CMOS Photodiodes with Substrate Openings for Higher Conversion Gain in Active Pixel Sensors

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Abstract

This article describes the capacitance and photocurrent trade-off of employing one or more substrate openings or 'holes' in photodiodes used in active pixel sensor. The discussion is based on experimental data from contact diffusion (n^+p_{epi}) photodiodes fabricated on a standard 0.35 µm CMOS technology.

I. Introduction

The readout amplifier for CCD detectors and CMOS active pixel sensors is usually a floating-diffusion device sensed by a source-follower; the capacitance of the device determines the conversion gain. In the case of CMOS active pixel sensor, the capacitance of the conversion node is typically dominated by the junction capacitance of the photodiode itself (Fig. 1). Thus, in order to improve the conversion gain, it is desirable to minimize this capacitance while maintaining the collection efficiency. The reset noise of active pixel sensor, which is generally modeled as kTC noise, also becomes less with reduced photodiode capacitance**.** For processes employing non-blockable silicide layers, the substrate openings can also enhance the photo-collection by allowing light to pass through the opening.

A shape of photodiode that offers lower capacitance at a minimal loss of collection efficiency is a photodiode shape with one or more substrate openings as shown in Fig. 2. Similar structures have been proposed in [1]. Making one or more substrate openings on the photodiode reduces area of lateral junction while adding extra side-wall junctions, hence, the dimensions of the substrate opening needs to be sufficiently large to reduce the net capacitance. Furthermore, given that the pixel's signal output is proportional to the product of an integration photocarriers and the conversion gain, the reduction of junction capacitance must outweigh the loss of photocurrent arising from the substrate opening to benefit from this photodiode shape. The reduction of junction capacitance with substrate opening dimension is illustrated in Fig. 3, where reported n^+-p_{epi} junction capacitances from standard 0.35 µm and a 0.18 µm CMOS processes were used.

II. Testing and Measurements

A number of 20 µm square n^+-p_{epi} photodiodes fabricated on a standard 0.35 µm CMOS process were employed in examining the effect of substrate openings (see Fig. 4). Fig. 5 reveals a plot of photocurrent as a function of the area of a square-shaped opening. The loss of photocarriers increased linearly with the area of the substrate opening, and the percentage of loss remained largely independent of the applied wavelength. We had anticipated that the photocurrent loss in the opening would noticeably diminish as the optical absorption distance approached the junction depth of the photodiode, causing a higher percentage of photocarriers to be collected by the enclosing side-wall junctions of the opening. From the experimental data, however, we believe that surface recombination is the principle cause of the observed photocurrent loss with substrate opening.

Fig. 6 shows a plot of the ration of photocurrent to photodiode capacitance, which is proportional to the pixel output signal. Despite the reduction of photocurrent, a small net gain in the pixel's signal output was observed for sufficiently large substrate openings. The loss of photocurrent was not sufficiently compensated by the reduction in the junction capacitance for small substrate openings due to its side-wall junction capacitance.

Another set of photodiodes containing multiple 4 µm x 4 µm openings was also fabricated. As shown in Fig. 7 the measured loss of photocurrent was again proportional to the sum area of the substrate opening supporting the belief that surface recombination is the primary mechanism of collection loss. Fig. 8 shows the corresponding plot of photocurrent divided by the photodiode capacitance.

The optical generation within the side-wall junction of n^+p_{epi} photodiodes was investigated in order to determine whether increasing the photodiode perimeter (while keeping the area constant) can significantly enhance the photo-collection. This was accomplished by applying 72 instances of 1 µm x 1 µm openings in a 20 µm square photodiode, which increased the length of side-walls from 80 µm to 368 µm. However, the additional $n+p_{epi}$ side-wall junctions resulted in only a modest improvement of the photocurrent as shown in Fig. 9.

Conclusions

In summary, modest improvements in conversion efficiency have been obtained by employing single and multiple substrate openings in the photodiode structures. Whether or not these gains will increase as CMOS technology develops will depend on a number of factors, including: surface recombination, minority carrier diffusion length, and photodiode size.

[1] E.R. Fossum, Quantum Efficiency Improvements in Active Pixel Sensors, US Patent No. 6,005,619, 1999.

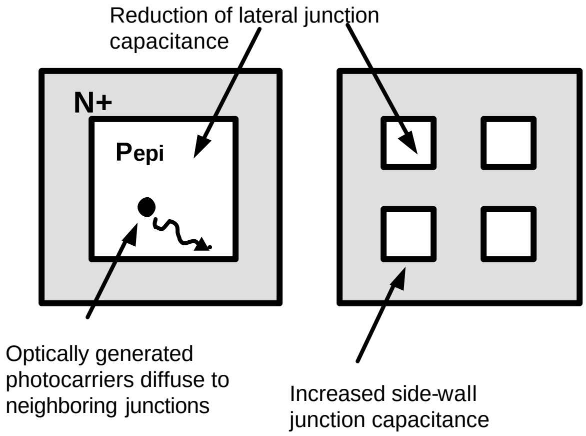

Fig. 2. Illustration of photodiodes with one or more substrate openings.

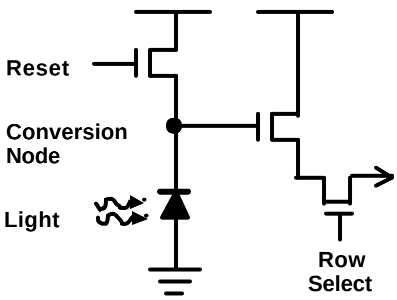

Fig. 1. Schematic of photodiode-type active pixel sensor.

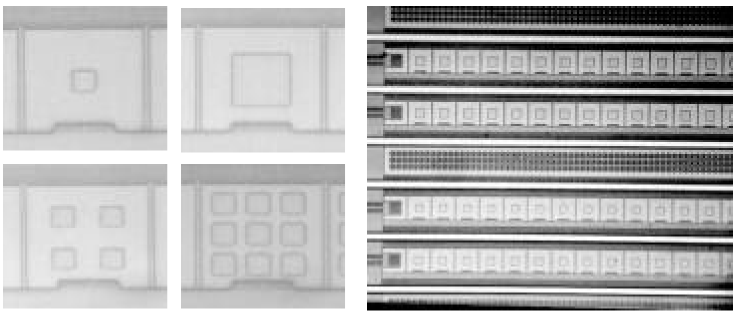

Fig. 4. Micrographs taken from some of fabricated photodiodes. Each photodiode shape was implemented in a linear array to reduce the effects of mismatch.

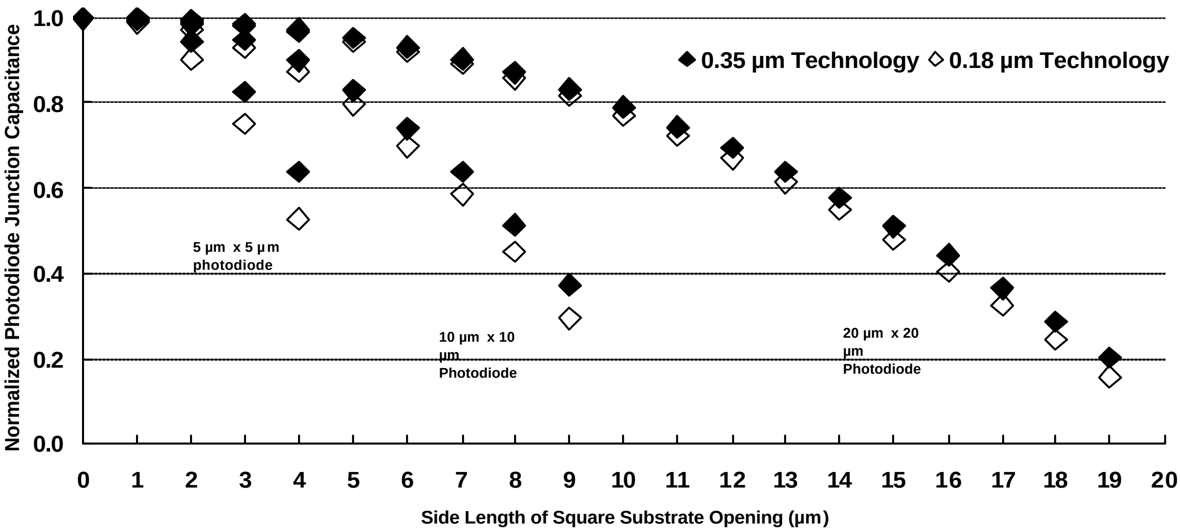

Fig. 3. An illustration of junction capacitance reduction via a single square-shaped substrate opening.

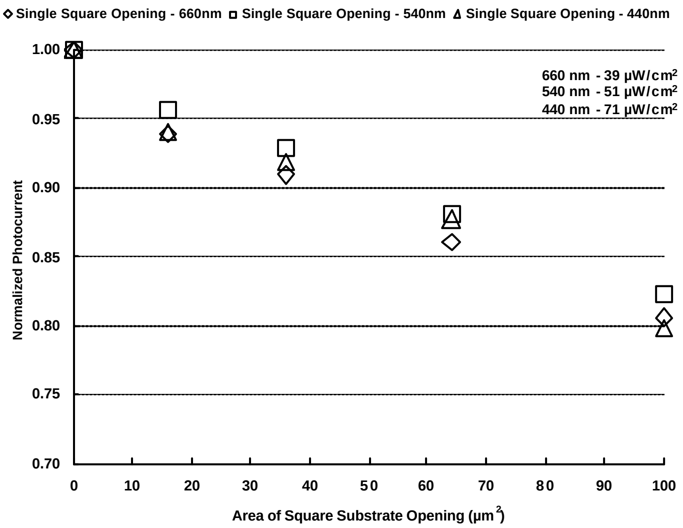

Fig. 5. Normalized photocurrent versus area of single square-shaped substrate opening on 20 µm x 20 µm n^+-p_{epi} photodiode.

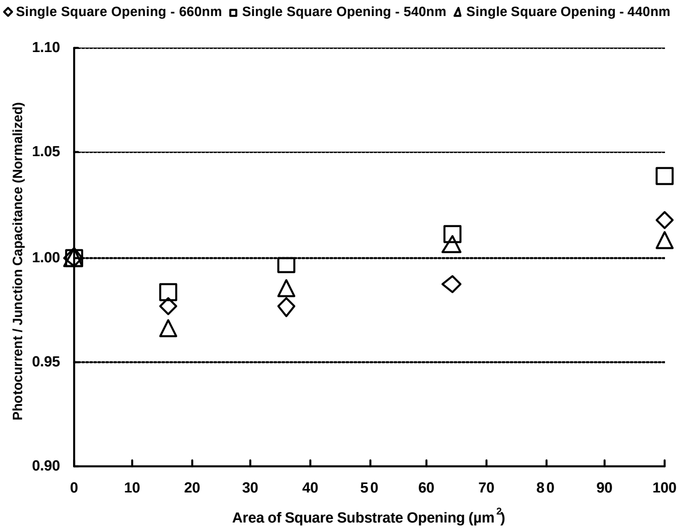

Fig. 6. Photocurrent divided by the junction capacitance (i.e. the signal gain) normalized to the case of no substrate opening.

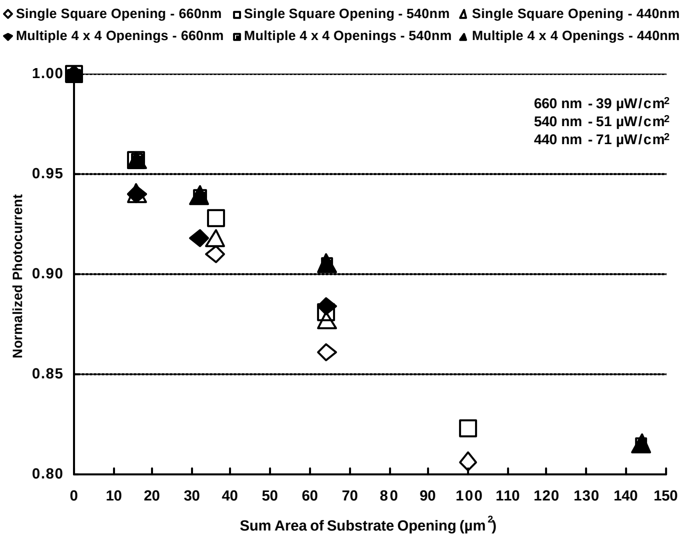

Fig. 7. Normalized photocurrent versus sum area of substrate opening. The plot compares the performance of a single opening versus multiple instances of 4 µm x 4 µm openings on 20 µm x 20 µm n^+-p_{epi} photodiode.

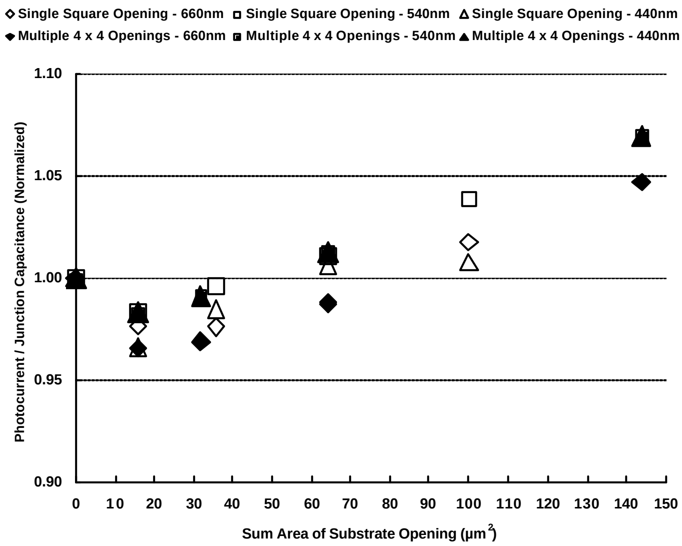

Fig. 8. The comparison of photocurrent divided by the junction capacitance from photodiodes with single substrate opening versus those with multiple 4 µm x 4 µm openings. The plots are normalized to the case of no substrate opening.

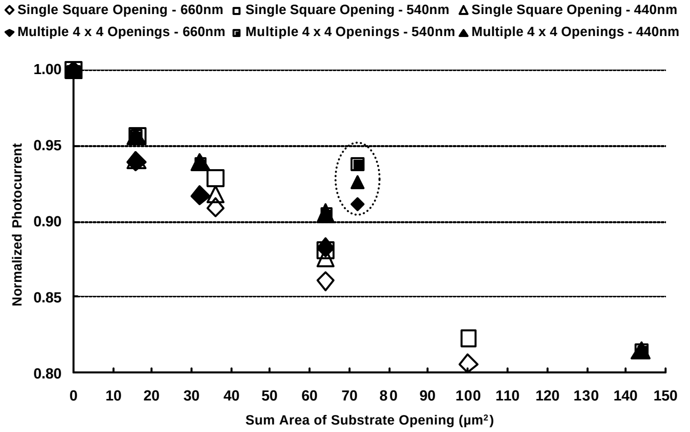

Fig. 9. Normalized photocurrent versus sum area of substrate opening. The measurements from 20 µm x 20 µm n^+-p_{epi} photodiode with 72 instances of 1 µm x 1 µm opening is shown above (enclosed in dotted lines) illustrating a modest improvement.