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Tilted deep trench isolation structure to increase quantum efficiency of a CMOS image sensor at the corner of an image sensor

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***Abstract---*We attempted to maximize Quantum Efficiency (QE) in CMOS Image Sensor (CIS) which is used in image sensor chips. In the Finite Differential Time Domain (FDTD) simulation, we shifted Color Filter (CF) and Micro Lens (ML), and tilted Deep-Trench-Isolation (DTI). We increased QE 3.80 %p in red, 4.70 %p in green, 0.30 %p in blue, and 2.70 %p in white. Also we decreased crosstalk (X-talk) 0.05 %p in red, 0.20 %p in green, and 0.10 %p in blue.** **The tilted DTI CIS can get clearer images than the shifted CIS at the corner of an image sensor chip.**

**Index Terms---CMOS Image Sensor (CIS), deep trench isolation (DTI)**

1. Introduction

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MOS Image Sensor (CIS) is used to camera image sensor. CIS has low power consumption and high readout speeds than Charge Coupled Device (CCD) on smartphone and digital camera [1]. However, CIS has low Quantum Efficiency (QE) and crosstalk (X-talk) ratio than CCD [2]. Therefore, we should increase QE of CIS. Usually, QE was varied by CIS structure. Several structure already introduced [3] [4] [5].

Also, QE vary among the distance from center of an image sensor. At the corner of an image sensor, the light propagate obliquely [6]. Therefore, the light was detected little than the center of an image sensor because of scattering. Different QE detection on the same image sensor causes irregular brightness or resolution in an image. One solution is to shift the ML and CF of CIS; this change causes the light to spread smoothly to the detection region. However, a shifted CIS still has low QE and high X-talk than normal CIS.

The tilting angle of Deep-Trench-Isolation (DTI) affects QE. Therefore, a tilted DTI CIS which can increase QE than shifted CIS. The tilted DTI CIS structure optimized by Finite-Differential Time Domain (FDTD) simulation with varying horizontality shifting distance of Micro Lens (ML), Color Filter (CF) and tilted angle of DTI.

1. Materials and Methods

*d*1

*d*2



oblique plane source ( )

Color Filter

Micro Lens

DTI

Photo Detector

Fig. 1. CIS Diagram

The ML is composed of SiO2. The ML focus light on CIS. The CF is composed of the materials which have high transmittance at one of the red, green, blue and white light. The CF serves to filter the light of the desired wavelength range. DTI is composed of SiO2. The DTI is composed of SiO2. The DTI blocks light from neighbor CISs and prevents leakage of internal light (Fig. 1).

The CIS was simulated by FDTD simulation (Lumerical Inc.) The program allows specification of material properties. We obtained the raw data by the square detector region composed of four monitors (top, left, right and bottom) which get transmittance (T). We used 4ⅹ16 CPU cluster to run the program and can simulate the CIS in 2-dimensional space because of symmetry.

We conducted three simulations, First, simulate the basic structure of a CIS on which light is shone in the normal direction. Second, we simulated the CIS in which the ML and the CF were shifted. We shifted the ML by *d*1 [nm] with 10-nm increments from 450-nm to 550-nm, and shifted the CF by *d*2 [nm] with 10-nm increments from 200-nm to 300-nm. Lastly, we simulated the CIS in which the DTI was tilted. We tilted the DTI by with 0.5 step from to . Our purpose to make the CIS with tilting DTI have almost the same QE as the CIS that has basic structure. We plotted the power flows to determine the effect of tilting the DTI, and to show how the light move into the detector.

Our goal is to find the optimal setting for *d*1, *d*2, and to maximize QE and minimize X-talk. If the top monitor is *T*1, the left monitor is *T*2, the right monitor is *T*3, and the bottom monitor is *T*4. Then

(1)

for all frequency spectra. To calculate the QE of each pixel, in each frequency band, we took an average value of them: QEred is the average from 590-nm to 650-nm, QEgreen is the average from 500-nm to 560-nm, and QEblue is the average from 420-nm to 480-nm. X-talk can be calculated as

(2)

(3)

(4)

When a QE increase, X-talk also increase. Therefore, we should choose the point which has proper QE and X-talk. In academia, the objective standard does not exist, so we suggest the point in our standard.

1. Result

The simulation was conducted on three structures: *d*1 was varied from 450 to 550 nm, *d*2 was varied from 200 to 300 nm, and was varied from 0.5 ° to 6 °. The tilted DTI CIS’ QE and X-talk had negative and positive quadratic relationships respectively with in the region.



Fig. 2. QE on d2 vs. d1 in the shifted CIS.

The shifted CIS was optimized at *d*1 = 510 nm and *d*2 = 230 nm (Fig. 2). A tradeoff occurred between high QE and low X-talk. The X-talk varied < 1%. Therefore, QE was given more weight than X-talk.



Fig. 3. QE vs. angle in tilted DTI CIS. Filled circle: red, Unfilled circle: green, Square: blue, Diamond: white.

The tilted DTI CIS was optimized at (Fig. 2). We find the point at which QE is maximum and X-talk is minimum. The X-talk looks constant because it varied < 1%. Therefore, we focus finding at which QE is maximum.



Fig. 4. QE on d2 vs. d1 in the tilted DTI CIS at .

The tilted DTI CIS was optimized at *d*1 = 510 nm, *d*2 = 230 nm, and (Fig. 3). We fixed for find the optimized *d*1 and *d*2.

Table 1. QE and X-talk of CF for three different CIS

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **CIS Structure** | | | | | | |
|  | **CF** |  | **Base** |  | **Shifted** |  | **Tilted DTI** |  | **Increment** |
| **QE [%]** | **R** |  | 58.2 |  | 44.5 |  | 48.3 |  | 3.80 |
| **G** |  | 68.0 |  | 59.0 |  | 63.7 |  | 4.70 |
| **B** |  | 61.6 |  | 59.3 |  | 59.6 |  | 0.30 |
| **W** |  | 66.4 |  | 55.2 |  | 57.9 |  | 2.70 |
|  |  |  |  |  |  |  |  |  |  |
| **X-talk [%]** | **R** |  | 1.96 |  | 2.88 |  | 2.83 |  | -0.05 |
| **G** |  | 31.7 |  | 31.6 |  | 31.4 |  | -0.20 |
| **B** |  | 12.7 |  | 13.6 |  | 13.5 |  | -0.10 |

In the tilted DIT CIS, QE of all four CFs increased compared to the shifted CIS (Table 1). Also, the X-talk decreased to < 0.2%.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 5. Power flow of the shifted CIS and the tilted DTI CIS. (a) red, (c) green, and (e) blue pixel of the shifted CIS. Also, (b) red, (d) green, and (f) blue pixel of the tilted DTI CIS.

The DTI caused the light to move to the center of the CIS which is the photo-detector region (Fig. 5). In a tilted DTI CIS, more light can be detected than in the shifted CIS. Also, the tilted design prevented the light leakage more than the shifted CIS did.

1. Discussion

The main challenge in use of a CIS is to increase QE and decrease X-talk to get a clear image. The position of CIS on an image sensor have important influences on uniform QE and X-talk. If we measure the QE and X-talk on the center and the side of an image sensor, values will be different because of a camera lens (Fig. 6). The light propagates normally to the center of the image sensor, but the light propagate obliquely to the side of the image sensor. Therefore, QE decreases and X-talk increases with distance from the center of a chip. One solution is to shift the CIS; this change causes the light to spread smoothly to the Photo Detector (PD) region (Fig. 5). However, this solution still has low QE and high X-talk. To solve this problem, we simulated the tilted DTI CIS.

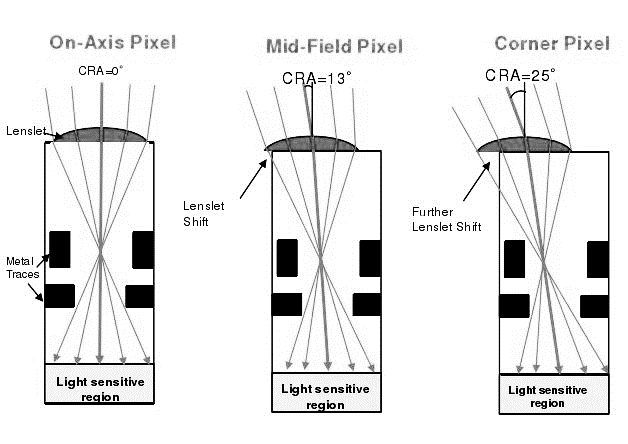


Fig. 6. Lay optics of a chip with distance from the center [6].

We increased QE 3.80 %p in red, 4.70 %p in green, 0.30 %p in blue, and 2.70 %p in white. Also we decreased X-talk 0.05 %p in red, 0.20 %p in green, and 0.10 %p in blue (Table 1). If we can more focus the light on PD region, QE will be further increased. We can use the tilted DTI CIS on the side of CMOS chip. However, the tilted DTI CIS needs more test about other effects: circuit effect (ex. dark current) and fabrication process for using this CIS structure in real product.

We decreased X-talk. However, decrements were less (<0.2%) than our goal because the transmittance of the DTI (related to spatial X-talk) and the CF (related to spectral X-talk) did not change. This small change means that the source of the X-talk did not change. Therefore, we should change the DTI’s material and the CF material. However, material design is not only optics work. For example, an air gap is a best material for the DTI. However, implementation of air is almost impossible in fabrication with present technology.

The tilted DTI cannot be manufactured. However, our results demonstrate that material of DTI and CF must be changed to increase QE and decrease X-talk.

We designed a DTI tilt 0.9-µm CIS. We shifted ML by *d*1 and CF by d2, and tilt DTI by . We performed FDTD simulation of the tilted DTI CIS. The optimal setting is *d*1 = 510 nm, *d*2 = 230 nm, and . The tilted DTI CIS has higher QE 3.80 %p in red, 4.70 %p in green, 0.30 %p in blue, and 2.70 %p in white than the shifted CIS. Also, X-talk decreased 0.05 %p in red, 0.20 %p in green, and 0.10 %p in blue, but it is less (< 0.2%) than desired we want. The tilted DTI CIS can get clearer images than the shifted CIS when incident light is oblique.

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