3-D Wave Optical Simulation of Light Wave-guide Structures by Localized Boundary Element Method

Hideki Mutoh and Shigetoshi Sugawa*
Link Research Corporation
*Graduate School of Engineering, Tohoku University

1-18-5, Kojima, Taito-Ku, Tokyo, 111-0056 Japan
*6-6-11, Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
Phone: +81-3-3851-9871, E-mail: hideki.mutoh@nifty.com
*Phone: +81-22-795-4835, *E-mail: sugawa@fff.niche.tohoku.ac.jp

Abstract

The analysis of the light gathering power and cross-talk in the light wave-guide structures by 3-D wave optical simulation is reported using Localized Boundary Element Method. Air is better isolation material than SiO2, aluminum, or tungsten to improve the light gathering power. If SiO2 is adopted as the isolation material, light absorbent or reflective material would be needed in the isolation region to improve cross-talk characteristics.

I. Introduction

The pixel size of image sensors has been reduced continuously. With reducing the pixel size of CMOS image sensors, their lower sensitivity than CCD image sensors becomes serious problem. Although CCD image sensors can use the low level micro-lens or inner lens structure [4], CMOS image sensors cannot adopt it, because of the multi-level metal wiring. Therefore, wave-guide structures have been proposed to improve the sensitivity of CMOS image sensors [1], [2]. In order to realize 3D wave optical analysis for image sensors, we have developed a 3D wave optical simulator by Localized Boundary Element Method (LBEM) [3], [5]. This method can execute 3D simulation much faster than conventional boundary element or FDTD method. The wave optical analysis of the light gathering power and cross-talk in wave-guide structures by LBEM is reported.

II. Light gathering power of single micro-lens

Fig. 1 shows the structure for the micro-lens light gathering power analysis consisting of sphere micro-lens made of material with refractive index of 1.7 and silicon substrate, where “w”, “h”, and “d” denote the cell size, micro-lens height, and the distance between the bottom of the micro-lens and the silicon surface, respectively.

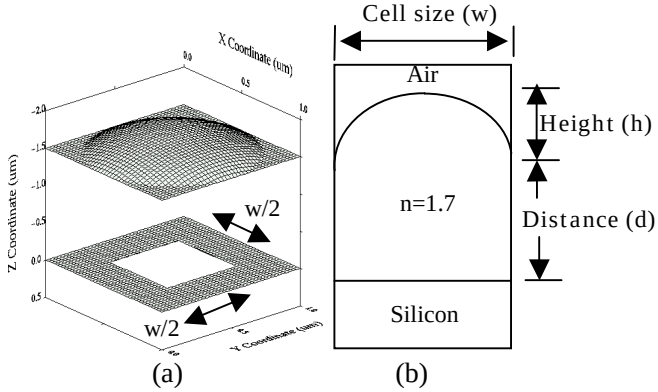


Fig. 1. Structure for wave optical simulation of light gathering power dependence on cell size, lens height, and distance. (a) Bird’s eye graph where center of the plane of Z=0 is the photo-sensitive region. (b) vertical cross-sectional view in XZ plane of y=w/2.

Fig. 2 shows the light gathering power dependence on d, h, and w, calculated by LBEM with 550 nm vertical incident light. The unit of the horizontal axis is cell size. The similar result has been obtained by FDTD method.

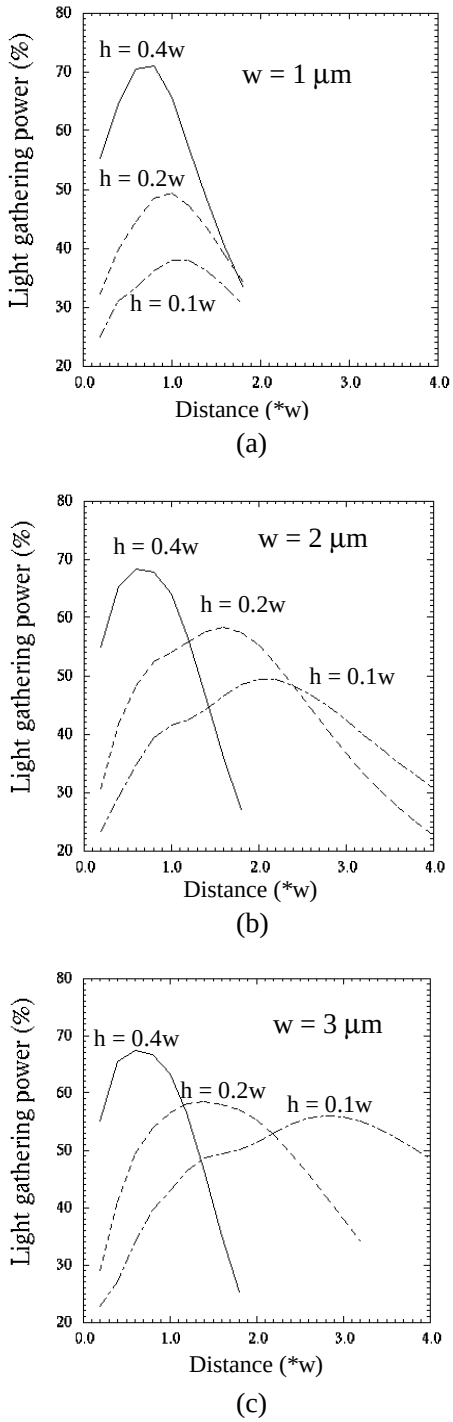


Fig. 2. Light gathering power dependence on cell size, lens height, and distance by 550 nm vertical incident light. (a) w = 1 μm, (b) w = 2 μm, (c) w = 3 μm.

It is found that the larger micro-lens height gives the larger peak of light gathering power. In the case of small micro-lens height, the distance for the largest light gathering power decreases with reduction of the cell size. Therefore, large distance micro-lens cannot obtain the large light gathering power in the small cell size case.

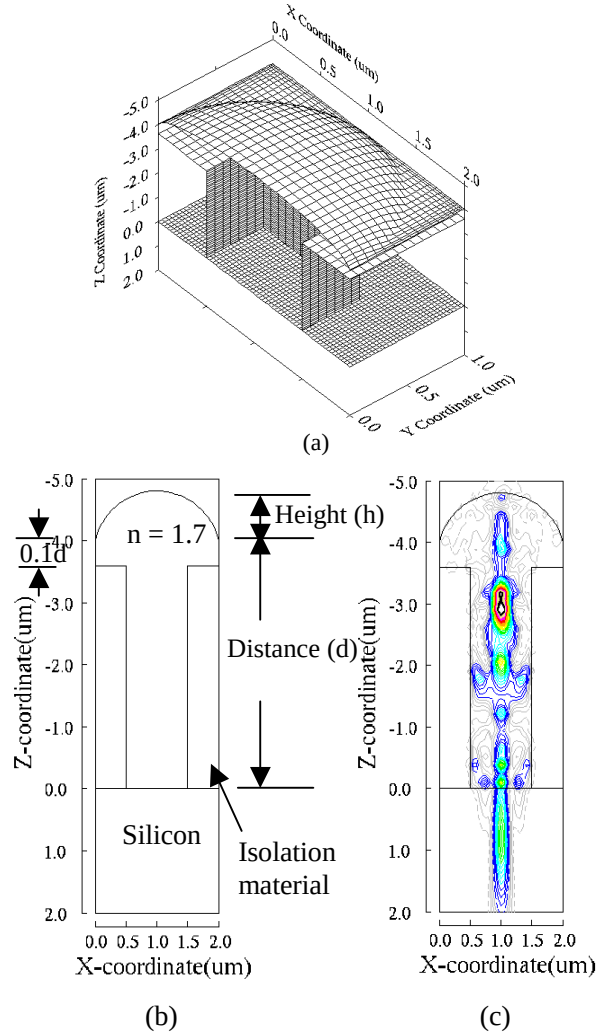


Fig. 3. Structure for analysis of Llight gathering power dependence on cell size, lens height, and distance. (a) Bird's eye view, (b) vertical cross-sectional view in XZ plane of y=0, (c) Light intensity distribution by 550 nm vertical incident light.

III. Light gathering power of wave-guide structures

Fig. 3 shows a wave-guide structure for this analysis, where h and d denotes the micro-lens height and the distance of wave-guide from entrance to exit, respectively. The inside material of the wave-guide has as same refractive index of

1.7 as the micro-lens, and the outside (isolation) material is assumed to be air (n=1), oxide (n=1.5), aluminum (n=0.5+3.9i), or tungsten (n=4+2.2i).

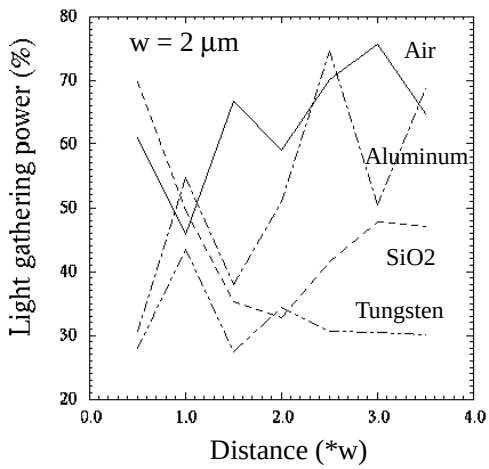


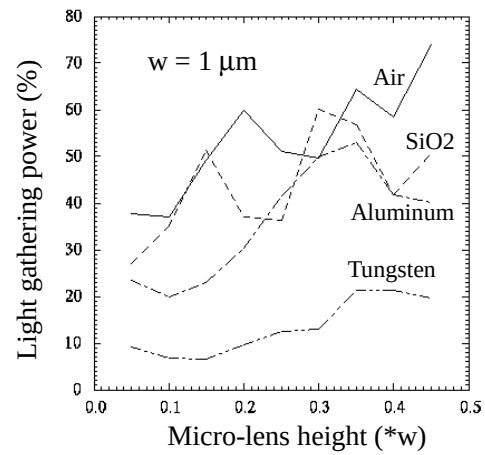
Fig. 4. Light gathering power dependence on the distance and isolation material by 550 nm vertical incident light.

A. Light gathering power dependence on distance

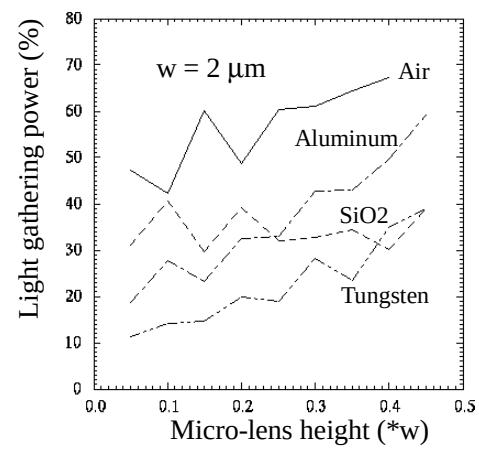
Fig. 4 shows the light gathering power dependence on the distance and isolation material in the case of w = 2 and h = 0.4 w. Although large interference exists, it is found that the light gathering power does not decrease with the increase of the distance d, except the tungsten case. In the tungsten case, the longer tungsten wall absorbs the lager part of incident light, because of its low reflectance and large absorption coefficient.

B. Light gathering power dependence on height

Fig. 5 shows the light gathering power dependence on the micro-lens height and isolation material in the cases of w = 1 and 2, where micro-lens distance d is 2 w. It is found that the light gathering power increases with increase of the micro-lens height as similarly shown in Fig. 2 and air is better isolation material than aluminum, SiO2, or tungsten to obtain large light gathering power. Because air isolation gives the largest total reflectance at the side-wall of the wave-guide in consideration of the angle range of the light through the micro-lens to the side-wall.



(a)



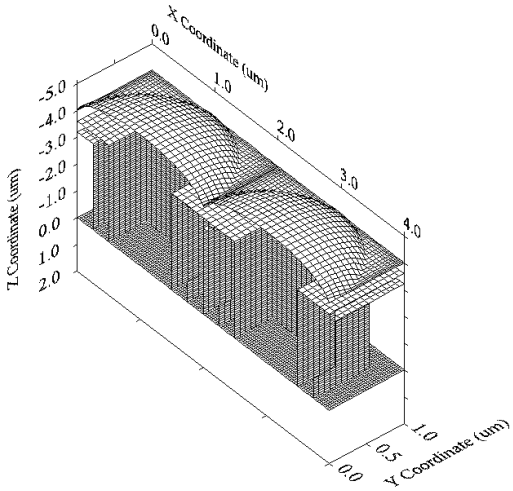
(b)

Fig. 5. Light gathering power dependence on the micro-lens height and isolation material by 550 nm vertical incident light. (a) w = 1 μm, (b) w = 2 μm.

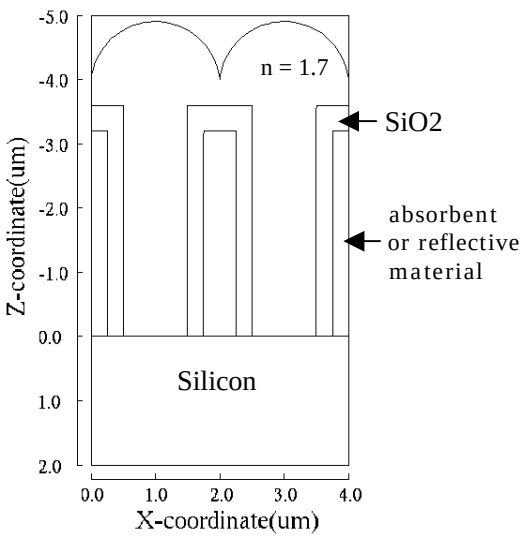
IV. Cross-talk of wave-guide structures

Fig. 6 shows the structure for the cross-talk analysis consisting of two cells of the wave-guide structure with the micro-lens height of 0.45 w and distance of 2 w, where only left micro-lens is illuminated. The isolation region is made of SiO2 and light absorbent or reflective material. Fig. 7 shows the cross-talk dependence on the incident light angle. The cross-talk value is defined as the light gathering power ratio between the right and left cell. The structure of SiO2 isolation without absorbent nor reflective material has large cross-talk, which increases with increase of the incident light angle. The absorbent or reflective

material in SiO2 isolation region can effectively reduce cross-talk.



(a)



(b)

Fig. 6. Structure for analysis of cross-talk dependence on incident light angle. (a) Bird's eye view, (b) vertical cross-sectional view in XZ plane of y=0.

V. Conclusion

The wave-guide structure can efficiently improve the sensitivity and cross-talk of CMOS image sensors. It was found that air is better isolation material than SiO2, aluminum, or tungsten for the structures to improve light gathering power. If SiO2 is adopted as the isolation material to avoid unfamiliar process or reliability problems, light absorbent or reflective material would be needed in the isolation region to improve cross-talk characteristics.

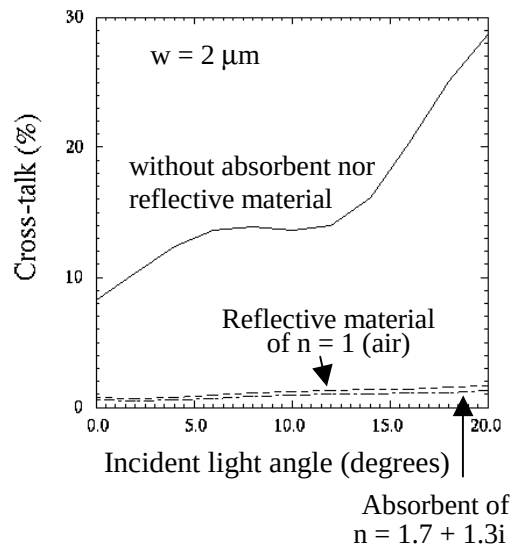


Fig. 7. Cross-talk dependence on the incident light angle in 2 μm cell by 550 nm incident light.

References

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