

A 3-Tap Global Shutter 5.0 μ m Pixel with Background Canceling for 165MHz Modulated Pulsed Indirect Time-of-Flight Image Sensor

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Introduction

Depth sensing is big incoming application of CMOS Image Sensors [1-4]. Pulsed indirect time-of-flight (TOF) [1] is one of the methods to measure depth by reflected light pulse from distant objects. In this method, high modulation frequency is desirable to increase signal-to-noise ratio (SNR) by summing up signals from multiple input light pulses. Additional improvement of SNR can be achieved by suppression of parasitic light sensitivity (PLS) and background cancelling [5]. In this paper, we report on our approaches to reduce PLS and to enhance pixel response to near-infra-red (NIR) light for high modulation frequency in 3-tap global shutter (GS) 5.0 μ m pixel based on GS technology in 65nm CIS [6] and stacked process with backside deep trench isolation (BDTI).

Stacked Process

2.5 μ m-pitch hybrid bonding process with metal-metal and dielectric-dielectric bonding is adopted for the pixel fabrication. Uniform operation of pixels in the whole array with high modulation frequency is achieved by In-pixel hybrid bonding connections. Figure 1 (a) shows cross-sectional view of hybrid bonding. Square arrangement of the metal-metal pad of hybrid bonding between 4-layers-metal sensor chip and 7-layers-metal logic chip is achieved. As shown in Figure 1 (a), each metal pad has only one via to the metal layers under the pads. This small pad-via connection makes it possible to utilize minimum line/space of the metal layers under the pad, and contributes increases of flexibility of routings of metal layers in the stacked process. Figure 1 (b) shows cumulative frequency of resistance per connection of 0.7k chain connection TEG in the whole wafer from multiple lots. Tight distribution and good connectivity without defects are achieved.

Pixel Schematic and Operation

Pixel schematic and operation timing are shown in Figure 2. Each tap (MG1-3) has a dedicated storage node (SN1-3) to store electrons for measuring depth in one frame. Two taps (MG1/2) are assigned to capture returned signal and to measure depth by the difference of signals of each taps, and the remaining tap (MG3) captures background signal for canceling in the period without returned signal. Charges in the SNs are transferred to one single floating diffusion to suppress noises from fluctuation of conversion gains and to save areas. Since SNs are pinned memory nodes by negatively biased gate (SG) [3], true correlated double sampling operation is enabled. In the readout period of signal of SNs, parasitic signal in photodiode is drained by DRN-transistor.

Figure 3 shows cross-sectional SEM view of fabricated pixels. 6 μ m-thick-epi and 4 μ m-depth BDTI are adopted. Metal reflector is placed under the photodiode. Both are designed to contribute to enhance quantum efficiency (QE) of NIR. The metal layer is placed as grid arrangement on the backside of sensor chip to reduce PLS into SNs.

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Approaches

SN1-3 are placed closely to equalize PLS of each SN for maximizing effectiveness of background canceling as shown in figure 4. BDTI is also introduced around photodiode. Figure 5 shows simulation results of returned light profile with oblique angle. Incident light is reflected by BDTI and prevented from being irradiated into SNs.

Fast response to NIR consists of 1) vertical transfer in thick epi and 2) lateral transfer into each tap as shown in Figure 6. In this pixel, all the photo-generated electrons in the photodiode is collected at the position A in Figure 6 by the vertical field in the photodiode. Then electrons transfer into each MG1/2/3.

Figure 7 illustrates electrostatic potential profile of process A/B having different vertical field. In Process B, additional n-type implants are applied in shallow and deep regions of photodiode to make electrostatic potential deeper for increasing electric field. Results of pixel response of MG1/2 are shown in Figure 8. In the measurement, phase between the returned pulsed light and the starting time of modulation of MG1/2/3 is varied, and signals of each SN1/2/3 are measured. As shown in figure 8, Process B shows smaller background signal of MG2 due to incomplete transfer of electrons of MG1 compared to Process A. Fast transfer in the photodiode is achieved in Process B thanks to stronger vertical electric field. Stable background signal of Process B due to PLS also make the canceling by MG3 effective.

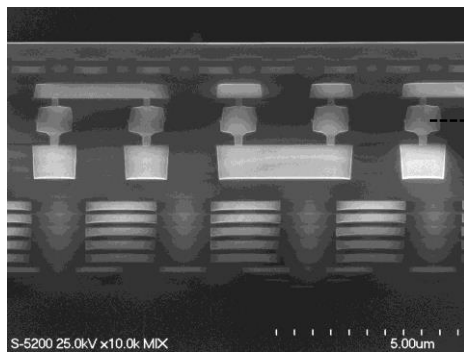
Lateral fields to MG1/3 are increased by layout design of n-type implant in the front of each MG, because MG1/3 have longer transfer path from position A shown in figure 6 compared to that of MG2. Figure 9 shows comparison of simulation results of electric field and measured demodulation contrast (DC) at 165MHz, 940nm wavelength. In optimized layout, difference of DC between each tap becomes smaller due to fast transfer assisted by larger electric field to MG1/3.

Conclusion

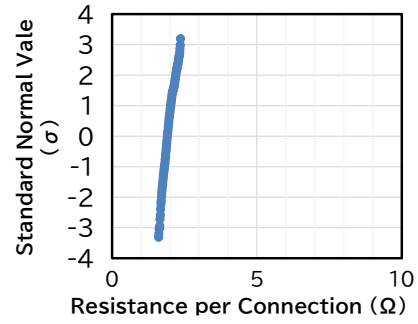
3-tap global shutter 5.0um pixel with background canceling for pulsed indirect TOF image sensor has been developed. 2.5um-pitch hybrid bonding is used for stacking sensor and logic wafers. PLS is suppressed by 4um-depth BDTI, and 6um-thick-epi is used to enhance QE at 940nm wavelength. To enhance pixel response for high modulation frequency of pulsed light, electric field in photodiode is carefully designed along all the transfer path. Demodulation contrast of 81% at 165MHz without background canceling is achieved. Figure 10 shows sample of depth sensing. Performances are summarized in table 1.

References

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a) Cross-sectional View of Hybrid Bonding



b) Normal Quantile plot of Resistance of Connection

Figure 1 a) Cross-sectional view of hybrid bonding and b) Cumulative frequency of resistance of hybrid bonding.

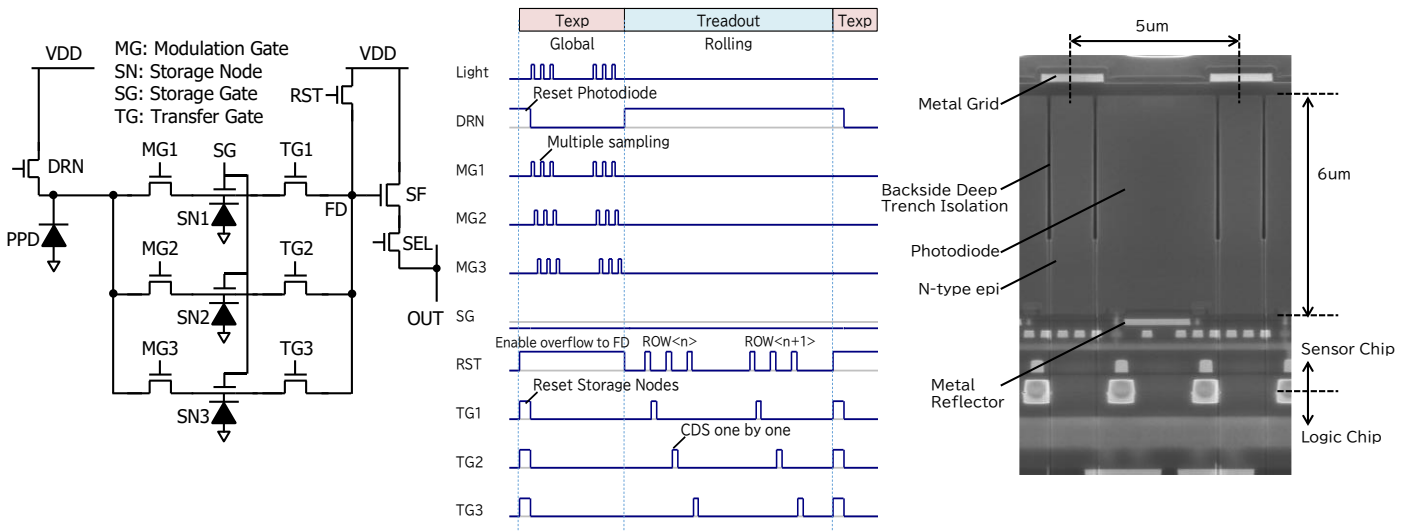


Figure 2 Pixel schematic and operation timing

Figure 3 Cross-sectional SEM view of fabricated device with 65nm stacked process

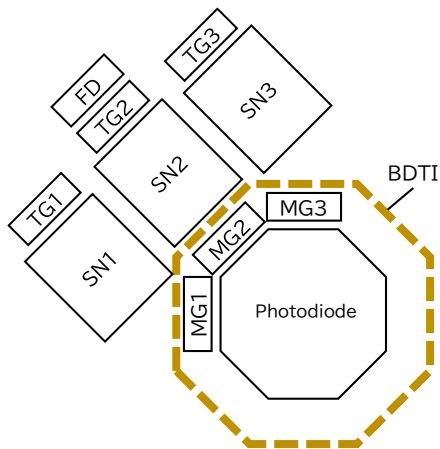


Figure 4 Schematic of top-view of pixel.

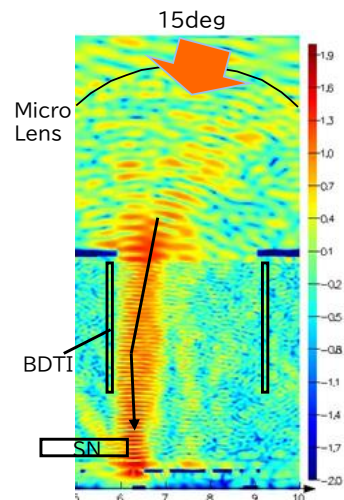


Figure 5 FDTD simulation result of pixel with 15 degrees returned light of 940nm wavelength

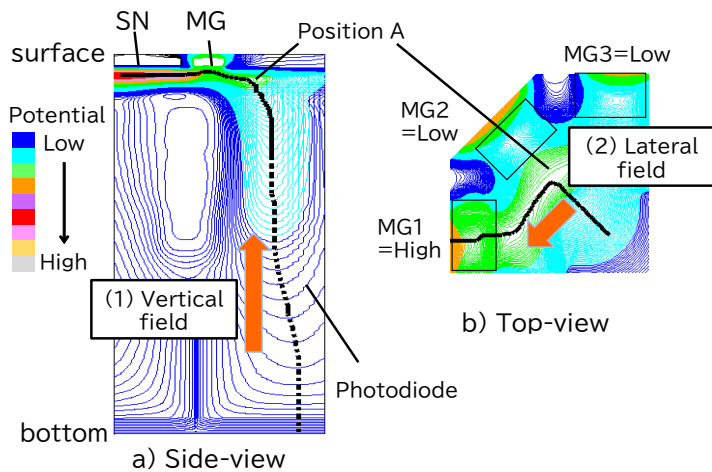


Figure 6 a) Side-view and b) top-view of electrostatic potential profile of photodiode. Dotted line shows transfer path of electrons. Position A where photo-generated electrons reaches at the surface after travelling in photodiode is also shown.

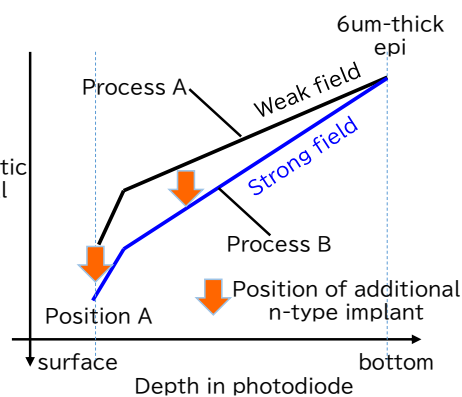


Figure 7 Illustrated electrostatic potential profile of process A/B in photodiode

Position A and MG1 are drawn in figure 6.

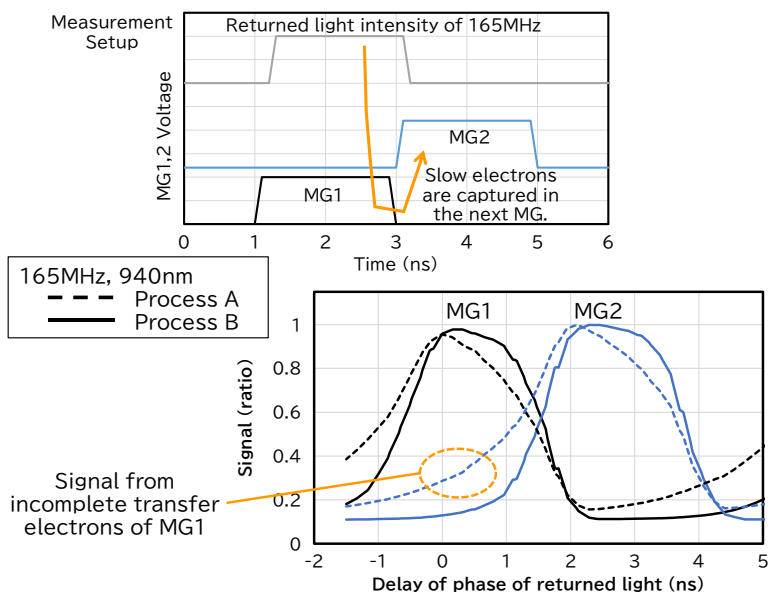
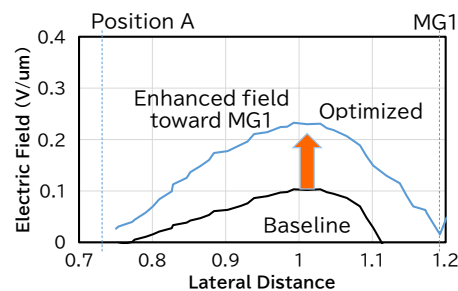


Figure 8 Pixel response of MG1/2 of process A/B of 6um-thick epi.

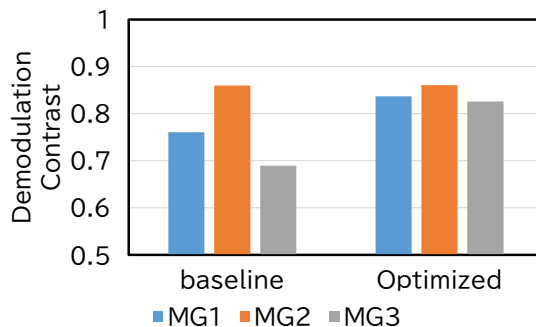


Figure 9 Comparisons of simulated lateral electric field toward MG1 and measured demodulation contrast with 165MHz, 940nm wavelength in layout optimization.

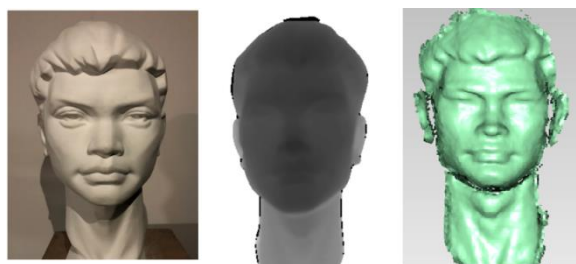


Figure 10 Target (left), Depth image (mid) and 3D point cloud (right) captured by fabricated iTOF sensor

Table 1 Summary of Performances of Fabricated Pixel

Process	65nm(sensor) + 65nm(logic) BSI+Stacking
Pixel pitch	5um
Number of taps	3
Modulation frequency	Up to 165MHz
Demodulation contrast	81%@165MHz with 2ns pulses 88%@100MHz
Read noise	3.5e-
Full well(per tap)	11ke-
Dark Current	17.7ke-/s/pix@ Environment temperature
Depth noise	<0.16% @0.5-5m w/o background light
QE	21%@940nm(simulation)