A Study on Photon Effect to Image Plane

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Abstract : Most contemporary researches in low-light conditions are focused on analyzing pixel characteristics induced by thermal effects from power consumption in peripheral circuits. These thermal effects create a contour in constructed images and manifest as a shading-like phenomena represented by difference in each pixel data. In this work, we present an additional source of shading in a constructed image. We have observed that band-gap reference circuit in CMOS Image sensors creates a local hot-spot and shading in an image. Experiments were performed to identify the relationship between the local hot-spot and the displacement of the band-gap reference circuit. We assumed that certain amount of photons are generated in an indirect bandgap silicon when forward biased and reach the nearby photo-diodes in active pixel array to induce the local hot-spot in an image. Our assumption on photon generation was confirmed through reducing the forward bias current in band-gap reference PN junction diodes and implementing a metal sidewall in-between the band-gap reference and active pixel array. By taking these measures, we were able to remove the local hot spot and its shading effect in CMOS Image Sensors. Moreover, as we carried out extensive experiments to pinpoint the cause of the local hot-spot, we have also noted that implementing a deep n-well or other implant blocking layers does not remove the shading effect.

Keyword CIS, Photon, Image Shading, Band Gap Reference.

1. Introduction

It is very important to maintain a uniform image in dark or low light condition for image sensors. In most cases, dark shading is due to traditional dark characteristics of photo diode. This dark characteristics is worsened by increase in temperature and integration time. Thus, most studies are focused on improving this dark characteristics. Moreover, additional source of dark shading comes from the periphery circuit. Circuits with high power consumption or comparatively high current with small area cause spatial thermal deviation in photo diode array. Thus spatial image patterns can be observed through dark characteristics of photodiode or power metal routing in a given image sensor [Fig 1]. However, we have observed another source of dark shading. The newly observed phenomena is dependent on integration time but independent on temperature. This new observation is identified with very steep shading image that appears as a local hot-spot. This paper focuses on finding the root cause of this new phenomena and concludes with a solution that prevents the occurrence of the local hot-spot.

2. Photon generation and radiation in PN junction

As we investigated the entire peripheral circuit and its relationship to a local hot-spot, we found that Band-Gap Reference (BGR) circuit corresponds to the location of a hot-spot in the pixel array [Fig2, 3]. Magnitude of the hot-spot correlated with the distance of BGR circuit to the pixel array. The relationship between the local hot-spot and its distance to the peripheral BGR circuit has led to a hypothesis that the local hot-spot is generated by the forward biased PN Junction diode within the BGR circuit.

Light emission from silicon has long been observed in forward-biased and reverse-biased avalanche silicon PN junction [1]. A forward-biased silicon PN junction not only injects minority carriers into the silicon substrate but also generates photons through radiative recombination [2]. In order to confirm photon emission from silicon in CMOS Image Sensors, we hypothesized a photon emission path and experimented the validity by blocking the hypothesized emission path. Fig. 4 shows generic cross section of a BSI CMOS Image Sensor. Typical forward biased PN junction diodes in CMOS Image Sensors can be BJTs in a Band-Gap Reference circuit. Photons emitted from BJTs can traverse through the entire sensor by moving along the transparent oxide layer. While path1 in Fig.4 shows the emitted photon entering the active photo-diode region by metal reflections, path2 depicts photons reaching photo-diode region through BSI insulation layer. For path1, experiments were carried to block the emission path by creating a partitioning wall along the BJTs by using metal, via and poly layers. For path2, the assumed emission path were block by creating a cut in the insulation layer. However, the two experiments failed to remove the dark shading observed in captured images. Thus, path3 was hypothesized for photon emission, and experiments were carried to confirm the hypothesis.

Fig. 5 shows collector current with respect to the collector and emitter distance when constant current sink is applied at the emitter terminal. When the distance between emitter and collector is short, collector current in Fig. 5 is characterized by that of a generic BJT device. However, as the distance between the two terminals increases, collector current cannot be characterized by the ideal BJT current equation. The non-ideality in collector current can be attributed to photon generation in forward biased PN junction. Photons generated in forward bias PN junction radiates until they recombine at far distance.

It has been found that silicon allows transmission of near infrared photons through its medium [3]. Fig. 6 shows the transmissivity of silicon for photons with wavelengths between 300nm and 1500nm at thicknesses of 200um, 600um and 1000um.

$$\lambda = 1240 / Eg \text{ (um)} \quad (1)$$

Bandgap energy of silicon, denoted as Eg in equation (1), is 1.12eV, and thus wavelength of photons generated from silicon is 1100nm. As shown in Fig. 6 transmissivity of silicon for photons with wavelength of 1100nm is 50% such that photons generated from BJTs in analog circuits can radiate directly to photo-diodes in active pixels. Direct radiation of photons from BJT to active pixels can be observed from the dark shading image in Fig.3, which depicts generation of two local hot-spots originated from two separate BJTs in analog circuitry. Magnitude of a local hot-spot measured from SK hynix's CMOS Image Sensors and its dependency on the distance between BJTs and active pixels are plotted in Fig. 7. As shown in Fig. 7, magnitude of the hot spot is inversely proportional to the square root of distance between photon generating BJTs and photon absorbing active pixels.

In order to block the photo-radiation from BJTs to active pixels, a reflective metal wall was placed in-between the BJT region and active pixels. Fig. 9 shows the vertical view of the reflective metal wall. TSV (Trough Silicon Via) mask was used to fill the hole created between the photo-emission path with metal and blocked the photo-radiation from BJTs to active pixels successfully.

3. Experiment Result

Fig. 10 shows the dark image of a CMOS image sensor with the reflective metal wall inserted. Because photons generated from BJTs are blocked by the reflective metal wall, hot-spot observed in Fig. 2 is removed in Fig. 10. Range of pixel magnitude in a dark image is reduced from 63.83~67.5 to 63.5~64.84. This reduction in pixel magnitude range quantifies the reduction of local hot-spot by 2.30 code. Further reduction in pixel magnitude range can be achieved by enhancing the reflective metal wall. As shown in Fig. 8, reflective metal wall was planted up to the Shallow Trench Isolation (STI) layer such that small transparent slit exists along the emission path. This transparent slit may still cause local hot-spot if considerable amount of photons are generated from BJTs through increased collector current. If local hot-spot is not completely removed, additional steps must be taken to remove the open slit through the STI layer.

4. Conclusions

This paper outlined the cause of dark shading induced by a local hot-spot, which serves as a critical factor in generating a superb image quality in CMOS Image Sensors. Along with temperature and bias voltages, placing a photon-generating source near active pixels can cause the dark shading induced by a local hot-spot. It was hypothesized that BJTs in analog circuits may be the source of generated photons in CMOS Image Sensors, and the hypothesis was confirmed through planting a reflective side wall at the assumed emission path.

References

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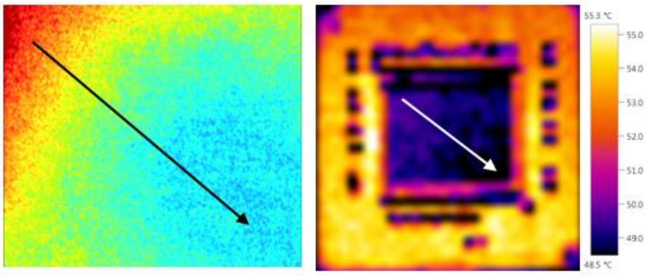

(a) (b)

Fig. 1 Temperature related image shading (a) image shading, (b) temperature shading (IR sensor image)

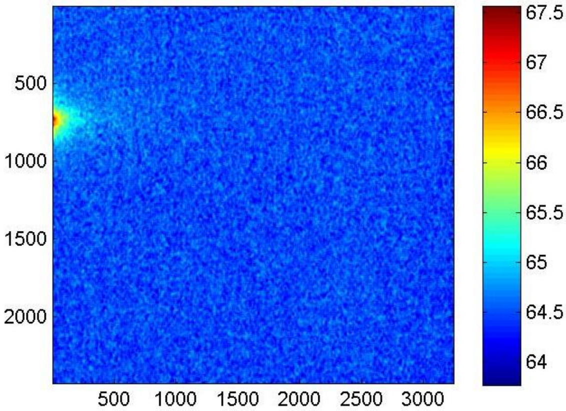

Fig. 2 BJT related abnormal dark hot spot image

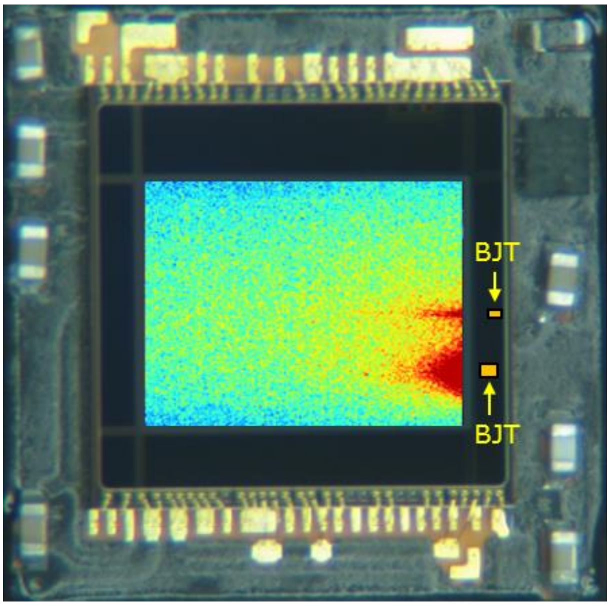

Fig. 3 Relation with dark hot spot and BJT location

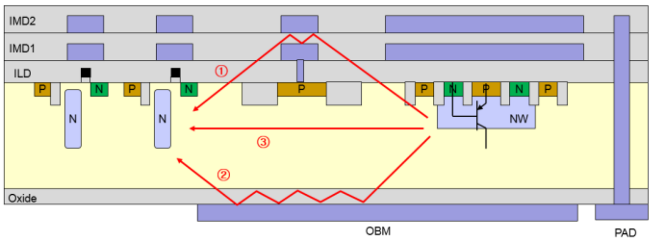

Fig. 4 Photon path scenario from P-N junction to CIS pixel.

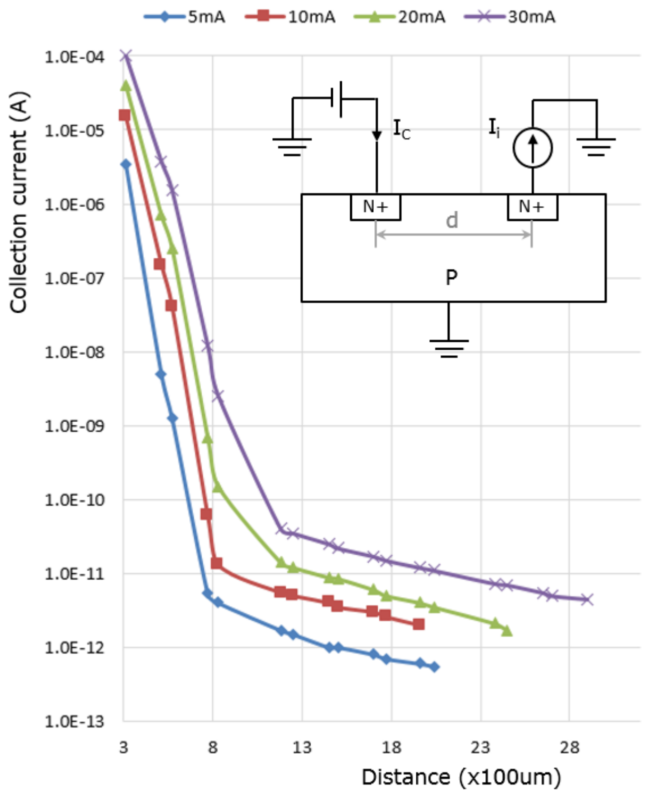

Fig. 5 The collection current versus distance with the injecting current as a parameter for the 6.6 x 10^15 cm^3 p-type substrate. [2]

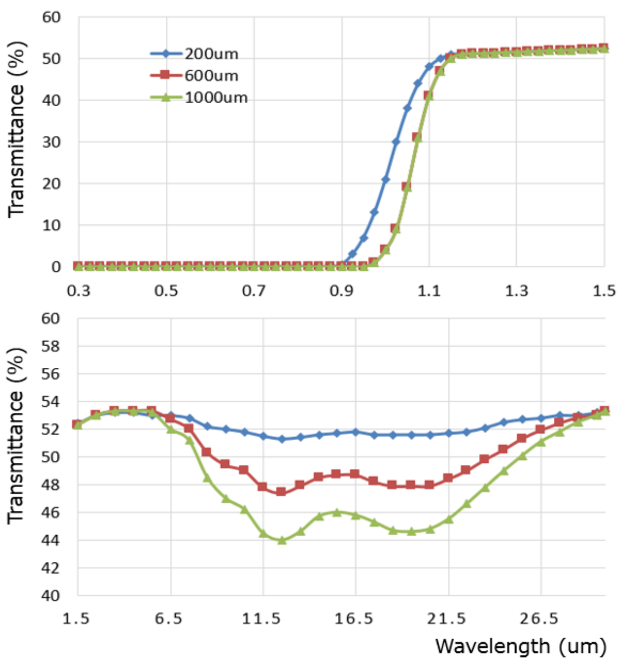

Fig. 6 . Silicon transmittance for 0.3um to 30um wavelength radiation and wafer thickness of 200um, 600um, 1000um[3]

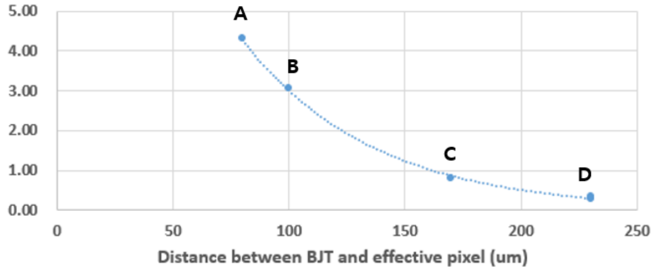

Fig. 7 Exponential relationship between dark image shading and the distance of effective pixel from BJT

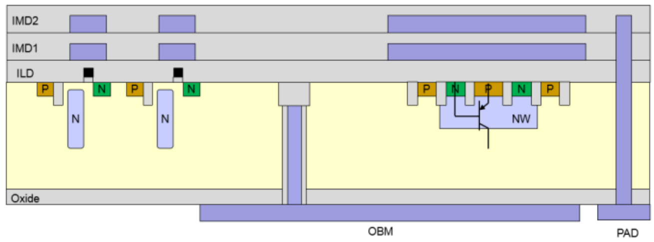

Fig. 8 Photon sidewall brief scheme

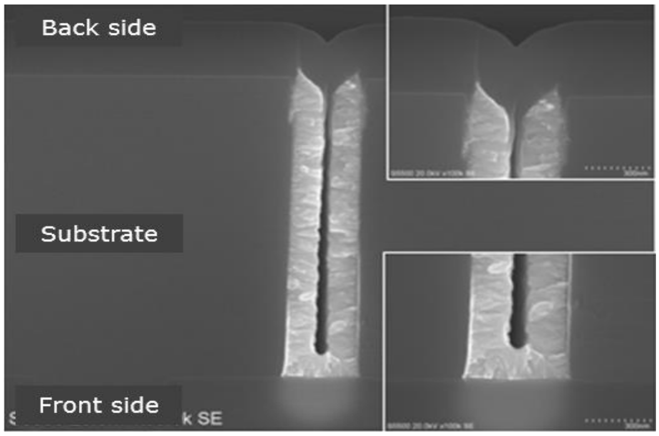

Fig. 9 . The vertical profile of photon sidewall around BJT

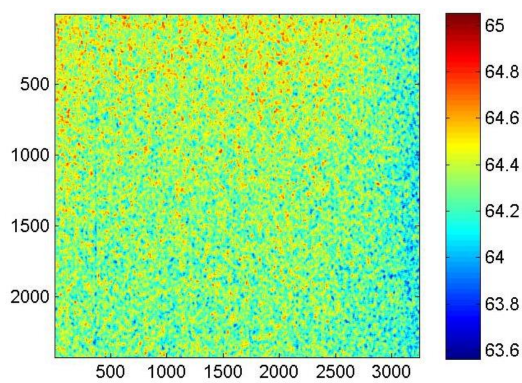

Fig. 10 Dark image after photon sidewall