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Modeling of the charge transfer in a lateral drift field photo detector

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ABSTRACT

In this article a model is introduced that describes the charge transfer in pixels of an image sensor. The model is suitable for image sensors where lateral drift field photo detectors were implemented and considers the effects of thermal diffusion, drift due to the built-in potential gradient, and self-induced drift.

The analytical result is compared with a numerical solution and confirmed by measurements. With this model it is possible to predict the amount of collected charge at the sense node for very short integration times in comparatively long pixel structures. This is particularly important for indirect time-of-flight applications with CMOS image sensors.

This approach enables the optimization of the pixel layout as well as an advanced calibration that might possibly enhance the distance precision. The model can also be applied to image sensors featuring pinned photodiodes.

1. Introduction

Image sensors for contactless distance measurements based on the pulse modulated (PM) time-of-flight (ToF) principle measure the time that elapses between the emission of a light pulse and the impact of the reflected light.

The indirect ToF principle offers a possibility to avoid the implementation of fast and complex time-to-digital converters by integrating the photo-generated signal at two different sense nodes. Additionally it enables the implementation of an advanced background light suppression.

In order to achieve a fast transfer from the photoactive area to the collection gate a lateral drift field photodetector (LDPD) is used in our application. This is basically a pinned photodiode with a built-in potential gradient (see Fig. 1) which causes an additional electric field. This potential gradient is formed by a doping gradient which increases towards the end of the well. In combination with the biased collection gate the charge carriers are accelerated in the direction of the transfer gates. Note that the device used in our application exhibits three floating diffusions (FD) and a draining diffusion (DD) together with four transfer gates (TX) operating as shutters. The LDPD and its properties have been introduced and described in detail in [1].

Fig. 2 shows the timing diagram. The floating diffusions and corresponding transfer gates serve as short-time charge integrators. The integration at the first integrator formed by FD1 and TX1 starts at the same time as the light pulse is emitted. It is directly followed by the charge integration at a second integrator (TX2 and FD2) of the same duration. Due to the time of flight the reflected signal arrives at the sensor delayed by the time t_{delay} in respect to the shutter windows t_{TX1} and t_{TX2}. Hence it is divided onto the two integrators and the actual distance information can be computed from the signal ratio. If we assume the ideal case of an infinitely fast charge transfer and a rectangular laser pulse exhibiting a pulse width t_{pulse} and choose the shutter window during which the photocharges can be acquired and accumulated as $t_{TX1} = t_{TX2} = t_{TX3} = t_{pulse}$ the accumulated photocharges at FD1, FD2, and FD3 can be determined as $N_{FD1} = N_{Laser1} + N_{HG}$ and $N_{FD2} = N_{Laser2} + N_{HG}$, where N_{Laser1} and N_{Laser2} are proportional to laser irradiance at the sensor and $t_{pulse} - t_{delay}$ and t_{delay}, respectively. N_{HG} is due to the ambient illumination and is proportional to t_{pulse}. The object distance can be found from

$$d = \frac{c}{2} \cdot t_{delay} = \frac{c}{2} \cdot \frac{N_{FD2} - N_{FD3}}{N_{FD1} + N_{FD2} - 2N_{FD3}} \cdot t_{pulse}, \quad (1)$$

where $N_{FD3} = N_{HG}$. Note that due to the case of ratios, the effect of laser irradiance and ambient illumination is eliminated. Since the image sensors are operated in daylight conditions the light pulse is superimposed by background light. To offer the possibility to take that parasitic signal into account a third shutter (TX3) is integrated

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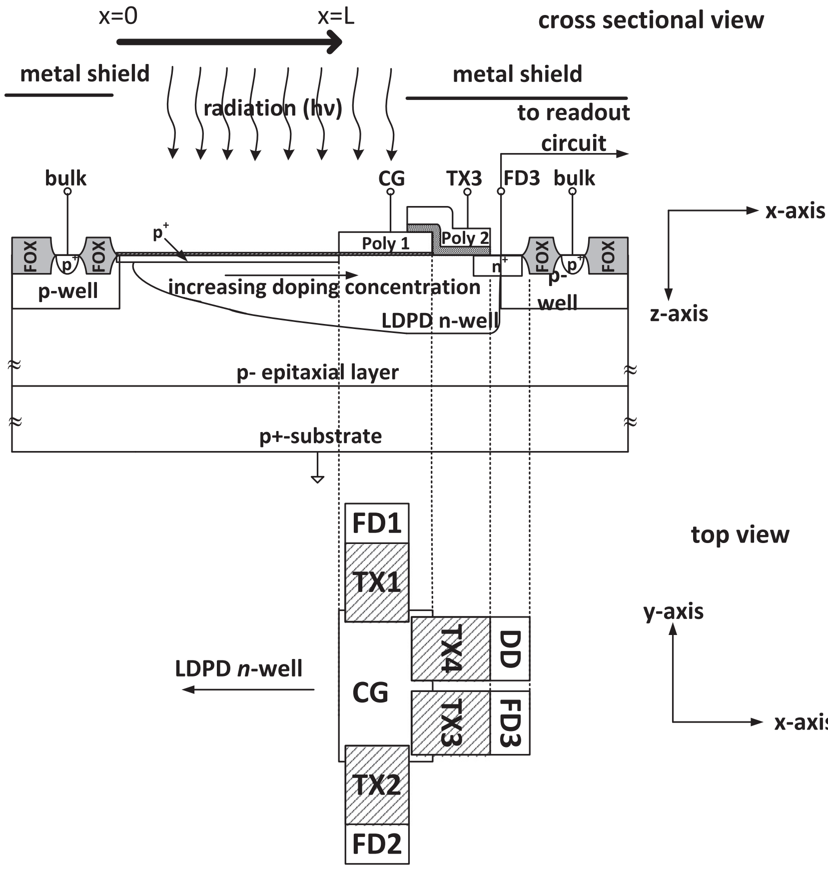

Fig. 1. Cross-sectional view of the LDPD as a ToF pixel. The doping gradient can be observed as well as the three transfer gates (TX1–3) with the affiliated floating diffusion (FD1–3) and the draining gate (TX4) with the draining diffusion (DD). Reprinted from [2].

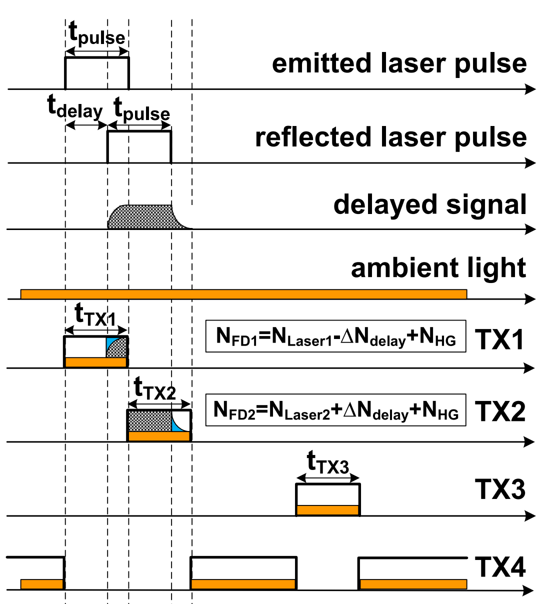

Fig. 2. Timing scheme and signal generation for indirect ToF measurements.

at FD3 to measure the signal in absence of any laser light. While the pixel is idle all generated charge carriers are drained via a draining gate (TX4). A detailed description of these implementations in a CMOS image sensor can be found in [3].

It can be seen that for this type of time-of-flight sensor, a precise definition of the accumulation time is crucial. Any additional delays which affect this time and are caused e.g. by control electronics, are not a problem as long as they are signal-independent because they can be eliminated by calibration. In Fig. 2 the charge defect by delayed signal generation is depicted by the blue area. It can be seen that the signal measured in FD1 is too low ($-\Delta N_{delay}$) to the same extend as the signal in FD2 is too high ($+\Delta N_{delay}$). In Section 3.4 it is shown how this error can be taken into account during calibration by introducing a modification to Eq. (1). Problems may arise, however, if these delays are signal dependent.

As a consequence of the self-induced drift, which is described in Section 2.1.3, the time behavior of the signal is partly irradiance dependent. This leads to a non-linear dependence of ΔN_{delay} on the irradiance. This implies that a ToF distance measurement leads to differing results for a dark and a bright surface in the same plane. The availability of a model that describes and predicts the effect can possibly enable its suppression. In addition it is expected that the influence of pixel design changes on the transfer speed during the design phase can be accounted for.

The advantage of an analytical solution is that it provides information about the influence of design parameters (e.g. length of the photoactive area) as well as the impact of irradiance changes.

It is assumed that the main contribution of the charge transfer originates in the drift in direction to the collection gate. Thus only one dimension was considered and the drift from deep in the silicon generated charge carriers to the *p*-*n*-junction are neglected as well as the drift from the sides of the photoactive area. A comparison of the calculated transient behavior with measured values from an actual image sensor prove that the error by this simplification is negligible.