A Low Noise and High Sensitivity Image Sensor with Imaging and Phase-Difference Detection AF in All Pixels

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Abstract In this paper, we describe a device structure and optical design for a CMOS image sensor with phase-difference detection photodiodes (PD) for autofocus (AF) function. The individual pixel of this image sensor is composed of two horizontally displaced PDs separated by a PN junction. All the effective pixels function as both the imaging and the phase-difference detection AF (PDAF). We have realized a low dark random noise (1.8e- at 1PD, 2.5e- at 1pixel) and high sensitivity (78Kε-1lx.sec at 1green pixel) image sensor with the imaging and the PDAF functions in all the effective pixels.

Keywords: CMOS image sensor, phase-difference detection AF (PDAF), image plane PDAF, separated photodiodes, PN junction separation.

1. Introduction

Recently, image sensors with the PDAF function at image plane has been developed 1), 2). These image sensors realize the AF function by arranging exclusive pixels to detect the phase-difference. In these image sensors, a pair of partially light shielded PD is arranged in a part of pixel array. The focusing speed is extremely fast in comparison with conventional contrast detection AF. The sensitivity, however, is degraded by the light shielding structure and interpolation processing by neighboring pixels is necessary for image generation 2). Therefore, the number of pixels for AF function is limited to avoid the deterioration of image quality.

In this work, we developed an image sensor with the imaging and the PDAF functions in all the effective pixels without exclusive pixel for AF function. All the effective pixels have two PDs each to detect phase-difference in one pixel without partially light shielding structure. Therefore, one pixel works as one AF point, and the sum of two PD outputs equals one pixel output.

2. Principle of PDAF

Fig. 1 shows the principle of the PDAF function. Exit pupil of a taking lens and a PD of the image sensor are in optically conjugate relation by on-chip micro-lens (ML). Therefore, each pixel by separating into two PDs

![Fig. 1 Principle of the PDAF function.](image-url)
has the pupil split function for the PDAF function. A light flux which passes through a right half of the taking lens is led to the PD-A (the PD at left side) and which passes through a left half of the taking lens is led to the PD-B (the PD at right side).

Defocusing amount is calculated from distance between the peak of the image-A (the image provided from PD-A group) and the peak of the image-B (the image provided from PD-B group).

The direction of the peak shift of the image-A and image-B is opposite between the front focus state and the back focus state.

These mean that in the camera system the taking lens is driven to a just focus instantly by calculated defocusing amount and the direction.

3. Pixel Architecture

Fig. 2 shows the schematic view of 2 x 2 pixels. One pixel consists of two sub-pixels, and has one on-chip ML and one color-filter (CF) each. One sub-pixel consists of one PD, one floating diffusion (FD), four transistors for one signal output and one column signal line (CSL), thus one pixel consists of two PDs, eight transistors and two CSLs. A pair of sub-pixel is symmetrically arranged left and right. To achieve high frame rate and readout speed, a different CSL is assigned to first row of the pixels and second row of the pixel each and four CSLs of two rows are driven simultaneously.

In case of this image sensor, the signal of PD-A and PD-B are read out separately for PDAF processing and these signals are added outside of the image sensor for imaging.

Fig. 3 shows the top view diagram of the pixels and Fig. 4 shows the cross section diagram of the PDs, respectively. The PD-A and the PD-B are separated by a PN junction. The PN junction separation does not consist of the insulating materials (e.g. SiO₂). By using the PN junction separation, non-sensitive area is minimized, light reflection at Si/SiO₂ boundary is reduced and defects at Si/SiO₂ interface is decreased. It is reported that band-gap shrinkage at Si/SiO₂ interface causes dark current and defects increase. In contrast, the pixel readout circuits are separated by the Shallow Trench Isolation (STI).

The photodiode area is decrease by addition of the separation region. On the other hand, the depletion of photodiode is promoted by the separation region. Therefore, the saturation level is compensated by increasing the concentration of PDs. As a result, the saturation level is approximately equal with the single photodiode.

In addition, an impurity concentration of the p-type region for the PN junction separation is lower than that of the surface region forming the pinned PD. Therefore, recombination rate in the p-type impurity of the separation region is low, and the loss of the incident light is minimized. The incident light is divided into PD-A and PD-B, as a result, low noise and high sensitivity image sensor is realized.
4. Optical Design

We performed a three-dimensional finite difference time domain (FDTD) optical simulation and a transient analysis device simulation to determine the curvature of the on-chip ML. We fixed ML height in 2.5µm and simulated the radius of curvature (RC) was from 3.3µm to 5.3µm.

Fig. 5 shows the representative simulation results (RC=3.3µm, 4.3µm, 5.3µm, respectively), the simulated RC dependence of the light intensity profiles for perpendicular green incident light (λ=550nm) to the image sensor surface, superimposed on the image sensor structure diagram. A red color means that the light intensity is strong. The condensing position of the incident light changes depending on the RC.

Fig. 5 also shows the incident light angle dependence of the quantum efficiencies (QE) of PD-A, PD-B and the sum of the two PDs. In the case (b) (RC=4.3µm), the simulated QE of a two PDs' summation is 59.5%, higher than the case (a) (RC=3.3µm) 51.6% and the case (c) (RC=5.3µm) 55.1%. By adding signals of two separated PDs, the sensitivity had no 'dimple' around 0 degrees and equivalent to that of one PD structure. Hence, the non-sensitivity region around the PD separation region is minimized.

The bottommost figure in Fig. 5 shows the incident light angle dependence of the QE ratio of PD-A to PD-B in the positive angle region and ratio of PD-B to PD-A in the negative angle region.
The angle range below the ratio of 0.2 is compared in three cases. In the case (b), the angle range is 25 degrees. The range is wider than the case (a) 21 degrees and the case (c) 24 degrees. The wider range means the image-A and the image-B can be separated at wider range of the incident light angle, and the AF performance is improved.

Similarly, the angle range above the ratio of 0.2 near 0 degrees is compared. In the case (b), the angle range is 9 degrees. The range is narrower than the case of (a) 10 degrees and the case of (c) 15 degrees. The narrower range near 0 degrees means the separation of image-A and the image-B is better at larger F-number (=smaller aperture) (Fig. 6).

Fig. 6 shows the aperture size dependence of image-A and image-B at front focus state. The incident light angle range at the small aperture (b) is narrower than at the large aperture (a). Even if the defocus amount of taking lens is the same, the distance between the peak of the image-A and the peak of the image-B differ with the aperture size (= F-number).

To realize both high sensitivity and high AF performance in the design of two PDs and one ML with the PDAF function, the accurate simulation of the height, the curvature, the shape of the ML and incident light angle dependence is required.

Table 1 summarizes the simulation results.

<table>
<thead>
<tr>
<th>ML</th>
<th>Height</th>
<th>2.5 µm</th>
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<tbody>
<tr>
<td></td>
<td>Radius of Curvature</td>
<td>3.3 µm</td>
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| Quantum Efficiency | 51.6% | 56.9% | 58.5% | 59.5% | 59.3% | 57.1% | 55.1% |
| Angle Range (Ratio=0.2, at Near 0 deg) | 10 deg. | 9 deg. | 9 deg. | 9 deg. | 10 deg. | 11 deg. | 15 deg. |
| Angle Range (Ratio=0.2, at Large Angle) | 21 deg. | 23 deg. | 25 deg. | 25 deg. | 26 deg. | 25 deg. | 24 deg. |

Table 1: Summarized simulation results.

Fig. 7 shows the measurement results of the image sensor in a condition of RC=4.3µm.

5. Results and Summary

Fig. 7 shows the measurement results of the
fabricated image sensor. The solid line shows measurement results and the dotted line shows simulation results, and the vertical axis is normalized. The both results are approximately equal, and the angle range above the ratio of 0.2 near 0 degrees is about 9 degrees.

Table 2 summarizes the specifications and performances of this image sensor. Fabrication process is 0.18µm 1Poly 4Metal CMOS process. Optical format is super 35mm. Pixel size is 6.4 µm x 6.4 µm. Number of effective pixels and the PDAF points are both 9.2M. Number of effective PDs is 18.5M. Full well capacity is 40Ke- (@one pixel = two PDs). Sensitivity is 78Ke-/lx.s (@2,856K light source with IR-cut-filter, one green pixel). Dark current is 50e- at one PD and 2.5e- at one pixel (@gain=32, RT). Dark current is 50e- at one pixel (@60C, one second). Maximum frame rate is 60fps with full pixel readout.

The effective AF area is 80% (H) x 80% (V) of effective pixels to guarantee accuracy of PDAF. AF speed is 4 times faster than conventional contrast AF.

Fig. 8 shows the photograph of packaged image sensor. Chip size is 29.9mm (H) x 21.6mm (V).

High grade and high speed imaging has been achieved by the low noise and high sensitivity image sensor with imaging and phase-difference detection AF in all effective pixels.

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