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Anomalous behavior of the excited state of the A exciton in bulk WS$_2$

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Results of optical spectroscopy studies on bulk 2H-WS$_2$ at energies close to its direct band gap are presented. Reflectance and absorption measurements at low temperature show only one dominant feature due to the A exciton of bulk WS$_2$ at $\sim$2.02 eV. However, a laser-modulated photoreflectance spectrum looks quite different, revealing a second even stronger feature $A^*$ $\sim$ 62 meV above A. The relative intensity of these two features is shown to change significantly in a lateral electroreflectance measurement with electric field applied perpendicular to the c axis of WS$_2$. The experimental results are analyzed by comparison with many-body perturbation theory calculations, including the solutions of the Bethe-Salpeter equation. $A^*$ is identified as the first excited state of the A exciton, that is, $A(n = 2)$. The anomalous behavior of $A^*$ is explained by its distinct wave function spread along the c axis, the direction of weak van der Waals bonding, which makes it more susceptible to perturbations. Our ab initio calculations suggest that the A exciton in the ground state has a two-dimensional (2D) nature with a large binding energy $E_b$, in fair agreement with $E_b$ $\sim$90 $\pm$ 20 meV estimated from a temperature-dependent reflectance study. The applicability of the 2D hydrogenic Wannier-Mott model for the exciton spectrum of a layered semiconductor like bulk WS$_2$ is discussed.

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I. INTRODUCTION

Recent studies on transition-metal dichalcogenide (TMDC) semiconductors [1] such as WS$_2$ are motivated by the discovery of novel properties in them that also hold promise for future electronic device applications. These layered materials, held together by weak van der Waals forces perpendicular to the layers, can exist in stable monolayer form. One finds that WS$_2$ in the monolayer two-dimensional (2D) form is a direct band gap semiconductor [2], although it has an indirect band gap in bulk crystal form. The monolayer shows a strong coupling of spin and valley degrees of freedom [3] and has very large exciton binding energy $E_b$ in monolayer WS$_2$ also makes it interesting for room-temperature exciton-polariton condensation studies and related applications [6]. The properties of excitons in these materials [7] in general seem quite different from conventional direct band gap group-III-V semiconductors. It has been shown that due to the rapid change in the dielectric environment across a monolayer, the energy spectrum of excitons can be dramatically different from what one expects from a 2D hydrogenic Wannier-Mott exciton model [8]. Earlier, it was thought that even in bulk TMDC crystals, excitons may have 2D character [9] originating from the large anisotropy in their properties between directions parallel and perpendicular to the layers, the latter defining the c axis. Recent studies also support this. For instance, exciton polarizability measurements show layer-independent behavior, indicating strong localization of electron and hole wave functions in individual layers of a multilayer sample [10]. Two-dimensional behavior of excitons in bulk has also been inferred from analyzing the optical absorption spectrum [11] and theoretical studies [12]. As such the electronic band structure around the fundamental band gap in a semiconductor determines the device characteristics. In monolayer WS$_2$ this gap, around which the excitons arise, is at the $K$ point of the Brillouin zone [13], which is also where the direct band gap arises in bulk WS$_2$ [14]. For all these reasons it is important to understand the electronic structure and exciton spectrum around the direct band gap of bulk WS$_2$.

Absorption studies on bulk WS$_2$ around its direct band gap show two dominant peaks, labeled $A$ and $B$, which arise from ground-state exciton transitions involving two spin-orbit split valence and conduction bands at the $K$ point of the Brillouin zone [14]. The lower-energy $A$ feature defines the direct excitonic band gap. These materials have two main allotropic crystal forms, 2H and 3R, the former being more common. It was thought that the exciton spectrum in the 3R form follows the 2D hydrogenic model and was three-dimensional-like in 2H [9]. A very weak feature seen between $A$ and $B$ in 3R-WS$_2$ was early on attributed [15] to the first excited-state transition of $A$, that is, $A(n = 2)$ in a 2D hydrogenic model. Other studies on similar materials such as bulk 2H-MoS$_2$ also showed additional features at energies between the $A$ and $B$ features which were also attributed to higher excited-state exciton transitions, but these identifications could not be reconciled fully with conventional hydrogenic exciton models [16]. Recent studies [17] have suggested that these weak features in 2H-MoS$_2$ could be altogether different exciton transitions at the $H$ point of the Brillouin zone of bulk 2H-MoS$_2$, but the matter is not settled. Such weak features in 2H-WS$_2$ at energies above the $A$ exciton feature have also been reported in recent reflectance contrast and modulated reflectance spectroscopy studies, but
there are competing claims of them being either $A(n = 2)$ or $H$-point transitions [18–20]. Here we present results of a study on bulk 2H-WS$_2$ around its direct band gap combining several complementary optical spectroscopy techniques. We show that an extra spectral feature, even stronger than the $A$-exciton feature, can arise in a photomodulated reflectance spectrum of bulk 2H-WS$_2$. We try to verify its origin through additional direct electromodulated reflectance measurements, spectral line shape analysis, and comparison with many-body perturbation-theory-based band structure calculations as well as two-particle excitations based on solving the Bethe-Salpeter equation. Temperature-dependent reflectance studies are used to verify the theoretically estimated $E_b$ values. Finally, we discuss the implication of these results for the hydrogenic model for excitons in bulk 2H-WS$_2$.

II. EXPERIMENTAL DETAILS

The C-plane-oriented 2H-WS$_2$ flakes, obtained from HQ-Graphene, were cleaned by exfoliation and transferred onto sapphire substrates. Their 2H crystal structure was verified using x-ray diffraction [21]. Sapphire was chosen as a substrate because its high thermal conductivity enabled efficient cooling of the sample; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements. The samples were cooled using a continuous-flow liquid-He cryostat with optical access. Measurements above room temperature were performed in a vacuum chamber; also, being transparent and insulating, it aided transmission and lateral electroreflectance (LER) measurements.

III. EXPERIMENTAL RESULTS

Figures 1(a) and 1(b) show the reflectance $R$ and absorption $\alpha$ spectrum of bulk 2H-WS$_2$ at 5 K. We have simulated the $R$ spectrum by considering the exciton contribution to the dielectric function $\varepsilon(E)$ as a function of energy $E$ as given by the Lorentz oscillator model [22]

$$\varepsilon(E) = \varepsilon_\infty + \sum_j \frac{C_j}{E_{0j}^2 - E^2 - i\Gamma_j E}.$$  (1)

Here $n_\infty$ and $k_\infty$ represent the real and imaginary parts of the background refractive index. $E_{0j}$ and $\Gamma_j$ are the transition energy and broadening parameter, while $C_j$ is a parameter proportional to the oscillator strength of the $j$th exciton transition. We find that by considering a single transition we are able to fairly reproduce the measured spectrum with $E_0 = 2.012$ eV. Also the absorption spectrum shows one dominant feature at 2.018 eV. These features arise from the ground-state $A$ exciton transition in bulk WS$_2$ [14]. The $B$ exciton transition is at a much higher energy of 2.433 eV [21]. We also studied the evolution of the $A$ exciton resonance in $R$ as a function of temperature, which we shall show and discuss later. Figure 1(c) shows the PR spectrum of the sample where in addition to the $A$ feature one finds a stronger feature labeled $A^*$. To estimate the transition energies in PR we have fitted to these feature Aspnes’s derivative functional form line shape function. We used a modified set of fitting parameters [21] which makes it easier to fit and compare feature strengths [23]. The transition energies for $A$ and $A^*$ in PR were found to be 2.017 and 2.082 eV, respectively, with the strength of $A^*$ being ~1.7 times larger than that of $A$. Figure 1(d) shows the LER spectrum of a sample where, again, one finds the extra $A^*$ feature, although now much reduced in strength. Again fitting Aspnes’s line shape function, the transition energies of $A$ and $A^*$ in LER were found to be 2.022 and 2.080 eV, respectively, with the strength of $A^*$ about 1/6.7 (15%) that of $A$. The measurement-technique-dependent differences in estimated $E_0$ values, which have been seen before in other [17] systems, are small and can be neglected here. Thus in bulk WS$_2$ there is another transition $A^*$ which is 62 ± 3 meV above the $A$ exciton transition. If $A^*$ corresponds to the $A(n = 2)$ transition of a conventional 2D hydrogenic model [4], then...
its oscillator strength, which goes as $1/(n - 0.5)^3$, should be $1/27 (3.7\%)$ that of $A$. The fact that it is larger than $A$ in PR and then becomes relatively much weaker in LER is clearly an anomalous behavior. To understand this we further explore the PR and LER results through simulations.

In modulation spectroscopy measurements like PR and LER, typically, there is a change in the net electric field which affects the exciton. In the case of PR the electric field change is due to the separation of laser-generated free electrons and holes, which reduces the built-in fields at the surface/interfaces of a semiconductor and in the case of LER directly due to the separation of laser-generated free electrons and holes, which reduces the built-in fields at the surface/interfaces. In modulation spectroscopy measurements like PR and LER, the consequent change in an $R$ spectrum arises from the separation of laser-generated free electrons and holes, which reduces the built-in fields at the surface/interfaces of a semiconductor and in the case of LER directly due to the separation of laser-generated free electrons and holes, which reduces the built-in fields at the surface/interfaces.

The direct gap at $K$ is a local potential minimum for carriers in the CB1 plane. In the CB1 plane, we find that it is a local potential minimum for carriers in the CB1 plane. The minimal direct gap of 2.07 eV is observed exactly at the $K$ point. In comparison to DFT (LDA) where the gaps were 0.97 eV (indirect) and 1.61 eV (direct), the gaps are distinctly larger in $GdW$, which reveals its many-body nature and shows reasonable agreement with previous results [29]. Focusing on the $H$ point, we find that the gaps are 0.97 eV (indirect) and 1.61 eV (direct), the gaps are distinctly larger in $GdW$, which reveals its many-body nature and shows reasonable agreement with previous results [29].

The direct gap at $H$ is 2.11 eV in $GdW$ (1.67 eV in LDA), and thus the difference relative to the gap at $K$ is 40 meV (60 meV in LDA). We note that all states/bands are doubly degenerate and the bands can be roughly attributed to only one layer [e.g., for the valence band (VB) the contribution from farther layers is less than 6%]. At the $K$ point carriers in the lowest-energy conduction band CB1 and next-higher-energy CB2 have opposite spins, which is also true for valence bands.
Next, we investigate the optical properties by including electron-hole interactions and solving the BSE [28]. We include four VBs and eight CBs, that is, two VBs and four CBs per layer. While the $GW/GdW$ calculations already require a fine mesh, the convergence of BSE results is typically even more demanding. All meshes in our calculation include the $K$ and $H$ points, and we have verified the convergence of exciton energy and oscillator strengths [21]. We find three optically bright excitons at energies close to the direct band gap [Fig. 4(a)]. We label them $X_1$, $X_2$, and $X_3$, wherein the lowest-energy $X_1$ exciton at 2.018 eV is by far the strongest ($X_2/X_1$ strength $\sim5\%$ and $X_3/X_1$ strength $\sim0.5\%$). $X_2$ and $X_3$ lie about 60 and 80 meV above $X_1$, respectively. We ignore $X_3$ hereafter given its weak strength, which makes it practically undetectable in experiment.

All exciton states have a degeneracy of 2 due to the degenerate bands and another 2 due to symmetry of $\pm K$. Further insights into the properties of the excitons can be gained from their band contributions and their localization and extent in $k$ space as well as in real space. As for band contributions, $X_1$ and $X_2$ show similar characteristics. We find that the transitions stem mostly from the highest valence band VB1 to the second-lowest conduction band CB2 [see labels in Fig. 3(a)]. The possible lowest-energy direct transition, involving CB1 and VB1, is optically dark, similar to the case of monolayer WS$_2$, MoS$_2$, and WSe$_2$ [30–33]. The CB1-CB2 splitting is about 30 meV at the $K$ point, making the VB1-CB2 direct “bright” band gap $\sim2.10$ eV. Since the $X_1$ exciton at 2.018 eV stems mostly from VB1 and CB2, its theoretical binding energy, relative to the gap of 2.10 eV, becomes $E_b \sim 85$ meV.

Significant contributions to both excitons $X_1$ and $X_2$ are only found along the $K-H$ line [21] centered around the $k_z = 0$ plane, that is, at the $K$ point. For $X_1$ the $k_z$ contributions decrease away from $k_z = 0$, while for $X_2$ the contribution becomes more complex and shows a node on this line (two nodes for $X_3$, etc.). This means that we can identify $X_2$ as the first excited state ($n = 2$ of a Rydberg-like series), which is not particularly located around the $H$ point. Indeed, we find no low-energy bright exciton that is prominently located at the $H$ point.

In addition to the properties in reciprocal space it is also instructive to look at the exciton’s spread in real space. To visualize the six-dimensional (three dimensions of the electron, three of the hole) exciton wave function we fix the hole in one layer and calculate the electron probability $|\Psi|^2$. To illustrate its distribution we integrate over the remaining directions. Figures 4(b) and 4(c) show such plots for the $X_1$ and $X_2$ excitons in the real-space $x-z$ plane. We find that for $X_1$ the electron is mostly confined to the same layer as the hole. $X_2$ is quite different in that, close to the hole, only a small contribution is found in the same layer, while a maximum is observed in the next but one layer along $z$. Thus $X_1$ is much more spread out along the $z$ axis (i.e., $\parallel c$) compared to $X_1$.

### V. Discussion

The similarity of the energy and strength of the bright $X_1$ exciton around the $K$ point as found above clearly identifies it with the $A$ exciton seen in our measurements. Although the $H$-point and $K$-point band gap difference is similar to the $A$-$A^*$ energy separation, there are no indications of any low-energy excitons predominantly located at the $H$ point in the calculations. This is essentially due to the absence of a potential minimum for carriers at the $H$ point along all $k$ directions. Given that the energy separation of $X_1$ and $X_2$ matches that of $A$ and $A^*$ and also that $X_2$ is much weaker than $X_1$, much like the barely seen $A^*$ in the $R$ spectrum, we identify $A^*$ with $X_2$. We note that the agreement between experiment and theory is surprisingly good. Since $X_1$ and $X_2$ originate from the same bands, $A^*$ can be considered an excited-state $A(n=2)$ transition. The simulated absorption spectrum in Fig. 1(b) considered two exciton transitions, with their relative oscillator strengths and energy spacing determined by $X_1$ and $X_2$ above, plus a step function to account for band-to-band transition beyond the band gap, and is convolved with a Gaussian to account for broadening. It agrees fairly well with the measurement. The above identification of $A^*$ as the effective $A(n=2)$ gives a clue to the relative strengths of the $A$ and $A^*$ features in PR and LER measurements as follows.

The crystal is held together in the direction $\parallel c$ axis of WS$_2$, mostly by weak van der Waals forces, and the wave function for the $A(n=2)$ exciton state has a considerable spread along this direction, unlike that for $A$, as seen in Figs. 4(b) and 4(c). Thus a perturbation in general is likely to modulate $A(n=2)$ much more than $A$. If the perturbation is an electric field $\parallel c$, then $A(n=2)$ will be modulated even more strongly. In PR the laser is incident $\perp c$, and its absorption will change the built-in field along this direction, as shown in the inset of Fig. 2(b). Thus in PR we should get very strong modulation of $A(n=2)$. However, if the field change is $\perp c$, then it may not affect $A(n=2)$ as much. In fact, it is to test this idea that we performed the LER measurements where the field change, as indicated in the inset of Fig. 2(c), is mostly $\perp c$. We saw
that in LER the total modulation strength for $A^*$, although still larger than that for $A$, is considerably reduced relative to its value in PR, clearly supporting this idea. We note in passing that we have not observed any indication of a bright interlayer exciton (as, for example, in MoTe$_2$ [19] and MoSe$_2$ [34]) in bulk WS$_2$ in our theoretical calculations. An interlayer exciton would also have been subjected to strong modulation for field changes parallel to the $c$ axis; however, we see no additional feature in PR other than the one identified as $A(n = 2)$ here.

We next investigate the theoretically predicted large $E_b$ value. As mentioned earlier, the VB1-CB1 transition is optically dark, and the A exciton transition involves carriers in VB1-CB2 with $E_b \sim 85$ meV. We tried to experimentally estimate $E_b$ using the decay of the exciton oscillator strength with an increase in temperature by studying the temperature dependence of the $R$ spectrum, as shown in Fig. 5(a). The oscillator features seen in Fig. 5(a) at subband gap energies are due to optical interference effects and have been ignored in the analysis. Consider that once an exciton is thermally excited to the continuum edge, the electron and hole are free to move independently in the lattice, get trapped by defects, and recombine nonradiatively, thereby leading to a loss of excitons. This would result in a reduced value of $C$ in Eq. (1) which is proportional to the oscillator strength, in effect the number of excitons. In the simplest analysis considering this to be a two-level system, neglecting other excited states since their oscillator strengths are negligible compared to the ground state, one can write the probability $p$ of excitation to the continuum state from the ground state at temperature $T$ as $p = \exp(-E_b/k_BT)$, where $k_B$ is the Boltzmann constant. Then the number of excitons that remain in the ground state is proportional to $1 - p = 1 - \exp(-E_b/k_BT)$, and the value of $C$ should be proportional to this. We have simulated the exciton-dominated part of the $R$ spectrum at different temperatures by varying the parameters in Eq. (1) to match the measured spectrum. The values of $C$ thus obtained are plotted in Fig. 5(b). One finds that although there seems to be a significant decrease in the $A$ exciton feature’s strength with an increase in temperature, the value of $C$ actually does not decay much. The changes occur mainly due to a large increase in the broadening parameter $\Gamma$ from 18 meV at 5 K to about 90 meV at 575 K, as shown in the inset of Fig. 5(a). The weak decay of $C$ indicates a fairly large $E_b$.

However, there are large uncertainties in the estimated $C$ values arising from the accuracy of spectral response (magnitude) corrections and the fact that $C$ and $\Gamma$ values are correlated; an increase in one can nullify the effect of the increase in the other. The simulated lines in Fig. 5(b), based on the above thermal decay model, indicate that $E_b \sim 90 \pm 20$ meV, which is close to the theoretical estimate of 85 meV, although one must note that the experimental error bars are large. Thus the “bright” band gap of bulk 2H-WS$_2$ obtained through experiment comes to $2.11 \pm 0.02$ eV. Note that in the above analysis we did not consider any influence of CB1 since, if it existed, the $A$ exciton oscillator strength should have increased with the increase in temperature as seen for the nonresonantly excited photoluminescence signal strength in monolayer WSe$_2$ [30,35]. CB1 can be excluded because the optically resonantly excited carriers in CB2 in a reflectance measurement cannot relax efficiently to CB1 due to its opposite spin orientation.

Finally, we discuss the appropriateness of the hydrogenic model in describing excitons in bulk 2H-WS$_2$. We note that the oscillator strength ratio of the transitions identified as $A(n = 2)$ and $A$ here was theoretically found to be $\sim 5\%$ from the BSE analysis. This is close to what one would expect (3.7%, as mentioned earlier) from a 2D hydrogenic model. If we consider the energy spectrum, then in the 2D hydrogenic model it should go as $Ry_{b\ast}^2/(n - 0.5)^2$ where $Ry^\ast$ is the effective Rydberg constant. From our experimental data one gets $Ry_{b\ast}^2 = (9/32)[E_{0,n=2} - E_{0,n=1}]$ and therefore $E_b = 4Ry_{b\ast}^2 \sim 70$ meV. This is lower than our measured average $E_b$ value but is still within limits set by measurement errors. In the three-dimensional (3D) model $Ry_{b\ast}^2 = (4/3)[E_{0,n=2} - E_{0,n=1}]$, so $E_b = Ry_{b\ast}^2 \sim 85$ meV, which is in slightly better agreement with experiment. However, the oscillator strength ratio in 3D goes as $1/n^2$, making $A(n = 2) 12.5\%$ of $A$ in strength, much larger than what is found experimentally and from GW-BSE analysis. The true picture in terms of the spread of the wave function along the $c$ axis, which was crucial for our understanding of the relative changes in the modulation strengths between $A$ and $A(n = 2)$ in PR and LER, cannot be captured by the 2D hydrogen-atom model.
VI. CONCLUSION

In conclusion we have shown that in a modulation spectroscopy measurement on bulk WS$_2$ one can observe a feature on the high-energy side of the $A$ exciton transition whose magnitude relative to $A$ can change significantly depending on the measurement technique. By comparison with theoretical $GW$-BSE calculations we identified this feature as the signature of an effective $A(n = 2)$ excited-state transition and not an $H$-point exciton transition. Furthermore, the theoretical study indicates that the lowest-energy direct transition at the $K$ point is optically dark. The bright $A$ exciton is associated with the next-higher-energy direct transition involving VB1-CB2 and has a large binding energy of about 90 meV, which is more than three times $k_B T \sim 26$ meV at room temperature. Excitons in bulk WS$_2$ show many characteristics of a 2D system, some of which can be roughly described by a 2D hydrogenic model. However, other properties, such as the wave function spread along the $c$ axis and its consequences, cannot be understood on the basis of a simple 2D hydrogenic model.

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