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Electronic and mechanical properties of half-metallic half-Heusler compounds CoCrZ (Z = S, Se, and Te)*

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The electronic structures, magnetic properties, half-metallicity, and mechanical properties of half-Heulser compounds CoCrZ (Z = S, Se, and Te) were investigated using first-principles calculations within generalized gradient approximation based on the density function theory. The half-Heusler compounds show half-metallic properties with a half-metallic gap of 0.15 eV for CoCrS, 0.10 eV for CoCrSe, and 0.31 eV for CoCrTe at equilibrium lattice constant, respectively. The total magnetic moments are 3.00μ_B per formula unit, which agrees well with the Slater–Pauling rule. The half-metallicity, elastic constants, bulk modulus, shear modulus, Pough's ratio, Frantesvich ratio, Young's modulus, Poisson's ratio, and Debye temperature at equilibrium lattice constant and versus lattice constants are reported for the first time. The results indicate that the half-Heulser compounds CoCrZ (Z = S, Se, and Te) maintain the perfect half-metallic and mechanical stability within the lattice constants range of 5.18–5.43 Å for CoCrS, 5.09–5.61 Å for CoCrSe, and 5.17–6.42 Å for CoCrTe, respectively.

Keywords: half-Heusler, half-metallicity, elastic constants, first-principles

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1. Introduction

In recent years, the first-principle methods based on the density function theory have become the most powerful tools to explain and to predict properties of solids which were previously only accessible by experiments.[1,2] By first-principle calculation, many materials with special properties are firstly predicted by theory and subsequently investigated by experiment.[3–7] In this sense, the theoretical calculation is an effective tool to study the physical properties of materials such as the structural, electronic, and mechanical properties in the absence of experimental evidence, and it will provide useful guidance for further experimental research.[8,9] Heusler compounds are a remarkable group of tunable materials due to their interesting physical properties such as half-metallic (HM) character with a high potential for spintronics.[10–13] Since the HM character of half-Heusler compound NiMnSb was firstly predicted by de Groot *et al.* in 1983,[14] the HM Heusler compounds have become a hot research topic in the field of spintronics due to their high Curie temperature and good compatibility with a lattice of two element semiconductors, which is favorable for the two epitaxial growth of HM thin films on semiconductor substrates spin electronics devices.[15–17]

Recently, many researchers have paid attention to the CoCr-based half-Heusler compounds. Luo *et al.*[18] used x-ray powder diffraction to investigate the crystal structure and magnetic properties of CoCrAl. A small magnetic moment of 0.06μ_B per unit cell was detected. Missoum *et al.*[19] found that CoCrAl and CoCrGa have a HM nature using the full-potential method within the generalized gradient approximation (GGA). Yao and colleagues studied theoretically electronic structure of CoCrP, CoCrAs, CoCrSb, and CoCrTe.[20,21] They found that these four half-Heusler compounds are all half-metallic. Huang and collaborators confirmed the HM property of CoCrBi under pressure.[22] Feng *et al.* indicated that the half-metallicity of CoCrSi, CoCrGe, and CoCrSn can be retained even when their lattice constants are changed near the equilibrium lattice constant.[23] To the best of our knowledge, among these CoCr-based half-Heusler compounds, CoCrS and CoCrSe have yet to be reported. In order to further design and develop novel half-Heusler compounds to meet the demand of spintronics, we performed the first-principles calculations on CoCrS, CoCrSe, and similar CoCrTe to identify these interesting compounds for spintronics applications.

2. Computational details

The first-principles calculations were carried out by the projector augmented wave (PAW)[24] method as implemented in the VASP program[25] to get the electronic and mechani-

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cal properties of CoCrZ (Z = S, Se, and Te). The Perdew–Burke–Ernzerh formulation[26] of GGA as parameterized was used for the exchange-correlation functional.[27] In all cases, a plane-wave basis set cut-off of 500 eV was used. The s and p electrons of S, Se, and Te are treated as valence in the following electronic configuration: $3d^7 4s^2$ for Co, $3d^5 4s^1$ for Cr, $3s^2 3p^4$ for S, $4s^2 4p^4$ for Se, and $5s^2 5p^4$ for Te. A mesh of $17\times17\times17$ k-points was employed for Brillouin zone integrations for the half-Heulser compounds CoCrZ (Z = S, Se, and Te). The convergence tolerance for the calculations was selected as a difference on the total energies and the forces on each ion, which are converged within 1.0×10^{-4} eV/atom and 0.02 eV/Å, respectively.

3. Results and discussion

In general, the half-Heusler compounds XYZ are viewed as zinc-blende sublattices in which the octahedral sites are occupied, and crystallize in the face-centered cubic $C1_b$ structure with the space group F-43m. In half-Heusler compound XYZ, X, Y, and Z atoms occupy (1/4,1/4,1/4), (0,0,0), and (1/2,1/2,1/2) sites respectively and the (3/4,3/4,3/4) site is empty.[28] Firstly, ferromagnetic (FM), anti-ferromagnetic (AFM), and non-magnetic (NM) states are considered to find the ground state by spin-polarized and spin-unpolarized calculation. The total energies as a function of the volume for CoCrS, CoCrSe, and CoCrTe are depicted in Fig. 1. One can see that the lowest energy corresponds to the FM state for all three half-Heusler compounds, which means that the FM state is the more favorable state energetically. That is, the ground state of half-Heusler compounds CoCrZ (Z = S, Se, and Te) is ferromagnetic. The total energy versus volume are fitted to the empirical Murnaghan equation of state,[29,30] from which the equilibrium lattice constants are obtained and listed in Table 1. Although the lattice constants of CoCrS and CoCrSe are not found in the literature, however, the lattice constants of CoCrTe are very close to the previous theoretical investigations.[21]

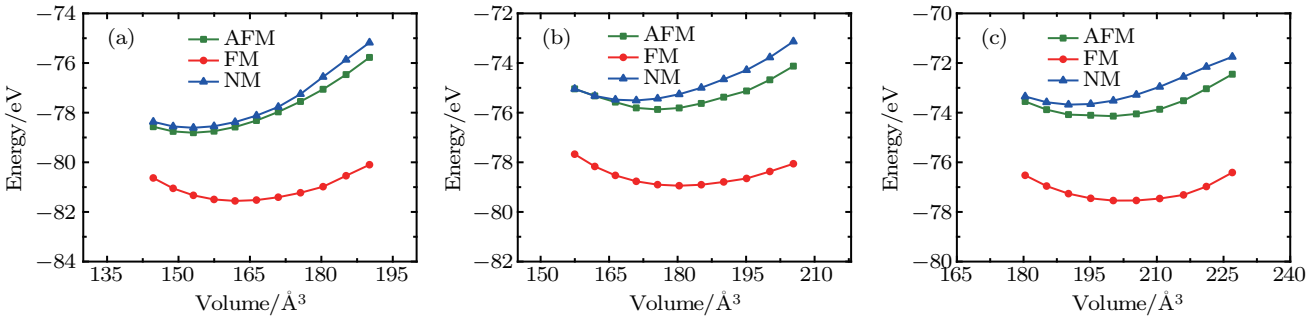


Fig. 1. (color online) The optimization for half-Heusler compounds CoCrZ (Z = S, Se, and Te). (a) CoCrS, (b) CoCrSe, and (c) CoCrTe.

Table 1. Calculated equilibrium lattice constants a (Å), local and total magnetic moments (μ_B) per formula unit, energy gap (eV), and half-metallic gap (eV) for half-Heusler compounds CoCrZ (Z = S, Se, and Te).

Compounds	a	M_{Co}	M_{Cr}	M_Z	M_{Total}	Gap	HM Gap
CoCrS	5.388	–0.066	2.846	0.004	3.000	1.06	0.15
CoCrSe	5.548	–0.149	2.941	–0.014	3.000	0.75	0.10
CoCrTe	5.827	–0.183	3.031	–0.059	3.000	0.87	0.31

The elastic constants C_{ij} provide a link between the mechanical and dynamical behavior of the crystals,[31] which is usually obtained by the stress–strain method. Chen *et al.* gave a very detailed description of the stress–strain method in their work.[30,32] The complete sets of single-crystal elastic modulus for half-Heusler compounds CoCrZ (Z = S, Se, and Te) at equilibrium lattice constant were calculated and listed in Table 2. The value of shear anisotropy factor A is equal to one for an isotropic crystal, and any deviation from one indicates anisotropy. From Table 2, we can see that all the half-Heulser compounds in the present work are anisotropic materials. For cubic crystals, the mechanical stability criteria are given by[30,32,33] $C_{11}-C_{12}>0$, $C_{44}>0$, $C_{11}+2C_{12}>0$, and $C_{12}<B<C_{11}$. One can clearly appreciate that the above relation is fulfilled for these three half-Heulser compounds, suggesting their mechanical stability.

The bulk modulus B measures the substance's resistance to applied pressure.[34] The larger the value of bulk modulus is, the stronger the capacity of the resist deformation is. From Table 2, it can be concluded that the largest bulk modulus of CoCrS shows that it has the strongest resistance to volume change by applied pressure. Similarly, the shear modulus G is a measure of resist reversible deformation by shear stress.[34] The larger the value is, the stronger the capacity of the resist shear deformation is. The results demonstrate that CoCrTe has the largest value, followed by CoCrSe and CoCrS. Hence, the deformation resistant capacity of CoCrTe would be much stronger than that of CoCrSe and CoCrS.

Pough's ratio B/G (Frantesvich ratio G/B) is one of the widely used criteria to provide information about the brittle or ductile nature of materials. If $B/G>1.75$ ($G/B<0.57$),

the material behaves in a ductile manner; otherwise, the brittle behavior is predicted.[35] According to the results in Table 2, the B/G ratios of CoCrZ (Z = S, Se, and Te) at equilibrium lattice constant are all higher than 1.75, i.e., the half-Heusler compounds CoCrS, CoCrSe, and CoCrTe are ductile. Furthermore, the calculated B/G for CoCrS is the largest, indicating that CoCrS is the most ductile among the three half-Heulser compounds.

Young's modulus Y characterizes the stiffness of a material. The material is found to be stiffer if the Young modulus is higher for a given material. From calculated results of Y, it can be stated that CoCrTe is stiffer than CoCrS and CoCrSe. The stiffness relationship among the three half-Heusler compounds is that CoCrTe>CoCrSe>CoCrS. Poisson's ratio υ plays an important role in the stability of the crystal against shear. The bigger the Poisson ratio is, the better the plasticity is. The calculated results demonstrate that CoCrS has the best plasticity because of the largest value of Poisson ratio, next CoCrSe, finally CoCrTe.

Table 2. Calculated elastic properties C_{ij}, shear anisotropy factor A, bulk modulus B , shear modulus G, Pough's ratio B/G, Frantesvich ratio G/B, Young's modulus Y, Poisson's ratio υ, Kleinman parameter ξ, and Debye temperature $\Theta_{\rm D}$ for CoCrZ (Z = S, Se, and Te) at the equilibrium lattice constant.

Properties	CoCrS	CoCrSe	CoCrTe
C_{11}/GPa	287.3	285.8	271.8
C_{12}/GPa	154.4	136.6	108.2
C_{44}/GPa	46.4	64.0	74.6
Shear anisotropy factor A	0.69	0.85	0.91
Bulk modulus B/GPa	198.7	186.6	162.7
Shear modulus G/GPa	53.6	68.0	77.4
Pough's ratio B/G	3.71	2.74	2.10
Frantesvich ratio G/B	0.27	0.36	0.47
Young's modulus Y/GPa	147.5	181.9	200.4
Poisson's ratio υ	0.37	0.33	0.29
Kleinman parameter ξ	0.65	0.61	0.53
Debye temperature $\Theta_{\rm D}$/K	426.1	418.6	405.9

As a fundamental parameter of thermodynamic properties, the Debye temperature $\Theta_{\rm D}$ correlates with many physical properties of solids, such as melting temperature and specific heat.[36] At low temperatures, the Debye temperature is calculated from elastic constants.[37] The Debye temperature is usually used to characterize the strength of covalent bonds in solids. From Table 2, we can conclude that the bond in CoCrS is stronger than CoCrSe and CoCrTe due to the largest Debye temperature among these three half-Heusler compounds.

The electronic structures play an important role in determining the physical properties of half-Heusler compounds. Figures 2–4 present spin-polarized band structures and total density of states of CoCrZ (Z = S, Se, and Te) at equilibrium lattice constant, where the Fermi level was set to zero. It is clearly seen that the energy bands cross the Fermi level and show a metallic character in majority-spin states, and the virtual energy gaps near the Fermi level in minority-spin states are about 1.06 eV for CoCrS, 0.75 eV for CoCrSe, and 0.87 eV for CoCrTe, respectively, indicating a semiconducting nature. Hence, the CoCrS, CoCrSe, and CoCrTe at their equilibrium lattice constant are half-metallicity. The HM gaps are 0.15 eV for CoCrS, 0.10 eV for CoCrSe, and 0.31 eV for CoCrTe, respectively. Among them, the HM gap of CoCrTe is very close to the previous theoretical reports.[21] It can also be seen that the band gap transition in minority-spin state are all direct (G-point) and the total magnetic moments are $3.00\mu_{\rm B}$ per formula unit. The total magnetic moments agree well with the Slatere–Pauling (SP) rule $M_{\rm t} = Z_{\rm t} - 18$,[11] where $M_{\rm t}$ is the total magnetic moment of half-Heulser compounds per formula unit, and $Z_{\rm t}$ is the number of valence electrons. The total and local magnetic moments of CoCrZ (Z = S, Se, and Te) are shown in Table 1. All the results were obtained based on the equilibrium lattice constant.

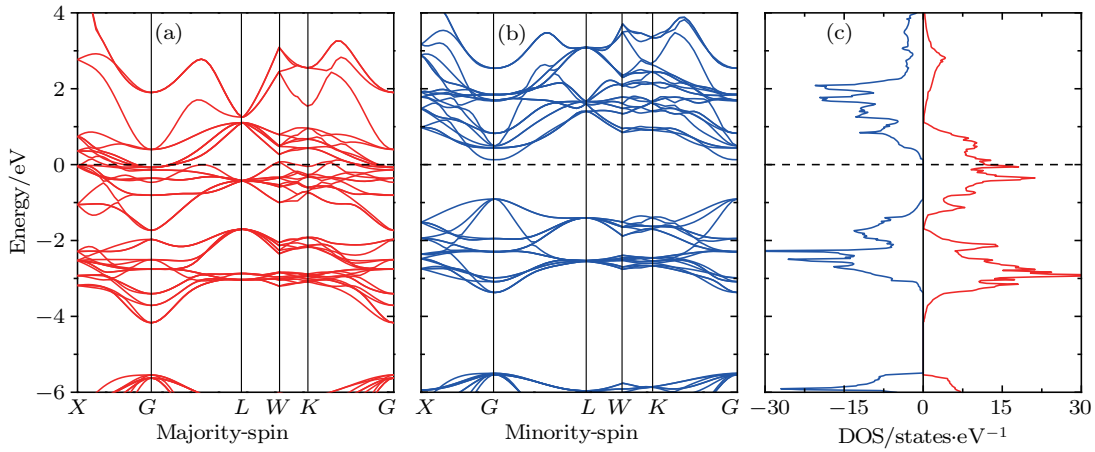


Fig. 2. (color online) Spin-polarized band structures and total density of states for half-Heusler compounds CoCrS.

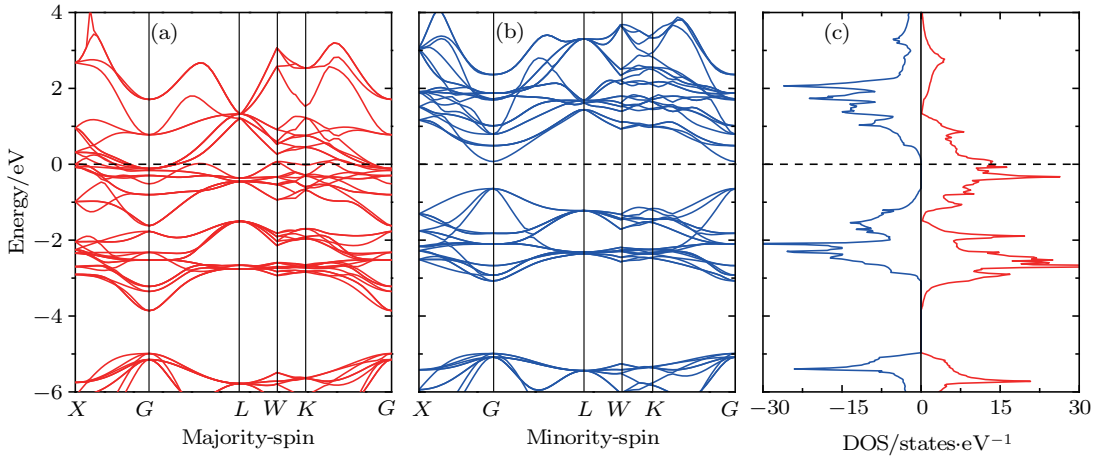


Fig. 3. (color online) Spin-polarized band structures and total density of states for half-Heusler compound CoCrSe.

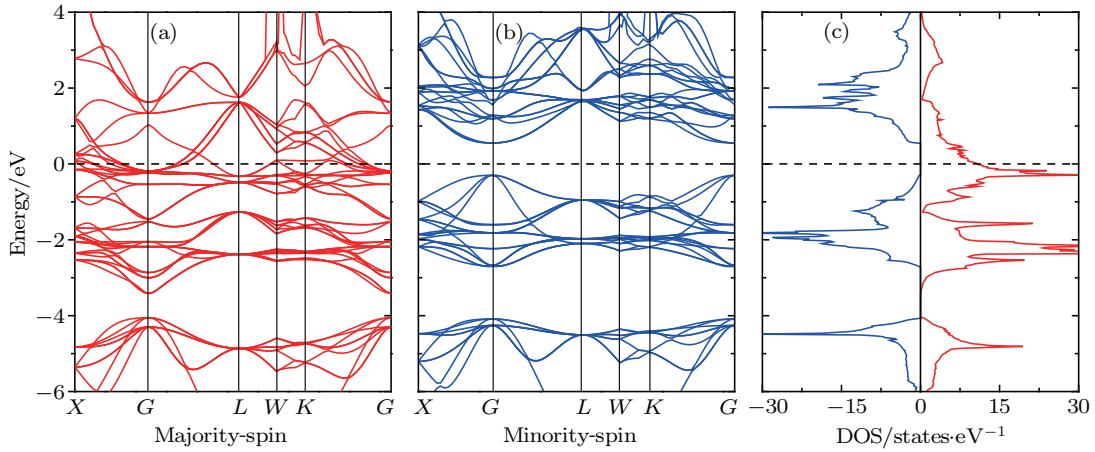


Fig. 4. (color online) Spin-polarized band structures and total density of states for half-Heusler compound CoCrTe.

To further explain and elaborate on the nature of electronic states, the spin-polarized partial densities of states are illustrated in Fig. 5. It can be seen that the partial density of states of CoCrS, CoCrSe, and CoCrTe have a similar feature, i.e., all states of Co-3d and Cr-3d play an important role in the vicinity of the Fermi level. By comparing the band structure and the density of states of CoCrS, CoCrSe, and CoCrTe, we can find that the valence band maximum in minority-spin states is controlled by the Co-3d and Cr-3d states, and conduction band minimum in minority-spin states is only determined by the Cr-3d states. The conduction band minimum of CoCrTe is higher than conduction band minimum of CoCrS and CoCrTe in energy. The states of Cr-3d almost determine the relevant physical characteristics due to their being more distributed around the Fermi level. Cr-3d states dominated the region from −1.71 to 1.08 eV for CoCrS, from −1.51 to 1.31 eV for CoCrSe, and from −1.28 to 1.65 eV for CoCrTe in majority-spin states, and also the region above 0.10 eV for CoCrS, above 0.15 eV for CoCrSe, and above 0.56 eV for CoCrTe in minority-spin states. The states are governed by Co-3d states from −3.34 to −0.91 eV for CoCrS, from −3.05 to −0.65 eV for CoCrSe, and from −2.70 to −0.31 eV for CoCrTe in minority-spin states, also from −3.56 to −1.71 eV for CoCrS, from −3.22 to −1.51 eV for CoCrSe, and from −2.97 to −1.28 eV for CoCrTe in majority-spin states. S-3p, Se-4p, and Te-5p states control the district lower −5.56 eV for CoCrS, −4.99 eV for CoCrSe, and −4.06 eV for CoCrTe in both majority-spin and minority-spin states.

The HM gap is an important parameter for application in spintronics. It is significant to know whether half-Heulser compounds CoCrZ (Z = S, Se, and Te) exhibit half-metallicity only at equilibrium lattice constants or can maintain the HM properties when the lattice constants change. In order to investigate the dependency of the HM characteristic of CoCrZ (Z = S, Se, and Te) on the lattice constants, the minority-spin band gaps versus lattice constants are calculated and displayed in Fig. 6. It is clearly seen that CoCrS, CoCrSe, and CoCrTe keep the HM properties with the lattice constants ranges of 5.18–5.43 Å for CoCrS, 5.09–5.61 Å for CoCrSe, and 5.17–6.42 Å for CoCrTe, respectively. The half-metallicity range of CoCrTe in the present work is consistent with the results of Yao *et al.*[21] In addition, the half-metallic gaps reach the maximum value of 0.18 eV at 5.29 Å for CoCrS, 0.32 eV at 5.40 Å for CoCrS, and 0.52 eV at 5.71 Å for CoCrTe, respectively.

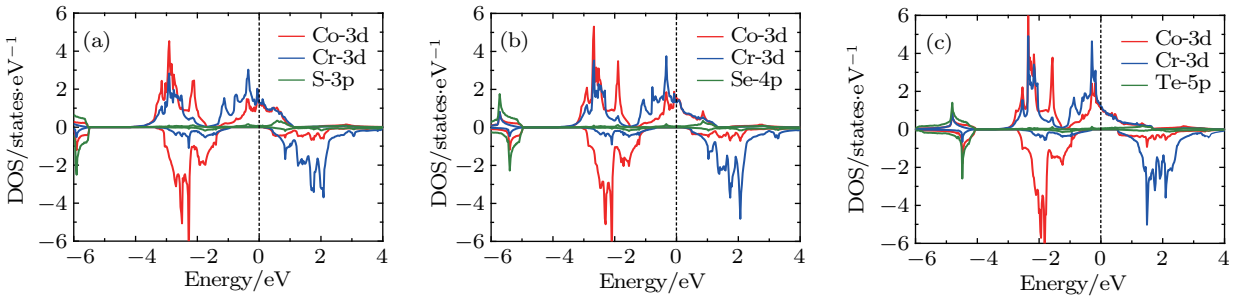


Fig. 5. (color online) Spin-polarized partial density of states for half-Heusler compounds CoCrZ (Z = S, Se, and Te). (a) CoCrS, (b) CoCrSe, and (c) CoCrTe.

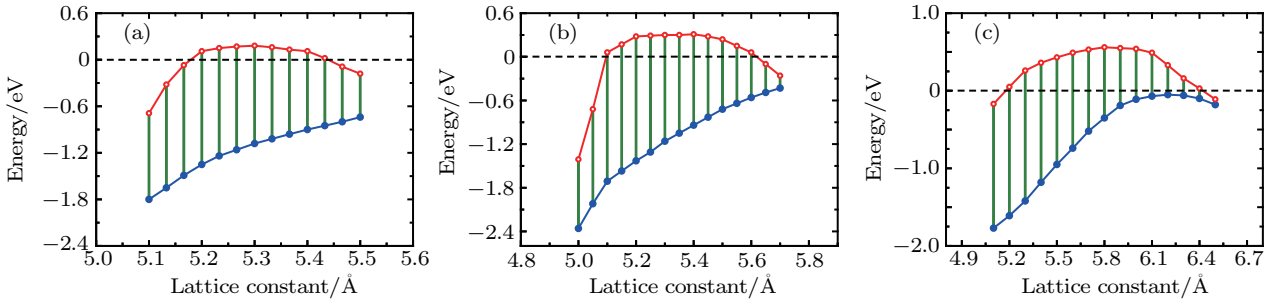


Fig. 6. (color online) The half-metallic gap of half-Heusler compounds CoCrZ (Z = S, Se, and Te) at different lattice constants. (a) CoCrS, (b) CoCrSe, and (c) CoCrTe. Blue points and red circles represent the valence band maximum and the conduction band minimum, respectively.

The variations of the total magnetic moment and local magnetic moments of CoCrS, CoCrSe, and CoCrTe with the lattice constant are shown in Fig. 7. It is interesting to note that, in the ranges of the lattice constants for CoCrS, CoCrSe, and CoCrTe with the HM property, the total magnetic moment is fixed 3.00μ_B, which obeys the SP rule very well. The local magnetic moments of Co and Cr atoms are quite sensitive to the change of lattice constant. With the increase of lattice constant, the local magnetic moment of Co atoms undergoes a transition from positive to negative. For Cr atoms, the local magnetic moment always keeps increasing with increasing lattice constant. However, the local magnetic moments of S, Se, and Te atoms have only a minor change. Furthermore, the local magnetic moments of Co and Cr underwent a transition from parallel to the anti-parallel relationship with the increasing of lattice constants. The total magnetic moment is counterbalanced by the change in the magnetic moment of both Co and Cr atoms, which retains the nearly fixed total moment 3.00μ_B when CoCrS, CoCrSe, and CoCrTe maintain half-metallicity.

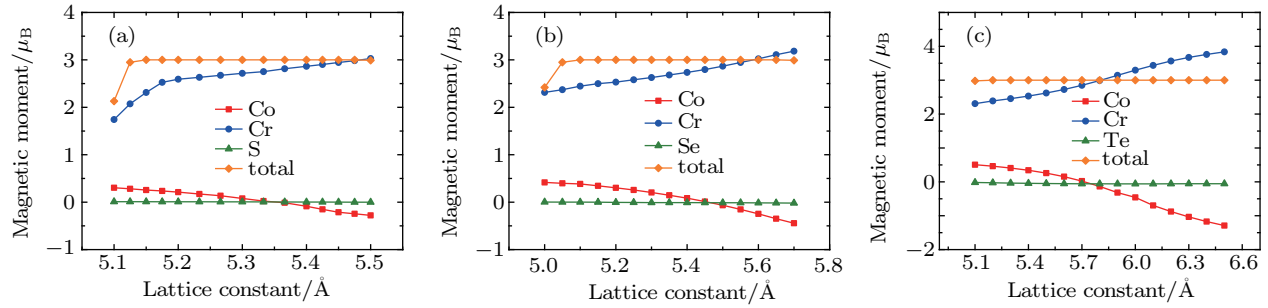


Fig. 7. (color online) Total and local magnetic moments of CoCrZ (Z = S, Se, and Te) at different lattice constants. (a) CoCrS, (b) CoCrSe, and (c) CoCrTe.

Up to now, the calculations presented neglect the spin–orbit coupling (SOC). In order to study the influence of SOC on the electronic properties, we depict the spin-polarized total density of states of CoCrS, CoCrSe, and CoCrTe in Fig. 8 by GGA+SOC calculations. One can see that the half-metallicity of these three half-Heusler compounds has not been destroyed. However, their energy gap and HM gap decreased slightly compared with that of GGA. In detail, the band gaps of CoCrS, CoCrSe, and CoCrTe are 0.99 eV, 0.71 eV, and 0.76 eV respectively, and their HM gaps are 0.09 eV, 0.05 eV, and 0.27 eV, respectively. The calculated total magnetic moments is still 3.00μ_B per formula unit, and the local magnetic moment of atoms has only a very small change. This proves that the SOC has no significant effect on the electronic properties of CoCrS, CoCrSe, and CoCrTe.

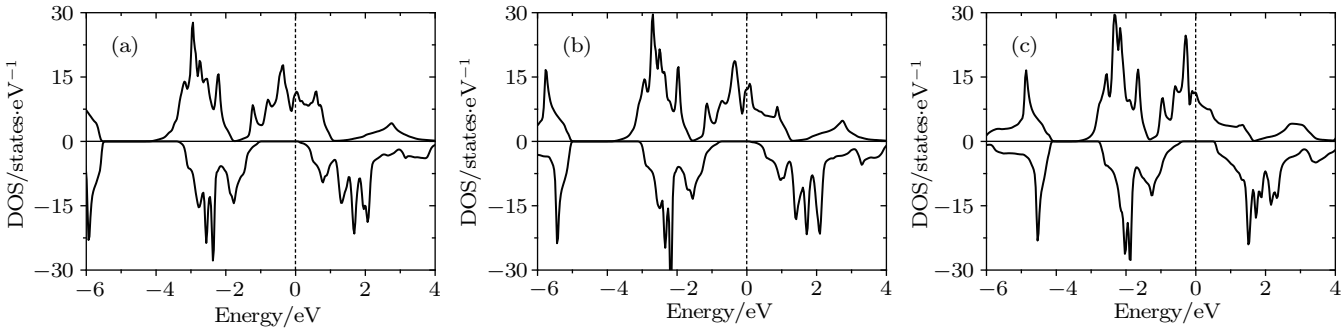


Fig. 8. Spin-polarized total density of states for half-Heusler compounds CoCrZ (Z = S, Se, and Te) in GGA+SOC. (a) CoCrS, (b) CoCrSe, and (c) CoCrTe.

It is known to all that the change of lattice constant can lead to the change of mechanical properties of materials and the change of lattice constant of a solid is often realized by pressure. Although the HM properties of half-Heulser compounds CoCrZ (Z = S, Se, and Te) can be kept in a wide range of lattice constants, the mechanical stability versus lattice constant is worth considering for the application in spintronics. The mechanical stability criteria under pressure effect for cubic crystal are $C_{11}-C_{12}-2P>0$, $C_{11}+2C_{12}+P>0$, and $C_{44}-P>0$.[32,38,39] Figure 9 depicts the elastic modulus $C_{11}-C_{12}-2P$, $C_{11}+2C_{12}+P$, $C_{44}-P$, and bulk modulus B of CoCrS, CoCrSe, and CoCrTe as a function of lattice constants. It can be clearly seen that the mechanical properties of CoCrS, CoCrSe, and CoCrTe are stable when they are half-metallic. For the three half-Heusler compounds, both $C_{11}+2C_{12}+P$ and B decrease with the increase of lattice constant. It means that when the lattice constant expands to a certain extent, the value of $C_{11}+2C_{12}+P$ will appear less than zero, at which point the mechanical properties of the half-Heulser compounds will be unstable. At the same time, we have noticed that when the lattice constant is relatively small, the value of $C_{44}-P$ will be less than zero, which indicates that high pressure can also lead to unstable mechanical properties of the three half-Heusler compounds. In fact, it can be seen from Fig. 9 that the mechanical stability will be destroyed when the lattice constant is less than 5.11 Å for CoCrS, 5.07 Å for CoCrSe, and 5.15 Å for CoCrTe, respectively.

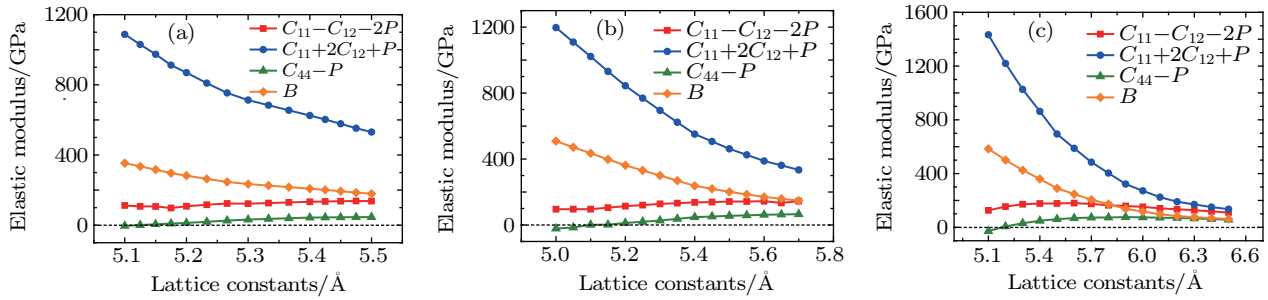


Fig. 9. (color online) Elastic modulus of CoCrZ (Z = S, Se, and Te) at different lattice constants. (a) CoCrS, (b) CoCrSe, and (c) CoCrTe.

Based on the elastic constants and bulk modulus B of different lattice constants, calculated shear anisotropy factor A, shear modulus G, Pough's ratio B/G, Young's modulus Y, Poisson's ratio υ, and Debye temperature Θ_{D} of CoCrS, CoCrSe, and CoCrTe were listed in Tables 3–5, respectively. Obviously, the increase of lattice constant does not change the nature of the anisotropy of these three half-Heusler compounds, but makes the capacity of the resist deformation weaker, which can be seen from the bulk modulus B in Fig. 9. With the increase of the lattice constant, the ability to resist shear deformation is gradually enhanced for CoCrS, and then weakened. For CoCrSe and CoCrTe, the ability to resist deformation shear becomes weaker and weaker due to decreasing shear modulus G. Moreover, CoCrS and CoCrSe are ductile within the lattice constants listed in Tables 4 and 5. However, CoCrTe is not so. When its lattice constant is less than 6.00 Å, CoCrTe is ductile, and when the lattice constant is greater than 6.00 Å, CoCrTe is brittle. The calculated Young modulus gives us the information that with the increase of lattice constants, the stiffness of CoCrS increases first and then decreases. However, the stiffness of CoCrSe and CoCrTe has been weakened. Furthermore, the plasticity of these three half-Heulser compounds is also reduced. Calculating the Debye temperature told us that when the lattice constant increases, the strength of covalent bonds in CoCrSe and CoCrTe becomes weaker gradually, while the bond strength in CoCrS increases first and then becomes weaker.

Table 3. Calculated shear anisotropy factor A, shear modulus G, Pough's ratio B/G, Young's modulus Y, Poisson's ratio υ, and Debye temperature Θ_D as a function of lattice constants a (Å) for the half-Heulser compound CoCrS.

a	A	G	B/G	Y	υ	Θ_D
5.10	0.27	39.0	9.07	112.9	0.45	357.0
5.20	0.46	48.3	5.85	137.0	0.42	399.6
5.30	0.58	51.8	4.52	144.7	0.40	416.7
5.40	0.65	52.0	4.00	144.1	0.38	420.9
5.50	0.63	47.5	3.78	130.8	0.38	405.2

Table 4. Calculated shear anisotropy factor A, shear modulus G, Pough's ratio B/G, Young's modulus Y, Poisson's ratio υ, and Debye temperature Θ_D as a function of lattice constants a (Å) for the half-Heulser compound CoCrSe.

a	A	G	B/G	Y	υ	Θ_D
5.00	0.49	89.6	5.68	253.8	0.42	460.9
5.10	0.52	81.8	5.32	230.9	0.41	444.5
5.20	0.58	77.0	4.70	215.6	0.40	434.7
5.30	0.61	74.2	4.21	197.9	0.39	431.5
5.40	0.75	73.2	3.25	196.0	0.36	429.6
5.50	0.80	68.9	2.91	185.6	0.35	420.0
5.60	0.85	65.5	2.60	174.2	0.33	412.2
5.70	0.89	62.5	2.36	164.3	0.31	405.4

Table 5. Calculated shear anisotropy factor A, shear modulus G, Pough's ratio B/G, Young's modulus Y, Poisson's ratio υ, and Debye temperature Θ_D as a function of lattice constants a (Å) for the half-Heulser compound CoCrTe.

a	A	G	B/G	Y	υ	Θ_D
5.10	0.53	136.2	4.29	379.2	0.39	510.4
5.30	0.64	121.6	3.49	333.0	0.37	490.1
5.50	0.77	104.5	2.77	280.0	0.34	461.0
5.70	0.85	87.9	2.34	230.7	0.31	428.7
5.90	0.95	73.5	1.87	187.2	0.27	397.1
6.10	1.01	60.6	1.61	150.6	0.24	365.1
6.30	1.04	50.9	1.49	124.7	0.23	339.4
6.50	1.04	40.6	1.53	100.0	0.23	308.2

4. Conclusion

In this work, first-principles calculations have been used to investigate the electronic and mechanical properties of half-Heulser compounds CoCrZ (Z = S, Se, and Te). The spin-polarization calculations show that the three half-Heusler compounds present half-metallic properties with integer magnetic moment 3.00μ_B per formula unit, following the SP rule $M_t = Z_t - 18$. The indirect band gaps are located at the G-point in minority-spin states. The half-Heulser compounds CoCrZ (Z = S, Se, and Te) can keep perfect half-metallic properties within the wide ranges of the lattice constants 5.18–5.43 Å, 5.09–5.61 Å, and 5.17–6.42 Å when Z = S, Se, and Te, respectively. In addition, calculated elastic constants of CoCrZ (Z = S, Se, and Te) indicate that the studied compounds obey the mechanical stability criteria of cubic crystals, and own the ductile nature at the equilibrium lattice constant. With the increase of the lattice constant, some mechanical properties, such as plasticity, ductibility, stiffness, and plasticity, have different degrees of change. In summary, these three half-Heulser compounds are promising candidates for the generation of spin-polarized currents due to the perfect half-metallic and mechanical stability, and hence can be used either in magnetic recording applications or in generation of high frequency radiation.

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