**Introduction**

The emergence of 2D materials has triggered a proliferation of new research topics with much focus placed on synthesizing and modifying these materials for use in a wide array of potential applications. Many members of the transition metal dichalcogenide (TMD) family possess a bandgap and so have been touted for use in applications ranging from transistors, to photodetectors, to sensors [1]. Most studies to date have focused on semiconducting group-6 TMDs, such as MoS$_2$ or WSe$_2$, which occur naturally in the 2H phase. However, recent reports have outlined the practicality of growing noble-metal, or group-10, TMDs such as PtSe$_2$, which occurs naturally in the 1T phase. Interestingly, the band structure of PtSe$_2$ is heavily dependent on its layer thickness with bulk films having semimetallic character while mono- and few-layer films are semiconducting [2–4].

Vapour-phase growth methods, such as chemical vapour deposition (CVD) and thermally assisted conversion (TAC), offer scalable growth of TMD layers with reasonable to good crystalline quality [5, 6]. While MoS$_2$ and related materials synthesized in this manner have shown impressive performance, their practical use has been somewhat hampered by the associated high growth temperature (typically $>600 \, ^\circ C$). This high temperature restricts the choice of substrate and renders the growth process incompatible with standard semiconductor processes, such as back-end-of-line (BEOL) processing. On the other hand, PtSe$_2$ can be grown at a relatively low growth temperature by a TAC process [7, 8]. The material grown in this manner is nanocrystalline but, despite this, studies have indicated that it holds promise for applications in photodetectors [9, 10], gas sensing [8], electronics [11–13] and electrocatalysis [14]. This relatively low growth temperature means that PtSe$_2$ can be grown...
directly on substrates that are inaccessible to standard vapour-phase growth processes for TMDs.

Strain gauges, simple sensors that undergo a change in electrical resistance under applied strain, have broad applications in areas such as health monitoring [15], civil engineering and construction [16] and semiconductor microsystems [17]. Recently, there has been an emergent need for robust, sensitive and low-power strain gauges in civil engineering that can be applied to monitor stresses on wind turbine blades [18] and bases [19] in extreme conditions. Through better understanding of the forces applied, the construction of more-efficient, green-energy generating structures is made possible. Such strain gauges are generally based on materials that exhibit piezoresistive properties. Upon the application of strain, $\varepsilon$, electrical resistance changes such that

$$\frac{\Delta R}{R_0} = G \varepsilon$$

where $G$ is the sensitivity metric known as the gauge factor measured at low strain, $R_0$ is the material’s zero-strain resistivity, $\rho$ is the resistivity and $\nu$ is the Poisson ratio [20].

Most commercially-available sensors are metal-based foils on a rigid polymer backing that tend to have low values of $G$ in the range of 2–4 [20]. This is due to metals undergoing small changes in resistivity with applied strain. However, for many semiconducting materials applying strain leads to changes in the band structure which can modify either carrier density or mobility, resulting in large changes in resistivity and thus high values of $G$. For p-type silicon, $G$ values up to ~175 have been reported [17]. However, such materials are often brittle resulting in small sensing ranges, i.e. failure occurs at low strain. Much research has also focused on the use of networks of nanomaterials, such as carbon nanotubes [21, 22], nanowires [23] and metal nanoparticles [24], as a conductive filler in a polymer matrix to produce composites with strain-dependent electrical properties. While such composites often possess large gauge factors they typically display poor environmental stability and need to be encapsulated.

Research has turned towards materials science, and more specifically 2D materials, in an effort to overcome these challenges. Many 2D materials display piezoresistive properties suggesting they could find use as active components in assorted electromechanical sensors such as strain gauges, as well as MEMS and NEMS devices [25–27]. Individual flakes of MoS$_2$, a semiconducting 2D material, have been shown to have negative gauge factors ranging from $-225$ for bilayers to $-50$ for few-layer samples [26]. Most recently, pressure sensors and strain gauges based on TAC-grown PtSe$_2$, which was grown on SiO$_2$/Si and subsequently transferred onto flexible substrates, have been demonstrated [28]. The fabrication process for such devices could be greatly simplified by direct growth of PtSe$_2$ on flexible substrates. Additionally, without the need for polymer-based transfer processes, cleaner interfaces and resultant improved device performance can be anticipated. Furthermore, TAC growth is compatible with standard processing and patterning techniques and so different device geometries could be patterned directly on flexible substrates.

Herein we demonstrate the growth of PtSe$_2$ layers directly on flexible polyimide foils. These films adhere strongly to the polyimide substrate and are continuous and conductive over large areas. The flexibility of polyimide means that the effect of flexure, and other strain, on the PtSe$_2$ layers can be investigated. The PtSe$_2$ layers show a strong and stable electrical response to flexure suggesting that they could be used in future electromechanical sensors.

### Results and discussion

PtSe$_2$ thin films were grown on polyimide substrates by a TAC process as depicted in figure 1(a) and described in more detail in our previous reports [7, 8]. Substrates were typically ~2 cm $\times$ 4 cm in area, as shown in figure 1(b), but larger or smaller substrates could readily be made. Scanning electron microscopy (SEM) and scanning probe microscopy were used to examine the topography and uniformity of the films grown. A SEM image of a PtSe$_2$ film derived from 1 nm Pt on polyimide, converted to PtSe$_2$ at 400 °C, is shown in figure 1(c). This image shows film continuity over a large area and also highlights the nanocrystalline morphology, which is typical for TAC-grown TMD films [13]. Additional SEM images at lower magnification are shown in figure S1(a) of the supporting information (stacks.iop.org/TDM/6/045029/mmedia) and indicate that the PtSe$_2$ conforms to features on the polyimide surface.

Atomic force microscopy (AFM) was also used to investigate the morphology of PtSe$_2$ on polyimide, prepared under the same conditions, as shown in figure 1(d). Like the SEM image, the AFM image shows the nanocrystalline nature of the PtSe$_2$. A root-mean-square (RMS) roughness of 4.6 nm was extracted for PtSe$_2$ films grown from 1 nm Pt on polyimide, which is comparable with TAC-derived PtSe$_2$ films grown on other substrates, such as SiO$_2$/Si. Conductive-AFM (or c-AFM) imaging was also performed on the PtSe$_2$ films as shown in figure 1(e). This image was taken over a large area (30 $\times$ 30 $\mu$m) and highlights the uniformity in the conductivity of the film at this scale. The chemical composition of the films grown was probed by x-ray photoelectron spectroscopy (XPS). The Pt 4f and Se 3d spectral regions for a 1 nm Pt film converted at 400 °C are shown in figure 1(f). These spectra are consistent with previous reports for PtSe$_2$ grown on more conventional Si-based substrates and indicate that stoichiometric PtSe$_2$ is formed by our
process [8]. The Pt 4f Pt\(\text{Se}_2\) component was found to be at a binding energy of \(~73\) eV, a minor component likely from platinum oxide was also present at \(~72\) eV. For the Se 3d core level spectral region the Pt\(\text{Se}_2\) main component was present at \(~54.5\) eV. A much lower concentration component at \(~55.5\) eV was attributed to the presence of edge/amorphous Se in the sample. Raman spectroscopy is usually one of the first tools used to confirm the presence of Pt\(\text{Se}_2\) or other TMDs [7] but in the case of direct growth on polyimide it is not possible to get a strong signal.

The electromechanical properties of Pt\(\text{Se}_2\) on polyimide were tested by flexing the films while simultaneously measuring the films’ resistance using a custom-made, three-point flexure rig, as detailed in the methods section. Under applied strain a decrease in resistance was observed, resulting in a negative gauge factor consistent with previous reports on other TMDs [26], and also with previous experimental reports on Pt\(\text{Se}_2\) films transferred onto a bending-beam cantilever setup [28]. In previous reports on TMDs, the negative gauge factor has been attributed to an increase in the density of states (DOS) and a decrease in the size of the bandgap under applied strain [26, 28]. The effect of film thickness on the electromechanical properties was examined by converting Pt films of different starting thicknesses to Pt\(\text{Se}_2\) at \(400^\circ\) C. Like other TMDs, the band structure and electronic properties of Pt\(\text{Se}_2\) depend on layer thickness; it is semiconducting in its mono- and few-layer form it is semimetallic in its bulk form [3, 7]. Plots of fractional resistance change versus applied strain, for different film thicknesses, are shown as a function of applied strain (figures 2(a) and (b)) and flexure angle (figures 2(c) and (d)). The labelled thicknesses on the plots refer to the starting Pt film thickness (i.e. the film thickness before TAC). It is clear from these data that the films from 1 nm starting thickness of Pt have the best properties in terms of electromechanical response and signal-to-noise ratio. This is supported by the extracted gauge factors, shown in figures 2(e) and (f), which are highest for the 1 nm film. The associated strain-related gauge factor is 12, which is superior to that of typical commercial metal-based strain gauges. This value is considerably lower than that reported for Mo\(\text{S}_2\) by Manzeli et al [26]. However, it is important to note that their experiments entailed measuring the response of an individual, suspended flake, with lateral dimensions on the order of microns, which was deformed using an AFM cantilever whereas we are looking at large-area films, consisting of nanocrystalline domains, grown directly on a polymer substrate. A closer point of comparison for our results is recently-reported work on Mo\(\text{S}_2\)/polymer composites which display similar gauge factors to our films [29]. It is likely that the electromechanical performance of our films could be improved through patterning of the channel i.e. a serpentine channel, similar to those used in commercial strain gauges, could be defined by optical lithography.

Our previous studies indicated that conversion of 1 nm of Pt resulted in Pt\(\text{Se}_2\) films with a thickness of \(~3.5\) nm (or \(~5\) layers).[13] At this layer thickness it is possible that the films are still partially semiconducting in character as there is some debate in the literature as to the exact layer thickness at which Pt\(\text{Se}_2\) transitions from semiconducting to semimetallic [2, 30, 31]. One would perhaps expect a film of 0.5 nm Pt starting thickness to be more sensitive as the resultant Pt\(\text{Se}_2\) would be more semiconducting in nature [13]. However, the film uniformity and conductivity must also be considered. Films grown from 1 nm Pt were also tested in a cantilever bending-beam setup and showed comparable results to previously-investigated transferred Pt\(\text{Se}_2\) films as detailed in the supporting information, S2. It is interesting that all films display a negative gauge factor given that the thicker films are expected to be semimetallic. This is consistent with previous results on transferred Pt\(\text{Se}_2\) films where density func-
tional theory calculations were used to explain the negative gauge factor in the high-strain regime [28]. These calculations indicated an increase in the DOS at the Fermi level under applied tensile strain which was offset slightly by a decrease in the DOS at the Fermi level due to the associated interlayer compression. Previous experimental reports have shown negative gauge factors for MoS2 [26] and positive gauge factors for graphene [32]. Whereas theoretical investigations have suggested that MoSe2 and WSe2 have positive gauge factors [33]. It is clear that more detailed investigation will be required to fully understand the sign of the gauge factor for PtSe2 and other 2D materials. This is particularly complicated in the case of TAC-grown PtSe2 where the layer thickness has a massive impact on the electrical properties and the nano-sized crystalline domains are very different to the idealized highly-crystalline scenario. Reference films of Pt only, with no selenisation treatment, show a smaller positive gauge factor when subjected to the same electromechanical tests, as detailed in the supporting information, figure S3. This is the expected behavior for metallic films. Interestingly, films which are sulfurised rather than selenised also show a positive gauge factor, as shown in figure S4 of the supporting information. In this case it is probable that PtS rather than PtS2 is formed under the low-pressure conversion conditions used, in line with previous reports [13].

Our previous studies indicated that a temperature of ~400 °C is required for complete conversion of Pt to PtSe2. However, other reports have shown that PtSe2 can be grown by epitaxial means on single-crystal Pt at temperatures as low as 270 °C [3]. With this in mind, we examined the electromechanical properties of PtSe2 films formed by converting 1 nm Pt at different temperatures. Shown in figure 3(a) is the fractional resistance change versus strain for films converted at temperatures in the range 250 °C–450 °C. It is worth

![Figure 2](image-url)
noting that the polyimide substrate would not survive temperatures higher than this and, furthermore, PtSe₂ would not form. Figure 3(a) indicates that the strongest electromechanical response is obtained from films with a conversion temperature of 400 °C. These films have the lowest resistance and highest (negative) gauge factor as shown in figures 3(b) and (c), respectively. This suggests that complete conversion of Pt to PtSe₂ is required for a strong electromechanical response—although it is also possible that the crystallinity, and in turn the electrical properties, of the films depends on the conversion temperature as seen previously for TAC-grown MoS₂ films [5]. XPS data for the films converted at different temperatures are shown in the supporting information, figure S5. These suggest a greater contribution from Pt oxides and amorphous Se at the lowest growth temperature used.

The results of cycled testing on a 1 nm Pt film on polyimide, which was converted to PtSe₂ at 400 °C, are shown in figure 4(a). It is clear from this that the electromechanical response is stable over many cycles. Data acquired over a longer timeframe are shown in the supporting information, figure S6. The effect of repeated peeling of the active PtSe₂ layer on a PtSe₂/polyimide sample (grown from 1 nm Pt) with sticky tape is shown in figure 4(b). While an increase in the film resistance is observed, this peeling does not have a drastic effect on the electrical properties of the chan-

![Figure 3.](image1)

![Figure 4.](image2)
nel suggesting that the PtSe$_2$ adheres very strongly to the polyimide substrate and that the sensors possess good mechanical stability. This strong adhesion to polyimide is noteworthy as structural robustness is paramount if any real-world sensing applications are to be considered. The strong adhesion is also interesting when one considers that previous studies have indicated that PtSe$_2$ can be easily transferred off SiO$_2$/Si substrates [8]. This indicates that the choice of growth substrate has a big influence on the strength of the PtSe$_2$/substrate interaction. The effect of soaking PtSe$_2$/polyimide (grown from 1 nm Pt) in water and acetone for a period of 5 d is shown in figures 4(c) and (d). Immersion in water has a minimal effect on the electromechanical properties suggesting that strain gauges based on PtSe$_2$/polyimide possess good environmental stability and could be used in aqueous conditions. Immersion in acetone on the other hand has a severe impact on the electromechanical properties. As polyimide is known to be resistant to acetone the reason for this performance degradation is unclear. A detailed study of the effect of different chemical environments on the properties of PtSe$_2$/polyimide would help to explain this behaviour and should form the basis of future work in this area. Additional detail on these solvent soak tests is presented in the supporting information, figures S7 and S8. Overall, the PtSe$_2$/polyimide strain gauges produced offer good cyclability and stability. These properties are worth highlighting as strain gauges based on nanomaterial/polymer composites typically suffer from poor environmental stability unless they are encapsulated.

Preliminary tests were carried out to investigate the response of piezoresistive sensors based on PtSe$_2$ on polyimide to vibrations of different frequencies. This was achieved by attaching a film to a speaker that was then operated at different frequencies. The results of this are shown in figure 5(a) where a strong signal, with a high signal-to-noise ratio, is seen for vibrations with frequencies of 95 Hz, 190 Hz and 380 Hz. This is further emphasized by the zoomed-in view of the response to vibrations of 380 Hz shown in figure 5(b). This strong response to high-frequency mechanical vibrations suggests that these sensors could potentially be used to monitor the performance of machinery or other structures with moving/vibrating parts.

**Conclusion**

Thin films of PtSe$_2$ have been grown directly on flexible polyimide foil and subsequently assessed for use as strain gauges. These films show superior gauge factors compared to commercial metal-based strain gauges. We have investigated the effect of growth temperature and film thickness on the performance of PtSe$_2$/polyimide strain gauges. The strain gauges were shown to be robust and stable over many cycles. The PtSe$_2$ layer adheres very strongly to the polyimide, with the films remaining conductive after repeated peel tests. The strain gauges show no sign of degradation following immersion in water for prolonged periods. A preliminary investigation showed that the strain gauges are well-suited to high-frequency operation. The combination of sensitivity, stability and robustness means that these strain gauges could potentially be used to monitor repeated vibrations, possibly in an outdoor setting. Lastly, strain gauges are but a very simple example of a technology based on PtSe$_2$ grown on a flexible substrate. We envisage that similar approaches could be developed to fabricate other, more complicated components for flexible electronics.

**Experimental section**

**PtSe$_2$ growth**

PtSe$_2$ layers were grown by a TAC process as detailed elsewhere previously [7, 8]. Pieces of polyimide foil of 125 $\mu$m thickness (Upilex 125S, UBE Europe GmbH) were used as substrates. Pt layers of different thickness were deposited on top of the substrates by e-beam evaporation (Temescal FC-2000). These Pt layers were then converted to PtSe$_2$ in a custom-designed, two-zone furnace whereby the Pt/polyimide was heated to
The DC bias ranged from 25–PF-TUNA mode, with standard PF-TUNA probes. were acquired by peakforce (PF) tapping using the system. The topographical and conductive mappings AFM was performed using a Bruker multimode eight parameter analyser with 0.1 ms pulses at ±

° a set-point temperature in zone 1 and Se powder was heated to 250 °C in the upstream zone 2 of the furnace. Forming gas (90% Ar, 10% H2) flow at 150 sccm carried Se vapour from zone 2 to zone 1 of the system. A dwell time of 2 h was used, previously shown to be sufficient for complete conversion of Pt to PtSe2.

Characterization AFM was performed using a Bruker multimode eight system. The topographical and conductive mappings were acquired by peakforce (PF) tapping using the PF-TUNA mode, with standard PF-TUNA probes. The DC bias ranged from 25–PF-TUNA mode, with standard PF-TUNA probes. The DC bias ranged from 25–PF-TUNA mode, with standard PF-TUNA probes.

The XPS data were collected using an Omicron XM1000 MkII x-ray source with monochromatic Al Kα x-rays alongside an Omicron EA125 energy analyzer. An analyzer pass energy of 15 eV was used for the collection of all core-level spectra. An Omicron CN10 electron flood gun was used for charge compensation and the binding energy scale was referenced to the carbon 1s core level at 284.8 eV. Analysis and fitting of the spectral components was performed using CasaXPS software. Spectral components were fitted using a Shirley background subtraction and Gaussian–Lorentzian line shapes.

SEM imaging was done using a Zeiss Ultra Plus SEM operating at 3 kV with an in-lens detector.

Electromechanical characterisation Electromechanical measurements during flexure tests were performed using a Keithley KE2601 source meter in 2-probe mode, controlled by LabView software, in conjunction with a Zwick Z0.5 ProLine Mechanical Tester (100 N Load Cell). For electromechanical flexure tests, sample specimens were hand-cut with a blade into 20 mm × 17.5 mm (L × W) dimensions. Silver wire contacts were painted directly onto the grown PtSe2 layer at each end of the sample and attached to the source meter via crocodile clips.

For the flexure testing, a custom made three-point flexure rig was used. Samples were placed with the PtSe2 side lying face down across two insulting support pins. The mechanical tester driven loading pin was then lowered into its start position (ε = 0) resting against the upward facing substrate side. Samples were then strained at a rate of 10 mm min⁻¹ until ε ~ 0.8%.

Bending-beam experiments were conducted by attaching hand-cut samples with super glue (super glue Z70 by HBM) to a steel beam (300 mm long, 30 mm wide and 3 mm thick) at a location 200 mm from the free-standing end of the beam. Masses of 2 kg and 1 kg were attached to the end of the beam resulting in a strain of 0.04% and 0.02%, respectively. The resistance across the PtSe2 was measured with a Keithley 4200 SCS parameter analyser with 0.1 ms pulses at ±3 V, ±5 V and ±7 V. Measurements were also conducted for tensile (sample at the top of the beam) and compressive (sample at the bottom of the beam) strain.

Durability testing For all testing, a new PtSe2 layer grown from 1 nm Pt on a 125 µm thick polyimide substrate was used for each test. This sample type was chosen due to its high electromechanical response. For cyclic testing, contacts were painted on the sample. The sample was then placed in the three-point flexure rig and deformed under a sine wave strain output at a frequency of 1 Hz between ε ~ 0.2% and ~1.2% for 500 cycles while measuring the electrical response as a function of time. For the tape peel test, clear domestic scotch tape was rubbed on the PtSe2 layer of the sample and peeled off, by hand, 50 times. After each peel, the piece of tape was replaced with a new one to maintain a constant adhesion. The electrical properties of the sample were measured at the 0th, 1st, 10th, 20th, 30th, 40th, and 50th peel using a multimeter. For the solvent soak test, three separate samples (one for reference) were soaked in normal tap water and acetone. Every 24 h, up to 120 h, samples were removed from their respective liquid and oven dried at 50 °C for 10 min. Electrical properties were then measured using a multimeter, after which, the samples were returned to their soak. After the 120 h had elapsed, flexure tests were performed on the three samples.

Acknowledgments NMeE acknowledges support from Science Foundation Ireland (SFI) through 15/SIRG/3329. GSD, CÓC and CPC acknowledge the support of SFI under 12/RC/2278 and 15/IA/3131. JBMcM acknowledges an IRC scholarship under Award 13653. GSD and MCL acknowledge the Graphene Flagship under Contract 785219. We thank UBE Europe GmbH for providing polyimide foils.

ORCID iDs

Conor S Boland https://orcid.org/0000-0003-4376-6770
Max C Lemme https://orcid.org/0000-0003-4552-2411
Georg S Duesberg https://orcid.org/0000-0002-7412-700X
Niall McEvoy https://orcid.org/0000-0001-5950-8755

References

[1] Choi W, Choudhary N, Han G H, Park J, Akinwande D and Lee Y H 2017 Recent development of two-dimensional transition metal dichalcogenides and their applications Mater. Today 20 116–30
[2] Ciarrocchi A, Avsar A, Ovchinnikov D and Kis A 2018 Thickness-modulated metal-to-semiconductor transformation in a transition metal dichalcogenide Nat. Commun. 9 919
[3] Wang Y et al 2015 Monolayer PtSe2, a new semiconducting transition-metal-dichalcogenide, epitaxially grown by direct selenization of Pt Nano Lett. 15 4013–8
[4] Van M et al 2017 High quality atomically thin PtSe2 films grown by molecular beam epitaxy 2D Mater. 4 045015
[5] Gatenby R, Hallam T, Lee K, McEvoy N and Duesberg G S 2016 Investigations of vapour-phase deposited transition metal dichalcogenide films for future electronic applications Solid-State Electron. 125 39–51
[6] Kim S-Y, Kwak J, Giobanu C V and Kwon S-Y 2020 Recent developments in controlled vapor-phase growth of 2D group 6 transition metal dichalcogenides Adv. Mater. 31 1804939
[7] O’Brien M et al 2016 Raman characterization of platinum diselenide thin films 2D Mater. 3 021004
[8] Yim C et al 2016 High-performance hybrid electronic devices from layered PtSe2 films grown at low temperature ACS Nano 10 9550–8
[9] Yim C, McEvoy N, Riazimehr S, Schneider D S, Gity F, Gatensby R, Hallam T, Lee K, McEvoy N and Duesberg G S 2020 Recent developments in controlled vapor-phase growth of 2D group 6 transition metal dichalcogenides Adv. Mater. 31 1804939
[10] Cui C, Xue F, Hu W-J and Li Z 2018 Two-dimensional materials with piezoelectric and ferroelectric functionalities npj 2D Mater. Appl. 2 18
[11] Li L et al 2018 Wafer-scale fabrication of recessed-channel PtSe2 MOSFETs with low contact resistance and improved gate control IEEE Trans. Electron Devices 65 4102–8
[12] Su T Y et al 2018 Phase-engineered PtSe2-layered films by a plasma-assisted selenization process PtSe2-based field effect transistor to highly sensitive, flexible, and wide-spectrum photodetector Small 14 10
[13] Yim C, Passi V, Lemme M C, Duesberg G S, Coleain C O, Pallecchi E, Fadil D and McEvoy N 2018 Electrical devices from top-down structured platinum diselenide films npj 2D Mater. Appl. 2 5
[14] Lin S et al 2017 Tunable active edge sites in PtSe2 films towards hydrogen evolution reaction Nano Energy 42 26–33
[15] Liu Y, Wang H, Zhao W, Zhang M, Qin H and Xie Y 2018 Flexible, stretchable sensors for wearable health monitoring: sensing mechanisms, materials, fabrication strategies and features Sensors 18 645
[16] Han B and Ou J 2007 Embedded piezoresistive cement-based stress/strain sensor Sensors Actuators A 138 294–8
[17] Barlian A A, Park W-T, Mallon J R Jr, Rastegar A J and Pruitt B L 2009 Review: semiconductor piezoresistance for microsystems Proc. IEEE Inst. Electr. Electron. Eng. 97 513–52
[18] Downey A, Laflamme S, Ubertini F and Sarkar P 2017 Experimental damage detection of wind turbine blade using thin film sensor array Proc. SPIE 10168 1016815
[19] Iliopoulos A, Weijtjens W, Van Hemelrijk D and Devriendt C 2017 Fatigue assessment of offshore wind turbines on monopile foundations using multi-band modal expansion Wind Energy 20 1463–79
[20] Fiorillo A S, Critello C D andPullano S A 2018 Theory, technology and applications of piezoresistive sensors: a review Sensors Actuators A 281 156–75
[21] Obiyo W and Liu T 2012 A review: carbon nanotube-based piezoresistive strain sensors J. Sensors 2012 15
[22] Yamada T, Hayamizu Y, Yamamoto Y, Yoshigusa Y, Izadi-Najafabadi A, Futaba D N and Hata K 2011 A stretchable carbon nanotube strain sensor for human-motion detection Nat. Nanotechnol. 6 296
[23] Ajamji M, Pichitpajongkit A, Lee S, Ryu S and Park I 2014 Highly stretchable and sensitive strain sensor based on silver nanowire-elastomer nanocomposite ACS Nano 8 5154–5
[24] Lee J, Kim S, Lee J, Yang D, Park B C, Ryu S and Park I 2014 A stretchable strain sensor based on a metal nanoparticle thin film for human motion detection Nanoscale 6 11932–9
[25] Cui C, Xue F, Hu W-J and Li L-J 2018 Two-dimensional materials with piezoelectric and ferroelectric functionalities npj 2D Mater. Appl. 2 18
[26] Manzeli S, Allain A, Ghadimi A and Kis A 2015 Piezoresistivity and strain-induced band gap tuning in atomically thin MoS2 Nano Lett. 15 5330–5
[27] Smith A D et al 2013 Electromechanical piezoresistive sensing in suspended graphene membranes Nano Lett. 13 3237–42
[28] Wagner S et al 2018 Highly sensitive electromechanical piezoresistive pressure sensors based on large-area-layered PtSe2 films Nano Lett. 18 3738–45
[29] Biccai S, Boland C S, O’Driscoll D P, Harvey A, Gabbett C, O’Sullivan R D, Griffin A J, Li Z, Young R J and Coleman J N 2019 Negative gauge factor piezoresistive composites based on polymers filled with MoS2 nanosheets ACS Nano 13 6843–55
[30] Kandemir A, Aksu B, Kahraman Z, Badalov SV, Ozcan M, Iyikanat F and Sahin H 2018 Structural, electronic and phononic properties of PtSe2 from monolayer to bulk Semicond. Sci. Technol. 33 085002
[31] Wang Z G, Li Q, Besenbacher F and Dong M D 2016 Facile synthesis of single crystal PtSe2 nanosheets for nanoscale electronics Adv. Mater. 28 10224–9
[32] Smith A D et al 2016 Piezoresistive properties of suspended graphene membranes under uniaxial and biaxial strain in nanoelectromechanical pressure sensors ACS Nano 10 9879–86
[33] Hosseini M, Elahi M, Pourfath M and Esbeni D 2015 Very large strain gauges based on single layer MoSe2 and WSe2 for sensing applications Appl. Phys. Lett. 107 235303