Application of Organic Photodetectors (OPD) in Photoplethysmography (PPG) Sensors: A small review

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Application of Organic Photodetectors (OPD) in Photoplethysmography (PPG) Sensors: A small review

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Abstract: *The application of organic photodetectors (OPD) in photoplethysmography (PPG) sensors has rapidly improved the skin compatibility of the sensors providing high flexibility and low weight that is essential for continuous and real-time physical condition monitoring, Combination of OPD with organic or inorganic LEDs with proper circuitry and algorithm can detect noise free accurate heart rate signal and measure the oxygen saturation in blood, very crucial for everyone including the critical patients. The advancement of the PPG sensor with the application of OPD along with the challenges associated with it and its way of further improvement has been presented in this paper. The improvement of PPG sensors with OPD will speed up the accurate measurement of everyday health conditions and reduce the possibility of sudden failure of human health conditions.*

Keywords: Organic Photodetector (OPD); oxygen saturation; photoplethysmography (PPG); PPG signal.

1. INTRODUCTION

Organic Photodetectors (OPDs) have gained much attention from the researchers in last few years due to their advantageous features like lightweight, flexibility, cost-effective and large area production capabilities using vacuum, printing, and solution-based techniques making them compatible with the current commercially available inorganic photodetectors to be used as safer and smarter sensors [1-4]. The chemical structures of the organic photon-absorber can be altered which successively provides the chance to tune the photoresponsivity of the material and enables it to cover a wide range of electromagnetic spectrums ranging from the ultra-violate (UV) to near-infrared (IR) region [5-6]. Due to its advantageous properties, OPD has an enormous potential to be employed in applications like artificial vision, image sensing, health monitoring sensors, optical communication, and other applications [7-10].

The demand for monitoring physiological conditions with wearable electronics in human bodies has increased exponentially in the last few decades with the rise of the population rate. By detecting a person's oxygen saturation, heart rate, sleep quality, muscle activity, and other physiological activities daily with wearable electronics, it may be predicted who is in danger of getting a coronary failure, seizure, or other chronic diseases [11]. Photoplethysmography (PPG) sensor is one quite such wearable device that uses light of two different wavelengths to see the changes in pulsatile blood flows at the skin interface noninvasively [12]. This PPG device can be applied for measuring arterial oxygen saturation (SpO_2), pulse rate and blood pressure, microvascular pressure level, respiration rate, etc. [13]. Till now, the PPG sensors depend upon silicon and other inorganic semiconductor photodiodes for higher carrier mobility, tunable bandgap, and low exciton binding energy but suffer from disadvantages like fragility, costly fabrication process, rough interface with the skin leading to less accurate data and limited usable positions on the body [1,14-15]. This problem can be eliminated using an OPD rather than conventional inorganic PDs. Application of OPD in PPG sensor can provide a flexible, miniaturized skin conformable biomedical device. But selecting an appropriate photo-absorber for achieving a high-performance PPG sensor is very crucial which is a topic to look at.

This review article aims to give an overview of the representative work done in the field of OPD application in PPG sensors including the innovations, drawbacks, and remaining challenges for such reasonable application of OPD in PPG sensors. We start by introducing the OPD fundamentals, i.e., working principle and figure of merit followed by the operational mechanism of the PPG sensor. Then we focus on the OPD application in PPG sensor and finally propose our future planning to prepare a PPG sensor with the combination of OPD and traditional inorganic LEDs.

2. ORGANIC PHOTODETECTOR FUNDAMENTALS

Photodetector generally converts the photon energy of a light signal into an electrical signal. According to their operation mechanism, OPDs can be organized into three categories- organic photoconductors (PC-OPDs), organic phototransistors (PT-OPDs), and organic photodiodes (PD-OPDs) the schematic structure of which have been shown in Fig. 1 [16-17]. PC-OPDs work with photoconductive phenomenon i.e., exhibit large resistance in dark conditions while showing conductive behavior under light illumination. In the case of PT-OPDs, there are three electrodes called source, drain, and gate with an additional photoconductive gain that can be achieved using external biasing conditions. Among the three kinds of OPDs, the most researched and used are the PD-OPDs in which extraordinary photosensitivity and photoresponsivity can be achieved. The three kinds of OPD structures are shown in Fig. 1. Over the last few decades, many methods like the synthesis of material, structural engineering, and modifying interface have been adopted by researchers to improve the OPDs further and eliminate their demerits.

2.1 Operation mechanism of OPD

OPD has an operating mechanism that adopts the photoelectric effect just like an organic solar cell (OSC)

[16-17]. When photons with energy higher than the band gap energy are absorbed in an organic semiconductor layer, bounded electron-hole pair, i.e., excitons are generated which diffuse to the donor-acceptor interface and shift to lower energy states. The built-in voltage or extra reverse bias present at the interface dissociates the excitons into free charge carriers- electrons and holes which transport through the organic semiconductor layer to the electron/hole transport layer and are finally collected at the electrodes. The generation of free charge carriers through efficient exciton dissociation is very critical for the performance of OPD. Through molecular engineering i.e., designing the donor and acceptor, controlling the OPD morphology, and novel device design, more free carrier generation can be achieved which in turn improves the OPD performance [18].

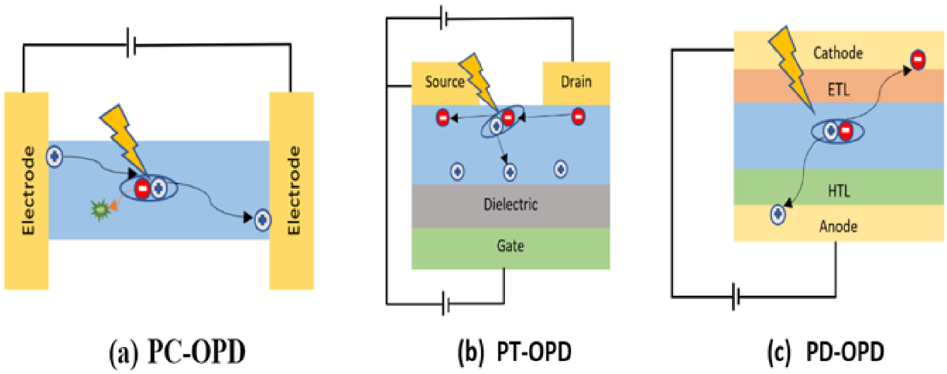

Fig. 1: The schematic structure of different kinds of OPDs

2.2 OPD performance metrics

There are some important parameters on which the performance of OPD depends. The parameters include- responsivity (R), external quantum efficiency (EQE), dark current density (J_{dark}), noise equivalent power (NEP), specific detectivity (D*), and linear dynamic range (LDR), and response speed.

(1) Responsivity (R) is the ratio of the photogenerated current (J_{ph}) and the incident light intensity (P_i) at a given wavelength which can be expressed as-

$$R = {J_{ph}}/{P_{in}} \quad (1)$$

(2) External quantum efficiency (EQE), also denoted by η is described as the ratio of the generated carrier numbers to the number of the incident photons. It is a unitless quantity that can be described as-

$$EQE = {J_{ph}hv}/{P_{in}q\lambda} = R({hv}/{q\lambda}) \quad (2)$$

where, h denotes the Planck's constant, represents the light speed, q is the elementary charge and λ is the incident light wavelength. EQE value can exceed 100% when there is a photoconductive gain.

(3) Dark current density (J_{dark}) is the current which can be attained under the dark condition with a reverse bias applied to the OPD. It can deteriorate the device sensitivity, linear dynamic range, and detectivity and so it must be controlled by adopting different strategies.

(4) Noise equivalent power is described as the lowest incident optical power which can result in a detectable output signal. It is generally used to measure the sensitivity of the detector. It can be given by-

$$NEB = {i_{noise}}/{R\sqrt{B}} \quad (3)$$

where B stands for the normalized detection bandwidth. Three types of noise are dominant in an OPD- the flicker or 1/f noise, thermal noise, and shot noise. The experimental measurement of noise is difficult that's why only the shot noise resulting from the dark current is used to find the dominant contribution of the noise current.

(5) Specific detectivity (D*) defines the NEP normalized by the device area and expressed as a unit of Jones (J). It can be expressed as-

$$D^* = {\sqrt{A}}/{NEP} = {R\sqrt{A}}/{i_{noise}} \quad (4)$$

(6) Linear Dynamic Range (LDR) defines the range up to which the photocurrent is proportional to the incident optical power. It is given by-

$$LDR = 20\log({J_{ph}(max)}/{J_{ph}(min)}) \quad (5)$$

J_{ph}(max) and J_{ph}(min) refer to the maximum and minimum current respectively.

(7) Response speed can be expressed using the response time with the rise time for the response to go 10% to 90% of its highest value and decay time to go from 90% to 10% of the response.

3. PPG SENSOR PRINCIPLE AND APPLICATION

A PPG sensor monitors the blood volume changes in the microvascular system to obtain the PPG signal. A conventional PPG sensor consists of two main components- a light-emitting diode (LED) as the light source and a photodetector (PD) for light detection. A PPG sensor can detect the signal in different breathing, hypovolemia, and circulatory conditions due to its noninvasive optical measurement system [19]. A PPG sensor can acquire a PPG signal in two different modes- one transmissive and one reflective. In the transmissive mode, the LED and PD are positioned on the opposite side of the skin, and only the transmitted light through the tissue, bone, and/or blood vessels is detected by the

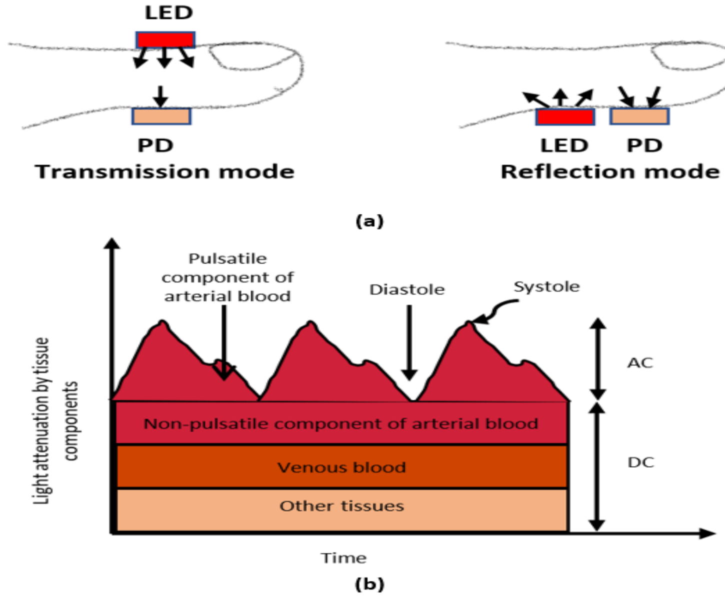

Fig. 2: (a) Demonstration of two PPG sensor modes (Transmission and reflection mode), (b) Light attenuation through tissue medium

PD. On the other hand, for reflective mode, both LED and PD are placed on the same side of the skin, and the backscattered or reflected light is collected by the PD. For this mode, the sensor can be positioned in various spots of the body like the finger, wrist, forehead, abdomen, and legs whereas in the transmissive mode the sensor can be placed only on fingers, earlobes, and neonatal feet due to the limited sensing location for confined transillumination [20]. The positioning of LED and PD for the two modes of PPG has been displayed in Fig. 2(a). The light from the LED of a PPG sensor illuminates the skin and creates a volumetric change of blood in the veins and the capillaries. Due to this change, light intensity variation occurs in the transmitted and reflected light through the skin which is detected by the photodetectors. A typical PPG waveform has both a direct current (DC) part created due to the absorption of non-pulsating arterial blood and scattering all over the tissue and an Alternating current (AC) part resulting in due to the arterial blood volumetric change between systolic and diastolic phase of cardiac cycle [21]. Light attenuation through different tissue mediums of human skin has been shown in Fig. 2(b).

Blood oxygen saturation (SpO_2) level measurement is an important feature of the PPG sensor where the pulse oximetry method is adopted for estimating the different concentrations of oxygenated hemoglobin (HbO_2) and reduced hemoglobin by measuring the PPG signal at two different wavelengths. The oxygen saturation of the arterial blood can be expressed as-

$$\%SpO_2 = \left({}^{HbO_2}\!/_{HbO_2 + Hb}\right) \times 100\% \qquad (6)$$

where HbO_2 and Hb are concentrations of oxygenated and deoxygenated hemoglobin respectively. In a typical PPG sensor, two different LEDs emit light of two different wavelengths (a combination of green and red or a combination of red and IR) depending on the oxygenated condition, the absorption intensity of light differs from each other. The modulation ratio, i.e., the double ratio of AC and DC components in two light sources is used to calibrate the SpO_2 level. The calculated SpO_2 value resembles the corresponding SpO_2 level in blood.

By adopting a convenient and low-cost technology, PPG sensors have now a vast field of application in the biomedical field for the detection of blood oxygen saturation, heart rate, blood pressure, cardiac output, respiration, and arterial aging. PPG waveforms can correlate with age and cardiovascular pathology [22]. The Apple Watch 6 series implemented Green, Red, and IR LEDs in its PPG hardware to measure the heart rate and oxygen saturation using the reflective photoplethysmography from the human wrist position. The Samsung Galaxy Watch 3 also implements a PPG sensor with which it can measure blood pressure also. Withings Scanwatch and other Garmin products can also measure oxygen saturation using the PPG sensor [23]. But all of these products have a combination of inorganic LEDs and PDs which doesn't allow a flexible and conformable connection with human skin. The skin conformability can be achieved through the application of organic electronics in the PPG sensor.

4. OPD IN HUMAN SKIN-COMPATIBLE PPG SENSOR

Organic materials application in PPG sensors has resulted in a highly flexible cost-effective device with an easy and large fabrication scale. Lochner et.al.[24] prepared an all-organic transmissive mode PPG sensor that consisted of two organics LED arrays- one green (wavelength peak at 532 nm) and one red (wavelength peak at 626 nm) and two OPDs. They chose green OLED instead of NIR OLEDs considering the fact of lower stability of solution-processable NIR OLED materials and having almost the safe molar extinction coefficient difference value of oxygenated an)IR)d deoxygenated hemoglobin in both green and NIR wavelength regions. For ensuring a high EQE, they adopted a blend of Poly({4,8-bis[(2-ethylhexyl)oxy]benzo [1,2-*b*:4,5-b′]dithiophene-2,6-diyl}{3-fluoro-2-[(2-ethylhexyl) carbonyl] thieno[3,4–b]thiophenediyl}) (PTB7) and [6,6]-phenyl C71-butyric acid methyl ester ($PC_{71}BM$). The fabricated OPD offered an EQE of 38% and 47% at the wavelength of 532 nm and 626 nm respectively at the short circuit condition with a leakage current of 1 nA/cm^2 at 2V applied reverse bias condition. They calculated the heart rate (60-70 beats per minute) and oxygenation (94-96%) from the PPG signal derived using inorganic with an error of 1% for the pulse rate and 2% for the oxygenation level.

Park et.al. [25] proposed an ultra-flexible near-infrared (IR) responsive skin conformal PPG sensor with sufficient mechanical conformability required for health monitoring applications for improving charge extraction. The OPD structure used a BHJ active layer consisting of PIPCP polymer as an acceptor and $PC_{61}BM$ as a donor fabricated on an ultra-thin (1 µm thick) Parylene substrate with an inverted structure configuration. The 3 µm ultrathin OPD exhibited high operational durability in the case of extreme mechanical deformation with the stability of charge carrier transportation. The ultrathin OPD device ensured rapid signal response (>1 kHz) in the near-IR region because of the beneficial self-organization of the polymer chain. A thickness of about 200 nm was chosen for the active layer of the PPG sensor for obtaining high switching properties and ensure good skin conformity characteristics. The peeled device from the glass substrate showed linear photocurrent and Voc behaviors during the electrical characterization process which indicated minimal trap-assisted charge recombination in the BHJ layer. Though the I_{sc} value of the device decreased with the shrinkage of the effective area for incident light, no change in Voc was found conforming to excellent charge generation and transportation under extreme mechanical deformation. Along with a commercial IR LED and the fabricated OPD, the author and his co-workers were able to gain repetitive systolic and diastolic pulse from which oxygenated situation and BPM of blood flux were calculated from the fingertip of an adult person. The peak-to-peak intensity of the gained signal went through a Fourier analysis, resulting in a 64 BPM heart rate which is in the acceptable range for an adult. Their results pointed out the possibilities of skin conformable electronics to be used as a portable cardiovascular sensor for emergency health care services.

Rather than using the transmission-mode pulse oximetry limited for only single point measurement of blood oxygen saturation, a 2D oxygenation mapping with reflective pulse oximetry can provide real-time measurement of physical condition as well as can help realize tissue damage and injury predisposition. Considering this issue, Khan and co-workers [15] reported a reflectance oximeter array (ROA) with a combination of eight OPDs and four red (612 nm), and four NIR (725 nm) OLEDs. The ROA was made by stacking the separately fabricated OPD and OLEDs using the printing techniques which ensures skin conformability along with high SNR. In the OPD array, there were eight OPDs, where each row contained two OPD pixels. As in the case of the OLED array, the four rows contained a total of eight OLEDs in alternating color patterns. The arrays in the ROA maintained 0.5 cm emitter-detector spacing. 30% EQE was achieved with a very low dark current and a cut-off frequency of 5 kHz had been achieved for the OPD array. The OLEDs were operated at 10 mA/cm^2 when used for the oximetry application. The ROA was connected with additional circuitry for the operation, where the analog front end (AFE) sequentially drove the OLEDs and read out the OPD signals. The device was applied to the forearms and forehead of human volunteers who were inhaling oxygen at varying levels. A mean error of 1.1% was observed while comparing the oxygen saturation with the proposed device and commercially available device. 2D contour mapping was done for the data collected from all the oximetry pixels for mapping the oxygen saturation created. The authors proposed that using the 2D mapping capability, the ROA can be used for monitoring the oxygenation of tissues, wounds, and also in newly transplanted organs. With the integration of the near-infrared spectroscopy (NIRS) system and ROA, they suggested that ROA interfaced with printed electromyography (EMG) and electrocardiography (ECG) electrodes can provide a lightweight, comfortable, and wearable sensor for muscle activities during normal and physical activities of the human body.

Acquiring a sufficient level of PPG signal sometimes requires a high-power consumption which hampers their use as stand-alone and continuous health monitoring systems. Lee et. al. [26] presented a reflective patch-type sensor with a combination of flexible OLEDs and OPDs with ultralow power consumption. The author and his co-workers adopted green OLED and red OLED for SpO_2 measurement that requires two spectral light sources of different extinction coefficients for HbO2 and Hb. The OPD consisted of an active layer of the mixture of C70 and 4,4’-cyclohexylidenebis[*N*,*N*-bis (4-methylphenyl) benzenamine] (TAPC). Using circular OLEDs with a radius of 0.4 mm wrapped around by OPD resembling the number “8”, they were able to couple light to the OPD coming from the OLEDs from all directions minimizing the waste of light. The completed OPO sensor was applied to different human body parts like the finger, wrist, neck, and nose and reliable heart rate and SpO2 signal were obtained with very low power consumption by the OLEDs (31 µW for the green OLED, 17 µW for the red OLED). The presented results in the paper proposed the possibility of using an all-organic device as an all-day wearable health monitoring system with a high form-factor advantage.

For accurately acquiring the PPG signals with reduced power consumption, designing the sensor geometry plays a crucial role. Khan and his co-workers [27] reported reflection mode PPG sensors giving much attention to the sensor geometry like proper shape, spacing between

OLEDs and OPD, and introduction of an optical barrier to reduce light scattering. Using three different geometries i.e., rectangular, bracket, and circular geometry with optical barriers, they were able to improve the performance of the PPG sensor. All types of sensors consisted of printed red and NIR OLEDs along with OPDs with EQE of around 20%. As a symbol of a conventional sensor, the rectangular-shaped sensor exhibited high noise whereas the bracket and circular-shaped sensors resulted in enhanced SNR measurement because of perimeter lighting and better light collection by the OPD. The author and his co-workers observed 39.7% and 18.2% improvement in the magnitude of PPG signal for red and NIR channels using bracket geometry while it was 48.6% and 9.2% improvement in the case of circular geometry respectively compared to the rectangular structure. The two new geometries also resulted in a reduced size of the sensor. Using black tape as a blocking medium for scattered light, they reported a 26.5% improvement in PPG signal amplitude for the red channel. Based on the results for different geometry, they made a PPG sensor applicable to various locations of human skin. Multichannel accurate data acquisition was obtained by them with the application of template matching (TM) and inverse variance weight (IVW) algorithms. The clearest PPG signals were obtained when the device was applied to the position close to the ulnar and radial artery rather than the wrist. This study indicated that the application of TM and IVW algorithm in a properly designed PPG sensor can result in a skin-compatible PPG sensor with good SNR.

Fahed and co-workers [28] presented a monolithic pulse oximeter consisting of a red OLED and an OPD fabricated on the same substrate for working in reflective mode. The ray-tracing method along with the Monte Carlo method was adopted for simulating two different structured devices (combination of circular OLED and ring-shaped OPD for one case, Device-A and ring-shaped OLED and circular OPD for another structure, Device-B). Maximum irradiance of 3.7×10^{-10} W/mm^2 and 2×10^{-9} was estimated through the simulation which resulted in the total power of 5.9×10^{-9} W and 6×10^{-9} when multiplying with the respective OPD area for both devices. The OPD structure comprised of DBP:C60 based active layer resulted in an EQE of around 37% for both devices at 625 nm wavelength at zero bias condition. The PPG signals were obtained with both devices along with other circuit components and passed through a designed digital finite impulse filter (FIR) for removing the noise caused by motion artifacts. Both the devices were applied to the finger of healthy male persons at the resting condition for acquiring PPG signals with a 1.5% error compared to a commercially available pulse oximeter. The application of the FIR filter resulted in a 5% improvement in the signal quality obtained by both devices. The devices were also applied to different body positions like different fingers, forearms, wrist, and forearms, and successful signals were obtained from Device A. Their study suggested a newly designed device that can be applied in different positions of the human body acquiring PPG signal high SNR and low power consumption.

Though having the excellent detection probability of PPG signals with low power consumption and high flexibility, all organic PPG signal detection device suffers from a short lifetime due to the structure of OLED. LEE et. al. [29] proposed a hybrid organic-inorganic device adopting inorganic LEDs and wrap-around OPD which can be easily integrated by lamination. The layer-resolved analysis done through optical simulation in the author's study supported their "near-zero-margin" design for the device with inorganic red and NIR LEDs wrapped around eight shaped OPD. The optical simulation resulted in a conclusion that indicated close positioning of the light source and OPD for detecting meaningful PPG signal resulting from a deeper layer rather than the epidermis. For the active layer of OPD, PTB7-Th was adopted as the donor and IEICO-4F was used as the acceptor fabricated through the spin coating process. Both LED and OPD were fabricated on different substrates allowing independent preparation of OPD. The device applied to the bottom side of the finger was able to detect the PPG signals and SpO_2 levels with an average power consumption of about 35 µm which is lower compared to the commercially available sensors. The proposed sensors exhibited a good performance (at over 90%) 40 days after fabrication which ensured its potentiality of being an ultralow power consumed pulse oximeter sensor for PPG signal detection.

5. PROPOSED HYBRID PPG SENSOR

As discussed earlier, all organic PPG sensor suffers from a short lifetime and complicated fabrication process, we are trying to make a hybrid PPG sensor adopting commercially available green and red LEDs along with a circular-shaped organic photodetector, OPD fabricated by an easy solution process. Lee et. al. [29] also proposed a hybrid PPG sensor described in the previous section where they adopted Red, and IR LED wrapped around an 8-shaped OPD. But in our device, we are planning to use green and red LEDs due to their emission spectrum in the visible region which can easily be absorbed by the donor-acceptor mixture of the OPD as the active layer which can be selected easily. Also, the green LED having almost the same penetration depth as the IR LED showed better performance and a higher correlation for measuring oxygen saturation both at room temperature and temperature below 15 ^{0}C experimentally. Our OPD will have a circular shape centering both the LEDs at its center which will reduce the size of the device [30]. The OPD will be fabricated on a very thin substrate which will be connected using some adhesive with the PCB containing the LEDs and all the circuit elements needed to control the LED switching, LED duty cycle controlling, acquiring the OPD signals, amplification, and filtering element for getting noise free PPG signal. BLE (Bluetooth low energy) chip will be adopted to communicate with a device to show all the information obtained from the PPG signal like heart rate and showing oxygen saturation level. For removing the effects of motion artifacts, some digital filters or algorithms will be applied to get noise-free signals.

As mentioned above, in a hybrid sensor configuration, the OPD and the LEDs will be placed in two different substrates which may rise a problem in placing them in an exact position to measure the PPG signal accurately without any noise introduced because of the distance between the two substrates. We are planning to use an adhesive like silver paste to make a good connection between the two substrates to get a noise-free signal.

6. CONCLUSION

The application of organic electronics in PPG sensors has improved skin compatibility as well as improved efficiency which have made great advances in the biomedical and self-health monitoring device sectors. In this paper, some studies about PPG sensors containing all organic or a combination of organic and inorganic materials have been summarized to make a clear understanding of the progress that has been achieved in PPG devices for heart rate signal detection and oxygen saturation rate calculation. By adopting different device structures, material combinations, and designs PPG signals can successfully be obtained but getting the signal without any noise from motion artifacts, low power consumption of the device, and device longevity are still some issues that need to be solved in the future for an effective PPG sensor device. Considering these issues, a hybrid PPG sensor device has been proposed which will be fabricated with a combination of inorganic LEDs and OPDs along with some algorithms to obtain a noise-free PPG signal. We believe that the application of organic electronics in skin-compatible healthcare monitoring systems with real-time signal detection will lead to many innovations and will expand the research field in this sector.

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