Characterization of monolayer WSe₂ sandwiched in a hetero-plasmonic dimer

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Abstract

Recent interests in layered transition-metal dichalcogenides (TMDCs), such as WSe₂, MoS₂, etc, arise due to their attractive electrical, optical, and mechanical properties with potential applications in energy storage, generation, and many more. Embedding these 2D materials in plasmonic cavities can further enhance light–matter interactions and alter their properties, resulting in diverse and efficient optoelectronic applications. The strain due to the geometry and charge transfer due to the plasmonic materials can further modify the TMDCs’ optical response for sensing applications and as single photon emitters in on-chip optoelectronic applications. This work discusses one such 2D-plasmonic hybrid configuration of a silver sphere on a gold disc with WSe₂ sandwiched in between. We perform non-invasive Raman and PL studies of this system to estimate the field enhancement and discuss strain and doping induced in the TMDC.

Introduction

Metal nanoparticles of different shapes, sizes, and materials like gold (Au), Silver (Ag), or Copper (Cu) show strong interaction with incident light through the excitation of collective and coherent electron oscillations known as localized surface plasmons. Applications include surface-enhanced Raman spectroscopy (SERS), photovoltaics, photocatalysis, and many more, making noble metal nanoparticles attractive for fundamental studies as well as technologically important [1–7]. The strength of these electromagnetic couplings depends on the number of such nanoparticles and their separation distance. Of all plasmonic systems, the most common is a two-nanoparticle system with nm and smaller spacings in between, also known as dimers, which has given scope in biological imaging, photodetection, and optical sensing, along with those mentioned above. The easiest way of maintaining such a sub-nm gap is by placing a material of equal thickness between the plasmonic particles. In this respect, two-dimensional materials like graphene and transition metal dichalcogenides (TMDCs) with atomic thickness have found much attention [8–14]. Previously we have shown how sandwiching a single layer of graphene between two silver nanoparticles resulted in unprecedented photosensitivity in graphene that allowed the realization of a new class of large-area color-selective plasmonic photodetector at room temperature [15]. The local electromagnetic field at the junction of the sub-nm spaced dimers increased dramatically, thereby resulting in the most sensitive graphene–plasmonic hybrid photodetector reported to date. Such an architecture signifies the tremendous promise of integrating plasmonics with atomically thin materials, especially TMDCs, in nanoelectronics and nanophotonic applications [15–19, 44], arising due to the direct bandgap of TMDC monolayers in the visible region.

It is necessary to recognize the various effects that can alter the physical properties of the TMDCs in a sandwich geometry. Quite well known are the local strains and possible defect localization in TMDCs on pillars. While the uncontrolled occurrence of many defects is typically detrimental to material properties, carefully structured and induced defects and strain engineering have led to new applications, including single-photon sources in monolayer WSe₂ [18, 19, 20, 21, 45] and inducing direct bandgap in multilayer WSe₂ [22].
In addition, the charge transfer by the Ag sphere or Au disc into the material can result in doping of the material, resulting in a shift in the optical bandgap of the material, offering another important handle towards engineering the properties of TMDCs for applications [23, 24]. This has led to critical applications in spintronics, high-speed transistors, and various sensors [25–28]. Metal nanoparticles are known to reduce lifetime/speed up the decay process.

Surprisingly, there have been only a limited number of studies on the effects of doping and strain on WSe2 characterized through PL and/or Raman shifts. These include a report on Niobium-induced p-doping of WSe2 causing a redshift in PL energy as well as a Raman shift, while other p-dopants like Magic blue or \([\text{N(C}_{6}\text{H}_{4}\text{-p-Br}_1])\text{SbCl}_3\) causing a blueshift [28–31]. In other work, while p-doping by Au is established in the WSe2 monolayer, the effect on PL energies has not been discussed [31].

With such an expanse of applications of TMDCs–plasmonic hybrid, here we present a careful investigation of the effect of a plasmonic cavity over WSe2 as the TMDC, specifically for strain and doping consequences, using Raman and PL. The dimer–2D cavity was fabricated on pillar geometry to induce deterministic strain in WSe2.

We modelled multiple plasmonic architectures to find one with resonance closest or equal to WSe2. Few of such examples are shown in supplementary information figure S1. Keeping in mind the feasibility of fabrication over pillars and other factors, we chose a sphere-disc geometry to be fabricated over pillars. A plasmonic–2D material hybrid device geometry, as shown in figure 1(a), which is reasonably close to the final experimental device, is studied here in detail. We consider a silver (Ag) sphere of radius 75 nm and a gold (Au) disc of radius 100 nm, thickness 40 nm, separated by monolayer WSe2 of thickness 0.7 nm, and simulated the scattering cross-section and electric field enhancement \(|\mathbf{E}/\mathbf{E}_0|\) using Finite Element Method (FEM) based COMSOL simulations. The dielectric function values of WSe2 were taken from Heinz et al [32]. The geometry parameters were chosen to have a resonance wavelength close to the WSe2 optical bandgap at 750 nm. Figure 1(b) shows \(E/E_0\) field enhancement in the hotspot as high as 5000. Figure 1(c) shows the spatial extent of the electric field enhancement in the hot spot region, which lies within a few nanometers. The device fabrication and characterization details of the geometry are explained in the Experimental section below.

**Results and discussion**

To inspect the effect of the plasmonic hotspots over WSe2 in our device geometry, we analyze the enhancement and shift in its Raman signal. Raman shift of bare monolayer WSe2 has a peak ∼260 cm⁻¹ which corresponds to the degenerate \(\text{E}^{+ \pm}_{2g} + \text{A}_{1g}\) in-plane vibration mode, and a peak ∼260 cm⁻¹ which corresponds to the 2LA(M) second-order mode [33, 34].

Figure 2(a) shows the Raman shift of monolayer WSe2 with and without the plasmonic confinement. To rule out the effect of the heat-induced shift in the Raman spectra of WSe2, we performed Raman measurements on W-bare sample before and after heating it at 260°C for 15 min figure S3 shows the respective Raman spectra with no difference in the mode position due to heating. To make a quantitative estimate of the enhancement of the electric field, we took the ratio of the total area under the \(\text{E}^{+ \pm}_{2g} + \text{A}_{1g}\) Raman band as a measure of the strength of the Raman signal, following the method outlined by Paria et al [15]. Accordingly, the ratio of the area under the curve of \(\text{E}^{+ \pm}_{2g} + \text{A}_{1g}\) Peak of the sandwiched nanostructure to the area under the peak for bare WSe2 on SiO2/Si substrate provided an estimate of the plasmonic enhancement of ∼2. For the theoretical estimation, we used the enhancement curve from the numerical simulation in figure 1(b). Theoretically, the net enhancement of the Raman signal for a laser focal spot of area A is given by

\[
\left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{abs}} \left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{emi}} \sigma A,
\]

where \(\left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{abs}}\) is the enhancement due to the component of the strongly enhanced near field parallel \((\text{E}_n)\) to WSe2 at the wavelength of the excitation laser (532 nm), \(\left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{emi}}\) is the local electric enhancement at the Stokes-shifted emission wavelengths (539 nm). The area of high field enhancement \(\sigma\) is calculated by taking the fwhm of the in-plane enhanced fields. From figure 1(b), the primary source of the enhancement \(\left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{abs}}\) at the wavelength of the excitation laser (532 nm) was 81. The largely enhanced EM fields were concentrated in a tiny region of area \(\sigma \approx 150 \text{ nm}^2\) at the junction of the 2D-plasmonic geometry, as shown in figure 1(c). The secondary source of enhancement \(\left(\frac{|\text{E}|}{|\text{E}_0|}\right)_{\text{emi}}\) was 121 (at 539 nm) for the \(\text{E}^{+ \pm}_{2g} + \text{A}_{1g}\) peak. Net estimated enhancement was, thus, ∼1.4, which is reasonably close to the experimental value obtained above, proving that the plasmonic geometry indeed results in a hundred-fold focussing of optical intensity.
We also studied the shift in the Raman bands and a comparison was drawn of the dimers with the control samples of WSe₂/SiO₂ pillar (W-pillar) geometry and WSe₂/Au Disc/SiO₂ pillar (W-monomer) geometry, both prepared using fabrication details mentioned in the experimental section. It was observed that addition of Au disc on WSe₂ redshifts the E₁₂⁺A₁₆ peak by 0.5 cm⁻¹ compared to the W-pillar, while the 2LA peak shifts by...
This shift, shown in figure 2(b), is in accordance with previous work where monolayer WSe₂ decorated with Au nanoparticles showed a redshift in the E₁²g + A₁g peak [31]. Adding Ag on top of this monomer structure further redshifts the in-plane vibrational mode by 0.5 cm⁻¹ compared to W-monomer and by 1 cm⁻¹ compared to W-pillar. The 2LA mode also sees a significant redshift of 2 cm⁻¹ (3 cm⁻¹) compared to its previous W-monomer (W-pillar) control geometry. This is one-of-a-kind reporting of the optical properties where the effect of silver on monolayer WSe₂ has been reported optically. The shifts have been summarised in figure 2(c).

A similar reduction in the Raman shift of WSe₂ observed in previous works says that a tensile strain is induced on WSe₂ [35–37]. The strain induced can be quantified using photoluminescence (PL) measurements. Raman does, however, establish that the strain induced is biaxial rather than uniaxial for the current device, as no splitting is observed in the E₁²g + A₁g peak [35].

We next carried out PL measurements on the dimer sample and control samples to understand the effect of charge transfer by Ag and Au onto WSe₂ in variable conditions and quantify the strain induced in WSe₂. Albeit doping through electrical control of carrier concentration is well established, such as through the application of voltage to the gate electrode, the purpose of this study was to understand the nature of doping induced by plasmonic materials in a transparent device architecture; followed by optical characterizations using PL [28–31]. Figure 3(a) shows photoluminescence (PL) spectra for W-bare, W-pillar, W-monomer, and W-dimer samples. The data has been normalized to accentuate the peak shifts. Pristine monolayer WSe₂ (W-bare) presents a prominent PL peak at 1.66 eV (A excitonic emission), corresponding to the direct bandgap transition. We find that the addition of Au to the device geometry redshifts the optical bandgap by 21 meV.

Interestingly, the addition of the top Ag sphere to the geometry further redshifts the optical bandgap by 14 meV (a total of 35 meV shift from pristine WSe₂). This material effect of Ag sphere onto monolayer WSe₂ has not been reported before to the best of our knowledge, and previous works have always associated redshift in PL of monolayer due to various dopants with p-doping of the material [28, 38–40]. Raman peak shift pattern observed matches with other work indicative of possible p-type doping of WSe₂ by our device structure;
however, a conclusive result would require an electrical measurement [31]. To investigate the effect of plasmonic parameters and structural variation on bandgap shift, we varied the diameter of the Au disc for W-monomer sample and the pillar diameter in W-pillar sample. Figure S2 in supplementary information shows that the PL peak position did not change dramatically in either case.

As established before, using Raman analysis, the type of strain acting on WSe$_2$ by our device is biaxial tensile; we quantified the amount of strain induced using the magnitude of peak shift values of PL spectra. We found that a strain of 0.2% and 0.3% was induced onto WSe$_2$ by the W-monomer and W-dimer geometry, respectively, following the work of Johari and Shenoy [41].

Apart from the PL peak position redshift, there was an apparent increase in the FWHM of the PL peak. An increase in FWHM is suggestive of other excitonic species formation. Hence, we deconvoluted the A exciton peak into the neutral exciton emission ($A^0$) at 1.66 eV and the trion ($A^T$) at $\sim$1.63 eV for the TMDC using Lorentzian fitting [38, 42, 46]. This assignment of the trion peak to $\sim$1.63 eV comes from works of Zhang R et al [38], Huang J et al [46] and Jones A.M. et al [43] who used optical and electrical measurements to assign the peaks. An accurate assignment would require altering the device to include electrical pads for gate measurements, which is out of the scope of this work. Figure S5 in supplementary information shows the FWHM of the $A^0$ and $A^T$ peak for bare to dimer samples. Figures 3(b)–(d) shows deconvoluted trion and exciton peaks for the three samples; W-pillars, W-monomer, and W-dimer. The deconvoluted trion and exciton peak for the W-bare sample has been added as figure S6 in supplementary information. It can be seen that the neutral excitons ($A^T$) dominate the PL emission of W-pillars. But as we introduce Au and Ag in the system, the intensity ratio of trion to neutral exciton ($A^T/A^0$) increases, indicating the existence of enhanced concentrations of excess carriers through doping effects. However, the literature suggests similar modifications can also happen due to induced defects in the system [38, 46]. The ratio in our system changes from 0.14 for W-pillar to 0.35 for W-monomer and 0.6 for the W-dimer sample. This encouraging observation suggests an efficient material route toward bandgap engineering in WSe$_2$ for single-photon emitter-type device applications.

**Conclusion**

We investigated the effect of strain and metallic (Au, Ag) dopants on monolayer WSe$_2$ by sandwiching it in a raised plasmonic cavity. We found that both Raman and PL peak positions shift on the introduction of strain and Au, Ag. The Raman shift suggests the strain to be biaxial, and the PL suggests approximately 0.3%. The change in the ratio of trion to exciton peak intensity indicated doping effects of Au and Ag. The effect of structure and material on bandgap is relevant to photodetector applications, where 2D materials are coupled with plasmonic devices, e.g., when plasmonic nanoparticles [14–16] are in close proximity to the 2D photosensitive material. In addition, these TMDC-plasmonic cavities, when strained, can be potential candidates toward deterministic and efficient sources of single photons for various quantum information applications.

**Experimental section**

**Device fabrication**

Fabrication of the base SiO$_2$ pillars on SiO$_2$/Si substrate was done using electron beam (e-beam) lithography. Photoresist (PR) PMMA 495k A4 was spin-coated on SiO$_2$/Si substrate. The desired hole pattern of radius 100 nm and pitch 1 $\mu$m was written and developed in MIBK:IPA solution for 1 min 35 s to obtain the hole array patterns in the PR. A 40 nm thick chromium (Cr) film was deposited on the hole pattern followed by lift-off to obtain 100 nm radius Cr discs. With Cr as a mask, the SiO$_2$ substrate was etched using Reactive Ion Etching (RIE) with CHF$_3$ gas forming SiO$_2$ pillars array. Cr was later removed using a Cr etchant, leaving arrays of 120–130 nm tall SiO$_2$ pillars, figure 1(f). A thin film of 40 nm Au thermally evaporated over the patterned pillar substrate formed the base plasmonic material of the dimer-on-pillar geometry, as shown in figure 1(g).

Commercially available CVD grown monolayer WSe$_2$ (from Six-Carbon Technology) was transferred to the Au-SiO$_2$ pillar substrate using a standard PMMA-based wet transfer process. WSe$_2$-Au disc-SiO$_2$ pillar configuration or W-monomer obtained is shown in figure 1(h). Overlay e-beam lithography was used to expose only the top of the pillars covered with WSe$_2$/Au. Post-development, an array of holes was obtained precisely at the location of pillars. A 40 nm thick silver film was deposited, followed by lift-off leading to Ag disc-WSe$_2$-Au disc on SiO$_2$ pillar configuration. This was further annealed at 260 °C for 15 min in nitrogen ambient to form an Ag nanoparticle-WSe$_2$-Au disc configuration, denoted as W-dimer sample ahead. Figure 1(i) shows the SEM image of the final fabricated dimer-on-pillar geometry with WSe$_2$ in between.
Optical characterizations

The optical characterizations of Raman and PL spectra of our samples were carried out using Horiba Jobin Yvon LabRAM HR spectrometer with excitation laser 532 nm, 100x objective of 0.9 NA. The effective spot size was 800 nm. The incident laser power was 50 μW, and spectra were collected with an integration time of 3 s for PL and 5 s for Raman. The signal was averaged three times for both. To confirm that input laser power used has no effect on the PL spectra, we performed power dependence of W-bare sample and found that spectra do not shift as a function of power for upto few 100 μW, as shown in figure S4.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflicts of interest

There are no conflicts of interest to declare.

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References

[1] Oh Y J, Kang M, Park M and Jeong K H 2016 Engineering hot spots on plasmonic nanopillar arrays for SERS: A review Biochip Journal 10 297–309
[2] Giannini V, Fernández-Domínguez A I, Heck S C, and Maier S A 2011 Plasmonic nanoantennas: Fundamentals and their use in controlling the radiative properties of nanoemitters Chem. Rev. 111 3888–912
[3] Gonçalves M R 2014 Plasmonic nanoparticles: fabrication, simulation and experiments J. Phys. D: Appl. Phys. 47
[4] Jeong H H, Adams M C, Günther J P, Alarcón-Correa M, Kim I, Choi E, Miksch C, Mark A F, Mark A G and Fischer P 2019 Arrays of plasmonic nanoparticle dimers with defined nanogap spacers ACS Nano 13 11453–9
[5] Sun C, Qin C, Zhai H, Zhang B and Wu X 2021 Optical properties of plasma dimer nanoparticles for solar energy absorption Nanomaterials 11
[6] Vazquez-Mena O, Sannomiya T, Villanueva I G, Voros J, and Brugger J 2011 Metallic nanodot arrays by stencil lithography for plasmonic biosensing applications ACS Nano 5 844–53
[7] Kuznetsov A I, Evlyukhin A B, Gonçalves M R, Reinhardt C, Koroleva A, Arnedillo M L, Kiyani R, Martí O and Chichkov B N 2011 Laser fabrication of large-scale nanoparticle arrays for sensing applications ACS Nano 5 4443–9
[8] Sun Y, Gao S and Xie Y 2014 Atomically-thick two-dimensional crystals: electronic structure regulation and energy device construction Chem. Soc. Rev. 43 530–46
[9] Zhao J, Jin X, Vdovenko M, Zhang L, Sakhavors I Y and Zhao S 2015 A WS2 nanosheet based chemiluminescence resonance energy transfer platform for sensing biomolecules Chem. Commun. 51 11092–5
[10] Tan C, Liu Z, Huang W and Zhang H 2015 Non-volatile resistive memory devices based on solution-processed ultrathin two-dimensional nanomaterials Chem. Soc. Rev. 44 2615–28
[11] Bernardi M, Palummo M and Grossman J C 2013 Extraordinary Sunlight absorption and one nanometer thick photovoltaics using two-dimensional monolayer materials Nano Lett. 13 3664–70
[12] Eda G and Maier S A 2013 Two-dimensional crystals: managing light for optoelectronics ACS Nano 7 5660–5
[13] Tedstone A A, Lewis D J and O’Brien P 2016 Synthesis, properties, and applications of transition metal-doped layered transition metal dichalcogenides Chem. Mater. 28 1965–74
[14] Ghosh P, Paria D, Balasubramanian K, Ghosh A, Narayanan R and Raghavan S 2019 Directed microwave-assisted self-assembly of Au-graphene–au plasmonic dimers for SERS applications Adv. Mater. Interfaces 6 1–9
[15] Paria D, Roy K, Singh H J, Kumar S, Raghavan S, Ghosh A and Ghosh A 2015 Ultrahigh field enhancement and photosresponse in atomically separated arrays of plasmonic dimers Adv. Mater. 27 1751–8
[16] Deshpande P, Suri P, Jeong H H, Fischer P, Ghosh A and Ghosh A 2020 Investigating photoresponsivity of graphene–silver hybrid nanomaterials in the ultraviolet J. Chem. Phys. 152
[17] Eckermeyer T J, Britnell L, Jasnos P K, Lombardo A, Gorbachev R V, Grigorenko A N, Geim A K, Ferrari A C and Novoselov K S 2011 Strong plasmonic enhancement of photovoltage in graphene Nat. Commun. 20 4
[18] Palacios-Berraquero C, Kara D M, Monblanch A R P, Barbone M, Latawe P, Yoon D and Atatüre M 2017 Large-scale quantum-emitter arrays in atomically thin semiconductors Nat. Commun. 8 1–6
[19] Tripathi I. N, Iff O, Betzold S, Dusanowski L, Emmerling M, Moon K and Schneider C 2018 Spontaneous emission enhancement in strain-induced WSe2 Monolayer-based quantum light sources on metallic surfaces ACS Photonics 5 1919–26
[20] Iff O, Tedeschi D, Martin-Sánchez J, Moczala-Dusanowska M, Tongay S, Yumigeta K and Schneider C 2019 Strain-tunable single photon sources in WSe2 monolayers Nano Lett. 19 6931–6
[21] Koperski M, Nogajewski K, Arora A, Cherkez V, Mallet P, Veuillen JY and Potemski M 2015 Single photon emitters in exfoliated WSe2 structures Nat. Nanotechnol. 10 503–6
[22] Desai S B, Seol G, Kang J S, Fang H, Battaglia C, Kapadia R and Javey A 2014 Strain-induced indirect to direct bandgap transition in multilayer WSe2 Nano Lett. 14 4992–7
[23] Fang H, Chuang S, Chang T C, Takei K, Takahashi T and Javey A 2012 High-performance single layered WSe2 p-FETs with chemically doped contacts Nano Lett. 12 3788–92
[24] Iqbal M W, Elahi E, Amin A, Hussain G and Aftab S 2020 Chemical doping of transition metal dichalcogenides (TMDs) based field effect transistors: A review Superlattices Microstruct. 137 106350
[25] Xiao D, Liu G, Bin, Feng W, Xu X and Yao W 2012 Coupled spin and valley physics in monolayers of MoS2, and other group-VI dichalcogenides Phys. Rev. Lett. 108 1–5
[26] Yuan H, Bahramy M S, Morimoto K, Wu S, Nomura K, Yang B J and Iwasa Y 2013 Zeeman-type spin splitting controlled by an electric field Nat. Phys. 9 563–9
[27] Lopez-Sanchez O, Lembke D, Kayci M, Radenovic A and Kis A 2013 Ultrahighly sensitive photodetectors based on monolayer MoS2 Nat. Nanotechnol. 8 497–501
[28] Nam H J, Kim J and Park J H 2017 Wide-range controllable doping of tungsten diselenide (WSe2) based on hydrochloric acid treatment J. Phys. Chem. C 121 14367–72
[29] Pandey S K, Alsalmam H, Azadani J G, Izquierdo N, Low T and Campbell S A 2018 Controlled p-type substitutional doping in large-area monolayer WSe2 crystals grown by chemical vapor deposition Nanoscale 10 21374–85
[30] Zhang S, Hill H M, Moudgil K, Richter C A, Hight Walker A R, Barlow S and Pookpanratana S J 2018 Controllable, wide-ranging n-doping and p-doping of monolayer group 6 transition-metal disulfides and diselenides Adv. Mater. 30
[31] Chen C H, Wu C L, Pu J, Chiu M H, Kumar P, Takenobu T and Li J 2014 Hole mobility enhancement and p-doping in monolayer WSe2 by gold decoration 2D Mater. 1
[32] Li Y, Chernikov A, Zhang X, Rigosi A, Hill H M, van der Zande A M, Chenet D A, Shih E M, Hone J and Heinz T F Measurement of the optical dielectric function of monolayer transition-metal dichalcogenides: MoS2, MoSe2, WS2, and WSe2 Phys. Rev. B 90 205422
[33] Tommorf P et al Photoluminescence emission and Raman response of monolayer MoS2, MoSe2, and WSe2 Opt. Express 21 4908–16 2013
[34] Zhao W, Ghorannevis Z, Amara K K, Zhang X and Eta G 2013 Lattice dynamics in mono- and few-layers of WS2 and WSe2 Nanoscale 5 9677–83
[35] Sahin H, Tongay S, Horzum S, Fan W, Zhou J, Li J and Peeters F M 2013 Anomalous Raman spectra and thickness-dependent electronic properties of WSe2 Physical Review B - Condensed Matter and Materials Physics 87 1–6
[36] Chang C H, Fan X, Lin S H and Kuo J I 2013 Orbital analysis of electronic structure and phonon dispersion in MoS2, MoSe2, WS2, and WSe2 monolayers under strain Physical Review B - Condensed Matter and Materials Physics 88 1–9
[37] Amin B, Kaloni T P and Schwingenschlögl U 2014 Strain engineering of WS2, WSe2, and WTe2 RSC Adv. 4 34561–5
[38] Zhang K, Drysdale D, Koutsos V and Cheung R 2017 Controlled layer thinning and p-type doping of WSe2 by Vapor XeF2 Adv. Funct. Mater. 27 1702453
[39] Kim J E, Kang W Y, Yu V T, Kim J Y R, Shin Y S, Lee I, Won U Y, Lee B H, Kim K, Phan T L, Lee Y H and Yu W J 2021 Ideal PN photodiode using doping controlled WSe2–MoSe2 lateral heterostructure J. Mater. Chem. C 9 3504–12
[40] Murali Y, Zhang S, Hotta T, Liu Z, Endo T et al 2021 Versatile post-doping toward two-dimensional semiconductors ACS Nano 15 19225–32
[41] Johari P and Shenoy V B 2012 Tuning the electronic properties of semiconducting transition metal dichalcogenides by applying mechanical strains ACS Nano 6 5449–56
[42] McCready K M, Hambicki A T, Sivaram S V and Jonker B T 2018 A- and B-exciton photoluminescence intensity ratio as a measure of sample quality for transition metal dichalcogenide monolayers APL Mater. 6 111106
[43] Jones A M et al Nat. Nanotechnol. 2013 8 634
[44] Radisavljevic B, Radenovic A, Brivio J, Giacometti V and Kis A 2011 Single-layer MoS2 transistors Nat. Nanotechnol. 6 147–50
[45] Kern J, Niehues I, Tommorf P, Schmidt R, Wigger D, Schneider R and Bratschitsch R 2016 Nanoscale positioning of single-photon emitters in atomically thin WSe2 Adv. Mater. 28 7101–5
[46] Huang J, Hoang T B and Mikkelsen M H 2016 Probing the origin of excitonic states in monolayer WSe2 Scientific Reports 6