

# Seamlessly Integrable Optoelectronics for Clinical Grade Wearables

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Health and fitness wearables present viable solutions for public wellbeing by providing remote personal control and clinical intervention through telemedicine networks. Due to their noninvasive and continuous vital sign monitoring, optoelectronic wearables are incorporated in number of studies to identify the onset and progression of the Coronavirus pandemic, and institutions deployed patient surveillance networks based on them. Today's optoelectronic wearables rely on rigid light emitting and sensing technologies that are vulnerable to motion artifacts due to discontinuous skin contact. However, wearable-based digital health systems require the extraction of clinical grade data for the actionable outcomes. Therefore, optoelectronic technologies that provide clinical grade data through seamless skin integration are in high demand. The seamlessly integrable optoelectronic technologies for wearable based digital health solutions are discussed here. The review of highlighted wearable optoelectronic materials and technologies provides a benchmark, therefore helps to define pathways through the realization of clinical grade wearables rising as strong contenders for the public health strategies.

Wearable technologies have reached millions of users so far and consumers who do not own any wearable are expected to be more interested in purchasing a smartwatch, wristband, or earbuds while chest straps and smart clothing are less preferable (Figure 1c).<sup>[4]</sup> On the other hand, consumers who already have a wearable device would like to be capable of tracking calorie burn, identifying the cardiac status and managing high blood pressure (BP) among the potential features (Figure 1d).<sup>[4]</sup>


An analysis of wrist worn wearables over 423 unique devices have demonstrated that the total number of devices constantly increases while the release of new brands is limited by the user acceptance and half-baked products (Figure 1e).<sup>[5]</sup> The noninvasiveness and accuracy of the measurement technology is a key factor for both clinical and user acceptance of wearables. To that end, advancements in

optoelectronic integration technologies yielded consumer-based wearables with photoplethysmography (PPG), a noninvasive and powerful technique to send a light of a certain wavelength to skin and collect vital health information. The percentage of PPG based wrist worn devices exhibits an abrupt change from 0% to 71% in 6 years (inset of Figure 1e) proving a high demand on optoelectronic wearables. Today almost all wrist worn fitness trackers commonly employ photodetectors (PDs) and light emitting diodes (LEDs) to perform PPG. However, rigid light emitting, and sensing elements of wearables provide discontinuous skin contact during active motion of the body, allowing the interference of motion artifacts. Although the data processing to cancel the noise interferences has become an important part of the wearable market, additional hardware requirement and case specific algorithms that remain insufficient under complex real-world conditions do not offer a complete solution. To provide clinical grade data by preventing the interference of motion artifacts, optoelectronic wearables can be laminated to skin surface or integrated into garments. Here we provide a review of seamlessly integrable optoelectronic technologies and materials enabling clinical wearables for digital health systems to represent a reliable health infrastructure. Starting from the prospects and challenges of PPG technique for clinical grade wearables we provide a brief outlook to the currently available consumer wearables based on the technique. After providing information on the status of optoelectronic wearables in monitoring the Coronavirus pandemic, we summarize the flexible and transparent optoelectronics for

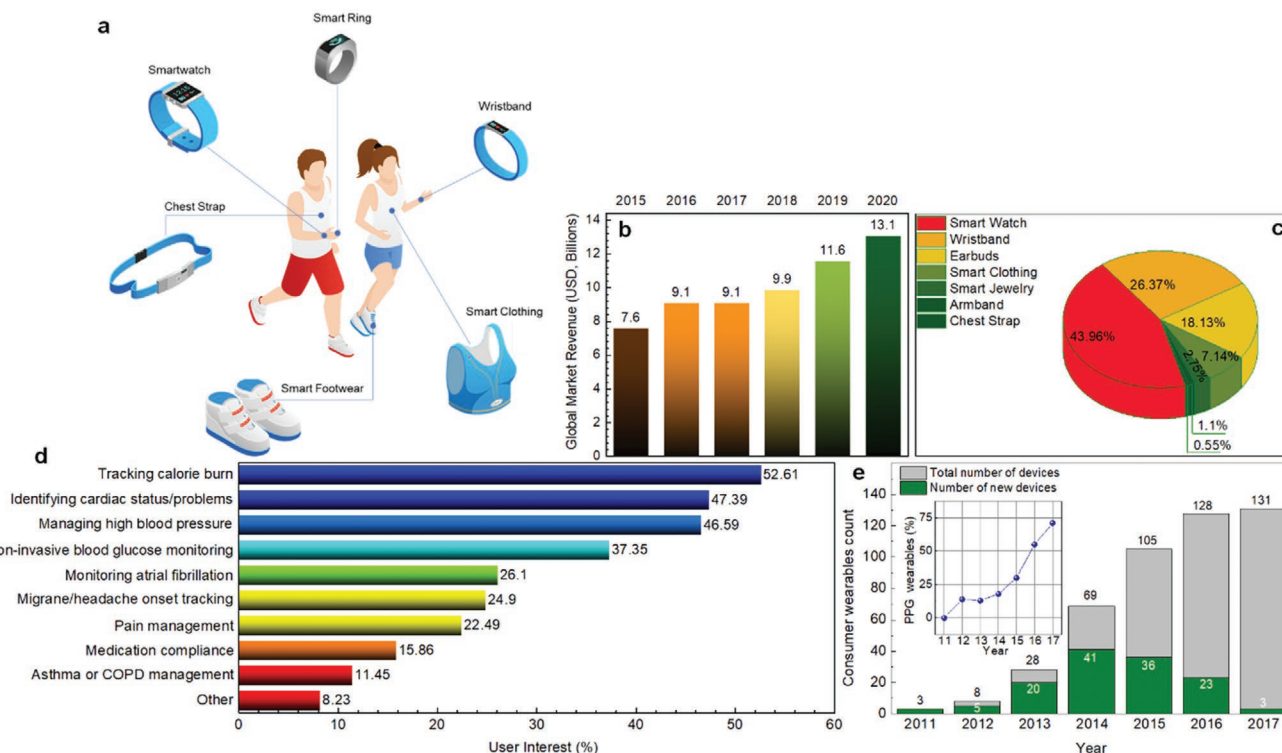
## 1. Introduction

Wearables represent a time and cost-effective platform allowing for the remote monitoring of physiological parameters. Either as fitness trackers or clinical setting devices, wearables contribute to the quality of human life by providing innovative solutions on tracking of personal health and wellness parameters. Wearables market accommodates variety of form factors from smart rings to fitness tracking wristbands (Figure 1a) holding a global market revenue of 13 billion USD in 2020 (Figure 1b).<sup>[1]</sup> Market growth is estimated to be 9.4% with a negative effect of the COVID-19 on the supplies in the first half of the year.<sup>[2]</sup> Virus crisis also hit the optoelectronics, sensors/actuators, and discrete semiconductors (OSD) after 10 years of record-high sales.<sup>[3]</sup> The 6% fall in the total OSD sales ends the decade long increment of the global market value which is expected to further affect the optoelectronic wearables. Therefore, new noninvasive materials and technologies are in high demand to lower the cost while providing more advanced control on vital health parameters.

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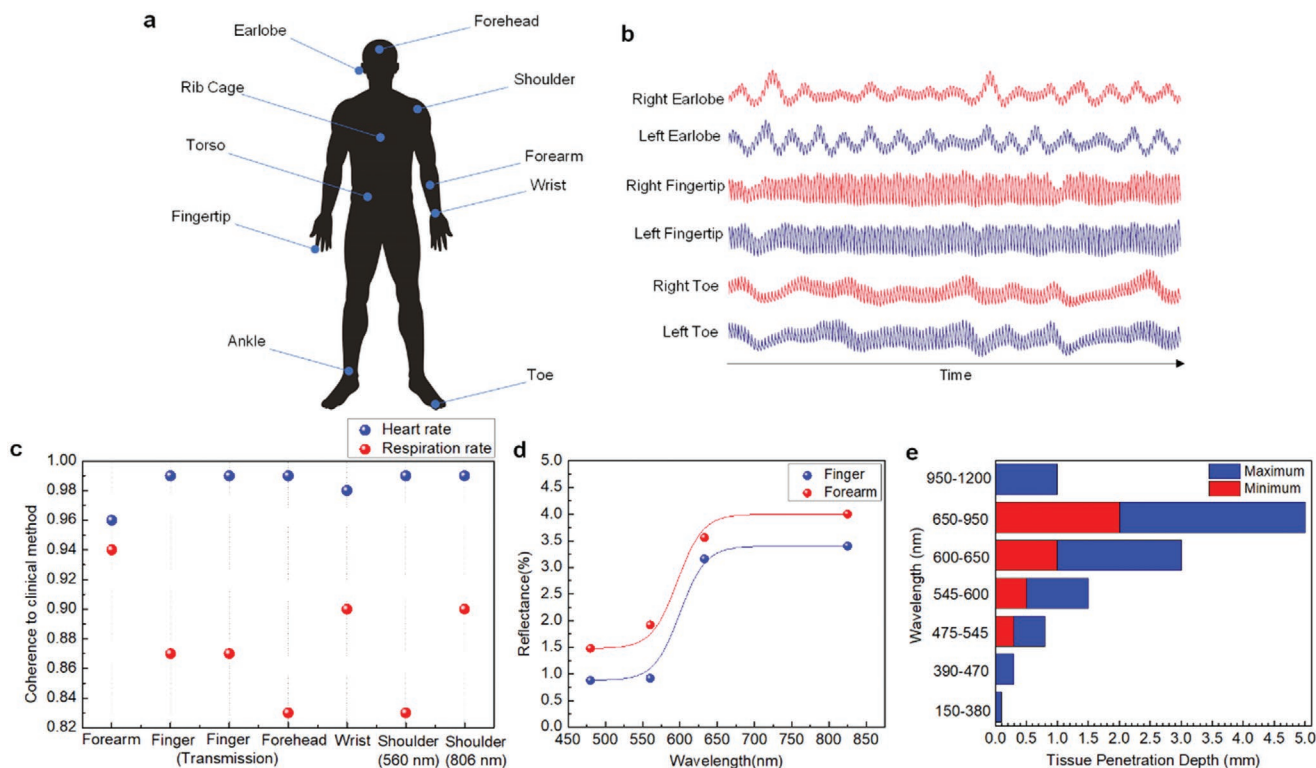
**Figure 1.** Market statistics, user interests, and the rise of optoelectronic wearables. a) Wearables' market encompasses variety of devices for different body locations. User adoption of each unit is strongly related to the functionality and compatibility to the active daily life. b) Bar graph of consumer wearables' 5-year market revenue. The global market reaches 13 billion USD in 2020 and the negative effect of Coronavirus pandemic is expected to slow down the growth for the second half of the year reaching a value of 9.4%.<sup>[2]</sup> Data taken from ref. [1]. c) Pie chart of the consumer interest on purchasing a new wearable. Survey of consumers who do not own any wearable device mostly consider purchasing a smartwatch (43.96%), a wristband (26.37%) or earbuds (18.13%), whereas there is less interest on smart clothing (7.14%), smart jewelry (2.75%), armband (1.1%) or chest straps (0.56%). Data taken from ref. [4]. d) Column graph of user interest on potential capabilities. Wearable device users have strong interest in potential capabilities such as tracking calorie burn (%52.61), identifying cardiac status (47.39), and managing high blood pressure (46.59%). User interest on potential capabilities are listed as noninvasive blood glucose monitoring (37.75%), monitoring atrial fibrillation (26.10%), migraine onset tracking (24.90%), pain management (22.49%), medication compliance (15.86%), asthma or chronic obstructive pulmonary disease (COPD) management and others (8.23%). Data taken from ref. [4]. e) Stacked bar graph showing the numbers of new wearables and the total number of wearables between years 2011–2017. Data taken from ref. [5]. Constant increase in the total number of wearables proves the high demand while the user acceptance and half-baked products limits release of new brands each year. Inset shows the percentage of wearables using photoplethysmography (PPG) with respect to years. Data taken from ref. [5]. The abrupt increase of PPG wearables from 0% to 71% proves the high demand on optoelectronic technologies to measure vital signs. Today almost all wrist worn fitness trackers use PPG to optically extract HR and related cardiac information. a) Adapted with free license macrovector/Freepik (www.freepik.com).

seamless integration giving access to clinical grade wearables. We also provide a system integration level review of different technologies and materials yielding skin integrable health devices. We compare them to clinical setting devices and standards. A general outlook and conclusions will be provided at the end.

## 2. PPG and Optoelectronic Wearables

PPG is a noninvasive technique to extract vital signs by sending a light of a certain wavelength to skin. Absorption in blood vessels creates a change in the intensity of the reflected (or transmitted) light and integrated PD registers the change as a heart rate (HR) and related cardiac information. PPG devices require a light source (typically an LED) and a light sensing element (PD) to extract the change of the vital parameter from skin. The measurement can be performed in transmission and reflectance

mode depending on the application and measurement site. Consumer based wrist worn wearables use the reflectance type PPG where the light source is placed along the PD. This way the skin reflected light is registered by the PD and the changes in the photocurrent are displayed as HR and related cardiac information. Since PPG uses local blood perfusion to extract cardiac information, it can be performed at different locations on the body and wide range of measurement sites have been reported from forehead to toe (Figure 2a).<sup>[6–10]</sup> On the other hand, in transmission mode, the PD and the light source are separated by the tissue, in which the light transmits through and reaches the PD. This limits the measurement positions on the body to the sites where transmitted light can be properly detected by the PD. Therefore, peripheral sites such as fingertips and earlobes are the most common positions for transmission mode PPG. Both the reflectance and transmission mode PPG present noninvasive measurement schemes for the extraction of various vital signs.



**Figure 2.** PPG for seamlessly integrable optoelectronic wearables. a) Reported body locations for PPG.<sup>[6–10]</sup> Unlike ECG, PPG uses local blood perfusion to extract the vital signs offering a design freedom for new generation wearables. b) Multiple site PPG measurements from left and right earlobes, fingertips, and toes. Adapted with permission.<sup>[6]</sup> Copyright 2007, IOP Publishing Ltd. Signals taken from the same sites shows nonsignificant deviation, while the proximal and distal site measurements possess differences in signal amplitude and phase. c) Coherence of PPG to clinical setting HR and RR measurements for different body locations. HR values extracted by PPG shows promising coherence (0.96–0.99) while RR measurements are reported to be less coherent (0.83–0.94). Data taken from ref. [7]. d) Percentage reflectance of finger and forearm with respect to illumination wavelength. Data taken from ref. [27]. e) Reported optical tissue penetration for wavelength intervals ranging from 150 to 1200 nm. Data taken from ref. [28]. a) Adapted with free license brgfx/FreePik (www.freePik.com).

Human skin provides a unique interface for wearables to extract physiological parameters. Although the various types of skin integrable wearables have been reported, the main goal of the wearable technology is to perform noninvasive and user-friendly operation; hence, certain approaches including implantable wearables do not represent the promises of the technology. Noninvasive extraction of biomarkers is generally performed optically,<sup>[11]</sup> therefore skin integration of optoelectronics offers clinical grade data extraction by preventing discontinuous skin contact.

Conventional electrocardiogram (ECG) techniques uses the electrical signal sourced from the heart; hence, the measured HR is generally affected by number of factors such as the electrode location and body fat.<sup>[12]</sup> Unlike ECG, PPG optically penetrates the tissue bypassing the anatomical factors that interfere with the measurements, therefore presents compatibility for development of smart clothing and electronic skin applications where the integration of multiple sensor systems over large area is required.<sup>[13–16]</sup>

It is worth noting for the design considerations that the simultaneous PPG measurements taken from distant body locations can alter in temporal characteristics due to the pulse transit time.<sup>[17]</sup> Allen performed a multi-site simultaneous PPG measurement to study the similarity and differences between

the left and right body sides.<sup>[6]</sup> The reported pulse waves show great similarity within the same side while there exists clear differences between the proximal and distal measurement sites (Figure 2b).

Operation of PPG in seamlessly integrated wearables has been demonstrated by the incorporation of nanomaterials and innovative device architectures.<sup>[18–20]</sup> When performed with highly sensitive PDs, the transmission type PPG bypasses the requirement of an integrated light source by using ambient light.<sup>[20]</sup> Alternately, usage of flexible LEDs,<sup>[19,21]</sup> and PDs,<sup>[20,22–24]</sup> makes PPG a body-integrable technology to realize clinical grade wearables. The noninvasiveness and efficiency of the technique makes it a common preference for consumer wearables and the level of coherence to clinical setting measurements demonstrates the reliability of the optical extraction technique. Nilsson et al. reported on the reliability of PPG taken from different body locations by comparing them to the clinical setting measurements.<sup>[7]</sup> Figure 2c shows the reported HR values extracted from finger, forehead, and shoulder that show excellent coherence (>0.98) to the clinical setting control unit. On the other hand, respiration rate (RR) extracted from forehead and shoulder does not provide enough coherence (0.83). This can be attributed to the technical difficulty of the used RR extraction algorithm. The act of respiration periodically modulates the

**Table 1.** Consumer-based wearables in different form factors to track the vital signs of Coronavirus progression. HR, heart rate; RR, respiration rate; T, temperature; A, activity tracking; S, sleep tracking. Data is collected and gathered from the official websites of each products.

Device model/brand	Design/form factor	Capabilities	COVID-19 involvement
Oura	Ring	HR, RR, T, A, S	Clinical research
Fitbit	Smart watch	HR, SpO <sub>2</sub> , A, S	Clinical research
BioIntelliSense	Skin patch	HR, RR, T, A, S	Telemedicine
Hexoskin	Smart clothing	HR, RR, A, S	Telemedicine
Cosinuss Two	Ear plug	HR, SpO <sub>2</sub> , T, A	Clinical research
Biovotion Everion	Armband	HR, RR, SpO <sub>2</sub> , T, A, S	N/A
Spry Loop System	Wristband	HR, RR, SpO <sub>2</sub>	Telemedicine
Masimo Sleep	Fingertip oximeter	HR, RR, SpO <sub>2</sub>	Telemedicine

baseline and the pulse amplitude of a PPG signal together with the respiratory sinus arrhythmia.<sup>[25]</sup> Therefore, incorporation of efficient wavelet transform algorithms yields extracted RR with high accuracy. In addition to HR and RR, a PPG signal contains components that can be extracted as BP, blood oxygen saturation (SpO<sub>2</sub>), cardiac output, arterial aging, endothelial function, microvascular blood flow, and autonomic function.<sup>[6,26]</sup> Thus, PPG based clinical grade wearables would perform coherent extraction of multiple vital signs simultaneously, offering more complete solutions for digital medicine.

Figure 2c also shows the reported coherence of different operation wavelengths used at the same measurement location. Operation wavelength is a key factor to define the efficiency of PPG and optical characteristics of measurement location may alter this efficiency. Lindberg and Öberg reported the reflectance characteristics of finger and forearm with respect to illumination wavelength (Figure 2d).<sup>[27]</sup> Due to the different optical characteristics of the measurement locations, the reflected (or transmitted) light components could yield insufficient intensity to extract a meaningful PPG signal. Each wavelength range provides different penetration into body; therefore, the optical tissue penetration depth is a decisive factor for the extraction of targeted vital sign. Wavelengths from 400–1000 nm provides maximum penetration reaching dermis and hypodermis, making this range of wavelengths a common choice for PPG.<sup>[28]</sup> Using shorter wavelengths generally do not provide enough tissue penetration (Figure 2e) whereas the longer wavelengths are more susceptible to motion artefacts due to the long light paths.<sup>[29]</sup> Current consumer-based wearables commonly employ green LEDs (540 nm) to measure HR while preventing the signal from motion artifacts that may occur at longer wavelengths. Motion artefacts are the physical activity sourced noise interferences whose frequency lies within the same band as the original HR signal. Thus, rendering a linear filter is generally inefficient to filter the motion artefacts out.<sup>[30]</sup> Although researchers brought forward alternative ways to cancel the noise with the incorporation of accelerometers,<sup>[31,32]</sup> and gyroscope,<sup>[33]</sup> additional bulky hardware hinders the compatibility of these technologies to the daily usage. The location freedom of PPG allows designs that can be worn as a ring or bracelet to minimize the motion artefacts; however, due to the usage of rigid components, consumer wearables are shown to be only accurate only in limited conditions such as resting and slow walking.<sup>[29]</sup> Therefore, PPG measurements of wafer-based

wearables still require post processing by software algorithms to eliminate present motion artifacts. Algorithm based approaches generally offers case specific solutions that remain insufficient for realistic cases including randomly interfered multiple noise sources.<sup>[34,35]</sup> Thus, the industrial and research demands for flexible and transparent optoelectronic technologies for motion artefact free PPG measurements keeps rising to realize clinical grade wearables.

## 2.1. Optoelectronic Wearables for Public Health

World Health Organization (WHO) guidelines recommend the measurement of vital signs—HR, RR, temperature, and SpO<sub>2</sub> during different of phases of COVID-19 disease.<sup>[36]</sup> **Table 1** lists wearables of various form factors to continuously monitor the recommended vital signs for Coronavirus pandemic. Even though many wearables can measure the recommended parameters noninvasively, clinical validation and accuracy of the collected data holds great importance for the action. In a recent clinical study by Breteler et al. it has been reported over 31 high risk surgical patient that some of the consumer wearables provide physiological data that are not in the clinically acceptable limits.<sup>[37]</sup> On the other hand, a particular wearable was studied in a clinical research that includes 32 participants and reported to be beneficial to improve the perceived sleep quality.<sup>[38]</sup> Although the factors such as feel and form factor greatly affects the user adoption of the wearables, these results points out that the clinical acceptance of a wearable strictly depends on its simultaneous accuracy on multiple patients.<sup>[39]</sup>

Incorporation of consumer wearables in clinical applications is very recent, however, COVID-19 health emergence has accelerated the marriage of both worlds with the pilot studies that may radically shape the near future health strategies. Our ring, an optoelectronic fitness wearable (**Figure 3a**), has currently sponsored a research study by University of California San Francisco (UCSF, TemPredict). By collecting physiological parameters from the individuals who wear the ring, the study aims to identify the onset and progression patterns of Coronavirus.<sup>[40]</sup> The optoelectronic wearables are capable of continuously monitoring of vital signs such as heart rate, pulse oxygenation, respiration rate and sleep patterns through PPG. While the subtle changes of these physiological parameters



**Figure 3.** Optoelectronic wearables in fight against Coronavirus. a) Photograph of Oura Ring, a consumer wearable that is used in TemPredic study to identify the onset, progression and recovery patterns of COVID-19.<sup>[40]</sup> b) Photograph of Masimo Radius PPG tetherless pulse oximetry sensor that operates through a secure health network to synchronize continuous monitoring of patients vital data against Coronavirus surge.<sup>[42]</sup> c) Photograph of Ionic by Fitbit. Device tracks HR, RR, RHR, and sleep stages while offering common smartwatch features. Fitbit's fitness trackers have been involved in number of studies for the identification and monitoring of the epidemics over large populations.<sup>[41,44]</sup> d) Photograph of Loop System by Spry Health. FDA approved wearable system provides telemedicine solution for the people with chronic diseases. a) Reproduced with permission (<https://ouraring.com>), Copyright 2021, Oura. b) Reproduced with permission (<https://www.masimo.com/products/hospital-automation/masimo-safetynet>), Copyright 2021, Masimo. (Disclaimer: Masimo products are not available in all markets. Check with the manufacturer for more details). c) Reproduced with permission (<https://www.fitbit.com>), Copyright 2021, Fitbit, Inc. d) Reproduced with permission (<https://spryhealth.com/>), Copyright 2019, Spry Health.

heralding COVID-19 detection can indicate the outbreaks and secondary waves earlier, individual alert algorithms would be implemented depending on these results. Therefore, mass deployment of optoelectronic health trackers would present a solution that can empower our preventive approaches against the pandemic.

To that end, researchers from Stanford University have also launched a study including five different brands of optoelectronic wearable device including Fitbit.<sup>[41]</sup> The study aims to build algorithms for each device to potentially detect the onset of the infection.

While recent clinical studies of wearables are yet to contribute to preventive health measures, University Hospitals (UH) and Masimo (a company of medical wearables) has officially deployed a telemedicine network against the COVID-19 surge. The optoelectronic pulse oximetry wearable by Masimo (Figure 3b) provides continuous measurements of SpO<sub>2</sub>, HR, and RR that are coupled with the patient surveillance network for the clinical investigation.<sup>[42]</sup> It is estimated that the tetherless pulse oximetry system would reach 200 million patients in top hospitals and various healthcare units around the globe.<sup>[43]</sup>

Optoelectronic wearables can be potentially used to harness large set of data to predict pandemics and seasonal

flus. In a recent report, Radin et al. demonstrated a potential improvement in the prediction of a forthcoming epidemic.<sup>[44]</sup> Authors harnessed a large dataset of resting heart rate (RHR) and sleep parameters obtained from 20 000 Fitbit (Figure 3c) devices to identify the seasonal respiratory infections. As the report presents a clear indication of the forthcoming seasonal flu, it is foreseen that the continuous tracking of multiple vital signs (such as SpO<sub>2</sub> and blood pressure) can provide more timely surveillance.<sup>[44]</sup>

The latest global health statistics of WHO reports that more than 40% of all countries has fewer than ten doctors per 10 000 people.<sup>[45]</sup> This indicates the clear need of low cost and widely available remote health wearables that can extract the physiological parameters and send for professional inspection. To satisfy the demand, current rigid and high cost wearable technology would evolve to mechanically flexible integrated systems yielding low cost and widely available health products such as smart medical plasters. An early version of consumer wearable based patient surveillance platform has been implemented by Spry Health, which offers a remote COVID-19 monitoring through the Loop System for elderly people with chronic conditions. Prior to Coronavirus outbreak, the Loop System, an optoelectronic wristband wearable with continuous pulse oximetry (Figure 3d),

received a clearance from The US Food and Drug Administration (FDA) and offered as a telemedicine for clinical intervention.

The current amount and availability of optoelectronic wearable based telemedicine solutions indicates the potential of the technology for the near future health strategies. In parallel, internet of things (IoT) and 5G technologies are to provide wearables with a direct connection to telemedicine networks bypassing the need of smartphones. In this way, clinical grade data provided by the skin integrable devices can be remotely inspected by health professionals to provide more efficient control schemes during the pandemics or can be actively used to reduce the losses due to late diagnosis and poor medical control of the individuals. To that end, in the next section, we will review the materials and technologies of wearable optoelectronics for the clinical grade extraction of health parameters.

### 3. Flexible and Transparent Optoelectronics for Seamlessly Integrable Wearables

Having mechanically flexible and transparent nature empowers optoelectronic components as seamless wearables that can be laminated on human skin. Conformal lamination of wearable optoelectronics guarantees their reliability under the human body motion or mechanical stress. The overall robustness and transparency of the wearable devices depends on the engineering of the device architecture together with the intrinsic properties of the active materials. In this section, we give a brief overview of the materials for the flexible and transparent device development giving access to seamless integration of wearable optoelectronics.

#### 3.1. Substrates

The wearable optoelectronic components that are built on the flexible substrates require certain amount of light intensity to perform, therefore skin interfacing optoelectronics should use flexible substrates with decent level of optical transparency for external light signal to reach the superimposed optoelectronics. The same transparency requirement is also present for the seamless conformation on human skin or garments; therefore, the importance of the flexible substrate's optical characteristics is twofold. The currently available flexible substrate groups for the development of optoelectronic wearables are the ultrathin glasses, metal foils, and polymer (plastic) films. Low oxygen and moisture penetrability and low surface roughness are the two main criteria of the flexible substrates that majorly affect the device fabrication and the durability of the fabricated devices. Although the metal foils possess excellent barrier properties their opaque and conductive nature prohibits the usage in most wearable optoelectronic applications. In that sense, plastic films have good optical transmittances in the visible spectrum similar to thin glass with more advanced mechanical flexibility.<sup>[46]</sup> Thin films and foils of polymers constitute a promising substrate group for wearable optoelectronics with their lightweight and low-cost fabrication allowing high-volume and robust commercial products. Despite the availability of wide range of plastic films, transparency criteria

make polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) the general choice for the development of flexible optoelectronics with their solvent and temperature resistance for the ease of fabrication.

In addition to mechanical and optical properties giving access to seamless wearables, there is a growing interest in biodegradability and biocompatibility of the substrate materials for sustainability. Biocompatible polymer foils can be processed at temperatures below 180 °C allowing device development by low temperature printing or evaporation techniques.<sup>[47]</sup> Alternately, plant fiber-based substrates receives attention of the researchers due to their biocompatible and biodegradable nature.<sup>[48]</sup> In this sense, paper is a cheap and biodegradable substrate for the development of wearable optoelectronics. Novel optoelectronic applications such as graphene-based e-paper and printed organic field effect transistors (OFETs) have been realized on conventional paper substrates.<sup>[49,50]</sup> Similarly silk has been used as a substrate for passive metamaterial antennas for in situ monitoring of food quality.<sup>[51]</sup> Research in this direction would boost the smart textile and clothing market as the developed technologies are compatible to fiber-based nature. Smart textiles can be manufactured to provide conformal contact to skin surface, therefore present opportunities to realize clinical grade wearables. However, fiber-based platforms have common drawbacks such as surface roughness, opaqueness and porous nature limiting the wide range of optoelectronic applications by requiring extra optimization and device fabrication costs.

#### 3.2. Transparent Electrodes

Components of seamlessly integrable optoelectronics require to be operated through the circuits made of transparent conductive electrodes (TCEs) providing visibly clear and compatible platform for integration on skin and garments. Indium tin oxide (ITO) is the commonly used TCE for most of the optoelectronic application that requires transparency. Commercially available ITO films on flexible PET substrates provide around 80% transmittance in the visible spectrum with sheet resistance of around  $50 \Omega \square^{-1}$ . However, brittle nature of ITO creates a challenge for overall mechanical flexibility of the devices. To compensate the brittleness of ITO, various materials have been explored as a replacement including, metallic nanowires (NWs), graphene, and hybrid structures of them. Ag NWs offers promising sheet resistances and high optical transmittance on flexible substrates, with the challenges of adhesion and partially high contact resistances that remain to be optimized.<sup>[52]</sup> Ag NWs are also reported to be environmentally friendly, however, fabrication of the uniform Ag NW batches is relatively hard due to the high oxygen affinity of the structure.<sup>[53]</sup>

On the other hand, graphene promises highest recorded mobilities offering advanced electronic conduction on flexible substrates.<sup>[54,55]</sup> Atomically thin nature of the material yields optical transparency and mechanical flexibility. The absorbance of single layer graphene is defined by the fundamental constant yielding 97% transparency in the visible spectrum with a young modulus reaching 1 TPa.<sup>[56]</sup> Graphene have been shown to be bendable to millimeter scale radius without degradation

with various device architectures.<sup>[57]</sup> Although graphene and related materials (GRMs) represent a promising class of TCEs, manufacturing and wet transfer of the material markedly degrades the pristine properties, yielding batch to batch variations. Reproducibility is still a challenge today for commercialization of graphene.

To overcome the drawbacks of both materials researchers have explored the possible ways of forming hybrid structures of Ag NWs and graphene. Typical defects and grain boundaries in graphene limits its uniformity as a TCE and hinders the possible wide application spectrum. By providing connection between those structures with Ag NWs, Li et al. reported the resistance drop in single layer graphene from 650 to 27  $\Omega \square^{-1}$  while maintaining 86.7% transparency at visible wavelengths.<sup>[58]</sup> Similarly, Dong et al. implement an encapsulation of Ag NWs with graphene and polymers to achieve hybrid flexible TCE with sheet resistance of 8.06  $\Omega \square^{-1}$  and 88.3% light transmittance.<sup>[59]</sup> Alternately, thin metal films have been reported as TCEs. Due to the trade-off between the film thickness and the transparency, it is rather challenging to form a transparent ultrathin metal with uniform conductivity and continuity.<sup>[53]</sup> Despite the fact that the ITO replacement flexible TCE materials are extensively being researched, large area uniformities and mass production compatibilities are not mature enough for most of them to be considered feasible for commercialization. To that end, advancements in the flexible TCE field will strongly enhance the performance and form factor of the new generation optoelectronics that can be conformed on nonplanar surfaces or to be seamlessly integrated for wide application spectrum.

### 3.3. Light Emitting and Sensing Elements

Organic and inorganic semiconductors, organic polymers, transition metal dichalcogenides (TMDs) and GRMs have been extensively researched for the wearable light emitting and sensing technologies and the device applications have been reported with the promising results. Despite their high performance and cost-effective fabrication, inorganic semiconductors were believed to be unsuitable for flexible optoelectronics due to their brittle nature. Park et al. reported the realization of compound semiconductors (GaAs and InP) on plastic substrates as flexible inorganic light emitting diodes (ILEDs).<sup>[60]</sup> The authors used an innovative fabrication technique that reproduces the mechanical robustness of organic light emitting diodes (OLEDs) while providing superior performance compared to OLEDs in brightness and efficiency.

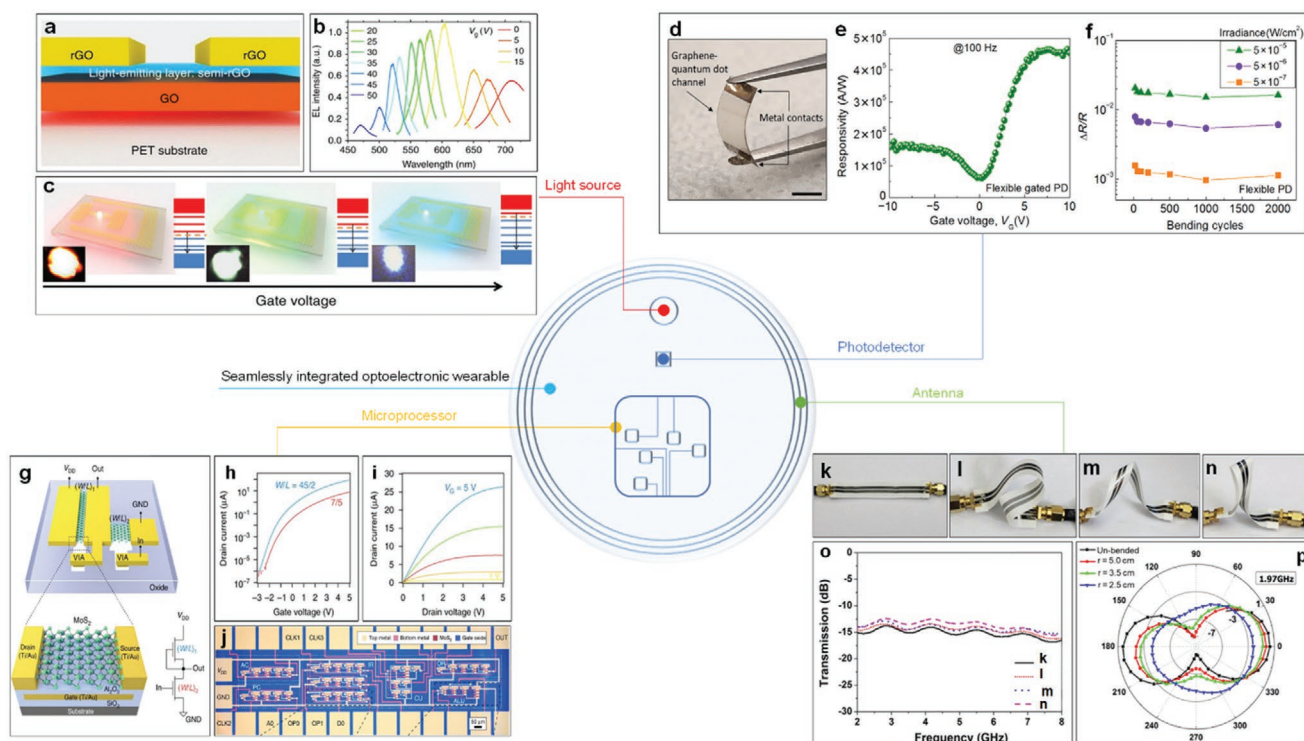
On the other hand, conjugated polymers present as high mobilities as poly-Si; however, their mechanical robustness is poor and not compatible to wearable optoelectronics.<sup>[61,62]</sup> By using the nanoconfinement of polymers to improve the stretchability of polymer semiconductors, Xu et al. demonstrated skin-like wearable driver for an LED.<sup>[63]</sup> Their thin film transistors (TFTs) made of polymer semiconductors provided competitive mobilities together with the good transparency and conformability for skin integration.

Being low cost and highly efficient, LEDs presents great compatibility for mobile health technologies. However, traditional

wafer-based LEDs are unbendable to be laminated on skin surface and only emit predefined colors defined by the material type. This indicates a demand on high performance LEDs with mechanical flexibility for skin conformation. Graphene is mechanically flexible,<sup>[64,65]</sup> and optical properties can be actively tuned by electrostatic doping.<sup>[66–69]</sup> Electrically tunable wavelength emission allows the control on the emitted wavelength from a single source, hence offers an advanced form factor when integrated into wearables. Benefiting from the intrinsic properties of graphene, Wang et al. demonstrated a graphene based spectrally tunable and flexible LEDs (**Figure 4a**).<sup>[21]</sup> Fabricated flexible graphene LEDs can emit a large spectrum from 450 to 750 nm with efficiency around 1% (**Figure 4b**) and sustain their performance under mechanical stress. The high performance of graphene based flexible LEDs rival the organic semiconductor-based counterparts, meanwhile the mechanical flexibility offers conformal contact to skin surface reducing motion artefacts. The gate tunable wavelength emission would enable compact designs for the extraction of health parameters that require emission of multiple wavelengths (such as SpO<sub>2</sub>) (**Figure 4c**). Therefore, incorporation of flexible graphene LEDs would be an important step through the reduction of motion artefacts by eliminating the usage of multiple rigid LEDs that hinders advanced form factors.

Advancements in PD technology and integration capabilities empower the wearables through extraction of multiple parameters simultaneously. As the identification and diagnosis through telemedicine networks requires the evaluation of several vital signs, capability of PDs directly affects the roadmap of wearable technology. The overall performance of integrated PDs is identified by multiple factors such as the response time, spectral detection width, and photosensitivity. While flexible photodetectors of wafer based technologies rely on the membranes and nanowires of bulk semiconductors with a limited operation spectrum, flexible photodetectors of 2D materials yields intrinsically transparent light sensors with broad spectral sensitivity.<sup>[20,22,24,70]</sup> For extended functionality, the responsivity of a PD should yield sufficient values at the predefined operation wavelength regime. Responsivity is defined as the ability of the light sensor to collect photocurrent from the applied optical power  $\left( R = \frac{I_{ph}}{P_o} \right)$ . The membranes of crystalline semiconductors are reported to exhibit insufficient responsivities for the development wearables and non-negligible performance degradation under mechanical stress hinders their usage for conformable device schemes.<sup>[71,72]</sup> To that end, GRMs emerge as viable materials for flexible photodetectors. De Fazio et al. demonstrated a large area graphene/MoS<sub>2</sub> flexible photodetector with high responsivity (45.5 A W<sup>-1</sup>) and decent optical transparency (82%). While the demonstrated responsivity is two order of magnitude higher than semiconductor flexible membranes, optical transparency promises for seamless integration. On the other hand, the usage of polymer electrolyte in the device structure requires specific device packaging that may limit the wide range of integration schemes.

Due to the brittleness of wafer-based technologies, flexible applications of them require strain engineering at utmost importance. At that point GRMs provide advanced flexibility and mechanical robustness due to their atomic thickness



**Figure 4.** Nanomaterial based optoelectronic technologies for wearable components. a) Device structure of graphene based spectrally tunable flexible LEDs. Device is fabricated on flexible PET substrates by laser scribing and current annealing. b) Reported electroluminescence spectra at various gate voltages. c) Active control of wavelength yields tunable color change of the LED. d) Large area flexible graphene photodetector that is sensitized by QD thin film. e) Gate tunable responsivity of flexible photodetectors at 100 Hz. f) Photosensitivity performance under 2000 bending cycles for various illumination conditions. g) Schematic illustration of MoS<sub>2</sub> FET structure and the inverter circuit using the integrated MoS<sub>2</sub> FET. h) Transfer curves for the FETs with different aspect ratios. i) Output curves for the gate voltage interval 1–5 V. j) Optical microscope image of 1-bit MoS<sub>2</sub> microprocessor. k–n) Demonstration of various bending schemes applied on graphene communication antenna. o) Transmission performances for depicted bending schemes with respect to frequency. p) Angular radiation patterns for bent and unbent graphene antennas at 1.97 GHz. a–c) Adapted with permission.<sup>[21]</sup> Copyright 2015, Springer Nature. d–f) Adapted with permission.<sup>[20]</sup> Copyright 2019, American Association for the Advancement of Science. g–j) Adapted with permission.<sup>[80]</sup> Copyright 2017, Springer Nature. k–p) Adapted with permission.<sup>[87]</sup> Copyright 2015, Springer Nature.

and lattice structures. Even though the usage of GRMs offers great design freedom in many cases, it is highly beneficial to fabricate GRM based optoelectronic devices with strain engineering taking the neutral plane considerations into account. This guarantees the operation of multiple-component optoelectronic systems including elements for biasing, energy storage and sensing under certain amount of mechanical stress.

While the strain engineered rigid semiconductor PDs provides high performance at specific wavelengths, graphene PDs step forward for the multifunctional device development with the broad spectral sensitivity and transparency.<sup>[18,20]</sup> To that end, flexible graphene PDs (Figure 4d), has been integrated into various device schemes such as, transparent bracelet, phone screen and a wireless UV patch benefiting from the broad spectral sensitivity and transparency of graphene. Demonstrated flexible and transparent photodetectors operate with  $10^5$  A W<sup>-1</sup> responsivities by using gate structures without the incorporation of ionic liquids. While gate tunability of graphene PDs allows for high frequency applications (Figure 4e), authors tested the photosensitivity of the devices under repetitive bending cycles. Devices show minimal degradation in photosensitivity for 2000 bending cycles (Figure 4f) and able to operate in UV, visible and infrared regimes. The usage of thin film quantum dots as an

absorber layer minimally degrades the overall transparency of the graphene PDs (maximum recorded absorbance is 25% at 633 nm) As common drawbacks, the abovementioned batch to batch quality difference in graphene synthesis and compatibility of specific fabrication to mass production remain as the major concerns for the commercialization of the technology.

### 3.4. Microprocessors and Communication

Microprocessors are the main processing units of consumer devices and they have been produced by using Si so far. Microprocessors perform multiple operations in optoelectronic wearables from maintaining the wireless communication to operation of integrated light sources. Due to resource constraints of storage capacity and power, it has been a challenge to implement microprocessors for advancing wearable technology.<sup>[73]</sup> Researchers have implemented the integration of Si to mechanically flexible substrates to be able to operate wearables while keeping a certain level of flexibility and transparency. Proof of concept demonstration of heterogeneous integration of silicon and printed electronics on fabrics have been reported.<sup>[74]</sup> Alternately, conventional integration methodologies



such as tape automated bonding, wire bonding and flip-chip bonding offers opportunities to create interconnects with the disadvantage of less compatibility to plastic substrates due to the high process temperature and pressure requirements.<sup>[75]</sup> Fabrication and integration of stretchable interconnects have been extensively studied to keep the high performance Si based wearable electronics on flexible and stretchable substrates.<sup>[76]</sup> Gold on PDMS (polydimethylsiloxane) is a common stretchable interconnect structure that is still actively used in stretchable sensor systems and optoelectronics.<sup>[77]</sup> It is reported to provide 200% stretchability, however, formation and motion of micro-rack structures with the application of mechanical stress limits the overall performance of Gold on PDMS stretchable interconnects.<sup>[78]</sup> Strain engineering of thin Si and gallium arsenide on elastomers yielded remarkable epidermal electronic devices with integrated temperature sensors, wireless power coils and ECG sensors.<sup>[79]</sup> While the devices benefit from the high performance of conventional electronic materials, the overall transparency can only be satisfied through the device design engineering due to opaque nature of the materials. The well developed technology has also been implemented to integrate rigid optoelectronic components on a stretchable platform to perform optical characterization of the skin.<sup>[18]</sup>

Si based microprocessor technologies are not expected to be replaced by an alternative material soon, however advancements in 2D material technologies provided alternative opportunities providing high performance together with the mechanical flexibility. Unlike graphene, molybdenum disulfide ( $\text{MoS}_2$ ) is a TMD with a direct bandgap of 1.8 eV required for the operation of transistors and diodes. Wachter et al. demonstrated a microprocessor based on  $\text{MoS}_2$ .<sup>[80]</sup> Authors first demonstrated a  $\text{MoS}_2$  based field effect transistor (FET) with an on/off ratio of  $10^8$  (Figure 4g) and promising transfer and output characteristics for the development of the microprocessors (Figure 4h,i). Then a  $\text{MoS}_2$  microprocessor that is composed of 115 devices was demonstrated (Figure 4j). Authors operated the microprocessor by running programs with a high yield. The proof of concept 1-bit design can be scaled up to process multi-bit data allowing the development of flexible microprocessors for wearable applications. Although the technology is in still proof of concept stage, developments in this field can transform unbendable semiconductor electronics into more integrable forms preserving and advancing the original device performance. In general, strong semiconducting nature through the atomic thickness of  $\text{MoS}_2$  emerges as a viable technology for wearable optoelectronics with the reported the devices on flexible organic light diode emitting displays, wafer scale flexible resistive random access memories, and optogenetic applications.<sup>[81–84]</sup>

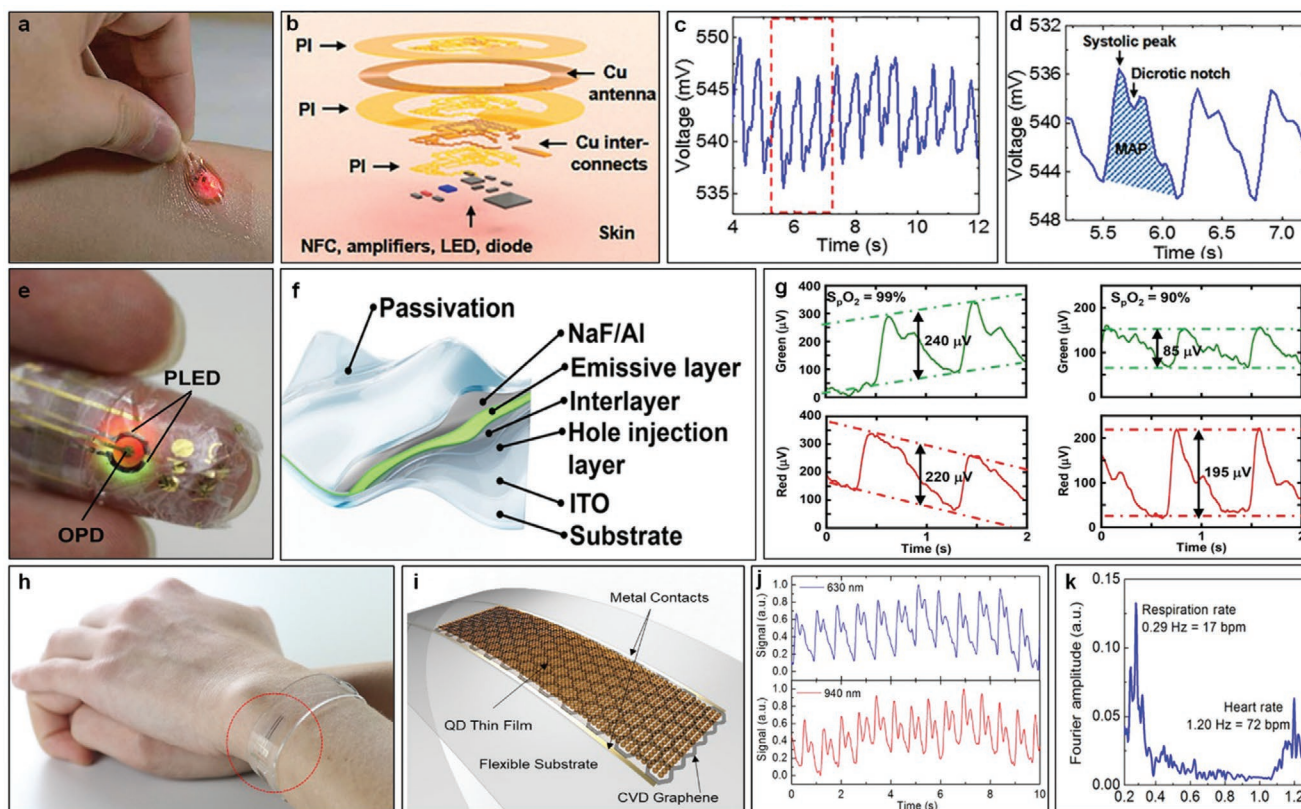
Healthcare and fitness wearables live up to the efficiency of wireless communications due to the remote nature of the technology. In wireless communications, the front end of the receiver plays an important role for the dynamic performance.<sup>[85]</sup> Standard radio frequency (RF) communication protocols used in near field communication (NFC), Bluetooth, and RFID technologies operate through the integration of passive components such as antennas and transmission lines into the active circuitry of bandpass filters, frequency mixers, and oscillators.<sup>[85]</sup> In most cases, integration of active and passive components takes place on printed circuit boards that limits the mechanical

flexibility of the wireless communication system for wearables. Although several material-based approaches have been brought forward for flexible communication antennas, high sheet resistance of the resulting structures hinder the efficiency of RF connections and low yield fabrication schemes limits the integration on nonplanar surfaces. Graphene is highly conductive and flexible by the nature; however, the exfoliation and chemical vapor deposition (CVD) techniques yield layers with high surface resistance limiting the usage as RF components. To achieve high conductivity graphene structures on nonplanar geometries, material printing technologies offers low cost and facile methods. Advantages of printing technologies include mask free patterning and compatibility to flexible substrates, which are promising for the development of skin conformable wearables. Moreover dispersions of 2D material and their derivatives allow inkjet and screen printing with the reported drawbacks of aggregation and low concentration that degrade the jetting performance.<sup>[86]</sup> By overcoming the common drawbacks of dispersion printing, Huang et al. reported highly conductive and flexible antennas for wireless communications of wearables by screen printing of graphene (Figure 4k–n).<sup>[87]</sup> Authors reported a binder free technique allowing high conductivity and continuous graphene film. The transmission efficiency under various bending schemes has been demonstrated to yield high performance (Figure 4o). While the effect of bending on transmission coefficients is minimal, much severe bending causes minor decrease of the maximum gain (Figure 4p). The usage of conventional paper as a substrate presents compatibility for integration into fiber-based fabrics whereas the robustness of the connection under severe bending allows for flexible wearables to perform on skin.

In summary, optoelectronics of advanced nanomaterials offers a mechanically robust platform for the development of wearable device components. Integration of GRM based components with high sensitivity, mechanical flexibility, and optical transparency can empower wearables to provide extended functionality and advanced integrability on body parts or textiles for clinical grade data extraction. The recently reported technologies open opportunities for seamlessly integrable wearables benefiting from the intrinsic properties of nano materials together with the strain engineering of high-performance semiconductors. In general, abovementioned materials and technologies can be incorporated in the applications where the optoelectronics are required to operate on nonplanar surfaces. The promising specifications of different technologies do not guarantee the overall wearable performance without detailed investigation in system integration level. In that sense, in the next section we highlight the innovative approaches yielding successful system integration of abovementioned material technologies.

#### 4. System Integration of Optoelectronic Components for Clinical Grade Wearables

The abovementioned available technologies of transparent and flexible optoelectronics present promising pathways for the development of clinical grade wearables, however, the system integration can be challenging due to the compatibility and



**Figure 5.** Innovative approaches for system integration of wearable optoelectronics. a) Photograph of battery-free, skin laminated pulse oximeter reported by Kim et al.<sup>[18]</sup> Heterogeneous integration of Si microelectronics and Cu antennas into a medical adhesive structure allows skin lamination providing stretchable operation while keeping most of its transparency. b) Schematic illustration of the device architecture. Despite the presence of rigid electronic components, miniaturization and strain engineering yields a mechanically robust device architecture providing operation under 30% stretchability. c) PPG trace recorded wirelessly by the laminated pulse oximeter on the forearm. d) Zoomed in PPG signal revealing systolic peak and diastolic notch of the peripheral pulse wave. e) Photograph of the flexible and transparent pulse oximeter wrapped around a finger. Device uses the developed PLED and OPD technology to perform PPG.<sup>[19]</sup> f) Structure of ultraflexible PLED used in the oximeter. Sandwiched structure of parylene and SiON as a passivation layer yields the realization of air stable organic optoelectronics. g) PPG performed with ultraflexible pulse oximeter at two different oxygenation levels with the illumination wavelengths of 517 nm (green) and 609 nm (red). Reported device can register a minimum SpO<sub>2</sub> change of 9% (between the oxygenation states of 99% and 90%). h) Graphene based transparent and flexible wearable.<sup>[20]</sup> i) Schematic illustration of the graphene PD structure that is sensitized with semiconducting quantum dots (GQD). Single layer graphene's limited absorption has been enhanced by sensitizing it with a thin quantum dot absorber keeping the overall transparency and flexibility preserved. j) PPG signal registered by the transparent GQD PD at 630 and 940 nm allowing optical extraction of SpO<sub>2</sub>. k) Fourier amplitude of the recorded PPG signal showing RR and HR values. The act of respiration has a periodic sinus arrhythmia effect on the PPG signal and Fourier transform yields RR with high accuracy. a–d) Adapted with permission.<sup>[18]</sup> Copyright 2019, American Association for the Advancement of Science. e–g) Adapted with permission.<sup>[19]</sup> Copyright 2019, American Association for the Advancement of Science. h–k) Adapted with permission.<sup>[20]</sup> Copyright 2019, American Association for the Advancement of Science.

communication problems. Since one type of material is less likely to be a solution of multiple challenges such as performance and robustness, approaches providing hybridization of different materials and technologies empowers the realization of the concept. To that end, researchers reported several system integrated materials and technologies that may radically transform the current form factor and functionality of optoelectronic wearables. Kim et al. reported a stretchable and battery free optoelectronic skin patch that can actively monitor the HR and SpO<sub>2</sub> (Figure 5a).<sup>[18]</sup> Authors demonstrated a heterogeneous integration of the rigid components such as Si microprocessors, Cu antennas, and Si PD into the commercially available medical adhesive (Figure 5b). The skin conformable device performs PPG with an integrated AlGaAs LED (at 950 nm) and a Si PD (Figure 5c). Device yields high quality PPG signal

revealing characteristics of cardiac beat such as systolic peak and diastolic notch (Figure 5d). The maximum elastic stretchability is reported to be 30% allowing conformal skin lamination. In terms of clinical grade wearable technology, the novelty of the approach is twofold: It introduces a fully wireless communication that removes the battery requirements and provides full conformation to skin to reduce motion artifacts. To further enhance the mechanical robustness of strain engineered skin patches nanomaterial-based sensing elements can replace the integrated rigid semiconductors which also allows for overall transparency and extended functionality.

Alternately, organic semiconductors yield fully flexible device components such as organic thin film transistors (OTFTs). Integration of TFT technology is well established in display industry and commonly used in the production of LCD screens. OTFTs

rival the inorganic counterparts with such advantages as being low cost and ultraflexible.<sup>[88]</sup> Due to the material sourced performance limitations of the technology, OTFTs operate at three order of magnitude lower mobility range than single-crystalline inorganic semiconductor transistors (Si and Ge).<sup>[89]</sup> Therefore, system integration of high performance flexible organic semiconductors remained as a great challenge so far. Yokota et al. demonstrated an efficient system integration of polymer LEDs (PLEDs) (Figure 5e) and organic PDs (OPD) and in a wearable device structure as ultraflexible pulse oximeter (Figure 5f).<sup>[19]</sup> While the device uses 1  $\mu\text{m}$  thick parylene substrate, the transparency of the structure is preserved by imposing ITO electrodes without substrate heating to preserve the integrity of the structure. Despite ITO's brittle nature, placing the active layer of PLED to neutral strain position of the structure yields a highly flexible platform and device was reported to perform correctly while bent down to 100  $\mu\text{m}$  curvature.<sup>[19]</sup> Although the reported devices show great durability in ambient conditions and perform under extreme bending schemes, fabricated pulse oximeter are shown to be capable of recording  $\text{SpO}_2$  changes of 9% (Figure 5g). As the devices require more sensitivity to perform clinical grade  $\text{SpO}_2$  measurements, low performance can be attributed to the abovementioned mobility limitations of OPDs yielding limited photosensitivity.

The performance of an integrated PD is a decisive factor defining the optical extraction capability of a wearable. Due to the high performance at visible wavelengths and large scale manufacturability, the PD market has been dominated by the Si and InGaAs PDs.<sup>[70]</sup> However, wafer-based technologies limit the development of skin conformable PDs due their thickness requirements. To that end various nanomaterial-based flexible photodetectors have been reported with promising light sensing and mechanical flexibility specifications. However, system integration of them as a transparent and flexible optoelectronic wearable had been remained as a challenge. Polat et al. integrated transparent and flexible graphene PDs in a fitness band, on a mobile phone screen and wireless UV skin exposure patch (Figure 5h).<sup>[20]</sup> Authors developed high performance flexible and transparent PDs by sensitizing graphene with semiconducting colloidal quantum dots (Figure 5i). The graphene-quantum dot PD technology has been well developed on rigid substrates and offers broad spectral response with responsivities up to  $10^8 \text{ W m}^{-2}$  while providing response time on the order of  $\mu\text{s}$ .<sup>[90–93]</sup> Benefiting from the mechanical flexibility of graphene, authors have integrated the technology onto flexible substrates hosting communication antenna and microprocessors. This way, broad spectral sensitivity of graphene-QD PDs allowed for the creation of UV skin exposure patches that wirelessly measure the UV index through NFC. Moreover, optical extraction of  $\text{SpO}_2$  under the illumination of 940 and 630 nm has been demonstrated (Figure 5j). As explained in the PPG section, the act of respiration modulates the PPG signal periodically. Therefore, authors used Fourier transform of PPG trace that yields RR together with the HR, which are vital signs used to identify and monitor the infections in abovementioned wearable based studies (Figure 5k). Graphene-quantum dot flexible PDs are shown to be compatible to commercially used reflectance type PPG transparency and high sensitivity of the PDs also enable transmittance type PPG, where the ambient light is

used as a light source instead of an integrated LED. Bypassing the requirement of an integrated light source offers low power consumption and presents an important step through seamless integration of next generation wearables. The air stability and unintentional doping related performance degradations are the common downsides of graphene and quantum dot technologies; therefore, incorporation of application-specific encapsulation strategies would enable consumer wearables of these materials.

## 5. Conclusion, Discussion, and Outlook

Development of wearable based telemedicine systems offers low cost and real time control on personal health parameters without physically visiting a healthcare unit. Coronavirus focused telemedicine systems are yet to prove themselves as reliable solutions and implementation of large scale telemedicine networks requires well-coordinated collaboration between tech firms, health providers, and governments.<sup>[94]</sup> As the supply of actionable data forms the basis of a reliable digital health system, incorporation of clinical grade wearables is a key factor to reach the goal. The current consumer wearables are incorporated in number of research studies to identify the onset and progression of COVID-19,<sup>[40,41]</sup> as well as seasonal flu,<sup>[44]</sup> however, accuracy of these devices is a common drawback of wafer based technologies used in the sensors and the circuitry of wearables. While the overall accuracy changes for each different consumer wearable,<sup>[95]</sup> reported several wrist worn PPG devices are not adequate when compared to reference instrumentation.<sup>[96]</sup> For daily life activity monitoring, clinical accuracy is not necessary therefore most of the consumer devices are not considered as a reference for any clinical action. However, development of standard protocols to test the uncertainty in consumer wearables and incorporation of them in clinical studies hold great promise for telemedicine networks to emerge as a remote health solution.

As pandemic health emergencies possess characteristic challenges, wearable-based digital medicine does not represent a unique solution covering all. However, it is expected to be well suited for the cases in which the infrastructure remains intact and clinicians are available to see the patients.<sup>[97]</sup> As the flexible and transparent optoelectronics emerge to develop clinical grade wearables, integration of these technologies would yield reliable telemedicine systems. While chemical and electrical wearables offer promising solutions for remote health,<sup>[98,99]</sup> devices based on optical detection mechanisms offer non-invasive solutions for complete set of physiological parameter including muscle oxygenation,<sup>[100,101]</sup> and hydration.<sup>[102,103]</sup> In the meantime, the progress in printed electronics and standardization of communication protocols majorly advances the system integration of wearable optoelectronics yielding new generation consumer devices. Besides the reviewed vital health parameters extraction by the flexible and stretchable optoelectronics, developments in this field also yielded integrable light sensors to probe and prevent from the environmental light conditions that can negatively affect the plant photosynthesis, artificial night light pollution, and retinal damage.<sup>[104]</sup> Therefore, future devices of flexible optoelectronic materials may serve as multipurpose wearables.

In this review we have provided a brief outlook to the status of optoelectronic wearables and the telemedicine systems incorporating them to fight against Coronavirus. Prospects and challenges of commonly used PPG technique have been discussed for possible skin conformation schemes. Based on the common drawbacks limiting the development of clinical grade wearables, we review the flexible and transparent optoelectronic technologies. Innovative approaches addressing the system integration have been evaluated.

Realization of clinical grade wearables with advanced feel and form factors strongly depend on the balanced combination of material technologies and strain engineering of the device architecture. To that end, we provided a component level comparison of wafer-based and nanomaterial-based technologies demonstrating the prospects and challenges of both. Recent advancements are highlighted to show the promises of material technologies in wearables. Although the battery-free and wireless technologies have been highlighted for the sake of the skin conformable devices, it is worth noting that the advancements in lithium-ion battery (LIB) technology have already allowed flexible and stretchable power sources,<sup>[105]</sup> and this demand can also be supplied by GRM battery technologies showing great compatibility to flexible and transparent nature of the reviewed devices.<sup>[106,107]</sup>

The recent increase in the demand and user adoption of optoelectronic wearables presents a milestone of progress in the field, however, is not enough to predict a clear way to realization of clinical grade devices. We believe that the review of highlighted technologies yields a meaningful benchmark, therefore contributes to clarify the pathways through the realization of the concept.

## Conflict of Interest

The author declares no conflict of interest.

## Keywords

2D materials, clinical grade wearables, flexible and transparent optoelectronics, seamless integration, telemedicine

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