Pixel Technology for Improving IR Quantum Efficiency of Backside-illuminated CMOS Image Sensor

Jonghoon Park[1], Yunki Lee[1], Bumsuk Kim[1], Bomi Kim[1], Junsung Park[1], Eunju Yeom[1], Yunji Jung[1], Taehan Kim[1], Hansik Yoon[2], Yongho Kim[2], Jinsu Park[2], Chang-Rok Moon[1], and Yongin Park[1]

[1]System LSI Division, Samsung Electronics Co., Ltd, [2]Foundry Division, Samsung Electronics Co., Ltd. Yongin-city, Gyeonggi-do, Korea. TEL:+82-31-209-1602, e-mail:jhoon14.park@samsung.com

Abstract

In this paper, we present CMOS image sensor containing suitable pixel structure for IR light harvesting. In order to enhance the IR sensitivity, several pixel process technologies have been applied such as silicon thickness increment, anti-reflecting layer (ARL) modification, and introduction of backside scattering technology (BST). The effect of each technology on the infra-red quantum efficiency (IRQE) of image sensor has been demonstrated. The BST patterns were formed at silicon surface for the light scattering effect. In order to investigate the effect of light scattering, the quantum efficiencies and the optical crosstalk between the neighboring pixels based on various BST shapes were measured. By using the above technologies, IRQE of the image sensor has dramatically increased up to 43% at 940nm wavelength, which is nearly 400% enhancement compared to the conventional image sensor.

Introduction

Recently, according to the demand of image sensor applications such as iris scanner, security camera and Time-of-Flight (ToF) sensor, the importance of the light sensing ability at near infra-red (IR) range has raised a lot. However, the IR sensitivity of conventional image sensor is insufficient for such applications. To enhance the IR sensing ability, appropriate pixel structure is needed. In this paper, we have developed CMOS image sensor containing optimized pixel structure for effective IR light harvesting. For the development of IR sensor, we utilized 2.1um backside-illuminated image sensor containing deep trench isolation (DTI) [1][2][3] and micro-lens arrays [4].

Results and discussion

The conventional pixel structure of back-side illumination (BSI) image sensor and the concept of pixel design for IRQE enhancement are described in Figure 1.

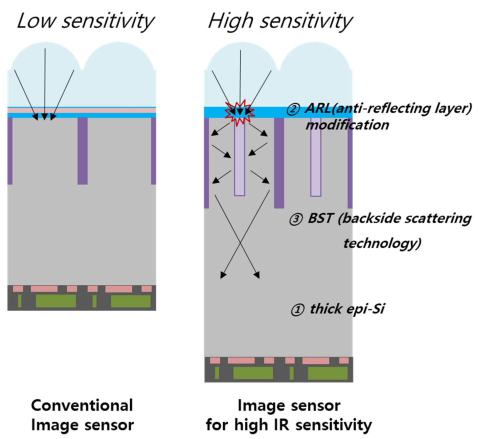

Figure 1. Schematic images of design concept for image sensor having IR sensitivity

For the conventional BSI pixel, an epitaxial silicon (Si) layer which contains the photodiodes is located above the metal-lines and transistors. [5] Due to the Si band gap energy of ~1.1eV, the photodiodes based on Si can absorb light effectively at the wavelength range of 400-1100nm. Between the photodiodes, deep trench isolation (DTI) is existed in order to suppress the optical/electrical crosstalk [1] and on the surface of Si, anti-reflection layer (ARL) which consists of various transparent oxide layers are deposited for the transmittance enhancement and dark current suppression. [6] Finally, planarization layer and micro-lens based on organic materials are formed on the top of the photodiodes and oxide layers. [4] Based on the BSI pixel structure, several pixel process technologies are applied for the IR light harvesting improvement such as (1) increase of the silicon thickness for effective light absorption, (2) anti-reflecting layer (ARL) modification for enhancing transmittance at IR region, and (3) introduction of backside scattering technology (BST) for light scattering effect at the surface of silicon.

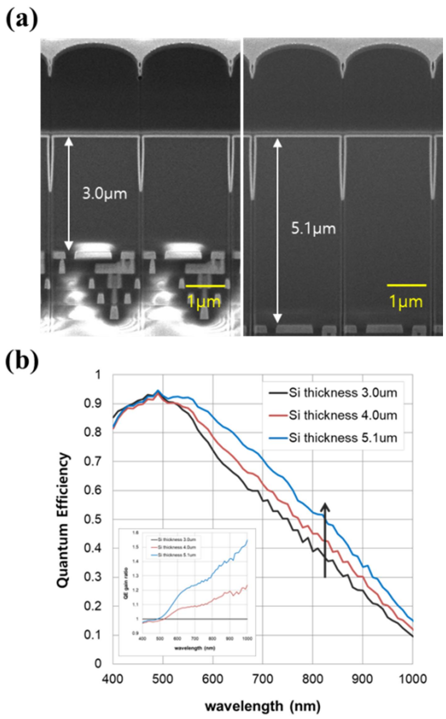

Figure 2. (a) Cross-sectional scanning electron microscope (SEM) of backside-illuminated CMOS image sensor pixel with silicon thickness of 3.0μm and 5.1μm. (b) QE curves of image sensors as increment of silicon thickness.

First, the effect of silicon thickness has been demonstrated. Figure 2a shows the cross-sectional scanning electron microscope (SEM) image of BSI image sensor with the Si thickness of 3.0μm and 5.1μm. As the Si thickness increased, the quantum efficiency (QE) increased at relatively long wavelength range over 600nm, as shown in Figure 2b. The insert graph in Fig. 2b indicates the QE gain ratio of increased Si thickness (4.0μm, 5.1μm) compared to the 3.0μm at the range of 400-1000nm. As shown in the graph, the QE of 5.1μm increased by nearly 40% Si at near-IR wavelength of 940nm compared to that of 3.0μm Si.

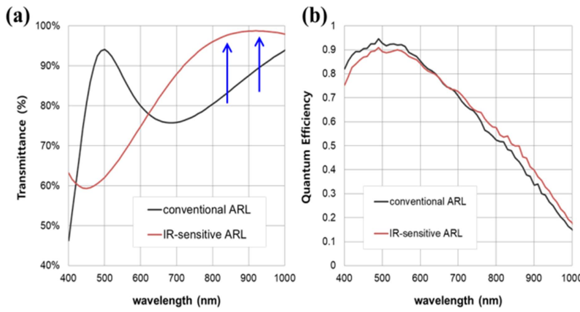

Figure 3. (a) Transmittance of conventional (for visible) and modified (for IR) anti-reflecting layer (ARL). (b) QE curves of image sensors with conventional and modified ARL.

Second, the effect of ARL modification has been investigated. The transmittance of ARL, which strongly affects the QE of image sensor, is determined by the refractive index and the thickness of composition oxide layers. Thus, by modifying material or thickness of the composition layers, the transmittance can be changed as shown in Figure 3. Figure 3a depicts the transmittance of ARL which is suitable for visible (black line, conventional) and IR (red line) wavelength range. For conventional image sensor, the transmittance showed high value at visible range and relatively low value at IR range. By modifying the composition and thickness of ARL, the transmittance had successfully optimized to IR range and increased from 90% to 98% at 940nm. As a result, the IRQE increased by approximately 4.5% at 940nm using IR-sensitive ARL as indicated in Figure 3b.

The light scattering effect on IRQE has been also determined. In order to investigate the light scattering effect, backside scattering technology (BST) patterns were formed at the Si surface. Figure 4 shows the cross-sectional and top-view SEM images of the pixel structure containing BST patterns. For effective light scattering, the BST patterns were developed at the center of the pixel, where the beam is focused by micro-lens.

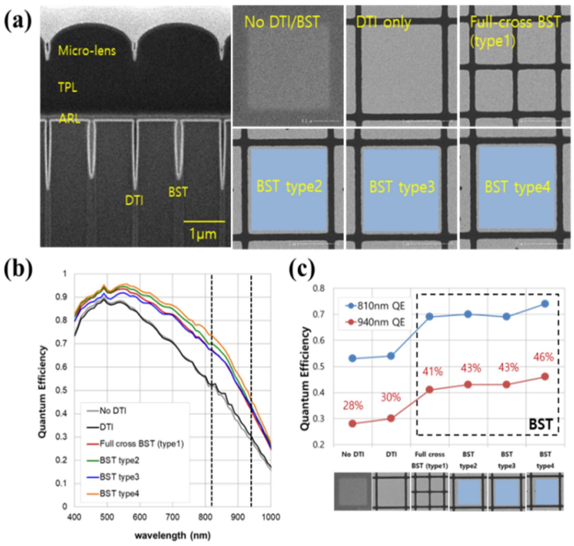

Figure 4. (a) Cross-sectional and top-view SEM images of the pixel structure which consists of backside scattering technology (BST) patterns. (b) QE curves of image sensors with no DTI, only DTI and DTI+BST pixel structures. (c) Quantum efficiencies of image sensors with various DTI and BST patterns at 810nm and 940nm wavelength.

The BST pattern dramatically enhanced the IR light harvesting of the pixel. At the same Si thickness of 5.1μm, the IRQE increased from 30% to 42~46% at 940nm wavelength by introduction of the BST patterns as shown in Figure 4b and 4c. The average QE of 43% at 940nm is one of the highest IRQE performed by CMOS image sensor so far. [7] Furthermore, various shapes were demonstrated in order to find the most suitable pattern for IR sensing. Approximately 5% of IRQE difference showed according to the BST shapes: 41% for full-cross BST (type1), 43% for BST type 2/3 and 46% for BST type 4, respectively. The enhancement of IR sensitivity can be explained by the increase of effective Si thickness due to the light scattering at BST patterns and DTI that guided along the photodiodes. [8] As the light induce to BST pattern, light scattering and reflection occur by the BST and DTI due to their lower refractive index compared to that of Si. As a result, the light path in Si increases which indicates the increment of effective Si thickness and improvement of light absorption. In addition, the introduction of BST pattern not only increase the IRQE, but visible-range QE as well, which reveals that the light scattering and BST also could be applied for developing highly sensitive conventional color image sensor.

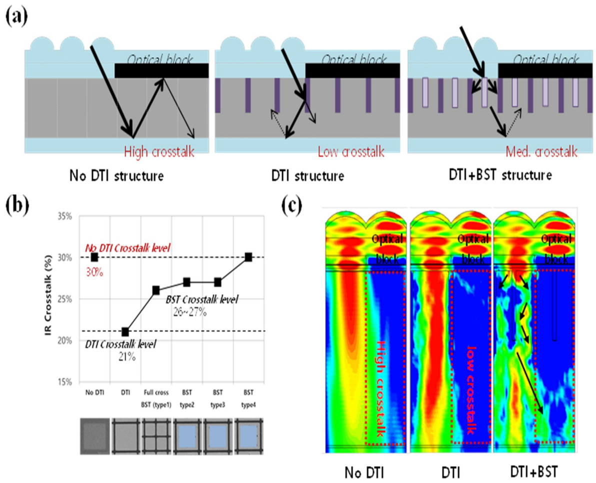

Figure 5. (a) Schematic images of optically blocked pixel array region generated on the sensor for the measurement of optical crosstalk of various types of pixel structure during light emission. (b) Measured IR crosstalk of image sensors with no DTI, only DTI and DTI+BST pixel structures. (c) IR beam profile images of image sensors using 3-D optical simulation tool.

On the other hand, the scattered light from BST patterns could induce the optical crosstalk between neighboring pixels. Therefore, the effect on both quantum efficiency and crosstalk should be investigated in order to identify the effect of BST and find the most suitable structure. For the investigation, optically blocked pixel array region was generated on the sensor to measure the optical crosstalk during light emission. Figure 5a depicts the schematic images of optically blocked pixel arrays generated on the active pixel region of image sensor. By generating the optically blocked region, the relative crosstalk level of each pixel structures was successfully quantified. As shown in Figure 5b, no DTI pixel structure showed relatively high crosstalk of 30% and pixel structure with DTI showed low crosstalk level of 21%, owing to the preference of fence to prevent the optical crosstalk. Pixel structure with BST type 1/2/3 showed crosstalk level of 26~27%, which is larger than that of DTI structure due to the scattered light but better compared to that of no DTI structure. This result induced from the experiment corresponds well with the finite difference time domain (FDTD) optical simulation results as demonstrated in Figure 5c. Interesting thing is that BST type 4 which performed the highest IRQE, showed high crosstalk of 30%, which is equivalent to the no DTI structure. This implies that the light scattering could enhance the QE but also cause a significant deterioration on crosstalk and the appropriate pixel structure should be determined taking into account both QE and crosstalk aspects. As a consequence, pixel structures with BST type 2/3 are most suitable for IR sensor in terms of both IRQE and IR crosstalk. Figure 6 shows the photographic image taken with conventional sensor (upper) and pixel technology-applied IR sensor (below). The photos were taken using 850nm-IR light source. The photo taken with IR sensor shows much brighter image compare to that of conventional sensor due to the enhanced IR sensitivity. Also, it seems that there is no significant image quality deterioration by the increased pixel crosstalk using IR sensor.

Conclusion

In summary, we successfully segmented and analyzed the factors that affecting the IR light harvesting ability of image sensor. The connection between IRQE and the pixel structure such as Si thickness, ARL on Si and BST was investigated. The enhancement of IRQE was shown as the modification of pixel structure, mainly due to the improved light absorption of Si by light scattering on BST patterns. The light scattering and reflection occurred by the BST and DTI resulting in the increase of light path in Si, which indicates the increment of effective Si thickness. The BST effect on the pixel crosstalk was also determined by developing optical block region in pixel arrays. It was found that the BST patterns improves the IRQE but also deteriorates the IR crosstalk, thus proper BST pattern is needed for the satisfaction of both IRQE and crosstalk. By optimizing the BST structure along with Si thickness and ARL, the IRQE dramatically improved, reaching up to 43% at 940nm wavelength. This was approximately 2.5 times higher than that of conventional pixel structure with Si thickness of 3.0µm. The image senor with high IR sensitivity gives the possibility that the image sensor can be applied to further applications which need IR sensing capability.

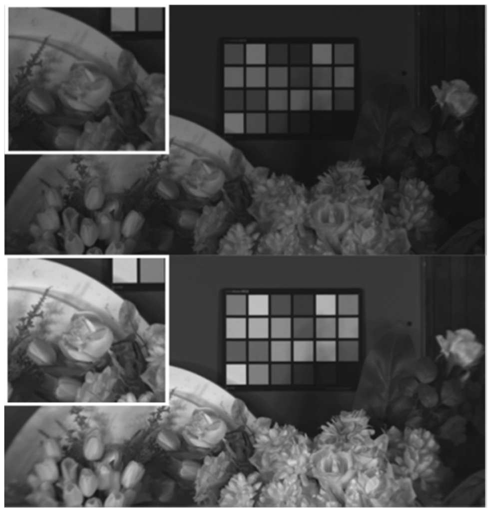

Figure 6. Photographic images taken by conventional image sensor (upper) and high IRQE image sensor (below) under 850nm-IR light illumination condition

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