Pressure-induced superconductivity and topological phase transitions in the topological nodal-line semimetal SrAs\(_3\)

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Topological nodal-line semimetals (TNLSMs) are materials whose conduction and valence bands cross each other, meeting a topologically protected closed loop rather than discrete points in the Brillouin zone (BZ). The anticipated properties for TNLSMs include drumhead-like nearly flat surface states, unique Landau energy levels, special collective modes, long-range Coulomb interactions, or the possibility of realizing high-temperature superconductivity. Recently, SrAs\(_3\) has been theoretically proposed and then experimentally confirmed to be a TNLSM. Here, we report high-pressure experiments on SrAs\(_3\), identifying a Lifshitz transition below 1 GPa and a superconducting transition accompanied by a structural phase transition above 20 GPa. A topological crystalline insulator (TCI) state is revealed by means of density functional theory (DFT) calculations on the emergent high-pressure phase. As the counterpart of topological insulators, TCIs possess metallic boundary states protected by crystal symmetry, rather than time reversal. In consideration of topological surface states (TSSs) and helical spin texture observed in the high-pressure state of SrAs\(_3\), the superconducting state may be induced in the surface states, and is most likely topologically nontrivial, making pressurized SrAs\(_3\) a strong candidate for topological superconductor.

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INTRODUCTION

In recent years, topological semimetals including Dirac, Weyl, and nodal-line semimetals have been theoretically predicted and experimentally verified, opening a new field in condensed-matter physics in which novel properties and new applications can arise from spin-polarized states with unique band dispersion\(^{1–3}\). Unlike the discrete points in momentum space in Dirac or Weyl semimetals\(^2,3\), the band crossings in nodal-line semimetals can form closed loops inside the BZ\(^4\); a nodal chain consisting of several connected loops\(^5\); or an extended line traversing the entire BZ\(^6\). These one-dimensional nodal curves are topologically protected by certain discrete symmetries, for example mirror reflection, time-reversal, or spin-rotation symmetries\(^2,3\). Upon breaking symmetries in a topological nodal-line semimetal (TNLSM), the nodal line is either fully gapped or gapped into several nodal points\(^6\). The nodal-line structure is expected to have several intriguing properties\(^5\), such as unique Landau energy levels\(^5\), special collective modes\(^5\), long-range Coulomb interactions\(^5\), or drumhead-like nearly flat surface states\(^10,11\), which can be considered a higher-dimensional analog of the flat band on the zigzag edge of graphene\(^3\). These drumhead states may host several connected loops inside the BZ\(^4\), or an extended line traversing the entire BZ\(^6\). These one-dimensional nodal curves are topologically protected by certain discrete symmetries, for example mirror reflection, time-reversal, or spin-rotation symmetries\(^2,3\). Upon breaking symmetries in a topological nodal-line semimetal (TNLSM), the nodal line is either fully gapped or gapped into several nodal points\(^6\). The nodal-line structure is expected to have several intriguing properties\(^5\), such as unique Landau energy levels\(^5\), special collective modes\(^5\), long-range Coulomb interactions\(^5\), or drumhead-like nearly flat surface states\(^10,11\), which can be considered a higher-dimensional analog of the flat band on the zigzag edge of graphene\(^3\). These drumhead states may host several connected loops inside the BZ\(^4\), or an extended line traversing the entire BZ\(^6\).

In the search for nodal-line semimetals, several systems have been theoretically proposed since 2011\(^{1–3}\). However, only a few candidates including PbTaSe\(_2\)\(^{13,14}\), ZrSiS\(_x\) (\(X = \text{Si, Se, Te}\))\(^{15,16}\), CaAg\(_X\) (\(X = \text{P, As}\)\(^{17,18}\), and MB\(_7\) (\(M = \text{Ti, Zr}\))\(^{19}\) have been verified experimentally. More recently, the CaP\(_3\) family of materials (MA\(_{3}\), for \(M = \text{Ca, Ba, and Sr}\), for \(X = \text{P, As}\)) was proposed as another potential host of TNLSMs\(^{20}\). Among these compounds, only SrAs\(_3\) shows a strongly topological nature at ambient pressure, while others need extra compressing\(^{20}\). SrAs\(_3\) displays semimetallic behavior with the hole carriers dominating\(^{21,22}\). Previously, unusual galvanomagnetic properties and a first-order longitudinal Hall effect have been found in SrAs\(_3\)\(^{23}\), and quantum oscillation experiments have been applied to map out the shape of the Fermi surface, finding two asymmetric, quasi-ellipsoidal Fermi-bodies as well as light cyclotron effective mass\(^{22}\). Recent magnetotransport measurements on SrAs\(_3\) single crystals found a nontrivial Berry phase and a robust negative longitudinal magnetoresistance (MR) induced by the chiral anomaly, which indicates the presence of topological properties in SrAs\(_3\)\(^{24,25}\). Subsequently, Song et al\(^{26}\) observed the complete nodal-line feature around the \(\mathbf{Y}\) point by means of angle-resolved photoemission spectroscopy, demonstrating the existence of Dirac nodal-line fermions. In contrast to most TNLSMs, the nodal-line structure in SrAs\(_3\) does not coexist with complex topologically trivial Fermi surfaces, which may pave an easy path to potential applications\(^{25,26}\).

Among the topological materials, intense effort has been applied to realizing topological superconductors (TSCs)\(^{27,28}\), one source of Majorana fermions, an effort which suffers from a severe
lack of suitable materials to study. Experimentally, applying chemical doping or pressure to search for superconductivity in known topological materials are two common methods to obtain new TSC candidates. While chemical doping introduces chemical complexity and disorder, pressure is a clean and effective approach for tuning the interactions among multiple degrees of freedom, and superconductivity has been found in many materials via this route. Among the CaP family of materials, CaAs3 was proposed to host a single nodal loop due to time reversal, spatial inversion, and accidental degeneracies. Li et al. reported its transport properties under hydrostatic pressure up to 2.9 GPa, finding a decrease in the resistivity and a possible superconducting transition under pressure. Since SrAs3 has already been demonstrated to be a TNLSM, the lack of any high-pressure report inspired us to explore its pressure dependence.

In this work, we present the results of high-pressure measurements on single-crystalline SrAs3. Upon applying pressure, the topologically protected \( \alpha \) pocket and trivial \( \beta \) pocket disappear around 1 GPa, and two higher frequencies denoted as \( \epsilon \) and \( \xi \) emerge, indicating a Lifshitz transition. More interestingly, a superconducting transition has been observed from 20.6 GPa, with a dome-like pressure dependence. High-pressure X-ray diffraction, discussed in more detail below, indicates a structural transition or a Lifshitz transition. But the ambient-pressure structure persists to ~20 GPa, excluding a structural transition. Fast Fourier transforms of the MR oscillations, displayed in Fig. 2d contain only the \( \alpha \) (1.4 T) and \( \beta \) (5.5 T) pockets from 0.14 to 0.69 GPa, as previously seen at ambient pressure. At 0.99 GPa, the \( \alpha \) and \( \beta \) pockets abruptly disappear, replaced by a single frequency of 21.5 T which we assign to a \( \xi \) pocket. Upon increasing the pressure to 1.47 GPa, the \( \xi \)-frequency pocket is joined by an even higher frequency of 48.3 T which grows rapidly to 63.2 T, which we assign to an \( \epsilon \) pocket. Figure 2e summarizes the pressure-dependent oscillation frequencies, with shading identifying the transition where the Fermi surface changes. The two obvious scenarios for this abrupt transition are a structural transition or a Lifshitz transition. But high-pressure diffraction, discussed in more detail below, indicates that the ambient-pressure structure persists to ~20 GPa, excluding a structural origin. In topological materials, different types of Lifshitz transitions are possible, involving other types of zeroes in the energy spectrum in addition to or instead of the Fermi surface, such as flat bands, Weyl and Dirac nodes, Dirac nodal lines, zeroes in the spectrum of edge states, Majorana modes, etc.

RESULTS
SrAs3 crystallizes in a triclinic (space group \( \text{P} \tilde{1} \)) or monoclinic (space group \( \text{C}2/m \)) structure; the latter is proposed to possess topological-nodal-line states protected by time-reversal symmetry, spatial-inversion symmetry, and mirror symmetry. Figure 1a shows the unit cell of monoclinic SrAs3. This crystal structure can be viewed as a stack of two-dimensional (2D) infinite polyanionic layers \( \text{As}^{\text{I}} \text{Sr}^{\text{II}} \text{P}^{\text{VI}} \) along the \( b \)-axis. The As layers form channels and the Sr cations are inserted into the channels, as shown in Fig. 1b. The inset in Fig. 1c shows the XRD rocking curves of SrAs3 single crystals grown from both Bi flux (which we refer to as BF) and self flux (SF). From an X-ray rocking curve of the (002) Bragg peak, a full width at half maximum (FWHM) of 0.04° indicates the high quality of the SrAs3 single crystal grown from Bi flux, while a broader FWHM of 0.15° for the SF sample suggests lower quality. In resistivity measurements (Fig. 1c), the SF sample exhibits semimetalllic behavior, while the BF sample exhibits metallic behavior. Inset: X-ray diffraction (XRD) rocking curves of the (002) Bragg peak for Bi-flux and self-flux single crystals. The full width at half maximum (FWHM) of bi-flux single crystal is 0.04°, while the FWHM of self-flux single crystal is 0.15°, indicating that the quality of bi-flux single crystals is higher.

Fig. 1 Characterization of SrAs3. a The unit cell of monoclinic SrAs3. b The side view along the \( b \)-axis. c Longitudinal resistivity of SrAs3 single crystal. The black and red curves represent data collected on SrAs3 single crystals obtained through Bi (BF) and self-flux (SF) methods, respectively. The red curve (SF) shows semimetalllic behavior, while the other one (BF) displays metallic behavior. Inset: X-ray diffraction (XRD) rocking curves of the (002) Bragg peak for Bi-flux and self-flux single crystals. The full width at half maximum (FWHM) of bi-flux single crystal is 0.04°, while the FWHM of self-flux single crystal is 0.15°, indicating that the quality of bi-flux single crystals is higher.
band topology. In SrAs$_3$, the $\alpha$ pocket is topologically protected, and the nodal line is situated around the $Y$ point in the BZ$^{24}$. Hence, we surmise that the Fermi surface of SrAs$_3$ is reconstructed below 1.0 GPa, in a Lifshitz transition which involves the 5.5 K. The pressure dependence of the superconducting transition, fig. S1) and discussions are only displayed in the Supplementary.

Fig. 2 Shubnikov–de Haas (SdH) oscillation study of SrAs$_3$ under low pressure. a Resistivity of a SrAs$_3$ single crystal grown from Bi-flux. Upon increasing the pressure to 1.18 GPa, the low-temperature resistivity is monotonously reduced. At 1.47 GPa, the resistivity slightly increases, relative to that at 1.18 GPa. b Pressure dependence of magnetoresistance (MR) of a SrAs$_3$ single crystal at 1.8 K. MR is a non-monotonic, with a maximum at 1.18 GPa and 9 T. c The oscillatory component $\Delta R_{xx}$ at different pressures, extracted from $R_{xx}$ by subtracting a smooth background. d Fast Fourier transform (FFT) results for SdH oscillations at different pressures. From 0.14 to 0.69 GPa, the $\alpha$ and $\beta$ bands have trivial Berry phase. e Pressure dependence of FFT frequency. The shaded area contains a Lifshitz transition. f Landau level index plots for the $\epsilon$ band at 0.99 GPa, and the $\xi$ band at 1.47 GPa. Both bands have trivial Berry phase.

To verify whether the pressure-induced superconductivity arises from a structural phase transition, we performed high-pressure synchrotron XRD measurements on the self-grown SrAs$_3$ samples, as shown in Fig. 4a for different pressures. The ambient-pressure synchrotron XRD measurements on the self-grown SrAs$_3$ samples (as shown in Fig. 5i) and discussions are only displayed in the Supplementary Information file). Figure 3a shows the resistance curves for SrAs$_3$ under higher pressures. No superconducting transition is observed till 20.6 GPa. At 20.6 GPa, a superconducting transition with $T_c^{\text{GL}}$ of 3.6 K appears, and the $T_c$ increases to 5.8 K at 54.7 GPa. Upon further pressurization to 63.6 GPa, the $T_c$ decreases slightly to 5.5 K. The pressure dependence of the superconducting transition, summarized in Fig. 3c, is clearly dome-shaped. To verify this is a superconducting transition, the effect of magnetic field at 39.4 GPa was studied, as plotted in Fig. 3b—the transition is gradually suppressed by magnetic field, as expected for superconductivity. Figure 3d plots the temperature dependence of the upper critical field ($\mu_0 H_{c2}$). We used the Ginzburg–Landau (GL) formula $\mu_0 H_{c2}(T) = \mu_0 H_{c2}(0) (1 - (T/T_c)^2)^{1/4}$ to fit the data at 39.4 GPa; the $\mu_0 H_{c2}(0)$ values are estimated to be 2.58(2), 2.00(2), and 1.48(3) T for $T_c^{(0)}$, $T_c^{(10)}$, and $T_c^{(0)}$, respectively, yielding coherence length $\xi_{GL}(0)$ of 11.3, 12.9, and 14.9 nm. These fields are much lower than the Pauli limiting fields $^{30-42}$ $H_P(0) = 1.84T_c - 9.5, 7.9, and 6.9$ T, respectively, indicating that Pauli pair breaking is not relevant.

To verify whether the pressure-induced superconductivity arises from a structural phase transition, we performed high-pressure synchrotron XRD measurements on the self-flux-grown samples, shown in Fig. 4a for different pressures. The ambient-pressure (denoted as AP) phase persisted up to ~20 GPa. New diffraction peaks (marked with a dashed line and asterisk) appear at ~23.3 GPa, indicating a pressure-induced structural phase transition, and these continue to strengthen upon further increasing pressure. Figure 4b depicts the crystal structure of SrAs$_3$ under ambient conditions. There are two Wyckoff positions (4i and 8j) for As atoms in each unit cell, and Sr (4i) atoms are coordinated to seven As atoms. The crystal structure of the ambient-pressure phase below 20.4 GPa was refined according to the initial model
example is found in the binary antimonides Li3 compounds with heavy elements of the same group. A typical adopts the structures observed at lower pressures in analogous compounds containing light elements tend at higher pressures to and Bi): Li3N crystallizes in the hexagonal “further effect, the corresponding static principle suggests the Cu3Au structure type as a strong structure (space group: Pm
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70% and 30% for the ambient and high-pressure phases, respectively. The coexistence of high and ambient-pressure phases up to 51.9 GPa indicates that the pressure-induced structural phase transition in SrAs3 is first order and that the two phases have only a minute difference in Gibbs free energy.

Since the pressure-induced superconductivity appears long after the topologically protected pocket is eliminated, it is important to check whether the high-pressure band structure of SrAs3 is topologically nontrivial, which is a necessary condition for topological superconductivity. To obtain more electronic structure information on the high-pressure phase of SrAs3, we performed DFT calculations for pressurized SrAs3 at 34 GPa, as summarized in Fig. 5. The band structure in the absence of spin–orbit coupling (SOC), shown in Fig. 5a, displays metallic behavior. The electron-dominant valence and hole-dominant conduction bands cross near the Fermi level along the Γ–M line. Owing to the cubic symmetry of this material, there are twelve band crossing points at symmetrically equivalent points in the full BZ. Upon turning on SOC, a gap will be opened at these crossing points, resulting in a continuous SOC gap with a curved chemical potential between valence and conduction bands at each k point, as shown in Fig. 5b.

To identify the topological nature of this material, the Fu–Kane parity criterion at eight time-reversal invariant momenta (TRIM) was utilized to determine the Z2 index. We obtain a trivial Z2 of (0;000) from the production of the parities of all occupied bands at the eight TRIM points, as seen in Fig. 5c. Because of SOC, these Dirac states host a helical spin texture as shown in Fig. 5f. The Wilson loop method was employed to determine the mirror Chern number (MCN), and get MCN = 1, in agreement with the

Fig. 3 Pressure-induced superconductivity in SrAs3. a Temperature dependence of the resistance of SrAs3 powder obtained by crushing a self-flux-grown single crystal. b Magnetic field dependence of the superconducting transition of SrAs3 at 39.4 GPa. c Contour plot of the pressure dependent of the superconducting transition. The color represents the magnitude of d(R/RT )/dT. d Temperature dependence of the upper critical field μ0Hc2. The superconducting transition temperatures (Tc) are defined according to the 10% drop of the transition (Tc0.1), the 50% drop of the transition (Tc50), and zero resistance (Tc0), respectively. The red line is the fit according to the Ginzburg–Landau theory, μ0Hc2(T) = μ0Hc2(0) (1–(T/Tc2)3)1/(1+((Tc/Tc2)−1)).

At ambient conditions, SrP3 and SrAs3 have the same crystal structure (C2/m), while SrBi3 forms in the cubic Cu3Au-type structure (space group: Pm–3m, No. 221). The corresponding static principle suggests the Cu3Au structure type as a strong candidate for the high-pressure structure. The crystal structure model for high-pressure SrAs3 was deduced by testing several candidates, and was ultimately refined with a SrBi3-like structure (space group: Pm–3m, No. 221). The schematic crystal structure of the high-pressure phase is depicted in Fig. 4d. Sr and As atoms occupy 1a (0, 0, 0) and 3c (0, 0.5, 0.5) Wyckoff positions, respectively, and the CN for Sr has increased to 12. Figure 4e shows the Rietveld refinement of SrAs3 under 49.8 GPa, yielding 70% and 30% for the ambient and high-pressure phases, respectively.
surface state behavior observed on the (001) surface $^{45-47}$. The continuous SOC gap, topologically trivial Z$_2$ index, nontrivial MCN and even number of surface Dirac points indicate that this material is a TCI $^{44-46}$. As a counterpart of topological insulators in which crystalline symmetry replaces time-reversal symmetry to enforce topological protection, TCIs possess topological surface states (TSSs) with an even number of gapless Dirac cones on the surface BZ and host a variety of exotic phenomena $^{47}$, for example, large-Chern-number quantum anomalous Hall effect $^{48}$ or strain-induced superconductivity $^{49}$. The superconductivity in high-pressure SrAs$_3$ may exist in or be induced in these surface states. Owing to their helical spin texture, any superconducting phase in these surface states would most likely be topologically nontrivial $^{34-36,47-49}$, making high-pressure SrAs$_3$ a strong candidate for TSC.

**DISCUSSION**

Searching for Majorana fermions has been fueled by the prospect of using their non-Abelian statistics for robust quantum computation, and they can be realized as a bound state at zero energy, i.e., Majorana bound states, in the vortex core of a TSC $^{27,28}$. To realize a TSC, two primary routes have been proposed, i.e., bulk spin-triplet superconductivity, and superconductivity in spin-nondegenerate TSSs induced by the proximity effect, for instance through heterostructures stacking conventional s-wave superconductors and topological insulators, quantum anomalous Hall insulators, nanowires, or atomic chains $^{27,28,30}$. In the former case, due to the breaking of spin degeneracy by asymmetric SOC, the parity-mixed superconducting state in non-centrosymmetric superconductors may also host Majorana fermions if the singlet component is smaller than the triplet component $^{51}$. Recently, the layered non-centrosymmetric compound PbTaSe$_2$ with strong SOC was reported to possess fully gapped multiband superconductivity $^{52}$. However, its spin-triplet component is small or absent $^{53,54}$. Bulk topological nodal-line states and fully spin-polarized TSSs have been also demonstrated in PbTaSe$_2$ $^{13}$, which may allow proximity-induced fully-gapped superconducting TSSs, which could pair in $p_x+ip_y$ symmetry and host bound Majorana fermions in the vortices $^{14}$.

The superconducting phase of SrAs$_3$ is centrosymmetric ($Pm-3m$), so barring the exceedingly unlikely possibility of bulk spin-triplet superconductivity, the bulk route to Majorana quasiparticles is not available. However, we propose a TCI state hosting TSSs with helical spin texture. Superconductivity in these states or induced in these states by proximity effect from the bulk could potentially be topologically nontrivial. However, unlike in other TCIs such as SnTe or Pb$_{1-x}Sn_xM$ ($M = Se, Te$), trivial bulk bands in pressurized SrAs$_3$ cross the Fermi level, and we are unable to distinguish which bands participate in the superconductivity. Further work will be required to elaborate the contributions from TSSs and bulk states to the superconductivity.

In summary, at ambient pressure, SrAs$_3$ is a TNLSM with 2D drumhead-like nearly-flat surface states, which may be strongly correlated and are often associated with the enhancement of superconductivity $^{55}$, although pressure did not succeed in driving this material superconducting before changing the electronic structure. A Lifshitz transition has been identified below 1.0 GPa, evidencing a topological phase transition, as the quantum oscillations associated with the TNLSM state vanish. Higher-pressure experiments on a powder sample reveal a dome-like superconducting transition accompanying a structural phase...
transition into a phase which we predict to host a topological-crystalline-insulator state with TSSs and helical spin texture. Besides its intrinsic interest as a TNLSM, SrAs$_3$ offers an alternative route to explore the topological-crystalline-insulator state beyond IV–VI semiconductors and, as a superconducting TCI, high-pressure SrAs$_3$ could serve as a candidate TSC. Doping studies or strain may still be able to induce superconductivity in the low-pressure phase, and should be pursued, and the evolution of the drumhead-like states with pressure remains to be clarified.

**METHODS**

**Sample synthesis.** Sr (99.95 %, Alfa Aesar), and As (99.999 %, PrMat) were mixed in a molar ratio of 1:3 and placed into an alumina crucible. The crucible was sealed in a quartz ampoule under vacuum and subsequently heated to 750 °C in 10 h. After reaction at this temperature for 300 h, the ampoule was cooled to 400 °C in 50 h and cooled freely to room temperature. SrAs$_3$ single crystals with black shiny metallic luster were obtained.

**BF method.** Sr (99.95%, Alfa Aesar), As (99.999%, PrMat) and Bi (99.9999%, Aladdin) blocks were mixed in a molar ratio of 1:3:26 and placed into an alumina crucible. The crucible was sealed in a quartz ampoule under vacuum and subsequently heated to 900 °C in 15 h. After reaction at this temperature for 20 h, the ampoule was cooled to 700 °C over 20 h, and then slowly cooled to 450 °C at 1 °C/h. The excess Bi flux was then removed in a centrifuge, and SrAs$_3$ single crystals with black shiny metallic luster were obtained.

**Pressure measurements**

**Resistance measurements under pressure.** For high-pressure experiments, samples were loaded in a piston-cylinder clamp cell made of Be–Cu alloy, with Daphne oil as the pressure medium. The pressure inside the cell was determined from the $T_c$ of a tin wire. A SrAs$_3$ single crystal was cut into a bar shape, and the standard four-probe method was used for resistivity measurements, with contacts made using silver epoxy. Higher-pressure measurements were performed on powder samples comprising crushed single crystals using a diamond anvil cell (DAC). The experimental pressures were determined by the pressure-induced fluorescence shift of ruby$^{56}$ at room temperature before and after each experiment. A direct-current van der Pauw technique was adopted. Resistance measurements were performed with a physical property measurement system, Quantum Design.

**XRD measurements under pressure.** SrAs$_3$ single crystals grown by the self-flux method were ground into fine powder in a mortar for use in the high-pressure synchrotron angle dispersive XRD (AD-XRD) measurement. The high-pressure synchrotron XRD experiments were carried out using a symmetric DAC with a 260-micron culet diamond. A silicon gasket was precompressed to 30 microns in thickness followed by drilling the central part by laser to form a 90-micron diameter hole as the sample chamber. The sample chamber was filled with a mixture of the sample, a ruby chip, and silicone oil as the pressure transmitting medium. The experimental pressures were determined by the pressure-induced fluorescence shift of ruby$^{56}$. Synchrotron AD-XRD measurements were carried out at beamline BL15U1 of the Shanghai Synchrotron Radiation Facility (SSRF) using a monochromatic beam of 0.6199 Å.

**Density functional theory (DFT) calculations**

DFT calculations were performed based on the Perdew–Burke–Ernzerhof-type generalized gradient approximation$^{57}$, and used the projector augmented wave method$^{58}$, as encoded in the Vienna ab initio simulation package$^{59}$. The cutoff energy for the plane-wave basis taken was 500 eV. The first Brillouin Zone was sampled, using a $\Gamma$-centered $12 \times 12 \times 12$ $k$-point mesh. The energy convergence criteria were defined as $10^{-8}$ eV.
The lattice constants were fully relaxed using a conjugate gradient scheme until the Hellmann-Feynman forces on the ions were less than 0.001 eV/Å. We constructed the maximally localized Wannier functions\textsuperscript{50–52} using Sr d and As s and p atomic orbitals. The topological features of surface state spectra were calculated using the iterative Green’s function technique\textsuperscript{35}, as implemented in the Wannier-Tools package\textsuperscript{36}.

**DATA AVAILABILITY**

All data that support the findings of this study are available from the corresponding author upon reasonable request.

**CODE AVAILABILITY**

The computer codes used to carry out the DFT calculations in this work are available upon request from the corresponding author.

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**AUTHOR CONTRIBUTIONS**

S.Y.L. and Y.F.G. conceived the idea and designed the experiments. E.J.C. was responsible for high-pressure transport experiments. W.X., Y.Z., X.W., Z.Q.Z., H.S., and W.G.Y. conducted the high-pressure X-ray diffraction measurements and structure analysis. C.C.Z. and D.Z.D. helped the data collection. S.Y.L., Y.F.G., and W. W.Z. supervised the project. E.J.C., D.C.P., Y.F.G., and S.Y.L. analyzed the data and wrote the paper. E.J.C., W.X., and X.B.S. contributed equally to this work. All authors discussed the results and commented on the paper.

**COMPETING INTERESTS**

The authors declare no competing interests.

**ADDITIONAL INFORMATION**

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