The unusual suppression of superconducting transition temperature in double-doping 2H-NbSe$_2$

**Dong Yan**, **Yishi Lin**, **Guohua Wang**, **Zhen Zhu**, **Shu Wang**, **Lei Shi**, **Yuan He**, **Man-Rong Li**, **Hao Zheng**, **Jie Ma**, **Jinfeng Jia**, **Yihua Wang** and **Huixia Luo**

1 School of Material Science and Engineering, Sun Yat-Sen University, No. 135, Xingang Xi Road, Guangzhou, 510275, People’s Republic of China
2 Department of Physics, Fudan University, Shanghai, 200433, People’s Republic of China
3 Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
4 School of Chemistry, Sun Yat-Sen University, No. 135, Xingang Xi Road, Guangzhou, 510275, People’s Republic of China
5 Key Lab Polymer Composite & Functional Materials, Sun Yat-Sen University, No. 135, Xingang Xi Road, Guangzhou, 510275, People’s Republic of China

E-mail: luohx7@mail.sysu.edu.cn

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**Abstract**

2H-NbSe$_2$ is one of the most widely researched transition metal dichalcogenide (TMD) superconductors, which undergoes charge-density wave (CDW) transition at $T_{\text{CDW}}$ about 33 K and superconducting transition at $T_c$ of 7.3 K. To explore the relation between its superconductivity and Fermi surface nesting, we have combined S substitution with Cu intercalation in 2H-NbSe$_2$ to make Cu$_x$NbSe$_{2-y}$S$_y$ ($0 \leq x = y \leq 0.1$). Upon systematic substitution of S and intercalation of Cu ions into 2H-NbSe$_2$, we found that when the Cu and S contents ($x = y \geq 0.06$) increase, the $T_c$ decreases in Cu$_x$NbSe$_{2-y}$S$_y$. At higher $x$ and $y$ values, $T_c$ keeps a constant value near 2 K, which is not commonly observed for a layered TMD. For comparison, we found that the simultaneous substitution of Nb by Cu and Se by S in Cu$_x$Nb$_{1-x}$Se$_2$S$_y$ ($0 \leq x = y \leq 0.06$) lowered the $T_c$ substantially faster. We constructed superconducting phase diagrams for our double-doping compounds in contrast with the related single-ion doping systems.

**Introduction**

Transition metal dichalcogenides (TMDs) with 1T (octahedrally coordinated) and 2H (trigonal prismatically coordinated) structures have attracted abundant research interest for decades due to their various novel properties, i.e. superconductivity, charge-density wave (CDW), and topological semimetal states [1–8]. 2H-NbSe$_2$ is one of the most widely researched layered superconducting TMD materials, bearing a CDW state with the superconducting transition temperature ($T_c$) of 7.3 K and a quasi-two-dimensional incommensurate CDW transition temperature ($T_{\text{ICDW}}$) of ~33 K [9]. The coexistence of superconductivity and CDW state, as well as its superconducting mechanism, have made it a research...
hotspot [10–13]. Even though 2H-NbSe2 has been taken as a representative superconductor for many years, it has only recently been found that 2H-NbSe2 is a multiband superconductor with some similarities to that of the superconductor MgB2 [14–16]. The relationship between its superconductivity and Fermi surface nesting is still under research.

In order to figure out this relationship, numerous theoretical and experimental articles have researched its behavior. In the experimental case, researchers have typically used familiar and effective ways to tune the superconducting and CDW transition temperatures of this class, including chemical doping (e.g. [17–22]), adopting high pressure (e.g. [23–26]), and gating [27]. An especially large number of research papers have been published on tuning its superconducting and CDW behavior by chemical doping. So far, all the inorganic doping 2H-NbSe2 systems show lower $T_c$ compared to pristine 2H-NbSe2. For example, the 3d transition metals such as Fe, Ni, Co, Zn, or Al have been used to intercalate into 2H-NbSe2, resulting in a remarkable $T_c$ drop [28, 29]. More recently, we have studied the effect of Cu intercalation of 2H-NbSe2 and found an unusual S-shaped superconducting phase diagram in 2H-Cu$_{x}$Nb$_{1}$Se$_{2}$ [20]. In most of the superconductors, the transition temperature $T_c$ decreases with increasing disorder [30]. However, in the 2H-Cu$_{x}$Nb$_{1}$Se$_{2}$ system, it is generally observed that the $T_c$ will drop off with an increased doping value when ‘impurities’ are introduced into an optimal superconductor, whereas modes in which $T_c$ declined under such instances is novel: an S-shaped superconducting phase diagram was obtained near $x = 0.03$ with an inflection point, and there appeared to be a leveling off of the $T_c$ at about 3 K (the usual value of layered TMD) at high doping content. In contrast, there is a minor change in $T_c$ of the S substitution for Se in the 2H-NbSe2 system [31, 32].

The superconducting state coexists with a CDW state or occurs in proximity of such a state in most metallic TMDs. It has been thought for decades that the occurrence of a CDW state was associated with superconductivity. 2H-NbSe2 is isostructural and isoelectronic to 2H-NbSe2 with a $T_c$ of 6.05 K, but no CDW order occurs [33], which does not accord with the diversity of electronic instabilities in the TMDs. Pristine 2H-NbSe2 and 2H-NbS2 are both multiband superconductors; the former has a CDW state but the latter does not [33–35]. On the other hand, S-doped 2H-NbSe2 slightly affects the $T_c$, but an unusual S-shaped superconducting phase diagram is obtained when Cu ions intercalate into 2H-NbSe2 [20, 31, 32]. 2H-NbSe2 and 2H-NbS2 thus open a door to the study of the interaction of CDW and multiband superconductivity phenomena in the bulk TMDs. Tuning the physical properties of CDW and superconducting states by chemical doping, including substitution and intercalation, is a common tool in the condensed matter field. In order to further study the interplay of the multiband superconductivity and CDW state in the TMDs, we proposed to combine S substitution and Cu substitution/intercalation of 2H-NbSe2. To the best of our knowledge, there have been no previous works about double doping in 2H-NbSe2 to date.

In this article, we report the double doping of Cu and S into 2H-NbSe2 to form Cu$_{x}$Nb$_{1}$Se$_{2}$–yS$_{y}$ ($x = y = 0.06$) and Cu$_{x}$Nb$_{1}$Se$_{2}$–yS$_{y}$ ($0 \leq x = y \leq 0.1$), respectively, retaining the 2H structure (see figures 1(A), (B)). The material is multiphase, with $x > 0.1$ in Cu$_{x}$Nb$_{1}$Se$_{2}$–yS$_{y}$ and $x > 0.06$ in Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$, and thus the corresponding $T_c$ cannot be reliably measured. Magnetic susceptibilities, resistivities, and heat capacity measurements were performed to characterize Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ polycrystalline samples systematically. For comparison, the magnetic susceptibilities of Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ polycrystalline samples were also measured. The results signify that the $T_c$ value decreases with increasing Cu and S content in both Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ and Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$, which was usually observed when ‘foreign matter’ was introduced into pristine 2H-NbSe2 superconductors. However, we obtained an S-shaped superconducting phase diagram with $T_c$ versus $x$ in the Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ case, having an inflection at $x = 0.06$ and tending to smooth out at high $x$ value, from original $T_c$ of about 7.3 K in 2H-NbSe2 to a low $T_c$ value near 2 K, which is similar to the single-doping case in Cu$_{x}$NbSe2. A half arc-shaped superconducting phase diagram with $T_c$ versus $x$ was also observed in the Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ case. The superconducting state competes with the CDW state in the layered Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ TMDs at low temperatures. Low-temperature scanning tunneling microscopy (STM) study reveals the formation of $2 \times 2$ commensurate CDWs on the sample’s surface, and tiny variety in the g vector of the CDW state arising from the Cu intercalation and S substitution weakens but does not eliminate the correlation of the CDW. The difference from other doped 2H-NbSe2 materials such as Nb$_{x}$Se$_{2}$–yS$_{y}$, Fe$_{x}$Nb$_{1}$Se$_{2}$, Cu$_{x}$Nb$_{1}$Se$_{2}$, and Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ in the superconducting phase diagram reveals its uncommon character.

**Experimental section**

Cu$_{x}$Nb$_{1}$Se$_{2}$–yS$_{y}$ ($0 \leq x = y \leq 0.1$) and Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ ($x = y = 0.06$) polycrystalline samples were synthesized via solid state method. First, the mixture of reagent of Cu (99.9%), S (99.999%), Se (99.999%), and Nb (99.9%) in corresponding stoichiometric ratios were heated to 850°C at a rate of 2°C min$^{-1}$ and held for 5 days in sealed vacuum silica glass tubes. Then the as-prepared polycrystalline samples were reground, re-pelletized, and sintered again at a rate of 5°C min$^{-1}$ to 850°C and held for 2 days. The selected compositions’ single crystals were grown by chemical vapor transport (CVT) method, using iodine as a transport agent. The Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ ($0 \leq x = y \leq 0.1$) as-prepared powders were mixed with iodine at quality ratio 20:1, and then heated in sealed vacuum silica tubes for 7 days in a two-zone furnace, where the growth and source zone temperatures were 625 and 725°C, respectively. We adopted the same method to synthesize the powder and single-crystal sample of Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ ($0 \leq x = y \leq 0.06$).

The morphologies of the single crystals were studied by scanning electron microscopy (SEM, Quanta 400F, Oxford) operated at 20 kV. The element distributions and compositions of single crystals of Cu$_{x}$Nb$_{1}$–Se$_{2}$–yS$_{y}$ were investigated by energy-dispersive x-ray spectroscopy (EDXS). The
Figure 1. Structural and chemical characterization of Cu$_x$Nb$_{1-x}$Se$_{2-y}$S$_y$ and Cu$_x$NbSe$_{2-y}$S$_y$.
(A) Powder XRD patterns (Cu Kα) for the Cu$_x$Nb$_{1-x}$Se$_{2-y}$S$_y$ samples studied (0 ≤ x ≤ 0.1). Inset shows the enlargement of peak (002). (B) Powder XRD patterns (Cu Kα) for the Cu$_x$NbSe$_{2-y}$S$_y$ samples studied (0 ≤ x ≤ 0.1). Inset shows the enlargement of peak (002). (C) Powder XRD pattern with Rietveld refinement for Cu$_{0.04}$Nb$_{0.96}$Se$_{1.96}$S$_{0.04}$. Inset shows the crystal structure of 2H-NbSe$_2$ with Cu- and S-doping. (D) Powder XRD pattern with Rietveld refinement for Cu$_{0.04}$Nb$_{0.96}$Se$_{1.96}$S$_{0.04}$. Inset shows the crystal structure of 2H-NbSe$_2$ with Cu intercalation and S-doping. (E) The evolution of lattice parameter a of Cu$_x$NbSe$_{2-y}$S$_y$ and Cu$_x$Nb$_{1-x}$Se$_{2-y}$S$_y$. (F) The evolution of lattice parameter c of Cu$_x$NbSe$_{2-y}$S$_y$ and Cu$_x$Nb$_{1-x}$Se$_{2-y}$S$_y$. 

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Cu_{0.06}NbSe_{1.71}S_{0.08} sample was also characterized by a low-temperature STM (USM-1600, Unisoku) with an ultrahigh vacuum (base pressure ~1 × 10^{-10} torr) at T = 4.8 K. The sample was cleaved in situ at room temperature and then transferred into the STM head immediately. Electro-chemically etched tungsten tips were used after heating and silver decoration.

We adopt powder x-ray diffraction (PXRD) with Bruker D8 Advance ECO equipping LYNXEYE-XE detector and Cu Kα radiation to determine the phase purity of polycrystalline samples. The unit cell parameters were determined by profile-fitting the powder diffraction data with the FULLPROF diffraction suite with Thompson–Cox–Hastings pseudo-Voigt peak shapes [36]. The temperature-dependent electrical resistivity (4-point means), magnetic susceptibility, and heat capacity of the polycrystalline samples were measured by the EverCool II Quantum Design Physical Property Measurement System. The materials showed no air-sensitivity signs in the vacuum base pressure 10 torr.

Results and discussion

Figures 1(A)–(F) show the unit cell parameters and PXRD pattern for Cu_{x}Nb_{y}Se_{z}S_{p} (0 ≤ x = y ≤ 0.1) and Cu_{x}Nb_{y}Te_{z}S_{p} (0 ≤ x = y ≤ 0.06). The results show that the powder samples obtained were pure. The doping limit for substitution of S and intercalated Cu into 2H-NbSe_{2} is x = 0.1. However, the limit for Cu and S co-substitution into 2H-NbSe_{2} is x = 0.06. Impurities will appear, as shown in figure 1(A), when the doping content is over the limit. The unit cell parameters c for both Cu_{x}NbSe_{z−x}S_{p} (0 ≤ x = y ≤ 0.1) and Cu_{x}Nb_{y}Se_{z−x}S_{p} (0 ≤ x = y ≤ 0.06) increase linearly with increasing Cu and S content within the solid solution. a augments linearly from 12.5680(6) (x = 0.00) to 12.6166(3) (x = 0.10) in Cu_{x}Nb_{y}Se_{z}S_{p} and from 12.5680(6) (x = 0.00) to 12.5853(3) (x = 0.06) in Cu_{x}Nb_{y}Se_{z−x}S_{p}, with Vegard’s law type behavior. The inset of figures 1(A), (B) show the position of peak (002) movement to the left with more doping content. This also demonstrates that c will increases with augmentation of doping (figure 1(F)). Figures 1(C), (D) show the refinement results of powder 2H-Cu_{0.04}Nb_{0.96}Se_{1.96}S_{0.04} and Cu_{0.08}NbSe_{1.96}S_{0.04}. These reflections can be indexed in the P6_{3}/mmc space group; the lattice parameters are derived to be a = 3.4480(3) Å and c = 12.5785(9) Å for Cu_{0.04}Nb_{0.96}Se_{1.96}S_{0.04}, a = 3.4457(3) Å and c = 12.5859(9) Å for Cu_{0.08}NbSe_{1.96}S_{0.04}. The Cu_{x}NbSe_{z−x}S_{p} crystal structure shows the central Nb in trigonal prismatically coordinated by randomly occupied chalcogen (S and Se) to form the MX_{2} layer, with Cu intercalating between these layers (figure 1(D)). The Cu_{x}Nb_{y}Se_{z−x}S_{p} crystal structure shows the central Nb with Cu-doping in trigonal prismatically coordinated by randomly occupied chalcogen (S and Se) to form the MX_{2} layer (figure 1(C)). Figures S1(A)–(C), available online at stacks.iop.org/SUST/32/085008/mmedia, show the SEM and EDX images of Cu_{0.06}NbSe_{1.71}S_{0.08} single crystal. From figure S1, we can confirm that the composition of the single crystal is Cu_{0.06}NbSe_{1.71}S_{0.08}, which has a layer structure and will be used for STM measurements later.

Figures 2(A), (B) show the temperature dependence of magnetic susceptibility under applied magnetic field of 20 Oe for Cu_{x}Nb_{y}Se_{z−x}S_{p} (0 ≤ x = y ≤ 0.06) and Cu_{x}NbSe_{z−x}S_{p} (0 ≤ x = y ≤ 0.1), respectively, in the temperature range 2–8 K. The measurements are performed under zero-field cooling. Figure 2(A) shows the rapid downturn for Cu_{0.04}Nb_{0.96}Se_{1.96}S_{0.04} (0 ≤ x = y ≤ 0.06), whereby the T_{c} almost drops to 3.5 K when x = 0.02. As shown in figure 2(B), in the case of Cu_{0.08}NbSe_{1.96}S_{0.04} (0 ≤ x = y ≤ 0.1), T_{c} also decreases with the increase of the content of intercalation of Cu and substitution of S. We next adopt systematic research on Cu_{x}NbSe_{z−x}S_{p}. We further conduct a test on Cu_{x}NbSe_{z−x}S_{p} polycrystalline samples, after pelletization and sinterization, for temperature dependence of the normalized electrical resistivities (ρ/ρ_{300K}), as shown in figure 2(C). We easily find an obvious, sharp drop of ρ(T) curves, which represents the onset of superconductivity at low temperatures (figure 2(D)). The T_{c}s declines with the increasing doping content. This tendency is also apparent from the susceptibility data of Cu_{x}NbSe_{z−x}S_{p} (figure 2(B)), which shows that the superconducting state moves to lower temperatures systematically with the increasing doping content in Cu_{x}NbSe_{z−x}S_{p} indicated by the negative magnetic susceptibility. The Cu_{x}NbSe_{z−x}S_{p} samples show a metallic temperature dependence between 8 to 300 K (dρ/dT > 0). At low temperature, the dρ/dT versus T curve shows peaks at the corresponding T_{c}s (inset of figure 2(C)).

In order to get more data of the superconductivity and electronic properties of the Cu_{x}NbSe_{z−x}S_{p} sossolid, we adopt heat capacity measurements on their polycrystalline samples. Figure 3 shows the temperature-dependent zero-field heat capacity, that is C_{p}/T versus T, for the Cu_{0.02}NbSe_{1.98}S_{0.02} sample. The heat capacity curve displays a sharp and specific heat jump, which indicates the superconducting transition temperature for this material. The obtained T_{c} from heat capacity is highly consistent with the T_{c} obtained by the χ(T) and ρ(T) tests. The normal state of specific heat at high temperatures of zero magnetic field obey the relation of C_{p}/T = βT^{2} + γ, where β and γ describe the phonon and electronic contributions to the heat capacity, respectively. We obtained the values of β and γ (inset of figure 3) from fitting the data obtained at the 0 T field. The normalized specific heat jump value ΔC/γT_{c} obtained from the data (figure 3) was 2.16 for Cu_{0.02}NbSe_{1.98}S_{0.02} which was much higher than the Bardeen–Cooper–Schrieffer weak-coupling limit value (1.43). Then we estimate the Debye temperature by the formula θ_{D} = (12π^{4}nR/5β)^{1/3} using the fitted value of β, where R is the gas constant and n is the number of atoms per formula unit. The lattice becomes more stable when the Se–Se Van der Waals bonds were changed into Se–Cu–Se ionic
bonds by increasing Cu content in Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$, which, as reflected in the result in figure 3 shows that the Debye temperature increases modestly (table 1). Thus, we can calculate the electron-phonon coupling constant ($\lambda_{ep}$) using the Debye temperature ($\Theta_D$) and critical temperature ($T_c$) from the inverted McMillan formula [37]:

$$\lambda_{ep} = \frac{1.04 + \mu}{(1.04 + \mu) \ln \left( \frac{\Theta_D}{T_c} \right) - 1.04}$$

The values of $\lambda_{ep}$ are 0.80 for Cu$_{0.02}$Nb$_{0.98}$Se$_2$ (table 1); this value suggests strong coupling superconductivity properties. The electron density of states at the Fermi level ($N(E_F)$) can be calculated from

$$N(E_F) = \frac{3}{2} \gamma + \frac{3}{2} \lambda_{ep} \gamma$$

with the $\gamma$ and $\lambda_{ep}$. This yields $N(E_F) = 4.08$ states/eV f.u. for NbSe$_2$ and $N(E_F) = 3.62$ states/eV f.u. for Cu$_{0.02}$Nb$_{0.98}$Se$_2$ (table 1). These results indicate that the density of electronic states at the Fermi energy thus decrease obviously with increasing Cu content into 2H-NbSe$_2$. With the goal of determining the critical fields $\mu_0H_C(0)$, we further examined temperature-dependent electrical resistivity under applied magnetic fields for selected

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**Figure 2.** Transport characterization of the normal states and superconducting transitions for Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$ and Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$. (A) Magnetic susceptibilities for Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$ ($0 \leq x = y \leq 0.06$) at the superconducting transitions; applied DC fields are 20 Oe. (B) Magnetic susceptibilities for Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$ ($0 \leq x = y \leq 0.01$) at the superconducting transitions; applied DC fields are 20 Oe. (C), (D) Temperature dependence of the resistivity ratio ($\rho/\rho_{300K}$) for polycrystalline Cu$_x$Nb$_{1-x}$Se$_2$−$y$S$_y$ ($0 \leq x = y \leq 0.1$). Inset of (C) shows metallic temperature dependence ($d\rho/dT$) in the temperature region of 2–8 K.

**Figure 3.** Heat Capacity characterization of Cu$_{0.02}$Nb$_{0.98}$Se$_2$. Debye temperature of Cu$_{0.02}$Nb$_{0.98}$Se$_2$ obtained from fits to data in applied field. Inset shows heat capacities through the superconducting transitions without applied magnetic field for Cu$_{0.02}$Nb$_{0.98}$Se$_2$. 

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Cu$_x$NbSe$_2$, samples. Figure 4 reveals the $\rho(T,H)$ data measured for Cu$_x$NbSe$_2$, (x = 0.01, 0.02), which was shown as an example. The inset of figures 4(A) and (B) show upper critical field values of $\mu_0H_{c2}$ plotted versus temperature, with $T_c$ obtained from resistively different applied fields. The solid lines through the data show the nicely linear fitting for $\mu_0H_{c2}$ versus $T_c$ of the two selected samples. The value of fit data slopes ($dH_{c2}/dT$) of the selected samples are shown in table 1. We can estimate the zero-temperature upper critical fields (upper inset of figures 4(A) and (B)) to be 3.5 T for Cu$_{0.01}$NbSe$_{1.99}$S$_{0.01}$ and 3.0 T for Cu$_{0.02}$NbSe$_{1.98}$S$_{0.02}$ from these data, using the Werthamer–Helfand–Hohenberg expression for the dirty limit superconductivity, $\mu_0H_{c2} = -0.693T_c (dH_{c2}/dT_c)$ [37–41]. The results obtained are summarized in table 1. The Pauli limiting field for Cu$_x$NbSe$_{2−y}$S$_y$ (x = 0.01, 0.02) was calculated from $\mu_0H^p = 1.86T_c$. The calculated values of $\mu_0H^p$ were larger than the estimated values. Then, with this formula $\mu_0H_{c2} = \frac{\mu_0H^p}{2\gamma_0}$, where $\gamma_0$ is the flux quantum, the Ginzburg–Laudau coherence length ($\xi_{GL}(0)$) was calculated ~9.7 nm for Cu$_{0.01}$NbSe$_{1.99}$S$_{0.01}$, and ~10.3 nm for Cu$_{0.02}$NbSe$_{1.98}$S$_{0.02}$ (table 1).

STM imaging gives rise to the real-space electronic state information, which has been proved to be the direct experimental evidence of CDW phases. The Cu$_{0.02}$NbSe$_{1.97}$S$_{0.03}$ sample was characterized by our low-temperature STM. Figure 5 presents the STM image, which clearly displays the formation of the 2 × 2 commensurate CDW on the sample’s surface. (The voltage-dependent STM images are shown in SI figure S1). We thus confirmed the formation of CDW on the sample.

Finally, we obtained the superconductivity phase diagram plotting $T_c$ versus doping content for 2H-Cu$_x$NbSe$_{2−y}$S$_y$, (0 ≤ x = y ≤ 0.1), summarized in figure 6. For comparison, the information for Cu$_{0.03}$NbSe$_2$, Fe$_x$NbSe$_2$, and NbSe$_{2−y}$S$_y$ (0 ≤ x = 0.1) were all taken from the previous literature. The $T_c$ was extracted from the resistivity measurements performed here for Cu$_x$NbSe$_{2−y}$S$_y$, the $x$ dependence of $T_c$. It is not surprising that the $T_c$ of the sulfur-doped material of 2H-NbSe$_2$ presents a very small change compared to the $T_c$ of pure NbSe$_2$ (2H structure) of 6.5 K. In contrast, intercalation of magnetic ions may lead to a sharp drop of $T_c$, such that the $T_c$ decreases very rapidly with increasing Fe content in Fe$_x$NbSe$_2$. However, nonmagnetic chemically Cu intercalation was found to act somewhere between the Fe- and S-doped extremes in the $T_c$ versus $x$ curves, with a previously unknown example of an S-shaped suppression of $T_c$ by substitution or doping in a single-phase material. This phenomenon also exists in Cu- and S-doping of 2H-NbSe$_2$ (Cu$_{0.01}$Nb$_{1−x}$Se$_{2−x}$S$_x$). Thus, when we adopt Cu intercalation and S substitution in 2H-NbSe$_2$ simultaneously.

![Figure 4](image)

**Table 1.** Characterization of the superconductivity in the Cu$_x$NbSe$_{2−y}$S$_y$ family.

| x = y in Cu$_x$NbSe$_{2−y}$S$_y$ | 0 | 0.01 | 0.02 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|
| $T_c$ (K) | 7.16 | 6.78 | 6.12 | 4.65 | 3.93 | 3.77 | 2.91 | 2.34 | 2.26 |
| $\gamma$ (ml mol$^{-1}$ K$^{-2}$) | 17.4(20) | — | 15.3(5) | — | — | — | — | — | — |
| $\beta$ (ml mol$^{-1}$ K$^{-4}$) | 0.56 | — | 0.55 | — | — | — | — | — | — |
| $\Theta_0$ (K) | 218(16) | — | 220(2) | — | — | — | — | — | — |
| $\Delta C/T_c$ | 2.04 | — | 2.16 | — | — | — | — | — | — |
| $\lambda_0$ | 0.81 | — | 0.80 | — | — | — | — | — | — |
| N ($E_F$) (states/eV f.u) | 4.08 | — | 3.62 | — | — | — | — | — | — |
| $-dH_{c2}/dT$ (T/K) | 1.95(4) | 0.735(2) | 0.713 (5) | — | — | — | — | — | — |
| $\mu_0H_{c2}(T)$ | 9.7(2) | 3.5(3) | 3.0(2) | — | — | — | — | — | — |
| $\mu_0H^p(T)$ | 13.2 | 12.6 | 11.3 | 8.6 | 7.3 | 7.0 | 5.4 | 4.3 | 4.2 |
| $\xi_{GL}(0)$ (nm) | 5.8 | 9.7 | 10.3 | — | — | — | — | — | — |
the $T_c$ decreases light rapidly, and the leveling off appears at larger $x$ content compared with Cu$_x$NbSe$_2$. Thus, Cu$_x$NbSe$_{2-x}$S$_x$ materials may provide a new platform for our understanding of multiband superconductivity phenomena and CDW in TMDs.

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**ORCID iDs**

Yishi Lin https://orcid.org/0000-0002-6124-1137
Huixia Luo https://orcid.org/0000-0003-2703-5660

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