Theoretical Investigation of Ferromagnetism and Optical Properties of CuCr$_2$X$_4$ (X = S, Se) Spinels via Ab-initio Calculations

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ARTICLE INFO

ABSTRACT

Article History:
Received: March 03, 2022
Revised: April 28, 2022
Accepted: June 29, 2022
Available Online: June 30, 2022

Keywords:
Density Functional Theory
Electronic Characteristics
Magnetic Properties
Crystal Field Energy

The spintronics technology improve the spin functionality which captivated the existence of ferromagnetism. The control of magnetic properties by electrons spin and transport effect have been illustrated in CuCr$_2$X$_4$ (X = S, Se) spinels DFT through Wien2k and BoltztraP codes. The negative formation of energy established the thermodynamic stability of the examined spinels. The half metallic ferromagnetism in the analyzed spinel’s assures density of states. Magnetic moment (Integer value) and the insulating nature with down spin is the reaction of 100% spin polarization. The $\Delta(d)>(\Delta_{CF})$ and negative $\Delta(pd)$ attainment of the condition have presented the prevailing part of electrons spin to create ferromagnetism.

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1. Introduction

The half metallic ferromagnetism has been a theme of intense attention due to inherent technologically usage in significant spintronic, ferroelectric, and ferromagnetic applications displaying in spinels (Lunkenheimer, Fichtl, Hemberger, Tsurkan, & Loidl, 2005; Mahmood et al., 2020; C. Sun et al., 2010). Researchers have fascinated in view of the attention of CMR (Colossal Maneto-resistance) between studied spinels due to transition metal ferro-spinels among these spinels (Baltzer, Wojtowicz, Robbins, & Lopatin, 1966; von Helmolst, Wecker, Holzapfel, Schultz, & Samwer, 1993). CdCr$_2$S$_4$ and CdCr$_2$Se$_4$ are technically the two vital transition of temperatures at 84.5K and 129.5K separately in ferromagnetic semiconductors (Hemberger et al., 2005). In these type of materials S ions (in CdCr$_2$S$_4$) or six Se ions (in CdCr$_2$Se$_4$) forms the surrounding and crystallize in cubic spinel structure. In ferro-magnets, electrostriction has been discovered for it (Lunkenheimer et al., 2005; C. P. Sun et al., 2010). By using electric field CMR may be stimulated in these spinels as it has been reported besides it (C. Sun et al., 2010). Magnetic properties of such materials has extended the significane by application view point in the study of field induced electrical characteristics (Kim, Myung, Yoon, Kang, & Sun, 2004). CuCr$_2$S$_4$ has been investigated by Wustrow et al investigated to exploit CuCr$_2$S couple at high voltage which belongs to Cu thiospinels family (Wustrow et al., 2018). In this presumed research work CuCr$_2$S$_4$ comprises of the synthesis, structural and electrochemical examinations. CuCr$_2$S$_4$ testified studies displays that stable compound with normal distribution of cations indicates that compound is stable (Zhang, Stevanović, d’Avezac, Lany, & Zunger, 2012). Pyrochlore lattice created at tetrahedral positions by the combination of Cr ions in which antiferromagnetic interaction among closest neighbors that restricts the spin alignment as well as magnetic prevention (Anderson, 1956). Though, the SOC effect reduces the ferromagnetism by producing balance states and least free energy, but this energy simultaneously helps the magnetic ordering. The least energy creates net magnetic ordering in it. Particularly magnetic frustrations due to Cr bonded by tetragonal contraction which by creating it valuable contender in spintronics and other electronic devices by ZnCr$_2$O$_4$ and CdCr$_2$O$_4$ (Dutton, Huang, Tchernyshyov, Broholm, &
Cava, 2011; Kumar, Fennie, & Rabe, 2012; Tran & Blaha, 2009). The MgCr$_2$O$_4$ and ZnCr$_2$O$_4$ studied ensure their sensitivity to ferromagnetism. Instead of limiting literature the ferromagnetic ordering and high magnetic moment had been explored in CuCr$_2$X$_4$ (X = S, Se). Furthermore, the insulting band gaps 0.938 eV and 0.638 eV for CuCr$_2$S$_4$ and CuCr$_2$Se$_4$ also reported which make them significant materials for transport applications (Madsen & Singh, 2006).

The literature analysis about these materials show the experimental research work is very limiting on CuCr$_2$Se$_4$ but few theoretical reports exist on CuCr$_2$X$_4$ (X=S, Se) which support to analyze them for spintronic applications. Therefore, in the view of above discussion, the theoretical studies of transport and magnetic behaviors of CuCr$_2$X$_4$ (X=S, Se) have been incorporated in this article.

For this task, the DFT based Wien2K code, and BoltzTraP code has been practiced exploring the structures of studied spinels (Perdew et al., 2008). These exact band gap structures are run for the transport analysis by BoltzTraP code (Tran, Blaha, & Schwarz, 2007). The existence of structures of spinels reveals their diverse applications in the field of spintronic. Therefore, the results are discussed step by step below for the complete of the studied spinels.

2. Method of Calculation

The thiospinels CuCr$_2$X$_4$ (X=S, Se) magnetism and transport characteristics have been done by FP-L-(APW+lo) method through the Wien2K code. The structural analysis and ground state study has been done by PBE-GGA (Koller, Tran, & Blaha, 2011). The optimizations of studied structures done until the all the strain forces becomes zero. In addition, for true electronic structures and band gap analysis, the TB-mBJ has been done through exchange and correlation configuration. The TB-mBJ improve the band gaps this high precision and less time (Blaha, Schwarz, Madsen, Kvasnicka, & Luitz, 2001; Rashid et al., 2019; Scheidemantel, Ambrosch-Draxl, Thonhauser, Badding, & Sofo, 2003). By using TB-mBJ exchange potential results achieved from thermoelectric as well as electronic band structures conveyed. The K-mesh of order 12×12×12 have been selected in first Brillion zone. Furthermore, the product R$_{MT}$$\times$K$_{max}$= 8, G$_{max}$ = 16 and l$_{max}$ are adjusted in the in put of the software.

3. Analysis Section
3.1. Electronic Characteristics

The spinel’s CuCr$_2$X$_4$ (X=S, Se) with cubic structure and and space group Fd-3m#227 are optimized to in ferromagnetic state and compared its energy released with nonmagnetic state. The energy is taken the default units (Ry) in both the FM and NM states. The relative investigation depicts that the more energy released in FM state than NM states, which approve the FM state is much stable than the NM states. The thermodynamic stability of the deliberate spinel’s, and also associated with the enthalpy formation which has been computed and reported in the Table 1. The thermodynamic stability guarantees the negative establishment of energy that declines from -1.46 eV to -0.34 eV as S is changed with Se. The stability, decreasing trend as we go down the group the exit of energy lessens by the substitution of S with Se. When structures optimized the lattice constants (Å) by Murnaghan equation of states and shown in Table 1. Bulk modulus decreases by increasing the S/Se size and distance among atoms whereas the lattice constant increase from CuCr$_2$S$_4$ to CuCr$_2$Se$_4$. The computed magnetic and electronic and electronic characteristics are illustrated to see the effect of electrons spin. Thorough explanation of band structures (BS) is essential to recognize the electronic behavior. Hence, the examined compounds are plotted in Fig.2. For the computation of band structures. At Γ-symmetry point direction the valence band maxima exist, and conduction band minima exists at X direction having EN on VB in up spin (↑) which depict the indirect band gap.
Figure 1: Optimized Energy Versus Volume Plots of (a) CuCr\textsubscript{2}S\textsubscript{4}, and (b) CuCr\textsubscript{2}Se\textsubscript{4} in FM and NM States

While in down spin (\(\downarrow\)) medium, both VBM and CBM exist at the \(\Gamma\) direction having Fermi level inside them which persuades the insulting gap because of exchange mode. Hence, the formation of ferromagnetic semiconductors results as the incorporation of up spin (\(\uparrow\)) and down spin (\(\downarrow\)) medium by insulting properties.

Figure 2: The Band Structures for Spin Up and Spin Down of (a, b) CuCr\textsubscript{2}S\textsubscript{4} and (c, d) CuCr\textsubscript{2}Se\textsubscript{4}
Table 1
The calculated lattice constant $a_0$ (Å), bulk modulus $B_0$ (GPa), Ground state energy difference ($\Delta E = E_{NM} - E_{FM}$), enthalpy of formation $\Delta H$ (eV) for CuCr$_2$X$_4$ ($X = S, Se, Te$).

| Compound  | $a_0$ (Å) | $B_0$ (GPa) | $\Delta E$ (eV) | $\Delta H$ (eV) |
|-----------|-----------|-------------|-----------------|-----------------|
| CuCr$_2$S$_4$ | 10.22     | 82.74       | 5.74            | -1.46           |
| Exp.       | 10.24$^a$ |             |                 |                 |
| CuCr$_2$Se$_4$ | 10.76     | 65.35       | 6.74            | -0.84           |
| Exp.       | -----     |             |                 |                 |

$^a$Ref (Tran & Blaha, 2009), Ref (Mahmood, Hassan, et al., 2019)$^b$

The density of states (DOS) shows identical functioning and shown in Figs.3. The $SP = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \times 100$ is the equation computed for spin polarization in which $N_\uparrow$ showing the total density of states in the up-spin mode while $N_\downarrow$ is the total density of states in the down spin mode? Densities of states exist at Fermi level in up spin (↑) mode however energy gaps are forbidden inside the Fermi level. Consequently, SP has been found hundred percent (Choi, Shim, & Min, 2006; Walsh et al., 2007). The SP can be maintained by the integer value of total MM of the studied compounds is 100% as presented in Table 2. Partial density of states (PDOS) Cu, Cr and S/Se demonstrates further the exchange mechanism and ferromagnetism and are examined thoroughly as shown in Fig.3. The hybridize in the energy interval -4.0 to -0.5 eV between 3d states of Cr/Cu and O-2p states exist near $E_F$ in up spinel mode. Whereas in down spin mode the range is from -3.0 to -1.0 eV for Cr-3d states, Cu-3d and S-3p states. Moreover, in the hybridization range for Cr-3d states, Cu-3d states and S-3p states in the conduction band in the range of 1.5 to 2.4 eV and 2 to 3.2 eV for spin up and down modes. Consequently, ferromagnetic semiconducting nature, generated by the interaction inside the valence band and separating of states in the down spin mode.

![Figure 3: The total and Partial DOS for spin up and spin down of (a, b) CuCr$_2$S$_4$ and (c, d) CuCr$_2$Se$_4$](image-url)
3.2. Magnetic Properties

The materials structures elaborated in this material generates crystal field and exchange energies by hybridization in distinct states. Tetrahedral arrangement of S/Se atoms effect the Cu site with valency +2, whereas Cr site having +3 valency is captured by the octahedron of S/Se atoms.

The repulsive effect of 3d-Cr creates the octahedral of S/Se which in the near octahedron is powerful and weaker as move away. The increasing energy $e_0$ of states as associated to $t_{2g}$ states that extend the octahedron medium of S/Se atoms separate the 3d-Cr into high energy ($e_0$) and low energy ($t_{2g}$) (Kumar et al., 2012; Mahmood, Rashid, et al., 2019) [30]. Energies of the crystal field energies in both spin modes described by $(\Delta_{CF}^+ = t_{2g}^+ - e_g^+)$ and $(\Delta_{CF}^- = t_{2g}^- - e_g^-)$ are shown in Table 3. Furthermore, the correlation of crystal energy with the exchange separating of 3d states of Cr determined by the relation $\Delta(d) = \Delta_d^+ - \Delta_d^-$. Ferromagnetism domination results in the larger value of exchange energy besides the crystal field energy. By the measurement of indirect exchange energy $\Delta(pd)$ another kind of energy is produced by 3d states of Cr and p states of S/Se. Lower energy support ferromagnetism when $\Delta(pd)$ is negative. CuCr$_2$S$_4$ to CuCr$_2$Se$_4$ the value of $\Delta(pd)$ and $\Delta(d)$ increases presented in Table 3 where $\Delta_{CF}^-$ decreases that clearly indicates that later one is more promising for ferromagnetism. Ferromagnetism can be elaborated by exchange constant that calculated by the relations $N_\alpha N_\beta = \Delta E_C / \langle x \rangle$ and $N_\alpha N_\beta = \Delta E_p / \langle x \rangle$, where $(\Delta E_v = E_v^+ - E_v^-)$ and $(\Delta E_c = E_c^+ - E_c^-)$ and the energies at valence band as well as on conduction bands, where $x$ is the absorption of Cr and $\langle x \rangle$ is MM of Cr atom. In usual cases the $(N_\alpha N_\beta)$ retain positive values and $(N_\alpha N_\beta)$ negative. Therefore, the similar effect of studied FM has been seen in Table 3.

Table 3
The calculated values spin down gap ($\uparrow E_g$ (eV)), crystal field energy ($\Delta E_{\text{crystal}}$), direct exchange $\Delta_x(d)$ and indirect exchange $\Delta_x(pd)$ and the exchange constants ($N_\alpha a$ and $N_\beta$) for CuCr$_2$X$_4$ ($X = S, Se, Te$).

| Compounds | $\uparrow E_g$ | $(\Delta E_{\text{crystal}})$ | $\Delta_x(d)$ | $\Delta_x(pd)$ | $N_\alpha a$ | $N_\beta$ |
|-----------|---------------|-----------------------------|--------------|----------------|--------------|-----------|
| CuCr$_2$S$_4$ | 1.45          | 3.70                        | 3.98         | -0.20          | 0.33         | -0.14     |
| CuCr$_2$Se$_4$ | 0.85          | 2.94                        | 4.10         | -0.25          | 0.52         | -0.16     |

Zenger’s exchange model supports the attraction of down spin mode whose energy reduces and shows the magnetic impurity operated have negative value $(N_\alpha N_\beta)$ (Hassan, Arshad, & Mahmood, 2017; Kant, Deisenhofer, Tsurkan, & Loidl, 2010; Mahmood, Yaseen, Haq, Laref, & Nazir, 2019). Therefore, the source of ferromagnetism confirm that this is due to exchange energies. The examined compounds of magnetic moments and partial MM are reported in Table 2. The transporting of magnetic moment towards nonmagnetic sites indicates that the exchange interaction Cr-3d states and S/Se p states causes the decrease of magnetic moment of Cr. Because of unlike exchanges included in the structures may be due to transition of MM from magnetic to nonmagnetic sites.

4. Conclusion

In short, the present article, ensure the detailed analysis of electronic and magnetic characteristics of CuCr$_2$X$_4$ ($X = S, Se$) by Wien2k code. The examined compounds are ferromagnetic semiconductors, that validates the electronic band structures and density of
The optimization analysis confirms the more energy release in FM states than in NM states ensures the stability of FM states. The FM is elaborated in terms of electrons spin which show strong hybridization. The FM is favorable because $\Delta(d)$ has higher values as compared to $(\Delta_{\text{CF}})$. The energy decreases in down spin mode have -Ve value of pd-exchange energy which is also the justification of FM and electrons spin. The p-d hybridization/exchange interaction is due to the growth of $\mu_{\text{CF}}$ and shifting of MM on nonmagnetic sits. Therefore, the complete analysis of magnetic characteristics ensures importance of studied materials for spintronics applications.

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