

Multicarrier electrical and thermal magnetotransport in altermagnetic CrSb

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Chromium antimonide has emerged as a key material platform for studying altermagnetism because of its simple binary composition, high Néel temperature, and semimetallic electronic structure. Here, we investigate electrical and thermal magnetotransport in single-crystalline CrSb using steady- and pulsed-magnetic fields up to 65 T, and complement these measurements with neutron diffraction and magnetization data. We confirm the compensated magnetic structure and observe a large nonsaturating magnetoresistance together with a pronounced nonlinear Hall response at low temperatures. Multicarrier modeling, supported by mobility-spectrum analysis, reveals coexisting electron- and holelike charge carriers with mobilities up to $\sim 3000 \text{ cm}^2/\text{Vs}$ and shows that the number of transport channels that can be resolved strongly depends on the accessible magnetic-field range. Thermal-transport measurements further reveal a nonlinear thermal Hall response and a thermal conductivity substantially exceeding a simple Wiedemann-Franz law. The broadly similar field and temperature evolution of electrical and thermal transport point to a dominant electronic contribution, while the remaining deviations indicate additional heat-carrying channels.

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I. INTRODUCTION

Recent theoretical predictions and experimental observations on magnetic materials have significantly advanced with the identification of a new phase of magnetism known as altermagnetism [1–3]. Altermagnets are compensated collinear magnets characterized by spin symmetries that allow a momentum-dependent nonrelativistic spin splitting despite an overall zero net magnetization [4–9]. The resulting spin polarization alternates in sign for different

momentum directions and can enable phenomena such as spin-current generation [10,11] and giant magnetoresistance [12]. In suitable magnetic symmetries, spin-orbit coupling can additionally allow a spontaneous anomalous Hall effect [13–18].

Many materials have been theoretically proposed to host altermagnetic order [1,19,20], and several have subsequently been investigated experimentally. For example, RuO_2 [10,11,14,21,22] and $\text{KV}_2\text{Se}_2\text{O}$ [9] have received considerable experimental attention. However, their interpretation is currently debated due to fragility or even absence of magnetic order in bulk RuO_2 [23–26], as well as a magnetic structure found in $\text{KV}_2\text{Se}_2\text{O}$ [27] that is incompatible with the altermagnetic spin splitting reported in Ref. [9]. Experimental studies have also addressed Mn_5Si_3 [15,16,20,28–33] and NiAs-type compounds including MnTe [4–6,13,34], CrSb [7,35–38], and the slightly distorted FeS [18].

Among these, CrSb stands out due to its high Néel temperature of around 700 K [39,40], and a significant spin-splitting energy of up to 1.2 eV [1,19]. It is a semimetal with a magnetic

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order that consists of collinear antiparallel spins aligned along the c axis characterized by $26/2m^2m^1m$ spin point group, making it a g -wave altermagnet (AM). The crystallographic arrangement of the Sb atoms prevents the two antiparallel Cr sublattices from being related by inversion combined with time reversal symmetry or by time-reversal combined with a lattice translation. Instead, they are related by rotational symmetry operations, giving rise to the g -wave altermagnetic spin symmetry and allowing momentum-dependent nonrelativistic spin splitting. Recent experimental studies using angle-resolved photoemission spectroscopy (ARPES) and soft x-ray measurements confirm the altermagnetic band splitting of CrSb [7,41], with splitting energies reaching 0.6 eV [7]. Moreover, further ARPES experiments revealed the presence of surface Fermi arcs near the Fermi level for the (100) cleavage plane, associated with bulk topological Weyl nodes [42,43]. These arcs are consistent with theoretical predictions and confirm the existence of topologically nontrivial surface states in CrSb and a coexistence of opposite-spin and same-spin Weyl points [43]. These unique topological properties arise from the altermagnetic nature of CrSb and render it a promising platform to study distinct electronic topologies with dominating nonrelativistic band splitting.

While various AMs, in agreement with predictions, show a spontaneous anomalous Hall effect [13,16,18], the magnetic structure of CrSb does not allow for this to emerge [35,38]. Nonetheless, a pronounced nonlinear Hall response was observed in bulk CrSb [35–37]. Such nonlinearities in the Hall response are common in compensated semimetals and are typically attributed to multicarrier transport; however, previous studies on CrSb have identified a varying number of contributing bands. Here, we utilize high-field magnetotransport for $H \parallel c$ to disentangle these multiple contributions and characterize the multicarrier electronic transport of CrSb.

Apart from electrical magnetotransport measurements, recent thermoelectric measurements on CrSb have revealed a significant conventional Seebeck response accompanied by an anomalous Nernst effect [44]. This was attributed to the altermagnetic band structure near the Fermi level and supported by first-principles calculations. Beyond CrSb, theoretical works on AMs indicate pronounced anisotropies in the thermal conductivity, as shown in RuO₂ [45] and MnTe [46]. These studies also propose thermal Hall and Nernst effects in suitable metallic and insulating altermagnets [47]. In these theoretical studies, magnon Berry curvature in insulating systems and electronic Berry curvature in metallic systems are proposed as possible microscopic origins of thermal Hall and Nernst responses.

In this study, we confirm the magnetic structure in single crystals of CrSb by neutron diffraction and magnetization measurements. We present magnetotransport measurements conducted over an extended magnetic field range up to 65 T. We observe a nonsaturating magnetoresistance (MR) and a nonlinear Hall resistance with magnetic field. Our multicarrier analysis of the transport data is consistent with the coexistence of high-mobility electron- and hole-type charge carriers.

Additionally, we conducted thermal-conductivity and thermal-Hall-effect (ThHE) measurements. The ThHE signal exhibits a nonlinear field dependence that, similar to

the electrical Hall effect, becomes more pronounced at low temperatures. We further observe a marked deviation from a simple Wiedemann-Franz law.

This manuscript is structured into three main sections: Experimental Methods, Results and Discussion—where the findings are presented and analyzed in detail, and Conclusions. The Results and Discussion section is further divided into three parts: A. Growth, structure, and magnetism; B. Magnetoresistance and Hall effect; and C. Thermal conductivity and thermal Hall effect.

II. EXPERIMENTAL METHODS

A. Growth and structural characterization

We used chemical vapor transport for the synthesis of high-quality CrSb single crystals. These crystals originate from the same batch as those used in the earlier x-ray magnetic circular dichroism study [48]. We cut samples for various measurements from these single crystals using a wire saw for bulk samples and gallium focused-ion-beam lithography for microstructures (see Appendix F for details).

We carried out structural characterization by Laue backscatter diffraction using a Photonic Science system. Powder x-ray diffraction was performed using a Panalytical Empyrean system with Cu K_α radiation and a rotating sample at room temperature. We conducted powder diffraction simulations with xrayutilities [49].

B. Neutron diffraction

We performed neutron diffraction from a CrSb single crystal with the time-of-flight neutron diffractometer WISH (ISIS, Rutherford Appleton Laboratory) [50]. A single crystal with volume of roughly 15 mm³, depicted in Fig. 1(a), was mounted on an aluminium strip using aluminium tape for measurements conducted at various sample orientations at a temperature of 1.5 K. We processed the data using MANTID [51] and nuclear and magnetic structure refinement were performed within JANA2020 [52,53]. The refinement was performed using 258 reflections, of which 256 were observed with finite intensity. In addition to the lattice-parameter refinements during the data processing using MANTID, four parameters were refined. These were: (i) an intensity scaling factor, (ii) the magnetic moment on the Cr site, (iii) isotropic atomic-displacement parameters (ADPs) which were constrained to be equal for both atomic species, and (iv) extinction which was treated using the isotropic Becker-Coppens Type-2 model [54].

C. Calorimetry and magnetometry

We performed differential scanning calorimetry (DSC) on CrSb crystals using a SETSYS Evolution 24 instrument (SETARAM Instrumentation) with an S-type DSC plate rod easy fit (50 °C to 1500 °C). Standard alumina crucibles with a diameter of 5 mm and a height of 8 mm were used; the total mass of each sample was less than 10 mg. The temperature dependence of the heat flow was measured in an He atmosphere in the temperature range of 300–1000 K, with a

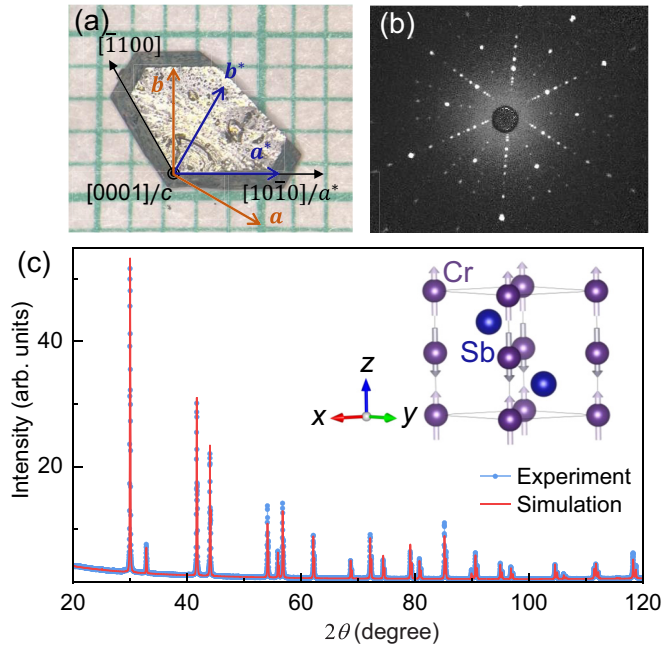


FIG. 1. Characterization of single crystals of CrSb: (a) Optical image of bulk CrSb single crystal with $[0001]/c$ axis perpendicular to the surface. The axes $[10\bar{1}0]/a^*$, $[0001]/c$, and $[\bar{1}100]$ are indicated. Blue axes indicate reciprocal lattice directions, whereas orange indicates real space directions. (b) Room temperature backscattered Laue diffraction pattern obtained from a flat single crystal. (c) Room-temperature powder x-ray diffraction pattern of CrSb. The inset shows the hexagonal unit cell of CrSb together with its magnetic structure (visualized using VESTA [57]). The magnetic moments of the chromium atoms are directed along the c axis.

heating/cooling rate of 5 K/min. Transition temperatures were determined as the onset of the observed peaks.

We performed magnetization measurements in a Quantum Design MPMS3 - SQUID magnetometer and a vibrating-sample magnetometer equipped with an oven insert for temperatures up to 1000 K. Additionally, we studied a powdered sample, prepared from one of the CrSb single crystals by pulsed-field magnetization in a compensated pick-up coil magnetometer up to 58 T and at different temperatures. We used a short-pulse magnet with a pulse duration of 50 ms at the Dresden High Magnetic Field Laboratory, Germany. For further technical details, see Ref. [55].

D. Electrical magnetotransport

We carried out high-temperature electrical resistivity in a rapid-thermal-annealing system, which can sweep temperature from 300 to 850 K. We used a bulk bar-shaped sample labeled S1 [see inset Fig. 2(a)], with dimensions $(3 \times 0.5 \times 0.1) \text{ mm}^3$, cut from CrSb single crystals. We used an electrical current of 5 mA at 333.33 Hz.

We did steady-field magnetotransport measurements on sample S2 [Fig. 3(a)] using a 14 T physical property measuring system (PPMS). We performed resistance measurements using a standard ac four-point lock-in technique. We applied an electrical current of 5 mA at 177.77 Hz along specified

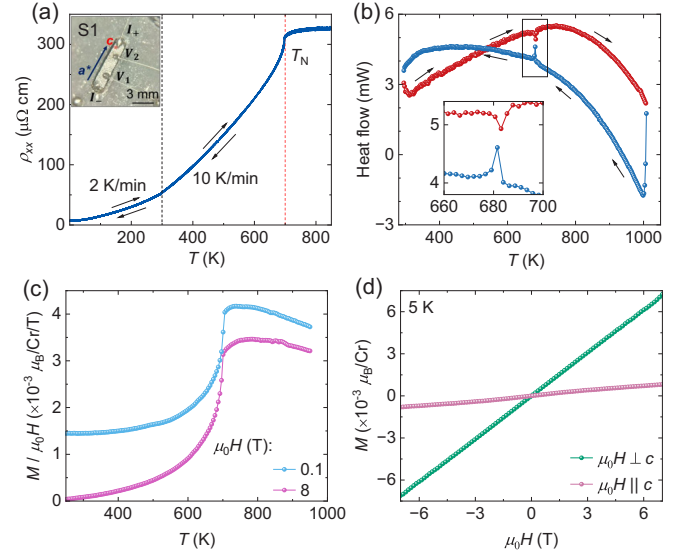


FIG. 2. Determination of the Néel temperature: (a) Zero-field resistance from 300 to 850 K of a bulk CrSb single crystal (inset), showing $T_N \approx 700 \text{ K}$. (b) Differential scanning calorimetry thermograms of CrSb from 300 K to 1000 K. (c) dc magnetic susceptibility, $M/(\mu_0 H)$, measured from room temperature to 1000 K with magnetic fields of 0.1 T and 8 T, indicating a Néel temperature of about 700 K. (d) Magnetization at 5 K for magnetic fields applied along c , as well as perpendicular to c within the basal plane.

crystallographic directions which results in a measurement accuracy of $\pm 0.1\%$ for the sample resistance.

We performed pulsed-field magnetotransport measurements on sample labeled S2, as well as on a focused-ion-beam microfabricated sample labeled L1 [Fig. 3(a)] in a 70 T pulsed magnet with a pulse duration of 150 ms at the Dresden High Magnetic Field Laboratory, Germany. We recorded data for excitation currents of 5 mA at 30 kHz for S2, and 100 μA at 33.33 kHz for L1. We applied a digital lock-in analysis after recording the raw ac voltages during each pulse. For our analysis, we used the slower and, therefore, less noisy down-sweep branch of the magnetic-field pulse. A comparison with the corresponding up-sweep data is provided in Appendix C.

E. Thermal magnetotransport

We carried out steady-field thermal conduction and thermal Hall effect measurements on the bar-shaped sample labeled S3 [Fig. 7(a)] with dimensions $(6.7 \times 1.5 \times 0.29) \text{ mm}^3$, which was mounted in a six-point measurement geometry. We measured thermal conductivity (κ_{xx}) and the thermal Hall (κ_{xy}) effects simultaneously. In our experiment, we applied the heat current within the hexagonal plane, while the magnetic field was applied out-of-plane ($\mu_0 H \parallel c$). We used a 2.7 k Ω chip resistor as a heat source and measured the input power using a four-point method. Both the longitudinal ($l_{xx} = 3.26 \text{ mm}$) and transversal ($l_{xy} = 1.5 \text{ mm}$) thermal gradients were measured with field-calibrated 2-mil (50 μm) E-type thermocouple pairs (Goodfellow Advanced Materials). For the sensitive measurement of κ_{xx} and κ_{xy} , we used a steady-state differential method: We measured the difference in the thermocouple

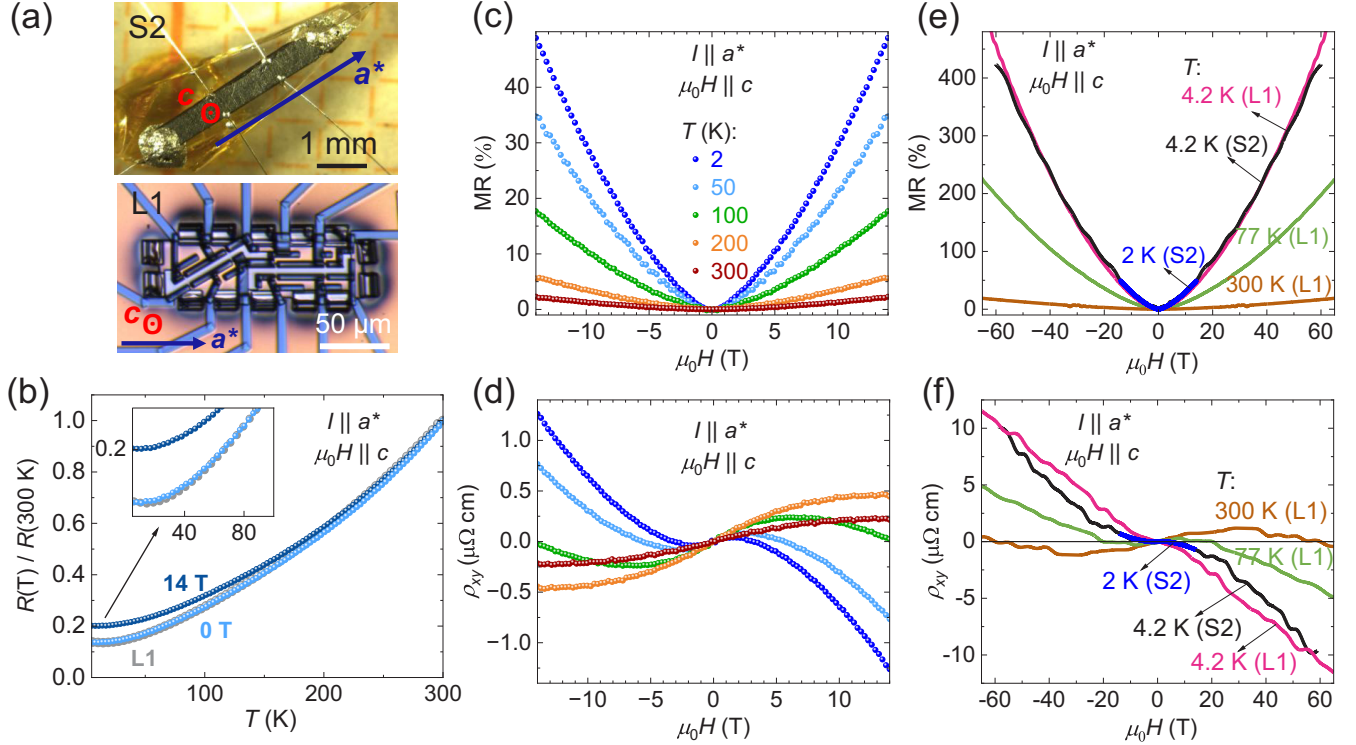


FIG. 3. Electrical transport measurements: (a) Optical images of the Hall bar bulk sample S2 and the multiterminal microstructure L1. Current is applied along the a^* axis, and magnetic field is applied along the c axis for both samples. (b) Longitudinal resistivity measured at 0 and 14 T. Inset: enlargement of the low temperature resistivity. The zero-field resistivity of L1 (grey) matches well with that of the bulk sample (light blue). (c), (d) Magnetic-field dependence of the magnetoresistance and Hall resistivity of the sample S2 recorded at various fixed temperatures between 2 and 300 K. (e), (f) MR and Hall effect recorded in pulsed fields up to 65 T. We compare steady-field data recorded at 2 K (blue) and pulsed-field data at 4.2 K (black) for S2 with pulsed-field data of sample L1 measured at 4.2, 77, and 300 K, pink, green, and brown, respectively.

signals in the presence and absence of a constant heat current at a stable base temperature and magnetic field.

III. RESULTS AND DISCUSSION

A. Growth, structure, and magnetism

We used chemical vapor transport for the growth of mm-sized single crystals [Fig. 1(a)]. The obtained crystals are typically platelike with the c axis perpendicular to the largest facet. We confirmed the crystalline quality by Laue diffraction patterns as shown in Fig. 1(b). The Laue pattern exhibits a pronounced sixfold rotational symmetry, consistent with the hexagonal c axis oriented perpendicular to the platelet surface. Repeated measurements at multiple positions on the same crystal yielded consistent results, demonstrating the uniform crystallographic orientation across the probed area.

Given that Laue diffraction is limited by the short penetration depth of x-rays, we also performed x-ray diffraction measurements on powder prepared from multiple grown crystals to ensure bulk phase purity. The obtained diffraction pattern [Fig. 1(c)] can be described by a nontextured model of single-phase CrSb, which verifies the phase purity, i.e., confirming the exclusive presence of CrSb in the NiAs phase. The determined lattice constants, $a = 4.122(2)$ Å and $c = 5.469(2)$ Å, agree with those reported previously [39,56].

The onset of magnetic order in CrSb is detectable in various properties. For example, a notable transition in the resistivity is observed around 697 K (estimated by the second derivative) in a bulk sample, as depicted in Fig. 2(a) for both heating and cooling. Above this temperature, the resistivity saturates. We conducted differential scanning calorimetry, as shown in Fig. 2(b), and found a clear heat-flow peak [inset of Fig. 2(b)] indicating the magnetic transition at $T_N = (680 \pm 5)$ K. The discrepancy to previously reported Néel temperature ($T_N \approx 713$ K) [58,59], as well as between the different measurements may arise from different temperature measurement schemes used by different probes. The magnetic origin of the observed anomalies is confirmed by the temperature-dependent magnetometry measurements shown in Fig. 2(c). The dc magnetic susceptibility, $M/(\mu_0 H)$, reveals a clear transition to a magnetically compensated state, whose transition temperature is largely independent of the applied external magnetic field up to 8 T. The susceptibility is only a few $10^{-3} \mu_B/\text{Cr/T}$. The magnetization recorded during magnetic field sweeps confirms this picture and reveals no spontaneous uncompensated magnetic moment [Fig. 2(d)]. The susceptibility of CrSb is, however, found to be larger for $\mu_0 H \perp c$ as compared to $\mu_0 H \parallel c$. This indicates a magnetic anisotropy with magnetic moments predominantly along the direction with low susceptibility, that is along the c axis.

In order to extend the characterization of the magnetic response to higher fields, we performed pulsed-field magnetization measurements on powdered CrSb (see Appendix A). The magnetization varies smoothly and approximately linearly over the full investigated field range. Hence, within the resolution of this experiment, we observe no signatures of field-induced changes in the magnetism of CrSb. Together with the small susceptibility determined from the static-field measurements, this shows that no substantial field-induced magnetization develops up to the highest applied fields.

To confirm the magnetic structure and, specifically, the Néel-vector orientation, we performed neutron diffraction on a single crystal. Our analysis focused on a potential lowering of the magnetic symmetry from the previously reported magnetic space group (MSG) $P6_3/m'm'c$ [39,40] (corresponding to the irreducible representation $m\Gamma_4^+$ with $^2_6/2m^2m'm$ spin point group). Such a symmetry reduction, specifically a rotation of the Néel vector, was predicted to induce an anomalous Hall effect [60]. However, our refinements, covering all possible MSGs obtained from the representation analysis performed using JANA2020 and their subgroups, indicate that no other compensated magnetic order is compatible with the observed diffraction data. The other MSGs tested are: $P6_3/mm'm'c$, $P6_3/2'2$, $P6_3$, $Am'm'2$, $Cmcm$, $Cm'c'm$, $Cmc'm'$, $Cm'cm'$, $P31c$, $P1$, $P2_1'$, $P2_1'/m'$, $P2_1/m$, $P3$, Cc , $C2'$, $C2/c$, $C2'/m'$, and $C2'/c'$. Solutions yielding a large uncompensated magnetization were excluded, as they conflict with the magnetometry measurements shown in Figs. 2(c) and 2(d). Crucially, the absence of the 001 diffraction peak is decisive for our refinement; this reflection gains magnetic intensity only if the Néel vector tilts away from the c axis (see Appendix B for details). Based on the background level at this position, we conclude that any possible tilt cannot exceed $\sim 0.5^\circ$. Our neutron-diffraction results, therefore, confirm the previously reported $P6_3/m'm'c$ symmetry with a propagation vector $\mathbf{k} = (0, 0, 0)$, as shown in the inset of Fig. 1(c). From the refinement, we obtain a sublattice magnetic moment of $(2.48 \pm 0.13) \mu_B/\text{Cr}$, consistent with previous reports [61]. Together with the magnetometry results, the neutron-diffraction refinement establishes the compensated magnetic structure of CrSb and its corresponding g -wave altermagnetic spin symmetry. Consistent with this symmetry assignment, the associated nonrelativistic spin splitting has been observed directly by momentum-resolved spectroscopy [7,41].

B. Magnetoresistance and Hall effect

We further studied the field-dependent electrical magnetotransport of a single-crystalline CrSb bar (S2) [Fig. 3(a)] between room temperature and 5 K. In Fig. 3(b), we show the temperature dependence of the longitudinal resistivity ρ_{xx} , measured between 5 and 300 K for zero field and 14 T, respectively. The room-temperature resistivity $\rho_{xx}(300 \text{ K}) = 52.7 \mu\Omega \text{ cm}$ is consistent with recent reports where it ranges from $57 \mu\Omega \text{ cm}$ [37] to $70 \mu\Omega \text{ cm}$ [36] at 300 K. The residual resistivity ratio (RRR) of 7.3 indicates a good metallicity and minor structural or chemical defects. We have reproduced this RRR for various single-crystalline samples and have consistently found values between 7 and 10. As can be seen in Fig. 3(c), the magnetoresistance (MR), defined as MR

$= \rho_{xx}(B)/\rho_0 - 1$, exhibits a nonsaturating, almost quadratic field dependence. Its magnitude increases significantly as the temperature is lowered—ranging from a few percent at room temperature to more than 50% at 2 K and 14 T—a behavior characteristic of metals and semimetals where the MR becomes more pronounced as phonon scattering is suppressed.

In Fig. 3(d), we present Hall-effect data recorded simultaneously with the MR data. ρ_{xy} shows a nonlinear field dependence for all investigated temperatures, which gets more pronounced at lower temperature. While for temperatures above 100 K the Hall-resistivity slope remains positive for the full field range up to 14 T, it crosses zero and turns negative at ever decreasing field values upon decreasing temperature. We extended the field range up to 65 T by conducting magnetotransport measurements in pulsed magnetic fields for the two samples S2 and L1 [Fig. 3(a)] with $\mu_0 H \parallel c$, see Figs. 3(e) and 3(f). For both samples, the MR does not show any sign of saturation up to the highest fields. Thanks to the reduced cross section of the microfabricated sample L1, the overall signal-to-noise ratio could be improved, as can be seen in the curves recorded at 4.2 K for S2 (black) and L1 (pink) in Fig. 3(e).

Interestingly, we find that the Hall resistivity [Fig. 3(f)] acquires an overall negative slope in the high-field range for all measured temperatures. We also observe slight differences in the overall field dependence of the Hall effect between the two samples. This may originate from differences in the purity or additional built-in stress induced in the microstructure from its fixation to the substrate. A more detailed discussion on the robustness of our analysis and sample-dependent effects is provided in Appendixes D and F. However, the overall negative slope at high fields appears to be a general property of CrSb.

To further analyze the MR and Hall data we have performed a multicarrier analysis following previous reports [35–37]. We provide details in Appendix D. Since it is *a priori* unclear how many bands need to be considered, we have performed the analysis with two, three, and four individual contributions.

The fit gradually improves as more bands and, therefore, more parameters are added, as seen in Fig. 4. In order to obtain a reasonable agreement with the experimental data recorded at 2 K and fields up to 14 T [Figs. 4(a) and 4(b)], at least three bands are required. Adding a fourth band, the matching with the Hall resistivity at higher magnetic fields is improved as seen in the inset of Fig. 4(d). By contrast, for smaller magnetic fields up to 10 T at 300 K already two bands reasonably well reproduce both MR and Hall data. In the following, to describe the data up to 14 T, we, therefore, chose four bands to perform a multicarrier analysis over the accessed temperature range between 2 and 300 K. Moreover, our recent work on the study of Shubnikov-de Haas oscillations and its analysis using the density-functional theory has also confirmed multibands in CrSb [62]. Other independent high-field studies of magnetic quantum oscillations are also in line with this picture [63,64].

The temperature dependence of the model parameters is shown in Fig. 5. The dominant band (the one with the highest charge carrier concentration) is of holelike character, consistent with previous reports [35–37]. At temperatures below 20 K, we find stable fit parameters and sizable mobilities of

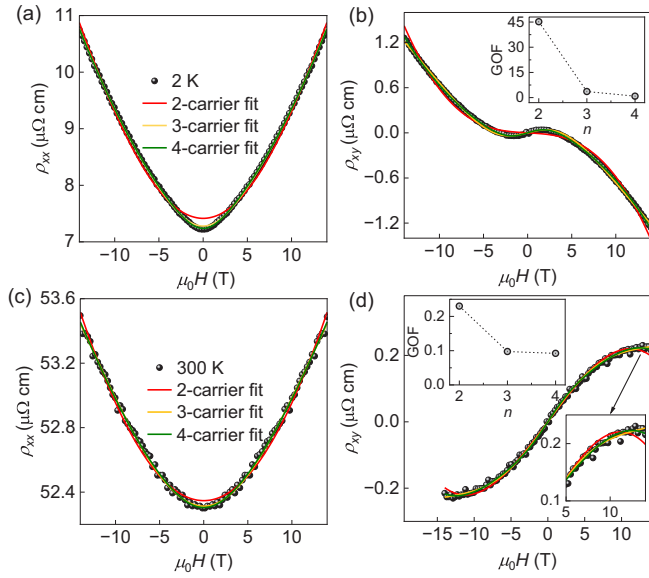


FIG. 4. Multicarrier fitting of MR and Hall resistivity: Magnetic-field dependence of the longitudinal resistivity at 2 K (a), (c) and 300 K (b), (d), respectively. In all panels, the experimental data are compared to fits considering the contribution of 2, 3, and 4 individual types of charge carriers. Insets in (b), (d) show the goodness-of-fit (GOF) statistics for the models with $n = 2, 3$, and 4 types of charge carriers, and a second inset in (d) shows the enlarged high-field range, highlighting the differences of the models.

electron- and holelike carriers. At higher temperatures, in particular above 100 K, the mobilities decrease.

Additionally, we employ the mobility-spectrum-analysis (MSA) technique, which extracts information about the charge-carrier distribution in a material from magnetotransport measurements [65,66]. MSA decomposes the measured longitudinal- and Hall-resistivity data sets into continuous spectra of carrier contributions as a function of mobility, meaning $\sigma_i = n_i q \mu_i \rightarrow \sigma(\mu)$ [65]. This allows for the simultaneous determination of the sign (electron- or holelike), the relative weight (contribution to conductivity), and the corresponding mobility without any assumption on the number of contributing charge carrier types. A more detailed description of the MSA is provided in Appendix E. In practice, the

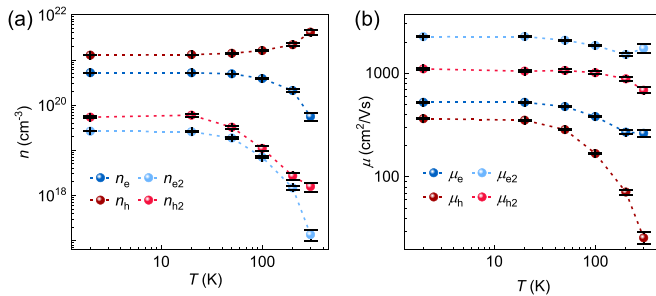


FIG. 5. Multicarrier analysis: Temperature dependence of (a) the charge-carrier concentration and (b) mobility obtained from the four-band model fitting. Error bars show the confidence intervals of the fit parameters, which at lower temperatures are smaller than the symbol size.

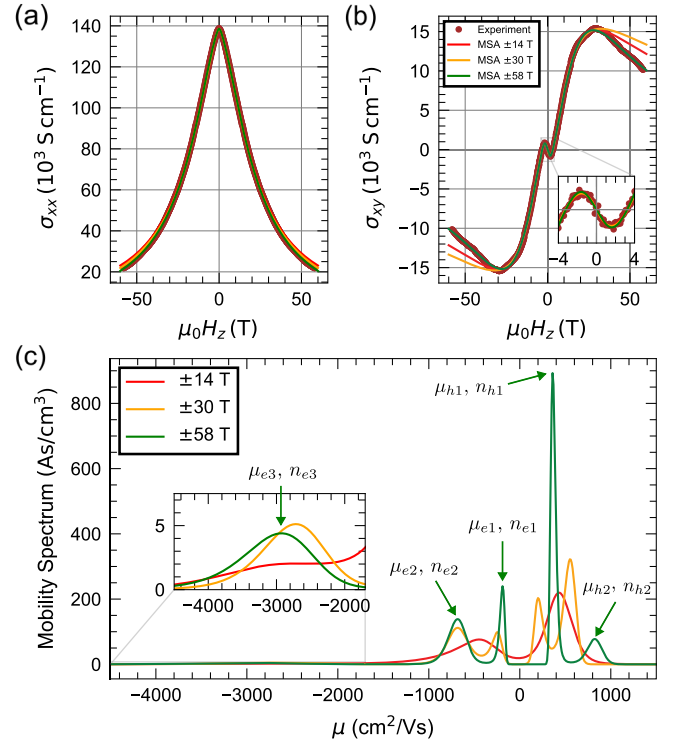


FIG. 6. Mobility spectrum analysis (a), (b) Conductivity reconstructed from the respective MSA models evaluated over different magnetic-field ranges (± 14 , ± 30 , and ± 58 T). (c) Mobility spectra obtained for various magnetic-field intervals.

method provides a way to analyze complex transport data, especially in multiband systems. The method benefits from using as large a field range as possible for the analysis. In Fig. 6, we present the modeling based on MSA for the 4.2 K data recorded for sample S2 in three different field ranges. For this purpose, the resistivity data [Fig. 3] were converted to conductivity. For increased sensitivity at lower fields, we have merged the pulsed-field data with data recorded in steady fields up to 14 T. When considering both the full field range of -58 T to 58 T and the restricted range of -30 T to 30 T, the resulting mobility spectrum, $\sigma(\mu)$, reveals five distinct peaks [Fig. 6(c)]. Only for the narrowest range of -14 T to 14 T low-mobility peaks are not well resolved, and the respective mobility spectrum consists of three broad peaks only. This clearly proves that to resolve low-mobility close-lying peaks, high-magnetic-field data are necessary. Each peak is associated with a charge-carrier population contributing to the magnetic-field dependence of both longitudinal and transverse resistivities. The sign of the mobility at each peak identifies the charge-carrier type, with negative values corresponding to electrons and positive values to holes. The integrated spectral weight of each peak serves as a quantitative measure of its contribution to the total conductivity. This, in turn, provides insight into the associated charge-carrier density and enables a comparison of the relative contributions of different charge-carrier populations to the overall transport response.

Table I provides an overview of the identified charge-carrier populations, which overall compare well with the parameters found by the multi-carrier analysis [Fig. 5]. The

TABLE I. Parameters of charge-carrier populations (e = electrons; h = holes) from MSA for sample S2 at 4.2 K. Contributions of electrons are labeled ei whereas holelike populations are labeled hi , with integer i consistent with labels in Fig. 6.

Label	MSA	
	n (cm^{-3})	μ (cm^2/Vs)
e1	8.25×10^{20}	190
e2	4.31×10^{20}	680
e3	2.0×10^{19}	2930
h1	1.13×10^{21}	360
h2	1.16×10^{20}	820

conductivity reconstructed from the mobility spectrum is shown in comparison with experimental data in Figs. 6(a) and 6(b). The presence of high-mobility bands is consistent with the predicted topological Weyl nodes in the altermagnetic band structure of CrSb [42,43]. The experimentally observed nonsaturating MR could, therefore, be related to the topologically nontrivial properties of CrSb's electronic band structure.

The MSA shows, consistent with previous studies, that multiple charge carriers contribute to the transport properties of CrSb. In particular, as for our analysis with a fixed number of bands, we find that the dominating band with the highest charge-carrier concentration exhibits a holelike character. The various charge-carrier populations show sizable mobilities in the range up to $\sim 3000 \text{ cm}^2/\text{Vs}$. The exact number of charge carriers needed to describe the transport data differs in various

studies [35–37]. These studies, however, also used different magnetic-field ranges. Our analysis based on the MSA, using various magnetic field ranges shows that indeed the field range determines how many independent charge-carrier populations can be resolved (Fig. 6). For magnetic-field ranges from $\pm 14 \text{ T}$ to $\pm 58 \text{ T}$, we find that the number of identified charge-carrier populations increases from 3 to 5, covering the 3 or 4 charge carrier types reported in Refs. [35–37]. A holelike band remains the dominant individual contribution across all analyzed field ranges, consistent with the characteristic Hall response observed throughout the entire temperature interval from 2–300 K. When extending the magnetic-field range, the MSA can resolve more and more individual contributions of different charge-carrier types. Therefore, these results highlight the importance of utilizing an extended magnetic-field range for a reliable characterization and resolution of multi-carrier transport.

C. Thermal conductivity and thermal Hall effect

We also carried out thermal-conductivity and thermal-Hall-effect measurements on two bulk CrSb single-crystals. Figure 7 presents an overview of the thermal-transport measurements on sample S3 performed between 7 and 300 K and for magnetic fields up to 12 T. Figure 7(a) shows a picture of S3 installed for the simultaneous measurement of thermal conductivity (κ_{xx}) and thermal Hall effect (κ_{xy}). A thermal gradient is applied along the long side of the sample within the hexagonal plane ($J \parallel a^*$), while the magnetic field is applied out of the plane ($\mu_0 H \parallel c$).

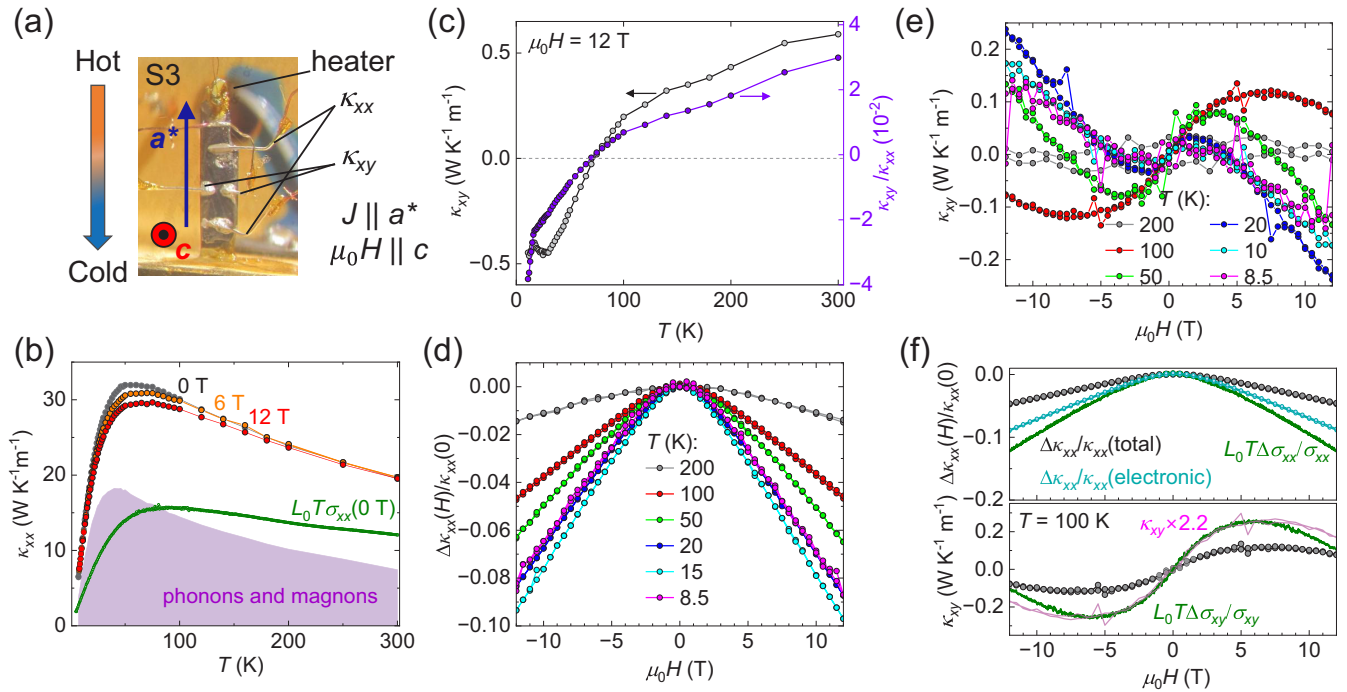


FIG. 7. Thermal transport measurements: (a) Optical image of the bar-shaped sample S3. (b) Temperature dependence of the longitudinal thermal conductivity κ_{xx} at selected magnetic fields. The green curve indicates the electronic contribution to the thermal conductivity, calculated from the Wiedemann-Franz law. (c) Temperature dependence of the thermal Hall conductivity and the thermal Hall angle. (d), (e) Magnetic-field dependence of the relative change in the thermal conductivity and the thermal Hall conductivity at selected temperatures. (f) Comparison of field dependences of the thermal and thermal-Hall conductivity in the context of the Wiedemann-Franz law at 100 K.

In Fig. 7(b), we show the temperature dependence of κ_{xx} at selected magnetic fields. The thermal conductivity increases rapidly towards 50 K, then peaks, and gradually decreases toward room temperature. In the presence of a magnetic field, κ_{xx} is slightly reduced, consistent with an additional magnetic-field-dependent scattering contribution. For comparison, we show the electronic contribution to the heat conduction, calculated from the Wiedemann-Franz law $L_0\sigma_{xx}T$ [67–69] (green curve). Our result shows a nonelectronic contribution to the thermal conductivity, caused by phonons and magnons, as the difference between the measured and Wiedemann-Franz electronic contribution. This nonelectronic part, $\kappa_{\text{non-el}} = \kappa_{xx} - \kappa_{\text{el}}$, dominates the total thermal conductivity at low temperatures, accounting for more than 50% (reaching approximately 60% at the peak near 40 K) of the total signal. The estimated nonelectronic thermal conductivity peaks around 40 K. However, it does not decrease to zero at high temperatures, as expected from the $1/T$ law, which is typical for a magnonic contribution in a high- T_N magnetic system. In Fig. 7(c), we show the temperature dependence of the thermal-Hall conductivity and the thermal-Hall angle, $\theta_H = \kappa_{xy}/\kappa_{xx}$, measured in a ± 12 T out-of-plane field. The thermal Hall conductivity changes sign around 70 K, suggesting competing contributions to the thermal Hall response.

In Figs. 7(d) and 7(e), we show the magnetic-field dependence of the relative change in the thermal conductivity, $\Delta\kappa_{xx}(H)/\kappa_{xx}(0)$, and of $\kappa_{xy}(H)$ at selected temperatures, respectively. The magnetic-field dependence of the thermal conductivity is quadratic and increases in magnitude as the temperature decreases. The strongest field dependence is reached around 15 K. The isothermal thermal Hall conductivity shows a nonlinear magnetic field dependence. At all temperatures, in the low-field region, the thermal Hall conductivity has a positive slope. However, below 70 K, a large component with a negative slope dominates the high-field region.

Finally, to provide a better insight into the possible origin of the field dependence of the heat conduction in CrSb, we compare the relative thermal-conductivity with the electronic component calculated from the magnetoresistance measurements (green) at 100 K, as shown in Fig. 7(f). We can calculate the corresponding $\Delta\kappa/\kappa$ ratio using different base values: the change can be related either to the total thermal conductivity, $\Delta\kappa_{xx}/\kappa_{xx}(\text{total})$ (black), or to the electronic component, $\Delta\kappa_{xx}/\kappa_{xx}(\text{electronic})$ (cyan). As shown in Fig. 7(f), top panel, the ratio $\Delta\kappa_{xx}/\kappa_{xx}(\text{total})$ (black curve) deviates substantially from the electronic component calculated from the magnetoresistance measurements (green), whereas $\Delta\kappa_{xx}/\kappa_{xx}(\text{electronic})$ (cyan) matches much better, though not perfectly. This suggests that, while the field dependence of the heat conduction is predominantly governed by the electrons, a minor contribution may be related to phonons [70] and magnons [71,72]. In the lower panel of Fig. 7(f), the thermal Hall conductivity (black) deviates from that calculated from the electronic contribution via the Wiedemann-Franz law (green). The total and electronic contributions can be brought onto a similar scale by an empirical factor of 2.2 (magenta); however, at higher fields, still deviations appear.

Our results establish a consistent picture of multicarrier electrical and thermal transport in the compensated altermag-

netic semimetal CrSb. On the electronic side, the extended magnetic-field range is essential for resolving the individual transport channels and reconciling the different charge carrier counts reported previously. On the thermal side, the nonlinear thermal Hall response, its sign change around 70 K, and the comparison to the Wiedemann-Franz law show that the heat transport follows the electronic response in broad terms, yet cannot be described fully within a single conventional metallic contribution. We, therefore, conclude that electrons provide the dominant contribution to both charge transport and the field-dependent part of the heat transport in CrSb, while additional heat-transport channels, caused by phononic and magnonic contributions, are relevant for the thermal response. In this sense, CrSb provides a useful benchmark system in which multicarrier semimetallic transport and thermal Hall physics can be addressed within a single material platform with an experimentally well-established altermagnetic state.

IV. CONCLUSIONS

We have synthesized high-quality CrSb single crystals using chemical vapor transport and conducted a comprehensive systematic study of the electrical and thermal magnetotransport properties. We observed a distinct Néel temperature ($T_N \approx 700$ K) in resistivity and magnetization measurements. Magnetization and neutron diffraction establish the compensated magnetic structure and corresponding g -wave altermagnetic spin symmetry of CrSb. Notably, CrSb single crystals exhibit large, positive, and nonsaturating magnetoresistance. Another intriguing observation is the nonlinear Hall response at temperatures ranging from 2 K to 300 K, which we successfully describe by a four-carrier Drude model. Moreover, our detailed mobility spectrum analysis, taking high-field data up to 58 T into account, confirms the presence of very-high-mobility bands ($\mu_{h2} \approx 800$ and $\mu_{e3} \approx 3000$ cm²/Vs) that contribute to the electrical transport at low temperature. This observation is consistent with the predicted topologically nontrivial properties of the altermagnetic band structure in CrSb. The overall field and temperature dependence of the thermal conductivity and thermal Hall response broadly follows that observed in the electrical transport. The thermal conductivity appears to be significantly enhanced relative to the simple Wiedemann-Franz law. This significant deviation at low temperatures further indicates that heat transport is not solely governed by the electronic charge carriers, suggesting a substantial contribution from magnons or phonons in this g -wave altermagnetic system. Furthermore, the sensitivity of the multicarrier fit to the magnetic field range highlights the complex topology of the Fermi surface in CrSb. Our results show that high-field transport is essential for resolving the multicarrier electrical and thermal responses of CrSb. CrSb bears the potential as a platform for studies of the interplay between altermagnetism, high-mobility topological fermions, and anomalous thermal transport.

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DATA AVAILABILITY

The numerical data presented in the figures of this manuscript are available in a Zenodo repository [73]. Raw data of the neutron measurements can be found at [74].

APPENDIX A: PULSED-FIELD MAGNETOMETRY

We performed magnetization measurements on powdered CrSb in pulsed fields up to 58 T at various temperatures. The powder contains crystallites with different orientations relative to the direction of the external magnetic field. Hence, it samples the magnetic response for both ($H \parallel c$) and ($H \perp c$), as well as intermediate orientations. The resulting field dependence is shown in Fig. 8. A conservative estimate based on the larger slope of the static-field magnetization in Fig. 2(d) indicates that the magnetization remains below approximately $0.1 \mu_B/\text{Cr}$ even at the highest applied field.

We also conducted measurements on oriented single crystals. A reliable quantitative magnetization could not be obtained, however, because the rapidly varying magnetic field induced strong eddy-current contributions in the metallic samples.

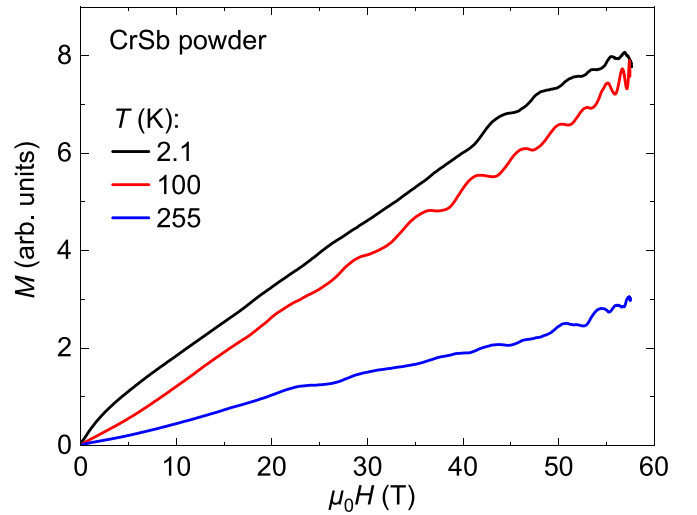


FIG. 8. High-field magnetization of CrSb powder: Pulsed-field magnetization measured on powdered CrSb at 2.1, 100, and 255 K for magnetic fields up to 58 T. The magnetization evolves smoothly with the magnetic field exhibiting no signs of field-induced changes or transitions.

APPENDIX B: NEUTRON-DIFFRACTION ANALYSIS

The correlation plot of the calculated versus observed structure factor for the single-crystal WISH data is shown in Fig. 9(a). The pronounced linear correlation between F_{obs} and F_{calc} demonstrates that the refined structural model satisfactorily reproduces the measured intensities. With respect to an eventual tilt of the Néel vector a particularly important observation is the absence of the 00 l diffraction peaks with $l = 1, 3, \dots$ (odd). This is shown in Fig. 9(b), where exclusively signals for CrSb 00 l for $l = 2, 4$ appear.

APPENDIX C: LONGITUDINAL AND TRANSVERSE RESISTIVITY

We symmetrized the measured longitudinal resistivity (ρ_{xx}) and anti-symmetrized the Hall resistivity data (ρ_{xy}) with respect to the external applied magnetic field using the following equations:

$$\rho_{xx}(\mu_0 H) = \frac{\rho_{xx}(+\mu_0 H) + \rho_{xx}(-\mu_0 H)}{2}, \quad (\text{C1})$$

$$\rho_{xy}(\mu_0 H) = \frac{\rho_{xy}(+\mu_0 H) - \rho_{xy}(-\mu_0 H)}{2}. \quad (\text{C2})$$

With this approach, we effectively eliminate additional contributions and artifacts introduced from geometric irregularities in the sample's shape or the positioning of the contacts.

We used a digital lock-in technique to process the pulsed-field data. We applied a third-order filter with a time constant of 300 μs for smoothing the measured data. We further smoothed data using a fast Fourier transform method in order to reduce noise during the magnetic pulses.

Figure 10 compares the up- and down-sweep branches of the pulsed-field measurements for sample S2 at 4.2 K. The up-sweep traces exhibit substantially larger noise and pronounced pickup features close to zero field due to the shorter rise time of the magnet. Away from this region, the up- and

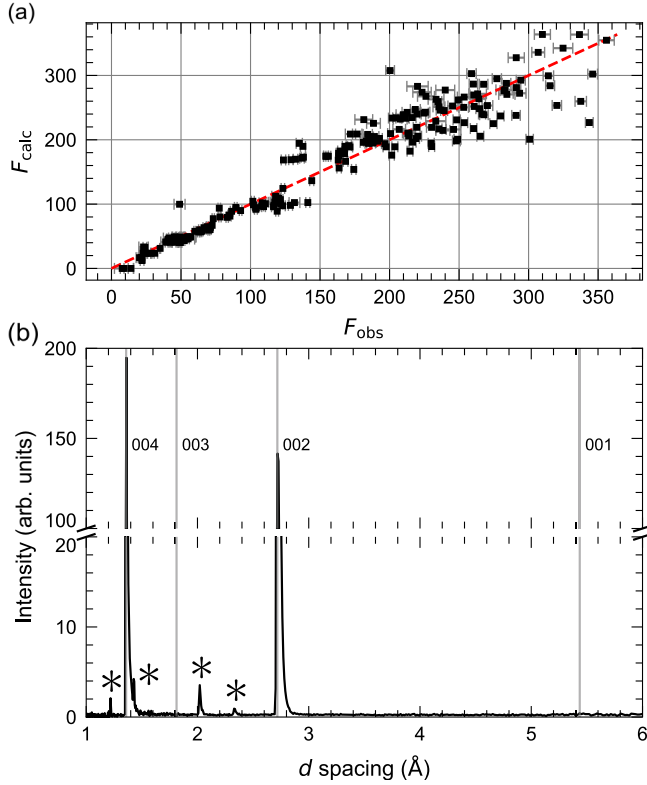


FIG. 9. Neutron diffraction correlation plot and 00 l line cut: (a) Correlation plot of observed versus calculated structure factors. Multiple observations of the same diffraction peak for different wavelengths and sample rotation are shown as individual data points. The associated statistical uncertainties of the experimental data are shown as error bars. (b) Measured intensity along the 00 l direction showing the absence of peaks with odd l . The signal from Al (indicated by *) originates from the sample holder.

down-sweep data show the same overall field dependence for both the longitudinal and transverse resistance. We, therefore, use the slower and much cleaner down-sweep data for the quantitative analysis.

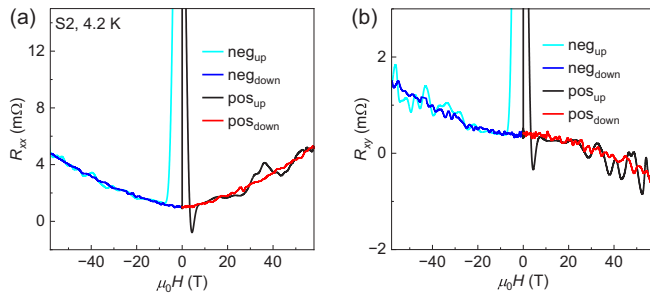


FIG. 10. Comparison of pulsed-field up and down sweeps. Magnetic-field dependence of (a) the longitudinal resistance (R_{xx}) and (b) the transverse resistance (R_{xy}) of sample S2 at 4.2 K. Positive- and negative-field pulses are shown separately for the up- and down-sweep branches. The up-sweep traces exhibit enhanced noise and pronounced pickup features close to zero field due to the shorter rise time of the magnet. Nevertheless, both sweep directions reproduce the same overall field dependence.

No individual data points were selectively removed from the down-sweep data shown in the manuscript. For the mobility-spectrum analysis, the pulsed-field data at ($|\mu_0 H| \leq 14$ T) were replaced by the higher-quality steady-field data, as described in Appendix E.

APPENDIX D: MULTICARRIER FITTING

For the multicarrier analysis with the magnetic field applied along the z direction ($\mu_0 H \parallel z$), the conductivity tensor of the i -th charge carrier type within the classical Drude model can be written as

$$\sigma_i = \frac{n_i e \mu_i}{1 + (\mu_i \mu_0 H)^2} \begin{pmatrix} 1 & s_i \mu_i \mu_0 H \\ -s_i \mu_i \mu_0 H & 1 \end{pmatrix}, \quad (\text{D1})$$

where i denotes the carrier index, e is the elementary charge, n_i the carrier density, μ_i the carrier mobility, and s_i the sign of the charge carrier with $s_i = -1$ for electrons and $s_i = +1$ for holes [75]. The charge carrier densities n_i and mobilities μ_i were treated as free parameters in the fitting procedure. For a system with N carrier types, the total conductivity tensor is obtained by summing over all individual contributions, yielding

$$\sigma_{xx}(\mu_0 H) = \sum_{i=1}^N \frac{n_i e \mu_i}{1 + (\mu_i \mu_0 H)^2}, \quad (\text{D2})$$

$$\sigma_{xy}(\mu_0 H) = \sum_{i=1}^N \frac{n_i e \mu_i^2 \mu_0 H}{1 + (\mu_i \mu_0 H)^2} s_i. \quad (\text{D3})$$

The numerical fitting procedure uses a weighted least-squares algorithm to account for the measurement error of the sample resistance. As goodness-of-fit statistics, we use the reduced χ^2 , which for the data shown in Fig. 4 reduces significantly when using a 4-carrier model, but stagnates when introducing additional charge-carrier contributions. Representative fits obtained within this multicarrier framework are shown in Fig. 11 for models including two and four charge carrier types, respectively.

APPENDIX E: MOBILITY SPECTRUM ANALYSIS (MSA)

The dataset employed for the MSA combines steady-field data recorded up to ± 14 T with pulsed-field data for $|\mu_0 H| > 14$ T. This approach was necessary because the higher noise level in the pulsed-field measurements obscures key features in the low-field regime, most notably the slope change at approximately ± 2.5 T.

The concept underlying the mobility spectrum analysis is that, in the limit where the number of charge-carrier types N in Eqs. (D2) and (D3) becomes very large ($N \rightarrow \infty$), the discrete sum over N can be replaced by a continuous integral over the mobility μ . In this formalism, the conductivity contribution of individual charge-carrier types is represented by a continuous conductivity spectrum $\sigma(\mu)$. For a magnetic field applied along the z direction, the longitudinal and transverse components of the conductivity tensor are then given by

$$\sigma_{xx}(\mu_0 H) = \int_{-\infty}^{\infty} \frac{\sigma(\mu)}{1 + (\mu \mu_0 H)^2} d\mu \quad (\text{E1})$$

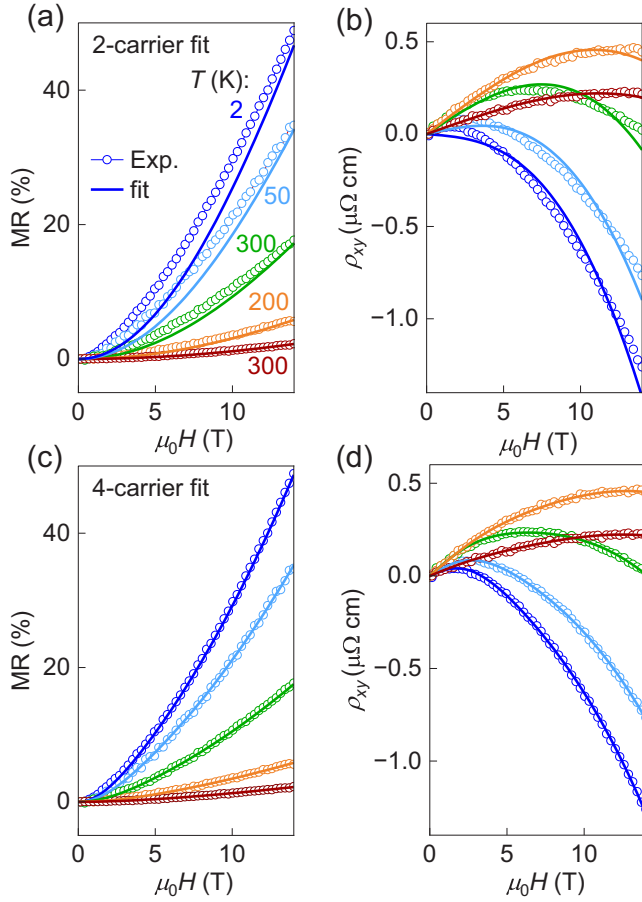


FIG. 11. MulticARRIER fitting of MR and Hall resistivity: (a), (b) Magnetic-field dependence of the longitudinal resistivity and Hall resistivity compared to fits of a two-band model. (c), (d) Magnetic field dependence of the longitudinal resistivity and Hall resistivity, respectively, are compared to a four-band model. ρ_{xx} is normalized to the zero-field resistivity of the respective data. Lines correspond to the respective fits.

and

$$\sigma_{xy}(\mu_0 H) = \int_{-\infty}^{\infty} \frac{\mu \mu_0 H \sigma(\mu)}{1 + (\mu \mu_0 H)^2} d\mu. \quad (\text{E2})$$

In contrast to the discrete multicARRIER model, where the sign of the charge carrier is explicitly introduced via the factor s_i , the MSA incorporates the charge-carrier type through the

sign of the mobility. Negative and positive mobilities correspond to electron- and holelike carriers, respectively, while the conductivity spectrum $\sigma(\mu)$ is required to be positive, $\sigma(\mu) \geq 0$, to ensure a physically meaningful representation.

APPENDIX F: FIB-ASSISTED FABRICATION OF MICROSTRUCTURES

We fabricated CrSb microstructures using gallium focused-ion-beam (FIB) lithography. First, we cut a lamella with dimensions of the order of $(30 \times 2.5 \times 150) \mu\text{m}^3$ from the bulk single crystal using a Ga-FIB and subsequently transferred it *ex-situ* onto a sapphire substrate. Next, an approximately 150 nm-thick gold layer was deposited over the entire lamella via magnetron sputtering. The gold layer was then partially removed from the central top surface using Ga^+ ion etching. Subsequently, trenches were milled into both the gold layer and the underlying sample using FIB to define well-controlled contact terminals. We patterned multiple voltage leads along the bar to enable measurements of both longitudinal and transverse voltages. Further details about the procedure are well explained in Ref. [76]. Microstructure L1 [shown in Fig. 3(a)] with the long axis parallel to the a^* axis has a cross-section of $(w \times t) = (4.3 \times 2.1) \mu\text{m}^2$ and a length of $32.1 \mu\text{m}$ between the voltage contacts. We performed magnetotransport measurements with $I \parallel a^*$ and $\mu_0 H \parallel c$. In Fig. 3(b), we present the temperature dependence of the zero-field longitudinal resistivity ρ_{xx} of L1, measured between 5 and 300 K. The room-temperature resistivity is $64.4 \mu\Omega \text{ cm}$ and the residual resistivity ratio is about 7. Both values are consistent with previously reported data and with those expected for bulk CrSb. It is worth noting that individual single-crystal samples can exhibit slight variations in quantitative parameters, such as the residual resistivity ratio (RRR), the magnitude of the magnetoresistance, and the precise values of the extracted mobilities. Such differences are common in high-quality crystals and typically arise from local variations in defect density, stoichiometry, or built-in strain. Additionally, FIB-assisted microfabrication can introduce minor surface damage or implantation of gallium ions. However, the qualitative magnetotransport features, specifically the nonsaturating MR, the nonlinear Hall response, and the requirement of high magnetic fields to fully resolve the multiband nature, remain robust across all investigated samples, confirming that these properties are intrinsic to CrSb.

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