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To cite this version:

A. Delhomme, G. Butseraen, B. Zheng, Läetitia Marty, V. Bouchiat, et al.. Magneto-spectroscopy of exciton Rydberg states in a CVD grown WSe2 monolayer. Applied Physics Letters, 2019, 114 (23), pp.232104. 10.1063/1.5095573 . hal-02154702

HAL Id: hal-02154702

https://hal.science/hal-02154702v1

Submitted on 24 Aug 2023

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Applied Physics Letters ARTICLE scitation.org/journal/apl

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Cite as: Appl. Phys. Lett. **114**, 232104 (2019); doi: 10.1063/1.5095573
Submitted: 11 March 2019 · Accepted: 16 May 2019 ·
Published Online: 12 June 2019

View Online Export Citation CrossMark

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ABSTRACT

The results of magneto-optical spectroscopy investigations of excitons in a CVD grown monolayer of WSe_2 encapsulated in hexagonal boron nitride are presented. The emission linewidth for the 1s state is of 4.7 meV, close to the narrowest emissions observed in monolayers exfoliated from bulk material. The 2s excitonic state is also observed at higher energies in the photoluminescence spectrum. Magneto-optical spectroscopy allows for the determination of the g-factors and of the spatial extent of the excitonic wave functions associated with these emissions. Our work establishes CVD grown monolayers of transition metal dichalcogenides as a mature technology for optoelectronic applications.

Published under license by AIP Publishing. https://doi.org/10.1063/1.5095573

Monolayers of semiconducting transition metal dichalcogenides (S-TMD), labeled as MX_2, where M = W, Mo, Re, or Zr and X = S, Se, or Te for the most studied compounds, are direct bandgap semiconductors with the bandgap located at the two inequivalent $K^{\pm}$ points of their hexagonal Brillouin zone.[1] They exhibit a large number of properties interesting both for fundamental science and for technology.[2] These properties include a bandgap in the visible range,[3] a strong light matter coupling,[4] the presence of single photon emitters,[5,6] very strong excitonic effects,[7–9] possibilities of tuning the emission energy by Coulomb engineering,[10,11] and the opportunity of combining them to obtain type II band alignment.[12] The spin–orbit interaction in these materials is strong and splits the spin levels in the valence band by few hundreds of millielectron volts and by few tens of millielectron volts in the conduction band.[13] This large splitting in the valence band defines two different excitons at the $K^{\pm}$ points attached to the two spin-split bands, named A and B excitons.[14] Because of the lack of inversion symmetry, the two different valleys can be excited independently using circularly polarized light,[15] opening the possibility of initializing an exciton population in a given valley, or creating coherent superpositions of both valleys.[16]

Best specimens of S-TMD monolayers are usually obtained by the mechanical exfoliation of bulk (natural or synthetic) crystals, which leads to micrometer sized flakes, suitable for scientific investigations or for demonstrating prototype devices, but preventing their use in realistic applications produced at an industrial scale. Growth techniques, mainly chemical vapor deposition (CVD)[17] and molecular beam epitaxy (MBE),[18,19] have been developed to produce large scale monolayers of S-TMD suitable for electronics and optoelectronics applications or to elaborate vertical/horizontal heterostructures.[20,21] In this letter, we demonstrate a CVD grown S-TMD monolayer with optical quality comparable to state-of-the-art exfoliated flakes. For that purpose, we have encapsulated it in between hexagonal boron nitride (h-BN) flakes in order to unveil its intrinsic properties. We show that the optical response of this CVD grown monolayer is comparable to the best exfoliated monolayers in the same environments, and we demonstrate this

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improved optical quality by performing spectroscopy and magnetospectroscopy of the Rydberg states of A excitons.

WSe_2 flakes were grown by chemical vapor deposition (CVD) in a quartz tube furnace on SiO_2. Tungsten diselenide powder was placed at the center of the furnace, and a piece of SiO_2/Si substrate was placed at the downstream of the quartz tube and heated to 1100 °C. Figures 1(a) and 1(b) present two optical photographs of typical flakes produced by CVD before and after encapsulation in hBN, respectively. They extend over typically 50–100 μm. We present in Fig. 1(c) the room temperature Raman scattering response of the monolayer measured with an excitation laser $\lambda_{exc} = 515$ nm. As already reported,[3] the nearly degenerate E^1_{2g} and A_{1g} phonons[22] [atomic displacement patterns shown in the inset of Fig. 1(c)] appear around 250 cm^{-1} with a full width at half maximum (FWHM) of 4.2 cm^{-1}.

We have performed band structure measurements using synchrotron radiation angle resolved photoemission spectroscopy (ARPES) at the Antares beamline (SOLEIL).[23] Figure 1(d) displays the measured band structure around the K valley of WSe_2 on SiO_2. The top of the valence band at the K point is mostly formed by planar d_{xy} and $d_{x^2-y^2}$ orbitals of tungsten, while at the Γ point, the band is mostly composed of W d_{z^2} orbitals and Se p_z orbitals. The observation of a single valence band at Γ with a higher binding energy than at K also excludes the contribution from bilayer or trilayer WSe_2. The maximum of the valence band is located at the K point (−1.14 eV, which is 0.44 eV higher than at the Γ point). The FWHM of the valence bands at the K point is of 75 meV, and the sharpness of the different bands can be attributed to the high quality of the CVD grown flake. The measured spin–orbit splitting at K is about 510 meV, in good agreement with previous reports.[24]

Optical experiments have been performed in a cold finger cryostat using a solid state diode laser at 515 nm and a 50 cm focal length spectrometer equipped with a nitrogen cooled charge couple device (CCD) camera. Reflectance measurements have been performed using a halogen white lamp, and the contrast is calculated using the reflectance spectrum of the structure without the TMD monolayer. Magneto-optical experiments have been performed in a 20 MW resistive magnet using an optical fiber based insert and piezo stages to move the sample below the excitation laser spot. Both experimental setups have a spatial resolution of ∼1 μm. Polarization of the photoluminescence (PL) signals was analyzed using a quarter-wave plate and a linear polarizer. PL experiments essentially probe the low energy A exciton, but it has been shown that in monolayers of S-TMD, exciton excited states, several hundreds of millielectron volts above the exciton ground state, can also give rise to PL emission.[25] Higher energy excitons such as the B exciton are investigated using reflectance spectroscopy or nonlinear optical techniques.[26,27]

The photoluminescence (PL) and reflectance spectra of the as-grown WSe_2 monolayer on SiO_2 are presented as the red and blue curves in Fig. 2, respectively. The PL shows a 40 meV wide A exciton emission at 1.717 meV and a broad band, attributed to exciton complexes (biexciton, trion, etc.) and to localized excitonic states, at lower energy. One can note a pronounced Stokes shift of 15 meV of the PL peak with respect to the resonance measured in reflectivity. As will be shown in the following, the observed linewidth of the exciton feature is highly misleading and does not reflect the intrinsic quality of the material but is more representative of its interaction with the SiO_2 substrate.

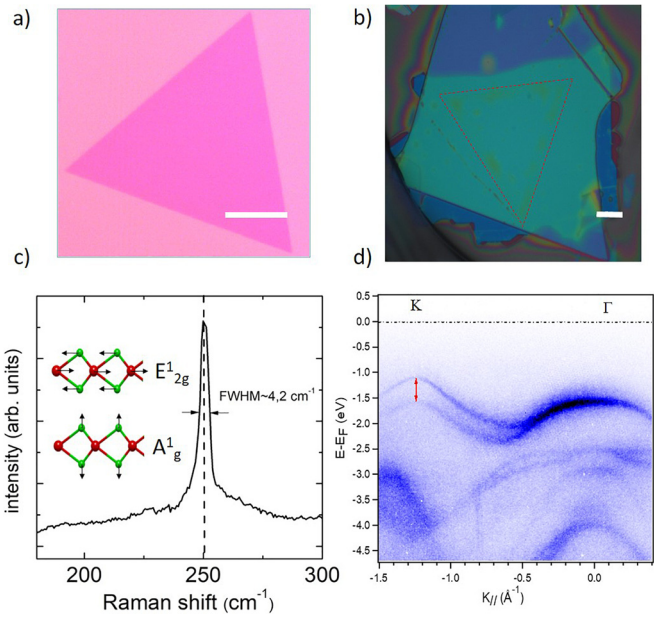

FIG. 1. (a) Optical image of the CVD grown monolayer on a SiO_2 substrate. (b) Optical image of the WSe_2 monolayer encapsulated in h-BN. The WSe_2 monolayer is indicated by the dashed red lines. The scale bars in (a) and (b) are 10 μm. (c) Raman scattering spectrum of the WSe_2 monolayer encapsulated in h-BN and measured with $\lambda_{exc} = 515$ nm. The inset shows the atomic displacements (W atoms in red and Se atoms in green) corresponding to the E^1_{2g} and A_{1g} phonons. (d) ARPES spectrum measured at $T = 77$ K. The high symmetry K and Γ points are indicated and the red double arrow indicates the 510 meV splitting of the valence band at the K point.

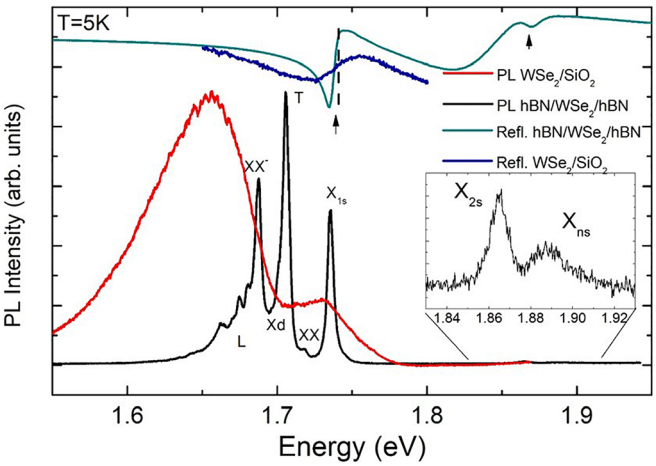

FIG. 2. PL spectrum measured at $T = 5$ K of the WSe_2 flake on a SiO_2 substrate (red solid line) and after encapsulation in h-BN (black solid line). Some excitonic complexes are identified: the biexciton XX, the trion T, the gray exciton (X_d), and the charged biexciton (XX−). The green curve is a reflectance contrast spectrum of the encapsulated flake and the two arrows point at the energy positions of the 1*s* and 2*s* state signatures. The blue curve is the reflectance spectrum of the WSe_2 monolayer on SiO_2. The inset is a zoom on the high energy range where the 2*s* Rydberg state is observed.

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These are the only observable features in the PL spectrum. Excitons are electron-hole pairs bound by Coulomb interaction. They have an internal energetic structure composed of a ground state indexed by a principal quantum number $n = 1$ and a series of excited states $n = 2$, 3, 4,…. The sequence of excited states is defined by the potential acting on the electron-hole pair. In monolayers of S-TMD, it was shown that the potential is a screened Coulomb potential, the Keldysh potential,[28] due to the reduced dimensionality and the high polarizability of the S-TMD monolayer with respect to the dielectric environment.[7,29] These excited states can be observed in the optical response of high quality and neutral monolayers of S-TMDs, i.e., in their reflectance and photoluminescence spectra. To improve the optical quality of the CVD grown WSe_2 monolayer, we have encapsulated it with two thin layers of h-BN using a dry transfer technique.[30] A polypropylene carbonate (PPC) stamp was prepared on a glass slide and was used to pick-up first the top h-BN layer and then the CVD grown WSe_2, and finally this stack was deposited on the bottom h-BN layer on a 300 nm thick SiO_2/Si substrate. As already reported for exfoliated monolayers of S-TMD,[31] we observe profound changes in the emission spectrum of our CVD grown monolayer after encapsulation in h-BN.

These changes are evidenced in Fig. 2 which shows the PL spectrum after encapsulation (black curve): most noticeable is the linewidth of the A exciton 1*s* peak which is strongly reduced down to 4.7 meV, the resonance corresponding to the exciton 1*s* peak in reflectance is red shifted by 4 meV as a result of the change in the dielectric properties of the surrounding environment (SiO_2 and vacuum with respect to h-BN), a new structure is observed at higher energies close to 1.87 eV which we attribute to the 2*s* excited state of the A exciton.[8,9] Finally, the broad band at lower energy acquires a rich structure of discrete peaks associated with[32] the biexciton XX, the singlet and triplet trions T, possibly the dark exciton, the charged biexciton XX−, and finally to localized excitons L. In Fig. 2, we also present a reflectance contrast spectrum of the encapsulated WSe_2 (green curve). The 1*s* and 2*s* resonances are indicated by black arrows and match nicely with the observed peaks in the PL spectrum, confirming our initial assignment. The energy difference between the 1*s* and 2*s* states is of 130 meV, in line with values reported for WSe_2 in a similar dielectric environment.[8,9] Exciton excited states are only visible in the emission spectrum of the encapsulated monolayer and are absent from the spectrum of the monolayer on SiO_2 as a result of the improved optical quality and of the charge neutrality provided by the encapsulation in the clean and inert h-BN layers. Exciton excited states with higher indices are not directly observable in the spectrum, possibly because their energy spacing is smaller than their linewidth. They only appear in the form of a broad feature at energies above the 2*s* emission and labeled *ns* in Fig. 2. A magnetic field should separate them[8,9] and allow for their observation, but, in the present case, their emission is too weak to be detected using our optical fiber based magneto-optical spectroscopy setup.

To confirm the origin of these different peaks in the PL spectrum of our encapsulated CVD grown WSe_2 monolayer, we have performed polarization resolved magneto-PL experiments in the Faraday configuration. When a magnetic field is applied perpendicular to the plane of the WSe_2 monolayer, K^+ and K^- valleys show an opposite energy shift, the valley Zeeman effect.[33–35] This effect is observed in our data as a splitting of the exciton 1*s* peak in opposite polarizations. This effect, presented in Fig. 3, allows for the determination of a

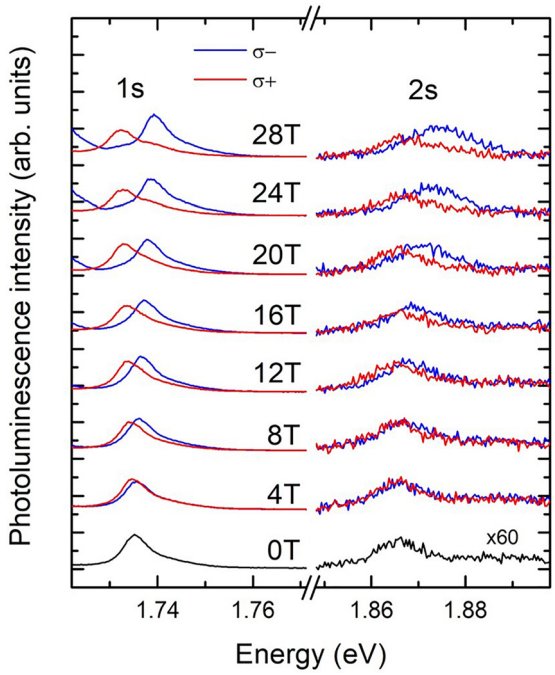

FIG. 3. Polarization resolved photoluminescence spectra at selected values of the magnetic field (red curves for σ^+ and blue curves for σ^- polarizations) for the 1s and 2s (multiplied by 60) states.

fundamental parameter characterizing the exciton, the excitonic Landé factor[8,9,33] $g = -4.3$ for the 1*s* resonance, and is slightly reduced to $g = -4.1$ for the 2*s* resonance.

Finally, different excitonic states are characterized by different spatial extents which will result in distinct quadratic diamagnetic shifts $\Delta E_{dia} = \frac{e^2}{8m_r} < r^2 > B^2 = \sigma B^2$, where m_r is the exciton reduced mass [$m_r = 0.2\ m_0$ (Ref. 8)], and $r = \sqrt{8m_r\sigma}/e$ is the radial coordinate perpendicular to B. Figure 4 shows the energy position of the polarization resolved 1*s* and 2*s* emission peaks as a function of the magnetic field. While the 1*s* peak mainly shows a splitting with a magnitude linear in B related to the valley Zeeman effect, a quadratic B dependence is clearly observed for the 2*s* state. This indicates a much reduced spatial extent for the wave function of the 1*s* state than the one of the 2*s* state. From these measurements, one can extract $\sigma_{1s} \sim 9 \times 10^{-7}$ $(\pm 8 \times 10^{-8})$ eV T^{-2} and $\sigma_{2s} \sim 6.6 \times 10^{-6} (\pm 2 \times 10^{-7})$ eV T^{-2}, corresponding to $r_{1s} \sim 2.7 \pm 0.2$ nm and $r_{2s} \sim 7.7 \pm 0.1$ nm. The radius corresponding to the 1*s* state deduced from our experiment is significantly larger than the one obtained with a similar sample at higher magnetic fields.[8] We speculate that this discrepancy is related to large thicknesses of the h-BN encapsulating layers, 160 nm and 25 nm for our top and bottom hBN layers, respectively, changing the average dielectric constant of the environment of the flake. Additionally, one should consider possible variations of the exciton reduced mass, the value of which also depends on the dielectric environment. The radius corresponding to the 2*s* state can be deduced with more accuracy and it matches the values reported so far for 2*s* states in WSe_2 encapsulated in h-BN. These values are in clear disagreement with expectations for the 2D

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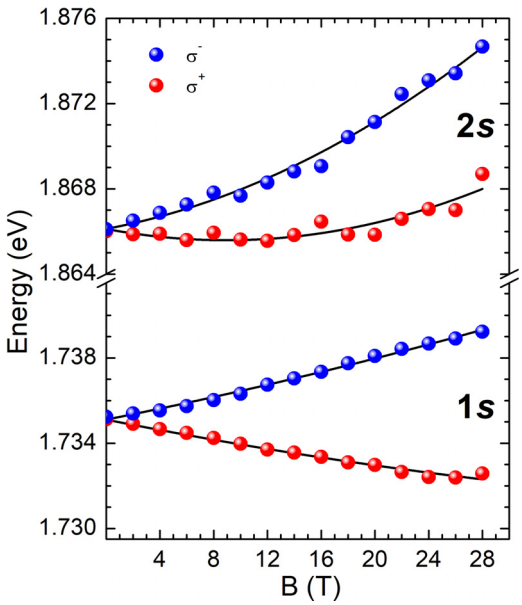

FIG. 4. Central energy position of A exciton 1s and 2s states as a function of the magnetic field for the two $\sigma^{\pm}$ polarizations. The solid black lines are the results of fits including both the valley Zeeman effect and the diamagnetic shift.

hydrogen model[36] and reflect the peculiar electrostatic screening in monolayers of S-TMD.

To conclude, we have demonstrated CVD grown WSe_2 with optical quality reaching the one of the exfoliated samples. This high optical quality is evidenced by a linewidth as small as 4.7 meV once encapsulated in h-BN for the emission from the 1*s* state of A excitons and by the observation of emissions from the 2*s* state and from higher index states. Magneto-optical spectroscopy confirms the origin of these emissions by allowing the measurement of their g-factor and of their diamagnetic shift. Our work shows that CVD grown monolayers of S-TMD are promising candidates for optoelectronic applications requiring large scale growth of materials.

This work was partially supported by the EU Graphene Flagship Project (Project No. 785219), by the French National Research Agency (ANR) in the framework of the J2D Project (No. ANR-15-CE24-0017), grants Labex Nanosaclay (No. ANR-10-LABX-0035) and RhomboG (No. ANR-17-CE24-0030), and in the framework of the Investissements d'Avenir Program (No. ANR-15-IDEX-02), and by the National Natural Science Foundation of China No. 51525202. Growth of hexagonal boron nitride crystals was supported by the Elemental Strategy Initiative conducted by the MEXT, Japan and the CREST (No. JPMJCR15F3), JST. We thank the Nanofab group at Institut Néel for help with the van der Waals heterostructure preparation setup.

We thank Dr. Jose Avila and Maria C. Asencio for the ARPES experiments.

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