Smart Sensing Systems Using Wearable Optoelectronics

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A wearable smart sensing system is capable of continuously monitoring biometric information such as respiration, pulse, and body temperature while attached to an arbitrary surface on the user’s body to be utilized freely during activities. Research conducted on new materials, fabrication processes, structure of electrodes, and wireless communication technologies has made constant progress in the development of smart sensing systems that use entirely wearable forms of devices to go beyond conventional devices that are based on intrinsically rigid components, such as silicon. Among various platforms that can be used in the development of smart sensing systems, optoelectronics provides innovative sensing functions (e.g., human–machine interfaces and phototherapy) that can be transferred from traditional healthcare to smart healthcare, such as point of care. Optoelectronics are light-mediated displays that allow a light source to be controlled and a large light spectrum to be detected. Recently, this platform that uses smart and wearable optoelectronic sensing systems has become increasingly advanced to better help human beings treat their diseases through self-healthcare. Herein, recent advanced technologies in materials, structures, and wireless platforms for smart sensors using wearable optoelectronics are reviewed.

1. Introduction

Monitoring human health and diagnosing disease are inarguably two of the most important functions that technology can provide. Sensor devices that are manufactured as wearable platforms would provide tremendous synergy in terms of compatibility with the human body. Wearable health sensor devices in which a sensor is attached to the human body enable self-healthcare monitoring. For example, sensors can be used to check an individual’s health status or disease symptoms in real time. Thus, by providing the constant monitoring of health status, wearable sensors offer the possibility of reducing the amount of time spent on hospital visits. In addition, wearable sensors would help healthcare providers and even individuals by preventing the onset of a sudden illness. Obtaining biometric information while wearing a wearable sensor is called a point-of-care test (POCT). POCT is a method of carrying out measurements that satisfy six conditions set by the World Health Organization (WHO) called “ASSURED,” which stands for affordable, sensitive, specific, user friendly, rapid and robust, equipment free, and deliverable.[1,2] POCT is expected to have a major impact on the simplification of medical systems and the development of self-healthcare monitoring systems. A POCT sensor requires a smart sensing system that provides accurate diagnosis via a wearable platform that is flexible, stretchable, and attachable to the human body. Therefore, various research efforts are being conducted to manufacture sensors for smart sensing systems that are suitable for wearable platforms.

Of the five human senses, eyesight is generally considered to be the most important and dependable. Therefore, optoelectronics (defined as the application of electronic devices that respond to and control light) has received tremendous attention in the field of optical sensor applications. Conventional optoelectronic devices were developed as photodetectors that sense incident light or electronic displays that control light. Recently, optoelectronics have been developed that are part of different sensor applications such as human-interactive visualization that simultaneously sense external stimuli and show their responses.[3] In addition, optoelectronics is being actively used in various interesting applications, including phototherapy and light-emitting diode (LED) masks, using micro-LEDs (μLEDs).[4–6] Currently, studies are being conducted to manufacture a sensor that has a smart sensing system suitable for a wearable platform. In addition, advances have been made in the application of optoelectronics to wearable platforms. To implement an optoelectronic wearable platform, it is necessary to develop materials with suitable characteristics of transparency, wireless, flexibility, and stretchability. Various types of research related to wearable optoelectronics are being conducted on new materials, new device structures, and additional functions such as wireless communications. In this report, we present recent advancements in optoelectronics, technologies, and materials applied to wearable...
smart sensing systems. In addition, we present opinions regarding the direction of development and improvement strategies of wearable optoelectronic sensors.

2. Advanced Strategies for Wearable Smart Sensing Systems Based on Optoelectronics

2.1. Advanced Materials for Wearable Platforms

There has been substantial development in the manufacture of wearable multifunctional optoelectronic sensors. Wearable optoelectronic sensors have advantages of resistance against mechanical deformations and in maintaining original electrode properties. When wearable optoelectronic sensors have flexible and stretchable forms, they have the following advantages: 1) they can conform and attach seamlessly to various surfaces; 2) they can maintain the properties of electrodes despite mechanical deformations; and 3) they can applicable to various devices such as biointegrated optoelectronics, human-activity monitoring, personal healthcare, and human-interactive platforms. Advances have been made in the fabrication of flexible and stretchable optoelectronics, along with the development of intrinsically flexible, stretchable materials, and structural designs of intrinsically rigid components. Materials and various structures of electrodes and underlying substrates have been developed to obtain entirely stretchable and flexible forms for devices. Figure 1a shows the schematic illustration of the flexible/stretchable optoelectronic devices with the integration of various smart sensing systems. The following sections discuss the advances in the materials and structures and underlying substrates for flexible and stretchable optoelectronics.

2.1.1. Substrate Candidates for Wearable Platform

To obtain flexible and stretchable forms of wearable electronics, underlying substrates require mechanically reliable properties capable of conforming to soft and seamless shapes. In addition, the ability to provide thermally applicable processing at higher temperatures than any glass transition or melting temperatures, along with large-area compatibility, has garnered tremendous interest for application in wearable optoelectronic sensors.

Several conventional candidates are available, such as polyimide (PI),[7,8] polyethylene terephthalate (PET)[9,10] as plastic materials, and silicone rubber matrices like Ecoflex and[11,12] polydimethylsiloxane (PDMS)[13–15] with a low Young’s modulus. In addition to choosing soft materials with a low Young’s modulus, another active area is in atomic scale or ultrathin underlying substrates, such as Cu or Al foils and glasses.[16] Although the flexibility or stretchability of the underlying substrates has been enhanced, there are still challenges due to breakage during repeated bending or stretching cycles. To overcome such constraints in ultrathin, underlying substrates, polymeric substrates with a low Young’s modulus have been developed. However, polymeric substrates have limitations due to a high thermal expansion coefficient and low glass transition temperatures. PI films have a low thermal expansion coefficient (3.4 ppm K\(^{-1}\)), good surface roughness, and chemical resistance.[17] Due to such positive characteristics, PI films are the most widely used material for this end of wearable optoelectronic sensor platforms, as shown in Figure 1b. However, the transparency of PI films is poor, which prevents the operation of wearable optoelectronics, and thus other options in terms of materials must be sought out. PET film provides a path to solve such problems. However, PET has disadvantages of low glass transition temperatures (70–80 °C), which are not desirable in high thermal processing for fabrication.[9] To solve constraints on thermal expansion and the low glass transition temperatures of polymeric substrates, wearable optoelectronic sensors researchers have turned to unconventional materials that are easy to fabricate and have high transparency. Among various candidates, cellulose nanofiber materials, based on renewable wood materials, have been superior options for wearable optoelectronic sensors while minimizing mismatches of the thermal expansion coefficient between individual layers. The conventional, singular cellulose nanofiber film has a high Young’s modulus (>100 GPa), and it is hard to form complex, fine designs and is limited in mechanical deformations. Ji et al. described a cellulose nanofiber–epoxy hybrid film that was fabricated using the electrospinning method, as shown in Figure 1c.[18] The fabricated hybrid film overcomes various constraints and can be applied to complex...
fine designs with mechanical resistance in bending (10,000 cycles at a 0.5 mm bending radius) and a stretching test (<50% stretching). Gao et al. fabricated a transparent, nanocellulose fiber that is disposable and biodegradable with a high mechanical resistance up to 1000 bending cycles (bending angle of 180°). In addition to hybrid films, polyurethane acrylate (PUA) elastomer is another candidate for wearable optoelectronic sensors due to the wide range of elasticity properties provided by the polymerization method, as shown in Figure 1d. The entire forms of devices using PUA elastomers can endure up to extreme stretchability (2500%) without failure. In addition to the good mechanical stability of underlying substrates, the conformal and robust coupling issues of skin have been another concern for wearable optoelectronic sensors. Reliable and robust coupling to wet, soft, and strain-induced tissues or surfaces is desirable, as these features promote reliable acquisition of sensing signals. Underlying substrates that have a weak coupling problem can be easily removed from wet and stain-induced tissues or surfaces. Many recent efforts have been made to enhance conformal and robust coupling. Yi et al. developed an ultra-adaptable and stably skin-mountable wearable photonic device using hydroxypropyl cellulose (HPC). HPC exhibited self-assembly, controllable swelling behavior, and shape-memory capabilities using a light source, which can be utilized for reversible adhesive materials to diverse surfaces. Yuk et al. presented another option for robust coupling of devices to diverse wet surfaces. Yuk et al. proposed the use of a promising adhesive in the form of a dry double-sided tape (DST) made from a combination of gelatin or chitosan and crosslinked poly(acrylic acid) grafted with N-hydroxysuccinimide ester. The coupling phenomenon of DST relies on the removal of interfacial water from wet
surfaces, which results in fast crosslinking to the surfaces. The adhesive using DST showed robust coupling properties to diverse wet and soft tissues of animals. Therefore, due to robust coupling properties, DST may provide advantages for wearable optoelectronic sensor platforms.

2.1.2. Electrode Candidates for Wearable Platforms

There are metallic nanowires, nanotroughs, and nanofibers as 1D nanomaterials. Flexible and stretchable optoelectronics are developed using such materials. Among 1D nanomaterials, silver nanowires (AgNWs) have been synthesized using a hydrothermal method, an electrochemical technique, an ultraviolet (UV) irradiation technique, and a template-assisted technique. The conductivity of AgNWs contributes to the conducting pathway in their networks. The electrons can travel through the conducting pathway. AgNWs have a low sheet resistance (\(\approx 35 \Omega \text{ sq}^{-1}\)) and high transparency (\(\approx 80\%\)). In addition, AgNWs have been used for potential wearable functions due to their superior mechanical properties. The conducting pathway in AgNW networks can be maintained even in mechanical deformations, which allow them to maintain their connected regions. However, such AgNWs have disadvantages of high sheet resistance due to high-junction contact points due to their low aspect ratio. To overcome these disadvantages, studies on the development of metallic nanowires have been actively conducted to increase the density of conducting pathways while reducing contact resistance. In a recent study, Kumal et al. developed synthesized AgNWs with a low sheet resistance down to 2.5 \(\Omega \text{ sq}^{-1}\).[23] To reduce junction contact resistance and synthesize AgNWs with a high-density conductive network, ethanol was dispersed with AgNWs and formed on the substrate through spray coating, followed by three postprocessing steps, including thermal embossing, photonic sintering, and N\(_2\) plasma treatment. The synthesized AgNWs have excellent mechanical properties (a dramatic failure not found during 100 bending cycles at 20 mm of bending radius) and electrical properties. In addition to silver nanowires, the fabrication of conductive materials with high aspect ratios, high density, and high sheet resistance against mechanical deformations has become essential for use in wearable optoelectronics. Based on this concept, metallic nanofibers have been produced by electrospinning continuous and ultralong nanofibers by mixing polymeric solutions. Jang et al. fabricated high-aspect-ratio silver nanofibers (AgNFs) using roll-to-roll systems, together with an electrospinning method. AgNFs with a high aspect ratio have low sheet resistance (8 \(\Omega \text{ sq}^{-1}\)) and excellent mechanical resistance against bending (70 \(\mu\text{m}\) of bending radius) and stretching (10,000 stretching cycles at 30\% strain).[26] 1D metal nanotroughs is another option for wearable optoelectronic sensors because of their good mechanical properties and low sheet resistance (10 \(\Omega \text{ sq}^{-1}\)) and high transparency (\(\approx 90\%\)). However, metal nanotroughs have challenges of poor adhesion properties with substrates, surface roughness, and incompatibility to thermal processing. To overcome such challenges, An et al. found 1D metallic nanotroughs using CuZr and metallic glasses (MGs) that have low sheet resistance (3.8 \(\Omega \text{ sq}^{-1}\)), with an acceptable duration against mechanical deformation of 70\% tensile strain.[28] In addition, to manufacture conductive materials having low sheet resistance, high transparency, and excellent mechanical properties, Ma et al. developed a hybrid composite material using aramid nanofibers and silver nanowires, as shown in Figure 1e. The hybrid composite material has low sheet resistance down to 0.12 \(\Omega \text{ sq}^{-1}\) and mechanical resistance against 3 mm of curvature.[29]

In addition to 1D nanomaterials, the 2D nanostructured materials constructed from monolayers at an atomic size have intrinsically flexible properties. Figure 1f shows the structure of graphene, which is the most widely used 2D nanomaterial.[30] The graphene as a 2D nanomaterial is mostly used for wearable platforms. As the carbon-based graphene layer is ultrathin (atomic layer), it is transparent and has good conductivity similar to that of conventional metals. In addition, graphene has the advantage that it can be contacted seamlessly and roughly on the surface without loss of transparency and conductivity due to ultrathin thickness.[31] As the spring constant of graphene is 1–5 N m\(^{-1}\), a graphene layer can endure up to 42 N m\(^{-1}\) of forces, which provides good stretching ability. Due to these advantages, they are widely used as electrode materials for wearable optoelectronic sensors.[34,35] This graphene monolayer can be coated onto a large area through chemical vapor deposition (CVD) and also can be patterned into complex patterns of various flexible and stretchable electrodes through photolithography and ion etching. Kang et al. fabricated MoS\(_2\)/graphene for photodetector devices. The photodetector was fabricated using MoS\(_2\)/graphene with a gapless-band structure and photopatternable characteristics that showed a photosensitivity of 6.3 A W\(^{-1}\) and a very small reduction in photosensitivity even at 10,000 bending cycles (bending radius is 9 mm).[36] Polat et al. fabricated sensitizing graphene with semiconducting quantum dot (QD) materials. These wearable optoelectronics using hybrid forms were attached to human skin and presented electronic devices capable of real-time wireless health tracking.[37] In addition to metallic nanostructured components, conductive polymer materials have intrinsically flexible and stretchable properties and have been used as conductive materials for manufacturing wearable optoelectronics. Among polymeric materials, poly(styrenesulfonate)-doped poly (3,4-ethylenedioxythiophene) (PEDOT:PSS) is the most widely used for conductive, flexible, and conformal optoelectronics, as shown in Figure 1g.[38] PEDOT with high conductivity is blended with PSS, an insulating material, where the conjugated PEDOT is a conducting pathway of carriers, but PEDOT crosslinks are water-soluble materials. As these polymeric materials can be easily dispersed in water, spin coating can be used to form conductive films on flexible, stretchable substrates. These conductive and polymeric materials have the advantages of flexibility, stretchability, and are easy to coat, but they are difficult to use in optoelectronics due to their relatively high sheet resistance compared with metallic materials. This is because PSS acts as an insulator layer, which blends in PEDOT networks to protect against the obstruction of the flow of carriers along the PEDOT networks. To overcome these shortcomings, various research groups reduce the density of PEDOT by doping with the addition of enhancers, while increasing conductivity by maintaining PEDOT crosslinks. Jin et al. engineered PEDOT:PSS by doping ethylene glycol.[39] Doping the ethylene glycol inside PEDOT:PSS can reduce PSS density, which makes the PEDOT’s...
rich domains. The engineered PEDOT:PSS has excellent mechanical properties and conductivity because it endures without fatigue at 10,000 cycles, has sheet resistance (<30 Ω sq⁻¹), and high transmittance (>90%). To use jet printing instead of spin coating, PEDOT:PSS is used on various carrier substrates with complex curvatures, An et al. printed PEDOT:PSS on various substrates with seamless complex, 3D architectures. The platform enabled the fabrication of 3D optoelectronics.[40]

In addition to the aforementioned materials, eutectic gallium-indium alloy (EGaIn) is a liquid metal suitable for stretchable applications.[41–45] Park et al. developed 3D printing technologies of intrinsically stretchable liquid metals, as shown in Figure 1h.[42] In addition, Park et al. fabricated self-healing, stretchable materials, consisting of silver and liquid metals.[44] These Ag-liquid metal composites can endure up to 1000 stretching cycles. In addition, although the composites had a failure ≈70% tensile strain, the composites can self-heal after release.

2.1.3. Structural Design of Electrodes Candidates for Wearable Platforms

In the previous section, we reported on recent research progress in underlying substrates and electrode material for the fabrication of wearable optoelectronics. In addition to materials, studies on wearable optoelectronic platforms have been conducted to engineer extrinsically flexible and stretchable properties by designing various structures of electrodes using other intrinsically rigid metallic components. The structural design of intrinsically rigid components can provide local strain and stress-free regions on mechanical deformation. Various structures have been developed to maintain the original performance of electrodes by minimizing strain and stress locally.

Among the various structures, the serpentine structure can provide stretchable or flexible properties to rigid, metallic components, thereby improving the mechanical properties of the electrodes, as shown in Figure 1l.[45,46] Xu et al. reported that intrinsically rigid metallic components using the serpentine structure had good mechanical properties, and the serpentine structure can be defined lithographically.[46] Such structures can locally reduce the strain and stress caused by mechanical deformation. Electrodes using a serpentine design showed no failure of the electrodes even after 300% stretching, and a red LED was driven efficiently even when the electrodes were bent, stretched, and twisted. Ahn and coworkers designed a serpentine shape for electrodes, an active matrix LED, and µLEDs. They found the devices endured a 40% tensile strain and 15 mm of bending radius without degradation of the luminescence property without electrode fatigue.[47]

In addition to serpentine designs of intrinsically rigid components for potential wearable optoelectronic sensors, wrinkles are another design option to make flexible and stretchable electrodes. Figure 1j shows the structures of wrinkles. Unlike a serpentine structure, the patterns can be formed through prestrains of the underlying substrates and then utilize lithography or jet print of the metallic materials.[48] After releasing the prestrained substrate, compressive stress is applied to the substrate, resulting in the formation of wrinkles after electrodes relax. These wrinkles provide spring characteristics at intrinsically rigid materials that do not have spring characteristics and thus endure mechanical deformations. Yin et al. found that organic light-emitting diode (OLED) pixels using this wrinkle design maintained luminescent properties even with 100% tensile strain because failure of electrode materials was not induced.[48] In addition, electrical properties with a wrinkle structure maintained their original form even after stretching for 10,000 cycles at 20% strain. In addition, electrode failure did not occur even in bending strain (≈0.68%), and flexible and stretchable optoelectronics have been developed for electrodes applying a wrinkles design. Ji et al. and Park et al. reported a rigid–soft hybrid for wearable electronics, as shown in Figure 1k.[18,49] The rigid–soft hybrid structures provided a locally strain-free region, which helps endure mechanical deformations in bending and stretching. Islands of functional devices, such as LED and antenna or Si-based transistors, were reinforced because strain–stress was all imposed on the soft materials due to the Young’s modulus difference between rigid and soft islands. The hybrid structure enables reliable driving of brittle, functional devices (LEDs, etc.), even at a 30% tensile strain, and reliable operation even after bending strain is generated after contacting all devices in the 3D frames. This was achieved by engineering the structure of various rigid, metallic components. Thus, wearable optoelectronics can be fabricated and utilized at the point of care for human beings, which enables future self-health caring functions and various applications.

In summary, mechanically stable wearable optoelectronics sensors can be fabricated through the design of structures for electrodes, the choice of underlying substrates that are capable of enduring stretching and bending, and the engineering of conductive materials.

2.2. Advanced Light-Emitting Materials for Wearable Optoelectronics

Devices based on a range of light-emitting materials are used to implement optoelectronic wearable sensors. Currently, LEDs based on existing inorganic materials are rigid, undeformable, and thereby unfit for wearable sensors. Importantly, light-emitting materials should provide flexibility, bendability, stretchability, and deformability in addition to superior inherent optical attributes, to build wearable sensors that are comfortable and conformable to the curvilinear and complex surface of the human body.[50,51]

Diverse research groups are exploring wearable sensors based on optoelectronics using various light-emitting materials to realize human-interactive technology such as monitoring optical signals, visualize the signals measured by sensor devices, and provide various therapeutic optical stimuli to the human body. To this end, various researches are being conducted to implement deformable properties through new material structure designs or using inherently flexible, stretchable materials such as polymers.[52] This section reviews the recent research on different types of light-emitting materials for optoelectronic wearable sensors and the application thereof.

2.2.1. Organic Light-Emitting Materials

As organic light-emitting materials composed of small molecules allow the implementation of extremely thin layers via thermal
evaporation, they are easily applicable to flexible optoelectronic devices. However, small molecule-based OLEDs are limited in the choice of flexible plastic substrates (e.g., PI, polyethylene naphthalate, polyethersulfone, etc.) due to thermal damage from the deposition process. In comparison, due to the easy formation of a large area with inkjet printing and spin-coating processes, solution-based polymer OLEDs (PLEDs) have been deemed as a robust candidate for optoelectronic wearable sensors. More recently, researchers used multiple emitting material layers to diversify colors, varying with the types and sizes of wearable sensor signals. Koo et al. reported on a wearable electrocardiograph (ECG) sensor based on color tunable OLEDs (CTOLEDs). The authors used small-molecule OLED materials. They deposited Parylene-C on Teflon-coated glass and then deposited each OLED material and the electrodes. Subsequently, an ultrathin (≈3 µm) wearable CTOLED was fabricated through a pick-up method using waterproof tape. The optoelectronic wearable device comprised a stretchable ECG sensor composed of a serpentine-structured ultrathin Au electrode, p-type metal oxide semiconductor (p-MOS) carbon nanotube (CNT) signal amplifier, and OLED output device, allowing for conformal attachment to the body surface due to its ultrathin thickness. As the CTOLED enables colorimetric configuration, various colors were displayed across the voltages applied by ECG signals, ranging from dark red to white and even to deep blue. The variation of colors is supported by the functional ultrathin exciton-blocking layer (EBL), located between two (red and blue) emitting layers, where the low-voltage domain emits red due to electronic barriers, resulting from the lowest unoccupied molecular orbit (LUMO) of EBL, whereas the high-voltage domain emits blue with the energy barrier overcome by electric charges accumulated in the red emission material layer (EML) (Figure 2a,b). The ultrathin ECG sensor device provided stable operation in repeated bending/fatigue tests and was successfully attached to the body, which substantiated its potential to monitor ECG as a wearable biomedical device. Han et al. simultaneously fabricated multicolor OLEDs via surface energy patterning (SEP) technology using a solution-based polymer light-emitting material (SEP) technology as an alternative to large-area fabrication. The authors demonstrated s-pulse oximetry sensors using light reflected from the fingertip by s-photoplethysmogram (PPG), using red and green PLEDs and silicon photodiodes, formed by blade coating, as light emitters and light detectors, respectively. Following the hydrophobic self-assembly monolayer (SAM) treatment on the indium tin oxide (ITO) substrate, oxygen plasma etching was performed using a Kapton tape mask. This SEP process created hydrophilic regions in the form of a pattern that is well interacted with the blade coating ink; thus, it is effective in improving the reproducibility of the device, using a small amount of solution and obtaining uniform thickness (Figure 2c,d).

### 2.2.2. Inorganic Light-Emitting Materials

The widely used inorganic light-emitting diode (ILED) is an essential component in the solid-state lighting industry. LEDs, in general, are fabricated with the epitaxial method on rigid substrates and thus are unsuitable for wearable sensors. Nevertheless, ILEDs emitting light via inorganic semiconductors have several advantages in terms of lifespan, brightness, and light-emitting wavelength spectrum in comparison with OLEDs using organic semiconductors. Thus, many research studies using ILEDs for optoelectronic wearable sensors have been reported. For instance, researchers explored μLED technology with III–V semiconductors that underwent micro-/nanoscale epitaxial growth on wafers and used the technology to fabricate flexible optoelectronics through transfer to plastic substrates. In addition to materials based on inorganic semiconductors, studies are under way to implement flexible optoelectronics using other inorganic light-emitting materials such as inorganic phosphor particles, colloidal QDs, and metal halide perovskites, which can be built through a low-temperature process on plastic substrates. In a recent ILED-related study, Lee et al. reported on a GaN-based vertical-structured μLED array that ensured both the thermal stability of flexible ILEDs and flexibility. They used the laser lift off (LLO) process to separate GaN-based LED chips from sapphire wafers and connected the LED vertically, not laterally, using AgNWs to secure the thermal stability of ILEDs (Figure 2e). The ultrathin and transparent flexible vertical LED (F-VLED) allowed for conformal attachment to the body surface and provided a high optical power (30 mW mm⁻²) as well as a stable mechanical endurance under repeated bending/unbending tests. They used the F-VLED for an experimental injection into mouse brains and found stable blue light emission without infection or inflammation. Inorganic fluorescent substances in wide use as a light-emitting material are easily mixed with other elastomeric materials to form light-emitting layers and ensure deformability attributable to elastomeric materials. Kim et al. fabricated composite films with light-emitting ZnS:Cu particles and elastomeric PDMS with a pyramid-shaped surface. The authors demonstrated wearable sensors using light-emitting composite films that sensed and simultaneously displayed biometric signals of the skin including body temperature, sweat, pressure, and fingerprint. Specifically, when wearable sensors are attached to the skin surface, the skin may serve as floating electrodes underneath an alternating current (AC) field which is located between two parallel electrodes on the sensors and reads the temperature, sweat, pressure, and fingerprint on the skin where the sensors are attached. That is, conductance and impedance vary with skin conditions, causing the AC field to change accordingly. Simultaneously, capacitance varies with changing electric fields and thereby induces change in the electroluminescent intensity of ZnS:Cu particles. Thus, the wearable sensors sensed signal changes based on a range of biometric information such as temperature, sweat, and pressure on the skin surface and simultaneously visualized the biometric information. QD materials are promising light-emitting materials for flexible optoelectronics because they facilitate adjustment of the light-emitting spectrum ranging from UV to near infrared (NIR), have high color purity (≥30 nm full width at half maximum, FWHM), and allow for fabrication on flexible substrates. In particular, as low-cost colloidal QDs support diverse approaches to implement the solution process, it is of much interest to researchers exploring wearable optoelectronics. Kim et al. proposed a stretchable optoelectronic sensor based on colloidal QDs using graphene electrodes with a view of it having superior optical and electrical properties. The colloidal QDs were formed at the top of the hole transporting layer (HTL) electrodes via a spin-coating or transfer process and then
transcribed onto the prestrained elastomer substrate to form the flexible quantum dot light-emitting diodes (QD LEDs). The device has a regular wavy pattern and thereby showed the photoluminescent stability of QD LEDs under 70% tensile strength and a 35 μm radius for bending curvature (Figure 2f). The stretchable optoelectronic sensor comprising QD photodetectors fabricated with QD LEDs showed potential as optoelectronic wearable sensors capable of continuously monitoring the blood wave change in the body. Despite superior optical properties of QD materials, most QD materials are based on toxic heavy metals (e.g., cadmium, lead, and mercury, etc.) and thereby are subject to environmental restrictions and limited industrial applications. Above all, in developing wearable sensors and other devices attached to the body, it is critical to developing QD materials based on nontoxic environment-friendly substances.\[64\] To this end, quite a few research groups are attempting to develop environment-friendly QDs using nontoxic materials such as carbon QDs, silicon QDs, and ternary compound QDs. Nonetheless, compared with existing QDs based on heavy metals, nontoxic QDs have a lower emission efficiency and thermal/chemical stability, which warrant ongoing studies to overcome such limitations.\[65–67\] Meanwhile, optoelectronics wearable sensors based on hybrid organic–inorganic metal halide perovskites such as CH\(_3\)NH\(_3\)PbX\(_3\) (X = Cl, Br, I) have been well documented.

**Figure 2.** a) Schematic illustration of the cross-sectional structure of a CTOLED. The magnified image shows the cross-sectional tandem emitting material (TEM) image of an EBL sandwiched between two EMLs. b) Real-time color changes of the CTOLED, synchronized with the shape of the measured (top) normal ECG signal and (bottom) abnormal ECG signal. Scale bars, 5 mm. a,b) Reproduced with permission.\[^{[54]}\] Copyright 2017, American Chemical Society. c) The yellow areas indicate hydrophobic regions and the dark gray dotted areas are reservoirs, where the solution is deposited prior to blade coating. d) Photograph of the optoelectronic sensor that uses green and red PLEDs as the light source and a silicon PD as the light detector (the sensor is placed on top of the wrist for collecting the PPG signal). c,d) Reproduced with permission.\[^{[51]}\] Copyright 2017, Wiley-VCH. e) Schematic illustrations of a monolithic LED with the AgNW network as a transparent electrode. Transparent AgNW electrodes overcome the step height of the polymer matrix. Reproduced with permission.\[^{[59]}\] Copyright 2018, Wiley-VCH. f) Photographs of the stretchable red, green, and blue QD LEDs at strains of 0% and 70%, biased at 7, 9, and 11 V, respectively. Scale bar, 5 mm. Reproduced with permission.\[^{[63]}\] Copyright 2017, American Chemical Society. g) Photographs of the timer after applying it on human skin immediately (top), and after 350 s (bottom), respectively. Inset shows the magnification of the timer. Scale bar, 1 cm. Reproduced with permission.\[^{[76]}\] Copyright 2019, Elsevier. h) (Top) Schematic illustration of the ECD consisting of a polyaniline nanofiber/electrolyte/V\(_2\)O\(_5\) with an ITO-coated PET film as an electrode. (Bottom) Color gradient and photographs of the device with color changes from yellow to dark blue upon the applied voltage. Reproduced with permission.\[^{[77]}\] Copyright 2017, Royal Society of Chemistry.
Organometallic halide perovskites are characterized by high power conversion efficiencies and photoluminescence quantum efficiencies with adjustment for different types and sizes of halide atoms. Due to outstanding properties, organometallic halide perovskites are applied to various optoelectronic devices including solar cells. Recent research utilized inkjet printing to explore patterning techniques, whereas a method of printing the 3D perovskite nanostructure was proposed. Such techniques are expected to facilitate the development of different types of wearable sensors suitable for the complex curvilinear body surface.

2.2.3. Chromic Materials

Chromic materials are color-changeable materials that change the chemical and physical molecular structures of a substance due to an external stimulus and cause a visible color change. Based on the external stimuli, chromic phenomena can be classified into photochromism, electrochromism, thermochromism, piezochromism, mechanochromism, and magnetochromism. Chromic materials can be produced in a variety of colors by a simple process, which is actively applied to the visualization of sensor signals. Of various chromic phenomena, electrochromism and thermochromism are useful to wearable optoelectronic sensors. Transforming measured electric signals into reversible optical information via oxidation–reduction reactions is important. Therefore, electrochromic materials are worth applying to wearable smart sensors not only for visualization of sensors but also for affordability, less power consumption, compatibility with flexible substrates, and applicability as electrochemical energy storage. Typically, electrochromic materials are categorized into conjugated polymers that are flexible in themselves, and metallic oxides such as WO₃, NiO, and TiO₂ are characterized by high electrical and thermal stability and high coloration efficiency. Particularly, they are capable of diversifying colors using the reactions of materials, and as such, colorimetric sensors are worth noting in relation to wearable sensors based on electrochromic materials.

Kai et al. used poly(3,4-ethylenedioxythiophene)/polyurethane (PEDOT/PU) and fructose dehydrogenase (FDH) which serve as the cathode and anode, respectively, based on organic electrochromic composite films, to demonstrate stretchable enzymatic skin patches with color depth varying with currents generated by redox reactions (Figure 2g). The PEDOT/PU composite films are subject to redox reactions, leading to reversible electrochromic reactions. The authors suggested that electrochromic timers applicable as skin patches should be developed and would be applicable to wound healing and detection of drug dosing.

Park et al. used organic–inorganic hybrid electrochromic materials based on a polyaniline nanofiber and vanadium pentoxide (V₂O₅) to propose wearable strain sensors combined with an electrochromic device (ECD). The fabricated ECD emits yellow and dark blue at −2.5 and +2.5 V, respectively (Figure 2h). The colors varied with the intensity of voltages applied through the strain sensor. The authors attached the ECD and strain sensor onto the surface of finger joints and demonstrated a variety of colors relative to the extent of strain associated with bending or unbending of the fingers. Thermochromic materials that reversibly change color in response to temperature changes are being used as temperature indicators in various industries. In particular, for wearable sensors, body temperature is an important factor for diagnosing human activity and health problems such as infection, inflammation, hyperthermia, and hypothermia. Thus, using thermochromic materials to visualize with temperature sensors is very meaningful. In addition, visualization methods based on thermochromic materials that convert signals from various sensors into heat have been widely studied. However, as thermochromic materials have long response times, slow recovery times, and slow reversible times, it is difficult to detect a rapid reaction or response to an applied external stimuli. Recently, Park et al. demonstrated a strain-visualizing sensor with fast thermal response based on a hierarchical thermochromic membrane. Inspired by the thermal management structure of termite mounds, Park et al. fabricated a hierarchical pattern on the thermochromic layer to achieve a fast color recovery time for the thermochromic material using a through-hole membrane on a microfluidic chip with a large surface area and small volume capacity that facilitated excellent heat dissipation. By integrating this hierarchical thermochromic layer with a nanoscale crack-based strain sensor, a wearable smart sensor for strain visualization that displayed fast response (<0.6 s) at extreme low strains (within 2%) was implemented. The authors suggested that this fast-responding strain sensor could be used in healthcare monitoring applications that require fast recognition, such as human respiration.

2.3. Advanced Wireless Sensing Systems

An indispensable component of smart sensing systems is wireless communication. The biggest difference between traditional sensing systems and smart sensing systems is whether or not the sensing is conducted by connecting wires to the sensor. Sensing systems integrated with wireless communication technology are divided according to the use of radiofrequency (RF). Wireless communications vary depending on the frequency range. Among them, wireless smart sensing systems using frequency bands that are compatible with smart mobile devices are likely to be used for POCT, which is the ultimate goal of smart sensing systems. In addition, large companies such as Samsung and Apple are actively investing in self-healthcare, which requires the application of POCT to devices such as smartwatches. In this regard, wireless communication technologies are considered a key technology.

2.3.1. Wireless Sensing Systems without RF

Among smart sensing systems using wireless communication, there wireless sensing systems do not use RF. Park et al. reported a smart contact lens sensor that responds to glucose concentrations above a certain level through LEDs. As shown in Figure 3a, the sensor uses a mechanism where the glucose sensor on the lens turns off the LED when a certain level of glucose concentration is detected. The smart sensing system integrates an antenna as a means of receiving external power to preclude the use of batteries. In Figure 3b, the system consists of a glucose sensor, an LED, AgNPs antenna, and a rectifier.
for converting power into a direct current (DC) signal. The circuit diagram in Figure 3c shows how the LED turns off for glucose levels above a certain level. In the schematic, the LED and the variable resistor as a glucose sensor use a field-effect transistor (FET) with graphene channels that are connected in parallel, influencing each other. As the concentration of glucose solution increases, the resistance of the graphene channel decreases. When the glucose concentration above a certain level comes in contact, the resistance of the sensor becomes very low, and most of the current flows only to the glucose sensor, which turns off the LED. This simple and smart sensing system was composed of components that provide stretchability, transparency, and is batteryless while being able to withstand a harsh environment of high humidity and human body temperature.

There are also smart sensing systems that measure intraocular pressure in the eye and then display the measured data without RF. Campigotto et al. reported an intraocular pressure lens sensor that exploits a microfluidic system to measure intraocular pressure and visually display the measured data.[82] The sensor measured intraocular pressure using a mechanism in which the gauge of microfluids varies depending on the strain of the substrate. The microfluidic gauge was designed to be able to be measured accurately using a reader device without any RF signal. Sensors on a lens platform to measure various data in the eye have to withstand a harsh environment of high humidity and human body temperature.

There are also smart sensing systems that measure intraocular pressure in the eye and then display the measured data without RF. Campigotto et al. reported an intraocular pressure lens sensor that exploits a microfluidic system to measure intraocular pressure and visually display the measured data.[82] The sensor measured intraocular pressure using a mechanism in which the gauge of microfluids varies depending on the strain of the substrate. The microfluidic gauge was designed to be able to be measured accurately using a reader device without any RF signal. Sensors on a lens platform to measure various data in the eye have to withstand a harsh environment of high humidity and human body temperature.

2.3.2. Wireless Sensing Systems with RF

The traditional method of sensor measurement is to connect the sensor to the equipment using wire. However, due to the needs of POCT and sensor measurement in harsh environments, further advances in the sensor are required, which has led to various wireless sensing systems. The most common wireless sensing system is using RF. To use RF, it is necessary to have an antenna capable of inductive coupling. Equipment must also measure and read the signal using a reader coil. Kim et al. reported a resistor-, inductor-, and capacitor (RLC)-structured smart sensing system using AgNW helix coils and Ecoflex capacitors in contact lenses.[11] In this study, they fabricated a smart contact lens to measure glucose concentration and intraocular pressure in the eye by integrating a glucose sensor composed of graphene FET and an intraocular pressure sensor of a capacitor type. As shown in Figure 4a, an Ecoflex of a capacitor role is integrated between two AgNW three-turn helix coils, and a glucose oxidase–bonded graphene FET is connected to the outer coil. Accordingly, the resonance frequency varies by the change in intraocular pressure, and signal strength varies according to glucose concentration. These changes in glucose concentration and intraocular pressure were measured by the reflection value (S11) and resonance frequency shift using a network analyzer. The mechanism of wireless measurement using a network analyzer is shown in the circuit diagram of Figure 4b. Sending an electromagnetic signal to the reader coil connected to the device causes inductive coupling with an inner coil integrated into the sensor, thereby causing inductive coupling together with the outer coil. When an external signal is applied to the outer coil by the reader coil, inductive coupling occurs between the outer coil and inner coil, thus reading the resistance of the glucose sensor, which retransmits the reflection (S11) value to the reader coil.

There are also wireless communication methods for identification using RF and a chip, which is called RF identification (RFID), where sensor data are read wirelessly by a tagging chip. RFID can be classified depending on the power type, and it can
be wirelessly powered without batteries. RFID driven only by the supplied power is called passive RFID, and RFID driven by a battery is called active RFID. Lee et al. fabricated a smart hydrogen sensor using a passive-type RFID and measured the reflection value according to the hydrogen concentration with a network analyzer, as shown in Figure 4c.\cite{83} As shown in the graph of Figure 4d, the reflection value was measured as smaller according to the higher resistance of the sensor with a higher concentration of hydrogen gas. Using an RFID system, it is possible to use a small reader device or even a smart mobile device to read the measured data without using equipment such as a network analyzer.

As mentioned, RFID varies according to frequency bands. Among them, the near-field communication (NFC) method uses a specific frequency of 13.56 MHz to communicate with a smart mobile device. Han et al. reported a smart sensing system that can measure pressure and temperature without a battery using the NFC communication method.\cite{84} As shown in Figure 4e, the sensor consists of an NFC chip with a built-in temperature sensor, a pressure sensor made of a silicon membrane sensor that responds to pressure, and other components such as a reference resistor. They demonstrated the possibility of full-body mapping due to the simple measurement method. In addition, Shin et al. reported an optogenetic wireless application that exploits the NFC chip.\cite{85} The device was designed for subdermal implants that control neural circuits using light. A batteryless system was highly useful for subdermal implants. Zhang et al. also reported an optoelectronic system for subdermal

Figure 4. Wireless communication system with RF. a) Schematic structure of the smart contact lens for measuring glucose and intraocular pressure. b) Circuit diagram of the wireless communication system using inductive coupling between a reader coil and the antenna. a,b) Reproduced under the terms of the CC BY 4.0 license.\cite{11} Copyright 2017, The Authors, published by Springer Nature. c) Schematic image of the wireless measurement system using NFC, as shown in Figure 4c.\cite{83} Copyright 2015, American Chemical Society. d) Illustration of the wireless, battery-free, skin-mounted temperature and pressure sensing system using NFC. Scale bar, 8 mm. Reproduced with permission.\cite{84} Copyright 2018, The American Association for the Advancement of Science. e) Illustration of the wireless, battery-free, skin-mounted temperature and pressure sensing system using NFC. Scale bar, 8 mm. Reproduced with permission.\cite{87} Copyright 2016, Springer Nature. f) Photographs of the smart sensing system with Bluetooth worn on a cycling subject. Reproduced with permission.
implants that exploits the NFC chip. In this regard, NFC is a promising wireless communication method that is suitable for use in harsh environments such as implantable or wearable devices.

There are other communication methods, apart from NFC, that can communicate with smart mobile devices. Generally, the Bluetooth communication method is currently used in various fields due to a wide communication distance of \( \approx 10 \text{ m} \). Gao et al. also reported an electrochemical sensor array using a Bluetooth communication system. As shown in Figure 4f, the sensor array was connected to a Bluetooth module to measure various types of biometric information such as glucose, lactate, potassium, and sodium concentrations in sweat. As Bluetooth is a wireless communication system supported by smart mobile devices, it is very user-friendly. Bluetooth also has an advantage in the long communication distance of \( \approx 10 \text{ m} \), compared with the short communication distance of within 10 cm of NFC. However, disadvantages also exist in comparison with NFC as Bluetooth requires power through a battery. A batteryless Bluetooth smart sensor that exploits a wireless power transfer system was recently reported that overcomes this disadvantage. In addition to NFC and Bluetooth, the wireless communication method using a printed circuit board (PCB) is one of the most frequently used wireless communication methods. Several other wireless communication technologies that can communicate with smart mobile devices include Zigbee, wi-fi, etc., all of which continue to be further developed.

3. Advanced Applications of Smart Sensing Systems Based on Optoelectronics

3.1. Smart Sensing Systems with Photodetectors

Photodetectors have been an indispensable technology in human history, from early camera charge-coupled devices (CCDs) to X-ray detectors, solar cells, and artificial retinas, and continue to be a promising field with active research. In particular, recent commercialized artificial retinal technologies, such as Argus2, are almost the only hope of regaining eyesight for people who have almost lost theirs. However, as the resolution is not high (the highest resolution of Argus2 is 60-electrode arrays) and a complete wireless system has not been achieved, the possibility of technological development and the research value are very high.

Recently, many wearable smart sensors using a photodetector in wearable platforms have been reported. Kim et al. developed a skin-attachable, wireless, and batteryless smart sensing system with a photodetector and LED. As shown in the photographs and schemes of Figure 5a,b, this wearable smart sensor consists of an NFC chip, a copper antenna, copper serpentine interconnects, an LED, and other components. The device hybridizes PI as the rigid substrate and silicon elastomer as the stretchable substrate. The rigid components of the device are placed on the rigid substrate to adjust the strain such that it is concentrated only on the stretchable substrate to achieve stretchability. The device uses LEDs and photodetectors to detect optical

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**Figure 5.** Photodetectors in a wearable platform. a) Photograph of an optoelectronic system integrated with LEDs and photodetector. Scale bar, 0.5 cm. b) Exploded-view illustration of (a). c) Schematic diagram of the optoelectronic sensor system. The device includes NFC wireless components, an external reader electronics, the analog/digital (A/D) converter, a photodetector, and LEDs. a–c Reproduced under the terms of the CC BY 4.0 license. Copyright 2018, The American Association for the Advancement of Science. d) Schematic image of the self-powered perovskite photodetector. e) Characteristics of the perovskite photodetector which present the photocurrent and responsivity under a variety of intensities of light. d,e) Reproduced with permission. Copyright 2018, Wiley-VCH.
characteristics of the skin, including heart rate, mean arterial pressure (MAP) tracking, peripheral vascular diseases, UV dosimetry, and spectrophotometric characterization. As shown in Figure 5c, the data can be transferred directly to a smart mobile device using an antenna and a batteryless NFC chip with a small built-in CPU capable of data processing. Leung et al. reported a photodetector integrated with triboelectric nanogenerators (TENGs), which are batteryless, flexible, and transparent.\(^{[92]}\)

The device exploits halide-structured methylammonium lead iodide (CH\(_3\)NH\(_3\)PbI\(_3\)) perovskite, which enabled high detectivity, flexibility, and transparency, thus enabling compatibility to a wearable platform. Figure 5d shows that the substrate and electrode materials are all transparent and flexible materials, such as PET, ITO, and PDMS, except for the gold electrode. The ITO material is sputter deposited with a thin thickness of 200 nm to realize flexibility. The device is composed of a perovskite photodetector, a voltage regulator, TENG, and other components.

The graph in Figure 5e shows that the responsivity of the fabricated perovskite was 79.4 V mW\(^{-1}\) cm\(^{-2}\), and the detectivity was 1.22 \times 10\(^{13}\) Jones. In addition, the photodetector gained flexibility, enabling it to run in a bent state, with 360° illumination. However, due to the limitations of materials, such as the ITO electrodes and PET, there are limitations in stretchability. It has been reported that it is possible to implement stretchable photodetectors using organic materials such as regioregular polyn-dacnodithiophene-pyridyl [2,1,3] thiadiazolecyclopentadiophene (PIPCP).\(^{[93]}\) Thus, the use of stretchable materials will be applicable to future-oriented devices such as bio-devices.

### 3.2. Smart Sensing Systems Integrated with Human-Machine-Interactive Visualization

Until now, research trends in wearable electronics with smart sensing functions utilize information of human motion, which is converted into electrical signals and stored as data to expand the range of effective use of stored signals and utilize them on various platforms. These human-interactive machine systems offer the advantage of applicability to a variety of applications, using stored data from human motion. However, they still have significant limitations in human-interactive functions. To store electrical signals converted from human motions and use them in a variety of platforms, additional components composed of rigid forms of devices must be integrated into the electronics. Significant advances have so far been made in attempting to overcome the limitations of materials and carrier substrates with smaller Young’s modulus for the development of multiplexed optoelectronic skins. For example, sensors consisting of flexible or stretchable substrates as skin-like devices have been developed with the integration of built-in active matrix arrays into the electronics to make these sensors function as user-interactive e-skin. Figure 6a shows the schematic illustrations of user-interactive active-matrix optoelectronics fabricated with integrations of pressure sensor arrays and light-emitting pixels on the flexible substrates.\(^{[13]}\) The user-interactive optoelectronics emitted green light from the light-emitting pixels due to the increased current flow toward emitting layers when pressure was applied. As shown in Figure 6b, the integrated systems with functional electronics provided user-interactive functions, which provide the advantage of pressure profiles that can be spatially mapped or that are visually visible to a human being. In another platform, user-interactive optoelectronics devices using changes in capacitance have been developed to measure a wide range of pressure without auxiliary fixtures to read out human motion. Figure 6c shows a human finger pushing tactile sensors, which results in changes in the capacitance of sensors.\(^{[94]}\) This change in capacitance is calibrated by a resistive-capacitive (RC) delay in real time. The RC delay is read by the microcontroller unit, and various symbols are displayed on the skin-mounted device. Figure 6d shows a visualization of pressures. Attempts to obtain wireless functions have been made to further integrate wireless modules, such as batteries and Bluetooth, to convert human motion information for analysis and viewing directly on mobile devices. These systems provided a pathway for future wireless functions of human-interactive optoelectronics, where information collected from pressure sensors can be sent to the light-emitting material layer to convert it into light and transmission to mobile phones. This approach allows a person to directly check information on various motions directly on a mobile device. In smartphone-based wireless functions, as shown in Figure 6e, Park and coworkers fabricated a platform for wireless human-interactive optoelectronics.\(^{[95]}\) This platform made it easy to identify sensing values that act in response to human actions through mobile devices, as shown in Figure 6f. Advances in the wireless functions of various devices can enable electronics or various devices, for example, with robotics that provide a wide range of applications and can receive various sensing results in real time for areas that are not directly accessible to a human being.

### 3.3. Smart Sensing Systems Applied with Phototherapy

In addition to monitoring biometric information and diagnosing diseases using optoelectronic wearable smart sensors, therapy using light emitted by optoelectronic devices is a promising application of wearable sensors in healthcare. Phototherapy includes photothermal, photomechanical, photochemical, and photobiological mechanisms, whereas optogenetics using the photoreaction of proteins has garnered considerable attention. As part of phototherapy technologies in modern medicine, artificial light sources are widely used to treat skin problems and diseases, including tumors. However, existing phototherapeutic approaches have to be administered to patients directly in hospitals, and the huge volume of light-curing units hinders long-term continuous real-time monitoring.\(^{[96,97]}\) In contrast, as optoelectronic devices combined with wearable smart sensors are attached to the body surface or injected into the body, they do not disturb physical activities, while at the same time enabling continuous accurate diagnosis and phototherapy. Therefore, optoelectronic wearable sensors are important for the phototherapy field and are being widely explored by various research groups. Photodynamic therapy (PDT) is a typical phototherapy well received as a technique for tumor treatment such as cancer. Light-based PDT has been developed to treat gastric, breast, skin, and brain tumors. As it uses light, PDT is characterized by less toxicity, minimal invasion, and precise spatiotemporal
stimulation and thus is of much interest to the healthcare industry. In PDT, photosensitive materials are injected into the body and exposed to light. Then photosensitive materials absorb and deliver light energy to molecular oxygen. Afterward, cytotoxic singlet oxygen is discharged to directly react to cancerous tumors and remove malignant cells.[98] As existing PDT uses optical fibers or a laser as optical sources, it must be injected into the body. Yamagishi et al. proposed a metronomic PDT (mPDT) device based on a wireless-powered ILED that can be inserted into the body.[99] They implemented mPDT by attaching the LED device to the endothelium of the skin without inserting the optical source. The LED device is implanted in the endothelium through a polydopamine-based tissue adhesive, stably remained and operated in the endothelial region for 10 days through NFC-based wireless power transmission. As PDT is persistently and stably applied to tumor sites, tumors have been treated without concerns on thermal tissue damage, because light intensity was ≈1000 times lower (<100 μW cm⁻²) than that of conventional PDT (>100 mW cm⁻²). Recently, optogenetic techniques have attracted much attention and are extensively explored in biomedical engineering. Optogenetic techniques utilizing light-sensitive optogenetic actuators such as channelrhodopsin, halorhodopsin, and archaerhodopsin selectively control and record the activities of neurons by applying light to a neuron bundle and precisely control the target sites and time compared with electrical stimulations.[100–102] In the early days of optogenetics, research was conducted to activate neurons in the brain, but recently its applications have been extended to the heart, bladder, and other tissues as well as the brain.[103–105] Representatively, Mickle et al. used resistive strain sensors to monitor bladder functions in real time and adopted optogenetic techniques for peripheral neuromodulation in the bladder via μLED.[106] They reported that the optogenetic technique of applying light to neurons helped the bladder function normally. The fabricated optoelectronic device could be implantable in the body and utilized wireless harvesting for wireless power transmission and communication. The fabricated optoelectronic wearable sensor is attached to the bladder via a dissolvable suture.

Figure 6. Optoelectronic skins for optical visualization and tactile sensing. a,b) The schematic illustration of human-interactive, active-matrix displays using flexible forms of substrates and the demonstration of light visualization by applied pressure. Reproduced with permission.[1] Copyright 2019, Wiley-VCH. c,d) The schematic illustrations for the interaction between pressure sensing and optical visualization and the photograph of the tactile sensor with the integration of the optoelectronic display. Scale bar, 1 cm. Reproduced with permission.[94] Copyright 2019, Wiley-VCH. e,f) The schematic of wireless communicating systems with integrations of pressure sensor arrays and tactile-interactive OLED display and their wireless communicating demonstration. Reproduced with permission.[95] Copyright 2019, Elsevier Ltd.
to the detrusor muscle. Even more than a month later, optogenetic stimulation and sensing modules continued to function well. As described earlier, wearable smart sensors based on optoelectronics are being developed and used to monitor and diagnose biometric signals continuously and in real time. In addition, applications to phototherapy activation and suppression of neurons through light irradiation according to signals sensed by a wearable smart sensor are also a promising research topic in the field of healthcare.

4. Conclusions

This article briefly reports on current advanced optoelectronics and recent researches that are integrated into smart sensing systems that are under development for a new platform. We suggest the potential of a new optoelectronic application that is integrated into a smart sensing system rather than into electronic monitors or general photodetectors. The potential of integrating optoelectronics into smart sensing systems has been demonstrated by applications such as photodetectors for biosensors, human–machine-interactive visualization, and phototherapy. Use of a photodetector as a biosensor provides tremendous advantages for integration into a wearable platform and immediate detection of optical characteristics of the body.

Another potential application in this field is a form of wireless communication that senses an external stimulus without RF. The method transports data by optically converting data without digitalizing the data. In other words, human–machine-interactive applications based on optoelectronics that directly respond to light according to human interactions is another emerging field. Such devices have been recently studied as an attempt to visualize the five senses. In smart sensing systems, optoelectronics can also be used for therapy purposes. The goal of self-healthcare is self-diagnosis based on the data collected by the sensor and feedback-based therapy. Phototherapy, such as through LED masks, has recently received considerable attention. Accordingly, research is being conducted on the integration of light-emitting optoelectronics, such as micro-LEDs, in smart sensing systems. Use of smart sensing systems for phototherapy on the surface of the body and inside the human body for treatment such as neurotherapy has been reported.

Optoelectronics applied in smart sensing systems are summarized in Table 1. This table was organized according to the function of optoelectronics. A comparison of smart sensing systems to conventional sensing systems reveals a number of differences. First, smart sensing devices are mostly wearable, which means that they are flexible or even stretchable, whereas conventional sensing systems are planar. Electrodes and substrates are chosen as the advanced material to achieve mobility or stretchability. Thanks to wearability, there are many advantages including continuity and sensing of surface characteristics. Second, smart sensing systems generally include a wireless communication system whereas conventional sensing systems require wired measurements using bulky equipment. Especially, in cases where wireless communication is compatible with smart mobile devices, they become the only equipment that is needed for measurements. This means that smart sensing systems can be used as POCTs. In summary, from a future-oriented perspective, optoelectronics in wearable or implantable smart sensing systems have great potential and research value. However, current smart sensing systems still lack the technology and materials necessary for complete POCT. Optoelectronics continue to be developed to overcome current limitations in materials and technologies that are necessary for integration into smart sensing systems.

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Conflict of Interest

The authors declare no conflict of interest.

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optoelectronics, smart sensors, wearable devices, wireless communications

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