Optical Simulation for Image Sensors by Wave Analysis

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Abstract: A wave analysis optical simulator TOCCATA-Wave was developed in order to analyze optical characteristics of image sensors including interference and diffraction phenomena. TOCCATA-Wave solves Helmholtz equations, which are derived from time independent Maxwell's equations, using boundary element method. In the combination with a device simulator SPECTRA, it is possible to simulate optoelectrical characteristics of image sensors such as sensitivity and smear dependence on wave length of the incident light. Micro-lens focus condition and smear characteristics of IT-CCD were studied. It was found that the focus region is stretched along the depth direction and the peak intensity strongly depends on the lens radius in the case of the small aperture size micro-lens and the major origin of smear is different between blue and red incident light.

I. Introduction

The reduction of pixel size of CCD image sensors has been a main trend because of the demand for compact and high resolution video equipment. Device simulation and optical simulation has played an important role for designing such small pixel image sensors[1]. Since the optical simulation has been mainly performed by the ray tracing analysis, the wave phenomena such as diffraction or interference have been seldom considered. But these phenomena cannot be ignored in the small pixel size image sensors, for example 1/4 inch 380K pixel IT-CCD. In order to treat these phenomena, a wave analysis optical simulator TOCCATA-Wave was developed. It can analyze optoelectrical characteristics of image sensors such as sensitivity and smear of IT-CCD considering diffraction and interference in the combination with a device simulator SPECTRA[2]. The studies of micro-lens focus condition and smear characteristics of IT-CCD by this method are reported.

II. Modeling

In the steady state, every component ϕ of the electric field and the magnetic field satisfies Helmholtz equation.

$$\nabla^2\phi + k^2\phi = 0 \qquad (1)$$

k is propagation number given by $k=2\pi/\lambda$ where λ is the wavelength in the material.

Equation (1) is rewritten by using Green function as

$$\phi(x) = \oint_S \left(G\phi^* - G^*\phi\right)dS \ . \qquad (2)$$

S represents the closed surface surrounding the point x and * denotes differential operation along the normal direction at each point on S. G is a Green function given as follows.

2-dimension: $$G = \frac{i}{4} H_0^{(1)}(kr), \qquad (3)$$

3-dimension: $$G = \frac{e^{ikr}}{4\pi r}, \qquad (4)$$

where $H_0^{(1)}$ denotes 0 th order Hankel function. The discretization is performed by the boundary element method because of the small number of the elements and the simple procedure of mesh generation. The following studies were achieved by 2-dimensional analysis.

III. Analysis of micro-lens focus condition and IT-CCD sensitivity and smear characteristics

1) Micro-lens focus condition analysis

The focus condition of micro-lens is studied by 2-dimensional wave analysis. Fig. 1 shows the structure, which is constructed by air and the lens material of which refractive index is set to 2.0. In the figure, a and r denote the aperture and radius of the micro-lens, respectively. The incident light is parallel to Z-axis and its wavelength λ is 550 nm. Fig. 2 shows the 2-dimensional intensity distribution of two kind of the small aperture (a = 4.4 μm = 8 λ) micro-lens whose radius are 2.2 μm (= a/2) and 4.4 μm (= a). There is large difference around the focus region between the two structures. Fig. 3 shows the intensity distribution of large (a = 64 λ) and small (a = 8 λ) aperture size lens along depth direction at the lens center. In the former case, the peak intensity scarcely affected by lens radius hence the focus region is well concentrated. On the other hand in the latter case, the peak intensity is decreased and the focus region is stretched to Z-axis direction with increase of the lens radius. These characteristics cannot be obtained by the ray tracing.

2) Sensitivity and smear analysis of IT-CCD

The sensitivity and smear characteristics is studied in IT-CCD with 5 μm horizontal pixel size, which corresponds to 1/4 inch 380K pixel IT-CCD. Fig. 4 shows the cell structure, where the periodic boundary condition is assumed. N-type substrate, P-well, buried photo-diode, poly-silicon gate, Aluminum light-shield, and micro-lens are involved in the device. L an d denote the aperture length of the light-shield and the distance between the light-shield and the silicon surface, respectively.

The smear dependence on L and d is investigated in the case without micro-lens. The incident light is parallel to Z-axis and the wavelength λ is set to 400, 550 and 700 nm. Fig. 5 shows smear dependence on L and d at the wavelength of (a) 400, (b) 550 and (c) 700 nm. Comparing (a), (b) and (c), it is found that the smear dependence on L and d is smaller in longer wavelength case. It can be explained by that the major origin of smear is

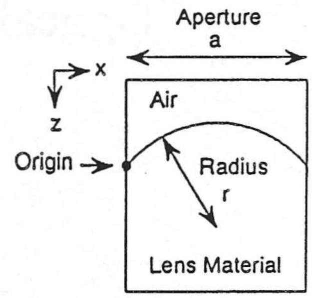


Fig. 1. Structure for the micro-lens focus condition analysis.

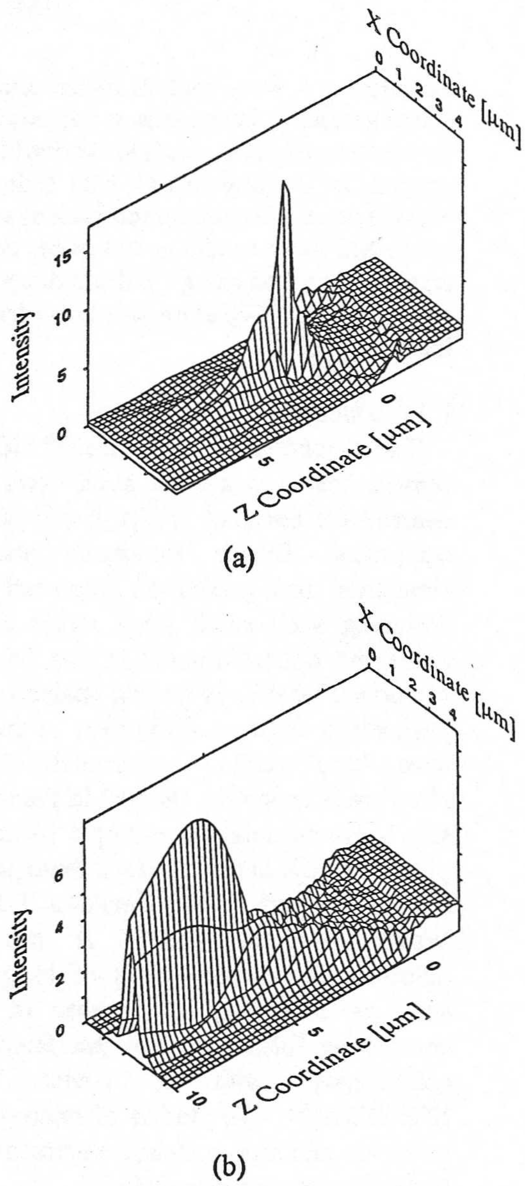


Fig. 2. Light intensity distribution
(λ = 550 nm, a = 4.4 μm)
(a) r = 0.5 a = 2.2 μm, (b) r = a = 4.4 μm

diffraction at long wavelength, and the wave propagation between the light shield and silicon surface at short wavelength. Because the absorption coefficient of light in silicon is smaller and diffraction phenomenon is more remarkable at longer wavelength.

The sensitivity and smear dependence on incident light angle θ and micro-lens focal length f are analyzed in the structure with micro-lens. Fig. 6 and 7 show the sensitivity and smear dependence on θ and f. It is found that the sensitivity and smear of longer focal length structures are more sensitive to the incident angle variations. Because the focal point lateral shift caused by the oblique incident light is larger in the longer focal length structure. It is also found that the smear dependence on θ is not symmetric as shown in Fig. 7. It is derived from the asymmetry of the impurity profile in the silicon substrate.

IV. Conclusion

An optical simulator based on wave optics was developed. It can treat the wave phenomena such as interference or diffraction, and analyze optoelectrical characteristics such as sensitivity and smear in the combination with SPECTRA. The focus condition of micro-lens and sensitivity and smear of IT-CCD were studied by this method. It was found that the focus region is stretched along the depth direction in the small aperture size micro-lens and the major origin of smear is different between blue and red incident light.

References

[1] H. Mutoh et al., "A 2/3 inch 800k Pixel Color Image Sensor," ITEJ Technical Report, vol. 13, No. 11, pp. 73-78, TEBS '89-13, ED '89-17, Feb. 1989.

[2] H. Mutoh, "Simulation for 3-dimensional optical and electrical analysis of CCD," Proceeding of 1995 IEEE Workshop on CCDs and AIS, 1995.

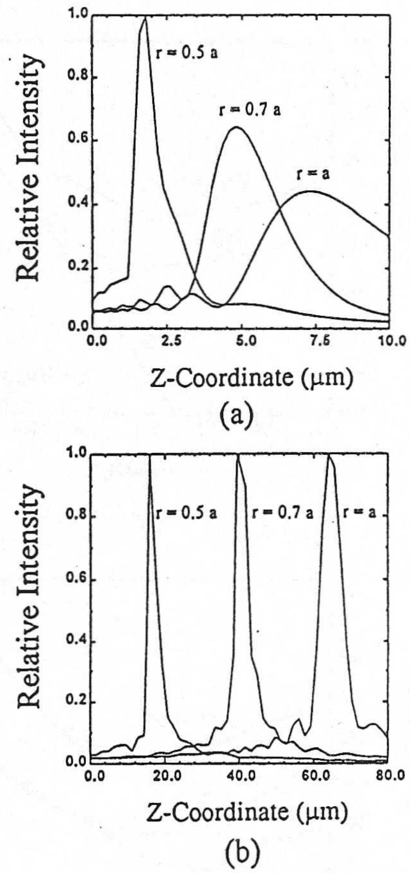


Fig. 3. Relative light intensity along Z axis at the center of the structures with lens radius r = 0.5 a, 0.7 a, and a. ($\lambda = 550$ nm) (a) $a = 8\lambda = 4.4$ μm, (b) $a = 64\lambda = 4.4$ μm

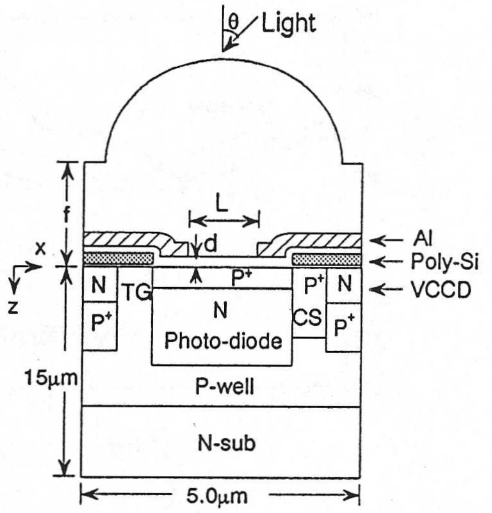
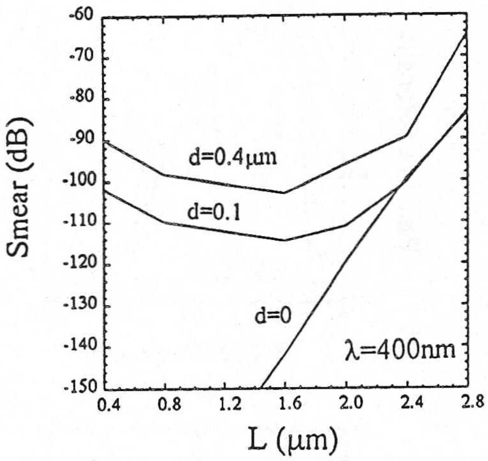
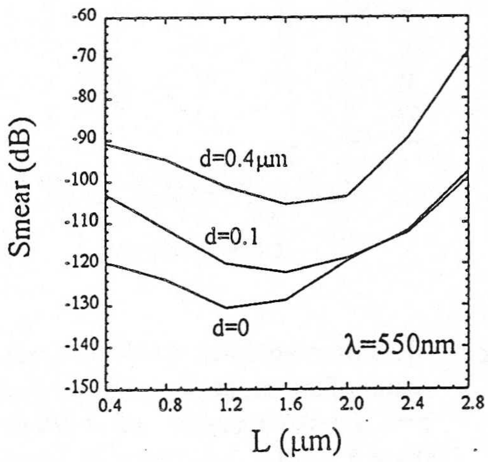


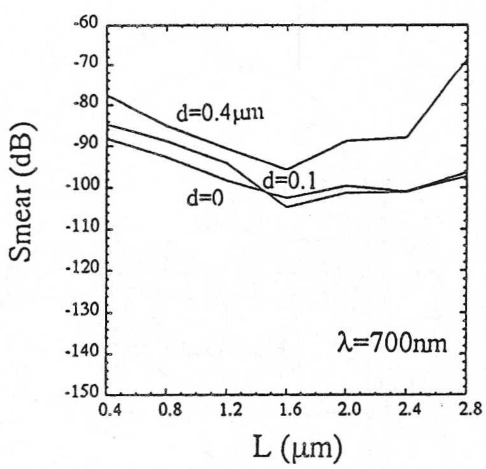
Fig. 4. Device structure for the sensitivity and smear analysis of IT-CCD.



(a)



(b)



(c)

Fig. 5. Smear dependence on the aperture length L and oxide thickness d (without micro-lens). (a) $\lambda = 400$ nm, (b) $\lambda = 550$ nm, (c) $\lambda = 700$ nm.

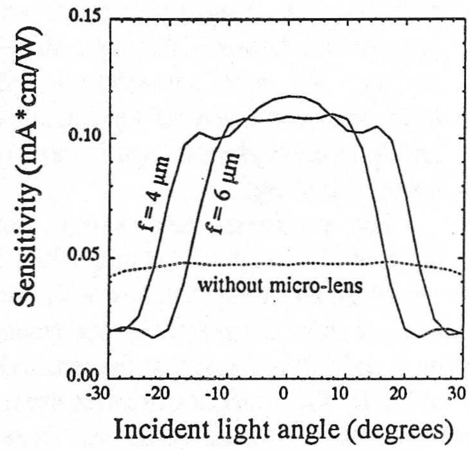


Fig. 6. Sensitivity dependence on incident light angle θ and micro-lens focal length f. ($\lambda = 550$ nm, $L = 1.6$ μm, $d = 0.2$ μm)

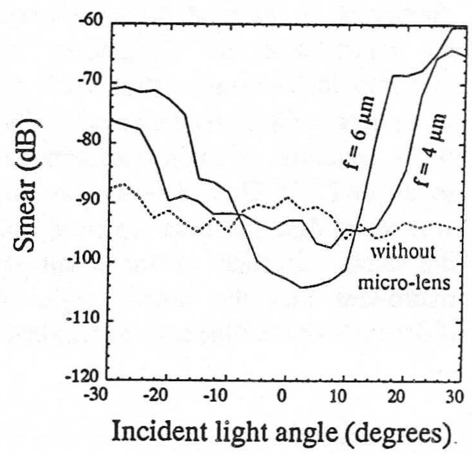


Fig. 7. Smear dependence on incident light angle θ and micro-lens focal length f. ($\lambda = 550$ nm, $L = 1.6$ μm, $d = 0.2$ μm)