

Active Area Shape Influence on the Dark Current of CMOS Imagers.

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Abstract

This work presents an empirical dark current model for CMOS Active Pixel Sensors (APS). The model is based on experimental data taken of a 256x256 APS chip fabricated via HP in a standard 0.5 μ m CMOS technology process. This quantitative model determines the pixel dark current dependence on two contributing factors: the “ideal” dark current determined by the photodiode junction, introduced here as a stable shot noise influence of the device active area, and a leakage current due to the device active area shape, i.e., the number of corners present in the photodiode and their angles. This part is introduced as a process induced structure stress effect.

Keywords: CMOS image sensors, APS, photodiodes, dark current, modeling.

I. INTRODUCTION

In CMOS APS arrays, the pixel area is constructed of two functional parts. The first part, that has a certain geometrical shape, is the sensing element itself, i.e., the active area that absorbs the illumination energy within it and turns that energy into charge carriers. The second part is the control circuitry required for readout of this charge. Pixel output is proportional to the incoming light power, quantum efficiency, pixel active area, and conversion gain.

Due to past several years intensive work [1- 5], CMOS APS imagers are now considered as a viable alternative to CCD's in many application fields. Investigations have still to be performed for improving APS performance in order to meet dedicated application requirements and to provide designers with better control. Therefore, it appears important to acquire experimental data concerning parameters affecting electro-optics performance, mostly responsivity and dark current generation, by designing special test structures including different pixel topologies.

Early CCD works have pointed out the geometry dependence of the dark current [6 - 9]. This paper studies the dark current generation within a CMOS APS photodiode array as a function of its active area geometry and shape. An empirical model which emphasizes dark current dependence on the presence of corners (internal and external) in the photodiode structure is presented. It takes into consideration dependence on both: the corner angle, and the number of such corners present in photodiode. It is based on experimental data acquired from a 256x256 APS chip measurement. Various topologies of the photosensitive area have been implemented. All the pixels are traditional three transistor pixels, and share a common readout circuitry, enabling behavior identification of different pixel types. It is the intent of this paper to present how deviations in the device geometry affect its overall performance and thus be used as a predictive tool for design optimization.

In this paper section 2 presents the proposed model, while section 3 describes the measurements. Section 4 shows the correspondence between the theory and the experimental data. Section 5 summarizes the work.

II. DARK CURRENT MODELING

The dark current is the leakage current at the photodiode node, which discharges the pixel capacitance even though there is no light over the pixel. The dark current measured at the pixel output depends on the photodiode, the transistors and the interconnectivity in the pixel.

One can distinguish two types of CMOS APS dark current sources:

a) “Ideal” dark current depending on doping concentrations, bandgap and temperature of the reversed biased diode. In an ideal p-n junction diode, there are two dominant current sources, i.e., injection-diffusion and generation-recombination current. The injection-diffusion current is due to the injection of thermal electrons and holes whose energies are higher than the built-in potential energy to the other side of the junction, and become the minority carrier diffusion current. The generation-recombination current is due to electron-hole generation or recombination, within the p-n junction depletion in the bulk, or at the surface. Both of these exhibit an exponential dependence on applied voltage and temperature, $\exp(qV/kT)$, where q , V , k and T are carrier charge, applied voltage, Boltzmann’s constant and temperature. On the other hand, an ideal dark current can be described as shot noise [2-5], i.e., a white noise that arises from the discrete nature of electrons themselves. This is a result of the random generation of carriers, either by thermal generation within the depletion region (i.e., shot noise of the dark current), or by the random generation of the photoelectrons, caused in turn by the random arrival of photons. If electrons are generated with a current density, J_{dark} , in a sensor of area A , over an integration time t_{int} , the dark current signal (obtained from shot noise variance) is: $I_{\text{dark}} = n_d \cdot q / t_{\text{int}} = J_{\text{dark}} \cdot A$, where n_d is the number of generated carriers, and the other parameters are as defined above.

b) “Defect generated” dark current, determined by the characteristics of the individual defects [3 - 11]. Some defects have high carrier generation rate, and some do not. How these affect the particular diode depends on the pixel layout (especially its active area shape, area/perimeter ratio of the photodiode and the fill factor), its readout scheme and the reverse bias applied to the diode during dark current integration (in combination, of course, with dopant profiles).

Any attempt to explain the observed APS dark current must consider these primary causes in a particular process. Naturally, the sources of dark current (defects, etc.) are not understood well enough to enable the development of a general CMOS APS dark current model. However, a flexible empirical model can be developed, and will be described herein.

III. DARK CURRENT - MEASUREMENTS

For measuring the dark current, the voltage drop at the pixel output can be measured at different integration periods. Knowing the pixel capacitance, one can calculate the actual dark current. The traditional presentation of dark current includes normalization by pixel area [A/cm^2]. However, in this work the photodiode area was chosen to be the normalizing factor, since the fill factor is small.

$$Dark_current \left[\frac{A}{cm^2} \right] = \frac{C_{diode}}{A_{diode}} \left[\frac{F}{cm^2} \right] \times \frac{\Delta V}{\Delta t} \left[\frac{V}{sec} \right]$$

ΔV - Voltage drop due to dark current [Volt]. C_{diode} - Photodiode capacitance [F]. A_{diode} - Photodiode area [cm^2]. Δt - Integration time [sec].

All the dark current measurements were taken at a room temperature (300K) that was kept constant. The statistically averaged data obtained from different APS chips measured is presented.

Fig. 1 shows four examples of pixels with different values of external corners, i.e., 90° , 108° , 120° , and 135° , correspondingly. Fig. 2 shows that the normalized dark current value of the square, pentagon, hexagon, and octagon

active area shaped pixels (of approximately equal area, capacitance and thus conversion gain) is inversely proportional to the external angle value.

In addition, Fig.1 shows two pairs of pixels with either one or two photodiode contacts. One can see from Fig. 2 that the dominant factor affecting the dark current value of these pixels is yet the photodiode geometry.

Fig. 1

Fig. 2

Fig. 3 describes examples of a sequence of pixels of approximately equal area and conversion gain, with internal corners rounding within the substrate openings: one, three, five, seven, nine and twelve internal corners were rounded correspondingly. Fig. 4 shows that the value of a photodiode dark current is linearly inverse with the number of the rounded corners presented in the device, while the total corners number is constant.

Fig.3

Fig.4

IV. DARK CURRENT - THEORY AND EXPERIMENTAL DATA COMPARISON

Based on the above dependencies, we have developed an empirical model, which quantifies the pixel dark current as a combination of contributions to dark current:

$$I_{\text{out}} = \alpha A + \beta n$$

Here, α - is the coefficient that determines the junction unity area contribution. It has a meaning of the dark current density, while A - consequently represents the junction area. This part represents the baseline value of the dark current and remains constant for all investigated pixels with the same area. The reason for this, as described before, is in the nature of ideal part of the dark current, i.e., the dark current density does not change from pixel to pixel, since they are close enough together within the array such that process differences associated with the impurity inhomogeneity are negligible.

The second part of the model deals with the stress induced leakage current. It describes the shape dependence of the output signal, on the presence of corners within the photodiode, their angle, and number. The influence of such a corner in the vicinity of the junction is obvious, since it gives rise to a high density of defects at the surface of a semiconductor. During irradiation, the formation of the interface traps in these stress regions enhances the generation velocity at the interface and therefore, results in an increased surface leakage current. The enhanced thermal generation follows from the creation of interface traps with energy levels within the silicon bandgap.

Here, β - is the coefficient that determines the corner contribution to the overall dark signal, n – the number of corners presented in the design. The above model also takes into consideration the angle dependence within the β coefficient, describing the corner contribution, e.g., for the structures presented in Fig. 1, β grows inversely with the angle, such that a contribution of a wider corner angle involves a smaller β value. The ratio between its magnitudes for 90° and 135° , for example, is $\beta_{90}/\beta_{135} \sim 1.5$.

For the particular case of commonly used pixel designs, which might be either rounded or non-rounded corners, the above expression reduces to:

$$I_{\text{out}} = A + nR + mN.$$

Here, A - is a baseline device active area dark current contribution, n - is the number of rounded corners, R - is the coefficient describing the rounded corner dark current contribution, m - is the number of non-rounded corners, N - is the coefficient describing the corresponding dark current contribution of a non-rounded corner. The solution of the above equations for the different pixels, in the minimum variance meaning, enables the extraction of the different parameters. Note that the total number of corners is kept constant.

We performed the above analysis for pixel sets of different sizes and shapes. In Fig. 5, a 3D graph illustrates an example of the correspondence between the measured and modeled dark current dependence on rounded and non-rounded corner quantities within the device, while the total number of corners is kept constant.

Fig.5

Good model correspondence can be noticed in the graph, where maximum divergence of the modeled result is constrained to 5%. We obtain that for this pixels set, the ratio is about $N/R \cong 2.5$, which means that each rounded corner significantly lowers the dark current magnitude of the pixel, in about 5% of the nominal value. Moreover the corner value increase of 45° enables more than 10% dark current value reduction. Thus, one can conclude that the magnitude of the dark current in a CMOS imager depends on the device geometry and shape, i.e., on the presence of the corners within the photodiode, their angle, and their number.

V. SUMMARY

A geometry based empirical model for dark current in CMOS APS, has been presented. The findings prove that CMOS APS dark current magnitude strongly depends on two contributing factors: the baseline dark current caused by the photodiode area junction (current depending on doping concentrations, bandgap and temperature of a reversed biased diode), and a leakage current due to the active area shape.

We believe this model enables better understand the design tradeoffs involved, and help achieve an optimum design in the dark current sense, by "smoothing" the photodiode shape as much as possible in order to minimize the dark signal for pixels with the same fill factor. One should note that this result is process dependant, and further research is required for a process-based model.

ACKNOWLEDGEMENTS

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VI. REFERENCES

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VII. LIST OF FIGURES

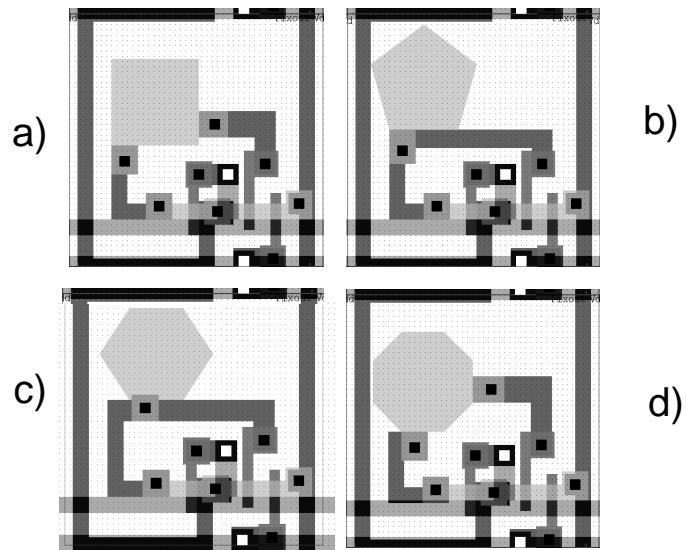


Fig. 1. Examples of pixels with various external corner angles: a) 90°, b) 108°, c) 120°, d) 135°.

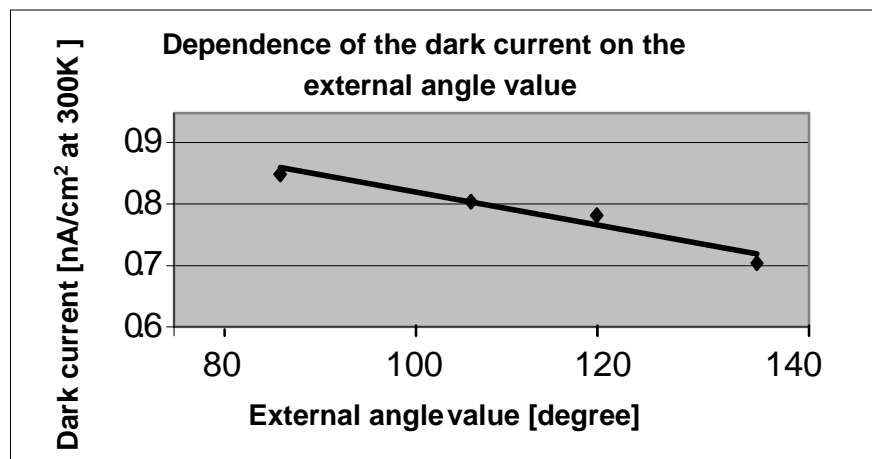


Fig. 2. The dark current dependence on the external angle value, corresponding to Fig. 1.

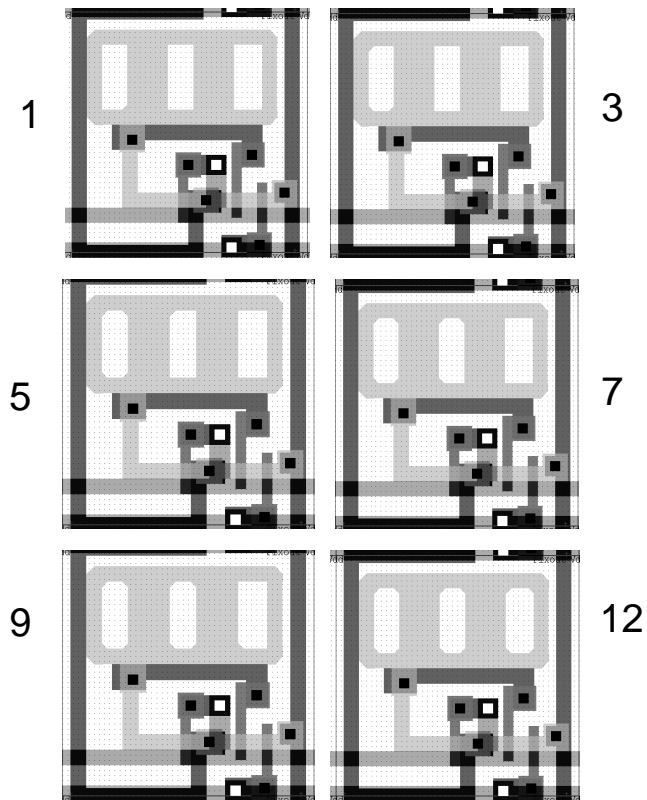


Fig. 3. Examples of pixels with a varying number of rounded internal corners.

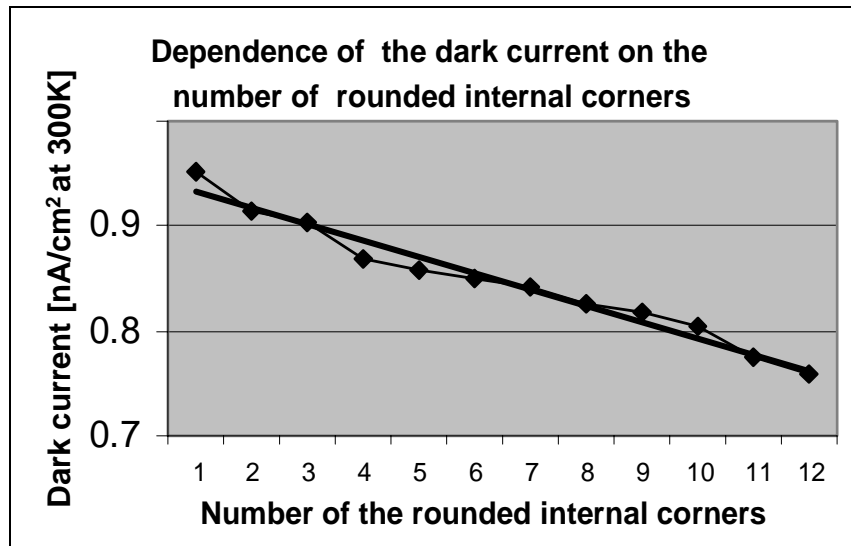


Fig. 4. The dependence of the dark current on the number of rounded internal corners.

Dark current dependence on the rounded corners number

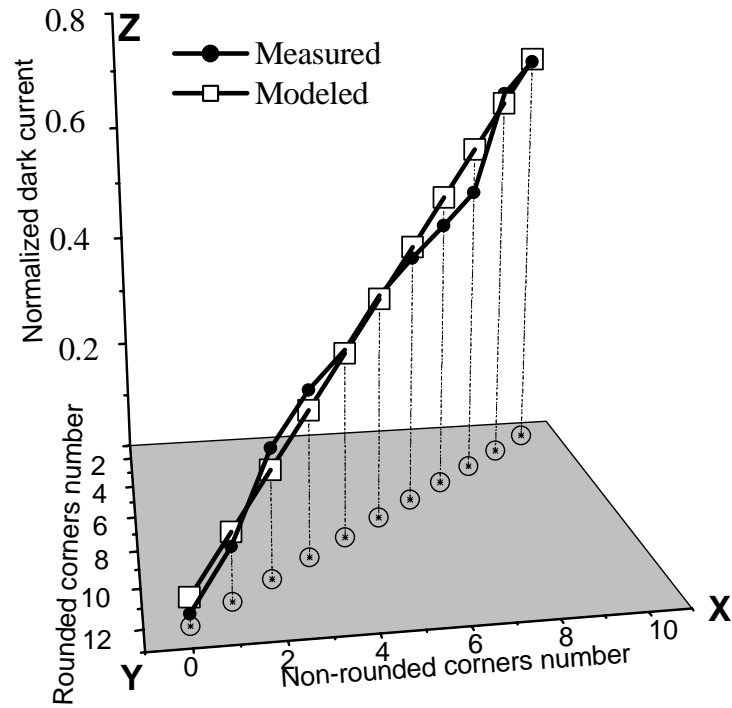


Fig. 5. The dark current dependence on the rounded and non-rounded corners number, in correspondence with Fig. 3 and Fig. 4.