Characterization of Dark Current in CMOS Image Sensors.

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Introduction

To optimize the performance of an active CMOS image pixel its architecture and photo diode structure have to be optimized. Dark current is one of the important parameters to characterize the performance of an image sensor [1]. Lowering the dark current will improve the dynamic range due to a reduction of the shot noise of the dark current. Furthermore, dark current reduction is correlated with a decrease of the fixed pattern noise and a reduction of the amount of white pixel defects in dark [2]. To get a good insight into the mechanisms of dark current generation and the location in the pixel where the leakage current is generated we have investigated dedicated test structures, such as diodes and pixel arrays (3016 pixels in parallel) and image sensors with various 3T active CMOS pixel layouts [3]. These structures have been designed and processed in Philips' 0.35µm CMOS baseline process.

Leakage current of photo diodes

A schematic drawing of a cross section of one of the diodes -an n^+/pwell test structure- is shown in figure 1. The LOCOS regions have been designed as stripes in active region; so all n^+ areas are connected to each other.

In figure 2 the reverse I (V) characteristics for n^+/nwell/psb and the n^+/pwell diodes are shown.

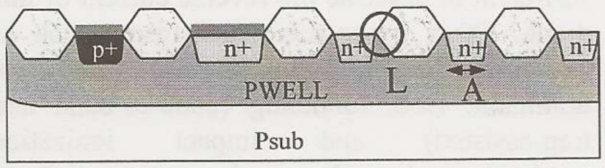
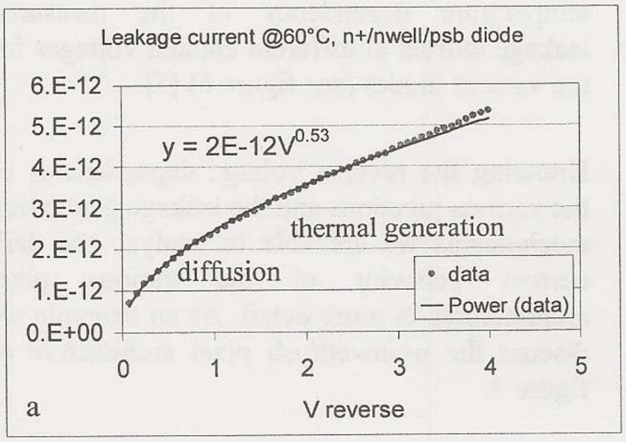


Fig. 1. Cross section of n+/pwell test structure. L and A indicate where length and area dependent contributions are located, respectively.



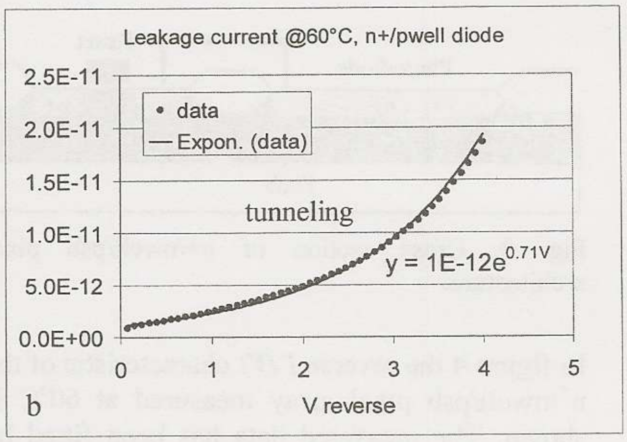


Fig. 2. Measured reverse I (V) characteristics for (a) n^+/nwell/psb and (b) n^+/pwell/psb together with fitted functions.

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The reverse characteristic of the n^+/nwell/psb diode shows approximately a square root dependence on the voltage, which corresponds to thermal generation current described by Shockley-Read-Hall recombination ($J_{gen} \propto W \propto \sqrt{V}$) [4].

The n^+/pwell diode, however, has a different behavior. This curve can better be approximated by an exponential function. So, diffusion current and thermal generation is not sufficient to describe the reverse current of this diode. Other generation mechanisms such as tunneling and/or impact ionization are dominant. Both tunneling (band-to-band and trap-assisted) and impact ionization mechanisms depend strongly (exponential) on the electric field inside the structure [5]. The occurrence of the various generation mechanisms has been confirmed by the temperature dependency of the measured leakage current at different applied voltages for the various diodes (see figure 6).[3]

Knowing the reverse voltage dependencies of the various junctions and the leakage generation mechanisms we are able to analyze the dark current behavior of the various pixel architectures in more detail. As an example we discuss the n+/nwell/psb pixel architecture of figure 3.

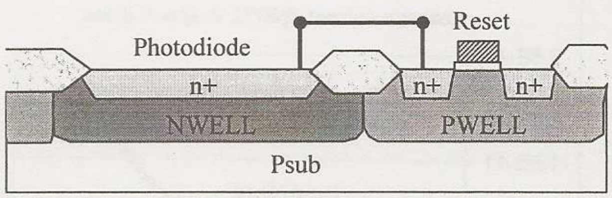

Fig. 3. Cross section of n+/nwell/psb pixel architecture.

In figure 4 the reverse *I (V)* characteristic of the n^+/nwell/psb pixel array measured at 60°C is shown. The measured data has been fitted by the sum of two functions: one with square root voltage dependence and one with exponential voltage dependence.

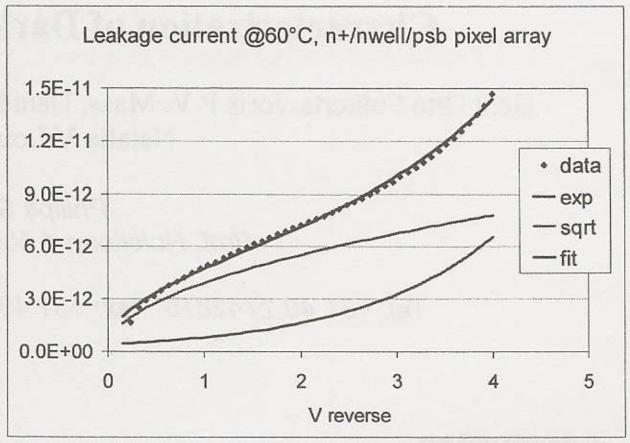

Fig. 4. Reverse *I (V)* characteristic of the n^+/nwell/psb pixel array measured at 60°C and fitted by the sum of a square root and an exponential voltage dependence contribution.

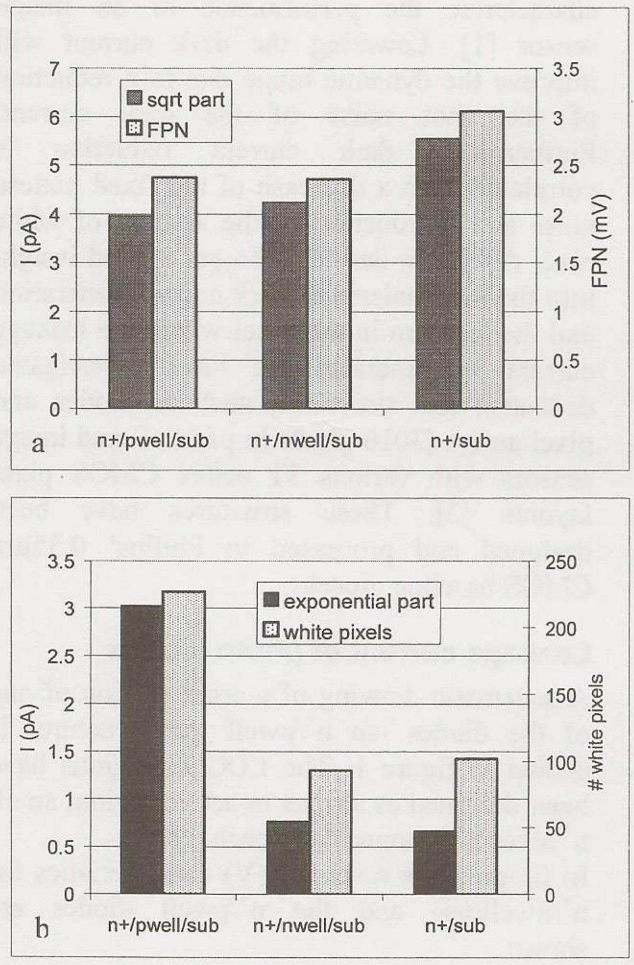

Fig. 5. Comparison between square root and exponential part of measured leakage current with FPN and number of white pixels, respectively, for various pixel layouts at 60°C.

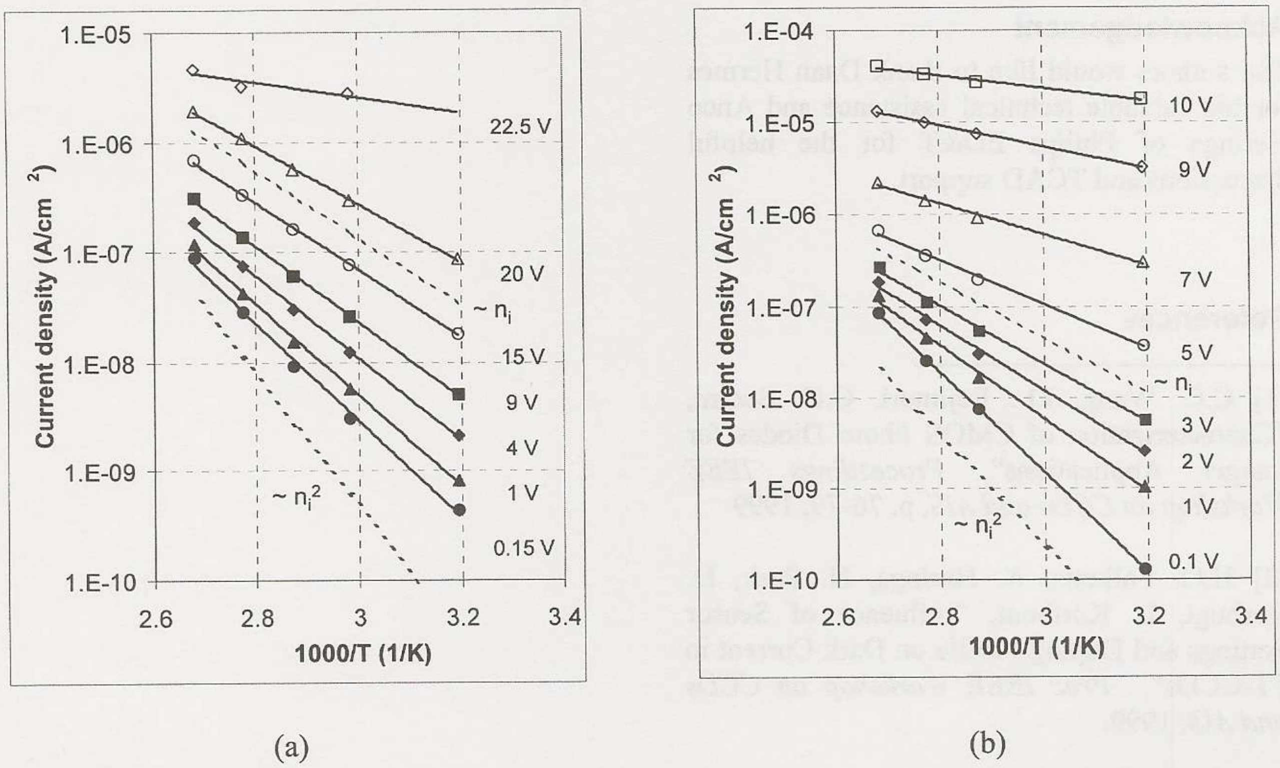

Fig. 6. Measured leakage current (in semi-logarithmic scale) at different applied voltages for n^+/nwell/psb (a) and for n^+/pwell (b) plotted versus 1000/T together with temperature dependencies of n_i (diffusion current) and n_i^2 (thermal generation).

From the evaluation of the diode test structures we know that the square root dependent contribution can be ascribed to the n^+/nwell/psb junction while the exponential contribution is due to the n^+/pwell. So the fast growing of the dark current at voltages above 2V is caused by the leakage current of the reset transistor source and not due to thermal generation current in the photodiode.

Fixed pattern Noise and Leaking pixels

For various pixel layouts we compared the leakage current measurements of the pixel array structures with the dark performance of the accompanying pixels in a VGA image sensor. From the leakage current we have determined the square root and exponential part. From the sensor evaluation we distinguish FPN (standard deviation of dark histogram; 1σ) and leaking pixels (dark signal > 6σ). In figure 5 we can see a rather good correlation between the exponential part of the leakage current and the number of white pixels in a VGA imager, while the square root part correlates with the measured FPN values.

Conclusion

With the reverse voltage dependencies of the various junctions and the leakage generation mechanisms we can describe and understand the dark current behaviour of the various pixel architectures. In case of n+/nwell/psb pixel architecture it is shown that the reverse bias dependence of the dark current is composed of two contributions, one from the photodiode and one from the contact area (n+/pwell). The leakage current of the nwell/psb photo diode is dominant and strongly related to the FPN, while the leakage current from the contact area is the main cause for white pixel defects.