https://doi.org/10.2352/ISSN.2470-1173.2021.7.ISS-066

A single chip PPG sensor with enhanced IR sensitivity for low power and small size

Jungwook Lim, Jihun Kim, Long Yan, Hyunpil Noh, Seungki Jung, Doosik Seol, Junghyung Pyo, Taesub Jung, Jungbin Yun, Dukseo Park, Howoo Park, Kyungho Lee, TAKASHI NAGANO, Jungchak Ahn

Abstract

A single chip Photoplethysmography(PPG) sensor was developed for continuous measurements of heart rate from a mobile device. In order to utilize it in various mobile applications, it was necessary to achieve low power and small size of PPG sensors. For low power and small chip size of the PPG sensor, a photodiode(PD) for sensing signals and an analog front end(AFE) for signal amplification and ADC should be implemented in a single chip. The single chip PPG sensor which is implemented on a standard CMOS process with low operating voltage could be more suitable for mobile devices. In order to operate at a low voltage, reduction of Si thickness is required, and for this, high quantum efficiency(QE) of 43% at 940nm were obtained at 3um thickness by back side trench(BST) pattern and ARL optimization. In addition, to improve the performance of the PPG sensor, the leakage current of <0.1nA and capacitance of <200pF were measured by 20um pixel array. As a result, the low-power, small size single-chip PPG sensor showed similar performance to conventional high-voltage and large PPG sensor.

Introduction

Recently, the technology is migrated to wearable devices such as wrist-worn smart watch or a wireless ear set. Among them, PPG sensor is a health sensor that measures the change in blood flow to be modulated by the heart rate. When a separate light source (LED) is irradiated to the skin, the light absorption by the blood vessel is changed in synchronization with the heart rate. A sensor measures, transmitted or reflected signal represented in Amplitude Modulation It has been used for a long time as a medical tool to measure oxygen saturation (SpO2) in a patient's finger in an emergency status[1]. For the use of PPG sensors as various health care products, features of low power and smaller size are essentially required.

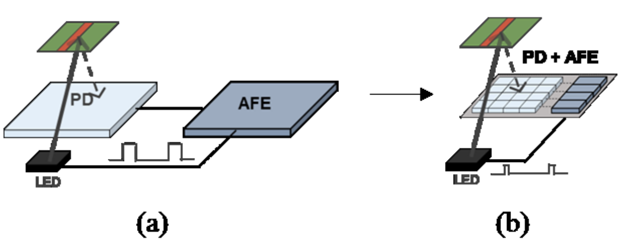


Figure 1. (a) Separated chip PPG sensor and (b) Single chip PPG sensor

As shown in Figure 1 the current PPG sensor has a structure in which photodiode and AFE are separated[1]. Due to this, application fields are limited, and a low power and miniaturized single chip PPG sensor was required for use as a small biosensor, but it was very difficult to implement. The reason was that the existing PPG sensor cannot use the conventional CMOS process because the thickness of PD reaches hundreds of um and the operating voltage is high. Moreover, if the PPG pixel was made small, it was difficult to operate normally due to poor sensitivity and increased capacitance.

In this paper, we developed a single chip PPG sensor that showed the same level of leakage current, capacitance, and IR sensitivity.

For a PPG sensor to operate normally, leakage current and capacitance were important from an electrical point of view, and sensitivity was important from an optical point of view.

Electrical characteristics

Photo diode leakage current

The PPG sensor with single chip structure was connected to the photodiode(PD) and Transimpedance amplifier(TIA). It was the structure in which photo current by LED light reflected from blood vessel in Photodiode was converted to Voltage by the operation of TIA. Since the PPG pixel measures the photo current generated by light reflected by blood vessels, the signal may be distorted if the leakage current increases in the dark state. Leakage current can cause problems not only in product problems such as devices, circuits, and processes, but also in environmental problems such as physical damage or high temperature and humidity. When a pixel is composed of one large photodiode, if the leakage current increases, the pixel cannot operate normally.

So we wanted to make a new structure. First, we created a pixel array that is traditionally used in CIS, and divide it into several sections with switches that control on and off. Then, all outputs were combined again.

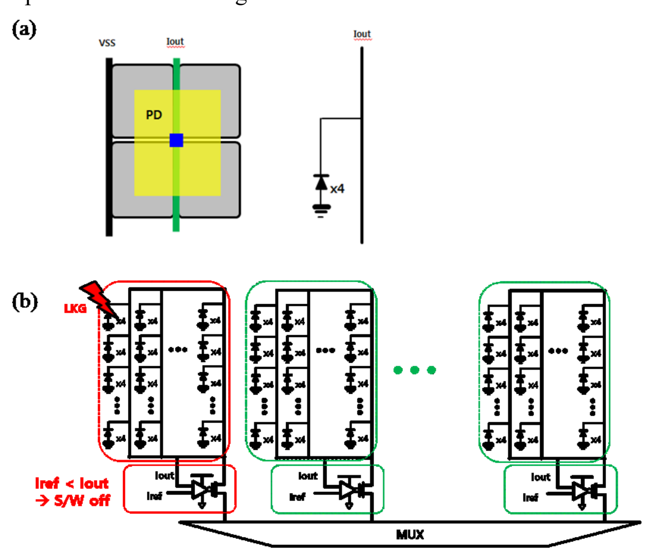
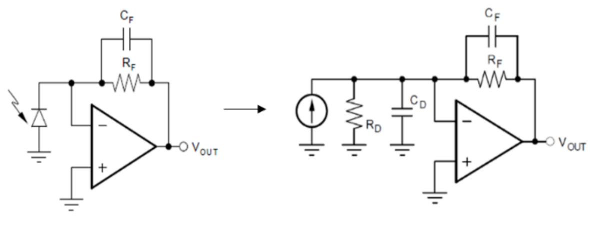


Figure 2. (a) Unit pixel (b) Pixel array divided into areas with comparator

Figure 2 shows that after dividing the pixel array into multiple zones, if a lot of leakage current occurs, the comparator blocks the signal in that zone. By using this method, even if a lot of dark current occurs at any pixel, only the signal of the zone is blocked and the rest of the zone can operate normally. Blocking some zone signals can reduce the effective area and reduce sensitivity, but it can be compensated by an algorithm that copies signals from neighboring areas. We achieved a dark current of less than 0.1nA at 25°C, which is typical product level. In addition, by using an array structure controlled by a switch, it can operate normally even if the dark current increases.

Photo diode capacitance



(a) (b)

Figure 3. (a) Typical PD and TIA (b) PD modeled with Ideal Elements

As shown in Figure 3, the new PPG sensor has a photodiode and a TIA connected, so the photodiode can be represented by an equivalent circuit that connects a current source, a resistor, and a capacitance. In order to support fast switching (<20us) PD while ensure stable sensor operation, small PD capacitance (<500pF) is required for a TIA. Moreover, small C_D(PD capacitance) will help TIA to minimize noise amplification originated in combination of C_F(Feedback capacitance) in Figure.3. First, in order to reduce the junction capacitance, the doping concentration of the PN junction should be reduced, but in this case, the resistance between Si and metal contacts increases. So, we found the process condition for ohmic contact and could control the PN junction leakage by optimization of layout and process.

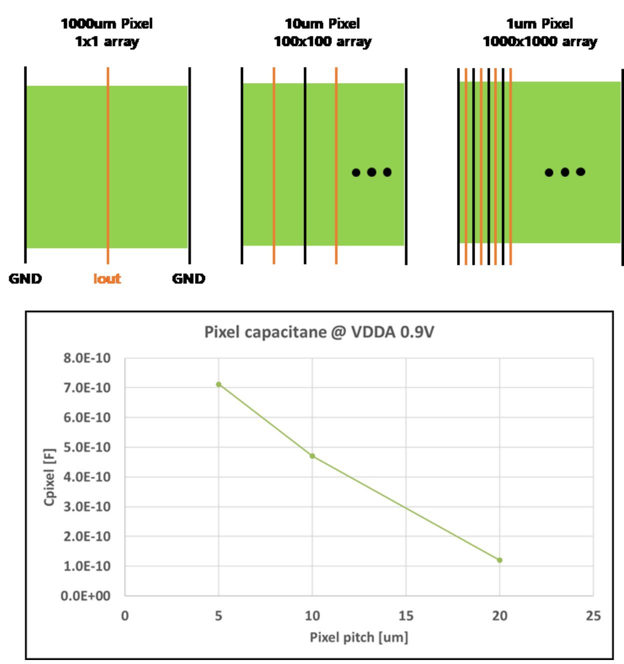


Figure 4. PD capacitance according to pixel pitch

In addition, pixel capacitance has a parasitic cap as well as a junction cap. As shown in Figure 4, as the pixel pitch decreases, the metal line becomes more complex and the parasitic cap increases.

In summary, the smaller the pixel pitch, the larger the capacitance value, and the larger the pixel pitch, the smaller the effect of controlling the dark current by dividing the zone. In this trade-off relationship, we found the optimal condition under the low power condition of VDDA 0.9V.

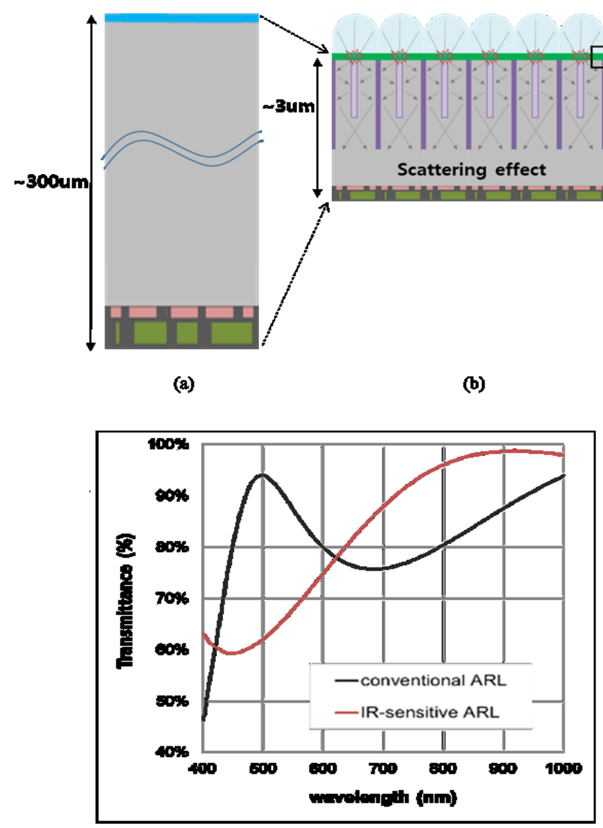
Optical characteristics

IR Quantum efficiency

For the low power PPG sensor, a low power IR light source should be used instead of the commonly used green light source. However, the light in the long wavelength region has a low quantum efficiency, so it is difficult for the PPG sensor to operate normally. We compared the light source with a wavelength of 540nm and 940nm and found that the sensitivity decreased from 0.37A/W (540nm) to 0.08A/W (940nm). By the following equation (1), it can be seen that the QE of the 940 nm wavelength is reduced to about 10% compared to about 80% of 540 nm.

$$\text{Responsibility (Sensitivity)} = (\text{Q.E.})*e/h\nu \qquad (1)$$

For a PPG sensor to operate normally at a wavelength of 940 nm, the sensitivity should be 0.3 A/W, which is equivalent to about 40% QE. As mentioned earlier, we have made the Si thickness thinner from hundreds of um to 3um to implement a single chip PPG sensor. But it was difficult to raise the IR QE because the light path decreases as the Si thickness becomes thinner.



(a) (b)

(c)

Figure 5. IR QE improvement item (a) Si thickness of conventional PPG PD, (b) Scattering effect by micro lens and BST pattern and (c) ARL optimization for IR

So as shown in Figure 5 we applied pixel processing techniques such as forming BST patterns, applying micro lenses, and modifying anti-reflection layers(ARL) to increase the QE of long-wavelength light sources[2]. Since the IR light source has a small photon energy, it was necessary to increase the light absorption rate due to ARL optimization, and increase the light travel path using the micro lens focusing and scattering effect of the BST pattern. In general, increasing the Si thickness is the most effective method, but we needed to reduce the Si thickness for miniaturization, so we had to increase the light path in the horizontal direction.

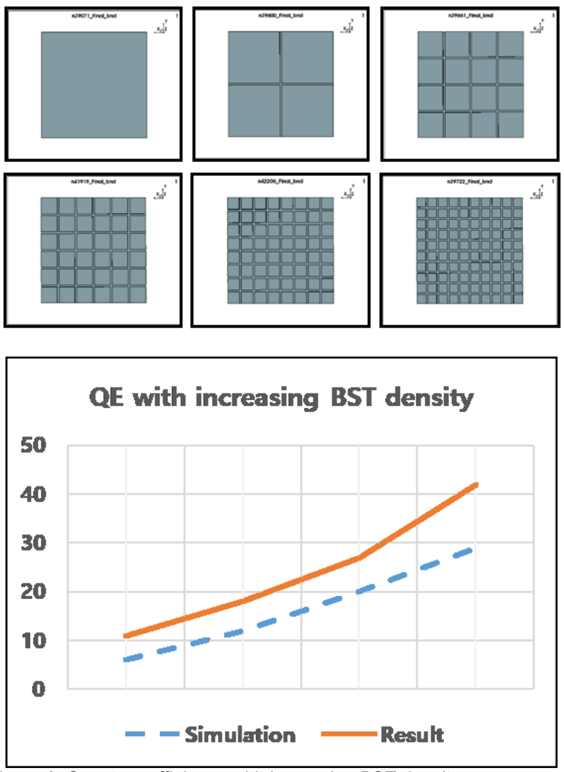


Figure 6. Quantum efficiency with increasing BST density

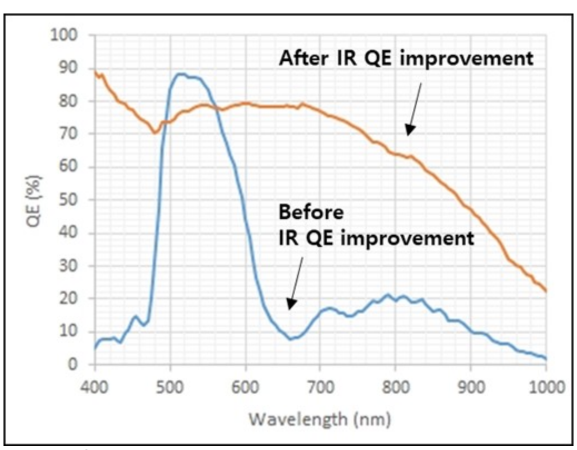


Figure 7. QE spectrum according to wavelength

As shown in Figure 6, we confirmed that the QE also increases as the pattern density of the BST increases. This is because the optical path is increased due to the BST pattern. The trend was the same between the optical simulation and the actual measurement results, and we used array of BST structures per unit pixel. And figure 7 shows the result of comparing the response and QE according to the wavelength before and after applying the IR QE improvement item. The reason for the decrease in sensitivity and QE at 550 nm is that the ARL is optimized for IR.

Conclusion

We reduced the thickness of the photodiode from hundreds of um to 3um, and by integrating large area pixel together with AFE, the sensor realizes low power, small size without compromising dynamic range >80dB supported by existing solution (PD and AFE separated). For that, we achieved a dark current of less than 0.1nA, a pixel capacitance of 200pF with a 20um pitch pixel utilizing the CIS pixel array structure and latest CMOS process. In addition, despite the 3um Si thickness, the QE of the IR light source is improved by 43%, and the operating voltage is lower from 5V to 0.9V, which enables lower power operation than before.

In summary, we developed a single chip PPG sensor that combines PD and AFE into one. And it was free from dark current by utilizing PD array structure instead of single large PD. Since the pixel capacitance of our PPG sensor was 200pF, which was smaller than 500pF (the standard for normal operation), so there was no noise problem and achieved a dynamic range of 89dB. The thickness of the PPG pixel has been thinned from hundreds of um to 3um, enabling product miniaturization. In addition, due to the decrease in Si thickness, the optical path has been reduced to about 1/100. Nevertheless, through the latest process technology, the QE of the IR light source was improved by 43%. And operating voltage lower than 0.9V enabled low power consumption. Therefore, single chip PPG pixel can be used not only in ear set but also in various healthcare fields.

References

[1] John G. Webster “Design of Pulse Oximeters” Boca Raton

[2] Jonghoon Park, “Pixel Technology for Improving IR Quantum Efficiency of Backside-illuminated CMOS Image Sensor”, IISW 2019

Author Biography

Jungwook Lim *received the B.S. degree in Applied-Physics from Hanyang University, Ansan, Korea in 2011. From 2011, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, high speed, low power, sub-micron pixel, global shutter sensors and 3D depth sensors.*

Jihun Kim *received the B.S. degrees in electronics communication engineering from Hanyang University, Ansan, Korea, in 2018, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel.*

Long Yan *(SM’17) received the Ph.D. degree in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2011. In 2010, he was with the Microsystems Technology Laboratory, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, as a visiting student. From 2011 to 2014, he ws with*

IMEC, Belgium, as a senior scientist. His research at IMEC has focused on the development of low-power mixed-mode circuits for wearable and implantable applications. He is currently working at Samsung Electronics, Hwaseong, South Korea as a principal engineer, where he leads advanced sensor developments for mobile and wearable devices. From 2015, Dr. Yan serves on the technical program committee of the IEEE International Solid-State Circuit Conference (ISSCC). He is member of ISSCC executive committee and chair of ISSCC Far East regional committee.

Hyunpil Noh *received the B.S., M.S. and Ph.D. degrees from department of Physics in Seoul National Univiersity, Seoul, Korea, in 1989, 1991 and 1995, he is working for Samsung Electronics as a process architecture engineer for CMOS image sensors. His research interests include process architecture engineering of image sensors with high sensitivity, low-noise, sub-micron pixel, and big-pixel.*

Seungki Jung *received the B.S. degrees in Electronic engineering from Kookmin University, Seoul, Korea, in 2016, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel.*

Doosik Seol *received the B.S. degrees in Electronic engineering from Chung-ang University, Seoul, Korea, in 2018, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel.*

Junghyung Pyo *he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel*

Taesub Jung *received the M.S.degree Pohang University of Science and Technology, Pohang, Korea, in 2006. From 2006, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel, global shutter sensors and 3D depth sensors.*

Jungbin Yun *received the B.S. and M.S. degrees in materials science and engineering from Kookmin University, Seoul, Korea, in 2004 and 2006. He is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research is interested a various image sensors, such as Dual pixels for All pixel AF, high SNR sensors and ToF sensors*

Dukseo Park *received the B.S., and M.S degrees from department of material science and engineering in Hanyang University, Seoul, Korea, in 2000, and 2002. He is working for Samsung Electronics as a process architect and has a wide experience from 180nm to 28nm technology specialized in process development for image sensor. He has also managed a team for developing PDK (Process Design Kit) and device for image sensor.*

Howoo Park *received the M.S degrees from department of semiconductor engineering in Sungkyunkwan University, Seoul, Korea, in 2006. He is working for Samsung Electronics as a pixel process engineer from 2005.*

Kyungho Lee *received the Ph. D degree in electronics & electrical engineering from POSTECH (Pohang University of Science & Technology), Pohang, Korea, in 2006. In 2006, he joined the System LSI Division, Samsung Electronics Company, Ltd., Yong-in, Korea. He is currently the principal engineer of Samsung Electronics and is leading a group developing CMOS image sensor pixel. He has been developing pixel shrinkage and various pixels for CMOS image sensor, including ISOCELL and dual pixels. Dr. Lee has published over 20 technical papers and filed 40 US patents (authored and co-authored).*

Takashi Nagano received the *B.S. in Engineering from Tokyo University of Agriculture and Technology, Fuchu, Tokyo, Japan, in 1991, From 2017, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel, global shutter sensors and 3D depth sensors.*

Jungchak Ahn *received the B.S.,.,M.S.and Ph.D degrees in electrical engineering from Pohang University of Science and Technology, Pohang, Korea, in 1993, 1995, and 1999, respectively.. From 1999, he is working for Samsung Electronics as a pixel designer for CMOS image sensors. His research interests include pixel structure of image sensors with high sensitivity, low-noise, sub-micron pixel, global shutter sensors and 3D depth sensors. He is currently in charge of pixel development team as a Vice President.*

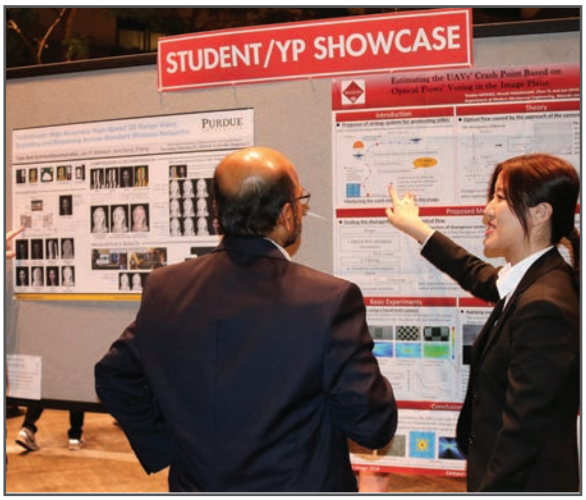
JOIN US AT THE NEXT EI!

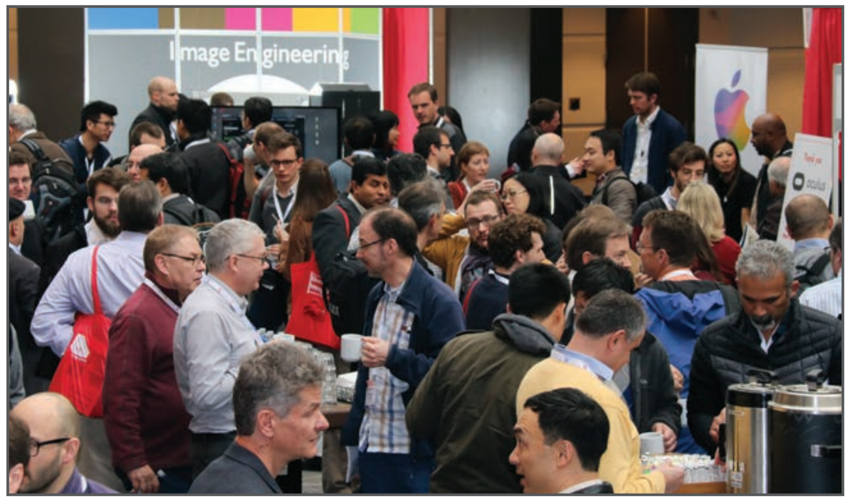
IS&T International Symposium on

Electronic Imaging

SCIENCE AND TECHNOLOGY

Imaging across applications . . . Where industry and academia meet!





• SHORT COURSES • EXHIBITS • DEMONSTRATION SESSION • PLENARY TALKS •
• INTERACTIVE PAPER SESSION • SPECIAL EVENTS • TECHNICAL SESSIONS •

www.electronicimaging.org

IS&T
imaging.org