P18 3-D Wave Optical Simulation of Inner-layer lens Structures

Hideki Mutoh
Link Research Corporation
1-18-5, Kojima, Taito-ku, Tokyo, 111-0056 Japan
Phone: +81-3-3851-9871
Fax: +81-3-3862-0570
E-Mail: hideki.mutoh@nifty.ne.jp

Abstract: A wave optical simulator TOCCATA-Wave 3-D was newly developed in order to analyze optical characteristics of 3-D structures including diffraction and interference. Optical characteristics of inner-layer lens structures are studied by this simulator. The inner-layer lens structure gives better concentrated focal region and smaller lateral shift of the focal region under the oblique incident light, comparing with the single lens structure. It is found that the improvement of the light-gathering power by the inner-layer lens structure is remarkable in the case of the small F-number and large top lens height.

I. Introduction

The on-chip micro-lens technology has been adopted to improve the sensitivity of small pixel image sensors. When the pixel size is reduced, it is difficult to proportionally decrease the thickness of layers formed on silicon substrate, because the wavelength of the incident light does not change. The inner-layer lens structure was developed in order to improve the sensitivity of such small cell size micro-lens structures [1]. For analyzing the optical and electrical characteristics of the cell structures, the 3-D device simulator SPECTRA and 3-D ray tracing and 2-D wave optical simulator TOCCATA has been used [2], [3]. However they cannot treat the wave optical characteristics of 3-dimensional structures including interference and diffraction phenomena. Therefore a 3-D wave optical simulator TOCCATA-Wave 3D was newly developed. The analysis of the inner-layer lens structures by the simulator is reported.

II. Modeling

In the 3-dimesional steady state, every component ϕ of the electric field and the magnetic field satisfies the following equation [2], [3].

$$\phi(\mathbf{x}) = \oint_S \left[\frac{e^{ikr}}{4\pi r}\phi^* - \left(\frac{e^{ikr}}{4\pi r}\right)^* \phi \right] dS \qquad (1)$$

k is propagation number given by $k=2\pi/\lambda$ where λ is the wavelength in the material, S represents the closed surface surrounding the point $\mathbf{x}$, and * denotes differential operation along the normal direction at each point on S. The discretization is performed by the boundary element method.

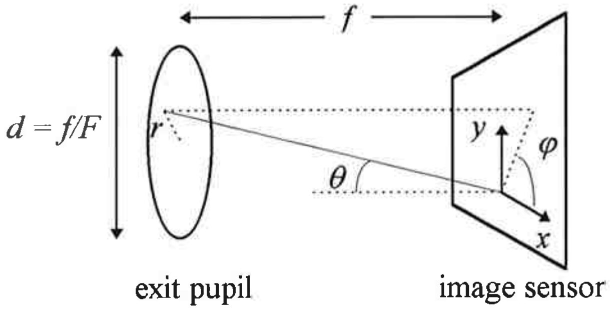


Fig. 1. F-number and incident light angle.

The light-gathering power P of a cell at the point (x, y) on the sensor plane is written as follows.

$$P(x,y) = P_0 \int_{r \le \frac{f}{2F}} \frac{\cos^3\theta}{f^2} g(\theta,\varphi) ds \qquad (2)$$

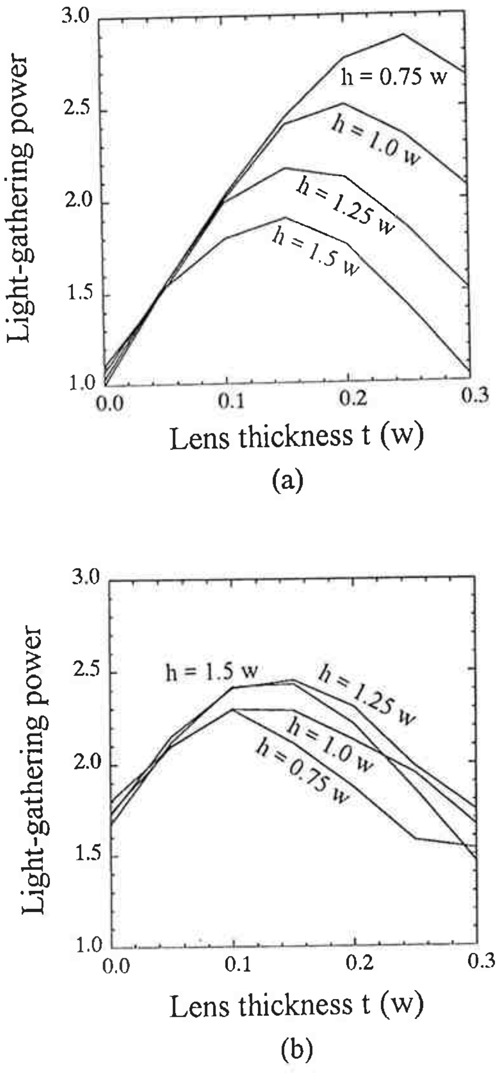


Fig. 6. Light-gathering power dependence on the top lens thickness and the top lens height (w = 2 μm). (a) single lens structure, (b) inner-layer lens structure.

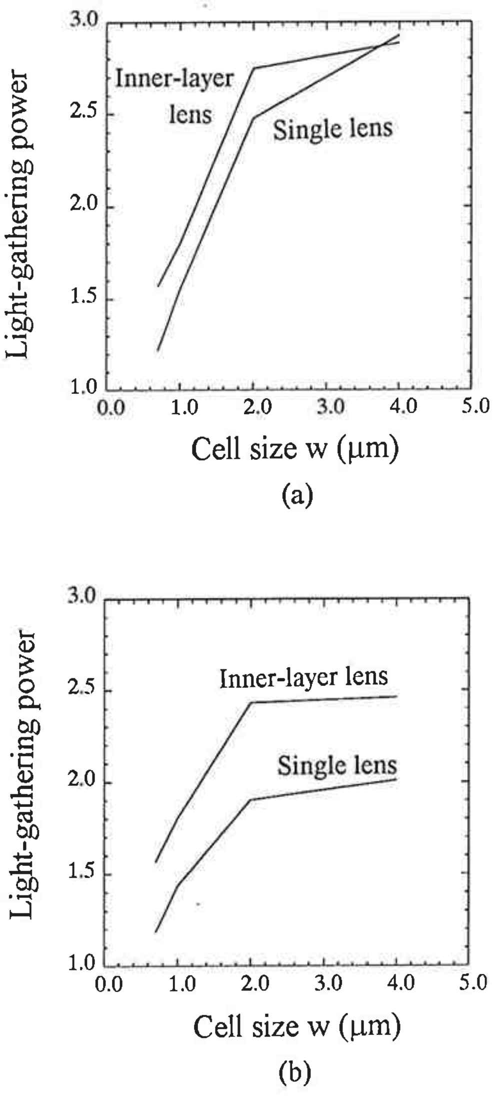


Fig. 7. Light-gathering power dependence on the cell size (h = 1.5 w). (a) F = 2.8, (b) F = 1.4.

IV. Conclusion

A 3-dimensional wave optical simulator TOCCATA-Wave 3D was newly developed and analyzed optical characteristics of inner-layer lens structures. It was found that the inner-layer lens structure gives better concentrated focal region and smaller lateral shift of the focal region under the oblique incident light, comparing with the single lens structure. The improvement of the light-gathering power by the inner-layer lens structure is remarkable in the case of the small F-number and large top lens height.

References

[1] Y. Sano, et al. "On-chip Inner-layer Lens Technology for an Improvement in Photo-sensitive Characteristics of a CCD Image Sensor," *J. ITEJ*, vol. 50, No. 2, pp. 226-233, 1996.

[2] H. Mutoh, " Simulation for 3-D Optical and Electrical Analysis of CCD," *IEEE Trans. Electron Devices*, vol. 44, No. 10, pp. 1604-1610, Oct. 1997.

[3] H. Mutoh, "Optical Simulation for Image Sensors by Wave Analysis," Proceeding of 1997 IEEE Workshop on CCDs and AIS, 1997.

where P_0 is a constant, f is the distance between the exit pupil and the sensor plane, F is the F-number, θ denotes the incident light angle between the normal vector of the sensor plane and the incident ray, and φ denotes the angle between X-axis and the projection of the incident ray on the sensor plane. The integral operation is performed on the exit pupil. $g(\theta, \varphi)$ is the angle distribution of the light-gathering power, which is defined as the total light intensity in the photosensitive area under the parallel incident light with the total intensity of unity at the top of the cell structure. The light-gathering power at the center point of the sensor plane P_{center} is rewritten as

$$P_{center} = P_0 \int_{\theta=0}^{\tan^{-1}\frac{1}{2F}} \int_{\varphi=0}^{2\pi} g(\theta, \varphi) \sin \theta d\theta d\varphi \,. \quad (3)$$

The following analysis is performed at the center of the image sensor in the case that the wavelength of incident light is 550 nm.

III. Analysis of the light-gathering power improvement by inner-layer lens structures

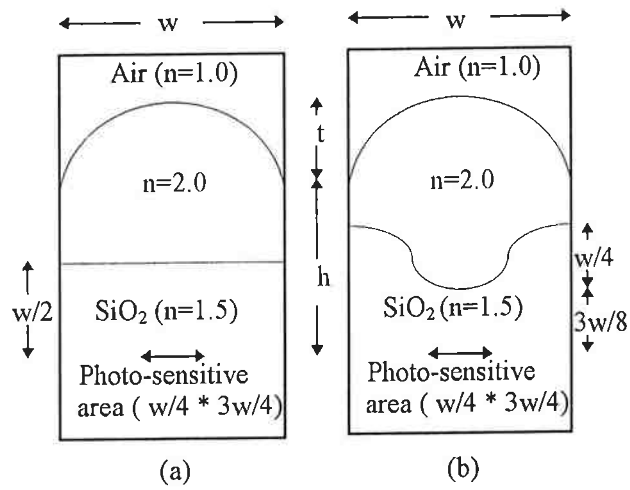


Fig. 2. Cross sectional view of the simulated structures. (a) single lens structure, (b) inner-layer lens structure.

Fig. 2 shows the analyzed structures, which consist of air, the lens material, and SiO_2, of which refractive indices are 1.0, 2.0, and 1.5, respectively. In the figure, w denotes the cell size (w by w square), t denotes the thickness of the top micro-lens, and h denotes the top micro-lens height which is the distance between the top planerization layer and the silicon surface. The shape of the top lens and the inner-layer lens are assumed as sphere and sine functions, respectively. As shown in Fig. 2 (a), the structure with the flat inner-layer is called single lens structure here. The angle distribution of the incident light intensity depends on the F-number of the total equipment. The light-gathering power is defined as the total light intensity at the w/4 (x) by 3w/4 (y) virtual photosensitive area which exists bottom center of the structure as shown in Fig. 3, when the total incident light intensity at the top of the structure is unity.

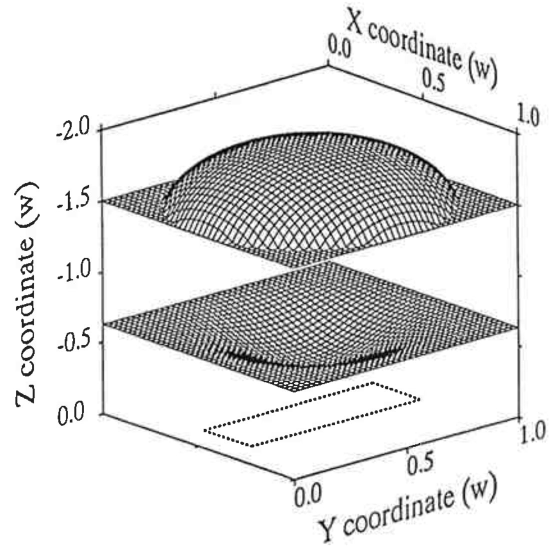
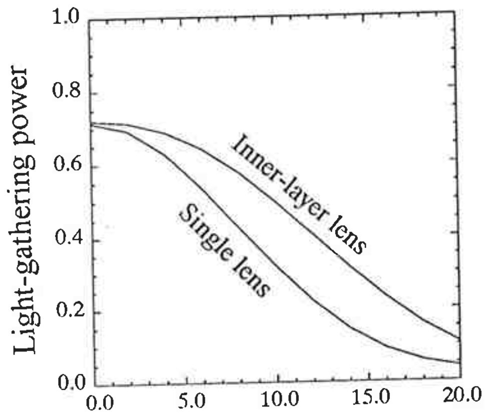


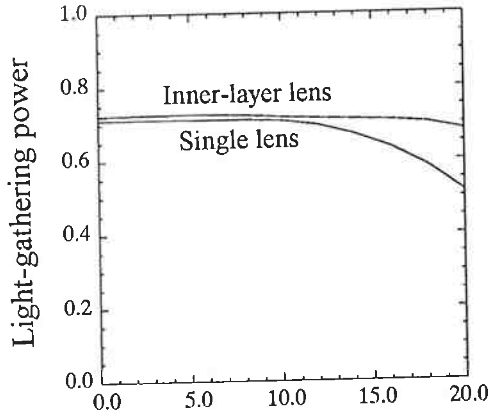
Fig. 3. Bird's eye plot of inner-layer lens structure. Dotted line indicates the w/4 (x) by 3w/4 (y) photo-sensitive area.

A. Angle distribution of light-gathering power

Fig. 4 shows the angle distribution of the light-gathering power of the cell size w of 2 μm. The light-gathering power of the single lens structure decreases with increase of the angle θ more steeply than that of the inner-layer lens structure especially in the case of φ=0. Fig. 5 shows the intensity distribution on the XZ-plane (y = w/2) when the incident light angle θ is 10 degrees. In the inner-layer lens structure, the focal region is concentrated better and its lateral shift is smaller than in the single lens structure case. Therefore the inner-layer lens structure improves the light-gathering power.



(a)

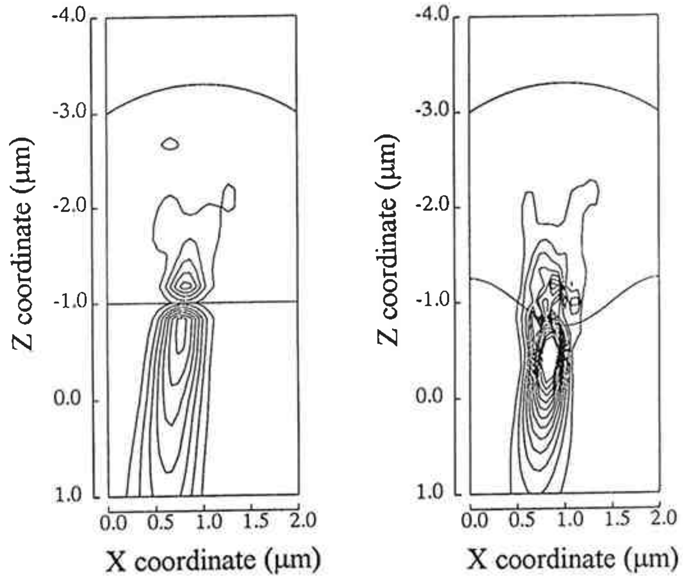


(b)

Fig. 4. Angle distribution of the light-gathering power (w = 2 μm). (a) $\varphi = 0$, (b) $\varphi = \pi/2$.

B. Light-gathering power dependence on the top lens thickness and height

Fig. 6 shows the light-gathering power dependence on the top lens thickness and height in the 2 μm cell with the F-number of 1.4. The value is normalized by that of the highest flat single lens structure (t = 0, h = 1.5 w). Increasing the top lens height, although the light-gathering power of the single lens structure is drastically reduced, that of the inner-layer lens structure slightly enhanced. Consequently, the light-gathering power of the inner-layer lens structure is higher in the large height case (h = 1.25 or 1.5 w), and lower in the small height case (h = 0.75 or 1.0 w) than that of the single lens structure.



(a) (b)

Fig. 5. Intensity distribution on XZ-plane (y = w/2, w = 2 μm). (a) single lens structure, (b) inner-layer lens structure. Contour step is 2.5.

C. Light-gathering power dependence on the cell size and F-number

Fig. 7 shows the light-gathering power dependence on the cell size and F-number in the single lens and inner-layer lens structures with h = 1.5 w and t of the thickness which gives the maximum light-gathering power. The light-gathering power in the both structures drastically reduced with decreasing the cell size in the region less than 2 μm. The light-gathering power in the inner-layer lens structure is larger than that in the single lens structure except in the case of large F-number (2.8) and large cell size (4 μm). The light-gathering power improvement by the inner-layer lens structure is remarkable in the small F-number case, because the smaller F-number gives the wider range of the incident light angle θ.