

Empirical dark current modeling for complementary metal oxide semiconductor active pixel sensor

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Abstract. We present an empirical dark current model for CMOS active pixel sensors (APSs). The model is based on experimental data taken of a 256×256 APS chip fabricated via HP in a standard $0.5\text{-}\mu\text{m}$ 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. © 2002 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1475995]

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1 Introduction

In CMOS active pixel sensor (APS) arrays, the pixel area is constructed of two functional parts. The first part, which 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 CCDs in many application fields. Investigations must still be performed to improve APS performance 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 that 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 256×256 APS chip measurement. Various topologies of the photosensitive area were 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 geom-

etry affect its overall performance and can thus be used as a predictive tool for design optimization.

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

2 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.

The first is “ideal” dark current, depending on doping concentrations, bandgap, and temperature of the reversed biased diode. In an ideal $p\text{-}n$ 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 $p\text{-}n$ 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 $I_{\text{dark}} = n_d(q/t_{\text{int}}) = J_{\text{dark}}A$, where n_d is the number of generated carriers, and the other parameters are as already defined.

The second source is “defect-generated” dark current, determined by the characteristics of the individual defects.^{3–11} Some defects have a high carrier generation rate, and some do not. How these affect the particular diode depends on the pixel layout (especially its active area shape, the 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 is described herein.

3 Dark Current Measurements

To measure 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 in amperes per square centimeter. However, in this work, the photodiode area was chosen to be the normalizing factor, since the fill factor is small.

$$\text{Dark_current} \left(\frac{\text{A}}{\text{cm}^2} \right) = \frac{C_{\text{diode}}}{A_{\text{diode}}} \left(\frac{\text{F}}{\text{cm}^2} \right) \times \frac{\Delta V (\text{V})}{\Delta t (\text{s})},$$

where ΔV is the voltage drop due to dark current, volts, C_{diode} is the photodiode capacitance in farads, A_{diode} is photodiode area in square centimeters, and integration time in seconds.

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

Figure 1 shows four examples of pixels with different values of external corners, i.e., 90, 108, 120, and 135 deg, correspondingly. Figure 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, the photodiodes described in Fig. 1 are of either one [Figs. 1(b) and 1(c)] or two contacts [Figs. 1(a) and 1(d)]. One can see from Fig. 2 that the dominant factor affecting the dark current value of these pixels is the photodiode geometry.

Figure 3 describes examples of a sequence of pixels of approximately equal area and conversion gain, with internal corner rounding within the substrate openings: 1, 3, 5, 7, 9, and 12 internal corners were rounded correspondingly. Figure 4 shows that the value of a photodiode dark current is

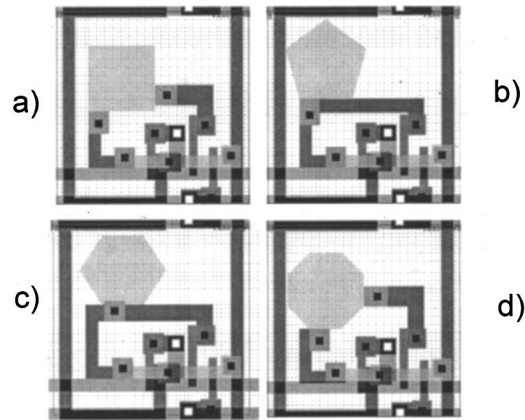


Fig. 1 Examples of pixels with various external corner angles: (a) 90, (b) 108, (c) 120, and (d) 135 deg.

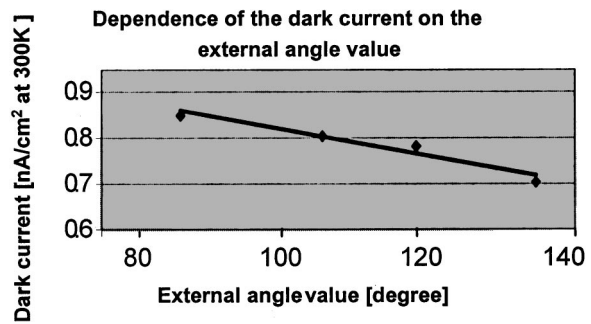


Fig. 2 Dark current dependence on the external angle value, corresponding to Fig. 1.

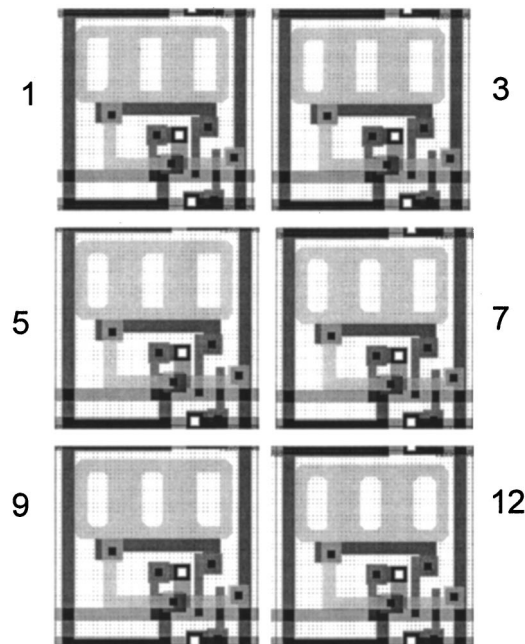


Fig. 3 Examples of pixels with a varying number of rounded internal corners.

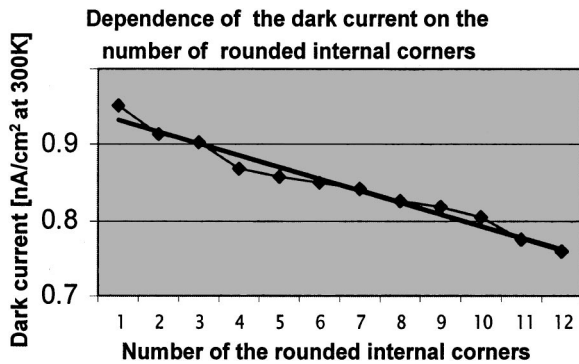


Fig. 4 Dependence of the dark current on the number of rounded internal corners.

linearly inverse with the number of rounded corners presented in the device, while the total corners number is constant.

4 Dark Current Theory and Experimental Data Comparison

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

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

where 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 already described, 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 their 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, and n is the number of corners presented in the design. The preceding 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 deg, for example, is $\beta_{90}/\beta_{135} \sim 1.5$.

Dark current dependence on the rounded corners number

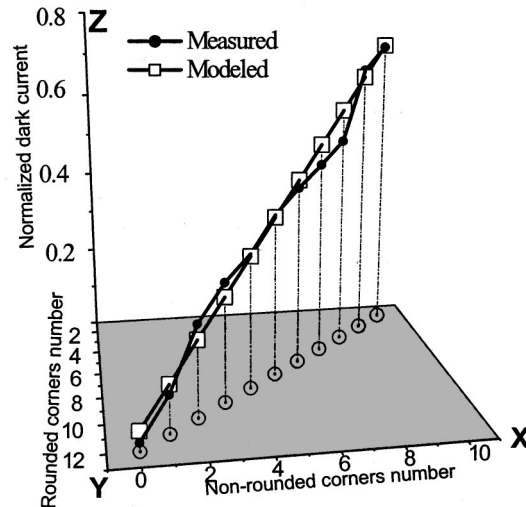


Fig. 5 Dark current dependence on the rounded and nonrounded corners number, in correspondence with Figs. 3 and 4.

For the particular case of commonly used pixel designs, which might be either rounded or nonrounded corners, the preceding 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 nonrounded corners, and N is the coefficient describing the corresponding dark current contribution of a nonrounded corner. The solution of the preceding 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 preceding analysis for pixel sets of different sizes and shapes. In Fig. 5, a 3-D graph illustrates an example of the correspondence between the measured and modeled dark current dependence on rounded and nonrounded corner quantities within the device, while the total number of corners is kept constant. 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, by about 5% of the nominal value. Moreover, the corner value increase of 45 deg 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.

5 Summary

A geometry-based empirical model for dark current in CMOS APSs was 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 the 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 trade-offs involved, and helps achieve an optimum design in the dark current sense by “smoothing” the photodiode shape as much as possible to minimize the dark signal for pixels with the same fill factor. Note that this results is process dependant, and further research is required for a process-based model.

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