Lens Solution for Intensity Enhancement in Large-Pixel Single-Photon Avalanche Diode

Sheng-Chuan Cheng(a), Chih-Ching Chang, Kuo-Feng Lin, Chien-Hsiung Huang, Lin-Ya Tseng, Hui-Min Yang, Ken Wu, JC Hsieh.

VisEra Technologies Company, No12, Dusing Rd.1, Hsinchu Science Park, Taiwan (30078)
[(a)]E-mail: Charles_Cheng@viseratech.com
Tel. : +886-3-6668788
Fax : +886-3-6662858

Abstract—
Single-photon avalanche diodes have been utilized in a variety of applications that acquire time-of-flight system information in addition to light intensity. To increase light intensity, spherical micro lenses are the commercial solution for a complementary-metal-oxide-semiconductor image sensor because of their excellent capability to concentrate incoming light on the photodiode. However, the application of spherical micro lenses in large pixel sizes (≥10 um) is limited because of inadequate materials and processes. To solve this problem, the concept of a planar lens has been presented to provide an alternative approach that can concentrate incoming light.

In our study, we develop an innovative and flexible process to demonstrate a robust process to address the problems related to a large pixel size of 850 nm. The finite-difference time-domain method is used to simulate the optimization of the new structural development, particularly the focus length to photodiodes, lens height, and refractive index of the lens. Simulation results indicate that the target scheme with an evident signal intensity has a pixel size of 10 µm and a focus length of 3 µm. The effects of focus height, lens height, and refractive index of lens are subsequently described.

Keywords—SPAD, planar lens, Fresnel lens.

I. Introduction

In 3D imaging technologies, the time-of-flight (TOF) system is an important tool for such applications as object recognition and remote sensing. The transverse spatial resolution of the TOF obtained is retrieved by using a pixelated array or a single-pixel detector with a scanning approach. To obtain a high-precision depth resolution, acquiring detectors with a fast response time and a high-speed electronic readout is necessary [1–3]. The operation of single-photon avalanche diodes (SPADs) is characterized by single-photon sensitivity and picosecond timing resolution that acquire TOF information aside from light intensity.

SPADs have been integrated in large arrays by using complementary-metal–oxide–semiconductor (CMOS) technology [4, 5]. As SPAD imagers integrate thousands of pixels, the acquisition of time-resolved images is allowed without the need for mechanical components, thus reducing the acquisition time. In CMOS technology, spherical micro lenses are the commercial solution to increase the light intensity because of their excellent capability to concentrate incoming light to the photodiode. The key development of the lens is the refractive index of the transparent material of the micro lens. However, the application of spherical micro lenses on large pixel sizes (≥10 um) is suboptimal because of inadequate materials and processes. To solve this problem, the concept of a planar lens has been presented to provide an alternative approach that can concentrate incoming light [6, 7]. This planar lens uses diffractive optics such as the Fresnel zone plate.

Near-infrared imaging is one application of SPAD that detects near-infrared light of 850 nm or 940 nm. We develop an innovative and flexible method to demonstrate a robust process to address the problems related to a large pixel size of 850 nm (Figure 1). The study of planar lens can be divided into three parts as explained in Figure 1(B): (1) diode region [Fig. 1(B)-①], (2) height of the planar lens [Fig. 1(B)-②], and (3) refractive index of the planar lens [Fig. 1(B)-③].

II. Design and Simulation of Planar Lens

The optical simulation is designed based on a backside illumination sensor. The finite-difference time-domain method is used to perform the quantum efficiency (QE) evaluation. We compare the optical performance of different pixel sizes without any lens, with a spherical micro lens, and with an optimized planar lens. The performances of pixel sizes of 3, 5, 10, 15, and 20 um are depicted in Figure 2. The planar lens and spherical micro lens are suitable in the QE (%) at a wavelength of 850 nm in all pixel splits. The planar lens evidently improves when the pixel size is larger than 10 µm.

In practical applications, the absorption area of SPAD is smaller than the area of pixel size. The shrinking performance of a 25% absorption area is summarized in Figure 3. The QE (%) of the planar lens is similar to the performance of the spherical micro lens when the pixel size is larger than 10 um and the height of the planar lens is lower than that of the spherical lens. Figure 4 presents the optimization summary of the lens height and the refractive index. A high lens height and a high refractive index are beneficial to improve the QE (%) at a wavelength of 850 nm.

III. PROCESS INTEGRATION DESCRIPTION

The planar lens with a Fresnel lens design of a 9.9 um pixel size is demonstrated in 1.1 um pixel array sensor. Figure 5(A) illustrates the simplified process flow of the planar lens that only processes one "photolithography" and "etch" step. The top view and cross-section of the fabricated planar lens is shown in Fig. 5(B). The focal length of the planar lens can be easily adjusted by verifying the coating speed.

The design of a planar lens is challenging because the target wavelength limits the number of rings. The focal point is also a key factor that needs to be considered and carefully optimized. We use scanning near-field optical microscopy (SNOM) to verify our design in terms of the number of rings and focal distance. The structure of the planar lens needs to be manufactured on a glass wafer. By positioning light sources on the surface of the glass and measuring the backscattered light at different locations, optical performance can be reconstructed by different absorbers. Figure 6 shows that optimization focusing on performance can be obtained: the focal distance is 3.0 um when the target wavelength is 850 nm.

IV. RESULTS

By using a 1.1 um pixel array, the analysis of the digital number (DN) of different pixel positions can describe the optical performance of a planar lens, as shown in Figure 7.

Figure 8 shows the real DN measurement of a planar lens with a 9.9 um pixel design with a lens height of 0.3 um. The DN value of Plana lens is 1.7~1.8 times improvement as much as no ML pattern and distribution is the same as the SNOM result, but the peak-to-noise ratio is not sufficient. According to the cross-section analysis, the focus distance needs to adjust to the target. After adjusting the focal length, the DN value shows an apparent improvement from 1.7~1.8 to 3.1~3.3 times in Figure 9.

According to the optical simulation, increasing the lens height is an effective method to improve the QE. The comparison between the lens height of 0.3 um and that of 0.5 um is shown in Figure 10. The DN value of the lens length of 0.5 um is higher than that of the lens length of 0.3 um. We assume that a high lens height, such as 0.7 um, can obtain a higher DN value.

V. CONCLUSION AND DISCUSSION

We have presented a fabricated planar lens solution for a large pixel (≥10 um) at a wavelength of 850 nm and verified the optical design by using SNOM and DN value. In this work, planar lens structures with large pixel sizes are proposed to obtain improved light intensity of the SPAD. Studies on the refractive index should be further conducted. However, the manufacture of a circle mask with a high aspect ratio of the lens height is challenging in planar lens. According to the optical simulation, the optical performances of the spherical micro lens and planar lens are comparable when material and process limitations are not considered and the scheme is optimized. Figure11 illustrates a big micro lens of 20um pixel that is on development in VisEra. The profile in diagonal direction is closely spherical and lens height can reach 10um. We intend to continue searching for suitable materials and creating lens solutions for large pixel SPADs.

VI. ACKNOWLEDGMENT

The authors would like to thank the dedicated IC Foundry-TSMC for the test wafers and all the members of VisEra's R&D group for their effort in the design, test, and process development.

REFERENCES

[1] Ming-Jie Sun. et al. Single-pixel 3D imaging with time-based depth resolution. Nat. Communications, 12010 (2016)

[2] Radwell, N. et al. Single-pixel infrared and visible microscope. Optica 1, 285–289 (2014).

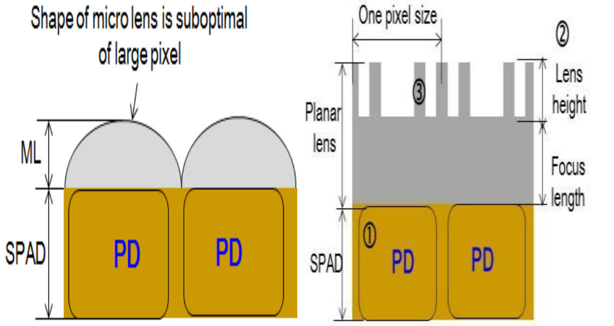
[3] Edgar, M. P. et al. Simultaneous real-time visible and infrared video with single-pixel detectors. Sci. Rep. 5, 10669 (2015).

[4] Rochas, A. et al. First fully integrated 2-d array of single-photon detectors in standard cmos technology. IEEE Photon. Technol. Lett., 15, 963–965 (2003).

[5] Juan Mata Pavia, et al. Measurement and modeling of microlenses fabricated on single-photon avalanche diode arrays for fill factor recovery. Optics Express Vol. 22, Issue 4, pp. 4202-4213 (2014).

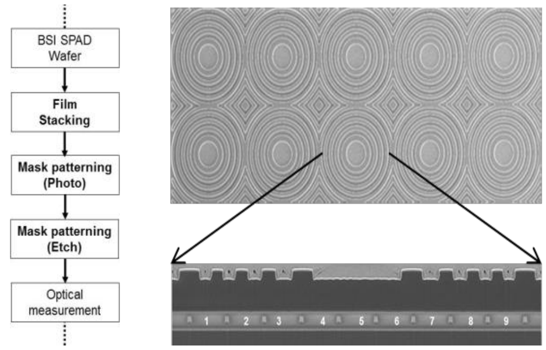
[6] B. E. A. Saleh & M. C. Teich. Wiley series in pure applied optics. Fundamentals of Photonics, 2nd edition (2007).

[7] Rochus, V. et al. Pixel performance enhancement by integrated diffractive optics. 2015 IISW, 82-85 (2015)



(A) Sphere ML (B) Planar ML

Fig.1. Scheme descriptions of sphere ML & planar lens for optical simulation



(A) Process flow (B) Top view & cross section

Fig.5. Planar lens structure in 1.1um pixel array

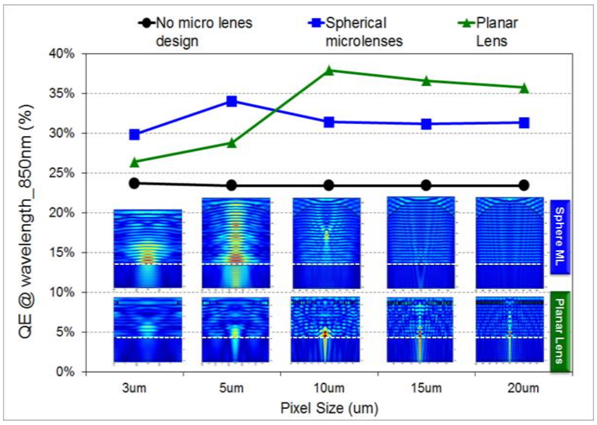
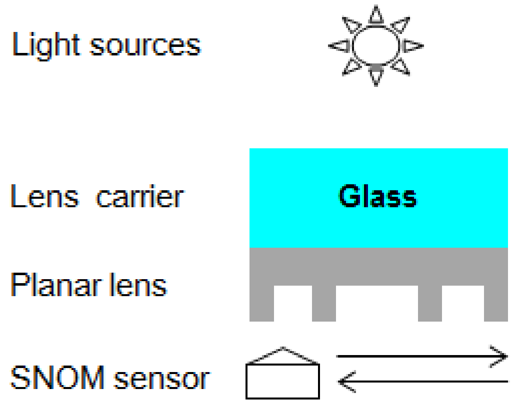


Fig.2. QE(%) comparison of different pixel size



(A) Scheme description of SNOM measurement

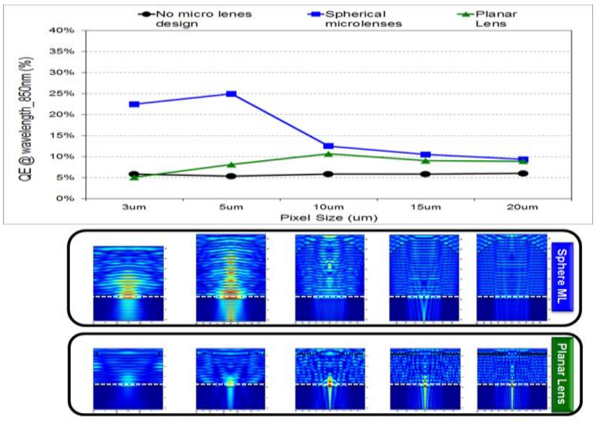
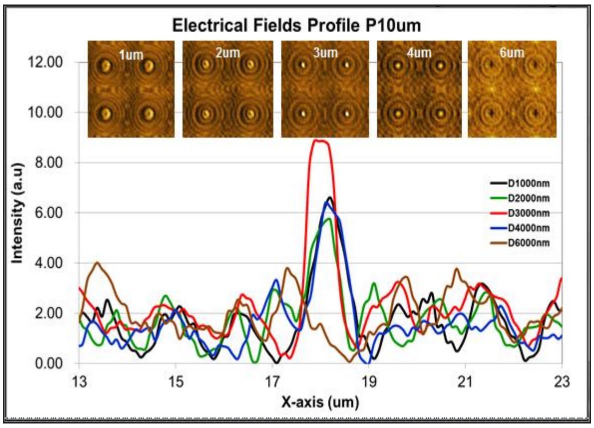


Fig.3. QE(%) comparison of different pixel size when photo diode area has 25% shrinking



(B) Test results of different focus lengths

Fig.6. Design verification by SNOM @ 850nm

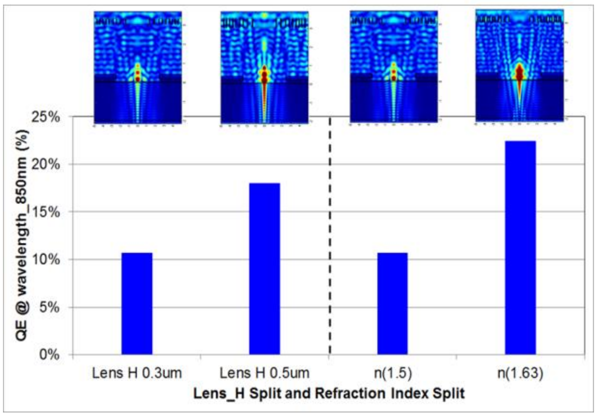


Fig.4. QE(%) comparison of different lens height and refraction index (25% shrinking in photo diode area)

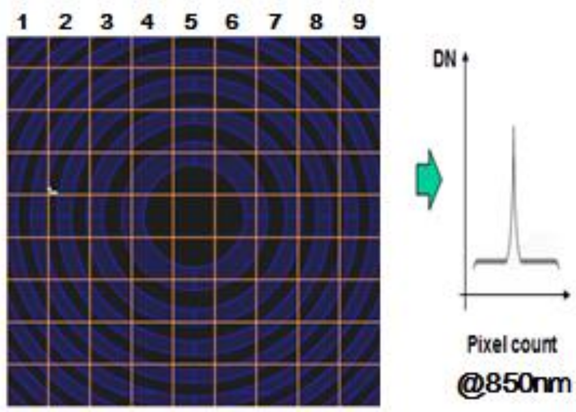


Fig.7. Wafer level measurement by using 1.1um pixel array sensor (Planar lens design: 9.9um pixle @ 850nm)

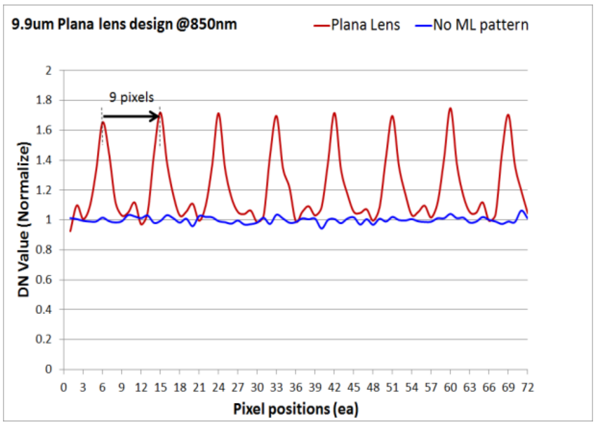


Fig.8. DN value detected by 1.1um pixel size

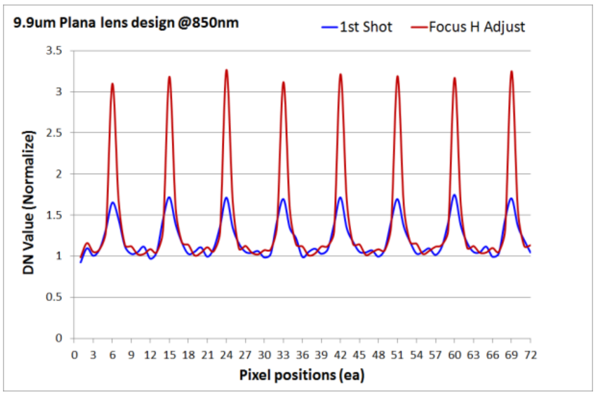


Fig.9. Real DN comparison of varying focus height

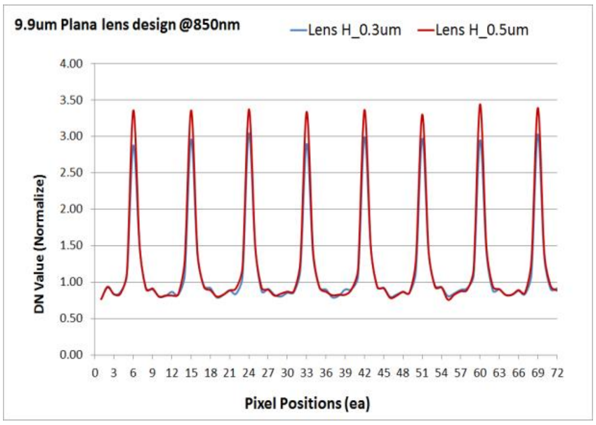
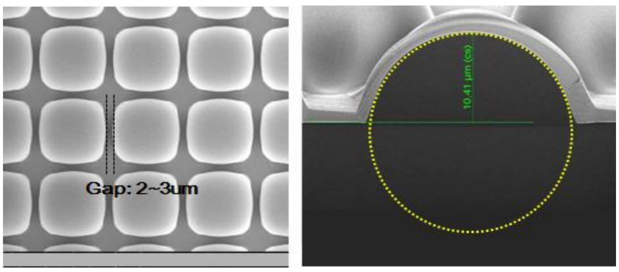


Fig.10. Real DN comparison of varying lens height



(A) Top view (B) Cross section

Fig. 11. Performance of micro lens in 20um pixel