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Stretchable photodetectors based on 2D materials: materials synthesis, fabrications and applications

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ABSTRACT

Rapidly evolving two-dimensional (2D) materials such as transition metal-dichalcogenides (TMDCs) and graphene, offer tremendous electrical and optical properties. Owing to these outstanding properties, these have achieved a huge interest in the developments of optoelectronic devices. 2D materials have played an indispensable role specifically in the fabrication of stretchable photodetectors. Numerous 2D materials based stretchable photodetectors reported till date are summarized and discussed here. This review emphases on the techniques used for the development of stretchable photodetectors, recent advances in 2D materials based stretchable photodetectors and their worthy applications which provide a broad view of this research eras. First, a brief insight is provided concerning the techniques for the development of stretchability, photodetection mechanism and methodologies in the directions of assembly of 2D material for stretchable photodetectors. After that, key characteristics of photodetectors, recent developments of stretchable photodetectors and basic applications of stretchable photodetectors based on novel 2D materials is reviewed. Finally, outlook and challenges for stretchable photodetectors based on 2D materials are discussed. Furthermore, this review may assist in developing new insights in favour of additional developments and practical applications of stretchable photodetectors based on 2D materials.

Introduction

The expediency of contemporary semiconductor devices has fuelled the inward connections between humans and next generation optoelectronic devices. In these days, advanced electronic devices like smart phones and smart watches, constantly interact with the human body which are beyond the conventional electronic devices such as computers and telephones. These modern electronic devices are now commercially available in market and many researchers believe that future development of electronic device integration will be the same as human body [1–5]. The promising semiconductor devices will be compatible with the human biological systems and will have the abilities of flexibility and stretchability with the different human body parts in the near future. For this purpose, stretchable transistors, light emitting diodes (LEDs), sensors and electronic embedded systems have already been demonstrated [3,6–9]. There are also a very few reports on stretchable photodetectors. It is challenging and needed to develop the efficient stretchable photodetectors which may offer comfort and convenience for human body. Conventionally reported stretchable electronic devices exhibit modules 1 MPa and strain 30 % with the human body which is not so satisfactory. More than 100 % strain capability and lower modules are the requirements of electronic devices for full human body integration. These key requirement for modern electronics with full integrated human body highlight the importance of robust development in methodologies and techniques for the assembly of stretchable electronic devices [10,11].

Transformation of light into electronic signals or energy is the basic phenomenon found in photodetectors. Photodetectors have various applications in medical imaging, ozone sensing, biological instruments, memristors and so on. Photoelectrical detector is a type of photodetectors in which electromagnetic radiation is converted into electrical

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currents. These are usually used as photodetectors nowadays and high-performance photodetectors are based on photoelectrical detectors [12–14]. In conventional photodetectors, there are five most important parameters for observing the performance of the photodetectors; sensitivity, signal to noise ratio, environmental stability, ON/OFF ratio and selectivity. However, in case of smart and next generation photodetectors, there is need of more properties to be considered such as flexibility, high photoresponsivity, low dark current, portability and stretchability which have great impact on the performance of photodetectors under the mechanical stress. Furthermore, smart and next generation photodetectors integration with human body parts requires more units such as compatibility with components of electronic devices [15–19]. Because of the craving for attaining robust, flexible, stretchable and soft materials to utilize them in energy devices, diagnostics and personal healthcare crafted the path for future electronics. Numerous electrical devices like such as sensors, capacitors, photodetectors and transistors can use stretchable compliant materials [20]. Since the stretchable photodetector is portable, implantable, stretchable along with wearable, these can well be utilized in extensive fields [21,22]. Recently, many devices and applications involved stretchable photodetector as a vital component. A light signal can be transmuted to electrical signal utilizing this device. Environment observation, electro-optical displays, military, optical interaction and security-associated checking are some fields in which the high-performance photodetectors play a significant role [23–26].

Stretchable photodetector based on compound semiconductors like GaN and InP, in addition to HgCdTe, outdo silicon counterparts in ultraviolet (UV) and infrared (IR) regions. The nanoscale materials have rendered rich selections to create high-performance photodetectors for budding application fields [27]. However, the detection gamut of these sorts of detectors is relentlessly constrained due to presence of bandgaps amongst such materials. Furthermore, the intricate fabrication process and cryogenic temperature along with inflexibility are some on the downsides. Therefore, to further ameliorate the performance of stretchable detector, some other materials should be considered in trouncing these issues [28].

Nanoscale materials have worthy potential to develop the soft optoelectronic devices owning to their suitable flexible and mechanical properties. Breakthrough discovery of graphene, 2D layered materials have opened new possibilities for the fabrication of advanced devices due to their incorporation characteristics involving magnificent properties including exceptional electrical conductance, excellent transparency, outstanding mechanical flexibility, and stretchability, etc [5,29]. Graphene has zero bandgap which limits some of its applications like it cannot be used for electronic switches. However, the other 2D layered materials like TMDCs have received marvellous attentions semiconductor devices due to their chiral optical characteristics. Especially, outstanding mechanical flexibility in 2D layered materials make them emerging candidate for the fabrication of wearable and stretchable devices [30–32].

2D layered materials have crystalline structure comprising excellent covalent bonds as well as weak van der Waals interlayer bonding which make these materials interesting choice for the development of electronic and optical technologies. These emerging materials are further divided into different categories: (1) graphene family group (graphene, reduced graphene, hexagonal boron nitride) in which graphene can be used as an electrode in some electronic and optical devices and hexagonal boron nitride (h-BN) can act as surface passivation layer or capping layer for protecting the device from humidity and air. (2) TMDCs semiconducting materials such as MoS_2, WS_2, WSe_2, $MoTe_2$, InSe, GaSe and GeSe etc. [33,34]. (3) Many other materials like 2D perovskite materials [35,36]. As per previous published reports, 2D materials are emerging candidates to develop the next generation flexible and stretchable optoelectronic devices [17,33].

2D materials have tunable bandgap characteristics which offer tremendous properties such as broader response, excellent mechanical stability, high charge carrier mobility and higher dielectric constant which makes these 2D materials an ideal candidate for the development various photodetectors such as broadband photodetectors, flexible photodetectors, and stretchable photodetectors. Furthermore, 2D materials combined with other low-dimensional materials (0-dimensional, 1-dimensional and 2D materials) such as quantum dots or perovskite materials can enhance the photo-electrical characteristics in terms of their broader response, ON/OFF ratio, photoresponsivity, detectivity and external quantum efficiency. Regarding practical applications, 2D materials are easily to synthesis, cost effective and can be produced in scalable on flexible and stretchable substrates as well as show the better compatibility with complementary metal oxide semiconductors (CMOS) [37–39].

Stretchable photodetectors are emerging candidates for the fabrication of wearable biological sensors and photonic imagers owing to their excellent photoresponse at very low power intensities [25,40]. However, a very limited number of literature reports are available on 2D materials based stretchable photodetectors [25,41]. The key challenge in fabrication of stretchable photodetectors is the assembly of efficient stretchable materials which offer remarkable response to incident light. Here, we are summarizing the notable outcomes of recent advances in stretchable photodetectors based on emerging 2D materials with respect to their material synthesis, device fabrications and applications in different research areas. During last decade, the research on 2D materials-based photodetectors had a focus on some selective areas of interests, including (i) enhancing the responsivity and detectivity, (ii) simplifying the techniques to develop the large area nanoflakes, (iii) further improving the response time, and (iv) making them human-friendly for biological and wearable applications [42,43].

In literature, various reviews reported on flexible photodetectors based on low-dimensional materials which focus on the materials processing, designing of photodetectors and their performance, and sensing applications [17,44]. However, few review papers have reported the literature on stretchable photodetectors based on the quantum dots and perovskite materials which emphases on materials processing and their applications [45,46]. Our review paper targets the recent advances in stretchable photodetectors based on novel 2D materials including techniques to enable the stretchability, photodetection mechanism, key characteristics for evolution the performance of photodetectors, working of photodetectors and their applications in different industrial sectors.

Photodetection mechanism

On account of unique structure endowed exceptional mechanical and physical properties of 2D materials, these have attained great attentions throughout the past decennium. The increasing needs of stretchable, effective, broadband, flexible and compact photonic and optoelectronic devices have suggested graphene and associated 2D layered materials as an ideal choice to meet the requirements [47,48]. Some of the significant 2D materials that are becoming the attractive and propitious candidate for the subsequent generation maximal-performance optoelectronic devices are graphene, elemental group V_A members, borophene, TMDCs (for instance, MoS_2 and WS_2), topological insulators, perovskites, h-BN and 3–4 layer semiconductors (like GaS, GaTe, GaSe, In_2Se_3 and InSe).These materials are efficient owing to their chemical characteristics, pre-eminent mechanical strength, maximal carrier mobility, extensive spectral response and higher dielectric constant, and these can be well employed as gate dielectric, photosensitive layer, contacts and channel of a photodetector [44,49]. The basic principle of photodetectors and other optoelectronic devices is to transfer the absorbed photons into the signal or energy. Various mechanisms such as photovoltaic effect, photoconductive effect, photo-thermoelectric effect, bolometric effect, and surface plasmonic effect have been reported for photodetection mechanism in photodetectors and optoelectronic devices [24,35].

Photovoltaic effect (PVE)

PVE is the phenomena in which generation of photocurrent occurs due to build-in electric field inside a material. In this phenomenon, the light incidence on the materials produces voltage inside the materials. Usually, this effect can be observed in different optical devices such as solar cells and self-powered photodetectors. In later, there is no need to apply the additional voltage. A report shows the demonstration of the MoS_2/graphene heterostructure based photodiode in which a layer of h-BN is introduced at the interfaces of heterostructures. Interlayer coupling is realized at the interfaces of MoS_2/graphene; however, after the introduction of h-BN layer, the interlayer coupling is blocked, and device offers electrons/holes generation due to quantum tunnelling. This leads to photovoltaic phenomenon in photodiode; the typical behaviour of PVE in photodetector is depicts in Fig. 1a. As reported self-powered photodetector delivers high sensitivity, high external quantum efficiency (greater than 80 %) and supressed dark current 5.9×10^{14} Jones. The fabricated device may find potential applications in different next generation optoelectronic devices [50]. Another report shows the fabrication of In_2S_3/graphene/Si double heterostructure based Schottky photodetector. The scheme of geometry enables the fast light absorption and exhibits the photogating effect and photovoltaic effect that realize the self-power operation mode at the zero-bias voltage. The device shows higher sensitivity, high responsivity (4.53×10^4 AW^{-1}) and fast photoresponse (fast/rise as 33/40 μs). The demonstrated photodetector could find promising applications in next generation optoelectronic devices [51].

Photoconductive effect (PCE)

PCE can be observed when light is incident on semiconductor materials and changes their conductance. Semiconductors absorb the incident photon energy in the form of light. This type of mechanism usually happens in optoelectronic devices such as phototransistors. Several 2D based photodetectors also work on this mechanism. For instance, a report presents the fabrication of MoS_2 based photodetectors combing with $CsPbBr_3$ colloidal quantum dots which have capability to achieve balanced photodetection. It was found that the fabricated heterostructure has capabilities to separate the generation region and transport carriers owing to the built-in electric field inside the material. This is the further evidence of presence of photoconductive effect in heterojunction. The device exhibits the outstanding photoresponsivity 10^4 AW^{-1} and a fast photoresponse (8 ms) at visible spectrum wavelength 633 nm. They demonstrated device could offer various applications in imaging and communication-based devices [52].

A non-layered 2D material Fe_3O_4 based photodetector was also reported which could operate from UV to NIR spectral regime. The photodetector exhibits high photoresponsivity (561.2 AW^{-1}) and notable EQE (6.6×10^3%) at 375 nm wavelength. Furthermore, the device has high sensitivity for all light intensities owing to photoconductive effect inside the device. In PCE mechanism, electron/hole pairs are produced when the device absorbs the incident photon energy under the presence of the light. Due to photo-absorption, the device conductance changes; the minority carriers are stacked in localized states, that change the fermi level as well as induce the majority carriers as shown in Fig. 1b. In this way, the device is enabled to achieve large photo-gain with high photoresponse. These devices can pave the pathways for non-layered 2D materials-based IR optoelectronic devices [53].

Photo thermoelectric effect (PTE)

The light incidence produced heating effect is known as PTE. In this mechanism, when the light is incident onto the semiconductor material, it did not change the internal electron/hole configuration of the

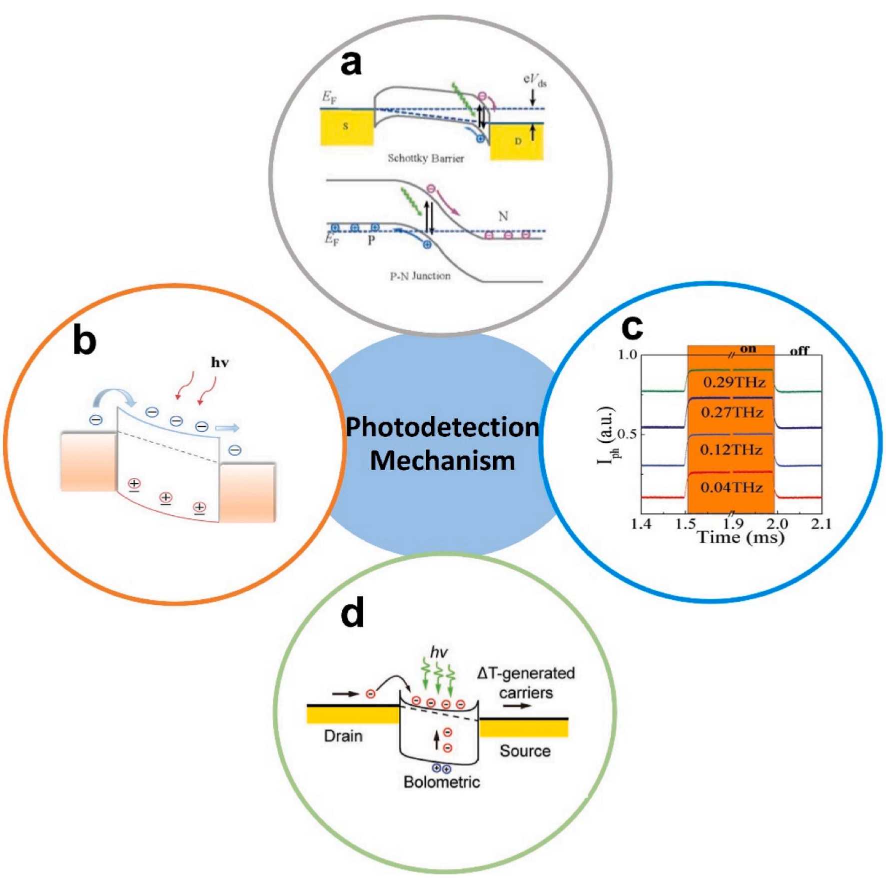

Fig. 1. (a) Schematic illustration of PVE arising from typical p-n junction and metal Schottky barrier [24]. Copyright (2018), with permission from John Wiley and Sons. (b) Schematic illustration of photoconductive effect [53]. Copyright (2021), with permission from John Wiley and Sons. (c) Time-resolve characteristics of device at different frequencies which reveal the broadband detection due to photo thermoelectric effect mechanism [56]. Copyright (2020), with permission from John Wiley and Sons. (d) Schematic diagram of photo-bolometric effect based Bi_2O_2Se photodetector [58]. Copyright (2019), with permission from John Wiley and Sons.

material; instead, it is absorbed into the material and converted to thermal energy. This effect is also known as seebeck effect. 2D materials offer strong interaction of electrons with incident light. Hence, as the light is incident onto 2D materials, photo excitons generated and heat the materials rapidly (it takes around 10^{-15} s to achieve the temperature 10^3 or 10^4 K). This phenomenon is responsible for the production of momentous photothermal electrical response in 2D materials [54]. A $SrTiO_3$ based photodetector with worthy functionalities has been demonstrated which works on the mechanism of PTE. The fabricated photodetector works for optical range from VIS (325 nm) to NIR (1067 nm) and exhibits excellent sensitivity 1.2 VW^{-1} which is attributed to the intrinsic high seebeck coefficient of the material [55]. Another report shows the fabrication of terahertz photonic detection device based on PTE. The device has an ultra-short channel (~30 nm in length) and contains black phosphorus as an active material. PTE based detector exhibits an ultra-high sensitivity 297 VW^{-1} and a short response time 0.8 ms which are superior parameters to other PTE based devices. The time photoresponse characteristics of the device under zero voltage upon different incident frequencies as illustrated in Fig. 1c. The results shows that device has better signal to noise ratio and offer notable compatibility for multiband detection [56].

Photo-bolometric effect (PBE)

PBE mechanism is associated with direct heating by incident light on 2D materials towards to change the transport conductance of the materials. Normally, it is found in highly sensitive detectors for sub-millimetre wavelength range. The thermal resistance of the material is determined by '$R_h = dT/dP$' which is associated with its sensitivity and heat capacity [36,54]. A report shows the fabrication of 2D material ReS_2 based phototransistor which works on photo-bolometric effect mechanism; light heating changes the conductance of material which makes the photodetector workable for sub-bandgap photodetection. Owing to photo-bolometric effect, the device exhibits excellent photoresponse in NIR spectrum up to 1200 nm which is beyond the cut-off bandgap of ReS_2 flakes. Furthermore, the device represents the very low noise equivalent power (NEP) $< 5 \times 10^{-3}$pWHz$^{-1/2}$ which makes the device enable to detect the ultra-low signal at longer wavelength. The PBE is an effective mode in photodetectors which is beneficial in enhancing the photoresponse at larger wavelengths [57].

Another report demonstrated the broadband UV (350 nm) to NIR (1600 nm) photodetector based on Bi_2O_2Se. The fabricated device works on PBE which is confirmed by local heating experiment. It is observed that due to this mechanism, persuaded conductance changes which may be responsible for distinction in number of carriers contributing to the current when the temperature is increased under the light incidence, as shown in energy band diagram for PBE (Fig. 1d) [58].

Surface plasmonic effect (SPE)

Interaction between 2D electron gas and plasma wave of 2D materials-based semiconductor transistor is known as SPE. In this scheme, two mechanisms can be there: (1) if the plasma wave is weakly damped, 2D electron gas and plasma wave go through interference and enhance the detection mode for plasma waver. (2) If the plasma wave is over damped, wide band detection mode is enabled which is much higher (5 to 20 time) than broadband detection mode. Normally, this type of effect is found in terahertz detection [54]. A report shows the demonstration of photodetector based on WS_2 nano disks/graphene heterostructure with lateral dimension range of about 200–400 nm. It is observed that the device has capability to allow surface plasmonic resonance upon incidence of light on device which increases the light absorption and photoresponsivity. It is found that the WS_2 nano disks/graphene heterostructure based device exhibited seven times higher photoresponsivity than continues WS_2 layer/graphene [59]. Another report reveals that, InSe based photodetector with Ti_2CT_x electrode can offer avalanche carrier multiplication effect (which is attributed to specific electrode design) which enhances key figures of merits for the photodetector. The device electrode is patterned with plasmonic nanostructures layer which is responsible for enhancing the light absorption of device. The device shows ultra-low dark current (3nA), excellent photoresponsivity (1×10^5 AW^{-1}) and high detectivity (7.3×10^{12} Jones) [60].

Key characteristics of efficient photodetectors

Key characteristics of the photodetectors are very significant to evaluate the level of the photodetection [61–63]. Some performance characteristics of 2D material-based photodetectors are reviewed in Table 1.

I-V characteristics of photodetector

The operation of photodetector in reverse bias scenario can be elucidated by plotting its reverse voltage (in volts) along the x-axis and reverse current (in microampere) along the y-axis. Reverse current is not contingent on reverse voltage. For no light illumination, the reverse current would be almost "0″. The minimal current existent is termed as dark current. As the light illumination elevates, the reverse current increases linearly. I-V characteristics are associated to the dark current as indicated in following relation [62]:

$$I_{dark} = I_{sat}\left[e^{\frac{qV_A}{k_g T}}\right] \quad (1)$$

Whereas I_{dark} realized as dark current, I_{sat} known as reversal saturation current, q is the electron charge, V_A is the bias voltage, k_g is the Boltzmann constant ($k_g = 1.38 \times 10^{-23}$ J K^{-1}) and T is absolute temperature constant.

Gain

Gain of a photodetector expressed as detected charge carriers per single incident photons [62].

$$G = \frac{I_{ph}/q}{P_{in}/h\nu}\eta \quad (2)$$

Whereas, h is Planck constant (6.63×10^{-34} Js), c is the velocity of light (3×10^8 m s^{-1}), η is quantum efficiency, elementary charge ($q = 1.6 \times 10^{-19}$C), λ is the excitation wavelength.

External and internal quantum efficiency

External quantum efficiency (EQE) is the state-of-the-art parameter used for the fruition of performance of a photodetector. Number of effective carriers produced by single incident photon is known as EQE [62]. It can be expressed as

$$EQE = \frac{I_{ph}/q}{P_{in}/h\nu} \quad (3)$$

Unlike EQE, photons carriers produced by single incident photon is known as internal quantum efficiency (IQE). In some cases, due to the optical interference effects, photon absorption occurs in ultra-thin photosensitive layer. These effects should be considered while evaluating the IQE of a photodetector [62].

Photoresponsivity

Photoresponsivity (R) is defined as capability of channel of device to produce the photocurrent upon irradiation. It can be calculated using following equation [62]:

Table 1
Performance characterization of 2D material-centric photodetectors.

Device composition	Photodetection mechanism	Detectivity (Jones)	EQE (%)	PR	ON/OFF Ratio	Ref.
Graphene/Si	PVE	2.83×10^{10}	NA	110 mA W^{-1}	NA	[64]
Tin selenide (SnSe)	PTE	NA	NA	140 mV W^{-1}	NA	[65]
Plasmonic graphene	PBE	NA	NA	1100 A W^{-1}	NA	[66]
WS_2	PCE	4.9×10^9	NA	5 mA W^{-1}	5.5×10^3	[67]
MoS_2	PTE	NA	NA	30 V W^{-1}	NA	[68]
$CH_3NH_3PbI_3$	PCE	1.36×10^{11}	33.7	0.227 A cm^{-2}	147	[69]
graphene/GaSe/WS_2/graphene	PVE	4.3×10^{12}	16.97	149 A W^{-1}	10^3	[70]
WS_2/Si	PVE	1.5×10^{12}	NA	224 mA W^{-1}	10^6	[71]
graphene/Bi_2Se_3	PVE	1.7×10^9	NA	1.97 A W^{-1}	NA	[72]
h-BN/b-AsxP1-x (hexagonal boron nitride/black arsenic phosphorus alloy)	PCE	2.4×10^{10}	60	1.2 mA W^{-1}	NA	[73]
MoS_2 NS	PCE	NA	NA	10^{-3}-10^{-1} A W^{-1}	10^5-10^6	[74]
$CH_3NH_3PbI_3$ (graphene/perovskite)	PCE	10^9	5×10^4	180 A W^{-1}	NA	[75]
$WS_2/(C_6H_5C_2H_4NH_3)_2PbI_4$	PVE	NA	NA	24.2 μA W^{-1}	$>10^2$	[76]
Black Arsenic Phosphorus	PVE	4.9×10^9	6.1	115.4 mA W^{-1}	NA	[77]
BP/HgCdTe	PCE	NA	NA	23 A W^{-1}	NA	[78]

$$R = \frac{I_{ph}}{P_{in}A} \tag{4}$$

Here, I_{ph} is the photocurrent ($I_{ph} = I_{light}$-I_{dark}), P_{in} is the power density and A is the irradiation area of the device.

Signal to noise ratio

SNR is the important characteristic of photodetector which is defined as ratio of the signal power and noise power. Decibel (db) is the unit of SNR [62].

$$SNR = \frac{P_s}{P_n} \tag{5}$$

Whereas, SNR is the signal to noise ratio expressed in decibel (db), P_s is the signal power and P_n is the noise power. It is very important parameter for determining the performance of photodetectors. For high performance and sensitive photodetectors, higher value of SNR is desired.

Noise equivalent power

The minimal input optical power equivalent to root mean square of noise current for 1 Hz bandwidth that is utilized for generating photo-current, is called NEP. It is evaluated as [62]:

$$NEP = \frac{I_n or V_n}{R} \tag{6}$$

Whereas I_n mean-square noise current, V_n is mean square noise voltage and can determined at the bandwidth of 1 Hz in darkness (in A $Hz^{-1/2}$) and in V $Hz^{-1/2}$ respectively.

Detectivity

It is the sensitivity measure of detaining weak signal and can be calculated as [62]:

$$D^* = \frac{\sqrt{AB}}{NEP} \tag{7}$$

In this relation, A is the area and B is the bandwidth of the photo-detector and expressed in unit of Jones (cm $Hz^{1/2}$ W^{-1}). If the total noise is contributed by the shot noise from dark current. D* can be calculated from the following equation

$$D^* = A^{1/2}.R/(2.eI_d)^{1/2} \tag{8}$$

Where, I_d is the dark current. Photodetector with low dark current is the higher D*. Noteworthy, the results calculated based on the assumption is usually-one order of magnitude higher than the results calculated from equation [62].

Response time

Important key parameter to determining the speed of photodetector to follow the light intensity variation. Usually, time rise 10 % (90 %) and time decay or fall time 90 % (10 %) method adopted by the researcher for evolution of response time of photodetector for the entire current increment. There is another method reported to determine the response time of photodetector which can be expressed by following relation [62]:

$$I = I_{pho} e^{-\left(\frac{t}{\tau}\right)\beta} \tag{9}$$

Here, I_{pho} represents the current in device in the absence of light, β represents the exponent co-efficient and τ denotes the response time. Response time of any photodetector reveals its robustness and gives an idea about how fast the photodetection mechanism is there in it. Usually, response time is expressed in units of micro-or milli-second.

Dark current

Dark current implies the current that is sent via photodetector in the unavailability of light. The dark current embraces saturation currents of the semiconductor junction and the photocurrent produced by back-ground radiation [62].

Technique to develop the stretchability

There are four major themes to develop the stretchability in device: (1) strain engineering, (2) rigid island structure, (3) fibre-based structure and (4) intrinsic stretchability.

Strain engineering

It is an effective technique which is employed for enhancement of strain capability of materials and devices. Mostly, strain engineering is employed on electronic devices in which anode and cathode designs are as per requirement of the technique. Strain engineering can also be employed in microstructures through a wavy structure. In this technique, the device is transformed into 3D wave-like structure which increases its stretchability and stability. The drawback of this approach is that the lack of energy density hinders its integration into other electronic devices due to 3D wave structure. Sponge structure is another approach to develop the stretchable devices like 3D wavy structures. The difference is that here a stretchable foam is employed as a substrate and rigid conductors, binders are penetrated the sponge which produce stretchability in electrodes. Usually, this technique is not much suitable for mechanical strength and did not offer strong bonding between the sponge template and rigid body materials which reduces the energy density of the device. Origami structures are also useful to produce the stretchability in devices. In this technique, strain engineering acts as a crease that can transform the fold to unfold structure of device. Here, the materials did not need to be stretchable but should be capable to assist ruckle at desired location. One disadvantage of this technique is that the stretchability depends on the design of fold which causes an anisotropic stretchability in the device [79–81].

Previous reports suggest that strain engineering can be effectively applied on conventional semiconductor materials like Si and Ge in which it can increase the performance of optical and electronic devices by tuning the band structure and hence optical response enhanced. In 2D layered materials, strain can be offered via mechanical deformation by transferring the materials or patterning the structures on flexible substrates. By applying small strain up to <2 %, the bandgap of 2D layered materials can be increase or decrease, even transition is possible from semiconductor to metal by applying 10 % strain like for monolayer of MoS_2 [82,83]. However, there are a very few reports on strain engineering based modified bandgap optoelectronic devices for longer wavelength (telecommunication spectrum band: 1550 nm) which are desirable to evaluate the stream of materials for next generation promising integrated photonic platforms. A report demonstrates the fabrication of $MoTe_2$ based photodetector modified through strain engineering which exhibits excellent photoresponse at 1550 nm, notable photoresponsivity of 0.5 A/W and shows compatibility with silicon photonic. Due to strain engineering, bandgap tuning of the device can be achieved up to 0.2 eV which makes it possible to achieve the photoresponse at longer wavelength. In other case, the unstrained mode enables the photoinactive medium which restricts to achieve it. Unlike band-gapless graphene-based photodetectors, the fabricated device exhibits up to 100-fold decrease in dark current and enables effective NEP up-to 90 pW $Hz^{-0.5}$. The strain engineering based such modified devices can be used for next generation wearable and stretchable photodetector [84].

Rigid body island structures

Rigid body island structures in which cathode, anode and collector are stacked on each other like spring wiring in an electronic device. These connected wires are not stretchable; however, a microscopic approach is employed to get the stretchability in device. Growth of these wires usually depends upon the serpentine structure that acts as a conversion from linear strain to buckling or bending strain. Materials used in this approach may not be stretchable but manipulate some amount of buckling strain as per equation [85].

$$\varepsilon = (d_f + \frac{d_s}{2r}) \times 100 \quad (10)$$

In the above equation, ε represents the peak strain, d_f and d_s respectively show the thickness of field and substrate, and r is radius of curvature. It is useful for the determination of amount of strain through the buckling motion. This technique is usually employed for electrochemical devices and considered not much suitable for electronic devices due to lower strain and difficult fabrications steps [11,86,87].

Intrinsically stretchable

These devices are fully stretchable and did not depend on any strain engineering or other conventional techniques. This approach is relatively emerging as compared to other approaches. However, this approach is very hard to achieve as full compatibility is required between the material system and electronic devices. In addition, intrinsically stretchable materials consist of various components and offer penetration between the active materials which endow them notable stretchability. This approach has the advantages of facile fabrication, cost-effective and isotropic strain capability [11,88].

2D materials based stretchable photodetectors

Broadband photodetectors are very important devices for variety of applications including military, civil, telecommunications and environmental monitoring [89]. Emerging 2D materials especially newly discovered group-10 noble metal dichalcogenides ($PdSe_2$, $PtSe_2$, PtS_2, PdS_2, etc.) are superior choices over conventional materials such as Si, PbS and HgCdTe for the development of broadband photodetectors owing to their tunable bandgap, facile synthesis techniques and cost effectiveness [90]. In addition, vdWs heterostructures of these 2D materials combined with others low dimensional materials (0D, 1D, 2D) can show distinct features such as broadband photodetection with excellent optical parameters. Based on this motivation, a group of researchers developed $PtSe_2$/GaAs based vdWs heterostructures that exhibit broadband photodetection ranging from deep UV (200 nm) to NIR (1200 nm) spectra. The as-fabricated device shows outstanding optical parameters such as high ON/OFF ratio (3×10^4), responsivity (262 mA W^{-1}), and detectivity (2.52×10^{12} Jones) at wavelength 808 nm [22].

Another report shows the assembly of vdWs heterostructures of $PdSe_2$/Perovskite materials (FA_{1-x} Cs_x PbI_3) that show broadband spectrum regime from UV (200 nm) to NIR (1550 nm). Notable optical response was obtained for wavelength 800 nm. At this wavelength, ON/OFF ratio, responsivity and detectivity are recorded as 10^4, 313 mAW^{-1} and 10^{13} Jones, respectively. In addition, as-fabricated devices can be employed as an image sensor at the wavelength of 800 nm [91]. A scheme of geometry of graphene/$PdSe_2$/germanium based vdWs heterostructure show a wider spectral response from deep UV (265 nm) to MIR (3043 nm). Moreover, the demonstrated devices can get higher responsivity (691 mAW^{-1}), noteworthy detectivity (10^{13} Jones) and faster photoresponse (6.4 μs /92.5 μs) for wavelength 980 nm [92].

Literature also shows a report in which researchers have demonstrated the 2D/3D vdWs Schottky junction heterostructures based on graphene/$PtSe_2$/β-Ga_2O_3 materials. In this device, graphene acts as an electrode to collect the charge carriers more effectively. Owing to the unique device design, as-fabricated device shows higher sensitivity for solar blind deep ultra-violet photodetection and offers an excellent responsivity (76.2 mAW^{-1}) and remarkable ON/OFF ratio (10^5) for the wavelength 245 nm. The authors claimed that the as-fabricate device may offer potential applications in next generation imaging devices [93]. These results indicate that the 2D materials incorporated with low-dimensional materials are promising to develop the next generation optoelectronic devices.

Different kinds of materials have been designed and prepared for the construction of stretchable photodetectors. However, here we are emphasising only on 2D materials like graphene, TMDCs, black phosphorus and h-BN which offer unusual roles owing to their distinct electronic and optical properties. Disparate sorts of methodologies are summarized in Table 2 which have been employed to assemble these 2D materials for stretchable photodetectors.

A report shows the assembly of extremely stretchable transparent conductors based on electrospun nanofiber network with kirigami substrates. These were used for the fabrication of stretchable photodetectors. A seed layer of ZnO was deposited partly onto polyvinylpyrrolidones (PVP) nanofibers utilizing masking tapes via radiofrequency (RF) magnetrons stammering to produce ZnO nano-rod channels. This strategy sheltered nanofiber coated with ZnO by means of masking tapes. Furthermore, gold platted such as Au layer was also coated onto the PVP nanofibers. The Kirigami-centred photoconductors exhibited exceptional electric-stability for countless stretching series

Table 2
Progress in assembly of 2D material for efficient stretchable photodetectors.

Technique	2D-Material	Advantages	Application	Ref.
Sequential 3-step sputtering deposition	Metal oxides including (Ag_xO/TiO_2/ITO)	Robust mechanical flexibility High detectivity with low dark current	Next-generation optoelectronic devices	[94]
Vapor phase transport method	Carbon-zinc oxide hybrid thin films (*n*-Si/C–ZnO/SiO_2/p-Si)	Fast responsivity	Next-generation energy-efficient optoelectronic devices	[95]
Organic molecule-centred *n*-doping technique	Rhenium diselenide ($ReSe_2$)	Low photo-switching time	TMDCs-based optoelectronic devices	[96]
Dry transfer process	2D ternary wide-bandgap semi-conducting materials	Higher crystalline quality and excellent UV photo-detecting performances	UV optoelectronic devices	[97]
Interfacial gating	Graphene	Efficient for ultrafast weak signals detection	Signal detection-based optoelectronic devices	[98]
Pattern transfer	Germanium nanomembranes	High response speed and higher stretchability	Flexible/wearable optoelectronic devices	[99]
Pulsed lasers deposition	Carbon film (a-C:N/p-Si)	Higher electron mobility with lower resistivity	Optical radiation detectors	[100]

within 0 and 60 % strain [101].

Another report shows fabrication of stretchable photodetector based on semiconducting composite film. It works as per change in capacitance of the modelled device. A translucent and stretchable polymer polyurethanes urea (PUU) was prepared which was compatible for Ag nanowires (NWs) and poly-di-methyl-siloxane (PDMS) based stretchable electrodes. ZnS:Cu was disseminated onto the PUU for assembly of sensory layer. The formulated '2′ faced Ag-NW-centred translucent electrodes were highly stretchable. On light irradiation of wavelength 420 nm and power 1.2 $mWcm^{-2}$, the induced capacitance changes the sensitively of device [102].

Surface plasmon resonance based asymmetric Schottky junctions in dual band InSe/Au fabricated that has capable to works on the photovoltaic mode. Initially, selenium powder and indium particles with a 1 to 1.1 mol ratio were kept within a quartz boat. The boat fused with a silica tube was placed in a horizontal furnace. Photoresponsivity of '2′ top-level dual-band self-powered photodetectors reached to 369 $mAW^{-1}$for wavelength 365 nm and 244 $mAW^{-1}$for wavelength 365 nm under higher "0″ bias voltage analogized to the preceding self-powered photodetector [103].

Fabrication and working of stretchable photodetectors

Several reports have been published in introducing suitable materials, unique structure, and efficient fabrication techniques for developing the stretchable photodetectors. Herein, we present the recent advancements in stretchable photodetectors based on the 2D materials. Graphene lattice has honeycomb structure and offers an ultra-high electrical carrier conductivity 25000 $cm^2\ V^{-1}\ s^{-1}$. Strong bonding occurs in the structure of graphene due to which it has excellent young's modules. Defect free graphene has young's modulus up to 1 TPa and gives outstanding light transmittance up to 97 % in visible region. Owing to its unusual properties, graphene and its variants such as reduced graphene oxide, suspended graphene, graphene nanopores and quantum dots of graphene have successfully been employed in wearable optoelectronic devices [104,105]. Another report shows the assembly of stretchable and printable transistors based on monolithic patterned graphene sheets. The device shows electron and hole mobilities up to 422 and 1188 $cm^2\ V^{-1}\ s^{-1}$, respectively. The device possesses outstanding stability and stretching up to 5 % for 1000 times [106].

Graphene has outstanding electrical, mechanical, thermoelectrical and optical properties. However, graphene-based photodetectors have not been suitable for stretchable and flexible electronics due to three main reasons: (1) graphene synthesis from CVD shows limited stretchability up to 6 %, (2) mechanically exfoliated graphene demonstrates 25 % stretchability without any structural loss and (3) atomically thin layer structure of graphene exhibits low light absorption of about 2.3 %.These are the major concerns for developing the flexible and stretchable optoelectronic devices [107,108].

A report on stretchable photodetectors based on graphene and graphene quantum indicates that graphene and graphene quantum dots is effective combination to realize the smart stretchable photodetector. In which, a PDMS sheet was used as a top layer which behaves as a pre-strain layer on to the substrate. After the pre-strain layer is separated from the substrate, graphene on it gets rippled structure which can be stretched under the external strain, as shown in Fig. 2a. Fig. 2b exhibits the experimental setup for the testing of stretchable photodetectors. The pre-strain technique is beneficial for avoiding the limitation of native stretchability. Furthermore, rippled structure is effective to enhance the production of carrier transformation in graphene quantum dots due to reflection of different light spots passing through the rippled structure, as shown in Fig. 2c. The fabricated stretchable photodetector offered stable response. The experimentally measured conductivity of graphene was directly proportional to the applied strain up to 25 % which is well consistent with theoretical values given in Fig. 2d. After reaching its strain limit, the conductivity of graphene decreases due to change in its morphology [109].

For improving the stretchability, different techniques have been employed. For example, crumpled structure is one of the best techniques to improve the mechanical stretchability of graphene. Crumpled structure is designed by delamination-buckling of graphene on a polymer substrate. A measured force is applied on it which releases the tensile strain from the polymer substrate and enhances its stretchability and optical absorption. Due to this technique, mechanical stretchability increases up to 200 % but responsivity remains limited [41].

A crumpled graphene and Au-NPs array-based photodetector has been demonstrated which offered higher stretchability and photoresponsivity, as depicted in Fig. 2e. An elastomeric substrate was used to fabricate the crumpled graphene/Au-NPs structure through buckle-delamination technique. Photoresponsivity and optical absorption was enhanced with the density of Au-NPs which is attributed to plasmonic nature of these nanoparticles. The fabricated device exhibited mechanical stretchability up to 200 % and a tunable photoresponsivity, as shown in Fig. 2f. The fabricated stretchable photodetector could be employed in next generation biomedical optical sensors and mechanical strain sensors [110].

Another work demonstrated the rippled structure based on graphene/ReS_2/perovskite quantum dots is the useful technique to construct the stretchable photodetector. In this scheme of geometry, novel 2D material behave as an arbiter between graphene and perovskite quantum dots, as shown in Fig. 2g. Due to unique structure of device, its optical sensitivity reached up to 22 times and photoresponsivity $>10^7$, as depicts in Fig. 2h. The fabricated device can work with mechanical strain up to 100 % and can find variety of potential applications in wearable electronics [111].

Graphene based photodetector exhibits low photo-absorption up to 2.3 % at visible and infrared spectrum. It can be increased by combining the graphene with other low dimensionality of materials, quantum dots, nanomaterials and plasmonic assisted nanostructures such as cavities and optical waveguides. However, this strategy has some drawbacks like

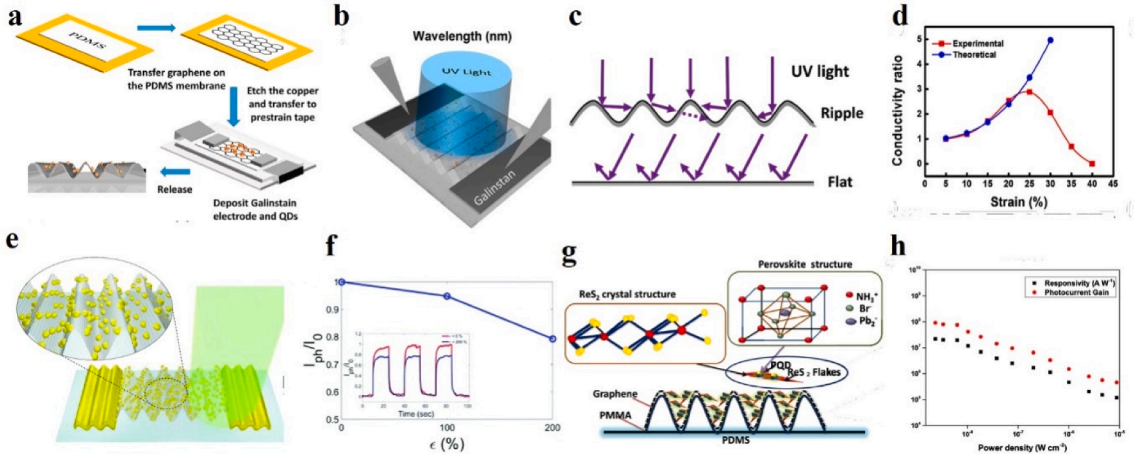

Fig. 2. Schematic diagram for the (a) fabrication and (b) testing of stretchable photodetector. (c) Schematic for interaction of incident light on rippled structure of stretchable photodetector. (d) Theoretical and experimental values of conductivity ratio against applied strain [109]. Copyright (2016), with permission from American Chemical Society. (e) Schematic diagram of stretchable photodetector based on crumpled graphene and Au-NPs structure and its (f) photoresponse characteristics upon applied tensile strain from 0 to 200% where inset shows the time resolved photoresponse for this strain [110]. Copyright (2009), with permission from Royal Society of Chemistry. Schematic diagram of (g) stretchable photodetector based on ReS_2/graphene/perovskite quantum dots and its (h) photoresponse and photocurrent gain as per power density [111]. Copyright (2019), with permission from American Chemical Society.

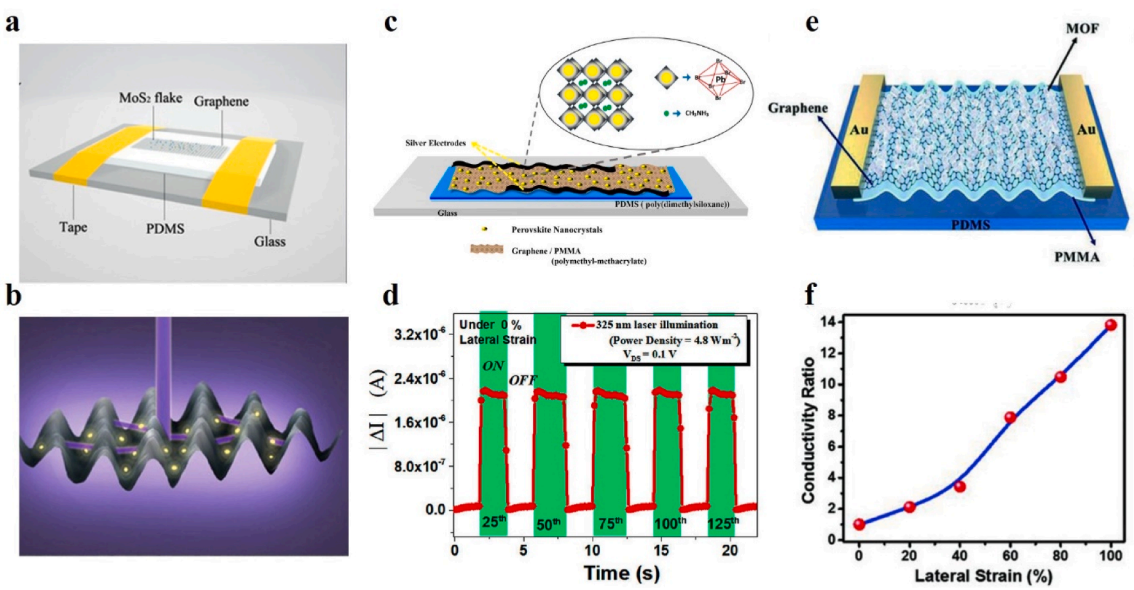

Fig. 3. (a, b) Schematic illustration of graphene/MoS_2 device with crumpled structure [118]. Copyright (2021), with permission from John Wiley and Sons. (c) Schematic diagram of 2D perovskite and graphene-based hybrid photodetector. (d) Time resolved photocurrent of device which reveals its stability and durability upon incidence of 325 nm wavelength [121]. Copyright (2019), with permission from American Chemical Society. (e) Schematic diagram of metal organic framework materials and graphene based crumpled photodetector. (f) Conductivity ration against applied strain for stretchability up to 100 % [122]. Copyright (2021), with permission from John Wiley and Sons.

reduction in carrier mobility of graphene, limited device performance, complexities while integrating the graphene with other electronic devices and most importantly, increase in production cost [112,113]. Graphene can manage the conical band structure around the Dirac point that leads to the situation in which electrons/holes act as massless Dirac formation with fermi velocity $\sim 10^{-6}$ ms^{-1}. This phenomenon causes the Pauli blocking effect in which electrons in graphene sheets accomplish band filling transit state through collisions among themselves. This tremendous property of graphene offers its potential applications in broadband photodetection, fast saturable absorber-based devices and stretchable devices [114,115].

Combing the graphene properties with that of other 2D materials through facile integration techniques can help to fabricate high performance devices. The combination of graphene with MoS_2 has been successfully achieved for high performance broadband photodetectors, solar cells, field effect transistors and biosensor [116,117]. However, such reports are very limited for stretchable devices and there is a strong need to deliver more efforts on it. A report shows the demonstration of a stretchable and cavity free laser device assembled through integration of graphene sheet with MoS_2, as illustrated in Fig. 3a,b. The device exhibited environmental stability under the external strain pressure and performance stability after the stretching for more than 200 times which evidence the robustness of the device. The findings could be paths towards developing the variety of stretchable electronic applications [118]. A photodetector based on 3D MoS_2/graphene layers is fabricated using origami 3D technique and finite element analysis in which MoS_2

serves as channel and graphene acts as electrode. 3D structure allows the photodetector to detect and sense the light from both directions (starting and ending point) [119].

Graphene is wonderful 2D material that can assist with 2D perovskite materials for realizing the stretchable photodetectors. 2D perovskite materials including methylammonium lead bromide (MA-$PbBr_3$), are easy to synthesize and cost effective. These offer facile fabrication, high quantum efficiency and remarkable physical characteristics. MA-$PbBr_3$ nanocrystal has tunable bandgap ~2.3 eV which exhibits high optical absorption, excellent stability at ambient temperature and narrow emission bandwidth due to unique structure like alkyl chain ammonium cation octylammonium bromide [120]. A report shows the fabrication of MA-$PbBr_3$ and graphene based rippled geometry hybrid photodetector on PDMS which acts as a flexible and stretchable substrate, as illustrated in Fig. 3c. The device with special geometry can offer higher photoresponsivity upto 6×10^5 AW^{-1} with tunable strain and 100 % stretchability. Moreover, the device shows strain stability even after 90 days and deliver similar performance as before, as shown in Fig. 3d. The fabricated device could be employed in wearable electronic devices, biomedicine, defence system and flexible display panels [121].

Recently, 2D thin films metal organic frameworks have been introduced as emerging materials owing to their fascinating tunable properties which may find potential applications in biomedical sensors, drug delivery and gas storage. These novel materials are excellent candidate for stretchable and flexible photodetectors. However, there are some drawbacks like poor electrical conductivity which restricts their applications in optoelectronic and electronic devices. Metal organic framework materials combined with graphene exhibits ultra-high mobility. A metal organic framework material and graphene-based hybrid, broadband and wearable photodetector on PDMS substrate has been demonstrated, as illustrated in Fig. 3e. The device shows ultra-high external quantum efficiency (5×10^8 %), photoresponsivity (10^6 A/W) and response time <150 ms. Moreover, the fabricated device has stretchability up to 100 % (Fig. 3f) which offers its potential applications in wearable, portable and stretchable electronics [122].

Typically, growth of nano-flakes with high crystal quality needs high temperature ranging between 500 and 1000 °C with several fabrication steps. The process is assisted with thermodynamic reactions of stoichiometric materials which offer low defect density. The fabrication of 2D materials for flexible and stretchable optoelectronic devices could not afford multiple steps and conventional substrates. The materials are needed to be deposited on polycrystalline films at lower substrate temperature and then transferred from conventional substrates to flexible or stretchable substrates. Different techniques have been developed for this purpose including additive manufacturing technique in which 2D materials in liquid form are transferred onto flexible substrates [123,124].

Theoretical study shows that MoS_2 can exhibit stretchability upto 30 % [125]. However, its layers deposited by CVD technique have been tested only 5 % applied tensile strain [126]. For the protection of intrinsic properties of materials, it is highly desirable to tune them through mechanical deformation, so that these could be made compatible with other electronic components. There are two notable ways to engineer the MoS_2 layers at large scale without damaging their properties. First, their synthesis and transfer at large scale on desired substrates without negotiating their intrinsic properties. Second, their 3D geometry scheme should be maintained with modified structure to certify their enhanced mechanical flexibility and stretchability. The layers with 3D geometry scheme can be synthesised through medication during the material growth and substrate engineering. However, it is difficult to achieve it at small scales (<1 cm^2) [127].

A report presents the growth of crinkled 2D MoS_2 layers and investigation of their tunable mechanical characteristics. Novel water-based transfer technique was developed to integrate the 2D layers of MoS_2 on 3D scheme of geometry patterned substate at large scale wafer (>2cm^2), as depicts in Fig. 4a. Fig. 4b depicts mechanical flexibility and stretchability of 2D MoS_2 layer combined with PDMS. The electrical,

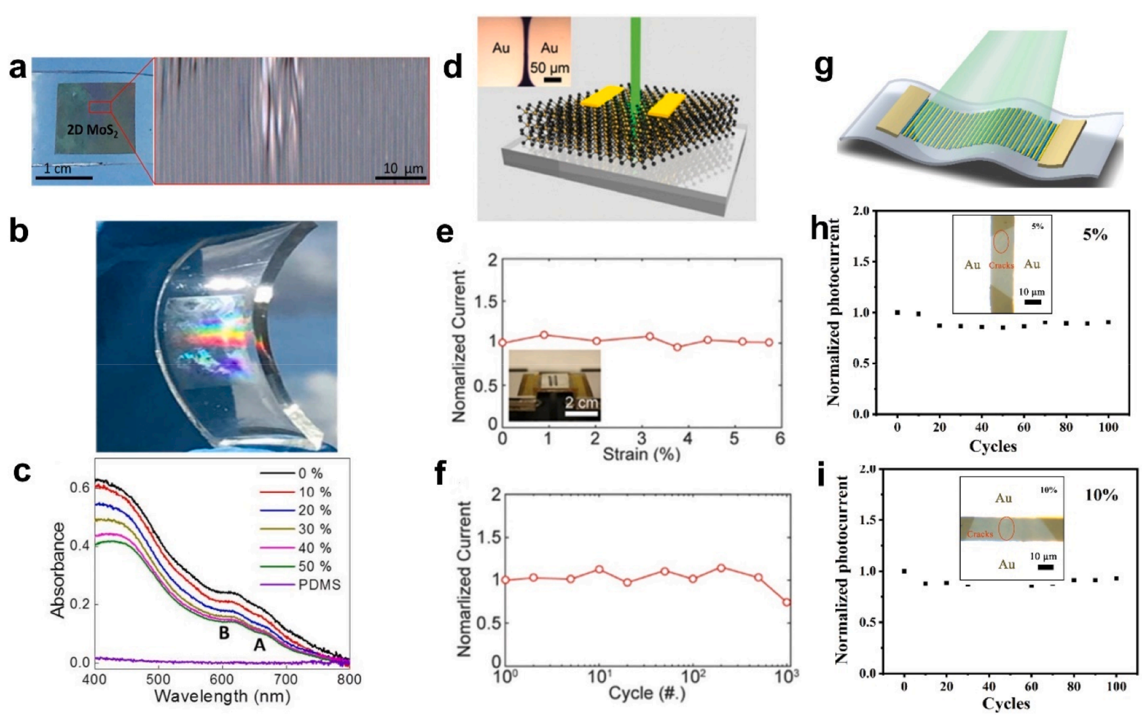

Fig. 4. (a) Optical images of corrugated MoS_2 layer on PDMS at low and high magnification. (b) Digital photograph of corrugated MoS_2 exhibiting holographic image in sunlight. (c) Absorbance spectra of MoS_2 based device under different applied strain [128]. Copyright (2018), with permission from American Chemical Society. (d) Schematic illustration of MoS_2 based stretchable photodetector (inset, optical image of actual device). (e) Response of device upon applied tensile strain from 0 to 5.72%, (inset shows measurement setup). (f) Testing of device for 1000 stretching cycles [129]. Copyright (2022), with permission from Royal Society of Chemistry. (g) Schematic diagram of MoS_2 combing with doping materials based stretchable photodetector. (h, i) High tensile strain observed as 5% and 10%, when the stretched applied in parallel and perpendicular to the direction of the current flow respectively [131]. Copyright (2022), with permission from Springer Nature.

optical, and structural properties of the prepared samples were investigated and compared with 3D structure of 2D MoS_2 layer under the applied tensile strain. Upon mechanical deformation, no change in characteristics of the device was found. It was observed that as the strain is increased, absorbance is monotonically decreased. This indicates the reflection in terms of surface to volume ration. The two peaks (A, B) appear at 600 and 700 nm which indicate the K point at Brillouin zone in 2D MoS_2 layer, as shown in Fig. 4c [128].

The synthesis of crystalline MoS_2 at large scale (>6.25 cm^2) and layered 2H-MoS_2 on stretchable PDMS substrate for photodetection application has also been reported. The fabricated stretchable photodetector showed photoresponsivity of 2.52 μWA^{-1} and response time 120 ms for wavelength 515.6 nm. The demonstrated device can work with tensile strain 5.72 % for more than 1000 stretching cycles, as shown in Fig. 4d-f. It was observed that such photonic crystal technique based developed 2D materials can directly transferred onto the polymer substrates which could be employed in wearable and flexible electronic systems [129]. A monolayer MoS_2 based photodetector on the polyethylene naphthalate substrate has also been fabricated and investigated for applied strain performance. It was observed that by applying to strain, the performance of device can effectively be enhanced in terms of their stretchability, photoresponsivity and photoresponse. When strain was applied between 0.8 % and 1.4 %, anisotropic changes were observed in I-V properties of device. Due to presence of this piezoelectric effect, the dark current, self-powered current and optical response of the device were improved which can offer its potential applications in 2D based optical detection technology. Furthermore, when the strain was applied in zigzag direction as per MoS_2 alignment, photosensitivity was observed in the device [130]. Recently, S. Qi et al. demonstrated a stretchable photodetector with excellent air stability that is comprising the materials of MoS_2 by combing the *n*-type doping (4-(1,3-Dimethyl-2,3-dihydro-1H-benzoimidazol- 2-yl) phenyl) dimethylamine (*N*-DMBI) via transfer technique as shown in Fig. 4g. The proposed doping technique is very efficient to bring the fast charge carrier transfer interaction between the MoS_2 and the doping materials. Due to the excellent, excellent carrier injection and fast photo electrons/holes separations at the surface, as demonstrated device shows excellent photoresponsivity (738 AW^{-1}) at the wavelength of 530 nm. For the prospective view of stretchability, the device shows the high tensile strain is about 5 % and 10 %, when the stretched parallel and perpendicular to the direction of the current flow as shown in Fig. 4h-i respectively. These outstanding parameters of stretchability indicates that as fabricated device has potential applications in wearable optoelectronic devices [131].

Alike graphene and other typical 2D layered materials, 2D perovskite materials earned great interest for the development of stretchable photodetectors. Since last decade, perovskite materials have become the hot topic for researcher to explore new world in optoelectronics especially in photo-detection. It offers low cost, high efficiency, wide range detection and extensive applications in optoelectronic devices. The perovskite materials can absorb the light and covert it to electrical signals in similar way to that of photodetectors. These can work for visible to mid-infrared spectral range at better efficiency as compared to conventional silicon based solar cells [132,133]. Many efforts have been made to make progress in perovskite materials for photodetector applications. A report shows the fabrication of photodetector based on ZnO-NWs and $CsPbBr_3$-nanosheets with broadband photoresponse via lower-dimension structural approach. Owing to specific structural design, the photodetector was capable to deliver outstanding functional stability under a variety of mechanical-associated stresses. The photodetector demonstrated a broadband response for ultraviolet to VIS spectra [134].

Graphitic carbon nitride (g-CNQDs) is known as 2D polymeric material. It offers potential applications for perovskites solar cell as well as broadband photodetectors. The g-CNQD commencement enhance the crystalline nature of absorber with higher phase purities, lower trap states, minimal grain boundaries and dormant carrier recombination owing to smoother surface and inherent cross-linking features. Consequently, with optimum alteration, completely air-processed perovskite solar cell attains an insignificant hysteresis and 21.23 % power transmutation effectiveness, whereas an extraordinary performance improvement is perceived in demonstrated photodetector [135]. Another report demonstrates a superficial solution technique for making $CsPbCl_3$ with higher crystallinity and 2D morphology which are favourable for effective UV photodetection. 2D Ruddlesden-Popper perovskites are prepared at intermediary stage which customarily grow into microplates owing to an inherent 2D architecture. The poor solubility issue is resolved by achieving the assembly via chemical route [136].

A photodetector based on 2D $(C_4H_9NH_3)_2PbBr_4$ perovskite crystals with top contact and graphene coating has been reported. A facile technique is developed to address the instability problem of 2D perovskite crystals. A higher photoresponsivity of ~2100 A/W and eminently low dark current is achieved for an inter-digital graphene electrode design. The work provides higher performance opto-electrical devices based on advanced materials [137]. Another report shows the modelled vertical-type higher performance photodetector grounded on 2D material, $CH_3NH_3PbI_3$ perovskite materials. The lower trap density of modelled perovskite and its brief carrier diffusion distance resulted in the performance of the perovskite-centric photodetector. Vertical-type photodetector has higher photoresponsivity (36 mAW^{-1}) in visible region which is better when analogized to conventional perovskite photodetectors (0.34 mAW^{-1}). On contrasting to conventional planar-type perovskite-based photodetectors, the modelled photodetector exhibits lower voltage operation [138].

Applications of stretchable photodetectors

Flexible and stretchable optoelectronic devices having compatibility with human body integration and e-textile have great potential to produce somatosensory systems that are effective for various applications for example, health monitoring, wearable sensors, biological functions and various technologies like soft robotics and human–machine interface [139,140]. Different techniques have been employed to enable the mechanical stretchability in optoelectronic devices such as engineering of geometry scheme in terms of percolative charge transport networks in elastomers and special designs for structure like wavy, origami and wrinkles-based structure [141,142]. Moreover, different nanosheets have been synthesised in the prospective of wearable semiconductor devices such as single crystal silicon nanoribbons, carbon nanotubes, graphene, amorphous carbon, 2D materials and conducting polymers [142,143].

2D materials including graphene, have unmatched mechanical properties due to their ultra-thin layers which are essential for making the 3D structure-based devices. Graphene has capability to construct kirigami 3D structures such as stretchable electrodes, springs and hings [144]. A report shows the assembly of 2D materials based on monolayers of MoS_2 and graphene for the fabrication of photodetectors having 3D structure, as shown in Fig. 5a. Graphene has outstanding flexibility, transparency, and conductivity whereas MoS_2 offers tunable bandgap and direct bandgap (1.9 eV in monolayer) characteristics. Owing to their potential feathers, these materials are well-suited for designing of flexible and stretchable photodetectors and imaging applications. Stretchable photodetectors have widely applications in different areas for example, artificial visions, skin-based sensors, bio-inspired cameras. In addition, photodetector can provide accurate and abundant information of the light falls on to the device. Inspired by this, Choi and their co-workers fabricated eye based hemispherical CurvIS array which is comprising the heterostructures of MoS_2/graphene as shown in the Fig. 5b. Owing to this heterostructure, as fabricated device shows excellent photoresponsivity which is higher than the Si based photodetector by 2 to 3 orders of magnitude. In addition, owing to excellent features of the MoS_2 and graphene as well as strain realizing origami design, as fabricated device high pixel density at hemispherical

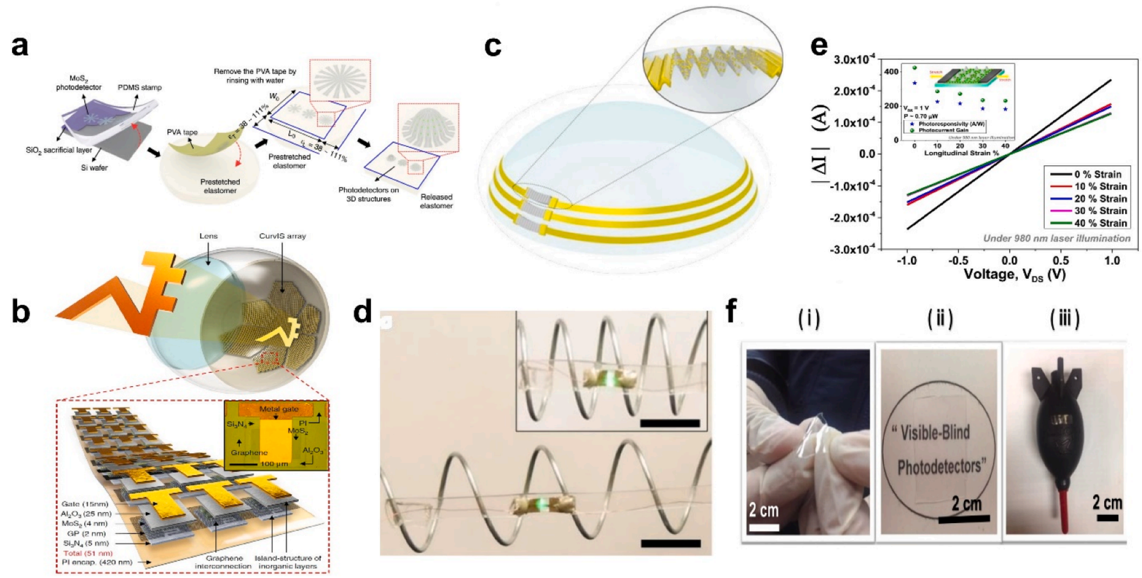

Fig. 5. (a) Schematic diagram showing the construction steps for 3D photodetector. (b) Schematic diagram of high density CurvIS array based on the MoS_2/graphene heterostructure [146]. Copyright (2017), with permission from Springer Nature. (c) Schematic diagram of crumpled graphene based stretchable photodetector integrated within contact lens. (d) Photograph of stretchable photodetector integrated with springs showing the setup for strain sensing. Inset shows the integration of photodetector with springs in absence of applied strain; the scale bar is 1 cm in both images [110]. Copyright (2009), with permission from Royal Society of Chemistry. (e) Response of photodetector upon different applied strains for wavelength 980 nm. Inset shows the photoresponsivity and photocurrent gain with respect to applied longitudinal strain. (f) Photographs of flexible, transparent and wearable photodetector devices [147]. Copyright (2018), with permission from American Chemical Society.

substrate. They proposed that as fabricated device could be employed for replacing the damaging retinas due to excellent compatibility of CurvIS array with neural interfacing electrodes. Owing to these excellent features, as fabricated devices have potential applications in biocompatibility in vivo [145,146].

A report reveals that photodetector based on crumpled graphene incorporated with Au nanoparticles can exhibits 1200 % photoresponsivity and 200 % stretchability upon applied tensile strain. The mechanical stretchability and optical absorption of device can be increased by further densification of materials. The demonstrated crumpled graphene-based photodetector can easily be integrated into contact lens, as shown in Fig. 5c. Furthermore, the device exhibits robust mechanical strain sensing via strain tunable photoresponse and shows high stretchability when integrated with spring, as depicts in Fig. 5d. Report shows that fabricated device may find potential applications in automobile industries (where it may work as a spring for an automotive vehicle integrated with light emitting diodes), medical industries (like for health monitoring in large damage and crack propagation in structures as device exhibits ultra-high mechanical stretchability) and wireless signal transmitting systems. The finding scan be a notable progress in fabrication of stretchable optoelectronic devices which may have potential applications in flexible optical sensors and robust mechanical strain sensors [110].

A superficial and filter-less design for wearable NIR photodetector based on the omnidirectional geometry has also been reported. It is based on graphene and lanthanide-doped up-conversion nanoparticles employed on PDMS substrate. The device offers capability to detect the light from visible to NIR regime due to unique configuration of lanthanides-doped up-conversion nanoparticles and exhibits stability at ambient temperature. Graphene provides a conducting path for charge carriers transmission through lanthanides-doped up-conversion nanoparticles and PDMS substrate which establishes an outstanding platform for NIR light detection. The phenomenon is desirable to get higher photoresponse up to 800 A/W for 980 nm spectrum, as shown in Fig. 5e. It is suggested that the device could be used for promising wearable semiconductor devices, as depicted in Fig. 5f [147,148].

Inorganic materials including several 2D materials have capabilities to be stretched more than fractal strain ($<1\%$) without any degradation in performance but strongly depend upon the geometry of structure. Honeycomb like structures offer promising ways to construct the stretchable devices due to their mechanical stability in stretching mechanism. Stretchable devices based on organic materials have been reported on honeycomb structure. However, these devices exhibit low performance as compared to that of inorganic materials based stretchable devices owing to their excellent carrier mobility and stability in ambient environment [149]. Honeycomb structure based stretchable devices are harsh to developed on elastomeric substrate. A report shows the transfer of K_2SiO_3/Si onto an elastomeric substrate assisted with hydrochloric acid solution which is used for selectivity removal of sacrificial layer. Inspired by this, inorganic materials based stretchable devices could be fabricated but not recommended for assistance of hydrochloric acid solution due to its higher toxic reaction which can damage the device [150].

There is a great need to develop the techniques which can be beneficial for stretchability and devices can be transferred onto the stretchable substrate. A report presents the indium gallium zinc oxide based stretchable photodetector. The structure of the device is based on honeycomb geometry and transferred onto the stretchable substrate without any sacrificial process. The device can be stretched upto 10 % without any failure. Furthermore, it is found that the Au electrodes can increase the performance of the device like 127-fold high photoresponsivity up to 295.3 $mAW^{-1}$for 365 nm wavelength. Honeycomb geometry-based photodetectors have the ability to be integrated within the human eye as and can be attached with convex or concave lens which can further be used for image detection [151].

There is a pretty enough space to further enhance the performance of photodetectors in terms sensibility, response time, fabrication cost and most importantly, well integration with human body. In contrast, metal oxide semiconductor such as indium gallium zinc oxide, ZnO, SnO_2 and conductors like indium tin oxide (ITO) are interesting candidates for the fabrication of rigid displays, touch screens as well as variety of sensors [152,153]. Recently, 3D inorganic nanofiber network layer has been developed by blow spinning method combined with indium gallium zinc oxide and ITO. Blow spinning technique is effectively used to achieve the large-scale fabrication of metal oxide semiconductor with high aspect ratio for the application of temperature sponges and heaters. 3D inorganic nanofiber network exhibited outstanding performance such as, no performance degradation even after the 1000 bending cycles and device also acted as room temperature gas sensor. Due to remarkable stretchability, device has capability be to integrate with e-skin devices and ability to detect various phenomena such as strain, pressure, light, temperature, and human body movements. Consider all these advantages, the fabricated device becomes an ideal candidate for future generation wearable optoelectronic applications [154].

2D materials have potential to be employed in textile semiconductor devices such as sensors, supercapacitors, nanogenerators etc. which have been reported recently for wearable electronics [155,156]. A report shows the assembly of nickel (as active material) based flexible fibre which can effectively be used for the fabrication of strain sensors and supercapacitors for wearable energy-based devices [157]. However, these types of wearable devices require external power supply via long wire connection which is not useful for wearable electronic devices. Therefore, there is a need to develop the schemes which can fulfil the basic requirements such as integration with wearable applications including sensors. Such type of devices has been reported which can act as textile type supercapacitors, photodetectors and strain sensors. However, such devices exhibit poor individual performance for devices including supercapacitors and strain sensors with similar electrodes [158].

A report presents the assembly of all stretchable in one system of textile soft electronics like supercapacitors and strain sensors which have the capability to detect the bioelectronic signals. Stretchable electrode based on multiwalled carbon nanotubes and molybdenum trioxide (MoO_3) offer excellent properties such as mechanical stability, high conductivity, low cost, nontoxicity, and environmental friendliness. The materials can effectively be used in controlling the sensitivity of strain sensors. The demonstrated device shows high sensitivity and fast response whereas supercapacitor exhibits mechanical stability under the deforming (folding and stretching). Both devices are fabricated in two different stretching directions of fabric, as shown in Fig. 6a (right image). All in one stretchable supercapacitor and strain sensor are sewn onto the cloth, as shown in Fig. 6a (left side). The integrated devices are the responsible for detection of movements associated with joints and wrist pulse. The findings are useful for various applications in daily life activities like healthcare, sports and next generation wearable electronic devices [159].

Graphene combined with nanoparticles such as lanthanide based up conversion nanoparticles shows outstanding performance including higher flexibility, notable stretchability and broadband photoresponse [160,161]. Various reports can be found in literature on this scheme, however, most of them show poor stretchability of demonstrated devices which remain unable to meet to requirements of the next generation technology [162,163]. To tackle these problems, graphene combined with lanthanide based up conversion nanoparticles on rippled structures exhibited broadband photodetection and ultrahigh sensitivity for wavelength 809 nm. Moreover, the device on PDMS substrate showed extra-ordinary stretchability, durability, compatibility and high photoresponsivity (190 A/W), as shown in Fig. 6b. The fabricated device makes a fruitful contribution to ongoing research in the field of wearable and stretchable optoelectronic devices [164].

Stretchable photodetectors can conformally integrated with human body or any arbitrary surface which may offer their promising applications for integration into human eye as hemispherical lens to enlarge the eye view, enhance the image capabilities and help to the blind peoples to regain their visual senses. Moreover, the stretchable photodetectors are useful for the fabrication of wearable biological systems like optoelectronic sensors for medical applications, wearable pulse and heart beat oximeters, and infrared cameras for military applications [165,166]. In addition, to provide the straightforward description of the 2D materials based stretchable photodetectors, we summarized the advantages and disadvantages of stretchable photodetectors as given in Table 3.

Outlook and future challenges

Emerging developments in stretchable photodetectors has allowed for noteworthy improvements in the progress of human-compatible optoelectronic devices. 2D materials based stretchable photodetectors have been widely fabricated on account of unique structure, high absorption coefficient, optoelectrical properties, narrow bandgap, and higher carrier mobility of these materials. The photodetectors exhibit high photoresponse, short response and recovery time, high detectivity, high-level ON/OFF ratio and higher EQE. In this review, various material synthesis approaches, physical mechanisms, device fabrications, key characteristics of different sorts of photodetectors based on 2D materials, their recent advancements, advantages, and applications have briefly been discussed. In addition, improved device designs, geometry and possible cost-effective techniques have been discussed for developing the stretchable photodetectors. A 2D material could not be found in literature which can offer maximum performance for all merits of photodetector simultaneously. All photodetectors perform in a unique way relying on the synthesis approaches, device fabrication methods

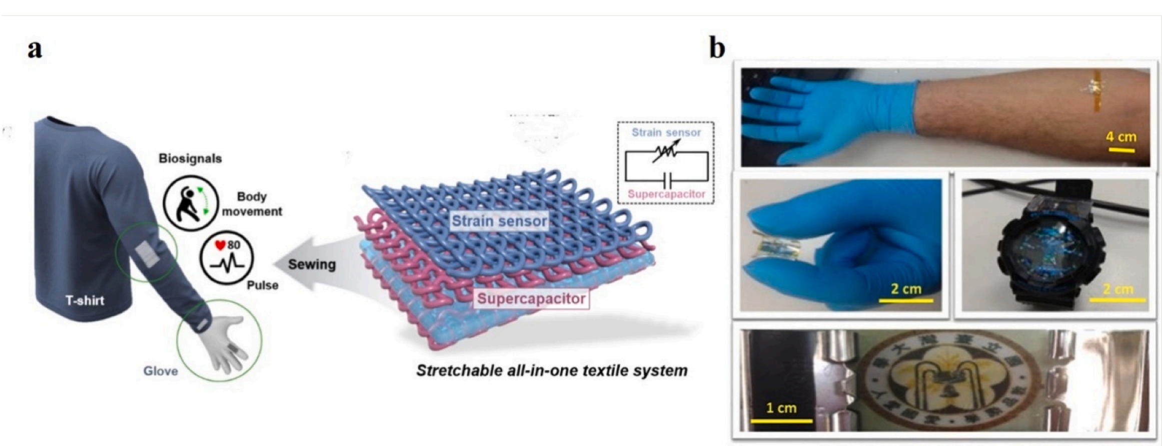

Fig. 6. (a) Schematic illustration for integration of strain sensor and supercapacitor (right side) into shirt and glove for detection the biological signals [159]. Copyright (2019), with permission from American Chemical Society. (b) Graphene rippled structure-based wearable, flexible and transparent photodetector [164]. Copyright (2018), with permission from American Chemical Society.

Table 3
Summary of advantages and disadvantages of stretchable photodetectors.

Advantages	Disadvantages	Ref.
Stretchable substrates such as styrene-ethylene-butylene-styrene (SEBS) and polydimethylsiloxane (PDMS) show flexibility and transparency	Large amount of scattering on polymer substrate seriously effects the intrinsic carrier density which leads to low intrinsic carrier density	[131]
Stretchable photodetectors can be fabricated via mechanically stretchable organic substrate	Buckling effects occur that cause serious limitations for the application of stretchable photodetectors	[167]
Fabrication of stretchable photodetectors involve easy steps such as low temperature process, cost effectiveness and ability to tune the optical properties	Performance depends on the structural designs of photosensitive material in stretchable photodetectors; performance degradation during moisture and oxygen	[85]
MoS_2 based stretchable photodetector shows high responsivity and durability in Vis spectral range	At longer wavelength such as NIR spectra, stretchability along with high responsivity is yet to be determined	[129,131]
Ultra-thin Stretchable phototransistor could be possibly integrated with skin compatible sensors	High sensitivity at low power density as well as maintain the high mobility is main challenge	[85]
Stretchable optoelectronic devices can be used in healthcare related applications including human pulse rate monitoring	Long term stability is big issue in the stretchable optoelectronic devices	[145]
Stretchable photodetectors can be integrated in soft optoelectronic devices such as bio-inspired applications, wearable applications, environmental applications, and imaging sensors	Commercial applications of stretchable photodetectors are yet to be achieved due to complex fabrication at large scale	[145]

and photodetection mechanisms. In addition, the present approaches do not fully compatible with human-friendly and skin-compatible photodetector devices. In the future, stretchable photodetector will require much needed consideration by incorporation of multidisciplinary devices and shrinking of feature size through with rapid speed, precise processing techniques and cost effective. Stretchable photodetectors compatible with human skin could have interesting applications in the biomedical diagnostic such as mobile phones and smart watches for monitoring their biological conditions. However, present techniques do not fulfil all the conditions and requirements to construct the effective stretchable photodetectors with compatibility for human skin as well as CMOS. Apart from stretchable optoelectronic devices, electronic components such as batteries, electronic circuits, and long-range antenna systems, should be further investigated to develop the more effective stretchable optoelectronic devices. The future development of the stretchable optoelectronic devices could be acquired by performing some research on optimization in device fabrication, material synthesis, and photodetection mechanisms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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