Sensor OLED Display-Based Mobile Cardiovascular Health Monitor

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Abstract

Displays can be one of the most user-interactive devices in electronic systems. Therefore, integrating various sensors into displays to fully leverage their user-friendly nature could lead to disruptive innovation in end systems. To demonstrate this, here we report the integration of a massively pixelated organic photodiode (OPD) into an OLED (referred to as "Sensor OLED"), which enables the monitoring of various cardiovascular health indicators with high accuracy, in a ubiquitous and convenient manner. As a result, we believe that smartphones adopting Sensor OLED could evolve into mobile cardiovascular health monitors and digital therapeutics, thereby replacing bulky, standalone medical devices and revolutionizing diagnosis and treatment.

Author Keywords

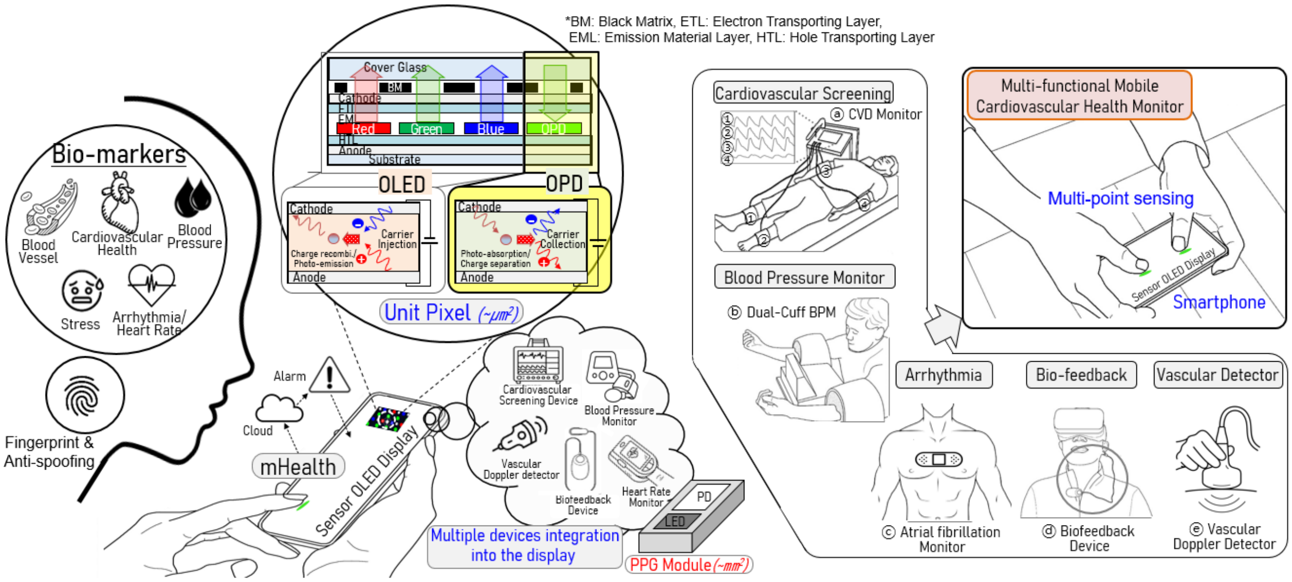
Organic photodiode, Sensor OLED, Cardiovascular monitor

1. Introduction

Currently, displays have evolved from simple optical output devices to more limited user-interactive devices that support classic interfaces (such as touch, pen, and authentication) due to the proliferation of smartphones. The conventional method of sensor integration (laminating standalone sensors to the display) creates redundancies in the system, such as increased cost, thickness, and complexity. Most importantly, it hinders the further evolution of smartphones. Given its user-friendly nature (providing instantaneous and impactful visual feedback), integrating optical sensors into OLED displays can create tremendous synergy, extending their application range and potentially evolving smartphones into more advanced and sophisticated user-interactive devices by leveraging the latest advancements in artificial intelligence (AI). Especially, an interactive and ubiquitous health monitoring application could be an excellent candidate for technical exploration. Consequently, we implemented the multi-functional Sensor OLED, which can capture high-resolution images and photoplethysmography (PPG) signals concurrently in a single device. We then applied it to the smartphone—the indispensable device—to enable a multi-functional mobile cardiovascular health monitor (MCHM) that demonstrates the aforementioned technological evolution.

Due to the high resolution and pixilated integration of the sensor into the display, the distinctive 1) concurrent multi-point sensing (MPS), 2) high-resolution dynamic image sensing (HDIS) and 3) user interactive sensing (UIS) capabilities were achieved. Thus it can extend new functions in smartphone, including high-accuracy (90%) screening of cardiovascular diseases (CVDs), blood pressure (BP) monitoring from both fingers with a medical device level accuracy, monioring of finger blood vessels and flow and new bio sensing methods (spatial, spatial-temporal sensing) utilizing the obtained high resolution dynamic images and single-device-based biofeedback, in addition to the conventional atrial fibrillation (AF), stress levels and heart and respiratory rate (HR, RR) sensing with a simple placement of fingers on the display. Those were throughly vailidated from the extensive clinical trials. As a result, the truly ubiquitous and self-monitoring with easy and convenient manner along with the medical device level accuracy have achieved by utilizing the Sensor OLED embedded smartphone without any additional wearable or attachable standalone PPG sensors.

As a result, it could advancing the evolution of smartphone into the ubiquitous health monitor and digital therapeutics, thus transforming the diagnostic and treatment which could affect enormous benefits to the individuals for healthier life and



(a) The concept (b) Technogical impact

Figure 1. The Sensor OLED based multi-functional mobile cardiovascular health monitor.

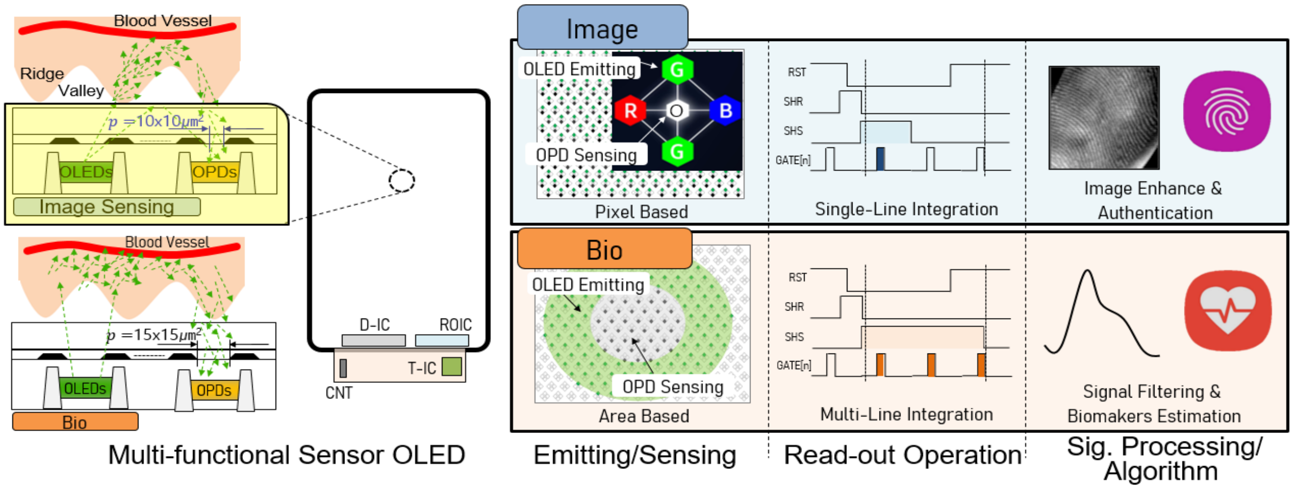


Figure 2. The Multi-functional Sensor OLED.

furthermore relief the medical burdens on society, especially for the low-resource settings where the access to the medical and wearable devices are limited.

Figure1(a) shows the concept of MCHM, the Sensor OLED based smartphone can merge expensive medical devices such as a CVD monitor, dual-cuff BP monitor and vascular doppler detector and also the standalone type devices such as an AF, biofeedback, HR monitor. It could evolve into a new type of MCHM to enable mobile Health (mHealth) by further utilizing the Internet of Thing (IoT) and AI. Figure 1(b) illustrates the technical impacts, the complicated CVD screening which can only be done in the hospital examination, dual-cuff BPM also only available in the hospital which can monitor more precise BP, irritating chest attachable AF monitor and the bulky biofeedback device (BFD) consists of multiple devices and also the vascular doppler detector can be replaced by the single smartphone. The complicated, time and cost-consuming various CVD indicators monitoring can be replaced by the simple placement of fingers on the OLED display applied smartphone which can be done whenever and wherever needed with easy usability (~15 sec of sensing time) while supporting multiple functions thus revolutionize the diagnostic and treatment.

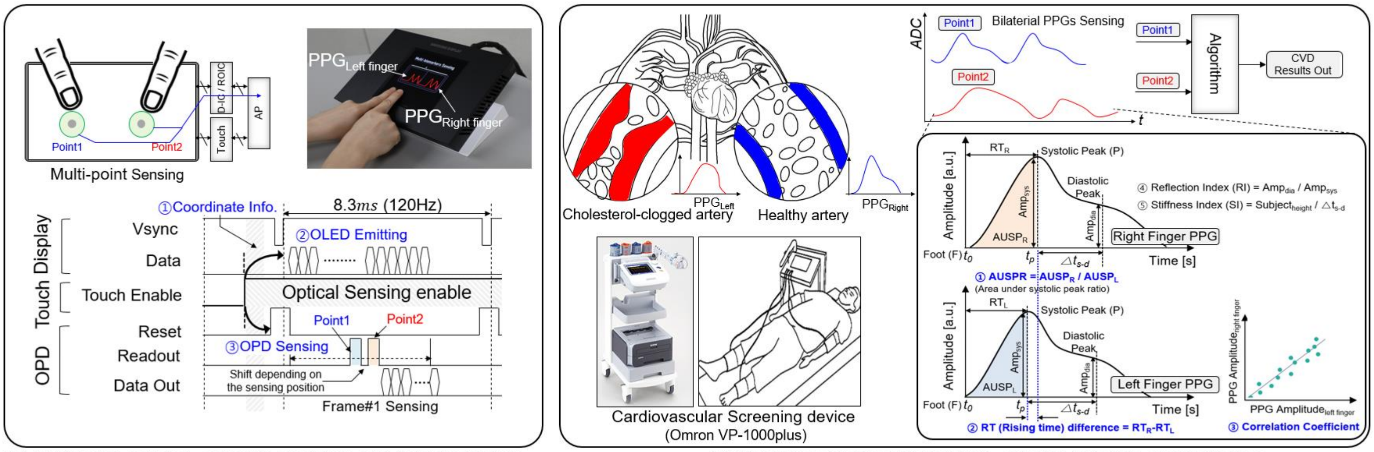
2. Results

Multi-functional Sensor OLED: Figure2 shows the concept of the multi-functional Sensor OLED which supports high resolution image and PPG sensing concurrently in a single device. It has an identical hardware including the Sensor OLED display and the electronics to support its operation but differentiated the OLED emitting, OPD sensing, readout operation, signal processing and algorithm depending on the applications as the sensing objects, method, key performance measures, frame rate and the optimum size of the optical system *(p)* are different between imaging and PPG sensing. The details about the implementation perspective can be founded in our previous report [1].

Multi-point sensing: Due to the high resolution and pixilated integration of the OPD within the display active area, a distinctive multi-point sensing can be obtained. Figure3 (a) shows the system block diagram and operation procedure. Once the user starts the sensing by placing the fingers, the touch enable signal from touch IC is activated, thus it triggers OLED and OPD operations by detecting and sending the touch coordinate information. The one frame of display images for sensing (the emitting pattern) and optical sensing data obtained from the multiple positions are displayed and sensed concurrently in every 8.3*ms* (refresh rate of 120Hz). The sensed OPD signal is quantized by analog-to-digital converter (ADC) in the ROIC then transferred to application processor (AP) for a pre-processing and input to the algorithms.

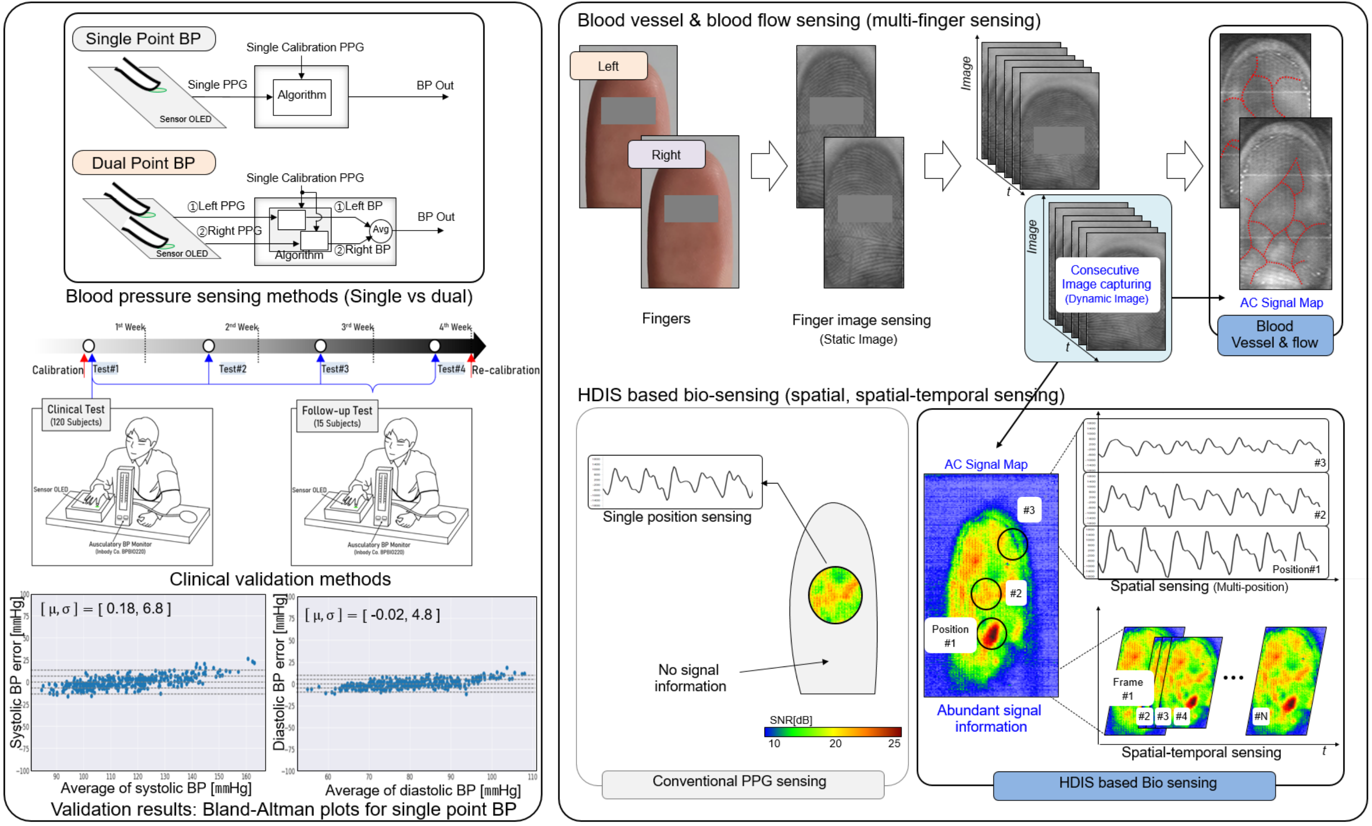
CVD Monitor: Bilateral PPG sensing from the left and right finger is allowed by utilizing the distinctive MPS. So, the differences in PPG pulses can be observed depending on the arteries condition. By obtaining and analyzing the signals on the left and right sites from the MPS capable Sensor OLED, we expect it has abundant potential to accurately screen CVDs. Among the PPG pulse waveform, we focused on the features related to the rising edge of the pulse from the foot to the systolic peak such as the area under the systolic peak ratio ($AUSP_{Ratio}$), rising time (RT) difference and correlation coefficient. Since, it is caused by pressure wave from the left ventricle to the extremities of the body thus directly implies artery conditions. (Figure3 (b)) To check the feasibility, we conducted a clinical trial recruiting 88 subjects (47 subjects with CVDs, 41 healthy subjects) in accordance with the Institutional Review Board (IRB) approved procedures. We compared the detection accuracy using the three indexes. $AUSP_{Ratio}$ shows the best CVD screening capability with an accuracy of 90% than other indexes. Thus, we reached the conclusion that the area related index is more suitable and performs well in CVD screening than time and amplitude related index. As a result, the ubiquitous CVD screening can be realized in a much more convenient way (~15 sec) without any restrictions (place, time and cost) whereas, the conventional CVD monitoring requires 5~10mins with the abundant restrictions (hospital visit, time and cost)

Blood Pressure Monitor: Cuffless BP monitoring technologies promise to measure BP comfortably with minimal user intervention by eliminating the need for a cuff, thereby facilitating ubiquitous self-monitoring. However, significant accuracy-related challenges must be addressed to enable widespread adoption in clinical practice. To address these issues, we employed two different approaches, as shown in Figure3 (c). The first approach involves developing a differentiated algorithm for single-point BP sensing, using a single calibration and a single-point PPG signal. The second approach utilizes both left and right PPG signals as inputs with a single calibration PPG, aiming to enhance estimation accuracy by effectively doubling the input information and maximizing the



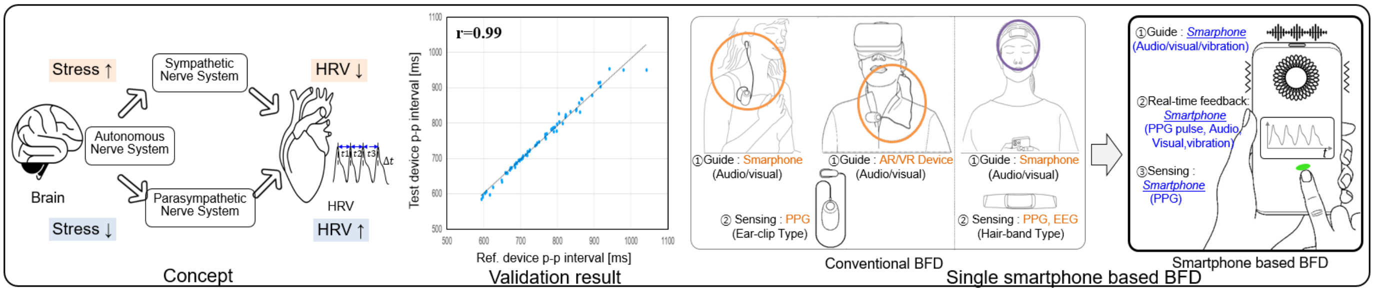
(a) Multi-point sensing: concept, operation and implementation

(b) Cardiovascular health monitor : sensing principle and validation



(c) Blood pressure sensing: concept, validation methods and results

(d) HDIS : Blood vessel & flow sensing, HDIS based bio-sensing concept and result



(e) Stress (Heart Rate Variation) sensing : concept, validation result and concept of the single smartphone based biofeedback device

Figure 3. Multi-functional Mobile Cardiovascular Health Monitor: Concepts, operation and sensing principles, validation methods and results

Table 1. Performance comparison with the current state-of-the-art PPG sensors

	Sensor			Form factor	Sensing capability			Supportable function	Ubiquitous sensing
					MPS		UIS		
	Material	LED	PD		PPG	HDIS			
[2]	Inorganic	Green, Red, IR : 4	PD: 4	Wrist-worn	×	×	×	HR (Motion Artifact ↓)	Limited support (Require separate processing units and sensors)
[3]		Green: 1	PD: 1	Finger-worn	×	×	×	HRV	
[4]		Red, IR: 1	PDs	Ear-warn	×	×	×	HR, HRV, SpO_2, RR	
[5]	Organic	OLED (G or R): 17×7	OPD: 1	Patch (Standalone)	×	×	×	HR	
[6]		OLED (Red, NIR): 2×2	OPD: 8		×	×	×	SpO_2, 2D Oxygnation maps	
[7]		-	OPD: 16×16		×	×	×	SpO_2, HR	
[8]		-	OPD: 256×256(508ppi)		×	×	×	Fingerprint, Vein (Single point only)	
This work		**OLED (R,G,B): 2,160×1,780(374ppi)**	**OPD: 1,024×1,768(262ppi)**	**Display**	○	○	○	**CVD1), BP1),2), AF2), HR2), HRV, RR, Blood Vessel & Flow1), Fingerprint**	**Fully support (Smartphone integrated)**

1) New functions integratable into the smartphones, 2) Equivalent performance with the medical devices, *LED: light-emitting diode, PD: photodiode, MPS: Multi-point sensing, PPG: Photoplethysmography, HDIS: High resolution dynamic image sensing, UIS: user interactive sensing

advantage of MPS capable Sensor OLED. For the single-point BP sensing, we focused on three different aspects to improve accuracy and validate performance. Firstly, for the dataset, we employed PulseDB for training and validation in a subject-independent manner, ensuring that no individual data from the training set appeared in the validation set. Secondly, we developed a differentiated preprocessing and machine learning (ML) model. Lastly, an extensive clinical trial was conducted in strict adherence to the standard protocol including an additional four-week follow-up test. This was done to validate the algorithm's accuracy, track BP changes, and assess long-term stability, ensuring that it reflects real-world clinical scenarios. Based on the clinical trial (employing 120 subjects in accordance with the IRB approved procedures), the algorithm achieved medical device level accuracy. For the second approach, dual-point BP sensing, we estimated BP values from bilateral PPG signals using a single calibration PPG signal as input for the designed BP algorithm. The final BP value was determined by averaging the estimates from the left and right measurements. Based on the pilot clinical trial with 57 subjects, we obtained further enhancements in accuracy and usability (reducing sensing failure rate from 8.82% to 2.75% as BP estimation is possible even if one signal is totally impaired due to the artifacts or low SNR)

HDIS sensing: Figure3 (d) shows consecutive high-resolution image captures from the fingers enable identification of blood vessel. Additionally, by analyzing the gray level changes in these images in relation to heart palpitations, blood flow can be detected through the generated pulsatile (AC) signal map. Consequently, the Sensor OLED embedded smartphone could replace traditional vascular Doppler detectors, typically only available in hospital settings, making it useful for diagnosing finger blood vessel conditions and assessing circulation quality. Moreover, new bio sensing methods have been developed based on the generated AC signal maps (spatial, spatial-temporal sensing) that we believe are beneficial and its effectiveness will be validated in the future.

User Interactive sensing: Due to the benefits of display and sensor integration, real-time interactive sensing is supported while the signal capture is in progress. Users can check the signal quality in real time while observing the GUI on the display and take immediate corrective actions, such as modifying finger contact conditions, including finger position and pressure. As shown in Figure3 (e), Stress sensing is possible thus enables a truly single smartphone-based biofeedback device (BFD) by fully taking advantage of UIS. So, it could replace the currently prevalent bulky, multiple-device-based BFDs to enable ubiquitous monitoring.

3. Conclusion

We presented a Sensor OLED-based, multifunctional CVD health monitor on a single smartphone. As summarized in Table 1, the benefits of the Sensor OLED are clearly demonstrated through its sensing capabilities, functions, and ubiquitous sensing ability. It also indisputably proves that the most user-interactive display device with sensors could drive disruptive innovation in smartphones. Therefore, we believe the Sensor OLED could serve as a key enabler in the evolution of smart devices toward mobile health monitoring and digital therapeutics, potentially revolutionizing diagnostics and treatment. Consequently, it could significantly reduce the healthcare burden on society.

4. Acknowledgements

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5. References

1. Kim C. et al., Sensor organic light-emitting diode display, combining fingerprint and biomarker capturing. *Commun Eng* 3, 92 (2024).
2. Lee J. et al., Motion artifact reduction in wearable photoplethysmography based on multi-channel sensors with multiple wavelengths, *Sensors*, 20, 1493 (2020)
3. Singstad B. et al., Estimation of heart rate variability from finger photoplethysmography during rest, mild exercise and mild mental stress, *J. Electrical Bioimpedance,* 12, (2021).
4. Ferlini A. et al., In-Ear PPG for Vital Signs, *IEEE Pervasive Computing*, 21, (2022).
5. Lee Y.J., et al., Standalone real-time health monitoring patch based on a stretchable organic optoelectronic system. *Science Advances*, 7.23 (2021).
6. Khan, Y. et al., A flexible organic reflectance oximeter array. Proceedings of the National Acad. of Sci, 115.47 (2018).
7. Simone, G. et al., High-accuracy photoplethysmography array using near-infrared organic photodiodes with ultralow dark current. Adv Optical Materials, 8.10 (2022).
8. Yokota, T. et al., A conformable imager for biometric authentication and vital sign measurement. Nat Elec.3,(2020)