Magnetic field induced polarization enhancement in monolayers of tungsten dichalcogenides: effects of temperature

T Smoleński1, T Kazimierczuk1, M Goryca1, M R Molas1, K Nogajewski2, C Faugeras2, M Potemski1,2 and P Kossacki1

1 Institute of Experimental Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warsaw, Poland
2 Laboratoire National des Champs Magnétiques Intenses, CNRS-UGA-UPS-INS-E-MFL, 25 rue des Martyrs, 38042 Grenoble, France
E-mail: Tomasz.Smoleński@fuw.edu.pl

Keywords: transition metal dichalcogenide monolayers, temperature dependence, magnetic field, optical orientation, dark excitons, localized excitons

Abstract
Optical orientation of localized/bound excitons is shown to be effectively enhanced by the application of magnetic fields as low as 20 mT in monolayer WS2. At low temperatures, the evolution of the polarization degree of different emission lines of monolayer WS2 with increasing magnetic fields is analyzed and compared to similar results obtained on a WSe2 monolayer. We study the temperature dependence of this effect up to \( T = 60 \) K for both materials, focusing on the dynamics of the valley pseudospin relaxation. A rate equation model is used to analyze our data and from the analysis of the width of the polarization dip in magnetic field we conclude that the competition between the dark exciton pseudospin relaxation and the decay of the dark exciton population into the localized states are rather different in these two materials which are representative of the two extreme cases for the ratio of relaxation rate and depolarization rate.

1. Introduction

The successful [5] isolation of graphene [1] followed by over a decade of its intense study has triggered the development of a vast area of research on a variety of two-dimensional (2D) crystals, whose properties substantially differ from those of their bulk counterparts [2–6]. Among these materials particularly much attention is currently attracted by semiconducting transitional metal dichalcogenides (s-TMDs) which exhibit robust optical properties. The research on these materials is driven by both scientific curiosity and a prospect of 2D optoelectronic applications.

One of the most intriguing properties of atomically-thin s-TMDs is the possibility of accessing the valley degree of freedom using circularly polarized light [7–10]. The simplicity of this approach paved the way to study \( T_1 \) and \( T_2 \) parameters of the valley degree of freedom, i.e. the inter-valley relaxation [11] and valley coherence [12]. Such experiments are typically carried out at cryogenic temperatures, which allows one to minimize the influence of thermal effects obscuring the investigated phenomena.

On the other hand, the bulk of application-oriented studies on s-TMD monolayers is carried out at room temperature. Due to extremely high exciton binding energy (of hundreds of meV [13, 14]) and short radiative lifetime (in the range of picoseconds [15]), the optical properties of s-TMD monolayers remain robust under such conditions, as evidenced by efficient room-temperature photoluminescence (PL) [16]. A disparity between these two regimes immediately raises a question about the changes in the intermediate temperature range, which is of particular interest, since even as basic quantity as the PL intensity exhibits a non-monotonic dependence on temperature [17].

In this work we present a study of temperature dependence of the magnetic-field-induced polarization enhancement (FIPE) of the optical orientation of localized excitons (LEs) in WS2 and WSe2 monolayers. Earlier investigations [18] established a link between the occurrence of the FIPE for monolayer WSe2 and the inter-valley relaxation of long-lived dark states, which could precede the localized excitons in the relaxation path (see figure 1). The key element in the proposed model was the process of inter-valley relaxation of these intermediate dark states, which could be effectively suppressed by the magnetic field. Regardless of its rate, the inter-valley relaxation is stopped by localization of the dark excitons (conversion to the
population of localized excitons). Thus, the analysis of the polarization degree of the subsequent localized exciton recombination shed some light on the nature of inter-valley relaxation of the considered dark excitons, which is much more elusive than the analogous relaxation of bright excitons [19].

2. Methods

The experiments described in this paper were performed on 2 sets of samples: monolayers of WS$_2$ and WSe$_2$. In each case the monolayer flakes were obtained by mechanical exfoliation of bulk crystals involving the use of a chemically clean back grinding tape and a polydimethylsiloxane stamp. The exfoliated flakes were non-deterministically transferred onto Si substrates covered with either 90 nm thick (WSe$_2$) or 300 nm thick (WS$_2$) layer of thermally grown SiO$_2$. Prior to that step the substrates were ashed with oxygen plasma to rid their top surfaces of possible organic contaminants. The monolayers of interest were first identified by their distinctive optical contrast and then double checked with photoluminescence and Raman scattering measurements.

Our optical investigations were based on photoluminescence spectroscopy. The samples were excited using either 561 nm or 647 nm continuous-wave diode lasers. The emitted light was analyzed using a 0.5 m spectrometer equipped with a CCD camera. The polarization state of the light was controlled by means of a combination of Glan–Taylor polarizers and achromatic $\lambda/4$ waveplates incorporated in the excitation as well as in the detection path. During the experiments, the samples were placed in a variable temperature insert (VTI) of a helium cryostat mounted inside a superconducting magnet. All measurements were carried out in the Faraday geometry.

3. Results

3.1. Field-dependent optical orientation in WS$_2$ monolayer

So far the FIPE effect has been only observed in WSe$_2$ monolayers [18]. In the reported experiments a rather weak magnetic field of 20 mT was shown to significantly enhance the efficiency of the optical orientation, $\eta(B)$, of the localized excitons, leading to a dip-like feature in the $\eta(B)$ dependence at $B = 0$. This observation was interpreted as related to the field-dependent inter-valley relaxation of the dark excitons. The fact that the energetically lowest excitonic state is optically dark in WSe$_2$ monolayers [20–22] has been a crucial point in the interpretation of the observation of the FIPE. Monolayer WS$_2$ is another system with an optically inactive exciton ground state, and as such might be expected to exhibit the FIPE too.

Figure 2 presents the effect of optical orientation of excitons in a WS$_2$ monolayer at low temperature ($T = 1.5$ K). The optical orientation manifests itself as a difference between the PL spectra measured in two circular polarizations upon circularly polarized excitation, as seen in figure 2(a). Such a difference is observed with different strength for various emission lines, which correspond to the recombination processes involving either free or localized excitons. Both kinds of excitons can be distinguished on the basis of their lifetime, as free excitons decay in single picoseconds while localized excitons can live for up to a few nanoseconds [18, 23]. In our case, the acquiring time-resolved data were obtained in an auxiliary experiment using a streak camera and pulsed excitation of the PL, which allowed us to obtain reference time-gated spectra plotted with green and black dashed lines in figure 2(a). The signal drawn with a black curve was integrated in a window from 200 ps to 1050 ps after the laser pulse, i.e. in the time range after the recombination of free excitons when only the localized excitons contributed to the spectrum. Using this method we unequivocally determined that the lines denoted in figure 2(a) by X and CX$_2$ are related to the free excitons (neutral and charged, respectively). Due to its intermediate lifetime, the line CX$_2$ cannot be easily classified as arising from either free or localized excitons. Based on the results of reflectivity experiments on similar samples [24], we tentatively ascribe it to another type of a charged exciton. Still, in the following analysis for the WS$_2$ monolayer...
we will limit ourselves to the three lowest-energy lines (L₁–L₃) in the spectrum, which can be unambiguously attributed to the localized excitons.

Similarly to the approach used for monolayer WSe₂ [18], we have repeated the measurements of optical orientation for various magnetic fields, with the results shown in figures 2(b)–(f). As expected, each of the lines recognized as originating from the localized states exhibits the effect of robust FIPE, i.e. a significant variation of the optical orientation efficiency at a rather weak magnetic field of 20–22 mT. Upon application of the magnetic field the optically-induced polarization is clearly enhanced, which may be interpreted as a signature of the slowdown of inter-valley relaxation [18].

Interestingly, the FIPE is also observed for the line denoted in figure 2(a) as CX₁, most probably related to the free charged excitons [25, 26]. In its present form, our model does not automatically account for this effect, which requires a special treatment, e.g. the assumption that dark excitons, which feed the localized states, may at least partially contribute to the formation of the trions. We note, however, that under an assumption that these dark excitons occupy the lowest-energy dark state of the system, such a process cannot be a simple phonon-assisted energy relaxation, since the CX₁ energy exceeds the energy of this ground state [27–29]. In fact, the conversion of such dark exciton to a trion requires an event of a single electron trapping, which might bring a missing energy, especially in the case of high electron concentration in the sample. More detailed verification of the presented hypothesis would necessitate precise polarization- and time-resolved measurements on gated structures, which remain beyond the scope of this work.

A separate issue is the relative amplitude of the FIPE (figures 2(d)–(f)). Depending on the particular localized exciton line, the amplitude of this effect in WS₂ monolayer is equal to about 2 percentage points. It is significantly weaker than the effect observed for monolayer WSe₂, which is about 25 percentage points [18]. Such a disparity cannot be explained by differences in the overall optical orientation efficiency, which was quite similar under our experimental conditions (∼13% for monolayer WS₂ and ∼30% for monolayer WSe₂ at B = 100 mT, respectively). We can speculate that the discussed disparity reflects a different interplay between the exciton localization time and the rate of inter-valley relaxation of the itinerant excitons. In particular, already at B = 0 the localization time in a WS₂ monolayer might be short compared to the inter-valley relaxation time. Under such conditions, an additional extension of the relaxation time by the magnetic field would have a limited effect, as in the case of the experiment. This conjecture will be revisited when discussing the temperature dependence of the width of the dip in the field dependence of the orientation efficiency.

3.2. Temperature dependence

Having established that monolayer WS₂ also exhibits the FIPE effect similar to that displayed by monolayer WSe₂, we repeated measurements for both systems at different bath temperatures. An overview of the observed changes is presented in figure 3. In both materials the increase in temperature leads to a systematic reduction of the PL intensity of the LE lines, which is interpreted in terms of thermal activation (de-localization) of the LEs [30]. This quenching effect limits the range of experimentally feasible temperatures to about 60 K, particularly for monolayer WSe₂. Within this limit we were able to accurately determine the efficiency of optical orientation of the LE and to study its field dependence.

As shown in figures 3(b) and (d), the characteristic dip in η(B) is present also at elevated temperatures. Still, its amplitude is gradually reduced upon increasing the temperature. We note that at the same time the overall optical orientation efficiency (defined by the level at B > 100 mT) also decreases. Yet, the disappear-
The quenching of the dip amplitude is similar in both analyzed materials. Notably, the reduction of the dip to half of its initial relative amplitude occurs at comparable temperature (about 25 K for monolayer WSe₂ versus 20 K for monolayer WS₂).

The main complication associated with an analysis of the FIPE amplitude is a possible opening of other relaxation channels for the intermediate dark states when increasing the temperature. Much more reliable is the second characteristic of the dip observed in the optical orientation efficiency, namely its width. Temperature dependence of the extracted width (half width at half maximum, HWHM) is plotted in figures 5(a) and (b) and evidences a qualitatively different behavior of WSe₂ and WS₂ monolayers. Within the experimental accuracy the latter system exhibits a constant width of the dip in the η(B) dependence, while for WSe₂ the dip becomes clearly broader upon increasing the temperature. This observation can be confirmed directly by comparing the magnetic field dependence of the optical orientation efficiency at low (6.5 K) and elevated (30 K) temperature, which is shown in figures 5(c) and (d).

Our interpretation of the observed behavior is related to the temperature variation of the underlying relaxation processes. In general, the width of the dip in the optical orientation efficiency reflects the magnetic field which slows down the inter-valley relaxation of the dark excitons to the time scales of the competing localization process. In principle both of these rates may depend on the temperature, but in view of large value of the localization energy in comparison with $k_B T$ in the studied range we neglect the temperature dependence of the localization rate. On the other
hand, more significant changes are expected to occur in the case of the inter-valley relaxation rate. This expectation is based on remarkably low efficiency of the invoked relaxation, which is directly inferred from a tiny magnetic-field-width of the dip in polarization degree of the localized excitons emission. In fact, such a width corresponds to a zero-field splitting between the two intermediate dark states of a few μeV, which is thus much smaller than recently reported splitting of at least 0.5 meV between the two dark ground states of the exciton in WSe$_2$ [22, 31] that are coupled by short-range exchange interaction [32, 33]. This finding indicates that the mechanism behind the inter-valley scattering of the dark states responsible for the FIPE effect must have different nature. Regardless of its microscopic origin, in view of its low efficiency, it is conceivable to assume that the scattering processes at larger wave vectors $k$ may significantly contribute to this relaxation, thus increasing its rate. Naturally, in the light of current knowledge we cannot provide any quantitative formula describing the invoked $k$-dependence. Nonetheless, on a qualitative level, the discussed rise of the inter-valley scattering rate is similar to the one known for the bright exciton in monolayers of TMDs, the inter-valley scattering of which scales as the square of the wave vector, $k^2$ [34]. Assuming the same $k$-dependence of the inter-valley scattering for the particular dark state responsible for the FIPE effect (possibility due to the presence of some bright state admixture in this dark state), we come to the conclusion that the rate of this scattering should increase accordingly, as higher and higher magnetic field is required to counteract the increase in the inter-valley relaxation rate.

The scenario described above is fully consistent with the data obtained for monolayer WSe$_2$ (figure 5(a)), but does not agree with the results for monolayer WS$_2$ (figure 5(b)), despite that a similar temperature dependence of the dark exciton inter-valley relaxation rate is expected in both cases. A possible explanation of this inconsistency is different relation between the rates of the discussed processes. If the localization rate outpaces the inter-valley relaxation rate even at $B = 0$ then the width of the dip will not correspond to slowing down of the latter one to the value of the former one. Instead, the width of the dip would correspond to the magnetic field which reduces the inter-valley relaxation to a given fraction (say, by factor of 2 at HWHM), independent of the threshold value of the localization rate.

The presented reasoning can be illustrated in a simple way with the following equations. In the model sketched in figure 1 the valley polarization degree of the localized exciton varies with time as

$$\eta_{DE} = \eta_\infty e^{-\gamma_{inter} t}. \quad (1)$$

However, the quantity relevant for the experiment is the final (i.e. after the localization but before the recombination) polarization degree of the localized excitons, which can be obtained by integrating separately each of the dark exciton populations with a decay rate $\gamma_{relax}$. In these calculations we neglect inter-valley scattering processes that take place at the level of localized excitons, in accordance with the results obtained in previous studies of s-TMDs.
monolayers \[11, 18, 23\]. Within these assumptions we obtain the expected degree of polarization of the photoluminescence:

\[
\eta = \frac{\eta_\infty}{1 + \gamma_{\text{inter}}/\gamma_{\text{relax}}}.
\]

(2)

Assuming that \(\gamma_{\text{inter}}\) is the only variable parameter, we can derive the relation between its value at HWHM of the dip and at \(B = 0\):

\[
\eta_{1/2} = \frac{1}{2} \left( \eta_0 + \eta_\infty \right)
\]

(3)

\[
\eta_\infty = \frac{1}{2} \left( \frac{\eta_\infty}{1 + \gamma_{\text{inter}}/\gamma_{\text{relax}}} \right) + \eta_0
\]

(4)

and therefore:

\[
\gamma_{\text{inter}},1/2 = \frac{\gamma_{\text{inter}},0}{2 + \gamma_{\text{inter}},0/\gamma_{\text{relax}}},
\]

(5)

Equation (5) clearly shows the two regimes. If \(\gamma_{\text{inter}},0 \gg \gamma_{\text{relax}}\) (case more suitable for monolayer WSe\(_2\)) then \(\gamma_{\text{inter}},1/2 \approx \gamma_{\text{relax}}\). The magnetic field needed to suppress growing \(\gamma_{\text{inter}},0\) to the threshold of \(\gamma_{\text{relax}}\) is larger and larger, hence the increasing dependence in figure 5(a). Conversely, if \(\gamma_{\text{inter}},0 \ll \gamma_{\text{relax}}\) (case applicable to monolayer WS\(_2\)) then \(\gamma_{\text{inter}},1/2 \approx \gamma_{\text{inter}},0/2\). Standard mechanisms of Dyakonov-Perel type predict that \(\gamma_{\text{inter}}(B) = \gamma_{\text{inter}},0(B)\), where the shape function \(f(x)\) is not related to the \(\gamma_{\text{inter}},0\) value itself. In such a case, the magnetic field required to reduce \(\gamma_{\text{inter}}\) to the half of its initial value is constant (independent of \(\gamma_{\text{inter}},0\)), which explains the behavior illustrated in figure 5(b).

4. Discussion

In our considerations we neglected a number of additional effects, such as the influence of other relaxation pathways (e.g. including the bright excitons) or temperature dependence of the localization or delocalization rate. Similarly, our working assumptions of \(\gamma_{\text{inter}},0 \gg \gamma_{\text{relax}}\) or \(\gamma_{\text{inter}},0 \ll \gamma_{\text{relax}}\) should be regarded as serving illustrative purposes only, since the actual difference between these rates might be less pronounced.

The presented model satisfactorily explains the experimental data concerning the temperature dependence of the width of the dip in optical orientation efficiencies for both studied materials. However, it fails to reproduce the temperature variation of the dip amplitude. Indeed, the model predicts that the dip amplitude should increase upon rising the temperature, which is just opposite to the behavior observed in the experiment. Notably, this discrepancy cannot be simply fixed by adjusting any of the model parameters. The underlying reason for that may be simply identified based on the comparison of the two characteristics of the polarization dip. In fact, the rise of its width (see figure 5(a)) clearly indicates that the dark exciton inter-valley scattering speeds up at elevated temper-atures, which in turn should lead to a decrease of the zero-field polarization degree of the localized excitons emission, and thus increase of the dip amplitude. One possible way of solving this puzzle would be to assume that the population of LEs is fed not only by the relaxation of the dark excitons, but also by some field-independent processes, the contribution of which is getting to be more important at higher temperatures. Such additional processes may significantly alter the temperature evolution of the dip amplitude without affecting previously predicted behavior of its width.

The presented understanding of the qualitative difference between the WSe\(_2\) and WS\(_2\) monolayers in regard of the temperature variation of the width of polarization dip was based on the assumption of different relation between the rates of inter-valley scattering and localization of the dark excitons in the two materials. However, it should be noted that this difference may also have deeper origin being related to the multitude of dark states existing in monolayers of s-TMDs. In principle, each of these states may act as an intermediate state in the process of formation of the localized excitons in both materials. In fact, recent studies report significant fine structure splitting for the dark ground-exciton state \[22, 31\]. Such regime does not exclude the possibility of FIPE effect \[35\]. However, splitting of that magnitude which would quench the valley polarization within single picoseconds, while according to our time-resolved measurements \[18\], the processes underlying the FIPE effect need to occur on 100 ps timescale, regarding the localization as well as the inter-valley relaxation. Discussed difficulties clearly show that deeper understanding of the FIPE effect requires further studies. For instance, the dark intermediate state being responsible for the FIPE effect most probably involves another type of dark exciton rather than its ground state. Moreover, it is fully conceivable that in one material the role of this intermediate state is played by the neutral dark exciton, while in the other - by the dark trion \[27, 29\]. Qualitatively distinct properties of these two states would be yet another plausible explanation of the difference in figures 5(a) and (b). Recently developed techniques allowing for optical studies of such dark states either under oblique geometry of the setup \[27, 28\] or upon application of in-plane magnetic field \[22, 29\] may aid in identification of the nature of the intermediate in each of the compounds.

5. Summary

In summary, we have shown that the application of a small magnetic field significantly enhances the efficiency of optical orientation not only in WSe\(_2\) but also in WS\(_2\) monolayers. Thus, we confirm our original hypothesis that the B-enhanced optical orientation is characteristic of s-TMD monolayers in which the energetically lowest excitonic state is dark (optically inactive in the first approximation). The amplitude
of this enhancement is observed to be suppressed by temperature for both WSe$_2$ and WS$_2$ monolayers. In particular, the B-enhanced optical orientation becomes hardly detectable at temperatures above 50K. The characteristic range of magnetic fields where the enhancement is observed is however found to expand with temperature in monolayer WSe$_2$ whereas is independent of temperature in monolayer WS$_2$. This distinct behavior is interpreted in terms of different regimes for the respective rates for intervalley relaxation and decay of dark excitons. We anticipate that the intervalley relaxation of dark excitons is fast as compared to their decay in monolayer WSe$_2$ while the opposite relation holds for monolayer WS$_2$. Our observation undoubtedly requires further investigation that will provide it with not only phenomenological but also theoretical explanation.

Acknowledgments

The work was supported by the ATOMOPTO project carried out within the TEAM programme of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund, National Science Centre, Poland under project no. DEC-2015/17/B/ST3/01219, the European Research Council (MOMB project no. 320590), and the European Graphene Flagship (No. 604391). One of us (TS) was supported by the Polish National Science Centre through PhD scholarship grant DEC-2016/20/T/ST3/00028.

ORCID iDs

T Smoleński https://orcid.org/0000-0002-4706-7777
T Kazimierczuk https://orcid.org/0000-0001-6545-4167
M Goryca https://orcid.org/0000-0001-7582-1880
M R Molas https://orcid.org/0000-0002-5516-9415
P Kossacki https://orcid.org/0000-0002-7558-1044

References

[1] Novoselov K S, Geim A K, Morozov SV, Jiang D, Zhang Y, Dubonos SV, Grigorieva IV and Firsov A A 2004 Science 306 666–9
[2] Osada M and Sasaki T 2012 Adv. Mater. 24 210–28
[3] Xu M, Liang T, Shi M and Chen H 2013 Chem. Rev. 113 3766–98
[4] Mas-Ballestre R, Gomez-Navarro C, Gomez-Herrero J and Zamora F 2011 Nanoscale 3 20–30
[5] Kopierski M, Molas M R, Arora A, Nogajewski K, Slobodeniuk A O, Faugeras C and Potemski M 2017 Nanophotonics 6 1289
[6] Wang G, Chernikov A, Glazov M M, Heinz T F, Marie X, Amand T and Urbaszek B 2017 (arXiv: 1707.05863)
[7] Xiao D, Liu G B, Feng W, Xu X and Yao W 2012 Phys. Rev. Lett. 108 196802
[8] Cao T et al 2012 Nat. Commun. 3 887
[9] Zeng H, Dai J, Yao W, Xiao D and Cui X 2012 Nat. Nanotechnol. 7 490
[10] Mak K F, He K, Shan J and Heinz T F 2012 Nat. Nanotechnol. 7 494
[11] Yang L, Sinitsyn N, Chen W, Yuan J, Zhang J, Lou J and Crooker S 2015 Nat. Phys. 11 830
[12] Jones A M et al 2013 Nat. Nanotechnol. 8 634–8
[13] Hill H M, Rigosi A F, Robert C, Amand T, Marie X, Reichman D R, Hybertsen M S, Brus L E and Heinz T F 2015 Nano Lett. 15 2992–7
[14] Ye Z, Cao T, O’ Brien K, Zhu H, Yin X, Wang Y, Louie S G and Zhang X 2014 Nature 513 214
[15] Lagarde D, Bouet L, Marie X, Zhu C R, Liu B L, Amand T, Tan P H and Urbaszek B 2014 Phys. Rev. Lett. 112 047401
[16] Amani M et al 2015 Science 350 1065–8
[17] Lezama I G, Arora A,UBLdini A, Barreto S, Giannini E, Potemski M and Morpurgo A F 2015 Nano Lett. 15 2336–42
[18] Smoleński T, Goryca M, Kopierski M, Faugeras C, Kazimierczuk T, Bogucki A, Nogajewski K, Kossacki P and Potemski M 2016 Phys. Rev. X 6 021024
[19] Yu T and Wu M W 2014 Phys. Rev. B 89 205303
[20] Kosmider K, González J W and Fernández-Rossier J 2013 Phys. Rev. B 88 245436
[21] Echeverry J P, Urbaszek B, Amand T, Marie X and Gerber I C 2015 Phys. Rev. B 91 121107
[22] Molas M R, Faugeras C, Slobodeniuk A O, Nogajewski K, Bartos M, Basko D M and Potemski M 2017 2D Mater. 4 021003
[23] Wang G, Bouet L, Lagarde D, Vidal M, Balocchi A, Amand T, Marie X and Urbaszek B 2014 Phys. Rev. B 90 075413
[24] Jadczak J, Kutrowska-Girzycka J, Kaucic F, Huang Y S, Wójc A and Bryja J 2017 Nanotechnology 28 395702
[25] Mak K F, He K, Lee C, Lee G H, Hone J, Heinz T F and Shan J 2013 Nat. Mater. 12 207–11
[26] Plechinger G, Nagler P, Kraus J, Paradiso N, Strunk C, Schfiller C and Korn T 2015 Phys. Status Solidi RRL 9 457–61
[27] Zhou Y et al 2017 Nat. Nanotechnol. 12 856–60
[28] Wang G et al 2017 Phys. Rev. Lett. 119 047401
[29] Zhang X X et al 2017 Nat. Nanotechnol. 883–8
[30] Godde T et al 2016 Phys. Rev. B 94 165301
[31] Robert C, Amand T, Cadiz E, Lagarde D, Courtade E, Manca M, Taniguchi T, Watanabe K, Urbaszek B and Marie X 2017 Phys. Rev. B 96 155423
[32] Slobodeniuk A O and Basko D M 2016 2D Mater. 3 035009
[33] Dery H and Song Y 2015 Phys. Rev. B 92 125431
[34] Glazov M M, Ivchenko E L, Wang G, Amand T, Marie X, Urbaszek B and Liu B L 2015 Phys. Status Solidi b 252 2349–62
[35] Dzhioev R I, Gibbons H M, Ivchenko E L, Khitrova G, Korenev V L, Tkachuk M N and Zakharchysna B P 1997 Phys. Rev. B 56 13405–13