The effect of microlenses in photodiodes' dark current measurement

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***Abstract*— This paper presents the influence of microlenses (MLs) in the photodiodes' (PD) dark current. A MLs array was aligned and fabricated directly on top of the PDs and their effects on the dark current was measured. Two square PDs with the sides measuring 24 and 240 µm were evaluated under two different reverse bias voltages, 0 and -4 V. For the 24 µm PD, when the MLs were fabricated on its surface, the dark current mean value was reduced by 35.47% and 35.42%, for 0V and -4V reverse bias voltage, respectively. In the case of the 240 µm PD, a reduction of 14.43% and 14.42% was obtained for 0 and -4V reverse bias voltage, respectively. Moreover, the dark current measurements along the time present a more constant value with the MLs.**

Keywords—Microlenses; photodiodes; dark current.

I. INTRODUCTION

The dark current is a residual current that flows in a photodiode without any impinging light and is a major source of noise in digital imagers, including CMOS image sensors [1]. This dark current in CMOS sensors can be caused by different factors: saturation current, *i.e.*, on the boundaries of the depletion region, minority carriers (electrons on the *p*-type region and holes on the *n*-type side) can diffuse in the depletion region; carriers can also be generated by thermal excitation; under sufficient reverse bias, the energy in the conduction region can fall below of the valence energy in the *p*-side, and there is a finite possibility that an electron in valence region of the *p*-side can tunnel through the bandgap into the *n*-side conduction band; surface leakage current, and other factors [2]. Therefore, many camera systems are cooled to decrease the generation of the dark current. However, in some cases, a cooling system is not feasible and dark current can become a problem [1]. The objective of this paper is to compare the dark current measurements present in PDs without and with microlenses, in order to conclude their effect on dark current generation. Conventional photolithography and thermal reflow were the processes required for MLs fabrication with a high quality level [3,4]. The dark current is a crucial limiting factor that needs to be studied [2,5]. A decrease of this limiting factor can be important for many applications in the micro scale. For a correct measurement of the dark current, a dark chamber was used, which prevents the environmental light interference. In this paper a description of the photodiodes used is also presented. In section III the microlenses fabrication on top of the photodiodes array is described. After that the measurement setup and the dark current measurements are presented. Finally the main conclusions of this research are shown.

II. TYPE N^+/P-SUBSTRATE JUNCTION PHOTODIODES

The photodiodes, cross-section illustration seen in Fig. 1, are based on the type n^+/p-substrate junction photodiode fabricated in a standard CMOS process. These PDs were chosen due to the fact that they are a good option for visible light detection and also present good quantum efficiency for the visible spectrum [6]. Moreover, the selected PDs yield high fill-factor, since a deep *n*-well is not required for every pixel. The *On-semiconductor* 2-metal/1-poly 0.7 µm CMOS process was selected for fabricating the array [7]. In this process, the junction depth of the photodiodes is fully defined and cannot be changed. However, the spectral responsivity (*i.e.*, sensitivity) can be improved by a suitable arrangement of dielectric layers on top of the photodiode surface. Basically, there are three major dielectric layers above the *p-n* junction that implements the photodetector. The first and second oxides are composed of silicon dioxide (SiO_2). The top protecting layer (overlayer) is made of both SiO_2 and silicon nitride (Si_3N_4). The *On-semiconductor* foundry allows the removing of the overlayer without providing any metal layer. For achieving this task, the regions of the layout must contain big polygons drawn with the overlayer mask (the mask used for defining the bonding pads locations) without polygons of Metal 2 beneath.

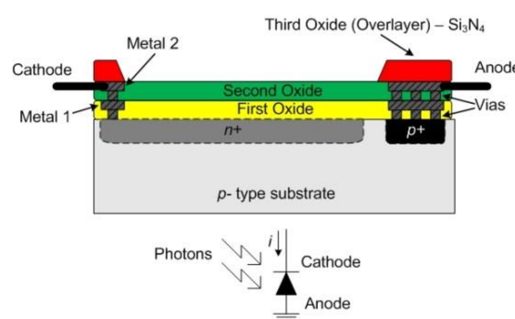

Fig. 1. Cross-section illustration of an n^+/p-substrate photodiode that is used in all the measurements made with and without MLs on top.

Fig. 2 shows a photograph of the fabricated CMOS device. The die is mainly occupied by a matrix of 8×8 square photodiodes with the side measuring 240 µm. Moreover, for different testing purposes, this die also contains single square PDs with sides measuring 5, 10, 24, 50 and 120 µm which are visible on the die's right flank. The PDs signaled in the following picture have a 10× difference between their dimensions so they were chosen as the ones to investigate

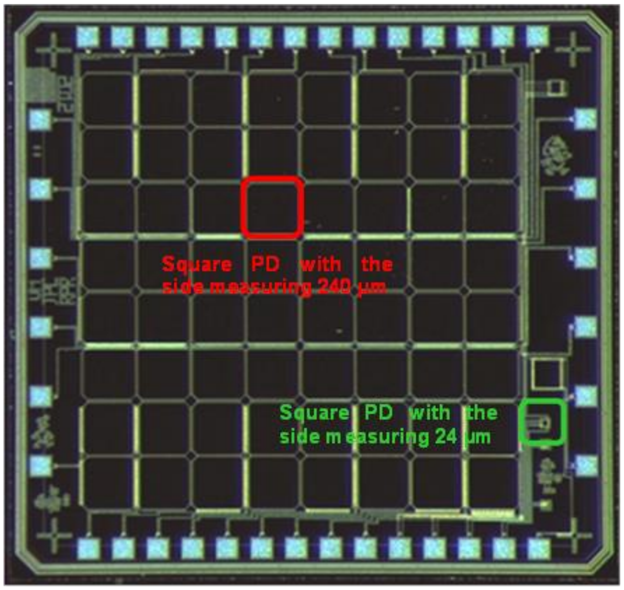

Fig. 2. Optical photograph of the die containing the photodiodes array. The two PDs under investigation are signaled.

III. Experimental Results

A. Microlenses fabrication

The MLs were fabricated using photolithography and thermal reflow. Due to the proposed objectives, the selected photoresist (PR) is the AZ4562 because of the fabrication requirements. This PR is appropriate for coating thicknesses roughly between 5 and 20 µm without having to increase the exposure energy considerably and still providing enough energy down to the substrate. Moreover, TR is achieved at a relatively low temperature (≈110-130 °C). TR is applied to the microfabricated structure for obtaining the lens' spherical profile. Above the PR's glass transition temperature the surface tension phenomenon induces the achievement of the minimum potential energy by reducing the surface of the fabricated microstructure. For a specific volume the smallest surface is a sphere. The die substrate with the fabricated microarray is placed on a hotplate at a temperature higher than the AZ4562's glass transition temperature for 5 minutes. Due to the dimensions of the ML and the PD, extreme care was needed to very accurately align the apex of the ML with the center of the PD. In Fig. 3 it is possible to see a close-up of the ML centered on top of the 24 µm PD (signaled with a red circle) and an array of 8 MLs on top of the 240 µm (in a green square). An alignment precision lower than 1 µm was achieved using a mask aligner *MJB3* from *Karl Suss*. When the fabrication is done directly on the surface of a die substrate close attention has to be given to the fabrication steps that involve temperature because silicon has a high thermal conductivity and the applied thermal profile rapidly crosses through the PR thus accelerating the TR.

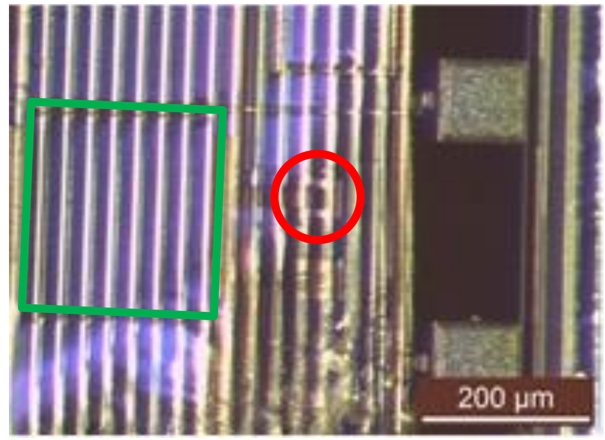

Fig. 3. Optical photograph showing a zoom-in of the 24 µm square photodiode (signalled with a circle) with a ML already fabricated on top of it. The 240 µm square photodiode under an array of 8 MLs is seen inside the green square.

B. Measuring setup

In order to measure the photodiodes' intrinsic dark current, without and with MLs fabricated on their surface, for determining an important noise inherent in this type of CMOS devices, the experimental setup seen in Fig. 4 was used. This setup is composed by a dark chamber, a metallic positioning/aligning mechanical support and by the integrated microdevice (PDs without and with MLs). The die was attached to a PCB to perform the electrical connections for reading the generated dark current. A *MEI 1204W Hybrid Wedge Bonder* was used for performing the wire bonding between the die's pads and the PCB. The PCB is used as an adaptation board for connecting to a picoammeter. The dark currents were measured using a *Keithley 6487 Picoammeter Voltage Source*, to read just the PD's output without the addition of hardware induced noise, under two different reverse bias voltages, 0 and -4V.

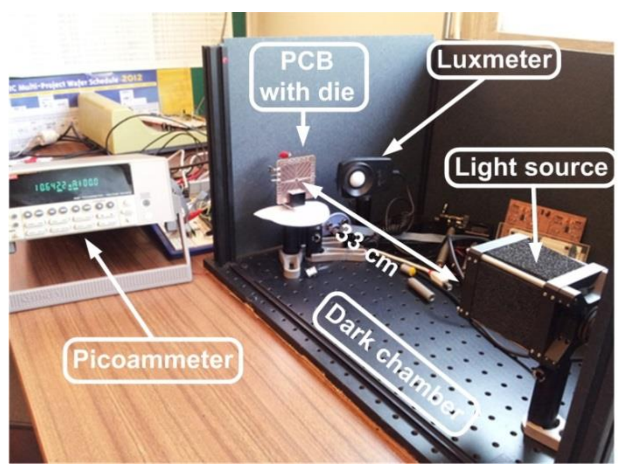

Fig. 4. Photograph of the setup that was used for characterizing the PDs without and with MLs.

C. Dark current measurements

The schematic used to measure the dark currents is illustrated in Fig. 5. The picoammeter allows measuring currents with a resolution of 10^{-14} A while being able to apply an electric potential difference to the measured photodiode for obtaining different reverse bias voltages.

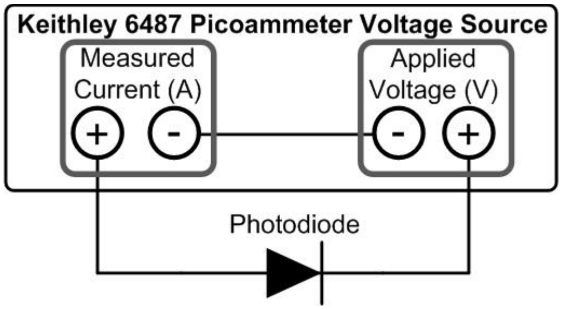

Fig. 5. Illustration of the schematic used for measuring the PDs with different reverse bias voltages.

In Fig. 6, is illustrated the typical dark current variation values. In this figure are represented the measurements for the 24 μm square PD without and with a ML on top of it at different values of the reverse bias voltages (0 and -4 V).

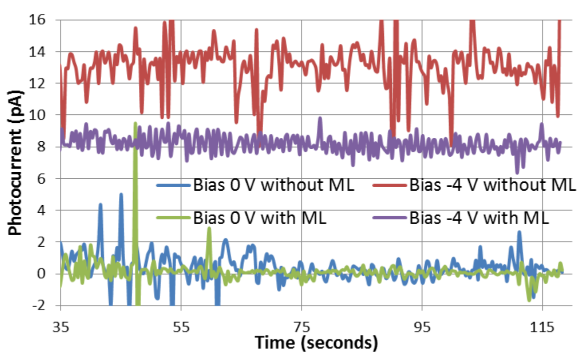

Fig. 6. Dark current, at room temperature, for the 24 μm square PD measured with the *Keithley 6487 Picoammeter Voltage Source* at 0 and -4 V reverse bias. These measurements were done without and with a ML.

Moreover, in Table I, the dark current values (in pA) obtained for the cases under investigation are shown.

TABLE I. DARK CURRENT VALUES (IN PA) FOR THE 24 AND 240 μM SQUARE PDS FOR TWO REVERSE BIAS VOLTAGES. THE MEASUREMENTS WERE DONE WITH AND WITHOUT MLS ON TOP OF THE PHOTODIODES.

	Without MLs		**With MLs**	
	Bias 0 V	**Bias -4 V**	**Bias 0 V**	**Bias -4 V**
24 μm square PD	0.685	13.426	0.442	8.67
240 μm square PD	1.06	21.5	0.907	18.4

IV. DISCUSSION

The dark chamber is ideal for measuring the dark current and also prevents interferences from the environmental light to impinge into the photodetectors for the light-current conversion measurements. The dark current is the limiting factor in a photodiode that can be measured directly and one of the most relevant parameters [2]. This current is defined as the residual current that flows in a photodiode when there is no light impinging on it. The dark current is temperature dependent and not constant along the time. As introduced in section I, there are several reasons causing these variations in the dark current measurements but it is not possible yet to differentiate them in the presented values. An obvious effect that the MLs have on the PDs' dark current is that the correspondent measurements are closer to a constant value, *i.e.*, the number and amplitude of the peaks is considerably reduced. It should be underlined that the 24 μm square PD has one ML on top of it and the 240 μm square PD has an array of 8 MLs. With MLs, not only the dark current values considerably decrease, from values ranging between 14.42% and 35.47%, depending on the case, but also the chart lines have less pronounced variations, *i.e.*, they get smoother.

V. CONCLUSIONS

The fabrication of polymer based MLs directly on the surface of type n^+/p-substrate junction photodiodes was shown to have a considerable effect on the dark current values. Also, when the bias voltage is increased, it increments the width of the PDs' depletion region thus they produce more dark current. The results demonstrated in this paper show that the inclusion of MLs in PDs enhances their efficiency by reducing a very important and unavoidable inherent type of noise. Nevertheless, the reasons why the MLs stabilize the measured dark currents mean values are not yet fully understood so further research is required.

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REFERENCES

[1] W. C. Porter, B. Kopp, J. C. Dunlap, R. Widenhorn, and E. Bodegom, "Dark current measurements in a CMOS imager," in SPIE-IS&T Electronic Imaging, 2008, vol. 6816, pp. 1–8.
[2] A. H. Titus, M. C.-K. Cheung, and V. P. Chodavarapu, "CMOS Photodetectors," in CMOS Photodetectors, Photodiodes - World Activities in 2011, In Tech, 2011, pp. 65–101.
[3] R. P. Rocha, M. J. Maciel, J. P. Carmo, and J. H. Correia, "High-quality surface microlenses based on rehydration," in 2013, Espoo - Finland, September 1-4, 2013, pp. 3–6.
[4] M. J. Maciel, R. P. Rocha, J. P. Carmo, and J. H. Correia, "Measurement and statistical analysis toward reproducibility validation of AZ4562 cylindrical microlenses obtained by reflow," Measurement, vol. 49, pp. 60–67, Mar. 2014.
[5] M. Bigas, E. Cabruja, J. Forest, and J. Salvi, "Review of CMOS image sensors," Microelectronics Journal, vol. 37, no. 5, pp. 433–451, May 2006.
[6] K. Murari, R. Etienne-Cummings, N. Thakor, and G. Cauwenberghs, "Which photodiode to use: a compararion of CMOS-compatible structures," IEEE Sens J., vol. 9, no. 7, pp. 752–760, 2010.
[7] "ON Semiconductor." [Online]. Available: http://www.onsemi.com/PowerSolutions/content.do?id=16697.