Open Archive TOULOUSE Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: http://oatao.univ-toulouse.fr/
Eprints ID: 14562

To cite this version: Pelamatti, Alice and Goiffon, Vincent and Chabane, Azizouz and Magnan, Pierre and Virmontois, Cédric and Saint-Pé, Olivier and Bréart-de-Boisanger, Michel Speed Analysis in Pinned Photodiode CMOS Image Sensors based on a Pulsed Storage-Gate Method (2015) In: Proceedings of European Solid-State Device conference (ESSDERC), 15 September 2015 - 17 September 2015 (Gratz, Austria).

Any correspondance concerning this service should be sent to the repository administrator: staff-oatao@listes-diff.inp-toulouse.fr
Charge Transfer Speed Analysis in Pinned Photodiode CMOS Image Sensors based on a Pulsed Storage-Gate Method

A. Pelamatti*, V. Goiffon*, A. Chabane*, P. Magnan*, C. Virmontois, †, O. Saint-Pé, †, M. Breart de Boisanger‡

*Institut Supérieur de l’Aeronautique et de l’Espace (ISAE), Université de Toulouse, Image Sensor Research Team, Toulouse 31055, France. Email: alice.pelamatti@isae.fr
†Centre National d’Etudes Spatiales (CNES), Toulouse, 31400, France
‡Airbus Defence and Space, Toulouse, 31030, France

I. INTRODUCTION

DRIVEN by low noise applications, Pinned Photodiode (PPD) [1]–[3] CMOS Image Sensors (CIS) have recently become the main image sensors technology for both commercial and scientific applications. The PPD (schematized in Fig. 1a) is formed by a double p-n junction, where the surface p+ implant, also referred to as pinning-implant, pins the surface at the substrate potential. This peculiar structure not only reduces the dark current (by isolating the collection buried channel from the charges generated at the SiO2-Si interface), but also limits the maximum PPD channel potential, often referred to as pinning voltage [4], which corresponds to the full depletion condition. The presence of this “potential floor” enables true charge transfer from the PPD to the collection node (or to another buried channel), whereas in standard photodiodes (forms by a single p-n junction), only charge sharing between two capacitances is possible. The combination of these unique features has led in the last decade to the development of several PPD-based detectors for Time of Flight (ToF) applications [5]–[8], which require high speed readout of small packets of photo-charges. One of the main challenges involved in PPD-based high speed detectors is to reach the best time resolution by maximizing the charge transfer speed from the photo-generation site to the collection node. The transfer speed becomes even more critical for applications, such as space imaging applications, which require pixel pitches of several tens of µm (for example for optics-related constraints [9]).

In the last decade much effort has been put into improving charge transfer speed by introducing a drift field in the PPD [5], [7], [10]–[13] by modulating the PPD local potential. However the existing solutions often involve design and/or geometrical constraints, can require the use of a custom technology, or might not be implementable for large pixel pitches (as the maximum potential difference which can be generated within the PPD is equal to the pinning voltage, which is often of the order of 1V, or lower to ensure optimum charge transfer toward the floating diffusion). For these reasons, it is important

• to be able to predict whether speed performances in a pure diffusion regime are sufficient or not for a target application (without the need of a custom design to

---

The authors would like to thank CNES and Airbus Defence and Space for supporting the Ph.D of A. Pelamatti.
generate an electric field),
- to have a characterization method which allows to fairly assess transfer efficiency improvements for a given pixel design / potential modulation method.

Charge Transfer Inefficiency (CTI) curves have been simulated in [14], [15] for different PPD lengths by considering a uniformly distributed charge density. Experimental CTI measurements have also been shown in [15] for 16 µm pixels. However to the authors knowledge, no experimental study on the CTI has yet been shown for PPD lengths up to several tens of µm.

In this study we propose a new method to measure the charge transfer speed, which reproduces the "worst-case scenario" of a ToF acquisition. This method is based on a double gate structure and is particularly suited to compare the CTI for different pixel geometries as the measured transfer time is not affected by the initial distribution of charges in the PPD. It is also shown that the biasing voltage of the TG can strongly affect the CTI and that time constants involved in charge transfer can be of two order of magnitude higher than what is predicted by diffusion equations. This study also reports transfer speed data for PPD lengths up to 32 µm.

II. DEVICE UNDER TEST

A schematic drawing of the device tested in this work is shown in Fig. 1b. The device has been realized in a commercially available 0.18µm PPD CIS technology. The pixel structure is similar to a standard 4T active pixel sensor (APS), with an additional gate, referred to as Storage Gate (SG), which is used for the storage and release of charges. The transfer time has been measured for different PPD lengths: 2µm, 4µm, 16µm and 32µm. All PPDs are 5µm wide. The charge to voltage conversion factor (CVF) is about 10 µV/e− for all the tested pixels. The TG is 5µm wide and 0.7µm long. The storage gate size is 0.3µm × 5µm.

III. EXPERIMENTAL set-up

The proposed transfer time estimation method is based on the injection of charges at the opposite side of the PPD with respect to the TG at a given instant in time. In particular it consists in releasing the charge stored under the SG at a given instant before the closure of the TG. The timing diagram used in this paper is represented in Fig. 2: during the integration time, both the TG and the SG are ON (VSG = 3.3 V and \( V_{TG} = V_{HTG} \)), thus charges generated in the PPD are either stored under the SG, either drained toward the FD. At the beginning of the acquisition, the FD potential is reset to \( V_{DD_{RST}} \) for 100 µs (RST signal set to 3.3V) to empty the PPD, then the TG is turned OFF \( (V_{TG} = V_{LTG}) \) to sample the reference signal \( (V_{ref}) \). Charge injection in the PPD corresponds to the instant at which the SG is turned OFF \( (V_{SG} = -0.4 V) \). The time delay \( \Delta t \) between the falling edges of the SG signal and the TG signal corresponds to the time during which charges can be transferred from the PPD to the FD. Once the TG is turned OFF, the signal \( V_{sig} \) is sampled. \( \Delta t \) is increased from tens of ns to several hundreds of µs. The CTI is estimated as

\[
CTI = 1 - \frac{V_{sig}(\Delta t)}{V_{sig}(\Delta t_{max})}
\]  

where \( \Delta t_{max} \) is the maximum tested delay, which must be chosen long enough to ensure that all charges have been extracted from the PPD (100 µs here).

IV. FIRST RESULTS

Figure 3 shows the first results obtained with the proposed estimation method. Both the \( V_{TG} \) and \( V_{SG} \) signals vary between 3.3V (pulse high level) and -0.4V (pulse low level). Data have been averaged over 1000 images and correspond to the output of single pixels (no spatial averaging is performed). Measurements have been obtained at room temperature in the dark. The integration time is 18 ms. Two main observations can be made based on these first results:

- The measured transfer time is almost 2 orders of magnitude larger than the one estimated by numerically solving the diffusion equation \(^1^) and 1 order of magnitude larger than the one measured in [15].
- As shown in Fig. 4, the transfer time (measured here as the time required to reach 0.01% CTI) increases as the square of the PPD length (except for the deviation at \( L_{PPD} = 2 \mu m \)) as predicted by the diffusion equations.
- Whereas the CTI is well fitted by an exponential curve at \( L_{PPD} = 32 \mu m \), at shorter PPD lengths the CTI deviates from the exponential behaviour for small time delays (at the beginning of charge transfer).

Figure 5 shows the CTI as a function of the SG-TG signals delay measured on a 16 µm long PPD for different TG biasing voltages \( V_{HTG} \) during charge transfer. As it can be observed, \( V_{HTG} \) has a strong influence on the CTI, thus despite the long PPD length, diffusion is not the only phenomenon limiting

\(^1^)\)The diffusion equation has been solved by assuming a perfect reflecting wall and absorbing wall at \( x = 0 \) and \( x = L_{PPD} \), respectively. The starting conditions correspond to a delta like charge density at \( x = 0 \) at \( t = 0 \). The diffusion coefficient has been set to \( D_n = 1.925 \times 10^{-3} m^2/s \)
The CTI has been simulated for a 4 \mu m PPD in a pure diffusion regime, with and without the presence of a potential barrier \( \Phi_b \). Charge diffusion of charges has been simulated as the random walk of 2500 single charges (Montecarlo simulation) located at \( x = 0 \) at \( t = 0 \). The diffusion coefficient used in the simulation is about \( D_b = 1.925 \times 10^{-3} m^2/s \) and charge confinement within the PPD has been simulated by means of a perfect reflecting wall condition at \( x = 0 \). For the zero barrier simulation, a charge is considered to be transferred as soon it reaches \( x = L_{PPD} \). The effect of the potential barrier has been taken into account by introducing the probability for a charge that reaches \( x = L_{PPD} \) to have sufficient energy to jump over the barrier [16]:

\[
P_{\text{jump}} = \exp(-\Phi_b / u_{\text{th}})
\]

with \( u_{\text{th}} \) the thermal voltage. If the condition on the particle energy is not satisfied, the potential barrier behaves as a reflecting wall. Electrostatic repulsion between charges has been neglected. As shown in Fig. 7, the presence of the potential barrier \( \Phi_b = 0.2 \) V can indeed increase the transfer time of almost 2 orders of magnitude. A second effect which might play an important role in slowing down charge transfer is the bottle neck along the charge transfer path at the TG-PPD interface, which can also reduce the probability for charges to be transferred toward the FD.

**V. Conclusions**

In this work a new experimental method to extract the transfer time in a PPD based on specific test structures has been proposed. It has been shown, with the support of experimental data and numerical simulations, that simple charge diffusion might not be sufficient to model charge transfer (as it would lead to an important underestimation of the transfer time), thus thermionic emission of charges across the potential barrier at the TG-PPD interface should also be taken into account, even for long PPDs. On the basis of these first results, it can be inferred that introducing an electric field in the PPD can bring a double advantage with respect to a pure diffusion regimes,
as it would not only reduce the time required for the charges to cross the PPD, but it would also maintain charges close to the potential barrier, increasing the probability of jumping across the barrier. In this work only rectangular PPDs have been tested, however the proposed CTI extraction method can also be easily applied to other geometries to quantify the effect of the electric field on the transfer speed. The proposed method has two main advantages with respect to in-pixel CTI extraction methods [19]:

- It allows to compare the transfer speed for different geometries with equivalent initial conditions.
- It reproduces a worst-case transfer time, when charges are photo-generated at the far end of the PPD with respect to the TG.

REFERENCES


