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Research Article

NANOMATERIALS FOR STRETCHABLE PHOTODETECTORS: FROM FUNDAMENTALS TO APPLICATIONS

***Junahn Choi**

Heritage Innovation School, 8 Olympic Garden Drive, North York, ON M2M 0B9, Canada

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Abstract

Stretchable photodetectors have become an essential component in the advancement of wearable electronics, providing real-time sensing capabilities combined with excellent mechanical stability. By incorporating advanced nanomaterials such as zero-dimensional quantum dots, one-dimensional nanowires, and two-dimensional layered materials, researchers have developed photodetectors that not only show high responsivity and broad spectral coverage but also maintain remarkable mechanical resilience under strain. Unlike conventional rigid or even simply flexible devices, these stretchable photodetectors are required to endure significant tensile strain while preserving stable optoelectronic performance. This review explores the fundamental principles of photodetection, key performance metrics, and recent material innovations. Focusing particularly on nanomaterial-based architectures that employ elastomeric substrates, deformable interconnects, and hierarchical designs to enhance stretchability. We also examine applications in health monitoring such as pulse oximetry and UV exposure detection as well as potential uses in imaging and optical communication networks. Recent experimental studies reveal that these nanomaterial-based photodetectors can sustain repeated mechanical deformations while keeping rapid response times and low power consumption, positioning them as strong candidates for next-generation wearable electronics, though challenges with large-area fabrication, long-term mechanical stability, and seamless integration with wireless systems still persist and require further research in materials engineering and device optimization.

Keywords: Stretchable electronics, Photodetectors, Nanomaterials, Wearable electronics, Imaging sensor, Wireless communication, Health monitoring.

INTRODUCTION

Wearable electronics emerged as an innovative method to revolutionize everyday life through their seamless integration with the human body. For instance, drug delivery patches, health monitors, power supplies, optoelectronic devices, and various sensors were designed to be worn with comfort as well as stable enough that they do not interfere with the body movement. (Koo *et al.,* 2021) As these electronics become more complex, they need to balance high performance with mechanical stability, requiring materials and design which can bend, fold, and stretch to meet the dynamic, real-world conditions. (Cho *et al.,* 2022; Choi *et al.,* 2019) Photodetectors are one of the key components in many wearable devices. They convert incident photons into electrical signals for a variety of applications ranging from environmental sensing to medical imaging and consumer electronics. (Taffelli *et al.,* 2021) Previously, photodetectors have been fabricated on rigid substrates that lack significant flexibility. (Cai *et al.,* 2019) The increasing demand for lightweight, compact, and flexible devices has promoted continuous research into photodetectors capable of bending, twisting, and stretching while maintaining reliable optoelectronic performance. Early efforts to improve photodetector wearable focused on transferring conventional device architectures onto thin polymer substrates that are flexible and lead to accomplish conformal contact with body tissue. Flexible photodetectors showed that foldable, lightweight device designs are possible. But as wearable technologies evolved, merely bending or folding was not enough. Next-generation devices now require the ability to sustain tensile strains without fracture or significant performance degradation.

This demand enabled the introduction of stretchable photodetectors, which provide a further aspect of mechanical flexibility through highly engineered materials and device designs. (Bai *et al.,* 2023). To meet the demand for the next-generation stretchable photodetectors, nanomaterials have been introduced as novel strategies for the material (Kim *et al.,* 2024) and structural challenges faced by stretchable photodetectors. (Figure 1) Zero-dimensional (0D) nanomaterials, including quantum dots, demonstrate excellent quantum confinement effects along with highly tunable optical properties.

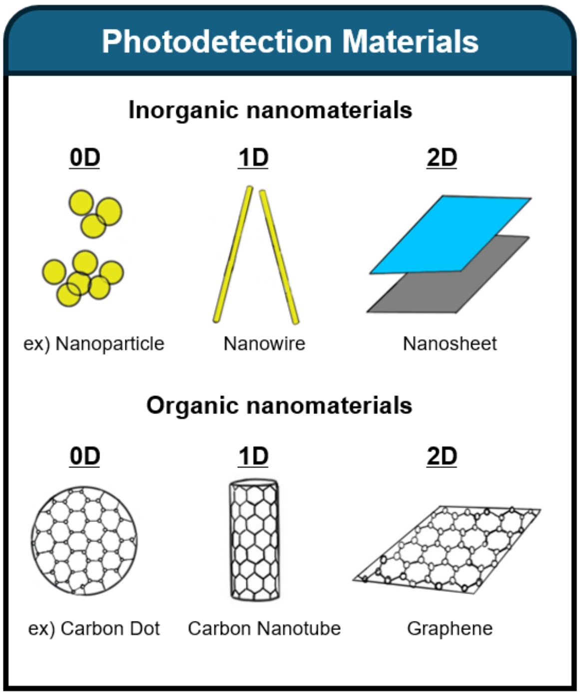

Figure 1. Types of nanomaterials for photodetection materials

Corresponding Author:** ***Junahn Choi,
Heritage Innovation School, 8 Olympic Garden Drive, North York, ON M2M 0B9, Canada.

In the meantime, one-dimensional (1D) nanomaterials such as nanowires and nanotubes offer an unprecedented combination of high conductivity and outstanding mechanical stretchability. Two-dimensional layered materials, characterized by their atomic-scale thickness and tunable bandgaps, exhibit robust in-plane bonding capable of withstanding specific levels of strain. In this review, we present the principles and key performance metrics of photodetectors. Then, materials for stretchable devices are discussed, covering both substrate choices and nanomaterials as active layers. Building on that foundation, we examine primary applications such as health monitoring, imaging systems, and optical communications. We also emphasize some remaining obstacles related to reliability, large-area fabrication, and integration, while highlighting future directions that may guide the development of fully stretchable photonic systems poised to shape emerging wearable technologies.

FUNDAMENTALS OF PHOTODETECTORS

Principles of Photodetectors

Photodetectors convert incoming photons into electrical signals via multiple critical mechanisms. One aspect refers to the photoconductive effect which absorbed photons excite electrons and holes in a semiconductor, thereby increasing its conductivity under external bias. The photovoltaic effect is exemplified by photodiodes, which an electric field in a p–n junction or hetero junction drives photogenerated charge carriers so that the current or voltage can be detected without any external bias. The third mechanism is the photoelectric effect where electrons from the material surface is excited under sufficiently energetic photon irradiation, causing them to be emitted and thereby generating a photocurrent that is essential for the operation of many optoelectronic devices. Photodetectors consist of a light-absorbing active layer and electrodes for carrier collection with a substrate that controls the mechanical and thermal properties of the device. Moving from rigid, wafer-based photodetectors to stretchable platforms requires reimagining all of these components to ensure that sensitivity, response time, and stability remain intact under bending, twisting, and strain. The interplay between materials selection, device architecture, and mechanical design thus becomes central to achieving high performance in stretchable photodetector technologies.

Key Performance Metrics

The performance of photodetectors is evaluated through several essential parameters that collectively determine its suitability for various applications. (Li *et al.,* 2022) One critical factor is responsivity, defined as the ratio of the generated photocurrent (I_{ph}) to the incident optical power (P_{in}) or $= I_{ph}/P_{in}$. A higher responsivity indicates a stronger output signal under the same illumination, which is particularly beneficial for detecting low-level light. Another important factor is response speed, which measures how quickly the sensor can follow changing light intensities.(Y. Wang *et al.,* 2022) Two time constants typically describe this property: the rise time (τ_{rise}), which is the interval needed for the photocurrent to climb from 10% to 90% of its peak value when the light is switched on, and the decay time (τ_{decay}), representing how long it takes for the current to drop from 90% back to 10% once illumination ceases. Devices with faster response times are essential for high-speed communications and real-time imaging. The spectral range of a photodetector indicates the wavelengths it can sense, largely dictated by the absorption profile of the photoactive layer. (Wang *et al.,* 2019) Stretchable photodetectors often integrate an array of nanomaterials or hybrid structures to achieve detection across ultraviolet, visible, or infrared bands. This broad coverage supports a wider variety of applications, from biosensing to environmental monitoring. Stretchability itself is a vital parameter to control how much deformation a device can endure while remaining functional. Typically expressed as a percentage of length change($\Delta l/l_0$), high stretch ability allows photodetectors to be mounted on soft or curvilinear surfaces, including human skin, without mechanical failure or significant performance loss.

Finally, specific detectivity(D^*)quantifies the smallest signal a photodetector can reliably detect once factors like noise and device area are taken into account, (Taffelli *et al.,* 2021) and is defined as$D^* = \sqrt{S\,\Delta f}\,/NEP$. Here,$S$ is the active area,Δf the noise measurement bandwidth, and NEP the noise-equivalent power. A higherD^*signifies an enhanced capability to discriminate weak optical signals against background noise, a critical advantage for low-light or long-distance sensing applications.

PHOTODETECTOR MATERIALS

Substrate Materials

Stretchable substrates play a pivotal role in enabling photodetectors to endure large deformations without losing functionality. Unlike rigid silicon or typical flexible substrates, stretchable substrates must accommodate repeated mechanical strain, often reaching or exceeding 50% elongation and maintain stable device performance at the same time. Polydimethylsiloxane (PDMS) and 3M VHB are two representative materials in this category. They exhibit stretchability, chemical stability, electrical insulation as well as optical transparency that are suitable material for the fabrication of stretchable photodetectors. One widely adopted strategy is to embed photoactive components within elastomeric substrates. This approach not only shields the active nanomaterials from environmental degradation but also integrates their optoelectronic functions directly into the stretchable substrate. (Figure 2) For example, one method involves the fabrication of elastomer with embedded nanomaterial pattern. (Yan *et al.,* 2014)

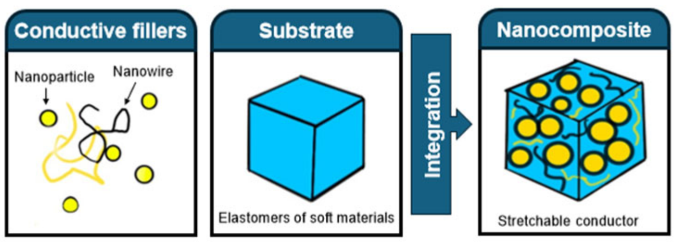

Figure 2. Fabrication of stretchable photodetectors with nanomaterials and substrate

The patterned nanowires (NWs) or nanoparticles is deposited on a sacrificial layer and encapsulated with elastomer such as PDMS or 3M VHB. Once cured, the elastomer can be peeled off along with the embedded nanomaterial network. This embedding process stabilizes the photoactive materials under stretching, since they move synergistically with the polymer matrix rather than experiencing direct tensile force at an interface. Researchers have shown that this design can preserve a high on/off ratio and rapid response speed in photodetectors, even as the device undergoes significant elongation. Building on this core principle, studies have compared different encapsulation approaches to enhance device performance. One approach leaves NWs partially exposed on the PDMS surface, rather than fully embedding them, to mitigate oxygen depletion effects that can arise when the elastomer is heavily stretched. (Wang *et al.,* 2014) When the elastomer is stretched, changes in oxygen concentration near the NWs can reduce carrier dynamics, which also may alter photoconductive properties. Allowing controlled exposure to ambient air can reduce these complications and improve the recovery speed after each strain cycle. Although PDMS remains the most common choice for stretchable substrates due to its biocompatibility and ease of processing, alternative elastomers offer additional advantages. Ecoflex, for instance, is an extremely soft silicone rubber that can accommodate even higher levels of strain, potentially exceeding 100%. (Young *et al.,* 2020) The softness as well as stretchability of Ecoflex makes it especially appealing for wearable applications where conformal contact with skin is crucial. Similarly, 3M VHB, a specialized acrylic elastomer, is also considered as one of primary substrate material used for stretchable electronic application due to strong adhesive and chemical resistance properties along with substantial stretchability. Regardless of the specific elastomer chosen, long-term reliability under cyclic loading remains a central challenge. Repeated stretching and compressing can gradually introduce microcracks and delamination in the polymer-nanomaterial interface. (Son & Bao, 2018) This damages reduce optical and mechanical properties over time. Addressing these limitations requires improved material synthesis and processing techniques, such as using amphiphilic surfactants to bond nanowires more securely to polymer matrices, optimizing curing conditions, or implementing protective encapsulation layers. In stretchable electronics, elastomeric substrates stand at the forefront of innovation. When combined with high-performance nanomaterials or sophisticated structural designs, they lay the foundation for robust, conformal photodetectors that can be integrated into skin-mounted sensors, soft robots, and other deformable platforms.

Active Photodetection Materials

Nanomaterials, broadly defined as materials with at least one dimension in the 1–100 nm range, offer remarkable advantages for stretchable photodetectors. Their high surface-to-volume ratio, tunable band structure, and often superior mechanical compliance enable enhanced photoresponsivity, carrier transport, and overall stability under tensile stresses. Among the diverse categories of nanomaterials, 0D, 1D, and 2D nanomaterials have each emerged as promising platforms for active photodetection layers.

Zero-Dimensional Nanomaterials: 0D nanomaterials are confined to the nanoscale in all three spatial dimensions. They typically appear as nanoparticles, quantum dots (QDs), or other small clusters that exhibit pronounced quantum effects due to their reduced size. This unique quantum confinement allows their optical and electronic properties, such as bandgap, absorption edge, and emission characteristics, to be manipulated by controlling particle size or shape. Quantum dot is primary example in the class of 0D nanomaterials. By changing their size, the bandgap of quantum dot can be controlled to achieve a desired spectral response, potentially spanning ultraviolet to infrared wavelengths. Lead sulfide (PbS) QDs, for instance, have a narrow bandgap (~0.4 eV) well-suited for detecting near-infrared (NIR) light.(Q. Yan *et al.,* 2019) Incorporating these QDs into a polymer matrix, such as a conductive organic layer (e.g., poly(3-hexylthiophene), P3HT), can yield broad-spectrum photodetectors covering UV–Vis–NIR ranges.(Yoo *et al.,* 2015) The concentration and size of the QDs are critical to optimizing device performance: higher QD loadings can boost absorption and photocurrent, while smaller QD diameters may enhance charge transfer, thus raising the on–off ratio and overall responsivity. 0D nanomaterials are also well-represented by upconversion nanoparticles (UCNPs), which convert lower-energy NIR photons into higher-energy visible or UV emissions through anti-Stokes processes. (Li *et al.,* 2017) Devices embedded with UCNPs can therefore detect NIR light but also display emission signatures at shorter wavelengths. Such upconversion effects extend photodetection capabilities to otherwise challenging spectral ranges, offering applications in bio-integrated sensors, security imaging, and other advanced optoelectronic systems. (Zhou *et al.,* 2017) In many reported stretchable photodetectors, a wrinkled or buckled structure integrates UCNPs with conductive layers (such as graphene), improving mechanical flexibility while ensuring efficient transfer of photogenerated carriers into the transport layer. This synergy has produced devices with broad spectral responses, high responsivity in both UV and NIR regions, and fast response speeds on the order of milliseconds.

A major advantage of 0D nanomaterials lies in their solution processability. Quantum dot inks or colloidal suspensions allow for large-area coating and relatively simple device fabrication at lower cost, which is critical for scalable production. Nonetheless, quantum dots can face challenges in carrier transport because discrete nanoparticles may hinder percolation network. To overcome this issue, conductive polymer, 1D, and 2D nanomaterials can be added to act as a carrier transport layer to facilitate the movement of photogenerated charges from the QD layer to the electrodes. Research in this area continues to focus on optimizing interfacial charge transfer mechanisms, minimizing trap states, and enhancing the mechanical stability of the composite. The 0D nanomaterials combine extraordinary versatility in spectral tuning with excellent mechanical adaptability, making them a strong candidate for next-generation stretchable photodetectors. Even as their light detection range and responsivity improve, continued efforts in material design and device engineering are crucial to addressing charge transport limitations and ensuring robust performance under repeated strain or deformation.

One-Dimensional Nanomaterials: 1D nanomaterials such as nanowires, nanotubes, nanorods, and nanoribbonsare widely studied as photoactive layers in stretchable photodetectors due to their large surface-to-volume ratios and efficient charge transport pathways. By extending primarily in one dimension, these structures can provide prolonged carrier lifetimes and rapid carrier mobility, which is conducive to high-sensitivity, fast-response photodetection. A variety of semiconductor 1D nanomaterials, including metal oxides like ZnO, metal sulfides such as ZnS and CdS, and other alloys, have been employed to capitalize on these advantages.

In one example, a straightforward casting method can be used to embed 1D nanowires in an elastomeric matrix to achieve fully stretchable photodetectors. (Yan *et al.,* 2014) This embedded design both protects the nanowire network from mechanical damage and preserves its optoelectronic properties. In relaxed state, the devices demonstrate reliable photoconductive behavior by showing significant differences between dark current and photocurrent. Under mechanical strain, small changes in current and response times are sometimes observed, typically caused by variations in the local environment around the nanowires as the elastomer deforms. A decrease in ambient oxygen concentration or changes in diffusion rates near the nanowire surfaces can slow the photocarrier generation or recombination processes, slightly impacting the speed or magnitude of the photoresponse. (Wang *et al.,* 2014). Another promising avenue involves combining different 1D materials into core–shell or other hybrid structures, wherein each component contributes distinct optical or electrical properties. For example, a piezo-phototronic effect may arise if the core and shell differ in their piezoelectric constants (Dai *et al.,* 2017). Under applied tensile or compressive strain, the resulting changes in the local Schottky barrier height can increase or decrease the photocurrent, effectively harnessing mechanical deformation to tune device performance. (Zhao *et al.,* 2016) In some cases, the responsivity can be significantly enhanced under compression due to the modified band structure and more favorable energy alignment for charge transport. Overall, 1D nanomaterials remain one of the most adaptable optoelectronic candidates for stretchable photodetectors. Their high aspect ratios naturally make them compatible with tensile forces along their growth axis. However, misaligned stresses can still pose risks for mechanical failure. Ongoing research into deposition techniques and patterning methods that can fix the orientation of nanowires is expected to further improve both reliability and electrical performance. Also, the inherent advantage of having a unidirectional conductive channel allows for rapid and efficient charge transfer, particularly when the free carrier diffusion length is well matched to the nanowire dimensions. By leveraging relatively simple vapor deposition or hydrothermal synthesis routes, these 1D nanomaterials can be synthesized cost-effectively and applied to mass production. The devices based on 1D nanomaterials not only offer compelling photodetection performance, characterized by high sensitivity, fast response, and low power consumption, but they also present an attractive path toward the scalable production of next-generation stretchable photodetectors.

Two-Dimensional Nanomaterials: The concept of two-dimensional (2D) materials grew in prominence following the successful isolation of single-atom-thick graphene. Beyond graphene, this category now encompasses a wide variety of layered structures, including transition metal oxides, metal sulfides, and black phosphorus. These 2D systems offer several compelling attributes for stretchable photodetectors. Their ultra-thin design results in exceptional transparency, and the adjustable bandgaps allow for a wide spectral response across various wavelengths. Additionally, the minimal thickness promotes swift in-plane carrier movement and robust light–matter interactions, leading to improved optical absorption and effective photoresponsivity. (Qi *et al.,* 2022) Graphene has attracted significant interest due to its remarkable carrier mobility and broad light detection abilities. While graphene features remarkable electrical and optical properties, its inherent stretchability is limited to approximately 10%, posing a challenge for applications that demand greater mechanical deformation. (Ahmad *et al.,* 2022) A potential approach to address this limitation is to incorporate wrinkled or folded geometries. Through the deliberate development of folded or buckled structures, the elongation capacity of graphene is enhanced, enabling devices to function under greater tensile strains without experiencing cracks or delamination. In certain instances, plasmonic nanoparticles can be integrated with wrinkled graphene to enhance localized electric fields, thus increasing the responsivity of the photodetector while maintaining mechanical flexibility. Such device designs have demonstrated potential for integration into wearable sensors, including those mounted on contact lenses or other curved surfaces. Building on these approaches, colloidal photonic crystals can be added to the supporting substrate of 2D-based photodetectors to achieve wavelength-tunable responses under varying degrees of strain. (Black *et al.,* 2019) These photonic crystals consist of periodic nanoscale structures whose lattice constant is correlated with the peak wavelength of reflected or transmitted light. When mechanical strain adjusts the lattice periodicity, the effective detection band shifts accordingly. (Liu *et al.,* 2021) Although this approach does not directly alter the intrinsic properties of the 2D material, it offers a unique method of tailoring the spectral response based on stretching, creating a new dimension of functionality for photodetection systems. Another approach for 2D-based photodetectors leverages microtectonic architectures, where thin oxide layers naturally form micron-sized plates or flakes that can peel apart and reassemble into high-surface-area configurations. (Wang *et al.,* 2019) These microstructures significantly enhance the optical and reactive properties of the material, creating larger adsorption regions for oxygen or other interacting species. This increased surface interaction, in turn, improves the device's sensitivity to variations in illumination, making it more responsive to subtle changes in light exposure. When combined with lightweight and transparent substrates, such designs can yield stretchable ultraviolet detectors and related systems that maintain reliable operation despite repetitive mechanical deformation. Beyond graphene, numerous other 2D materials demonstrate comparable promise through adjustable bandgaps, simple solution processing, and straightforward large-area fabrication. These properties create opportunities for enhancing performance across various spectrums, from ultraviolet to infrared, while still satisfying the mechanical requirements of wearable, on-skin, or otherwise deformable devices. As such, two-dimensional nanomaterials represent a fertile research domain for achieving next-generation photodetectors with tunable response, robust stretchability, and streamlined manufacturing processes.

Applications for Stretchable Photodetectors

Stretchable photodetectors open new frontiers in applications that demand continuous or conformal light sensing in dynamically changing environments. By integrating nanomaterials with elastomeric or otherwise mechanically compliant device architectures, these photodetectors maintain stable optoelectronic performance even under repeated tensile strain. Three prominent domains, health monitoring, imaging, and optical communication, have showcased the potential impact of stretchable photodetectors based on 0D, 1D, and 2D nanomaterials. (Figure 3) This chapter highlights key developments in each field, emphasizing how unique properties of nanomaterials can address the practical challenges of stretchability and high-fidelity photodetection.

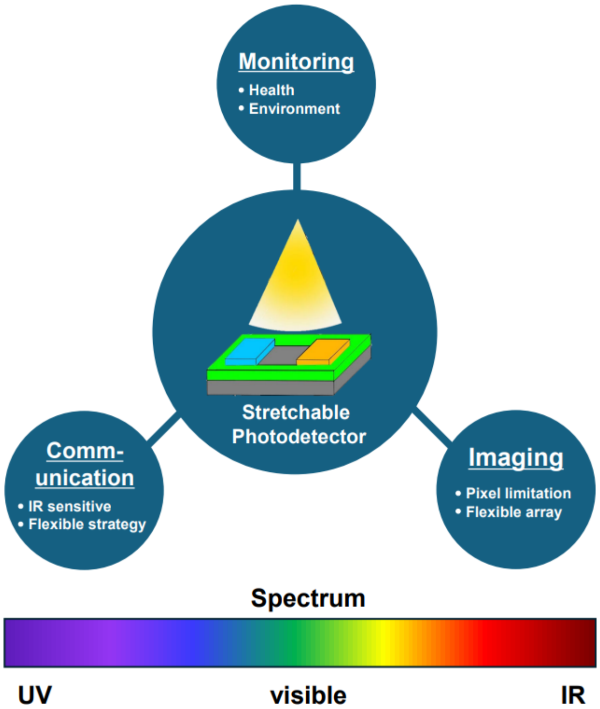

Figure 3. The applications of stretchable photodetectors

Health Monitoring

Stretchable photodetectors have attracted considerable interest in health monitoring applications such as pulse oximetry, photoplethysmography (PPG), and UV-exposure sensing.(F. Liu *et al.,* 2023) Their exceptional capacity to adapt to soft, curvilinear skin surfaces allows the comfortable and long-term monitoring of vital signs as well as environmental factors. In these devices, nanomaterials are important to provide exceptional responsivity and broad spectral coverage within lightweight and flexible layers. (Song *et al.,* 2021)

Furthermore, real-time monitoring of blood oxygen saturation, heart rate, and various physiological signals can be obtained through techniques like PPG and pulse oximetry. Integrating LEDs that emit red or infrared light with nanomaterial-based photodetectors on soft, skin-friendly substrates allows these systems to detect variations in optical absorption within blood vessels, offering vital insights into cardiovascular health. (Park *et al.,* 2021) Several groups have demonstrated miniaturized and battery-free platforms that rely on near-field communication (NFC) for power and data transfer. Embedding commercial photodiodes or organic photodetectors alongside red polymer LEDs has enabled ultrathin optoelectronic skin sensors. The use of elastomeric encapsulation layers such as SiON–parylene ensures mechanical durability, maintaining high responsivity and minimal signal drift under repeated bending or stretching. (Lan *et al.,* 2022) Inorganic semiconductor-based systems, such as ZnO nanowire photodetectors, also exhibit promising performance in continuous on-body operation, thanks to high carrier mobility and good mechanical robustness. Quantum dots (QDs) and upconversion nanoparticles, for example, can be embedded in or transferred onto elastomeric substrates to detect optical signals from the human body. The adjustable bandgaps of these zero-dimensional materials enable targeted sensitivity in the visible or near-infrared spectrum, which is crucial for assessing blood flow parameters. In the meantime, 1D nanowires (NWs) composed of ZnO or various metal oxides can be designed in serpentine patterns and integrated into flexible polymer matrices to ensure reliable device performance under repeated strain cycles. These NW networks often yield high on/off ratios and fast response times, even when tension alters the local environment around the active region.

Excessive UV exposure is recognized as a key risk factor for skin cancer and photoaging. Fiber-shaped p–n junction photodetectors and hierarchical ZnO nanoparticle networks have been fabricated to achieve high photocurrents, ultralow dark currents, and strong selectivity to UV wavelengths.(Huynh *et al.,* 2024) Conformal coating strategies, such as depositing CuZnS films onto TiO_2 nanotube arrays, enhance carrier collection while maintaining flexibility (Gao *et al.,* 2009). These designs can generate sufficient electrical output to interface with smartphones or other wireless modules, enabling real-time UV exposure monitoring. Despite this advancement, numerous challenges remain for the implementation of clinical-grade solutions. A significant number of devices depend on external power sources or data acquisition systems, which hinders their long-term portability. Innovative self-powered photodetector structures utilizing p–n junctions or metal–semiconductor–metal (MSM) designs stand out as leading solutions for overcoming these challenges.(Z. Zhao *et al.,* 2023) Furthermore, continuous mechanical stress can lead to the formation of microcracks, ultimately shortening the lifespan of the device. To guarantee operational stability, it is essential to utilize strong material interfaces, implement strategic encapsulation, and apply cutting-edge adhesive techniques. Ultimately, merging signal processing with wireless communication enhanced by AIinto a compact design continues to pose a significant challenge. Creating a fully autonomous, stretchable health monitor that continuously tracks multiple biomarkers represents the next groundbreaking advancement in wearable photonics.

Imaging

In imaging system, large arrays of pixelated photodetectors capture and interpret complicated spatial information across the visible or infrared spectrum. Transitioning to stretchable formats poses significant challenges, including the need for high pixel density, consistent responsivity under strain, and reliable interconnects that preserve signal integrity. Nanomaterials enhance optical absorption and mechanical flexibility. Stretchable imaging systems are designed to capture high-resolution images even under large strains. They consist of pixelated arrays of photodetectors using nanomaterials such as nanowires, quantum dots, and 2D materials. Their micromechanically compatible structures enable the active layer to withstand bending or stretching while maintaining electrical performance. Flexible ZnO/Zn_2SnO_4 quantum dot photodetectors shows remarkable responsivity, which is around 10^7 A/W, and response times under 47ms.(L. Li *et al.,* 2017) Outstanding photoelectronic gains is obtained by the extraordinary potential of quantum confinement and customized band alignments. Broadband sensing is another emerging trend, achieved by integrating p-type SnS_2 quantum dots or heterojunctions that extend sensitivity into the near-infrared range. (Li *et al.,* 2018) Such hybrid nanomaterial systems can be deposited on polymeric substrates that are pre-engineered by serpentine or wrinkled architectures to dissipate strain uniformly. Flexible imaging arrays have thus demonstrated the potential for wearable cameras, artificial vision aids, and omnidirectional photodetection. A key challenge for practical stretchable imaging systems is scaling pixel density to commercially viable levels. While proof-of-concept devices feature arrays as large as 10 × 10 pixels, recognizing even simple patterns (e.g., QR codes) often requires substantially higher resolutions (e.g., 117 × 117 pixels). (Cai *et al.,* 2019) Fabrication techniques must ensure pixel uniformity, consistent readout electronics, and minimal cross-talk during mechanical deformation. Research emphasizes the integration of memristors and alternative memory components to achieve "visual memory," enabling the retention of captured images even after the light source is removed.(Chen *et al.,* 2018) This innovative method of utilizing photoconductors like In_2O_3 nanowires in conjunction with memory elements on flexible substrates, allows for the capture and retention of images in real-time under bending or stretching conditions. While still in their infancy, these multifunctional imaging systems suggest exciting possibilities for the future of wearable vision platforms.

Optical Communication

Optical communication typically relies on precise emission and detection of light in specific wavelength bands, ranging from visible to infrared. Stretchable photodetectors can facilitate new paradigms of body-area communication or wearable data exchange, provided they maintain strong optoelectronic performance under mechanical deformation. Nanomaterials offer promising solutions for such systems by combining superior optical response with structural tunability. Two-dimensional semiconductors often serve as broadband detectors with a wide dynamic range, making them advantageous for short-range visible light communication or Li-Fi networks. Gate-based architectures using 2D channels can effectively suppress dark currents, which is critical for reliable signal detection in IR-based communication. (Li *et al.,* 2022) Additionally, 1D nanostructures that are laser-written or grown directly on elastomeric substrates can align along pre-strained directions, forming stretchable light-communication modules capable of large-area coverage.(Xu *et al.,* 2020) Zero-dimensional materials such as colloidal QDs may also be deployed in multi-layer structures to detect or filter specific communication wavelengths, offering potential for wavelength-multiplexed signals. Furthermore, strain-engineered approaches, like wrinkled graphene or serpentine nanoelectrodes, preserve the mechanical integrity of these photodetectors, allowing them to be integrated into soft robotics, on-skin networks, or next-generation "Internet of Things" communication platforms. Optical communication relies on modulating light for data transfer. In stretchable devices, this may occur through visible or UV wavelengths, integrating fiber-shaped diodes and photodetectors onto deformable substrates. Some prototypes have demonstrated data transmission over short distances (e.g., 1 m), suitable for body-area or device-to-device networks. (Rein *et al.,* 2018) However, maintaining stable signal quality under continuous mechanical strain remains a challenge, partly due to alignment and interference issues. Infrared (IR) communication is crucial for long-range or high-data-rate applications. Although IR photodetectors typically require more sophisticated architectures (e.g., gate-based transistors to suppress dark currents), advances in 2D materials and hybrid nanostructures have begun to yield flexible phototransistors with decent IR responsivity. Another approach involves the "rigid island" concept, wherein small, rigid IR photodetector segments are mounted on an elastic substrate connected by stretchable interconnects, preserving overall mechanical compliance while maintaining high optoelectronic performance in sensitive semiconductor regions (Petti *et al.,* 2016). Wearable communication systems are poised to play a central role in the "Internet of Things" and advanced human–machine interfaces. (Cai *et al.,* 2019) Achieving reliable, low-power optical links under mechanical deformation requires further optimization of device encapsulation, waveguide integration, and packaging. In particular, large-area manufacturing and consistent device performance over repeated strain cycles are pressing concerns. Ongoing improvements in nanomaterial synthesis, transistor design, and micro/nanofabrication techniques will undoubtedly push stretchable photodetector networks toward practical optical communication solutions.

Conclusion

Stretchable photodetectors have emerged as an exciting branch of wearable electronics, merging the high optoelectronic performance seen in rigid semiconductor devices with the mechanical compliance needed for on-body or dynamic applications. As noted in the introduction, the push toward more conformal electronic systems has amplified the need for photodetectors that not only capture and transduce light signals accurately, but also withstand repeated tensile, bending, and twisting strains. Nanomaterials play a particularly critical role here due to their unique optical and electrical properties. Zero-dimensional quantum dots exhibit tunable bandgaps and strong light absorption, one-dimensional nanowires provide efficient charge transport pathways, and two-dimensional layered semiconductors deliver broad spectral coverage with minimal thickness. These properties have been instrumental in enabling stretchable devices to match—and sometimes even surpass—the performance of their rigid counterparts, while the synergy between these low-dimensional materials and innovative mechanical designs has paved the way for applications in health monitoring, imaging systems, and optical communication.

In health monitoring, stretchable photodetectors have facilitated real-time, on-skin measurements of vital signs like heart rate and blood oxygenation, as well as UV exposure. These accomplishments demonstrate that it is feasible to integrate photodetection functionalities directly with the human body, offering immediate feedback and improved user comfort. Similarly, stretchable imaging arrays hold promise for wearable or even implantable cameras capable of omnidirectional detection and biometric security screening. Although scaling to higher-resolution arrays remains a challenge, their demonstrated stability under mechanical strain suggests that flexible imaging systems could reshape robotics, human–machine interfaces, and medical diagnostics. In optical communication, the drive toward body-area networks, Li-Fi (Light-Fidelity), and advanced data transfer methods align well with these nanomaterial-based detectors, provided that dark current levels and signal integrity can be maintained under continuous mechanical loading. Looking ahead, progress in material synthesis, such as creating intrinsically stretchable semiconductors, refined nanomaterial inks, and advanced doping or compositing methods, will likely expand the scope of stretchable photodetectors. Complementary efforts in fabrication, including roll-to-roll printing and solution-based processing, are anticipated to lower costs and enable large-scale production. Emerging concepts like self-healing polymers, neuromorphic photodetectors, and biomimetic architectures signal a future where these devices not only serve as passive sensors but also evolve into intelligent, adaptive systems. In conclusion, the integration of fundamental photodetection principles with innovative materials and device architectures has propelled stretchable photodetectors from a conceptual novelty to a rapidly maturing field, and continued multidisciplinary collaboration will be key in overcoming current bottlenecks.

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