Sulfur-alloyed Cr$_2$O$_3$: a new p-type transparent conducting oxide host

Samira Dabaghmanesh,$^{*}$a,b,c Rolando Saniz,a Erik Neyt$^b$ and Bart Partoens$^a$

Doped Cr$_2$O$_3$ has been shown to be a p-type transparent conducting oxide (TCO). Its conductivity, however, is low. As for most p-type TCOs, the main problem is the high effective hole mass due to flat valence bands. We use first-principles methods to investigate whether one can increase the valence band dispersion (i.e. reduce the hole mass) by anion alloying with sulfur, while keeping the band gap large enough for transparency. The alloying concentrations considered are given by Cr$_{x}$S$_{2}$O$_{4-x}$, with $x = 1-5$. To be able to describe the electronic properties of these materials accurately, we first study Cr$_2$O$_3$, examining critically the accuracy of different density functionals and methods, including PBE, PBE+U, HSE06, as well as perturbative approaches within the GW approximation. Our results demonstrate that Cr$_{2}$S$_{2}$O$_{4}$ has an optical band gap of 3.08 eV and an effective hole mass of 1.8 m$_e$. This suggests Cr$_{2}$S$_{2}$O$_{4}$ as a new p-type TCO host candidate.

1 Introduction

There exist many theoretical and experimental studies on transparent conducting oxides (TCOs). The interest stems mainly from the fact that these materials offer both optical transparency and electrical conductivity for optoelectronics applications. According to the type of carriers that mainly contribute to the conductivity, the TCOs are divided into p-type, i.e. hole conducting, and n-type, i.e. electron conducting. To date, the n-type TCOs, with application in optoelectronic devices, solar cells, organic light emitting diodes (OLEDs), and sensors, see ref. 1 and references therein, have received more attention rather than p-type's. However, advanced applications of TCOs requiring p-n junctions, such as the active electronic devices, bipolar transistors and diodes, are still severely limited due to the lack of efficient p-type TCOs.$^{1,2}$

Generally, p-type TCOs suffer from low conductivity compared to their n-type counterparts. In contrast to the latter, developing a p-type TCO has always been challenging. The main reason for the low hole conductivity in most of these oxides is that the top of the valence band is dominated by oxygen p-states, which are highly localized and lead to flat bands and consequently a large effective hole mass.$^3$

The CuAlO$_2$ delafossite was reported by Kawazoe et al.$^4$ as the first TCO with p-type conductivity and transparency in the visible range. This study opened a route to look for further p-type Cu-delafossites structures such as CuMO$_2$ M ∈ {Ga, Sc, B, Cr}.$^5$ The highest p-type conductivity, 220 S cm$^{-1}$ (resistivity of 0.45 $\times$ 10$^{-2}$ $\Omega$ cm), in this family has been reported in the case of Mg-doped CuCrO$_2$ (CuCrO$_2$:Mg).$^6$ In comparison with the best reported n-type TCO, Sn-doped In$_2$O$_3$, with a conductivity of the order of 10$^5$ S cm$^{-1}$ (ref. 9), this amount of conductivity is very low. The spinel ZnRh$_2$O$_4$ (ref. 10) and distorted delafossite SrCu$_2$O$_3$ (ref. 11) are the other examples of p-type TCOs, with conductivities of 2.75 S cm$^{-1}$ and 0.053 S cm$^{-1}$ respectively.

Cr$_2$O$_3$ has been considered as a candidate p-type TCO host in several studies. Doping with Ni$^{12,14}$ and with Li$^{15,15}$ have been shown to induce p-type conductivity in Cr$_2$O$_3$. Cr$_2$O$_3$:N has received attention for applications in optoelectronic devices, in particular, as hole transporting layer in organic solar cells.$^{16,17}$ Farrell et al.$^{18}$ investigated the possibility of using dopants to create a p-n homojunction with Cr$_2$O$_3$. These authors studied the influence of Mg dopants and oxygen pressure in Cr$_2$O$_3$ as a p-type TCO.$^{18}$ Arca et al.$^{19,20}$ used a co-doping mechanism to obtain a Cr$_2$O$_3$-based p-type TCO. They investigated the conductivity and transparency of Cr$_2$O$_3$ by co-doping with Mg and N impurities. They found a resistivity of 3 $\Omega$ cm and an optical transmission up to 65% for a 150 nm thick Cr$_2$O$_3$ film. These properties are low compared to those reported for CuCrO$_2$:Mg and n-type TCOs.

Chromia, Cr$_2$O$_3$, has the corundum structure, with a rather large experimental optical gap of 3.3–3.4 eV.$^{21,22}$ However, the flat non-dispersed nature of the valence band of Cr$_2$O$_3$ causes a large hole effective mass, of the order of 12–13 m$_e$ at the valence band maximum (VBM).$^{23,24}$ resulting in the relatively poor conductivity of doped Cr$_2$O$_3$.

A general idea to improve the p-type conductivity in oxides was proposed by Hosono in 2007.$^3$ He proposed to increase the
VB dispersion by anion alloying, i.e., forming hybridized orbitals between O 2p states and chalcogen p orbitals (S, Se, and Te) which are more delocalized than O 2p orbitals. The hybridization is expected to lead to an increase in the VB dispersion, resulting in a smaller effective hole mass and, consequently, a higher mobility and conductivity. In this study we follow this idea to try to find new Cr₂O₃-based p-type TCO host candidates. We use first-principles techniques to investigate the effect of partially substituting oxygen atoms with sulfur. Since our main goal is to improve Cr₂O₃ as a p-type TCO host, we should keep in mind that increasing the VBM dispersion may close the gap and reduce the optical transparency of the host. In order to obtain both critical properties for a p-type TCO host, i.e., a large enough band gap (larger than 3 eV) and low hole mass, we consider different concentrations of sulfur. Applying state of the art ab initio techniques we study the compounds CrₓSₓO₆₋ₓ, with x = 1–5. The most advantageous properties are obtained for x = 2, Cr₂S₂O₄, having a much lower hole effective mass (1.8 m₀) than Cr₂O₃ (12–13 m₀), and with a gap still larger than 3 eV (3.08 eV).

The paper is organized as follows: in Section 2 we present the methods and approaches we used in our work. In Section 3 we discuss the results and we end the paper with concluding remarks in Section 4.

2 Methods

Within a density functional theory (DFT) approach and using the plane-wave basis sets and the projector augmented-wave method²⁵ we obtain the structural and electronic properties of Cr₂O₃ and CrₓSₓO₆₋ₓ (x = 1–5) compounds. All the calculations were performed using the VASP (Vienna Ab-initio Simulation Package) code.²⁶–²⁹ To the best of our knowledge, there exist no experimental data for any of the CrₓSₓO₆₋ₓ cases in the literature to compare with. In order to select the best computational scheme for the CrₓSₓO₆₋ₓ cases, we first examine various approaches for Cr₂O₃ and compare the results with experiment. The spin polarized generalized gradient approximation of Perdew–Burke–Ernzerhof (PBE) is used for the exchange correlation functional.³⁰ In order to correct the strong correlation effects in the partially occupied Cr d states a +U correction is used in the form proposed by Dudarev et al.³¹ First, we performed geometry optimization, total energy, band structure and density of states calculations based on PBE and PBE+U. We used various U parameter values, as proposed in previous studies on Cr₂O₃,²³,³²,³³ and compared them with the results obtained with the hybrid functional approach proposed by Heyd, Scuseria, and Ernzerhof (HSE)³⁴ with the screening parameter μ = 0.2 Å⁻¹ (HSE06).³⁵ Next we compared all PBE, PBE+U, and HSE06 results with two levels of approximation within the perturbative GW approach,²⁶ as implemented in the VASP code.²⁷–²⁸ In the first level, Kohn–Sham eigenvalues and eigenfunctions are used to compute the Green’s function G and screened Coulomb interaction W in a single step (GₜWₜ). In the second level, the eigenvalues in the Green’s functions are updated self consistently (scGWₜ). In the case of PBE, PBE+U, and HSE06 we used a 8 × 8 × 8 k-point grid for total energy and structure optimization calculations, and a 21 × 21 × 21 grid for the density of states calculations. A cutoff energy of 500 eV was used for the plane-wave basis set. Both lattice parameters and atom coordinates are relaxed. For the electronic structure calculation we considered the results as converged when the energy difference between two successive steps was smaller than 10⁻⁶ eV and for the geometry optimization we considered a convergence criterium for the forces on the atoms of less than 0.01 eV Å⁻¹. For the GW calculations, a 4 × 4 × 4 k-point grid was used. Convergence of the band gap was checked. The number of bands was increased to 1500 in GW calculations based on the convergence test. In the partially self-consistent GW (scGWₜ) four steps were found to be enough for the convergence of the band gap energy within 0.01 eV.

3 Results and discussion

3.1 Cr₂O₃

Cr₂O₃ has a rhombohedral primitive cell with 2 formula units, cf. Fig. 1(a). Oxygen atoms form a hexagonal close-packed structure while Cr atoms occupy two-thirds of the interstitial octahedral sites.⁴⁰ In its ground state, Cr₂O₃ adopts the R3c structure⁴¹,⁴² and is antiferromagnetic (AFM), with a Néel temperature of 308 K.⁴³ The magnetic structure corresponds to a + − + − spin sequence on the Cr atoms along the c-axis.⁴⁴,⁴⁵

The calculated lattice constants, magnetic moments, and direct band gap, calculated with the different DFT methods mentioned above, are compared with experiment in Table 1. For the PBE+U calculations we employed U parameters as proposed in the ref. 23, 32 and 33. Ref. 32 proposed U = 3 eV and ref. 33 used U = 5 eV and J = 1 eV for the on-site Coulomb-repulsion and exchange integral for the Cr d electrons. In ref. 23, the authors proposed a +U correction of Uₜₗₜ = 3 eV and Uₜₗₜ = 5 eV for the Cr 3d and O 2p states by comparing the electronic density of states (EDOS) of Cr₂O₃ with their experimental spectra obtained using ultra violet photoemission spectroscopy and X-ray photoemission spectroscopy. The PBE and PBE+U methods tend to overestimate the lattice parameters while underestimating the band gap compared to experiment. We compared the band structure and density of states obtained using three U parameter values with experiment. The experimental valence band-width, measured by XPS, is about 9 eV.
We found that $U_{\text{Cr}d} = 3$ eV and $U_{\text{Op}} = 5$ eV, proposed in ref. 23, gives a larger band gap, wider band width (i.e. almost 6 eV), and narrower second gap inside the valence band compared to the other $U$ parameters and in better agreement with experiment. Henceforth, we use these $U$ parameters for all our results in the case of PBE+U calculations. Fig. 2 and 3 show the band structures, total EDOS and partial density of states PEDOS of Cr$_2$O$_3$ calculated with the PBE, PBE+U, and HSE06 approximations. Since HSE06 overestimates the band gap (by about 1 eV) using the standard Hartree–Fock mixing parameter ($\alpha = 0.25$), we tuned the $\alpha$ parameter. We found that the optimized value $\alpha = 0.17$ gives the experimental band gap (3.4 eV). The calculated VB width obtained by HSE06 (about 7.22 eV) is wider than the PBE and PBE+U methods, in better agreement with experiment. HSE06 also gives the second gap in good agreement with the DOS obtained by Robertson et al. using the screened exchange (sX) hybrid density functional. In order to find a reliable predictor for the band gap of the Cr$_x$S$_{6-x}$O$_6$ compounds, we also calculate the band gap of Cr$_2$O$_3$ using two flavors of the GW approximation, $G_0W_0$ and scGW$_0$, as indicated above. We used as input for these the eigenvalues and eigenfunctions of both PBE and PBE+U. In Table 2 we summarize our results. Clearly, $G_0W_0$ largely overestimates the band gap whenever PBE+U results are used as the starting point, independently of the $U$ values used. On the other hand, the band gap is underestimated when PBE results are used as a starting point. Updating $G$ self-consistently (scGW$_0$) on top of PBE as the starting point gives the direct band gap of 3.55 eV, which is close to HSE06 and experimental results. We also performed scGW$_0$ on top of PBE+U, using the optimum $U$ values mentioned before, and found a largely overestimated band gap of 4.489 eV. Fig. 4 shows the scGW$_0$ quasiparticle energies (red dots) for several $k$-points on top of PBE band structure (blue lines). We see that scGW$_0$ opens the gap by moving both the conduction and valence bands, up and down respectively. ScGW$_0$ on top of PBE gives the wider band width (about 7.45 eV) compared to PBE, PBE+U, and HSE06 approaches, and closer to experiment. Also, the PBE second band gap tends to be closed by scGW$_0$, again bringing it closer to experiment. Comparing these key properties, band gap, band

Table 1  Optimized lattice parameters $a$ and $c$ in Å and degree, magnetic moments, and direct band gap $E_g$ in eV, of the Cr$_2$O$_3$ bulk, for different DFT functionals, PBE, PBE+U, HSE06 and experimental values

<table>
<thead>
<tr>
<th>Method</th>
<th>$a$</th>
<th>$c$</th>
<th>$\mu$</th>
<th>$E_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBE</td>
<td>5.40</td>
<td>54.12</td>
<td>2.51</td>
<td>1.44</td>
</tr>
<tr>
<td>PBE+U ($U_{\text{Cr}d} = 3$)</td>
<td>5.42</td>
<td>55.08</td>
<td>2.78</td>
<td>2.60</td>
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<tr>
<td>PBE+U ($U_{\text{Cr}d} = 5$)</td>
<td>5.43</td>
<td>55.19</td>
<td>2.83</td>
<td>2.89</td>
</tr>
<tr>
<td>PBE+U ($U_{\text{Cr}d} = 3$, $U_{\text{Op}} = 5$)</td>
<td>5.40</td>
<td>55.01</td>
<td>2.80</td>
<td>2.80</td>
</tr>
<tr>
<td>HSE06 ($\alpha = 0.17$)</td>
<td>5.36</td>
<td>55.15</td>
<td>2.85</td>
<td>3.4</td>
</tr>
<tr>
<td>Experiment</td>
<td>5.35 (ref. 39)</td>
<td>55.12 (ref. 39)</td>
<td>3.8 (ref. 40)</td>
<td>3.4 (ref. 21 and 22)</td>
</tr>
</tbody>
</table>

Fig. 2  (a) PBE (b) PBE+U ($U_{\text{Cr}d} = 3$ eV, $U_{\text{Op}} = 5$ eV) and (c) HSE06 band structure of Cr$_2$O$_3$. The VBM is set to 0.

Fig. 3  (a) PBE+U ($U_{\text{Cr}d} = 3$ eV, $U_{\text{Op}} = 5$ eV) and (b) HSE06 calculated total (states per eV per unitcell) and partial (states per eV per atom) density of states of Cr$_2$O$_3$. The VBM is aligned to 0.

Fig. 4  (a) PBE+U ($U_{\text{Cr}d} = 3$ eV, $U_{\text{Op}} = 5$ eV) and (b) HSE06 calculated total (states per eV per unitcell) and partial (states per eV per atom) density of states of Cr$_2$O$_3$. The VBM is aligned to 0.
Table 2  Direct band gap in eV of the Cr2O3 bulk, calculated with single shot G0W0 and partially self consistent scGW0 using different approximations as the starting point.

<table>
<thead>
<tr>
<th>Method</th>
<th>G0W0</th>
<th>scGW0</th>
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</thead>
<tbody>
<tr>
<td>PBE</td>
<td>2.845</td>
<td>3.556</td>
</tr>
<tr>
<td>PBE+U (U_Crz = 3)</td>
<td>4.20</td>
<td>—</td>
</tr>
<tr>
<td>BE+U (U_Crz = 5)</td>
<td>4.58</td>
<td>—</td>
</tr>
<tr>
<td>PBE+U (U_Crz = 3, U_Ox = 5)</td>
<td>4.238</td>
<td>4.489</td>
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</table>

Table 3  Optimized lattice parameters in Å and α, β, γ in deg, magnetic moment in μB, and fundamental band gap E_g in eV of CrxS4O6−x calculated using the PBE+U (U_Crz = 3 eV, U_Ox = 5 eV) method.

<table>
<thead>
<tr>
<th>Compound</th>
<th>α, β, γ</th>
<th>μ</th>
<th>E_g</th>
</tr>
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<tr>
<td>CrxSO3</td>
<td>5.38, 5.55, 5.55</td>
<td>55.92, 54.55, 54.55</td>
<td>±2.93, ±2.99</td>
</tr>
<tr>
<td>CrxS2O4</td>
<td>6.08, 5.65, 5.65</td>
<td>57.31, 54.56, 54.56</td>
<td>±3, ±3</td>
</tr>
<tr>
<td>CrxS3O3</td>
<td>6.21, 5.75, 6.04</td>
<td>56.66, 54.11, 55.41</td>
<td>3, −2.98, −3.04, 3.06</td>
</tr>
<tr>
<td>CrxS4O5</td>
<td>6.37, 5.16, 6.16</td>
<td>55.72, 54.02, 54.02</td>
<td>±2.99, ±3.09</td>
</tr>
<tr>
<td>CrxS5O6</td>
<td>6.43, 6.25, 6.43</td>
<td>55.76, 54.44, 55.76</td>
<td>±3.04, ±3.08</td>
</tr>
</tbody>
</table>
when substituting two oxygen atoms with sulfur atoms: (i) replacing two S atoms on opposite planes by O (atoms a and c) and (ii) on the same plane (atoms a and b) (see Fig. 1(b)). We found that the first configuration is considerably more stable energetically, with an energy difference of 0.83 eV. Table 4 presents the optimized lattice parameters, magnetic moments and direct band gaps of Cr$_4$S$_2$O$_4$ obtained using the HSE06 and scGW$_0$ approaches. PBE and PBE+U results are included for completeness (for the scGW$_0$ calculations we use the PBE lattice parameters). The results show that the HSE06 band gap is close to the scGW$_0$ gap (the difference being 0.19 eV). This indicates that the HSE06 ($\alpha = 0.25$) electronic structure is reliable. In Fig. 6, we show the band structure of Cr$_4$S$_2$O$_4$ calculated using (a) PBE+U and (b) HSE06. This shows that the valence band dispersions from the two methods are very similar. We therefore calculate the hole mass of Cr$_4$S$_2$O$_4$ using the PBE+U method. We find that the average hole effective mass at the VBM is 1.8 m$_e$ in the directions of $G$–$X$ and $M$–$G$.

The effect of sulfur on the electronic structure can be better understood as follows. The total EDOS and the Cr 3d, O 2p and S 3p partial PEDOS calculated with (a) PBE+U and (b) HSE06 are shown in Fig. 7. We can divide the valence region into the two energy regions. The first region, with $-7$ eV $< E < -2.8$ eV, consists mainly of O 2p and Cr 3d electrons, with a smaller contribution from S 3p (PBE+U and HSE06 show almost the same contribution). The second region, close to the valence band maximum, with $-2.8$ eV $< E < 0$, shows the Cr 3d electrons play the leading role, with a smaller mixing of O 2p and S 3p electrons. The conduction band minimum (CBM) is mainly composed of Cr 3d electrons with very small contributions from O 2p and S 3p electrons. The partial density of states shows a significant mixing of O 2p and S 3p toward the VBM. This leads to delocalization of the hole states and increasing the dispersion of the VBM compared to Cr$_2$O$_3$ (see Fig. 8). The higher VBM dispersion leads to significantly smaller hole mass, 1.8 m$_e$ compared to 13 m$_e$ in Cr$_2$O$_3$ (i.e., more than 7 times smaller). An equally large increase in mobility can be expected. Furthermore, in Fig. 8 we align the Cr$_2$O$_3$ and Cr$_4$S$_2$O$_4$ PEDOS according to the position of the O 2s level. This shows that replacing oxygen with sulfur shifts the VBM upwards and is the

![Fig. 5](image1.png) Band structures of Cr$_4$S$_x$O$_{6-x}$ ($x = 0$–$5$) calculated using PBE+U ($U_{Cr} = 3$ eV, $U_{O} = 5$ eV). The blue and grey curves show the spin up and down. The VBM is aligned to 0.

![Fig. 6](image2.png) The band structure of Cr$_4$S$_2$O$_4$ calculated by (a) PBE+U ($U_{Cr} = 3$ eV, $U_{O} = 5$ eV) and (b) HSE06. The VBM is aligned to 0.

![Fig. 7](image3.png) Total (states per eV per unitcell) and partial (states per eV per atom) density of states of Cr$_4$S$_2$O$_4$ calculated using (a) PBE+U ($U_{Cr} = 3$ eV, $U_{O} = 5$ eV) (b) HSE06 methods. The VBM is aligned to 0.

### Table 4

<table>
<thead>
<tr>
<th>Method</th>
<th>$a$, $b$ (Å)</th>
<th>$a$, $\beta$ (deg)</th>
<th>$\mu$ (μB)</th>
<th>$E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBE</td>
<td>5.96, 5.62</td>
<td>56.77, 53.68</td>
<td>$\pm 2.55$</td>
<td>1.09</td>
</tr>
<tr>
<td>PBE+U ($U_{Cr} = 3$ eV, $U_{O} = 5$ eV)</td>
<td>6.08, 5.65</td>
<td>57.31, 54.56</td>
<td>$\pm 3$</td>
<td>1.77</td>
</tr>
<tr>
<td>HSE06 ($\alpha = 0.25$)</td>
<td>6.00, 5.58</td>
<td>57.28, 54.55</td>
<td>$\pm 2.95$</td>
<td>2.89</td>
</tr>
<tr>
<td>scGW$_0$</td>
<td>5.96, 5.62</td>
<td>56.77, 53.68</td>
<td>$\pm 2.66$</td>
<td>3.08</td>
</tr>
</tbody>
</table>

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main reason for the band gap decrease with sulfur alloying. On the other hand, a higher VBM (smaller ionization potential) should make p-type dopability easier.\textsuperscript{3}

We now address the stability of Cr$_2$S$_2$O$_4$. We obtained the mixing enthalpy $\Delta H$ from the calculated total energy of each compound\textsuperscript{22}

$$\Delta H = 3E_{tot}(\text{Cr}_2\text{S}_2\text{O}_4) - 4E_{tot}(\text{Cr}_2\text{O}_3) - 2E_{tot}(\text{Cr}_2\text{S}_3)$$  \hspace{1cm} (1)

We found a mixing enthalpy of 144 meV per atom. The positive $\Delta H$ indicates that the ground state of Cr$_2$S$_2$O$_4$ at zero temperature corresponds to phase separation to Cr$_2$O$_3$ and Cr$_2$S$_3$. However, at finite temperatures, the mixing entropy will tend to stabilize Cr$_2$S$_2$O$_4$. Note, however, that the lattice mismatch between Cr$_2$O$_3$ and Cr$_2$S$_3$ is large nearly 23%. This is one of the main reasons why the mixing entropy above is high. But this large lattice mismatch can be exploited to stabilize Cr$_2$S$_2$O$_4$. Indeed, if grown on suitable substrate (e.g. by epitaxy), phase separation can be avoided because of this would require overcoming high kinetic energy barriers.\textsuperscript{32} Al$_2$O$_3$ and stainless steel are popular substrates used to grow Cr$_2$O$_3$.\textsuperscript{33-35} These materials can also be appropriate substrates for Cr$_2$S$_2$O$_4$. For instance, Al$_2$O$_3$ in its trigonal phase\textsuperscript{36} has only 4% lattice mismatch with Cr$_2$S$_2$O$_4$ and is thus a reasonable candidate. Stainless steel is composed of different oxides, i.e. Cr, Fe, Ni, Co, and depending on growth conditions the surface can be covered by one of the oxides. In the case of, for example, Fe$_2$O$_3$ which has the same structure as Cr$_2$O$_3$ (corundum) and similar lattice constant (2% different) with Cr$_2$S$_2$O$_4$, stainless steel could be a good candidate as well. Note, however, that deciding on a substrate requires the latter to have not only appropriate lattice constant but also suitable electronic and thermodynamic properties. This requires further works going beyond the scope of this paper.

### 4 Concluding remarks

We investigated the possibility of improving the properties of Cr$_2$O$_3$ as a p-type TCO host by anion alloying with sulfur. We employed different DFT approaches, namely PBE, PBE+U, HSE06, as well as GW approximation methods, in order to obtain the structural, electronic and magnetic properties of both pristine Cr$_2$O$_3$ and sulfur-alloyed Cr$_{3-2x}$S$_x$O$_{6-x}$ ($x = 1-5$). We demonstrated that substituting oxygen atoms with sulfur can overcome the issue of the flat VBM in Cr$_2$O$_3$ and induce a highly-curved VBM, while preserving the transparency. Indeed, we found that Cr$_{3-2x}$S$_x$O$_{6-x}$ is the best candidate among the sulfur concentrations considered, with an optical band gap of 3.08 eV and average effective hole mass of 1.8 m$_c$. Although the stability of this material has not yet being confirmed experimentally, we think our study presents an incentive for future theoretical and experimental works.

### Acknowledgements

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### References

53 The lattice mismatch between Cr$_2$O$_3$ and Cr$_3$S$_3$ is as follows: $(\bar{a}_{\text{Cr}_2\text{S}_3})_\text{O}_3 - \bar{a}_{\text{Cr}_2\text{O}_3} = 7\%$ and $(\bar{a}_{\text{Cr}_2\text{S}_3})_\text{Cr}_3\text{S}_3 - \bar{a}_{\text{Cr}_2\text{S}_3} = 13\%$, where $\bar{a}_{\text{Cr}_2\text{S}_3}$ is the average of lattice parameters of Cr$_2$S$_3$O$_4$, i.e. $a = 6$ Å, $b = 5.58$ Å, and $c = 5.58$ Å. The lattice parameters of Cr$_2$O$_3$ and Cr$_3$S$_3$ are $a = 5.366$ Å and $a = 6.61$ Å respectively. Note that the above are HSE06 values.