^2 + g_m^2 C_D^2 + C_{gs}^2 \omega^2 (C_{gs} + C_D)^2]\right\} \quad (2)$$

where g_m is the tranconductance of an injection gate, G_D is the conductance of a photodiode , C_{gs} is the capacitance of the injection gate, C_D is the capacitance of the photodiode, and ωis a sampling frequency.

2. The direct injection model operated at a low frequency

The expressions 1 and 2 indicate the injection efficiency does not vary with the frequency at low operation frequencies, however, it decreases with raising of the sampling frequency at high operation frequencies. If the sampling frequency extends to zero and the related injection efficiency is presented by$\eta_{inj}(o)$, η_{inj} approaches the$\eta_{inj}(o)$ at the low operation frequencies . The expression 1 is simplified as follows.

$$n_{inj} = \frac{g_m}{g_m + G_D} \quad , \quad (3)$$

$$n_{inj} = \frac{g_m \cdot R_D}{1 + g_m R_D} \quad (4)$$

where R_D is the impedance of the photodiode which is equal to $1/G_D$. The expressions (3) and (4) show that the direct injection efficiency may increase by increasing both the tranconductance of the injection gate and the impedance of the photodiode. Usually, a photodiode has high impedance and it is suitable to the direct injection model.

The efficiency expresses (3) and (4) are the basic formulas for a conventional direct injection circuit operated at low frequencies. They are also fundamental formulas for recent developed direct injection model including CCD, CMOS and infrared focal plane array [4-6].

3. High injection efficiency circuit with low photodiode impedance

According to the expressions 1, 3 and 4, increasing the tranconductance (g_m) of an injection gate and increasing the impedance (R_D) of a photodiode will increase the injection efficiency for the direct injection circuit. However, the increasing g_m and R_D is finite, the injection efficiency can not approach 1. A current mirroring direct injection method is provided which can satisfy the injection efficiency of 100% even for a low impedance of the photodiode.

Fig. 2 shows a principal circuit. M_{P1} and M_{P2} are a couple of p-MOS current mirroring MOSFETs with the same geometry. M_{N1} and M_{N2} are an other couple of n-MOS current mirroring MOSFETs.

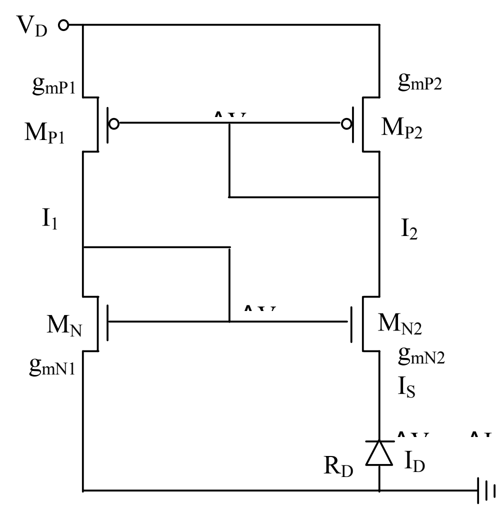

Fig. 2. Principal circuit for the current mirroring

Therefore, I_1, I_2 and I_s are the same, and

$$\Delta I_1 = \Delta I_2 = \Delta I_S \quad (5)$$

For M_{N2}:

$$\Delta I_S = g_{mN2}(\Delta V_{gN} - \Delta V_S) \quad (6)$$

For M_{N1}:

$$\Delta I_1 = g_{mN1} \cdot \Delta V_{gN} \quad (7)$$

Combining (6) with (7), the input impedance of M_{N2}:

$$R_{in} = \frac{\Delta V_S}{\Delta I_S} = \frac{g_{mN2} / g_{mN1} - 1}{g_{mN2}} . \quad (8)$$

Since both the tranconductances for g_{mN2} and g_{mN1} are almost the same, the expression (8) indicates the injection impedance of the M_{N2} approaches zero. That is the input tranconductance of the M_{N2} is limitless. According to the expressions 3 and 4, the injection efficiency for the direct injection current mirroring circuit is near 100%, at a low operation frequency, even for a low photodiode impedance.

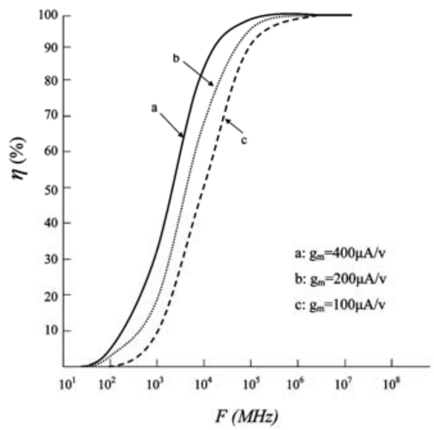

Fig. 3. Injection efficiencies as a function of photodiode impedances.

Fig. 3 shows the injection efficiencies as a function of photodiode impedance, indicating the injection efficiency increasing with the photodiode impedance for the conventional injection model (curves a, b and c) and the injection efficiency is almost 100% even the photodiode impedance is low for the current mirroring direct injection model.

4. Experimental circuit of high injection efficiency with a low photodiode impedance

A practical design and implement of the current mirroring direct injection circuit with 64 pixel linear InSb array was completed. A pixel of the linear array is shown in inside of the dashed line and a common output amplifier is shown in outside of the dashed line shown in Fig. 4. A integration capacitance C_{INT} is placed between M_{P2} and M_{N2}. The integrated signal charge in the capacitance is transited in turn from 1 to 64 to both the output amplifier and the feedback capacitance C_{FB}. Finally, the reset MOSFET turns on to reset a voltage at the C_{FB} to the origin level in order to next readout. The test shown in Fig. 5 indicates the injection efficiency approaches 100% at low operation frequencies for the first time, which is consistent to the theoretic analysis based on the current mirroring direct injection model.

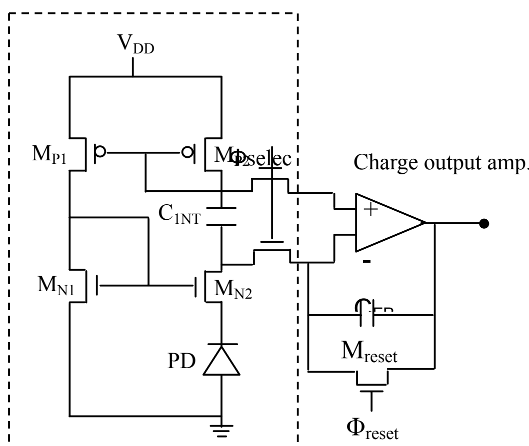

Fig. 4. Experimental InSb 64 pixel linear array with the current mirroring direct injection.

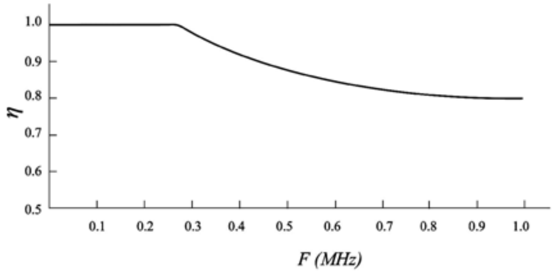

Fig. 5. The injection efficiency Vs operation frequencies for the experimental injection circuit.

Fig. 5 also presents the injection efficiency behavior at high operation frequencies, indicating the injection efficiency decreases with the operation frequencies, which is consistent with the results shown in expression 1. The test in detail will be discussed in other paper.

5. Conclusions

The photodiode arrays have been widely utilized for recent imaging sensors including visible CCD imaging, CMOS imaging, and infrared focal plane arrays. The direct injection model is usually used for the design of a signal readout circuit. The injection efficiency effects directly on the imaging qualities, including sensitivity, dynamic range, nonuniform, pixel size and consumption. Both increasing the tranconductance of the injection gate and increasing the impedance of the photodiode are usefully utilized to increase the injection efficiency for the conventional direct injection circuits at low operation frequencies. Recently, a current mirroring direct injection model with a high injection efficiency of 100% even for a low impedance of the photodiode has been proved by our experimental circuit. This significant progress will further drive future applications of infrared readout electronics for military and commercial uses.

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