# Fabricating Microlenses on Photodiodes to Increase the Light-Current Conversion Efficiency

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***Abstract*— This letter presents a microlenses (MLs) fabrication process for enhancing the photocurrent (PC) generation efficiency of photodiodes (PDs). The concept was demonstrated with a plano-convex spherical ML fabricated directly on top of a PD. The PDs are of type $n^+$/p-substrate junction fabricated in a standard CMOS process. The base and sag height of the MLs measure 26 and 5 $\mu$m, respectively. The PC generation was measured inside a dark chamber under normally incident red light illuminance both with and without the ML on top of the PD. The illuminance was linearly incremented from 0 to 2000 lux. The ML forces more light to impinge into the PDs active area and, therefore, promotes more PC generation. The measurements show that the PD generates, at an approximately constant rate of 14%, more PC with the MLs than without the MLs.**

***Index Terms*— OPTO.**

## I. Introduction

MICROLENSES are an important element in many optical applications, due to their capacity to converge light. Particularly, the microlenses integration in a CMOS image sensor can be the key for an efficiency improvement. For the successful integration of microlenses in the photodiodes, in many cases the heart of CMOS sensors, there are a set of factors to consider: scalability, materials compatibility, degree of complexity in integration and fabrication costs. Currently the main interest is their integration onto CMOS sensors for improving the light efficiency acquisition and increase the correspondent current generation [1].

## II. Fabrication

Fig. 1 shows the MLs typical fabrication process using photolithography and thermal reflow (TR). 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 $\mu$m 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).

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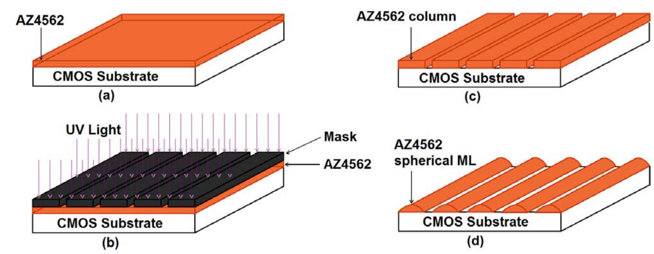


Fig. 1. MLs array fabrication steps: (a) spin coating, prebake and rehydration; (b) exposure; (c) developing and cleaning; and (d) thermal reflow.

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. Based on the focal length $f$ and radius $R$, equations $f = R/(n-1)$ and $R = (r^2 + h^2)/2h$, respectively, the curvature of the MLs is controlled by the PR's coated thickness $h$. In the previous equations $n$ is the refractive index for a given wavelength and $r$ is half the line segment of the reflowed PR interfacing with the substrate. 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. An alignment precision lower than 1 $\mu$m 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 thermal profile applied rapidly crosses through the PR thus accelerating the TR.

## III. Experimental Result

A red light source ($\lambda_0 = 632$ nm with FWHM = 17 nm) was used for measuring the PCs generated by a square PD (24 × 24 $\mu$m) without and with a ML on top of it. This comparison served for determining and quantifying the ability of the ML for improving the PD's light-current conversion. The tested system presented a transmission ratio of 98.73%. For quantifying the enhancement in PC generation promoted by the ML, the concept demonstrated in Fig. 2 was tested. This setup increments the light acquisition because it converges light that would impinge outside the PD into its active area. Using a photomask, an array of MLs is fabricated directly on top of the PD (Fig. 3). Fig. 4 shows the experimental setup that was used for measuring the PD without and with a ML on its surface. The setup is composed by a dark chamber,

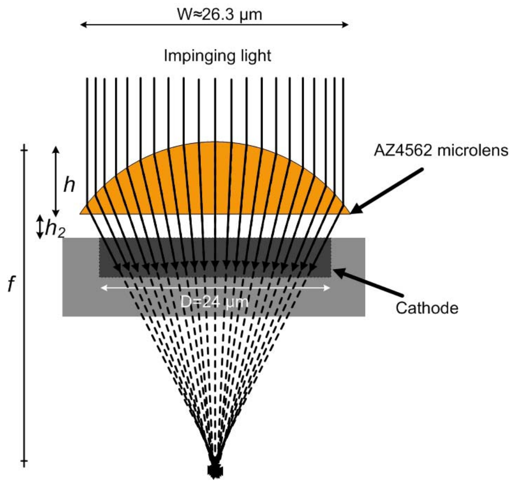


Fig. 2. Cross section illustration of the MLs direct fabrication on a photodiode. It should be noted that $h_2$ is the PD's oxides' thickness.

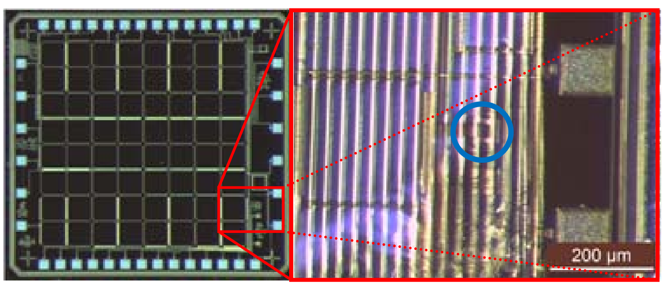


Fig. 3. On the left is an optical photograph of the die and on the right is a zoomed-in view of the 24 $\mu$m square photodiode (signaled with a circle) with a ML already fabricated on top of it.

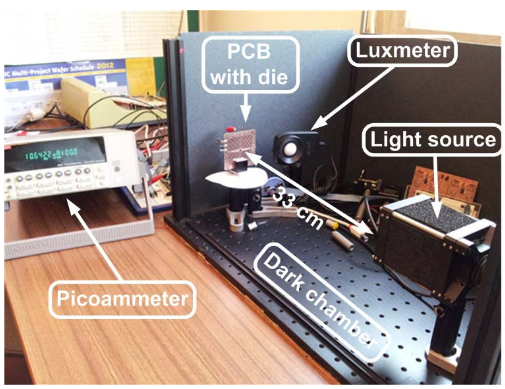


Fig. 4. Photograph of the setup that was used for characterizing the PD without and with ML.

the light source, a collimating lens for obtaining a parallel light beam, a luxmeter with a resolution of 0.1 lux (*CET CT 1330B High Accuracy Lux Digital Light Meter*) to measure and calibrate the impinging light's optical power, a metallic positioning/aligning mechanical support and by the integrated microdevice (PD without and with a ML).

The die was attached to a PCB to perform the electrical connections for reading the generated PC. 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 distance between the collimating lens and the die is 33 cm. The PCs 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.

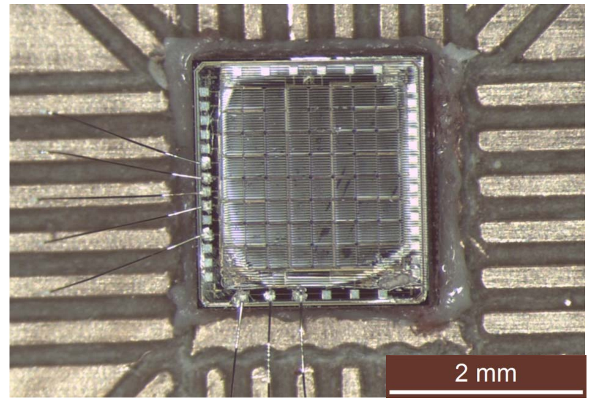


Fig. 5. Zoom-in optical microscope photograph of the die placed on the PCB and with the wire bonding already performed.

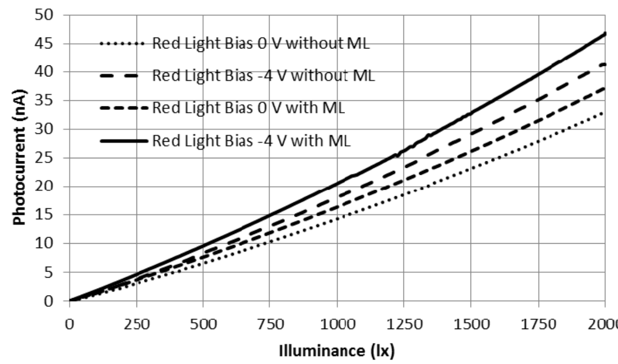


Fig. 6. Comparison between the photocurrents measured for different reverse bias voltages under red light, without and with the ML.

The PD was subjected to a linear increment of the illuminance from 0 to 2000 lux and even for an illuminance above 2000 lx the PD still presented a clear linear response. Fig. 5 shows a zoom-in optical microscope photograph of the die on the PCB, and with the wire bonding already performed, for measuring purposes using the picoammeter. Fig. 6 displays the PD's measured PCs without and with a ML. With ML, the gain in PC generation is the same across the linear increment of illuminance with either a reverse bias voltage of 0 or −4 V. These results demonstrate an increase of the PD's photocurrent generation of 14%. The integration of a properly designed ML, and its fabrication process, is able to surpass the intrinsic losses that occur due to absorption, reflectance and scattering within different materials and their interfaces.

## IV. Conclusion

The dimensions of both the ML and the PD, as well as using a silicon substrate, require special attention in all the fabrication steps. Very precise fabrication and integration processes are quintessential for obtaining a considerable gain in PC generation. The 14% enhancement in light-current conversion is mainly obtained by collecting more light into the photodiode's active area and the results that were shown validate the use of MLs for optical microsystems integration.

## References

[1] W. Wang and J. Fang, "Variable focusing microlens chip for potential sensing applications," *IEEE Sensors J.*, vol. 7, no. 1, pp. 11–17, Jan. 2007.