Superconducting dome associated with the suppression and re-emergence of charge density wave states upon sulfur substitution in CuIr$_2$Te$_4$ chalcogenides

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Abstract

We report the path from the charge density wave (CDW)-bearing superconductor CuIr$_2$Te$_4$ to the metal insulator transition (MIT)-bearing compound CuIr$_2$S$_4$ by chemical alloying with the gradual substitution of S for Te. The evolution of structural and physical properties of the CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq$ x $\leq$ 4) polycrystalline system is systematically examined. The x-ray diffraction (XRD) results imply CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq$ x $\leq$ 0.5) crystallizes in a NiAs defected trigonal structure, whereas it adapts to the cubic spinel structure for 3.6 $\leq$ x $\leq$ 4 and it is a mixed phase in the doping range of 0.5 $<$ x $<$ 3.6. Unexpectedly, the resistivity and magnetization measurements reveal that small-concentration S substitution for Te can suppress the CDW transition, but it reappears around x = 0.2, and the CDW transition temperature enhances clearly as x augments for 0.2 $\leq$ x $\leq$ 0.5. Besides, the superconducting critical temperature ($T_c$) first increases with S doping content and then decreases after reaching a maximum $T_c = 2.82$ K for CuIr$_2$Te$_{3.85}$S$_{0.15}$. MIT order has been observed in the spinel region (3.6 $\leq$ x $\leq$ 4) associated with $T_{MI}$ increasing with x increasing. Finally, the rich electronic phase diagram of temperature versus x for this CuIr$_2$Te$_{4-x}$S$_x$ system is assembled, where the superconducting dome is associated with the suppression and re-emergence of CDW as well as MIT states at the end upon sulfur substitution in the CuIr$_2$Te$_{4-x}$S$_x$ chalcogenides.

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Supplementary material for this article is available online
(Some figures may appear in colour only in the online journal)

1. Introduction

The family of ternary chalcogenides has been studied intensively due to their rich structural and physical properties [1–3]. Notably, the copper chalcogenides with cubic spinel structure exhibit rich quantum states, including metal–insulator transition (MIT), magnetism, superconductivity (SC) and so on [4–8]. Normal thiospinel CuIr2S4 is of particular interest because it sustains a MIT at around 230 K under normal pressure, where the energy gap for the insulating phase is around 0.094 eV [8]. So far, many researches on the effect of chemical doping or adding physical pressures on the MIT in CuIr2S4 have been reported. In most cases, external disturbances include chemical doping (such as CuIr2Se4, CuIr2–xTi1xS4, CuIr2–xRh1xS4, CuIr2–xPt1xS4, CuIr2–xAg1xS4, Cu1–xNi2xS4, Cu1–xZn1xS4) and adding physical pressures disrupt the MIT and even further induce SC in CuIr2S4 [9–18].

On the other hand, CuIr2Te4 adopting a NiAs defected structure with a trigonal symmetry features the occurrence of SC and charge density wave (CDW)-like transition, characterized by magnetization and resistivity measurements [19, 20]. The first-principles calculation analysis implies that the density of states (DOS) near the Fermi energy for CuIr2Te4 mainly originates from the Ir d and Te p orbitals [20]. Subsequently, it is experimentally proved that the CDW and SC are both sensitive to the diverse chemical dopants and the threedopingsites (Cu-site, Ir-site and Te-site) in the pristine CuIr2Te4 [21–23]. Therefore, it is still of interest to explore the path from the layer CuIr2Te3 chalcogenide to the CuIr2S4 spinel by chemical alloying.

Here, we focus on studying the substitution of S for Te in the CuIr2Te4 host material based on the following aspects: (i) there is a big difference between the structures of two end compounds—CuIr2S4 crystallizes in a cubic spinel structure, but CuIr2Te4 adopts a layered structure. (ii) Two end compounds show distinct physical properties—CuIr2Te4 shows the coexistence of CDW-like transition and SC, whereas CuIr2S4 exhibits MIT. (iii) S belongs to the same chalcogen family as Te but has a smaller ionic radius. Therefore, these aforementioned significant differences between the two compounds engendered us to probe the path between CuIr2Te4 and CuIr2S4 by chemical alloying, in which rich structural and physical properties are expected in the new CuIr2Te4–xS4 (0 ≤ x ≤ 4) solid solution. The structural and physical properties of CuIr2Te4–xS4 (0 ≤ x ≤ 4) are characterized through XRD, resistivity, magnetization and heat capacity tests.

2. Experimental section

Polycrystalline specimens of CuIr2Te4–xS4 (0 ≤ x ≤ 4) were synthesized from the stoichiometric admixture of high-purity elements of Cu (99.999%), Ir (99.99%), Te (99.99%) and S (99.9%) with 0.1 wt% excess of Te and S. The mixtures were sealed in evacuated quartz tubes and heated up to 850 °C (1 °C/min) for four days, followed by furnace cooling with the rate of 3 °C/min to room temperature. Subsequently, the resultant specimens were ground and heated in pelletized cylinder form at 850 °C (3 °C/min) for another five days.

Powder x-ray diffraction (PXRD, MiniFlex, Rigaku) with Cu Kα1 radiation was used to examine the phase structure of the CuIr2Te4–xS4 (0 ≤ x ≤ 4) compounds. Rietveld refinements using the FULLPROF suite software were carried out to acquire the lattice parameters [24]. The element ratios were confirmed by scanning electron microscope combined with energy-dispersive x-ray spectroscopy (SEM-EDXS, COXEM EM-30AX). Quantum design physical property measurement system [PPMS was used to measure the electrical resistivity (four-probe method) (ρ(T)) on rectangular samples (5 × 1 × 0.8 mm3) down to 1.8 K and heat capacity measurement was performed in the range of 1.8 K–15 K. Quantum interference device (SQUID) Quantum Design MPMS system was used to measure the magnetic susceptibilities (χ(T, H)). Tc were extracted from the average of superconducting transition region in ρ(T) data and the extrapolation point of the steep slope of the superconducting state and the normal state susceptibility, Tc was also determined from the specific heat capacity Cp(T) from the equal area entropy construction. The values of Tc were determined from the inflection of the ρ(T) and χ(T) curves at high temperatures.

3. Results and discussion

Figures 1(a) and (b) and table 1 exhibit the refinement results of the XRD measurement for the selected layered CuIr2Te3.85S0.15 and cubic CuIr2Te0.1S3.9 compounds. The reflection peaks of CuIr2Te3.85S0.15 are corresponding to the trigonal phase of CuIr2Te4–xS4 having the space group P3m1 (the inset of figure 1(a)), whereas the CuIr2Te0.1S3.9 sample has a cubic spinel phase with the space group Fd3m (the inset of figure 1(b)). Small amount of unreacted Ir exists in all studied specimens. Rietveld refinements for the other examined compounds are represented in figure S1 in online supplementary information (https://stacks.iop.org/JPCM/34/205602/mmedia). From figures 2(a) and (b) and S2, it is evident that
Figure 1. Rietveld refinements for the representative samples (a) CuIr$_2$Te$_{3.85}$S$_{0.15}$ and (b) CuIr$_2$Te$_{0.1}$S$_{3.9}$. The insets show the crystallographic structures of CuIr$_2$Te$_{4-x}$S$_x$ compounds.

There are three distinct crystal structure zones at $0 \leq x \leq 0.5$, $0.5 < x < 3.6$ and $3.6 \leq x \leq 4$, respectively. It can be seen that the obtained powder diffraction patterns for CuIr$_2$Te$_{4-x}$S$_x$ ($0 \leq x \leq 0.5$) samples are mainly indexed to the trigonal phase. In zone $0.5 < x < 3.6$, the cubic spinel phase starts to appear, which indicates the coexistence of the layered and cubic phases (see figure S2). The main cubic spinel phase is obtained at the doping region of $3.6 \leq x \leq 4$.

In order to show the influence of sulfur substitution on the crystal structures, we magnified the (002) peaks for CuIr$_2$Te$_{4-x}$S$_x$ ($0 \leq x \leq 0.5$) and the (311) peaks for CuIr$_2$Te$_{4-x}$S$_x$ ($3.6 \leq x \leq 4$) as depicted in figures 2(a) and (b). We distinguished an obvious shift toward higher angles upon increasing the doping concentration $x$ in the CuIr$_2$Te$_{4-x}$S$_x$ ($0 \leq x \leq 0.5$, $3.6 \leq x \leq 4$) compounds as presented in the inset of figures 2(a) and (b), illustrating the incorporation of S into the CuIr$_2$Te$_4$ lattice. This shift is linked to the change on lattice constants $a$ and $c$, as presented in figure 2(c).

| Label | Site | Occupancy | $x$ | $y$ | $z$ | $a$ | $b$ | $c$ | $R_p$ | $R_p$ | $R_{exp}$ |
|-------|------|------------|-----|-----|-----|-----|-----|-----|-------|-------|----------|
| Cu    | 8a   | 0.45       | 0.5 | 0   | 0.625 | 9.852 Å | 3.957 Å| 5.347 Å | 3.65% | 4.2%  | 4.02%    |
| Ir    | 8d   | 0.45       | 0.5 | 0   | 0.625 | 9.852 Å | 3.957 Å| 5.347 Å | 3.65% | 4.2%  | 4.02%    |
| Te    | 32e  | 0.037(2)   | 0   | 0.3879 | 0.3879 | 0.3879 Å| 0.3879 Å| 0.3879 Å | 3.65% | 3.65% | 3.65%    |
| S     | 32d  | 0.963(1)   | 0   | 0.3716 | 0.3716 | 0.3716 Å| 0.3716 Å| 0.3716 Å | 3.65% | 3.65% | 3.65%    |

Table 1. Rietveld refinement structural parameters of CuIr$_2$Te$_{4-x}$S$_x$ with space group $P\overline{3}m1$ (no. 164) and CuIr$_2$Te$_{4-x}$S$_x$ with space group $F\overline{2}m$ (no. 227).
Figure 2. (a) and (b) Room temperature PXRD patterns for CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq x \leq 0.5$). (b) Room temperature PXRD patterns for CuIr$_2$Te$_{4-x}$S$_x$ (3.6 $\leq x \leq 4.0$). (c) The variation of unit-cell constants $a$ and $c$ with $x$ content. Blue hollow circle stands for $c$, and red hollow circle notes for $a$.

peaks also gradually shift to higher angles. From figure 2(c), we can see that the lattice parameters ($a = b = c$) in the cubic phase are also reduced since the ionic radius of Te$^{2-}$ (2.21 Å) is larger than that of the S$^{2-}$ ion (1.8 Å) [26]. Further, SEM-EDXS is performed to explore the morphology and atomic ratio (see figures S3 and S4) for the light doping powder samples. From figure S3, we can see that all the elements are evenly distributed in the powder samples. In addition, the obtained atomic ratios (see the inset of figure S4) are very close to those in the target compositions. Now we turn to investigate the physical properties for CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq x \leq 0.5$) by combining the temperature-dependent resistivity $\rho(T)$ and magnetization $\chi(T)$ measurements. The temperature-dependent resistivity $\rho(T)$ is present in figure S5. The normalized resistivity $\rho/\rho_{300K}(T)$ data are displayed in the main panel of figure 3(a). The resistivity results suggest that tiny amounts of S substitution suppress the CDW transition ($T_{CDW}$) ($T_{CDW}$ is defined by the minimum of $d\rho/dT$ as shown in the inset of figure 3(a)). CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq x \leq 0.5$) samples show metallic behaviors above 3 K. From figure 3(b), abrupt superconducting transitions can be seen in the $\rho/\rho_{300K}$ curves of the CuIr$_2$Te$_{4-x}$S$_x$ (0 $\leq x \leq 0.4$) compounds at low temperatures. We have estimated the residual resistivity ratio (RRR = $R_{300K}/R_{5K}$) and the results are given in table 2. RRR increases from 4.07 for the host sample to 5.28 for optimal samples ($x = 0.15$).
Figure 3. Transport and magnetization characterizations for CuIr$_2$Te$_{4-x}$S$_x$ series (0 ≤ x ≤ 0.5). (a) The resistivity measurements as a function of temperature for polycrystalline CuIr$_2$Te$_{4-x}$S$_x$ series (0 ≤ x ≤ 0.5). (b) The resistivity ratio (ρ/ρ$_{300K}$) as a function of temperature for the polycrystalline CuIr$_2$Te$_{4-x}$S$_x$ series at low temperatures (0 ≤ x ≤ 0.5), showing the superconducting transition temperatures. (c) Magnetization curves for CuIr$_2$Te$_{4-x}$S$_x$ (0 ≤ x ≤ 0.5) at low temperatures under 30 Oe applied fields, marking the onset of the superconducting transition temperatures. (d) Magnetization curves under applied field H 10 kOe for polycrystalline CuIr$_2$Te$_{4-x}$S$_x$ (0.2 ≤ x ≤ 0.5).

Table 2. Doping dependent residual resistance ratio (RRR = R$_{300K}$/R$_{3K}$), superconducting transition temperature ($T_c$), and CDW transition temperature ($T_{CDW}$) for CuIr$_2$Te$_{4-x}$S$_x$.

| S amount (x) | RRR | $T_c$ (K) | $T_{CDW}$ (K) |
|-------------|-----|----------|-------------|
| 0           | 4.07| 2.5      | 186         |
| 0.025       | 4.5 | 2.61     | —           |
| 0.05        | 4.33| 2.66     | —           |
| 0.075       | 4.33| 2.74     | —           |
| 0.15        | 5.28| 2.82     | —           |
| 0.2         | 2.85| 2.72     | 110         |
| 0.3         | 3.2 | 2.46     | 138         |
| 0.4         | 2.88| 2.15     | 166         |
| 0.5         | 2.50| 1.8      | 217         |

Normally, there should be a decrease in value of RRR with doping as result of induced disorder. In this case, one possible way to understand this behavior of the increased RRR in the low region S-doping samples could be that the introduction of small amount of S might cause an improvement in the sublattice order. This would improve local chemical and electronic uniformity, resulting in the suppression of CDW in the low region S-doping samples.

Surprisingly, CDW transition feature is absent in CuIr$_2$Te$_{4-x}$S$_x$ (0 < x < 0.2), while it reappears for 0.2 ≤ x ≤ 0.5 and the $T_{CDW}$ gradually raises with enhancing S doping concentration. Simultaneously the RRR gradually reduces from 5.28 for x = 0.15 to 1.8 for x = 0.5 (see table 2). The reduction of RRR implies that higher S doping can significantly induce disorder and S ions are effective scattering centers [28–30], which may possibly explain the recurrence of the CDW. SC was further investigated by the magnetization tests, from figure 3(c), we can see the evolution of the $T_c$s, which is consistent with the resistivity data. The temperature-dependent normalized magnetic susceptibility $4\pi\chi(T)$ is getting smaller by increasing the S concentration x. However, no superconducting transition is detected in magnetic susceptibility data for x = 0.5 down to 1.8 K, which agrees with the $\rho(T)$ data. Figure S7 shows the $d\chi/dT$ vs T for the layer phase CuIr$_2$Te$_{4-x}$S$_x$ (0.1 ≤ x ≤ 0.5) samples. From figure S7, it can see the $d\chi/dT$ transition is getting broader with the increasing of S doping content and the $d\chi/dT$ transition vanishes when x = 0.5. From resistivity and magnetic susceptibility results, we can see that only layered phases show SC with $T_c$ slightly descending with x increasing and attains the highest value of 2.82 K for CuIr$_2$Te$_{3.85}$S$_{0.15}$, which is rather higher than the $T_c$ obtained by the optimal Ru (2.79 K) and Al doping (2.75 K) [23, 31].
Subsequently, there is a small drop of $T_c$ with the increase of $x$ and a SC dome can be observed. To confirm the re-appearance of the CDW-like order for $(0.2 \leq x \leq 0.5)$ samples, we further investigate the temperature dependent-magnetic-susceptibilities $\chi(T)$ with heating and cooling under a 10 kOe magnetic field. The inset of figure 3(d) presents the cooling d$\chi$/d$T$($T$) revealing the $T$CDW, which are consistent with the resistivity data (see the inset of figure 3(a), as well as the curves obtained from the cooling process). It seems like that these investigated compounds with the layered structure near the Fermi level, the Peierls-like phase transition is enhanced as a result of the lattice reduction [17]. One more obvious feature is that all samples exhibit the magnetization's upturn as a result of the lattice reduction [17]. Hence, as $x$ increases, the magnetic susceptibility below MIT ($T_{MI}$) decreases abruptly as temperature decreases as a result of the spin–dimerization transition. Below $T_{MI}$, the decrease by increasing the low temperatures, the magnetic susceptibility almost maintains constant as shown in figure 4(c). The fitting result on CuIr$_2$Te$_{0.3}$S$_{3.7}$ is shown in table 3. Evidently, both $\chi_{MI}^+$ and $\chi_{MI}$ decrease by increasing the doping amount of S. The magnetic step at $T_{MI}$ is associated to DOS at the Fermi level $E_F$ by the equations [39]:

$$\Delta \chi = \chi_{MI} - \chi_{PDMI} = \frac{1}{2} \Delta \chi = \mu_0 \mu_B N(E_F),$$

where $N(E_F)$ represents the vacuum magneto-conductivity and $\mu_B$ is Bohr magneton, respectively, $\Delta \chi$ is the hysteresis.

Next, we perform the temperature dependence of zero-field resistivity measurements with heating and cooling for the cubic spinel CuIr$_2$Te$_{4-x}$S$_x$ $(3.6 \leq x \leq 4)$ to investigate the MIT, as exhibited in the main panel of figure 4(a), it is clear that $T_{MI}$ raises with S concentration $x$ in the spinel phase as the inset of figure 4(a). From figure 4(a), it can be seen that the resistivity slightly decreases with the decreasing temperature above MIT, but whereas it increases abruptly with the decreasing temperature below MIT. For example, it increases from around $1 \times 10^{-2}$ Ω cm to $1 \times 10^3$ Ω cm with cooling run for the composition $x = 3.9$. Below MIT, the resistivity displays insulating behavior, which is consistent with the previous report [9]. To further confirm the MIT, we performed the temperature-dependent magnetic susceptibility measurements with heating and cooling for the spinel compositions CuIr$_2$Te$_{4-x}$S$_x$ $(3.6 \leq x \leq 4)$ with applied magnetic field 10 kOe. Figure 4(b) presents the temperature-dependent magnetic susceptibility under $H = 10$ kOe for CuIr$_2$Te$_{4-x}$S$_x$ $(x = 3.6, 3.7, 3.8, 3.9$ and $4)$ compositions. $\chi(T)$ behaviors for different compounds seems to be analogous, we can find that there is an obvious hysteresis on heating and cooling in all these spinel compounds, the peak around 50 K for the composition with $x = 4$ is related to oxygen contamination [37, 38]. However, one feature is that $\chi(T)$, which is primarily consisted of Landau diamagnetism, Larmor diamagnetism, and Pauli paramagnetism, is practically temperature-independent above $T_{MI}$ [17].

| $S$ amount ($x$) | $\chi_{MI}$ ($10^{-4}$ emu mol$^{-1}$) | $\Delta \chi$ | $\chi_0 + C/T$ ($10^{-4}$ emu mol$^{-1}$) | $C$ (emu K$^{-1}$ mol$^{-1}$) |
|-----------------|-------------------------------|----------------|---------------------------------|-------------------|
| 3.6             | 1.29                         | 1.25           | $-0.312$                        | 0.0130            |
| 3.7             | 0.97                         | 1.33           | $-0.435$                        | 0.0023            |
| 3.8             | 0.90                         | 1.38           | $-0.588$                        | 0.0031            |
| 3.9             | 0.85                         | 1.42           | $-0.620$                        | 0.0016            |
| 4               | 0.69                         | 1.49           | $-0.770$                        | 0.0048            |

Thus, the following formula can be used for fitting the magnetic susceptibility below $T_{MI}$: $\chi = \chi_0 + \frac{C}{T}$, where $\chi_0$ represents the magnetic susceptibility excluding the Curie paramagnetism; $C$ is the Curie parameter. The fitting result on CuIr$_2$Te$_{0.3}$S$_{3.7}$ is shown in figure 4(c) by green solid curves (the fitting data for the other compounds are given in figure S8 in supplemental information). The fitting constants $\chi_0$ and $C$ are given in table 4. Both $\chi_0$ and $C$ decrease by increasing $x$. A previous report shows that the Ag doping in CuIr$_2$S$_3$ deteriorates the Peierls-like phase transition [17], therefore weakening the spin–dimerization. Then, for the system CuIr$_2$Te$_{4-x}$S$_x$, the number of non-dimerized Ir$^{4+}$ ions will be decreased below $T_{MI}$ reducing the paramagnetism [17]. Hence, as $x$ increases, the paramagnetism becomes weaker resulting in an increase in the Curie constant $C$. The decreased $\chi_0$ may be attributed
to the weak remnant ferromagnetism as it has been revealed in different site doped CuIr$_2$S$_x$ [15, 17, 18]. Correspondingly, the $T_{\text{MI}}$ extracted from the magnetic susceptibility (figure 4(b), inset) is consistent with the resistivity data. With increasing the S doping concentration $x$ in the range of 3.6 $\leq x \leq 4$, the $T_{\text{MI}}$ increases gradually. This behavior is similar to that reported in reference [9]. In comparison with the substitution of Se in CuIr$_2$S$_x$, Te doping is expected to have a robust suppression on the MIT [9]. Nagata et al reported the phase diagram for CuIr$_2$(S$_{1-x}$Se$_x$)$_4$, which displays that the MIT can be kept in a broad substitution range of 0 $\leq x \leq 0.7$ [5].

With the aim of calculating the lower critical field ($\mu_0H_c1$), the magnetization isotherm $M(H)$ measurements were performed at different fields. Figure 5 displays the temperature-dependent $\mu_0H_c1$ for the optimal CuIr$_2$Te$_{3.85}$S$_{0.15}$ sample. The bottom inset of figure 5 presents the magnetization $M(H)$ data versus field. The inset at the upper corner of figure 5 displays the full process for estimating $\mu_0H_c1$ at different measuring temperatures. To get an accurate $\mu_0H_c1$ value, the demagnetization effect should be considered. The demagnetization factor ($N$) values can be estimated according to the equation: $\chi_V = dM/dH$, in which $\chi_V$ denotes the slope of the linearity fitting (see green line in the bottom inset in figure 5). $N$ value is calculated to be 0.53–0.63. Then, we can plot the experimental data based on the relationship $M_{\text{exp}} = e + fH$ at low magnetic fields, where $e$ and $f$ represent the intercept and the slope of the linear fitting of the $M(H)$ data, respectively. The relationship of $M-M_{\text{fit}}$ ($H$) is plotted in the top inset of figure 5, which is used to estimate $\mu_0H_c1$ at the field when $M-M_{\text{fit}}$ deviates by $\sim 1\%$ below the fitted data ($M(1\%)$) [44, 45]. Subsequently, one can obtain $\mu_0H_c1$($T$) value by using the expression: $\mu_0H_c1(T) = \mu_0H_c1^{*}(T)/(1-N)$ [46, 47]. Accordingly, we can fit the $\mu_0H_c1(T)$ values on the basis of the expression: $\mu_0H_c1(T) = \mu_0H_c1(0)[1-(T/T_c)^2]$. Finally, the lower critical field ($\mu_0H_c1(0)$) at zero temperature for the CuIr$_2$Te$_{3.85}$S$_{0.15}$ compound is calculated to be 17 mT. Compared to the pristine CuIr$_2$Te$_4$ compound (28 mT) and Ru doping compound CuIr$_1.95$Ru$_{0.05}$Te$_4$ (98 mT) [31], the isoelectronic S doping compound has smaller $\mu_0H_c1(0)$s, as summarized in table 4.

Additionally, we analyzed the upper critical field ($\mu_0H_c2$) via the temperature-dependent resistivity measurement under increased applied magnetic fields $\rho(T, H)$ (figure 6, insets). Here, we calculate the $\mu_0H_c2$ using 50\% criteria of the superconducting transition value from the normalized resistivity ($\rho_T$). It is clear that the $T_c$ decreases upon applying a magnetic field. Consequently, one can calculate the $\mu_0H_c2$ values on the basis of Werthamer–Helfand–Hohenburg (WHH) and Ginzburg–Landau (GL) theories. Then, we can adopt the simplified WHH equation [48]: $\mu_0H_c2(0) = -0.693T_c(dH_c2/dT)_c$ to obtain the $\mu_0H_c2(0)$s [49–53], where $(dH_c2/dT_c)$ represents the slope of $\mu_0H_c2(T)$ in the vicinity of $T_c$. Based on the simplified WHH model, we can get the $\mu_0H_c2(0)$ for the CuIr$_2$Te$_{4-x}$S$_x$ ($x = 0.05, 0.075$ and $0.15$) compounds, which are $0.140, 0.174$ and $0.168$ T, correspondingly. These values are all greater than that of the parent CuIr$_2$Te$_4$. Nonetheless, the highest value of $\mu_0H_c2(0)$ does not correspond to the highest $T_c$. It has been assumed that the obtained $\mu_0H_c2(0)$s for weak-coupling Bardeen–Cooper–Schrieffer (BCS) superconductors are not more than that of the Pauli limiting field ($H^P = 1.86\mu_0T_c$) [54]. The values of $H^P$ are calculated to be 4.95, 5.09 and 5.25 T, respectively, which is larger than that of the undoped CuIr$_2$Te$_4$. Correspondingly, we further calculate the Ginzburg–Landau coherence length $\xi_{\text{GL}}(0)$ from the formula $H_c2 = \phi_0/(2\pi\xi_{\text{GL}}^2)$ using the $H_c2(0)$ data from the WHH model, where the flux quantum $\phi_0 = 2.07 \times 10^{-3}$ T m$^2$. The calculated values of $\xi_{\text{GL}}(0)$s for CuIr$_2$Te$_{3.85}$S$_{0.15}$, CuIr$_2$Te$_{3.92}$S$_{0.075}$ and CuIr$_2$Te$_{3.85}$S$_{0.15}$ are

Figure 4. (a) Temperature-dependent resistivity for the cubic spinel samples of CuIr$_2$Te$_{4-x}$S$_x$ ($3.6 \leq x \leq 4$). The close circles are for cooling and the open ones are for warming. (b) Magnetization measurements as a function of temperature for the spinel samples of CuIr$_2$Te$_{4-x}$S$_x$ ($3.9 \leq x \leq 4$) measured under applied field $H = 10$ kOe. The insets of (a) and (b) show the amplified plots near the MIT. (c) The temperature dependence of magnetic susceptibility for CuIr$_2$Te$_{3.85}$S$_{3.7}$. The magnetic susceptibility between 4 K and $T_{\text{MI}}$ are fitted by $T_{\text{MI}}\chi = \chi_0 + \chi_{\text{GL}}$. The results are consistent with the theoretical predictions and previous experiments.
Table 4. Superconducting parameters of different telluride chalcogenides compounds.

| Material               | Parameter                  | $S_0.05$ | $S_0.075$ | $S_0.15$ |
|------------------------|----------------------------|----------|-----------|----------|
| CuIr$_2$Te$_3$S$_{0.05}$ | $T_c$ (K)                  | 2.66     | 2.70      | 2.79     |
|                        | $\gamma$ (mJ mol$^{-1}$ K$^{-2}$) | 0.212    | 0.209     | 0.217    |
|                        | $\beta$ (mJ mol$^{-1}$ K$^{-4}$) | 0.174    | 0.168     | 0.176    |
|                        | $\Delta C/\gamma T_c$      | 3.17     | 3.17      | 3.17     |
|                        | $\lambda N(eV atom^{-1})$  | 0.203    | 0.196     | 0.203    |
|                        | $\mu H_{c1}(T)$ (mT)        | 4.95     | 4.95      | 4.95     |
|                        | $\mu H_{c2}(T)$ (T)         | 5.28     | 5.28      | 5.28     |
|                        | $\lambda_{GL}$ (nm)        | 47.81    | 42.88     | 45.21    |

47.81, 42.88 and 45.21 nm, respectively. On the other hand, $\mu_0 H_{c1}$ is correlated to the coherence length $\xi$ and the magnetic penetration depth $\lambda$ through the relation $\mu_0 H_{c1} = (\phi_0^{1/2} \lambda)^3 [\ln(\kappa) + 0.5]$, where $\kappa = \lambda / \xi$ is the GL parameter [55].

The lower critical fields for CuIr$_2$Te$_3$S$_{0.15}$, with the optimal doping level CuIr$_2$Te$_3.85$S$_{0.15}$, which is slightly higher than that of the undoped CuIr$_2$Te$_3$ compound (0.12 T) [12], but smaller than that of the optimum Ru-doped CuIr$_2$Te$_4$ (0.247 T) [13]. We have also calculated the $\mu_0 H_{c2}$ values from the GL equation [56]: $\mu_0 H_{c2}(T) = \mu_0 H_{c2}(0) [1 - (T/T_c)^2]^{-1}[1 + (T/T_c)^2]$, where $T_c$ is taking from the criteria 50% of $\rho_N$. The $\mu_0 H_{c2}(0)$ values from GL model are 0.203, 0.212 and 0.209 T, respectively. As can be seen on the main panels of figure 6, the $\mu_0 H_{c2}$ values from the GL model are higher as compared to the $\mu_0 H_{c2}$ values calculated using the WHH model.

The heat capacity measurements deliver more details about the properties of normal and superconducting states. Results of temperature-dependent specific heat capacity at low temperature of the optimal sample CuIr$_2$Te$_3.85$S$_{0.15}$ are displayed in figure 7. The data collected under 10 Koe field up to 10 K is well described by

$$\gamma = 10.84 \text{ mJ mol}^{-1} \text{ K}^{-2}$$

and the lattice coefficients $\beta = 3.39 \text{ mJ mol}^{-1} \text{ K}^{-4}$. Debye temperature ($\Theta_D$) of about 160 K is calculated from the formula $\Theta_D = (12\pi^4 n R/5\beta)^1/3$ where $n = 7$ is the number of the atoms per formula unit and $R$ is the gas constant. Having $T_c$ and $\Theta_D$, we can gain the electron–phonon coupling coefficient ($\lambda_{ep}$) on the basis of the inverted McMillan expression [49]:

$$\lambda_{ep} = \frac{1}{0.045} \frac{1}{T_c} \ln \left( \frac{\Theta_D}{1.45 T_c} \right) \mu^2.$$
Figure 6. (a)–(c) The temperature dependence of upper critical fields curves for CuIr$_2$Te$_{3.95}$S$_{0.05}$, CuIr$_2$Te$_{3.925}$S$_{0.075}$ and CuIr$_2$Te$_{3.85}$S$_{0.15}$ respectively. The data are fitted using WHH (the color solid lines) and GL (the color dashed lines) models. The insets depict the corresponding resistivity measurements as a function of temperature under different magnetic field $\rho(T, H)$.

used commonly-used with the McMillan equation for metals [49, 57–59]. The obtained value of $\lambda_{np}$ is around 0.65. Having $\gamma$ and $\lambda_{np}$, the DOS at the Fermi level $N(E_F)$ can be figured out by using the formula $N(E_F) = 3\gamma / (\pi^2 k_B^2 (1 + \lambda_{np})$, where $k_B$ denotes Boltzmann’s constant, $N(E_F)$ is found to be 3.17 states/eV per f.u. which is somewhat enhanced compared to that of the host CuIr$_2$Te$_4$. The increase in $T_c$ and the suppression of CDW in CuIr$_2$Te$_{3.85}$S$_{0.15}$ compound can be explained by the enhancement of $N(E_F)$ and it may also be related to the enrichment of the electron–phonon coupling by the S-ion substitution as compared to parent CuIr$_2$Te$_4$ (see table 4). Figure 7(b) exhibits the electronic contribution to the heat capacity collected at 0 Oe. The obtained $T_c$ for this sample is 2.81 K. The magnitude of the heat capacity jump is estimated to be 1.48, close to the predicted value (1.43) based on the weak coupling BCS theory.

Finally, a rich electronic phase diagram for the CuIr$_2$Te$_{4-x}$S$_x$ series is constructed, which features multiple regions separated by the $T_c$, $T_{CDW}$ and $T_{MI}$ versus the doping level $x$, as displayed in figure 8. Orange regions represent the suppression and re-emergence of the CDW states upon the sulfur substitution. Concretely, the CDW signature in the resistivity disappears with a small S doping content $x$, whereas it reemerges for $0.2 \leq x \leq 0.5$ and is enhanced as $x$ increases in the doping range of 0.2 to 0.5. This phenomenon is similar to the case of single doped Cu$_{1-x}$Ag$_x$Ir$_2$Zr$_{1.5}$Te$_4$ (I/Se)$_z$ [22, 32, 60, 61], but it differs from the CuIr$_2$Te$_{4-x}$(Ru/Ti)$_x$Te$_4$ and Cu$_0.5$Zn$_x$IrTe$_2$ systems without reappearance of CDW transition in the high doping range [21, 31, 62]. Meanwhile, light blue represents the emergence and evolution of SC upon sulfur substitution, in which a small amount S substitution for Te can slightly enhance the $T_c$ and yields the highest $T_c$ of about 2.82 K at $x = 0.15$ for which the improvement of the SC may be due to the enhanced in electron–phonon coupling induced by the S doping, followed by a drop of $T_c$ where the degradation of $T_c$ is due to the continuous shrinkage of the lattice which is not beneficial for the SC, which was observed in some other reported superconductors.
In summary, we have synthesized the polycrystalline CuIr2Te4.85S0.15 with the highest Tc (0 ≤ x ≤ 0.4). TCDW and TM increase with decreasing unit cell volume. With shrinking atomic spacing, one would expect an increase in MIT because the overlap of electron wave functions favors a metallic state [65].

4. Conclusions

In summary, we have synthesized the polycrystalline CuIr2Te4−xSx (0 ≤ x ≤ 0.4) solid solutions via a solid state reaction method. A rich electronic phase diagram has been established, which simplifies the rather complicated structural and electrical features in the system CuIr2Te4−xSx (0 ≤ x ≤ 0.4). Altogether, CuIr2Te4−xSx (0 ≤ x ≤ 0.4) stabilize in two types of structures and divided into three zones with a layered trigonal structure for 0 ≤ x ≤ 0.5, cubic spinel structure near the end of their solid solutions (3.6 ≤ x ≤ 4), and mixed-phase that intermediates between these two regions. Even with the substitution of a small amount of S for Te, CDW can be suppressed. However, the signature of the CDW-like transition can be observed again in the region of 0.2 ≤ x ≤ 0.5 with and increased TCDW. On the other hand, S substitution for Te can slightly enhance the Tc and the optimal doping lever is x = 0.15 (CuIr2Te3.85S0.15) with the highest Tc ≈ 2.82 K. The MIT exists in the region of 3.6 ≤ x ≤ 4 and TM is enhanced by S substitution. Based on our results, CuIr2Te4−xSx is a potential platform for further study of the interrelationships between different types of electronic orders. Future systematic studies will be important to better understand these interactions and ascertain the physical origin of these electronic instabilities.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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References

[1] Wagner K E et al 2008 Tuning the charge density wave and superconductivity in Cu, Ta2S3 Phys. Rev. B 78 104520
[2] Luo H, Xie W, Tao J, Inoue H, Gyenis A, Krizan J W, Yazdani A, Zhu Y and Cava R J 2015 Polytypism, polymorphism, and superconductivity in TaSe2−xTe Proc. Natl Acad. Sci. USA 112 E1174
[3] Luo H et al 2015 Cr-doped TiSe2—a layered dichalcogenide spin glass Chem. Mater. 27 6810–7
[4] Tang J, Matsumoto T, Naka T, Furubayashi T, Nagata S and Matsumoto N 1999 Instability of metallic phase in CuIr2Se4 at high pressure Physica B 259–261 857–9
[5] Nagata S, Matsumoto N, Kato Y, Furubayashi T, Matsumoto T, Sanchez J P and Vulliet P 1998 Metal–insulator transition in the spinel-type CuIr2(S1−xSe1x)4 system Phys. Rev. B 58 6844–54
[6] Luo H, Klimczuk T, Müchler L, Schoop L, Hirai D, Fucillo M K, Felser C and Cava R J 2013 Superconductivity in the Cu(Ir1−xPt1x)2Se4 spinel Phys. Rev. B 87 214510
[7] Furubayashi T, Kosaka T, Tang J, Matsumoto T, Kato Y and Nagata S 1997 Pressure induced metal–insulator transition of selenospinel CuIr2Se4 J. Phys. Soc. Japan 66 1563–4
[8] Nagata S, Hagino T, Seki Y and Bith T 1994 Metal–insulator transition in thiospinel CuIr2S4 Physica B 194–196 1077–8
[9] Yue S, Du J, Zhang Y and Zhang Y-H 2009 Metal–insulator transition in CuIr$_2$(S$_{1-x}$Te$_x$)$_4$ Chin. Phys. Lett. 26 117126

[10] Nagata S, Ito S, Endoh R and Awaka J 2002 Metal–insulator transition in the spinel-type Cu(1−x−y)Ir$_x$S$_2$ system Phil. Mag. B 82 1679

[11] Endoh R, Awaka J and Nagata S 2003 Ferromagnetism and the metal–insulator transition in the thiospinel Cu(1−x−y)Ir$_x$S$_2$ system Phys. Rev. B 68 115106

[12] Matsumoto N, Endoh R, Nagata S, Furubayashi T and Matsumoto T 1999 Metal–insulator transition and superconductivity in the spinel-type CuIr$_2$(1−x−y)Rh$_x$S$_2$ system Phys. Rev. B 60 5258–56

[13] Matsumoto N, Yamauchi Y, Awaka J, Kamei Y, Takano H and Matsumoto T 2001 Metal–insulator transition in the thiospinel Cu(Ir$_{1-x}$Pt$_x$)$_2$S$_4$ system Int. J. Inorg. Mater. 3 791–5

[14] Cao G, Kitazawa H, Suzuki H, Furubayashi T, Hirata K and Matsumoto T 2000 Superconductivity in Zn-doped CuIr$_2$S$_2$ Physica C 341–348 735–6

[15] Zhang L, Qu Z, Pi L, Ling L, Zhang S, Tan S and Zhang Y 2010 The remnant ferromagnetism in the Cu$_{1−x}$Ag$_x$Ir$_2$S$_4$ system Solid State Commun. 150 1665–9

[16] Endoh R, Matsumoto N, Chikazawa S, Nagata S, Furubayashi T and Matsumoto T 2001 Metal–insulator transition in the spinel-type Cu$_{1−x}$Ni$_x$Ir$_2$S$_4$ system Phys. Rev. B 64 075106

[17] Zhang L, Ling L, Tan S, Pi L and Zhang Y 2008 The effect of equivalent pressure and localized magnetism in Cu$_{1−x}$Ag$_x$Ir$_2$S$_4$ system J. Phys.: Condens. Matter. 20 255205

[18] Oomi G, Kagaya T, Yoshida I, Hagina T and Nagata S 1995 Effect of pressure on the metal–insulator transition in thiospinel CuIr$_2$S$_4$ J. Magn. Magn. Mater. 140–144 157

[19] Endoh R, Matsumoto N, Awaka J, Ebisu S and Nagata S 2002 Metal–insulator transition in the spinel-type CuIr$_2$(1−x−y)S$_2$ system J. Phys. Chem. Solids 63 669–74

[20] Yan D et al 2019 CuIr$_2$Te$_4$: a quasi-two-dimensional ternary telluride chalcogenide superconductor (arXiv:1908.05438)

[21] Yan D et al 2021 Robust superconductivity in (Zn$_{1.05}$Cu$_{0.95}$)$_{0.5}$Ir$_2$Te$_2$ J. Phys. Chem. C 125 5732–8

[22] Boubeche M et al 2021 Superconductivity and charge density wave in iodine-doped CuIr$_2$Te$_2$ Chin. Phys. Lett. 38 037401

[23] Yan D et al 2020 Charge density wave and superconductivity in the family of telluride chalcogenides Zn$_{1−x}$(Cu$_{1−x}$Ir$_x$)$_2$N$_x$(N = Al, Ti, Rh), Te$_2$ (arXiv:2003.11463)

[24] Rodríguez-Carvajal J 2001 Recent developments of the program FULLPROF Newsletter in Commission on Powder Diffraction (ICUCr) vol 26 p 12

[25] Vegard L 1921 Die Konstitution der Mischkristalle und die Raumfüllung der Atome Z. Phys. 17 16–26

[26] Shannon R 1976 Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides Acta Crystallogr. A 32 751–67

[27] Kim J, VanGennep D, Hamlin J, Wang X, Sefat A and Stewart G 2018 Unusual effects of Be doping in the iron-based superconductor FeSe J. Phys.: Condens. Matter. 30 445701

[28] De Silva K, Xu X, Wang X, Wexler D, Attard D, Xiang F and Dou S X 2012 A significant improvement in the superconducting properties of MgB$_2$ by co-doping with graphene and nano-SiC Scr. Mater. 67 802–5

[29] Wang X, Dou S, Hossain M, Cheng Z, Liao X, Ghorbani S, Yao Q W and Kim J 2010 Enhancement of the in-field $J_c$ of MgB$_2$ via SiCl$_4$ doping Phys. Rev. B 81 224514

[30] Wang H, Li L, Ye D, Cheng X and Xu Z 2007 Effect of Te doping on superconductivity and charge density wave in chalcogenides 2H-NbSe$_2$–Te$_x$ (x = 0.1, 0.2) Chin. Phys. 16 2471

[31] Yan D et al 2019 Superconductivity in Ru doped CuIr$_2$Te$_4$ telluride chalcogenide Phys. Rev. B 100 174504

[32] Boubeche M et al 2021 Anomalous charge density wave state evolution and dome-like superconductivity in Cu$_{1−x}$Te$_y$–Se$_z$ chalcogenides Supercond. Sci. Technol. 34 115003

[33] Li L et al 2017 Superconducting order from disorder in 2H-TaSe$_2$–Se$_y$ npj Quantum Mater. 2 11

[34] Scholz G 1997 Charge-density-wave behaviour in intercalated single crystal Nb$_2$Te$\text{Se}_x$ Sol. State Ion. 100 135–41

[35] Baranov N V, Maksimov V I, Mesot J, Pleschov V G, Podlesnyak A, Pompjakushin V and Seleznева N V 2006 Possible reappearance of the charge density wave transition in MxTiS$_2$ compounds intercalated with 3D metals J. Phys.: Condens. Matter. 19 016005

[36] Harper J M E, Geballe T H and Disalvo F J 1977 Thermal properties of layered transition-metal dichalcogenides at charge-density-wave transitions Phys. Rev. B 15 2943–51

[37] Chiew Y L, Miyata M, Koyano M and Oshima Y 2021 Clarification of the ordering of intercalated Fe atoms in Fe$_3$TiS$_4$ and its effect on the magnetic properties Acta Crystallogr. B 77 441–8

[38] MPMS Application Note 1014-210 Oxygen Contamination 1997 Retrieved from Quantum Design website https://qdusa.com/siteDocs/appNotes/1014-210.pdf

[39] Yagasaki and Nakama T 2007 Diamagnetism in spinel compound Cu$_{1−x}$Pt$_x$J. Magn. Magn. Mater. 310 12–5

[40] Kang H, Barner K, Rager H, Sondermann U, Mandal P, Medvedeva I V and Gmelin E 2000 EPR spectra of Cu$_{1−x}$S$_x$J. Alloys Compd. 306 6–10

[41] Zhang L, Ling L, Fan J, Zhang R, Xi C, Zhu X, Zhang C and Zhang Y 2013 Orbitally induced Peierls phase transition driven by phonon change in Cu$_{1−x}$S$_x$J. Magn. Magn. Mater. 335 104–6

[42] Gupta R, Dhar S K, Thamizhavel A, Rajeev K P and Hossain Z 2017 Superconducting and charge density wave transition in single crystalline LaPt$_2$Si$_2$ J. Phys.: Condens. Matter. 29 255601

[43] Ibuka S and Imai M 2016 Possibility of charge density wave transition in a SrPt$_2$Sb$_2$ superconductor J. Phys.: Condens. Matter. 28 165702

[44] Luo H, Strycharska-Nowak J, Li J, Tao J, Kimczuk T and Cava R J 2017 S-shaped suppression of the superconducting transition temperature in Cu-intercalated NbSe$_2$ Chem. Mater. 29 3704–12

[45] Kong T, Górnicka K, Golbá S, Wiendlocha B, Kimczuk T and Cava R J 2018 A family of Pb-based superconductors with variable cubic to hexagonal packing J. Phys. Soc. Japan 87 074711

[46] Winiański M J, Wiendlocha B, Golbá S, Kushwaha S K, Wiśniewski P, Kaczkowski D, Thompson JD, Cava R J and Kimczuk T 2016 Superconductivity in CaB$_2$Phys. Chem. Chem. Phys. 18 21737

[47] Yadav C S and Paulose P L 2009 Upper critical field, lower critical field and critical current density of FeTe$_{0.60}$Se$_{0.40}$ single crystals New J. Phys. 11 103046

[48] Helfand E and Werthamer N R 1966 Temperature and purity dependence of the superconducting critical field $H_c$ Phys. Rev. 147 288–94

[49] McMillan W L 1968 Transition temperature of strong-coupled superconductors Phys. Rev. 167 331–44

[50] Wilson J A, Di Salvo F J and Mahajan S 1974 Charge-density waves in metallic, layered, transition-metal dichalcogenides Phys. Rev. Lett. 32 882–5

[51] Kohn W 1967 Excitonic phases Phys. Rev. Lett. 19 439–42

[52] Werthamer N R and McMillan W L 1967 Temperature and purity dependence of the superconducting critical field $H_c^\ast$ IV. Strong coupling effects Phys. Rev. 158 415–7

[53] Kresin V Z and Wolf S A 1990 Fundamentals of Superconductivity (New York: Plenum)
[54] Clogston A M 1962 Upper limit for the critical field in hard superconductors Phys. Rev. Lett. 9 266–7
[55] Brandt E H 2003 Properties of the ideal Ginzburg–Landau vortex lattice Phys. Rev. B 68 054506
[56] Ginzburg V and Landau L 1950 On the theory of superconductivity J. Exp. Theor. Phys. 20 1064
[57] Górnicka K, Cava R J and Klimczuk T 2019 The electronic characterization of the cubic laves-phase superconductor CaRh2 J. Alloys Compd. 793 393
[58] Klimczuk T et al 2012 Superconductivity in the Heusler family of intermetallics Phys. Rev. B 85 1705
[59] Ge Y and Liu A Y 2013 Phonon-mediated superconductivity in electron-doped single-layer MoS2: a first-principles prediction Phys. Rev. B 87 241408(R)
[60] Boubeche M et al 2022 Enhanced superconductivity with possible re-appearance of charge density wave states in polycrystalline Cu1−xAgxIr2Te4 alloys J. Phys. Chem. Solids. 163 110539
[61] Zeng L et al 2022 Negative chemical pressure effect on superconductivity and charge density wave of Cu1−xIr1−yZryTe2 (arXiv:2202.04071)
[62] Zeng L, Yan D, He Y, Boubeche M, Huang Y, Wang X and Luo H 2021 Effect of Ti substitution on the superconductivity of CuIr2Te4 telluride chalcogenide J. Alloys Compd. 885 160981
[63] Chen H, Zhang G, Zhang H, Mu G, Huang F and Xie X 2015 Selenium doping in potential topological superconductor Sn0.5In0.5Te J. Solid State Chem. 229 124–8
[64] Attfield J P, Kharlanov A L and McAllister J A 1998 Cation effects in doped La2CuO4 superconductors Nature 394 157–9
[65] Tsuji S, Kumagai K, Matsumoto N and Nagata S 1997 Metal insulator transition in the spinel CuIr2(S1−xSex)4 system studied by NMR Physica C 282–287 1107–8