Electronic structure and optical properties of ZnX (X=O, S, Se, Te): A density functional study

S. Zh. Karazhanov,1,2 P. Ravindran,1 A. Kjekshus,1 H. Fjellvåg,1 and B. G. Svensson3
1Centre for Material Science and Nanotechnology, Department of Chemistry, University of Oslo, P.O. Box 1033 Blindern, N-0315 Oslo, Norway
2Physical-Technical Institute, 2B Mavlyanov Street, Tashkent 700084, Uzbekistan
3Department of Physics, University of Oslo, P.O. Box 1048 Blindern, N-0316 Oslo, Norway
(Received 5 July 2006; revised manuscript received 15 November 2006; published 6 April 2007)

Electronic band structure and optical properties of zinc monochalcogenides with zinc-blende- and wurtzite-type structures were studied using the ab initio density functional method within the local-density approximation (LDA), generalized-gradient approximation, and LDA+U approaches. Calculations of the optical spectra have been performed for the energy range 0–20 eV, with and without including spin-orbit coupling. Reflectivity, absorption and extinction coefficients, and refractive index have been computed from the imaginary part of the dielectric function using the Kramers-Kronig transformations. A rigid shift of the calculated optical spectra is found to provide a good first approximation to reproduce experimental observations for almost all the zinc monochalcogenide phases considered. By inspection of the calculated and experimentally determined band-gap values for the zinc monochalcogenide series, the band gap of ZnO with zinc-blende structure has been estimated.

DOI: 10.1103/PhysRevB.75.155104 PACS number(s): 71.15.–m, 71.22.+i

I. INTRODUCTION

The zinc monochalcogenides (ZnX; X=O, S, Se, and Te) are the prototype II-VI semiconductors. These compounds are reported to crystallize in the zinc-blende-(z) and wurtzite (w)-type structures. The ZnX-z phases are optically isotropic, while the ZnX-w phases are anisotropic with c as the polar axis. ZnX phases are a primary candidate for optical device technology such as visual displays, high-density optical memories, transparent conductors, solid-state laser devices, photodetectors, solar cells, etc. So, knowledge about optical properties of these materials is especially important in the design and analysis of ZnX-based optoelectronic devices.

Optical parameters for some of the ZnX phases have widely been studied experimentally in the past. Detailed information on this subject is available for ZnO-w,1–9 ZnS-w,9 ZnS-z,9–11 ZnSe-z,9,10 and ZnTe-z,9,10,12,13 and see the systematized survey in Ref. 14. However, there are no experimental data on optical properties of ZnSe-w, ZnTe-w, and ZnO-z. Furthermore, there is a lack of consistency between some of the experimental values for the optical spectra. This is demonstrated in Fig. 1, which displays reflectivity spectra for ZnO-w measured at T=300 K by three different groups. Dielectric-response functions were calculated using the Kramers-Kronig relation. As is seen in Fig. 1, intensity of the imaginary part of the dielectric function (ε′′) and reflectivity (R) corresponding to the fundamental absorption edge of ZnO-w are higher than those at the energy range 10–15 eV, while in Ref. 14 it is vice versa. The optical spectra in Fig. 1 measured using the linearly polarized incident light for electric field (E) parallel (∥) and perpendicular (⊥) to the c axes are somehow close to those of Ref. 7 using unpolarized incident light.

Using the experimental reflectivity data, a full set of optical spectra for ZnO has been calculated for the wide energy range 0–26 eV. Density functional theory (DFT) in the local-density approximation (LDA) has also been used to calculate optical spectra for ZnO-w (Ref. 18) and ZnS-w (Ref. 18) by linear combination of atomic orbitals and for ZnS-z19 and ZnSe-z19 by self-consistent linear combination of Gaussian orbitals. The optical spectra of ZnO (including excitons) has been investigated by solving the Bethe-Salpeter equation. Band-structure studies have been performed by linearized-augmented plane-wave method plus local orbitals (LAPW+LO) within the generalized gradient and LDA with the multiorbital mean-field Hubbard potential (LDA+U) approximations. The latter approximation is found to correct not only the energy location of the Zn 3d electrons and associated band parameters (see also Refs. 21 and 22) but also to improve the optical response. Despite the shortcoming of DFT in relation to underestimation of band gaps, the locations of the major peaks in the calculated energy dependence of the optical spectra are found to be in good agreement with experimental data.

It should be noted that the error in calculation of the band gap by DFT within LDA and generalized-gradient approximation (GGA) is more severe in semiconductors with strong Coulomb correlation effects than in other solids.21–25 This is due to the mean-field character of the Kohn-Sham equations and the poor description of the strong Coulomb correlation and exchange interaction between electrons in narrow d bands (viz., the potential U). Not only the band gap (Eg) but also the crystal-field (CF) and spin-orbit (SO) splitting energies (ΔCF and ΔSO), the order of states at the top of the valence band (VB), the location of the Zn 3d band and its width, and the band dispersion are found to be incorrect for ZnO-w by the ab initio full potential (FP) and atomic-sphere-approximation (ASA) linear muffin-tin orbital (LMTO) methods within the pure LDA (Refs. 26 and 27) and by the projector-augmented wave (PAW) method within LDA and GGA.21,22 These findings were ascribed to strong Coulomb correlation effects. DFT calculations within LDA plus self-interaction correction (LDA+SIC) and LDA + U are found to rectify the errors related to ΔCF and...
In this work, electronic structure and optical properties of the ZnX-w and -z phases have been studied in the energy range from 0 to 20 eV based on first-principles band-structure calculations derived from DFT within the LDA, GGA, and LDA+U.

II. COMPUTATIONAL DETAILS

Experimentally determined lattice parameters have been used in the present ab initio calculations (Table I). The ideal positional parameter $u$ for ZnX-w is calculated on the assumption of equal nearest-neighbor bond lengths:

$$u = \frac{1}{3} \left( \frac{a}{c} \right)^2 + \frac{1}{4}.$$  

(1)

The values of $u$ for the ideal case agree well with the experimental values $u'$ (see Table I). Self-consistent calculations were performed using a $10 \times 10 \times 10$ mesh according to the Monkhorst-Pack scheme for the ZnX-z phases and the $\Gamma$-centered grid for the ZnX-w phases.

A. Calculations by vasp package

Optical spectra have been studied based on the band-structure data obtained from the VASP-PAW package,55 which solves the Kohn-Sham eigenvalues in the framework of the DFT (Ref. 16) within LDA,17 GGA,56 and the simplified rotationally invariant LDA+U.23,24 The exchange and correlation energies per electron have been described by the Perdew-Zunger parametrization7 of the quantum Monte Carlo results of Ceperley and Alder.58 The interaction between electrons and atomic cores is described by means of non-norm-conserving pseudopotentials implemented in the VASP package.55 The pseudopotentials are generated in accordance with the PAW (Refs. 59 and 60) method. The use of the PAW pseudopotentials addresses the problem of inad-
TABLE I. Theoretically and experimentally (in brackets) determined unit-cell dimensions \(a\) and \(c\), volumes \(V\), ideal \(u\) [calculated by Eq. (1)], and experimental \(u'\), as well as values of the parameters \(U\) and \(J\) from Refs. \(21\) and \(22\), were used in the present calculations. For \(w\)-type structure, \(a=b=c\) and all atoms are in fixed positions.

<table>
<thead>
<tr>
<th>Phase</th>
<th>(a) (Å)</th>
<th>(c) (Å)</th>
<th>(V) (Å(^3))</th>
<th>(u)</th>
<th>(u')</th>
<th>(U) (eV)</th>
<th>(J) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO-(w)(^a)</td>
<td>3.244(3.250)</td>
<td>5.027(5.207)</td>
<td>45.82(47.62)</td>
<td>0.383</td>
<td>0.380</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>ZnS-(w,h,c)</td>
<td>3.854(3.811)</td>
<td>6.305(6.234)</td>
<td>81.11(78.41)</td>
<td>0.375</td>
<td>0.375</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>ZnSe-(w,d)</td>
<td>4.043(3.996)</td>
<td>6.703(6.626)</td>
<td>94.88(91.63)</td>
<td>0.375</td>
<td>0.371</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>ZnTe-(w,e)</td>
<td>4.366(4.320)</td>
<td>7.176(7.100)</td>
<td>118.47(114.75)</td>
<td>0.375</td>
<td>0.373</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>ZnO-(z)(^g)</td>
<td>4.633(4.620)</td>
<td>99.45(98.61)</td>
<td>8</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnS-(z,i)</td>
<td>5.451(5.409)</td>
<td>161.99(158.25)</td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnSe-(z)(^h)</td>
<td>5.743(5.662)</td>
<td>189.45(181.51)</td>
<td>8</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnTe-(z,j)</td>
<td>6.187(6.101)</td>
<td>236.79(227.09)</td>
<td>8</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Reference 46.  
\(^b\)Reference 18.  
\(^c\)Reference 47.  
\(^d\)Reference 48.  
\(^e\)Reference 49.  
\(^f\)Reference 50.  
\(^g\)Reference 51.  
\(^h\)Reference 52.  
\(^i\)Reference 53.  
\(^j\)Reference 54.

The base geometry in this computational method consists of a muffin-tin part and an interstitial part. The basis set is comprised of linear muffin-tin orbitals. Inside the muffin-tin spheres, the basis functions, charge density, and potential are expanded in symmetry-adapted spherical harmonic functions together with a radial function and a Fourier series in the interstitial.

C. Calculation of optical properties

From the DFT calculations, the imaginary part of the dielectric function \(\varepsilon'_2(\omega)\) has been derived by summing transitions from occupied to unoccupied states for energies much larger than those of the phonons:

\[
\varepsilon'_2(\omega) = \frac{V e^2}{2 \pi h n^3 \omega^2} \int d^3 k \sum_{n n'} \langle k n | p_j | k n' \rangle \times \langle k n' | p_j | k n \rangle = \frac{1}{f_{kn}}(1 - f_{kn}) \delta (\varepsilon_{kn} - \varepsilon_{kn} - \hbar \omega).
\]

Here, \((p_x, p_y, p_z) = p\) is the momentum operator, \(f_{kn}\) the Fermi distribution, and \(|kn\rangle\) the crystal wave function corresponding to the energy \(\varepsilon_{kn}\) with momentum \(k\). Since the ZnX-W phases are optically anisotropic, components of the dielectric function corresponding to the electric field parallel (\(E \parallel c\)) and perpendicular (\(E \perp c\)) to the crystallographic \(c\) axis have been considered. The ZnX-Z phases are isotropic; consequently, only one component of the dielectric function has to be analyzed.

The real part of the dielectric function \(\varepsilon_1(\omega)\) is calculated using the Kramer-Kronig transformation. The knowledge of
both the real and imaginary parts of the dielectric tensor allows one to calculate other important optical spectra. In this paper, we present and analyze the reflectivity $R(\omega)$, the absorption coefficient $\alpha(\omega)$, the refractive index $n(\omega)$, and the extinction coefficient $k(\omega)$:

$$R(\omega) = \frac{\sqrt{\epsilon(\omega) - 1}}{\sqrt{\epsilon(\omega) + 1}}^2,$$

$$\alpha(\omega) = \omega \sqrt{2\sqrt{\epsilon_1^2(\omega) + \epsilon_2^2(\omega)} - 2\epsilon_1(\omega)},$$

$$n(\omega) = \sqrt{\frac{\sqrt{\epsilon_1^2(\omega) + \epsilon_2^2(\omega)} + \epsilon_1(\omega)}{2}},$$

$$k(\omega) = \sqrt{\frac{\sqrt{\epsilon_1^2(\omega) + \epsilon_2^2(\omega)} - \epsilon_1(\omega)}{2}}.$$  

Here, $\epsilon(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ is the complex dielectric function. The calculated optical spectra yield unbroadened functions and, consequently, have more structure than the experimental ones.  

To facilitate a comparison with the experimental findings, the calculated imaginary part of the dielectric function has been broadened. The exact form of the broadening function is unknown. However, analysis of the available experimentally measured optical spectra of ZnX shows that the broadening usually increases with increasing excitation energy. Also, the instrumental resolution smears out many fine features. These features have been modeled using the lifetime broadening technique by convoluting the imaginary part of the dielectric function with a Lorentzian with a full width at half maximum of 0.002(eV)$^2$, increasing quadratically with the photon energy. The experimental resolution was simulated by broadening the final spectra with a Gaussian, where the full width at half maximum is equal to 0.08 eV.

### III. RESULTS AND DISCUSSION

#### A. Band structure

The optical spectra are related to band dispersion and probabilities of interband optical transitions. So, it is of interest to analyze the electronic structure in detail. Band dispersions for ZnX-w and ZnX-z calculated by DFT within LDA and LDA+U are presented in Fig. 2. The general features of the band dispersions are in agreement with previous studies (see, e.g., Refs. 26, 62, and 72). It is seen from Fig. 2 that the conduction-band (CB) minima for ZnX-w and ZnX-z are much more dispersive than the VB maximum, which shows that the holes are much heavier than the CB electrons in agreement with experimental data for the effective masses and calculated with FP LMTO and (Ref. 26) linear combination of atomic orbitals, as well as with our findings. Consequently, mobility of electrons is higher than that of holes. Furthermore, these features indicate that $p$ electrons of X (that form the topmost VB states) are tightly bound to their atoms and make the VB holes less mobile.

Hence, the contribution of the holes to the conductivity is expected to be smaller than that of CB electrons even though the concentration of the latter is smaller than that of the former. These features emphasize the predominant ionic nature of the chemical bonding. Another interesting feature of the band structures is that the VB maximum becomes more dispersive with increasing atomic number of X from O to Te.

As noted in our previous contributions, the band gaps of ZnX calculated by DFT within LDA, GGA, and LDA+U are underestimated and the question as to whether it is possible to shift the CB states rigidly was kept open. As found from the optical spectra discussed on the following sections, rigid shifts of the CB states up to the experimentally determined locations can provide a good first approximation for the stipulation of the band gap. So, for the band dispersions in Fig. 2, we have made use of this simple way for correcting the band gaps calculated by DFT. The only problem in this respect was the lack of an experimental band-gap value for ZnO-w. To solve this problem, the experimental and calculated (by DFT within LDA) band gaps ($E_g$) of the ZnX series were plotted as a function of the atomic number of X. As seen from Fig. 3, $E_g$ for the ZnX-w phases are very close to the corresponding values for the ZnX-z phases and the shape of the experimental and calculated functional dependencies is in conformity. On this basis, the
The band gap of ZnO-z is estimated by extrapolating the findings for ZnX-z from ZnS-z to ZnO-z. This procedure gave $E_g = 3.3$ eV for ZnO-z.

It is well known that not only band gaps are underestimated within LDA and GGA, but also band dispersions come out incorrectly, whereas location of energy levels of $3d$ electrons are overestimated (see, e.g., Refs. 20–22 and 63). As also seen from Fig. 2, calculations within the LDA+U approach somewhat correct the location of the energy levels of the Zn 3d electrons. The elucidation of the eigenvalue problem and the order of states at the topmost VB from LDA, GGA, and LDA+U calculations are discussed in Refs. 20–22 and 26 and will not be repeated here.

Examination of Fig. 2 shows that the VB comprises three regions of bands: first a lower region consists of s bands of Zn and X, a higher-lying region of well localized Zn 3d bands, and on top of this a broader band dispersion originating from X-p states hybridized with Zn 3d states. The latter subband is more pronounced in ZnO than in the other Zn-X-Z phases considered. The hybridization is most severe according to the LDA and GGA calculations, whereas the LDA+U calculations somehow suppress this and improve the band-gap underestimation. A more detailed discussion of these aspects is found in Refs. 21 and 22.

The SO splitting at the topmost VB is known to play an important role for the electronic structure and chemical bonding of solids.28,29,32 In semiconductors with z-type structure, the SO splitting energy is determined as the difference between energies of the topmost VB states with symmetry $Γ_{8u}$ and $Γ_{7v}$.28,29,32 In the w-type compounds, the topmost VB is split not only by SO interaction but also by CF, giving rise to three states at the Brillouin-zone center. To calculate the SO splitting energy for w-type phases, the quasicubic model of Hopfield75 is commonly used.

It is well known that the SO splitting energy derived from ab initio calculations agrees well with experimental data only for some of the semiconductors. This is demonstrated, for example, for all diamondlike group IV and z-type group III-V, II-VI, and I-VII semiconductors.28 w-type AlN, GaN, and InN,29 ZnX-w and -z ($X=S$, Se, and Te).21,22 and CdTe.31

However, the errors in estimated SO splitting energies by LDA calculations are significant for semiconductors with strong Coulomb correlation effects, as demonstrated, e.g., for ZnO.21,22,26 For such systems, DFT calculations within LDA+U (Refs. 21, 22, and 26) are shown to provide quite accurate values for $Δ_{CT}$ and $Δ_{SO}$. Overestimation of the p-d hybridization in various variants of the DFT can also lead to the wrong spin-orbit coupling of the valence bands.76,77

Systematic study of the SO coupling parameters was performed for zinc-blende II-VI semiconductors (Ref. 30) using the TB and LMTO methods, as well as for all diamondlike and zinc-blende semiconductors (Ref. 28) using the FLAPW method with and without the $p_{1/2}$ local orbitals and the frozen-core PAW method implemented into VASP. The corrections coming from the inclusion of the local $p_{1/2}$ orbitals are found to be negligible for the compounds with light atoms. Analysis of these results shows that the SO splitting energy coming from calculations using the VASP-PAW shows good agreement with the experimental data. This result was also obtained21 recently for ZnX of wurtzite and zinc-blende structures. As demonstrated in Refs. 21 and 22 the SO splitting energy ($Δ_{SO}$) increases when one moves from ZnO-z to ZnTe-z, in agreement with earlier findings of Ref. 28.

To study the role of the SO coupling in band dispersion, the present ab initio calculations have been performed by VASP and MINDLAB packages and spin-orbit splitting energy is found. The results are presented in Table II. Analysis of Table II shows that ($Δ_{SO}$) calculated by MINDLAB is quite accurate.

As expected, band dispersions calculated with and without the SO coupling differ little when the SO splitting energy

<table>
<thead>
<tr>
<th>$ZnO$-z</th>
<th>$ZnS$-z</th>
<th>$ZnSe$-z</th>
<th>$ZnTe$-z</th>
</tr>
</thead>
<tbody>
<tr>
<td>-31</td>
<td>66</td>
<td>432</td>
<td>914</td>
</tr>
<tr>
<td>-31</td>
<td>66</td>
<td>432</td>
<td>914</td>
</tr>
<tr>
<td>$-34^a$</td>
<td>66$^a$</td>
<td>393$^a$</td>
<td>889$^a$</td>
</tr>
<tr>
<td>$-34^b$</td>
<td>66$^b$</td>
<td>398$^b$</td>
<td>916$^b$</td>
</tr>
<tr>
<td>$-37^c$</td>
<td>64$^c$</td>
<td>392$^c$</td>
<td>898$^c$</td>
</tr>
<tr>
<td>$-33^d$</td>
<td>64$^d$</td>
<td>393$^d$</td>
<td>897$^d$</td>
</tr>
<tr>
<td>65$^e$</td>
<td>420$^f$</td>
<td>910$^f$</td>
<td></td>
</tr>
</tbody>
</table>

aLAPW, Ref. 28.
bLAPW+$p_{1/2}$, Ref. 28.
cVASP-PAW, Ref. 28.
dVASP-PAW, Ref. 21.
eExperiment, Ref. 78.
fExperiment, Ref. 79.

FIG. 3. Band gaps for ZnX-w (circles) and ZnX-z (triangles) phases determined experimentally (filled symbols, from Refs. 21 and 22) and calculated (open symbols) by DFT within LDA as a function of the atomic number of the X component of ZnX.
Symmetry labels for some of the high-symmetry points are shown.

For the Zn structure, the Fermi level is located at the topmost one.

Energy at the center of gravity of the VB is set at zero energy.

In order to simplify the presentation of the findings of this work, the labels $E_0$, $E_1$, and $E_2$ of Ref. 11 (from the reflectivity spectra) were retained in Table III and Fig. 4.

The subscripts 0 and 1 are ascribed to transitions occurring at $\Gamma$, the subscript 2 to transitions at points in the [111] direction, and the subscripts 0 and 1 to transitions at points in the [100] direction (referred to the k space for the z-type structure). Assignment of the $E_0$, $E_1$, and $E_2$ peaks to optical transitions at high-symmetry points is presented in Table III and Fig. 4.

The optical spectra $\varepsilon_1(\omega)$, $\varepsilon_2(\omega)$, $\alpha(\omega)$, $R(\omega)$, $n(\omega)$, and $\kappa(\omega)$ calculated by DFT within LDA, GGA, and LDA+U are displayed in Figs. 5–8 and compared with available experimental findings. The spectral profiles are indeed very similar to each other. Therefore, we shall only give a brief account mainly focusing on the location of the interband optical transitions. The peak structures in Figs. 5–8 can be explained from the band structure discussed above.

All peaks observed by experiments (see, e.g., Refs. 11 and 14) are reproduced by the theoretical calculations. Because of the underestimation of the optical band gaps in the DFT calculations, the locations of all the peaks in the spectral profiles are consistently shifted toward lower energies compared with the experimentally determined spectra. Rigid shift (by the scissor operator) of the optical spectra has been applied, which somewhat removed the discrepancy between the theoretical and experimental results. In general, the calculated optical spectra qualitatively agree with the experimental data. In our theoretical calculations, the intensity of the major peaks is underestimated, while the intensity of some of the shoulders is overestimated. This result is in good agreement with previous theoretical findings (see, e.g., Ref. 19). The discrepancies are probably originating from the neglect of the Coulomb interaction between free electrons and holes (excitons), overestimation of the optical matrix elements, and local-field and finite-lifetime effects. Furthermore, for calculations of the imaginary part of the dielectric-response function, only the optical transitions from occupied to unoccupied states with fixed k vector are considered.

Moreover, the experimental resolution smears out many fine features, and, as demonstrated in Fig. 1, there is inconsistency between the experimental data measured by the same method and at the same temperature. However, as noted in the Introduction, accounting for the excitons and Coulomb correlation effects in ab initio calculations by the LAPW +LO within LDA+U allowed correcting not only the energy

TABLE III. Relation of the basic $E_0$, $E_1$, and $E_2$ peaks in the optical spectra of ZnX to high-symmetry points (see Refs. 11 and 14) in the Brillouin zone at which the transitions seem to occur.

<table>
<thead>
<tr>
<th>Peak</th>
<th>$z$ type</th>
<th>$w$ type, $E\parallel c$</th>
<th>$w$ type, $E\perp c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>$\Gamma_8 \rightarrow \Gamma_6$</td>
<td>$\Gamma_1 \rightarrow \Gamma_1$</td>
<td>$\Gamma_6 \rightarrow \Gamma_1$</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$L_{4,5,6} \rightarrow L_6$</td>
<td>$A_{3,5,6,1,3} \rightarrow A_{1,3}$</td>
<td>$M_4 \rightarrow M_1$</td>
</tr>
</tbody>
</table>

B. General features of optical spectra of ZnX

Since optical properties of solids are based on the band structure, the nature of the basic peaks in the optical spectra can be interpreted in terms of the interband transitions responsible for the peaks. Such an interpretation is available for semiconductors with z- and w-type structures. In order to simplify the presentation of the findings of this work, the labels $E_0$, $E_1$, and $E_2$ of Ref. 11 (from the reflectivity spectra) were retained in Table III and Fig. 4. The subscripts 0 and 1 are ascribed to transitions occurring at $\Gamma$, the subscript 2 to transitions at points in the [111] direction, and the subscripts 0 and 1 to transitions at points in the [100] direction (referred to the k space for the z-type structure). Assignment of the $E_0$, $E_1$, and $E_2$ peaks to optical transitions at high-symmetry points is presented in Table III and Fig. 4.

The optical spectra $\varepsilon_1(\omega)$, $\varepsilon_2(\omega)$, $\alpha(\omega)$, $R(\omega)$, $n(\omega)$, and $\kappa(\omega)$ calculated by DFT within LDA, GGA, and LDA+U are displayed in Figs. 5–8 and compared with available experimental findings. The spectral profiles are indeed very similar to each other. Therefore, we shall only give a brief account mainly focusing on the location of the interband optical transitions. The peak structures in Figs. 5–8 can be explained from the band structure discussed above.

All peaks observed by experiments (see, e.g., Refs. 11 and 14) are reproduced by the theoretical calculations. Because of the underestimation of the optical band gaps in the DFT calculations, the locations of all the peaks in the spectral profiles are consistently shifted toward lower energies compared with the experimentally determined spectra. Rigid shift (by the scissor operator) of the optical spectra has been applied, which somewhat removed the discrepancy between the theoretical and experimental results. In general, the calculated optical spectra qualitatively agree with the experimental data. In our theoretical calculations, the intensity of the major peaks is underestimated, while the intensity of some of the shoulders is overestimated. This result is in good agreement with previous theoretical findings (see, e.g., Ref. 19). The discrepancies are probably originating from the neglect of the Coulomb interaction between free electrons and holes (excitons), overestimation of the optical matrix elements, and local-field and finite-lifetime effects. Furthermore, for calculations of the imaginary part of the dielectric-response function, only the optical transitions from occupied to unoccupied states with fixed k vector are considered.

Moreover, the experimental resolution smears out many fine features, and, as demonstrated in Fig. 1, there is inconsistency between the experimental data measured by the same method and at the same temperature. However, as noted in the Introduction, accounting for the excitons and Coulomb correlation effects in ab initio calculations by the LAPW +LO within LDA+U allowed correcting not only the energy
position of the Zn 3d electrons and eigenvalues but also the optical response. Consequently, accounting for the excitons plays an important role in the optical spectra.

The optical spectra calculated within LDA, GGA, and LDA+U do not differ significantly from each other for the ZnX-w and -z phases except for ZnO-w and -z, for which the optical spectra calculated within LDA+U are significantly different from those obtained by LDA and GGA. The difference between the optical spectra calculated by LDA and GGA and those calculated by LDA+U decreases when one moves from ZnO to ZnTe. For ZnTe, the difference can be said to be very small. This feature shows that in ZnO-w and -z, Coulomb correlation effects are strong compared to the other ZnX-w and -z phases, in agreement with recent LAPW+LO calculations including electron-hole correlations.

Comparison of the optical spectra for \( E \parallel c \) and \( E \perp c \) for each of the ZnX-w phases with the isotropic spectra of the corresponding ZnX-z phases shows that the locations of the peaks almost coincide. This similarity reflects that there is only small differences in the local arrangement of the atoms in the ZnX-w and corresponding -z phases.
C. ZnO-\textit{w} and ZnO-\textit{z} 

The optical spectra of ZnO-\textit{w} and -\textit{z} calculated by DFT within LDA, GGA, and LDA+\textit{U}, together with measured data, are displayed in Fig. 5. One clearly sees three major peaks in the experimental spectra located in the energy ranges 3.1–3.3 eV, 7.5–8.5 eV, and 10–15 eV. In the \textit{E}_2 peak, \(\varepsilon_2(\omega)\), \(\alpha(\omega)\), \(R(\omega)\), and \(k(\omega)\) are seen to take larger values than those in the \textit{E}_0 and \textit{E}_1 peaks. This is one of the major features, which distinguishes ZnO-\textit{w} and -\textit{z} from the other ZnX phases.

It should be noted that with increasing value of the parameter \(U\) in the LDA+\textit{U} calculations, the intensity of the \textit{E}_0 and \textit{E}_1 peaks of ZnO-\textit{w} decreases compared with the LDA and GGA findings as well as with the experimental data. However, the intensity of the \textit{E}_1 peak of ZnO-\textit{z} from the LDA+\textit{U} calculations has increased and has become even larger than those derived from the LDA and GGA calculations as well as the experimental data. The intensity of the \textit{E}_2 peak from the LDA+\textit{U} calculations oscillates significantly, showing disagreement with the LDA and GGA calculations as well as the experimental measurements. Hence, although LDA+\textit{U} calculations\textsuperscript{21} were good in increasing the LDA-derived band gap and the SO splitting energy as well as in decreasing the crystal-field splitting energy and improving

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{Optical spectra of ZnS-\textit{w} for \(E\parallel c\) (first column) and \(E\perp c\) (second column) and ZnS-\textit{z} (third column) calculated within LDA (thick solid lines), GGA (thin solid lines), and LDA+\textit{U} (dashed lines) and compared with experimental data (open circles) from Ref. 14. \(\alpha(\omega)\) is given in cm\(^{-1}\) divided by 10\(^5\).}
\end{figure}
the band dispersion, it was poorer than LDA and GGA in describing the optical properties of the ZnO phases. Probably, this discrepancy comes about because in our ab initio calculations, electron-hole interactions and SO coupling are not included. The strong variation of the optical properties with increasing values of $U$ indicates appreciable Coulomb correlation effects in ZnO- and -z, in agreement with our previous band-structure findings and LAPW+LO calculations including excitonic effect. This feature is not present in the spectra for the other ZnX-w and -z phases considered.

For convenience of analysis, the $\varepsilon_2(\omega)$ profile was analyzed by adjusting the peak location to the experimental data of Ref. 14 by rigid shift. On comparing this result with that of Ref. 8, it is concluded that the peaks at 3.40 eV for $E\parallel c$ and that at 3.33 eV for $E \perp c$ of $\varepsilon_2(\omega)$ and $R(\omega)$ can be ascribed to transitions at the fundamental absorption edge. As shown in Ref. 8, the energy difference (0.07 eV) between these two peaks gives the separation between the so-called A and B (for $E \perp c$) and C (for $E \parallel c$) states forming the topmost VB of w-type semiconductors, in agreement with 0.083 eV according to the band-structure analyses in Refs. 21 and 22.

FIG. 7. Optical spectra of ZnSe-w for $E\parallel c$ (first column) and $E \perp c$ (second column) and ZnSe-z (third column) calculated within LDA (thick solid lines), GGA (thin solid lines), and LDA+$U$ (dashed lines) and compared with experimental data (open circles) from Ref. 14. $\alpha(\omega)$ is given in cm$^{-1}$ divided by 10$^5$. For convenience of analysis, the $\varepsilon_2(\omega)$ profile was analyzed by adjusting the peak location to the experimental data of Ref. 14 by rigid shift. On comparing this result with that of Ref. 8, it is concluded that the peaks at 3.40 eV for $E\parallel c$ and that at 3.33 eV for $E \perp c$ of $\varepsilon_2(\omega)$ and $R(\omega)$ can be ascribed to transitions at the fundamental absorption edge. As shown in Ref. 8, the energy difference (0.07 eV) between these two peaks gives the separation between the so-called A and B (for $E \perp c$) and C (for $E \parallel c$) states forming the topmost VB of w-type semiconductors, in agreement with 0.083 eV according to the band-structure analyses in Refs. 21 and 22.
There are two broad shoulders of the peak $E_0$ located at 4.44 and 5.90 eV for $E \parallel c$ and 3.90 and 5.29 eV for $E \perp c$. Similar shoulders are found at lower energies in the experimental spectra of Refs. 8 and 82 observed at 3.35 and 3.41 eV for $E \parallel c$ and 3.39 and 3.45 eV for $E \perp c$, and the origin of these shoulders has been ascribed to exciton-phonon coupling. However, in our ab initio studies, excitons and lattice vibrations are not taken into consideration.

D. ZnS-w and ZnS-z

The experimental optical spectra for the ZnS-w and -z phases are displayed in Fig. 6, together with those calculated according to the LDA, GGA, and LDA+U. It is seen that the magnitudes of the experimentally observed shoulders around the $E_2$ peak in the reflectivity spectra of ZnS-w are overestimated in the DFT calculations. As a result, the intensities of the shoulders are almost the same as the intensities of the peaks $E_1$ and $E_2$ for $E \perp c$ and even exceed them for $E \parallel c$.

The calculated optical spectra for ZnS-w by LDA, GGA, and LDA+U turned out to be almost identical at energies below 10 eV. However, at higher energies, the LDA- and GGA-derived peaks differ from those obtained by LDA+U. This difference can be associated with Zn 3$d$ electrons.
which were shifted toward lower energies in the LDA+\textit{U} calculations. Hence, in ZnS-\textit{w} and -\textit{z}, the Coulomb correlation effects appear to play a significant role in optical properties at energies higher than 10 eV.

Compared to ZnO-\textit{w}, the calculated optical spectra of ZnS-\textit{w} and -\textit{z} show larger disagreement with the experimental data. The discrepancy is quite pronounced in the absorption and reflectivity spectra of ZnS-\textit{w} and -\textit{z}, especially at energies exceeding 7 eV. The magnitude of the peaks located at higher energies are overestimated significantly compared to the experimental data. The overestimation is more severe in ZnS-\textit{z} than in ZnS-\textit{w} as judged from the intensity of the \textit{E}_2 peak.

\section*{E. ZnSe-\textit{w}, ZnTe-\textit{w}, ZnSe-\textit{z}, and ZnSe-\textit{z}}

The optical spectra for ZnSe-\textit{w}, ZnSe-\textit{z}, ZnTe-\textit{w}, and ZnTe-\textit{z} calculated by DFT within LDA, GGA, and LDA +\textit{U} are displayed in Figs. 7 and 8, together with the corresponding experimental spectra. Since experimental optical spectra for ZnSe-\textit{w} and ZnTe-\textit{w} are not available, rigid shift of the parameters toward higher energies has been performed on the basis of the reflectivity spectra for ZnSe-\textit{z} and ZnTe-\textit{z} (Figs. 7 and 8). A closer inspection of Figs. 7 and 8 shows that the optical spectra calculated within LDA, GGA, and LDA +\textit{U} are almost the same for all selenide and telluride phases. The small differences noted in the absorption and reflectivity spectra appear to originate from the Zn 3d electrons.

The location and magnitude of the experimentally measured \textit{E}_1 peak in the reflectivity spectra of ZnSe-\textit{z} and ZnTe-\textit{z} have been assigned\textsuperscript{14,11} to fundamental absorption and \textit{\lambda}_3\rightarrow\textit{\lambda}_1 transitions at the [0.17,0.17,0.17] point of the Brillouin zone. These assignments agree well with theoretical calculations. However, the theoretical calculations did not locate the \textit{E}_1+\textit{\Delta}_1 peak on the high-energy side of the \textit{E}_1 peak, which was observed experimentally for both ZnSe-\textit{z} and ZnTe-\textit{z}. The reason is certainly that SO coupling was not included in the calculations.

The experimental\textsuperscript{13} \textit{E}_0 peak in the reflectivity spectra, corresponding to transitions at \textit{k}=\textbf{0} [viz., from the highest state of VB (\textit{\Gamma}_15) to the lowest state of CB (\textit{\Gamma}_1)], is well reproduced by the theoretical calculations. One also sees the \textit{E}_0+\textit{\Delta}_0 peak in the theoretical spectra, which was previously\textsuperscript{13} ascribed to SO splitting. Since SO coupling was neglected in the theoretical calculations, the origin of the \textit{E}_0+\textit{\Delta}_0 peak is not likely to be related to SO coupling.

Similar to the findings for ZnS-\textit{z}, the theoretically calculated optical spectra for the lower-energy regions of ZnSe-\textit{z} and ZnTe-\textit{z} agree with experimental findings. However, the intensity of the peaks located at higher energies is overestimated in the DFT calculations. Anyway, this discrepancy is not as severe as that for ZnS-\textit{z}. The calculated reflectivity spectra agree well with experimental data in the energy range \(\approx\)6 eV. At higher energies (6–15 eV), LDA, GGA, and LDA +U all overestimate the intensity of the reflectivity. Fairly good agreement with the experimental data is achieved in the energy range 15–20 eV for the real and imaginary parts of the dielectric function for ZnSe-\textit{z} and ZnTe-\textit{z}. For the other optical spectra of ZnSe-\textit{z} and ZnTe-\textit{z}, the agreement between theory and experiment is poorer.

\section*{F. Influence of spin-orbit splitting on the optical spectra of ZnX}

It is well known that SO splitting at the top of the VB of a semiconductor is very important for optical transitions, and one should expect large difference in the optical spectra calculated with and without the SO coupling. In this section, we shall analyze how the SO coupling influences the optical spectra of ZnX. For this analysis, \textit{ab initio} band-structure calculations have been performed using the MINDLAB software with and without SO coupling. Based on the band-structure studies, the dielectric-response function \(\varepsilon_2(\omega)\) has been calculated. The results for ZnX-\textit{z} are presented in Fig. 9 and compared with experimental data, where it is seen that \(\varepsilon_2(\omega)\) calculated for ZnO-\textit{z} without SO coupling is slightly higher than that with the SO coupling, with the main deviations occurring at 3.44–6.00 and 10.00–12.00 eV. The reason for the small distinctions in \(\varepsilon_2(\omega)\) in this case is the small SO splitting energy.

Our findings show that the SO splitting influences the calculated optical spectra and, in particular, it is most pronounced at energies lower than \(-12\) eV. At higher energies, the difference between the optical spectra calculated with and without SO coupling is fairly small and agrees reasonably well with the experimental data.\textsuperscript{14} This statement applies to all ZnX phases studied. It should be noted that intensities of the peaks calculated with SO coupling are generally lower than those obtained without SO coupling and the latter set agrees better with the experimental data than the former. Furthermore, in the experimental spectra, there are low intensity peaks located at 9.4 eV in ZnS-\textit{z}, 8.4 eV in ZnS-\textit{z}, and 7.0 eV in ZnTe-\textit{z}. However, these peaks are not seen in the calculated spectra with the SO coupling. As noted, this discrepancy can be related to the neglect of many of the above factors such as Coulomb interaction between electrons and holes, local-field effects, and indirect transitions etc.

\section*{G. Role of the ground-state structure in the optical spectra of ZnX}

In this section, we shall analyze optical spectra of ZnX calculated using the experimentally and theoretically determined lattice parameters. To find the lattice parameters from the \textit{ab initio} calculations, the structural optimization has been performed, which includes the following steps: atoms are relaxed keeping the volume and shape of the lattice. After convergence is reached, the resulting lattice and positional parameters have been used as input to optimize atomic positions, shape, and volume of the unit cell altogether. Then, dependence of the total energy on volume is studied. The minimum of the dependence was accepted as the equilibrium state. Lattice and positional parameters corresponding to the minimum are referred to as the theoretically determined lattice parameters. The thus determined theoretical lattice parameters do not deviate much from the experimental ones. These parameters along with the experimentally determined
ones were used for subsequent computations of the electronic structure and optical spectra. The results are presented in Fig. 10 for ZnX-w for E/H11036. Analysis shows that the optical spectra of ZnO-w for E/H11036 deviate from each other at energies near the fundamental absorption and at higher energies in the range 8–13 eV. The reason for the difference can be related to changes of the p-d coupling because of the changes of the Zn-O bond lengths coming from structural optimization. Optical spectra of ZnO-w for E/H20648 and those of other ZnX-w and -z calculated using the theoretical and experimental lattice parameters do not differ from each other significantly.

IV. CONCLUSION

The band structures of the ZnX-w and -z phases (X=O, S, Se, and Te) are calculated by DFT within LDA, GGA, and LDA+U. The topmost VB states are found to be more dispersive than the bottommost CB states. Spin-orbit coupling is found to play an important role for band dispersion, location, and width of the Zn 3d band and the lowest s band. By analyzing the dependence of the band gaps on the atomic number of X for ZnX, the band gap of ZnO-z is estimated to be ~3.3 eV. Using the electronic band structures as references, the optical spectra of ZnX-w and -z are analyzed in the energy range 0–20 eV. The locations of the peaks corresponding to transitions at the fundamental absorption edge calculated by DFT are shifted to lower energies relative to the experimental peaks. This deficiency originates from the well-known errors in band gaps calculated according to DFT. In order to correct the underestimation of band gaps calculated by DFT, the location of the calculated peaks of the optical spectra has been rigidly shifted toward higher energies to match the experimentally determined locations. In the
thus obtained spectra, the locations of the peaks in the lower-energy region agree well with the experimental data. However, the peaks in the higher-energy region agree only tolerably well with the experimental findings. The overall conclusion is that the $k$-independent scissors operator provides a good first approximation for correlation of the underestimated band gaps for the ZnX-w and -$z$ phases. Based on this result, “corrected” band structures of the ZnX phases are arranged by adjusting the band gap up to experimentally measured value (viz., rigidly lifting the lowest CB). Not only the locations but also the intensities of the calculated low-energy peaks agree with available experimental data for all ZnX phases. However, the intensities of some peaks located at higher energies and shoulders have been overestimated. The GGA approach slightly improved the band-gap values. Also, the optical spectra of ZnO-w for $E \perp c$ calculated within the GGA agree better with the experimental data than those calculated within the LDA and LDA+U approaches. The value for the corresponding transition at the fundamental absorption edge is decreased and becomes sharper with the use of the GGA, thus providing better agreement with experimental data than LDA. For $E \perp c$, inhomogeneity in the electron gas plays an important role, while it is not so important for $E \parallel c$. The optical spectra for ZnO-w and -$z$ calculated within LDA+U for the energy range 0–20 eV are found to depend significantly on the location of the energy levels of the Zn 3d electrons. For the other ZnX-w and -$z$ phases, such changes are not so pronounced, in fact, only noticeable at energies above 10 eV. Strong Coulomb correlation effects are established for ZnO-w and -$z$. According to the present LDA+U calculations, the probability for the optical transitions at the fundamental absorption edge of ZnO-w and -$z$ decreases with increasing $U$. Optical spectra for ZnO-$z$, ZnSe-w, and ZnTe-w have been predicted. The influence of the spin-orbit coupling is found to increase with increasing the atomic number of the X component of ZnX.

ACKNOWLEDGMENTS

This work has received financial and supercomputing support from the Research Council of Norway and Academy of Sciences of Uzbekistan (Project No. N31-36,24-06). The authors are thankful to R. Vidya for critical reading of the manuscript and comments. We also thank P. Vajeeston, A. Klaveness, and Dr. K. Knizek for computation-practical help.

37. P. Rinke, A. Qteish, J. Neugebauer, C. Freysoldt, and M. Scheff-