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## Engineering the near-edge electronic structure of SnSe through strains

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### Abstract

The discovery of the unprecedented figure of merit  $ZT$  of SnSe has sparked a large number of studies on the fundamental physics of this material and further improvement through guided materials design and optimization. Motivated by its rich chemical bonding characters, unusual multi-valley electronic structure, and the sensitivity of the band edge states to lattice strains, we carry out accurate quasiparticle calculations for the low temperature phase SnSe under strains. We illustrate how the band edge states can be engineered by lattice strains, including the size and the nature of the band gap, the positions of the band extrema in the Brillouin zone, and the control of the number of electron and/or hole valleys. The distinct atomic origin and orientation of the wave functions of the different band edge states dictates the relative shift in their band energy, enabling active control of the near-edge electronic structure of this material. Our work demonstrates that strain engineering is a promising way to manipulate the low-energy electronic structure of SnSe, which can have profound influences on the optical and transport properties of this material.

## Introduction

As one of the most promising candidates for thermoelectric applications [1-4], tin selenide (SnSe) has recently attracted much research interest. This material displays the highest thermoelectric figure of merit  $ZT$  without doping [2,3], and, importantly, its composition is earth-abundant and non-toxic. SnSe crystallizes in a low-temperature (LT) phase (Fig. 1a) with the Pnma space group under ambient conditions, and undergoes a second-order phase transition to a high-temperature (HT) phase (Fig. 1b) with the Cmcm space group at about 750 to 800 K [2]. Both the Cmcm and Pnma phases have layered structures, in which the intra-layer bonds are much stronger than interlayer interactions.

In spite of its impressive performance, the record-high  $ZT$  value of 2.6 is only achieved at above 800 K [2]. At room temperature, the  $ZT$  value is less than 0.5 [2]. This greatly limits the potential applications of SnSe-based thermoelectric devices. Compared with the LT phase, the HT Cmcm phase has a lower lattice thermal conductivity, which may be attributed to the greater phonon anharmonicity in the HT phase [5,6]. Moreover, the smaller band gap of the Cmcm phase ( $E_g^{\text{Cmcm}} = 0.54$  eV, to be compared with  $E_g^{\text{Pnma}} = 0.86$  eV) leads to an increase of the electrical conductivity  $\sigma$  by one order of magnitude as the temperature changes from 500 K to 800 K [2]. The large variation of phonon and electronic properties evidently stems from the structural difference between the two phases.

In order to further optimize the performance and extend the range of working temperature of SnSe, several approaches have been explored, for example, hole doping [1], applying hydrostatic pressure [7,8], and nanostructuring [9,10]. Another important alternative is strain-engineering, which has long been used as an effective and predictable means for tuning the materials properties [11-16], including strain-induced structural phase transitions [17-19], indirect-direct band gap transition [11-13], and semiconductor-metal transition [12,20]. Previous work [4,21,22] also demonstrated the possibility of applying strains to tune the thermoelectric power factor. The band edges of SnSe have several competing local extrema within a small energy window, and the wave functions of the electronic states near these local extrema have different atomic origins. These states may respond differently to various types of strain, enabling an effective means for engineering the electronic structure of this material.

In this work, we present a detailed investigation on how the near-edge electronic structure and the quasiparticle band gap of the LT phase SnSe can be engineered using strains within density functional theory (DFT) [23] and the GW approximation [24-26]. Our results show that the band gap of the LT SnSe can be broadly tuned from 0 to 1.2 eV and from indirect to direct gap under strains. In particular, SnSe is predicted to undergo a semiconductor-metal transition under a biaxial compressive strain of 4% in the  $bc$  plane (lattice  $a$ ,  $b$ , and  $c$  are defined in Fig. 1a). More importantly, we find that strain can be used to control the number of electron and/or hole valleys in this material. Unlike modifying materials properties through chemical means, strain-engineering enables active

control of materials properties. We mention that although there have been previous DFT-based studies [21] of the strain effects on the electronic properties of SnSe, our GW results provide more accurate predictions which can be compared directly with experiment and guide future materials design.

### Computational Details

Table 1: Comparison between the experimental and calculated lattice parameters of bulk LT (Pnma) phase SnSe. Here  $a$ ,  $b$ , and  $c$  are lattice constants defined in Fig. 1a,  $\Delta a/a$ ,  $\Delta b/b$ , and  $\Delta c/c$  are the relative errors of the theoretical lattice constants, and  $d$  is the averaged absolute deviation of the atomic positions of the optimized structure compared with experiment.

Functional	$a$ (Å)	$\Delta a/a$ (%)	$b$ (Å)	$\Delta b/b$ (%)	$c$ (Å)	$\Delta c/c$ (%)	$d$ (Å)
LDA	11.334	-1.46	4.120	-0.79	4.324	-2.83	0.11
PBE	11.794	2.54	4.212	1.42	4.527	1.73	0.16
DF2	12.529	8.93	4.330	4.26	4.866	9.35	0.61
optPBE	11.916	3.60	4.240	2.09	4.563	2.54	0.23
optB88	11.809	2.67	4.229	1.83	4.488	0.85	0.16
optB86b	11.614	0.97	4.198	1.08	4.413	-0.83	0.07
Experiment [40]	11.502		4.153		4.450		

The VASP package [27,28] is used for optimizing the crystal structures of the LT phase SnSe under various strains ranging from -8% (compressive) to 8% (tensile), and for computing the DFT band structures. The lattice parameters and atomic positions are fully relaxed within the constraint imposed by the strain. The generalized gradient approximation (GGA) [29] of Perdew-Burke-Ernzerhof (PBE) [30] is used for the DFT band structure calculations. The Brillouin zone integration is carried out using a  $3 \times 9 \times 9$   $k$ -grid.

Since SnSe assumes a layered structure, it is important that the van der Waals (vdW) interaction between layers is accurately captured in DFT calculations. We have compared the performance of several methods, including the local density approximation (LDA) [31,32], GGA-PBE, DFT-D2 [33], and various vdW density functionals (vdW-DF), namely, optPBE [34], optB88 [34], and optB86b [35], for their reliability in predicting the crystal structure of LT (Pnma) SnSe as shown in Table 1. We find that the optB86b functional performs best in predicting both the lattice parameters and the internal atomic positions of SnSe. Hence, we use the optB86b functional for all structural optimizations. In this work, we will focus on the evolution of electronic properties of the LT Pnma phase SnSe when it is subjected to uniaxial strain along the  $b$  (zigzag) and  $c$  (armchair) directions, and biaxial strain in the  $bc$  plane.

Considering the fact that Sn is a rather heavy element, one might expect that the spin-orbital coupling (soc) effects be important in this material. This is not the case here, however, due to the low symmetry of the system. The left panel of Fig. 2 compares the PBE band structures of Pnma SnSe calculated with (shown in red) and without (shown in blue) including the soc, which shows no noticeable soc effects. We shall call this

phenomenon *quenching of the soc* effect due to the low symmetry of the structure. In other words, although the soc potential  $\Delta V_{\text{soc}}^L(\vec{r})$  is large for Sn, the low symmetry of the structure removes the degeneracy of the electronic states (there are, however, still accidental degeneracy and near degenerate states), resulting in vanishing soc effects on the Kohn-Sham eigenvalue, i.e.,  $\langle \psi_{nk} | \vec{S} \cdot \vec{L} | \psi_{nk} \rangle \sim 0$ . To better illustrate this point, we have also carried out calculations for the high symmetry rock-salt SnSe as shown in the right panel of Fig. 2. As expected, the soc effects are clearly seen for degenerate states (for example, at the  $\Gamma$  point). We mention that quenching of soc has been discussed in the context of other symmetry-lowering mechanisms such as dynamical Jahn-Teller systems [36]. Therefore, we will neglect soc effects in Pnma SnSe in the following discussion.

The GW calculations are carried out using a local version of the BerkeleyGW package [37]. The Hybertsen-Louie generalized plasmon-pole (HL-GPP) model [25] is used to extend the static dielectric matrix to finite frequencies. Although the GW approximation is recognized as one of the most accurate theories for predicting the quasiparticle properties of materials, large-scale GW calculations using the conventional approach are still very computationally expensive. Recently, we proposed an efficient energy-integration method [38] that can greatly speed up large-scale GW calculations without sacrificing the accuracy. This timely development enables fast and accurate predictions of the quasiparticle properties of SnSe under various strains. We have carefully tested the convergence of the GW results (to be discussed in more detail later) with respect to the k-point sampling, kinetic energy cutoff of dielectric matrices, and the number of conduction bands included in the dielectric function and self-energy calculations.

## Results and Discussion

### A. Quasiparticle band structure of the unstrained LT Pnma phase SnSe

Figure 3 compares the DFT-PBE and GW band structures of the LT Pnma phase SnSe using the structure relaxed with the optB86b-vdW functional. The valence band maximum (VBM) is placed at zero in both plots. We employ the Wannier interpolation [39] method to generate the GW band structure using the results calculated on a  $3 \times 9 \times 9$  uniform  $k$ -grid. The PBE functional gives an indirect minimum gap of about 0.46 eV and subsequent GW calculations predicts a gap of 0.83 eV, which agrees rather well with the experimental band gap of 0.86 eV [2]. We mention that the calculated GW band gap is slightly larger (0.87 eV) if the experimental crystal structure [40] is used. The VBM is located between Z and  $\Gamma$  near  $k = [0, 0, 1/3]$ , and the conduction band minimum (CBM) is located between Y and  $\Gamma$  near  $k = [0, 1/3, 0]$ . The band structure of SnSe has been discussed by several groups [3,41,42] and our results are consistent with previous ones.

An interesting feature of the band structure is the existence of several competing local extrema in the band edges that are within an energy window of 0.2 eV. Since these competing band edge states are derived from different atomic states (shown in Fig. 4), they may respond differently to various type of strains, opening up the possibility of

engineering the band edge states via strains. For example, strain may induce an indirect-to-direct band gap and/or semiconductor-metal transitions, as we will discuss later.

Sn  $5s$  derived states (the lone pair states) lie around  $-8.5$  to  $-5.5$  eV (PBE result) but also contribute significantly to the top valence states through hybridization with Se  $4p$  states (Fig. 4a). In particular, the local maximum of the valence band along the  $\Gamma$  to  $Y$  direction (labeled  $\Delta_1$  Fig. 4) shows a strong hybridization between the Sn  $s$  and the Se  $p_y$  orbitals (Fig. 4a and 4e). The VBM state along the  $\Gamma$  to  $Z$  direction (labeled  $\Lambda_1$  Fig. 4), on the other hand, is a result of the hybridization between the Sn  $s$  and the Se  $p_z$  orbitals. (The definition of the Cartesian coordinates is shown in Fig. 1.) These two local maxima are very close in energy. When the system is under strain, their distinct wave function characters lead to rather different behaviors as we will discuss later. The low energy conduction bands are mainly derived from the Sn  $5p$  states (Fig. 4b - 4d) whereas the valence states from  $-5.0$  to  $0$  eV are mostly of Se  $4p$  character with some hybridization with Sn  $5s$  and  $5p$  states. Se  $4s$  states lie at much lower energies ( $-13$  to  $-12$  eV) which are not shown in the figure.

## B. Atomic origin dependent quasiparticle self-energy correction

Considering the different atomic characters of the valence and conduction states, it is not surprising that the GW self-energy correction depends strongly on the atomic origins of these states. Figure 5 shows the energy (and atomic-origin) dependent GW correction  $\Delta E_{nk}^{\text{GW}} = E_{nk}^{\text{GW}} - E_{nk}^{\text{DFT}}$ . For simple materials such as Si or Ge, the GW quasiparticle corrections can sometimes be conveniently modeled with a scissors operator, which typically scales linearly with the band energy [25]. The situation is a little more complex here since different atomic states may have, among other factors, different degrees of localization, thus different self-energy corrections. For example, Se  $4p$  states are slightly more localized than the Sn  $5s$  states. As a result, although the Se  $4p$  derived states are higher in energy, overall they have a greater self-energy correction as shown in Fig. 5. It is interesting that within each group of states (as indicated by the circles in the figure) the self-energy correction depends approximately linearly with the band energy. However, even within each group of states, the deviation of the GW correction from a simple linear scaling is still large ( $\sim \pm 0.1$  eV), stressing the importance of accurate GW calculations.

The distinct atomic characters of the band edge states also give rise to different convergence behaviors of the GW results with respect to various cutoff parameters such as the kinetic energy cutoff ( $E_{\text{cut}}$ ) for the dielectric matrix and the number of conduction bands ( $N_c$ ) included in the GW calculations [43]. It is important to inspect the convergence behavior of the GW results since under-converged results may lead to false predictions. Figure 6 (a) shows the calculated GW band gap (minimum indirect gap) as a function of  $N_c$  and  $E_{\text{cut}}$ . It can be seen that a kinetic cutoff for the dielectric matrix of about 20 Ry ( $\sim 270$  eV) is needed to converge the band gap to about 0.02 eV, and the number of bands requires to converge the GW result is about 3,000 (or 375 per atom). If

a small  $E_{cut}$  of 5 Ry ( $\sim 70$  eV) is used, the minimum gap is predicted to be only about 0.65 eV. Figure 6 (b) shows similar convergence behavior for the direct gap at  $\Gamma$ .

In this work, we have carried out GW calculations for about 20 strained structures. It would be extremely time consuming if the conventional method [25] were used. Recently, we developed an efficient integration method [38] that can drastically speed up fully converged GW calculations. Our method exploits the asymptotic behavior of the density of states (DOS) of materials at high energies and approximates the summation over high-energy conduction bands in both the dielectric function and self-energy calculations by a numerical integration on a sparse energy grid. Using this new method, we have achieved a speed-up factor of about 10 times for small to medium-sized systems, and up to 100 times for large systems containing hundreds of atoms [38].

### C. Engineering the band edge states through uniaxial and biaxial strains

With the above understanding at hand, we now investigate the effects of the uniaxial strain along the lattice  $b$  (zigzag, or  $y$ ) and  $c$  (armchair, or  $z$ ) directions (defined in Fig. 1a) on the electronic structure of SnSe. The crystal structures are fully relaxed under fixed strains using the optB86b functional as we discussed earlier. For uniaxial strains along the zigzag direction, the lattice constant  $c$  decreases from 4.77 Å to 4.17 Å as the strain along the  $b$  direction  $\varepsilon_b$  varies from -8% to 8%; lattice  $a$  changes from 11.59 Å to 11.62 Å.

The dependence of band gap on the uniaxial strain applied along the zigzag and armchair directions is shown in Fig. 7. For the strain applied along the zigzag direction, the GW band gap decreases monotonically from 0.83 eV to 0.22 eV with compressive strains as shown in Fig. 7a. Under tensile strains, the band gap first increases slightly, reaching a maximum value of about 0.92 eV, then the band gap decreases with increasing strain. Perhaps more interesting is that the system becomes a direct gap material under a moderate strain ranging from about 2.5 to 4.5% as shown in Fig. 7a. Defining the band gap deformation potential  $\alpha_\varepsilon = dE_g / d\varepsilon$ , we get  $\alpha_\varepsilon = 7.8$  eV for moderate compressive strains (evaluated at around  $\varepsilon = -4\%$ ) and -6.7 eV for tensile strains (evaluated at around  $\varepsilon = 4\%$ ) along the zigzag direction. The different band gap deformation potential under compressive and tensile strains and the indirect-to-direct band gap transition are a manifestation of the distinct wave function characteristic of the band edge states, which respond rather differently to applied strains, as we have discussed earlier.

To understand the effects of strain on the band edge states, therefore the band gap, we show in Fig. 8 the projected DFT band structures calculated with different strains; Figures 8(a-e) are for uniaxial strains along the zigzag direction, whereas Fig. 8(f-j) are for strains along the armchair direction. We use the Sn semicore  $4d$  as the reference level to align the band structures. For the strain applied along the zigzag direction, the energies of local band extrema at the  $\Lambda_1$  point (labeled as states A and C in Fig. 8c) both move lower as the tensile strain increases. These states are derived from the Se  $p_z$  (state A, local

VBM) and Sn  $p_z$  (state C, local CBM). As the strain increases, lattice  $c$  ( $z$ -direction) shrinks, resulting in the lowering of the energy of these states.

In contrast, the energies of local band extrema at the  $\Delta_1$  point (labeled as states B and D in Fig. 8c) move higher with increasing strain along the zigzag direction. These states are derived from the Se  $p_y$  (state B, local VBM) and Sn  $p_y$  (state D, local CBM). Note that the lattice  $b$  is oriented along the  $y$ -direction as shown in Fig. 1a. As the strain increases, states derived from the  $p_y$  orbitals move higher whereas states derived from the  $p_z$  orbitals move lower. As a result, there is an indirect-to-direct band gap transition at strain ranging from about 2.5% to 4.5%. The position of the CBM changes from  $\Delta_1$  to near  $\Lambda_1$  beyond 4.5% tensile strain. The VBM position, which is located at  $\Lambda_1$  at zero strain, moves to near  $\Delta_1$  under tensile strains greater 2.5%. The charge densities of the four states, namely A, C, B, and D, are shown in Fig. 9 to illustrate their atomic origins. The strain dependence of the energy of these four states are also summarized in Fig. 9.

Interestingly, the two Se  $p_z$  derived valence states near  $\Lambda_1$  (shown in cyan color in the figure) respond differently to strains along the zigzag direction as shown in Fig. 8 (a-e), presumably due to the bonding and antibonding characters of the two states. The opposite movement of the two bands results in the development of two degenerate hole valleys along the  $\Gamma$ -Z direction (or four hole valleys in the Brillouin zone) under about -3% compressive strain as shown in Fig 8b. Another remarkable feature of the strain effects on the electronic structure is the simultaneous development of multiple electron and hole valleys at around 3% of tensile strain as shown in Fig. 8d. Strain-induced multi-valley electronic structure is also predicted for uniaxial strains along the armchair direction (bottom panels of Fig. 8) and for biaxial strains as shown in Fig. 11.

We now discuss briefly the effects of strains  $\epsilon_c$  along the lattice  $c$  (armchair, or  $z$ ) direction. Lattice constant  $a$  changes from 11.73 Å to 11.43 Å and lattice constant  $b$  changes from 4.38 Å to 4.08 Å as  $\epsilon_c$  varies from -8% to 8%. The behavior of the strain-dependent band gap is quite different from the previous case as shown Fig. 7b. The band gap remains nearly constant (within 0.1 eV) when  $\epsilon_c$  varies from -2% to 8%. The gap, however, decreases monotonically for compressive strains beyond -2%. Figures 8(f-j) show the movement of the band edge states under uniaxial strains along the armchair direction. Compared with Fig. 8 (a-e), the valence band edge states near  $\Delta_1$  (Se  $p_y$  derived) and  $\Lambda_1$  (Se  $p_z$ ) show an opposite trend. In other words, the Se  $p_y$  derived states near  $\Delta_1$  moves downward relative to the Se  $p_z$  derived states near  $\Lambda_1$  with increasing strain. As the strain increases from -8% to 8%, the position of the VBM state moves from near  $\Delta_1$  to near  $\Lambda_1$ . The CBM state is of Sn  $p_y$  character for  $\epsilon_c > -1.5\%$ , located at  $\Delta_1$ . For  $\epsilon_c < -1.5\%$ , the Sn  $p_x$  derived state becomes the CBM. It should be pointed out that DFT calculations using the PBE functional predict an insulator-metal transition when the compressive strain exceeds about -8% in both cases. Our GW results suggest, however, that such a transition happens at a much greater strain of about -11%. Therefore, extra



caution must be taken when one attempts to predict an insulator-metal transition using DFT results.

Biaxial strains can be realized in experiments by growing thin film samples on lattice mis-matched substrates. The calculated band gap decreases rapidly under compressive biaxial strains applied on the  $b$ - $c$  (or  $y$ - $z$ ) plane as shown in Fig. 10. Our results indicate that a compressive biaxial strain of less than 4% is able to induce an insulator-metal transition. The rapid closing of the band gap is a result of the reduced bonding-antibonding splitting between the hybridized Se and Sn  $p_x$  states under compressive strains as shown in Fig. 11. The lattice constant  $a$  ( $x$ -direction) expands with the compressive strain, changing from 11.61 Å to 12.52 Å as the biaxial strain varies from 0 to -8%. Since the bonding-antibonding splitting depends strongly on the overlap between the Se and Sn  $p_x$  orbitals, the expanded  $a$  lattice greatly reduces this splitting, thus rapid closing of the band gap with compressive strains. Under tensile strains, the band gap first increases with increasing strain, reaching a maximum value of about 1.25 eV at a 6% tensile strain. The band gap then decreases with further increasing strain because of the downward movement of conduction Sn  $p_z$  states.

Finally, we summarize the strain-dependent number of electron/hole valleys of the Pnma SnSe in Fig. 12, which may provide useful guidance for experimental realization of band-edge state engineering through strains. We mention that the role that multi-valley electronic structure plays in enhancing the thermoelectric properties [44-46] and, in general, exploiting the valley degree of freedom for various applications, have generated a lot of research interest recently. Our results suggest that strains may be an effective (and active) mechanism for tuning the band edge states to obtain multi-valley electronic structures in this and other related systems. In addition, this kind of strain-induced movement of the CBM and VBM states suggests a convenient means to tune the Fermi surface topology and to realize the Lifshitz transition [47-51] in doped SnSe. These abrupt transitions of the topology of the electron or hole pockets under strains shall have profound effects on various thermal and transport properties of doped SnSe and deserve separate studies.

## Conclusion

Control of the near-edge electronic structure, thus materials electronic, transport and optical properties, is of fundamental importance for materials design and optimization for a wide-range of applications. Layered structure SnSe, with its feature-rich chemical bonding, offers a unique system for strain engineering and active control of the near-edge electronic structure. Using a combined DFT and GW approach, we illustrate how the energy the band edge states with distinct atomic characters can be selectively manipulated by applying different strains. As a result, both the size and the nature (i.e., direct or indirect) of the band gap can be engineered with moderate strains. The band gap can be broadly tuned from zero to 1.2 eV. More interestingly, we propose that strain can be an effective means to realize multi-valley electronic structures, providing another mechanism for optimizing SnSe for both electronic and transport applications. It is likely

that the predicted strain-engineering of the electronic structure be more easily realized in experiment for structures with reduced dimensions including thin films, nanocrystals and nanowires. The general results we present here should be applicable for these structures as long as quantum confinement does not strongly affect their electronic and structural properties.

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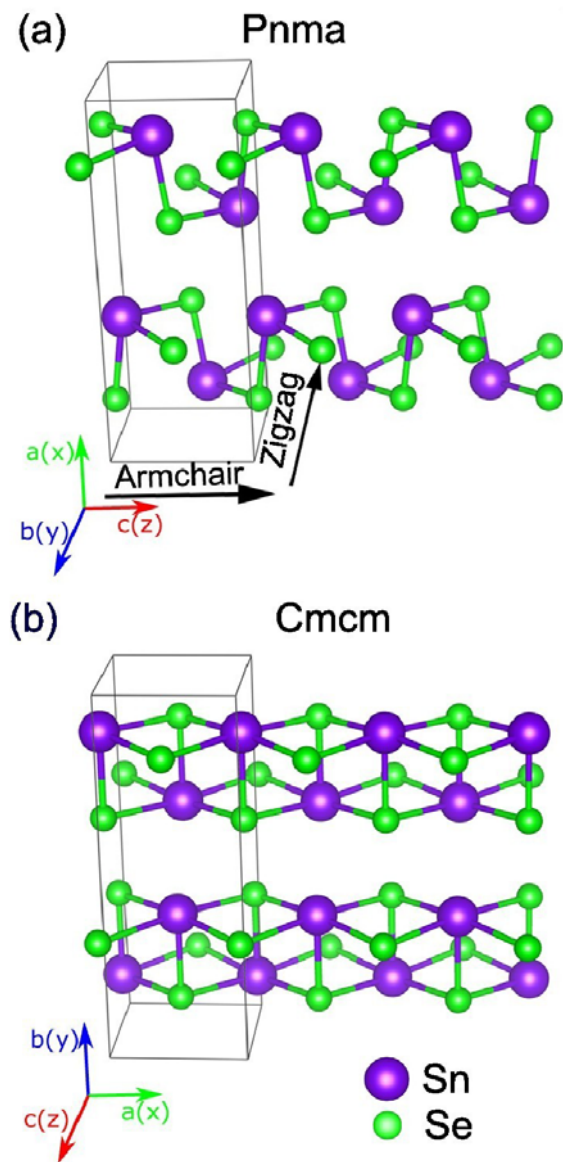


Fig. 1. Crystal structures of orthorhombic SnSe. (a) Low-temperature Pnma phase, (b) high-temperature Cmcm phase.

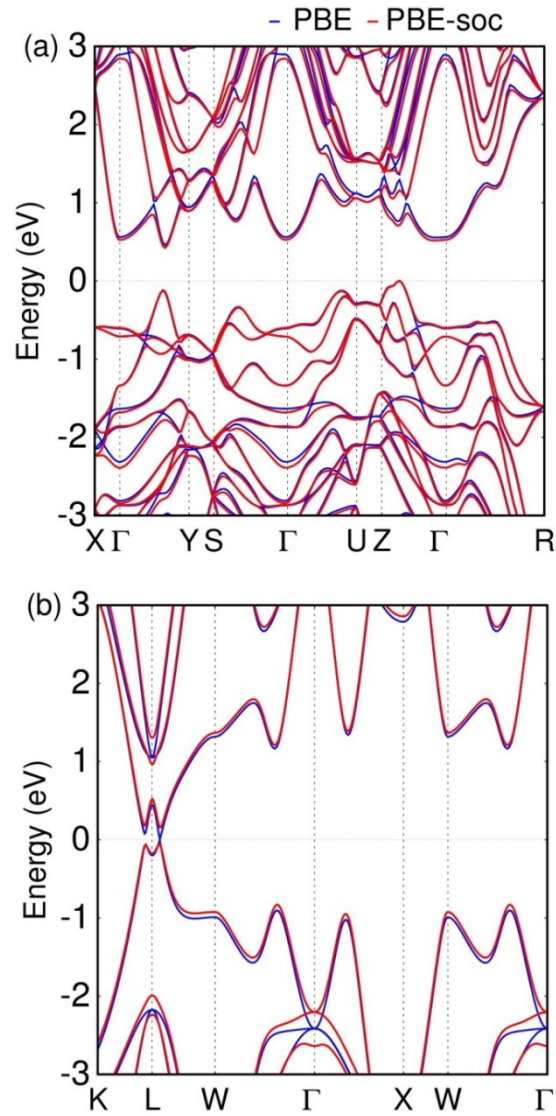


Fig. 2. Calculated band structures of SnSe with (shown in red) and without (shown in blue) including the spin-orbital coupling effect for the low symmetry Pnma SnSe (left panel) and high symmetry rock-salt SnSe (right panel).

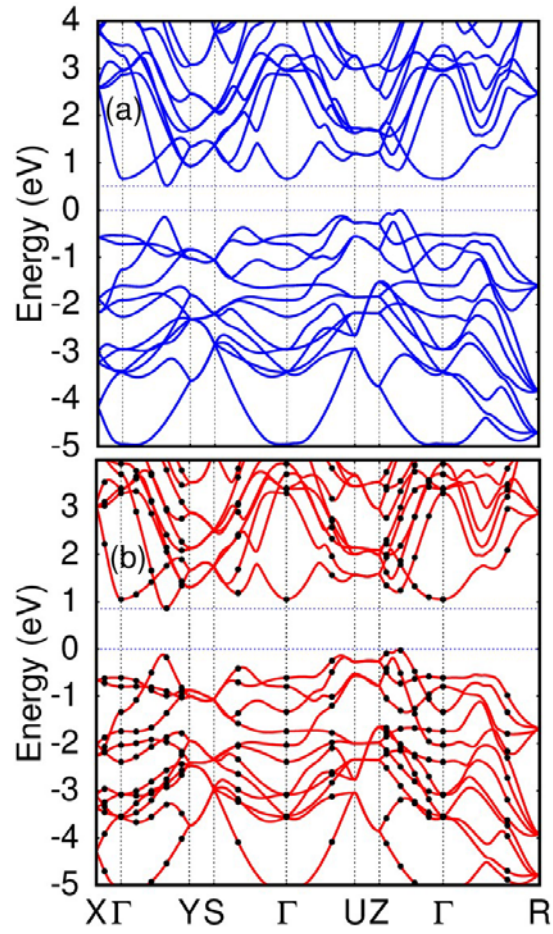


Fig. 3. Band structure of LT Pnma SnSe calculated using (a) the PBE functional and (b) the GW approximation. The black dots in (b) are the calculated GW energies, and red lines are the Wannier interpolated GW band structure.



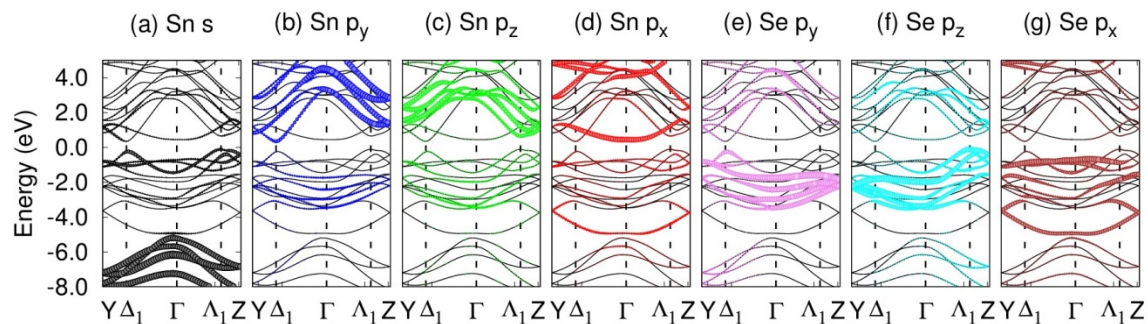


Fig. 4. Projected band structure of LT Pnma SnSe showing the distinct atomic characters of the low energy valence and conduction states.

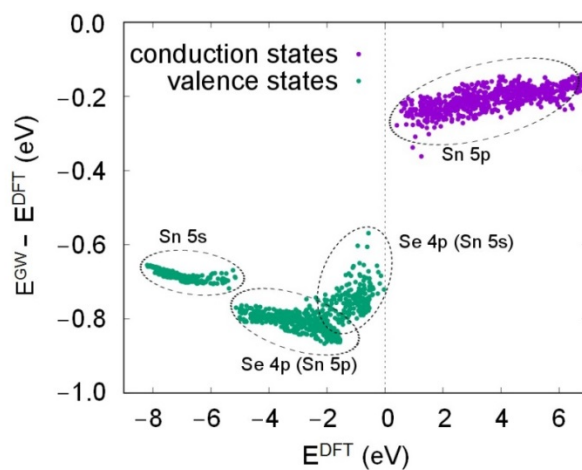


Fig. 5. Quasiparticle corrections to the Kohn-Sham DFT eigenvalues of LT Pnma SnSe. The distinct atomic-origin dependence of the self-energy correction is emphasized by circles indicating the primary atomic characters of the states.

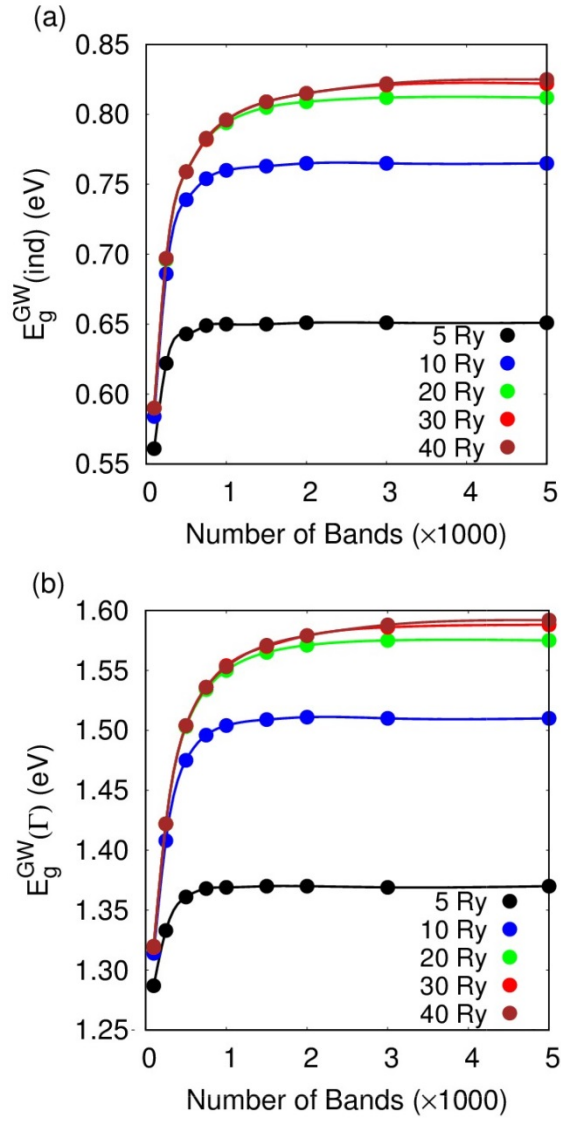


Fig 6. Calculated quasiparticle band gap of LT phase SnSe as a function of the number of empty states included in the GW calculations and the kinetic energy cutoff for the dielectric matrices. (a) Minimum indirect band gap; (b) direct gap at the  $\Gamma$  point.

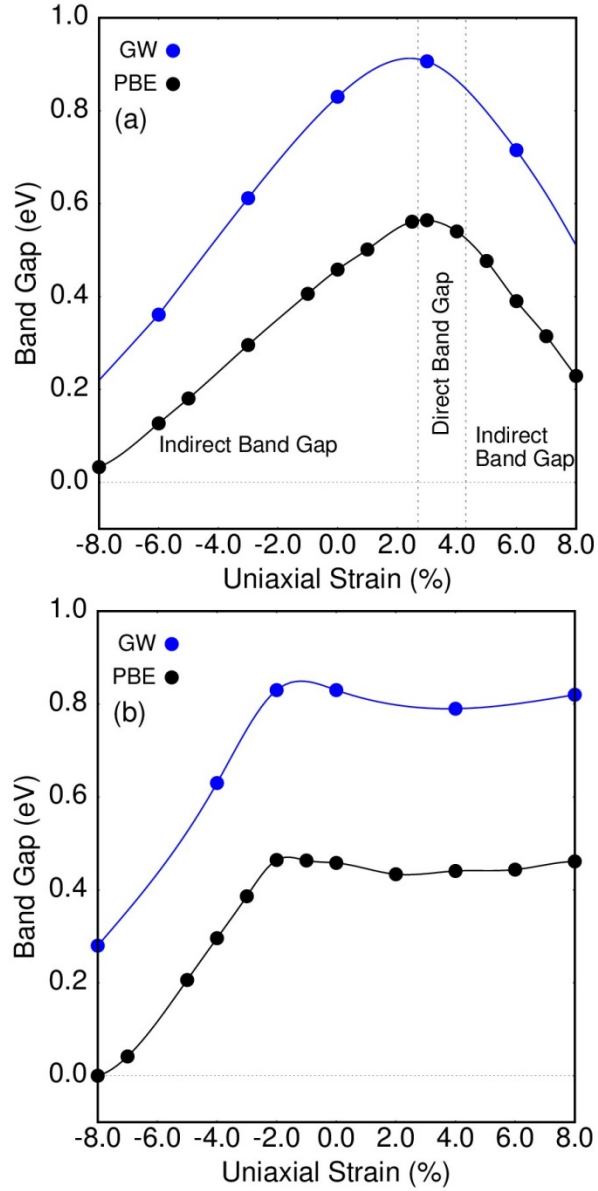


Fig. 7. Strain-dependent band gap of LT phase SnSe under uniaxial strain along (a) the zigzag (lattice  $b$ ) direction, and (b) the armchair (lattice  $c$ ) direction. GW results are shown in blue, and PBE results in black.

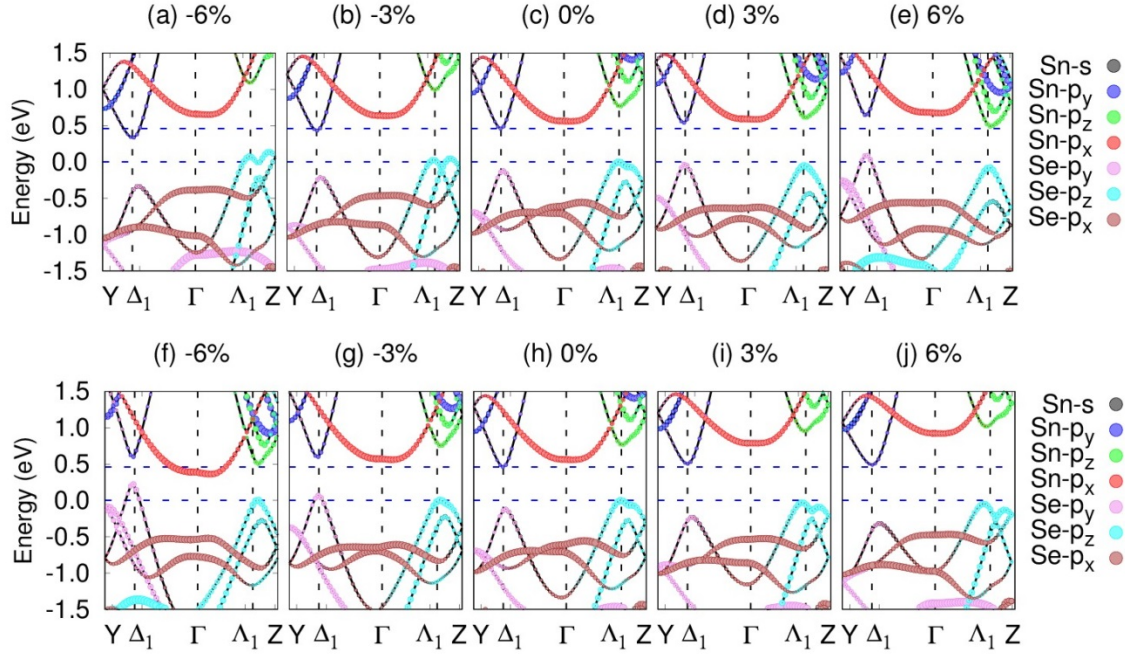


Fig. 8. Projected band structure of LT phase SnSe calculated using the PBE functional under strains along the zigzag direction (upper panels) and the armchair direction (bottom panels).

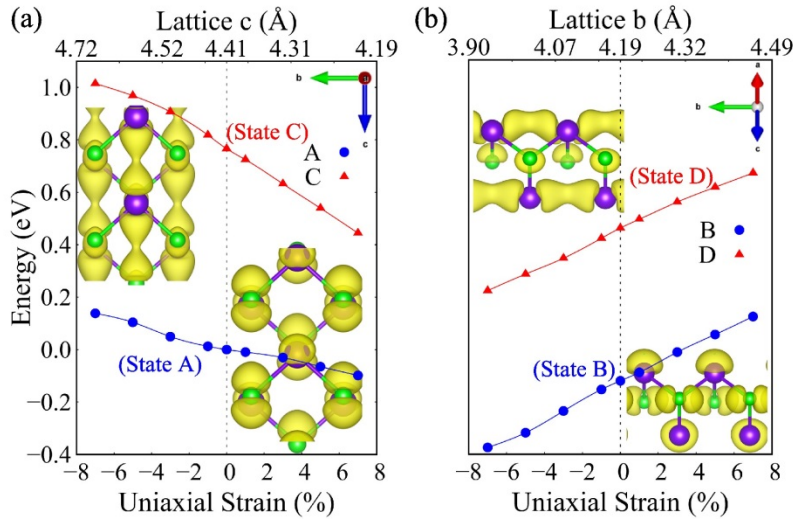


Fig. 9. Charge densities of the four local extrema labeled A, C, B, D and their strain-dependence, illustrating their distinct wave function characters and response to lattice strains.

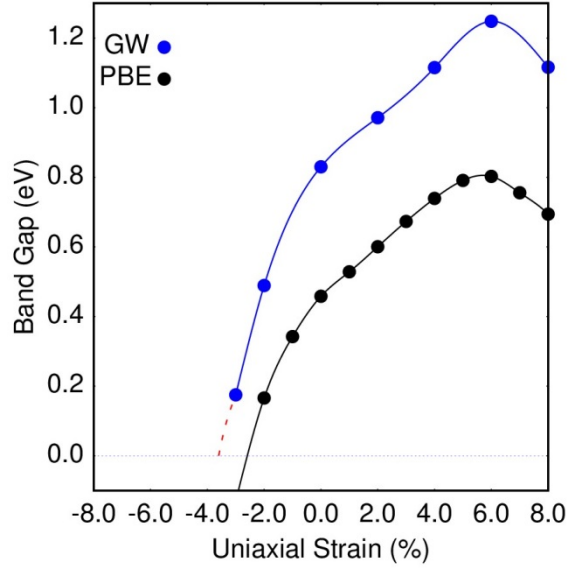


Fig. 10. Variation of the band gap of LT phase SnSe under the biaxial strain applied on the  $bc$  plane. The GW results are shown in blue, and the DFT-PBE results in black.

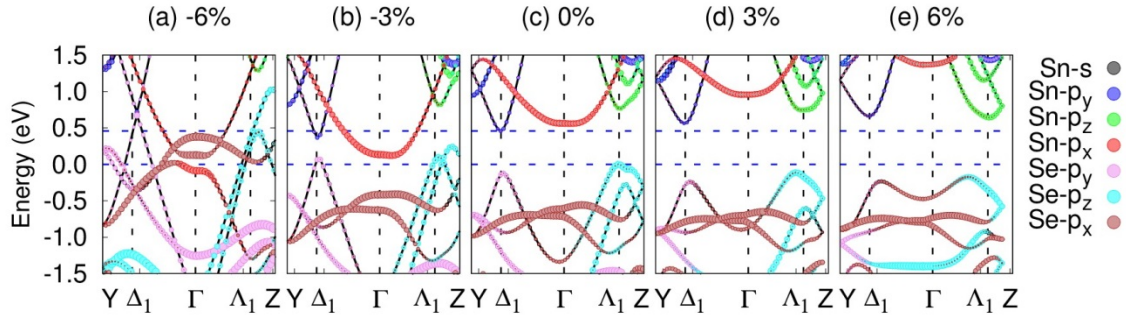


Fig. 11. Projected band structure of LT phase SnSe calculated using the PBE functional under the biaxial strain on the  $bc$  plane.

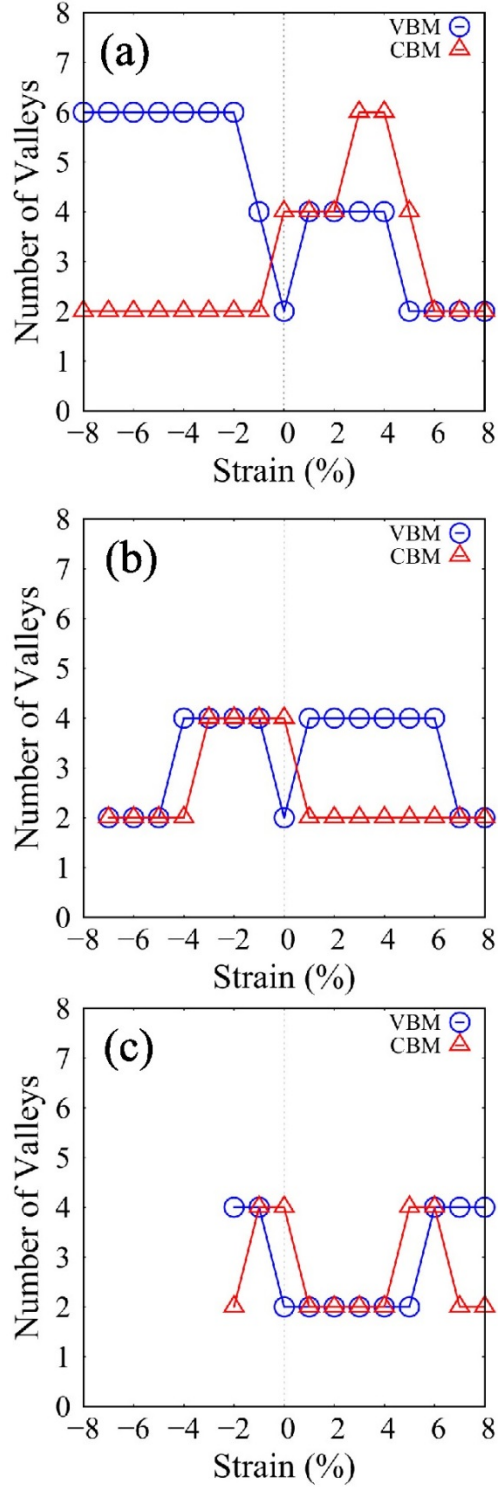


Fig. 12. Number of electron/hole valleys of the Pnma phase SnSe as a function of (a) strain along the zigzag (i.e., lattice *b*) direction, (b) strain along the armchair (i.e., lattice *c*) direction, and (c) biaxial strain (i.e., *bc* plane).