Charge domain type 2.2um BSI Global Shutter pixel with Dual Depth DTI Produced by thick-film epitaxial process

Toshifumi Yokoyama*[1], Yoshihiro Noguchi[1], Masafumi Tsutsui[1], Yoshiaki Nishi[1], Masahiko Takeuchi[1], Masahiro Oda[1] & Fenigstein Amos[2]

[1]Tower Partners Semiconductor Co., Ltd. 800 Higashiyama, Uozu City, Toyama, Japan 937-8585.
*[1]E-mail address: yokoyama.toshifumi@tpsemico.com TEL: +81-80-4603-4179
[2] Tower Semiconductor Migdal Haemeq 23105, Israel

Abstract

We developed a 2.2µm Backside Illuminated (BSI) Global Shutter (GS) pixel with true charge-domain Correlated Double Sampling (CDS) and achieved a record-low GS read noise of 0.6e-. A thick-epi deep DTI (Deep Trench Isolation) process was implemented to enhance 1/PLS (Parasitic Light Sensitivity) using a dual-depth DTI structure. This newly developed pixel represents the smallest ever charge-domain GS pixel to date. Despite its compact size, it demonstrates exceptional performance by means of read noise level, Quantum Efficiency (QE), and 1/PLS.

INTRODUCTION

The demand for small pixel-size Global Shutter (GS) sensors continues to grow. Previously, we demonstrated a Front-Side Illuminated (FSI) 2.5µm GS pixel using a light pipe structure [1]. However, as pixel size shrinks, it becomes “photon starved” so BSI becomes essential for achieving higher QE and enabling flexible wiring patterns. Consequently, the development of BSI GS pixels is underway [2]. Another critical requirement for small pixels and low photon counts is noise suppression. Charge-domain pixels are particularly well-suited for reducing pixel noise, making them ideal for visible light sensors. However, BSI introduces challenges in suppressing PLS. For a high-performance GS sensor, the target 1/PLS value should be around 10,000 or higher. In this paper, we present a 2.2µm charge-domain BSI GS pixel with best-in-class performance, achieved through an especially deep dual-depth DTI structure and a thick-epi process.

PIXEL DESIGN

Figure 1 presents a basic cross-section of the charge-domain BSI GS pixel [3]. Incident light is focused by a micro-lens and directed to the Photo Diode (PD) area, which is surrounded by DTI. A fully buried Memory Node (MN) is positioned near the front-side surface to store charges until readout. This fully buried MN structure is effective in reducing dark current, as previously reported [4].

PLS arises when photoelectrons are generated in the MN or when electrons generated elsewhere in the pixel are collected by the MN. This parasitic signal can introduce image artifacts in GS operation, particularly in highly dynamic scenes. PLS from photoelectrons generated outside the MN can be effectively mitigated through device design that ensures the PD collects all generated photoelectrons. However, avoiding photoelectrons generated within the MN remains critical.

In earlier FSI GS pixels, the MN was shielded from incoming light by a Tungsten shield (WS). In BSI pixels, WS is implemented on both, the front and back sides to prevent direct illumination and reflections from the pixel backend, as illustrated in Figure 1. Light penetration into the MN is further minimized by DTI. However, these measures alone are insufficient to achieve the target PLS suppression level. To further reduce PLS, we increased both the DTI depth and the epitaxial layer thickness, ensuring almost complete absorption of visible light. The deeper the epitaxial layer and DTI, the better the PLS suppression. However, electron transfer from the PD to the MN must not be obstructed by the DTI, thus a dual-depth DTI structure was adopted, where the DTI depth differs between the readout and non-readout sides. The inter-pixel DTI nearly reaches the Si surface, while the intra-pixel DTI remains slightly shallower to facilitate electron transfer (Figure 2).

Figure 3 shows the results of optical simulations using the 3D-FDTD method, highlighting the effects of a thicker epitaxial layer and deeper DTI. The deep DTI effectively blocks light from reaching the MN, while a thicker epitaxial layer reduces light penetration. A 6µm epitaxial thickness allows green and red light to reach the MN, making PLS reduction difficult. However, with an 8.5µm epitaxial thickness, green light is entirely blocked, and red light intensity is significantly reduced. This ensures low PLS under short-wavelength light sources used in inspection and measurement applications.

Next, the optimal DTI depth was determined through TCAD simulations, indicating that an epitaxial thickness of 8.5µm and DTI depths of 7.2µm and 7.5µm would achieve a 1/PLS of over 10,000. The process was accordingly tuned.

Figure 4 illustrates the circuit schematic of the developed GS pixel. To maximize the PD area, the row-select transistor was eliminated, and the Floating Diffusion (FD) was shared between two pixels in a diagonal configuration. Additionally, a narrow MN was designed to balance angular response and full-well capacity.

THICK-FILM-EPI AND DUAL DEPTH DTI PROCESS

The main process challenges involved fabricating the thick epitaxial layer and the deep dual-depth DTI structure. For the first time, we employed an 8.5µm-thick epitaxial layer in a BSI GS pixel, comparable to the thickest commercial BSI GS products. The dual-depth DTI structure (7.2µm and 7.5µm) was achieved with a cost-effective, single-mask process. The DTI layout, including its length and width, were carefully optimized.

Although DTI sidewalls are a known sources of photodiode dark current, which is typically proportional to DTI depth, we successfully suppressed dark current by optimizing DTI etching conditions and the film formation within the DTI.

RESULTS OF NEWLY DEVELOPPED BSI GS

Figure 5 presents the cross-section of the newly developed BSI GS sensor, fabricated using a 65nm stacked BSI process with three Cu layers on the sensor wafer. The superior performance of the dual-depth DTI and thick epitaxial substrate was confirmed.

Figure 6 shows QE curves for both color and monochrome samples. The QE for the green pixel (530nm) reached 73%, while the QE for blue (450nm) and red (600nm) pixels were 66% and 68%, respectively. The peak QE of the monochrome sample was 83% at 550nm.

Figure 7 presents the wavelength dependence of 1/PLS, demonstrating values exceeding 10,000 for wavelengths of 570nm or less. Figure 8 illustrates the F# dependence of 1/PLS, showing that the monochrome sample achieved 1/PLS of 10,380 (-80.3dB) at F#=9, while a sample with a 6µm epitaxial thickness had a lower 1/PLS of 4,300.

Figure 9 shows the angular QE response, indicating that the pixel maintains 80% of its peak value at ±15 degrees. Figure 10 compares dark current levels between a 6µm epi process and the new deeper-epi, deeper-DTI process. By optimizing DTI etching and buried material, dark current was minimized despite increased DTI depth.

Table 1 summarizes the pixel performance, highlighting a noise level of 0.6e- due to the charge-domain GS-CDS architecture. The pixel array MTF is at least 40% at Nyquist frequency, making this a best-in-class high-resolution, low-noise global shutter sensor.

SUMMARY AND CONCLUSION

We developed the world's smallest charge-domain 2.2µm BSI GS pixel, suitable for high-resolution machine vision sensors and consumer applications. To mitigate 1/PLS degradation from pixel miniaturization, we implemented a thicker epitaxial layer and a dual-depth DTI structure. A novel thick-film epi process was developed, achieving a peak QE of 83% (monochrome). The pixel maintains 80% of its peak QE at ±15 degrees.

The 1/PLS achieved 10,380 at F#9, meeting the target of over 10,000. Even at F#2.8, 1/PLS remained high at 9,770 (79.8dB). This innovative design successfully enhances GS sensor performance, offering industry-leading noise suppression and light sensitivity.

References

[1] T.Yokoyama, et al., High Performance 2.5um Global Shutter Pixel with New Designed Light-Pipe Structure. In Proceeding of the IEDM 2018, San Francisco, USA, 2018.

[2] Y. Kumagai, et al., Back-Illuminated 2.74um-Pixel-Pitch Global Shutter CMOS Image Sensor with Charge-Domain Memory Achieving 10k e-saturation Signal. In Proceeding of the IEDM 2018, San Francisco, USA, 2018.

[3] S. Lauxtermann, et al., Comparison of Global Shutter Pixels for CMOS Image Sensors. In Proceedings of the 2007 International Image Sensor Workshop, Ogunquit, ME, USA, 7–10 June 2007.

[4] M. Tsutsui, et al., Development of Low Noise Memory Node in a 2.8um Global Shutter Pixel with Dual Transfer. In Proceedings of the 2017 International Image Sensor Workshop, Hiroshima, Japan, 2017; pp.28.

[5] K.Ito et al., A Back Illuminated 10um SPAD Pixel Array Comprising Full Trench Isolation and Cu-Cu Bonding with Over 14% PDE at 940nm In Proceeding of the IEDM 2020, Virtual Session, 2020.

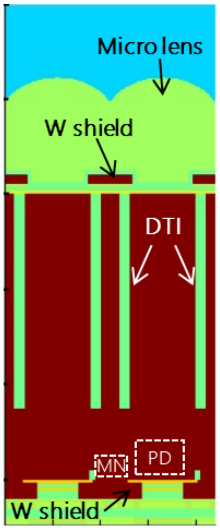


Figure 1: Cross section BSI_GS sensor.

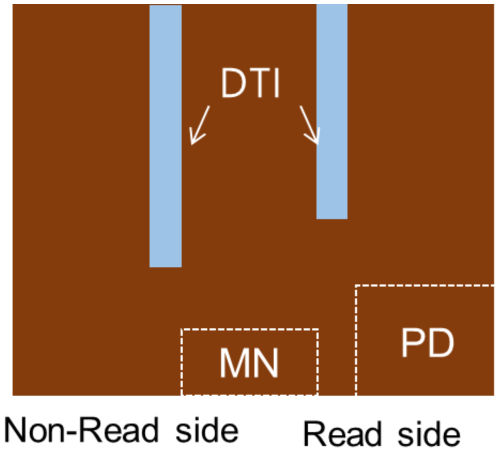


Figure 2: Dual depth DTI structure.

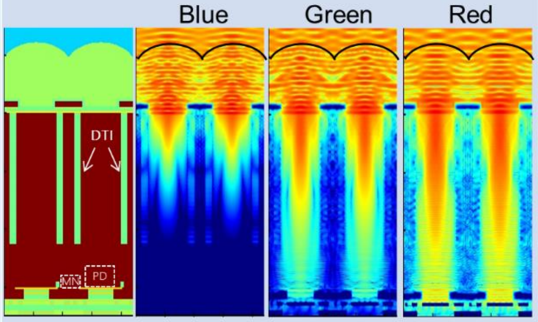
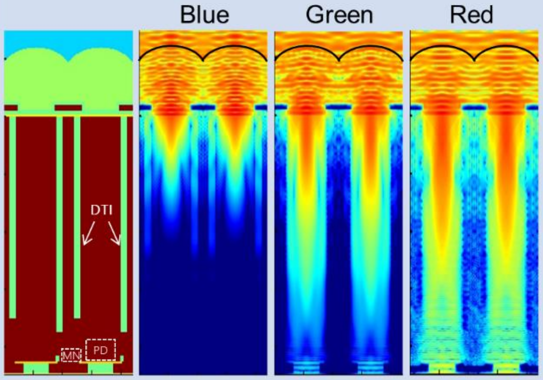
Structure	Ref	Epi 8.5um + dual depth DTI
Epi thickness	6um	8.5um
DTI depth	4.5um	7.2um + 7.5um
X-section λ=600nm	Blue Green Red 	Blue Green Red 
1/PLS (F#9)	4425	10169

Figure 3: Simulation results and developed structure.

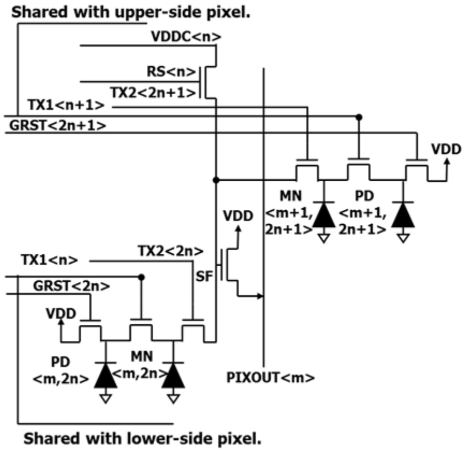


Figure 4: Pixel circuit schematic of GS pixel.

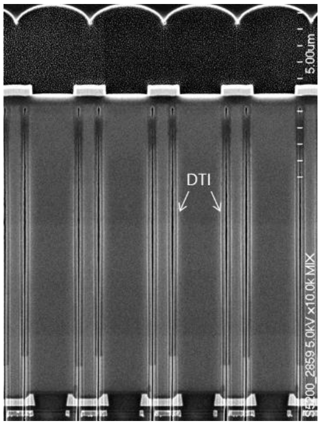


Figure 5 : Cross section of the dual depth DTI.

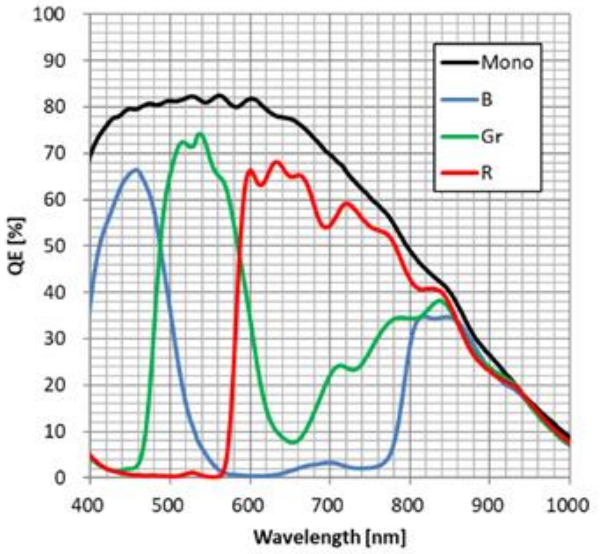


Figure 6 : QE curve (Color & Mono).

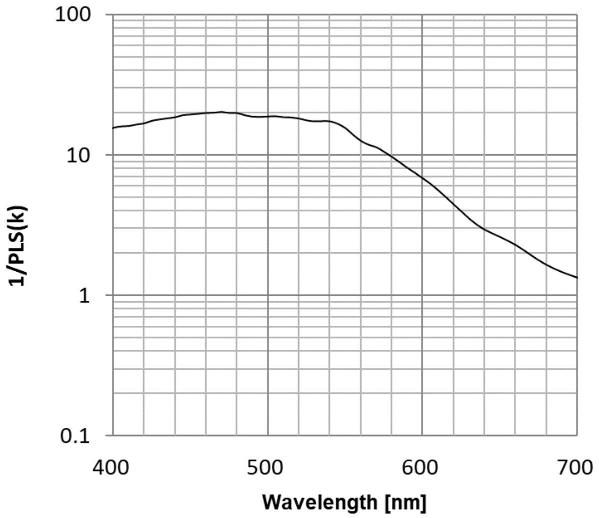


Figure 7 : Wavelength dependence of 1/PLS (Mono).

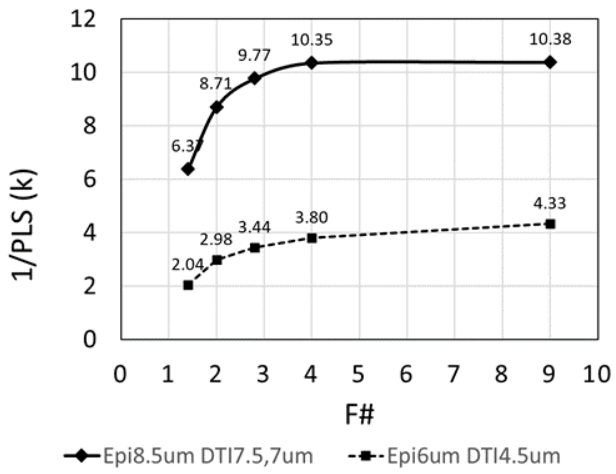
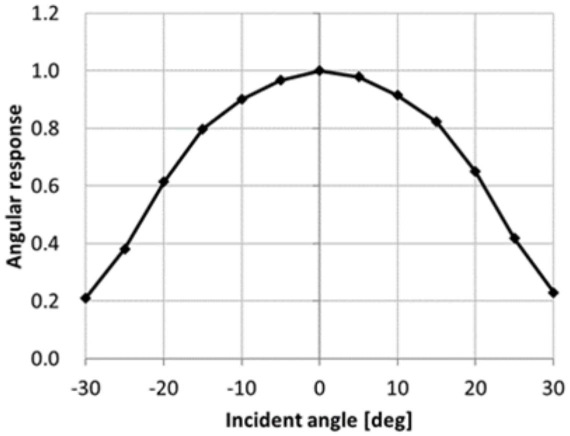
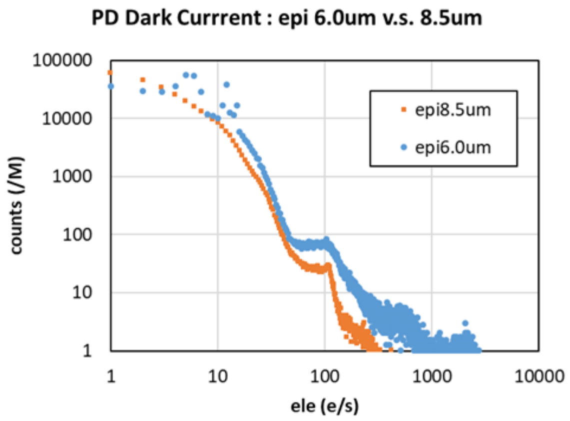


Figure 8 : F#dependence of 1/PLS (Mono).



Fifure 9 : Angular response of QE.



Fifure 10 : Comparison of dark current.

Table 1: Pixel performance.

Process Technology	65nm CIS BSI
Pixel Size	2.2 μm × 2.2 μm
Peak QE (Mono)	83 %
1/PLS (F#9, white light, Mono)	10380
Angular response (80 %)	>15 degrees
MTF @Nyquist frequency	> 40%
Linear Full Well Capacity	5400 ele
Pixel noise @SF out (25 deg.C)	0.6 ele