

Shubnikov–de Haas oscillations in half-metallic ferromagnetic CrO₂ epitaxial films

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We present a study of the low-temperature, high-field magnetotransport behavior of epitaxially grown CrO₂ thin films on (100) TiO₂ substrates. Electron transport measurements confirm high sample quality, with a residual resistivity ratio as large as 45. A logarithmic fit of the low-temperature regime yields a $T^{4.5}$ power law, indicative of the elusive double-magnon scattering in half-metallic ferromagnets. Angle-dependent anisotropic magnetoresistance (AMR) measurements reveal a large projected density of states along [001] with a maximum AMR value of 2.4%. Pronounced, axis-dependent Shubnikov–de Haas (SdH) oscillations are observed in the longitudinal magnetoresistance (MR), with discrete Landau levels mapped at various tilt angles of the magnetic field. Their angular dependence follows a $1/\cos\theta$ relation pointing to a highly anisotropic Fermi surface, and amplitude scaling adheres closely to the thermodynamic Lifshitz-Kosevich formalism. The out-of-plane MR reaches 6.58%, the largest reported for CrO₂ thin films. Notably, this study presents an observation of SdH oscillations in a half-metallic oxide with near-perfect spin polarization, a significant advancement in the field of spintronics.

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I. INTRODUCTION

Chromium dioxide (CrO₂), a prominent half-metallic oxide [1], has garnered significant attention due to its near-perfect spin polarization of 96%–98% at the Fermi level [2–7] and relatively high Curie temperature T_C of about 390 K [8]. The double-exchange ferromagnetic ordering above room temperature makes CrO₂ highly suitable for spintronic applications requiring precise control over spin states. Additionally, CrO₂ exhibits a large bulk saturation magnetization reaching 480 emu/cm³ at room temperature [9] and increasing to 640 emu/cm³ at low temperatures [10].

The single-spin conduction channel in half-metals like CrO₂ offers technological advantages, including enhanced magnetotransport performance. Its structural compatibility with emergent rutile altermagnets XF₂ ($X=\text{Mn, Fe, Co, Cu}$) and unconventional torque sources such as RuO₂ and IrO₂ [11,12] further expands its multifunctional potential [13–16]. CrO₂ is also chemically robust and easy to fabricate, making it attractive for durable, long-term applications. A key feature of its half-metallic nature is its pronounced magnetoresistance (MR), which is critical for magnetic sensing technologies.

Despite these favorable characteristics, the quantum electronic and magnetotransport behavior of CrO₂, particularly in thin films below 100 nm, remains insufficiently explored under extreme conditions. Prior studies focused on bulk films, microcrystals, and polycrystalline samples in low-field or high-temperature regimes [8,17,18]. In this work, we investigate the high-field, low-temperature MR behavior of epitaxial CrO₂ thin films and uncover distinct quantum oscillations in the longitudinal resistivity ρ_{xx} , providing insights into the underlying quantum phenomena.

Our results reveal nontrivial features in ρ_{xx} at low temperatures, including axis-dependent Shubnikov–de Haas (SdH) oscillations under large magnetic fields. Systematic exploration of field- and temperature-dependent characteristics as a function of tilt angle reveals an MR as large as 6.58% at 1.8 K, the highest reported for CrO₂ films to date. Through detailed analysis of the temperature and angular dependence of these quantum oscillations, we extract key information about the complex and anisotropic Fermi surface, consistent with theoretical predictions [19]. This study bridges a critical experimental gap, advancing our understanding of the quantum behavior of CrO₂ thin films and reinforcing their potential for spintronic and magnetotransport applications.

II. MATERIALS AND METHODS

High-quality CrO₂ films were epitaxially grown via chemical vapor deposition, optimized for uniformity and minimal lattice strain. A two-zone tube furnace accommodates the critical temperature requirements of the precursor (240 °C) and the single-crystal TiO₂ substrate (370 °C). TiO₂ substrates with a (100) orientation, measuring 25 mm² in lateral area,

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were pretreated with diluted hydrofluoric acid to ensure a pristine, activated surface for deposition.

During the deposition process, an oxygen-rich environment was maintained with a controlled O₂ gas flow rate of 100 sccm, ensuring a consistent deposition rate and high film quality. Once the system stabilized at the target temperatures, the hexavalent chromium precursor (CrO₃) was introduced.

Following deposition of the CrO₂ film, we cool the system to remove the precursor and further bake the sample for an additional 1 h at 370 °C with O₂ gas flowing. This last step helps improve the sample quality by enhancing the oxidation state of CrO₂, which is metastable and prone to reducing to Cr₂O₃ or CrO₃. Postdeposition baking helps to maintain the desired Cr⁴⁺ oxidation state and minimizes the formation of nonstoichiometric defects. Additionally, this annealing step promotes higher crystallinity of the epitaxial film by reducing structural defects.

Structural characterization was performed via high-resolution x-ray diffraction using a Rigaku Smartlab diffractometer with a Ge (220) double-bounce monochromator. Reciprocal space mapping (RSM), symmetric θ -2 θ scans, and asymmetric in-plane ϕ scans confirmed the epitaxial quality of the film [20,21]. The results confirm an isostructural crystal phase matching the rutile structure of TiO₂, indicating that the film is relatively unstrained, with compressive strain values of 0.48% and 0.38% for the *a* and *c* lattice parameters, respectively (see Supplemental Material, Sec. I [22]).

For transport measurements, CrO₂ films were patterned into 55 × 20 μm² Hall bars using a mask aligner. Hall bar arrays were designed along both the [010] and [001] current directions to enable simultaneous transport measurements under identical conditions. The patterned films were chemically dry etched via reactive ion etching for 60 s using a mixture of 80 sccm CF₄ and 40 sccm O₂. After removing the photoresist, the Hall bars were wire bonded for transport measurements. Electrical characterization was conducted using a Quantum Design DynaCool physical property measurement system, with a horizontal rotator insert enabling measurements across various magnetic field tilt angles relative to the sample's surface normal.

III. RESULTS AND DISCUSSION

A. Transport properties

Temperature-dependent ρ_{xx} measurements were performed on a 53 nm CrO₂ film with current injected along the *b* [010] and *c* [001] in-plane axes, as shown in Fig. 1(a). We measure T_C at approximately 396 K and a residual resistivity ratio (RRR), which we define as $\rho(400\text{ K})/\rho(2\text{ K})$, as large as 45 along [001], indicating high sample quality. Typical values for the RRR of CrO₂ films range from 5.9 to 50, depending on the composition and orientation of the substrate used as

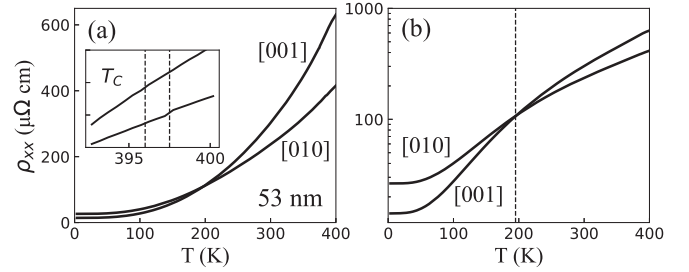


FIG. 1. Electron transport measurements. (a) Longitudinal resistivity ρ_{xx} of the CrO₂ film with current applied along the [010] and [001] directions. (b) Data replotted with logarithmic scaling to show details at low temperature.

well as the thickness of the film [3,23–25]. The crossover in ρ_{xx} between the two axes occurs around 195 K [Fig. 1(b)], consistent with previous reports [17].

To identify the dominant scattering mechanisms, we extrapolate ρ_{xx} to 0 K and extract the residual resistivity ρ_0 , as summarized in Table I. The values are relatively low and comparable to those in prior studies [26,27]. We model the temperature dependence of ρ_{xx} using a power law of the form

$$\rho_{xx}(T) = \rho_0 + AT^n, \quad (1)$$

where n characterizes the scattering processes. Figures 2(a) and 2(b) present the temperature-dependent resistivity given by $\rho_{xx} - \rho_0$ on a logarithmic scale, enabling precise determination of the critical temperatures T_H and T_L which distinguish the high- and low-temperature regimes, respectively. Linear fits yield the exponent n , providing insight into the underlying transport mechanisms.

Along [010] we observe two distinct regimes: $n = 2.44$ above $T_H = 112$ K and $n = 4.52$ below $T_L = 56$ K. Various spin fluctuation scattering models predict exponents between 2 and 3.5 [19,28], while some suggest that Anderson localization in the minority spin band prevents conduction, leading to $\rho_{xx} \propto T^{2.5}$ above a critical temperature of ~ 60 K [29]. This aligns with our observed transition range between 56 and 112 K. Above 100 K, spin disorder scattering likely dominates, where n falls between 2.0 and 2.5. In half-metallic ferromagnets, spin-flip scattering is suppressed due to the absence of accessible minority spin states, making double-magnon scattering the dominant scattering mechanism at low temperatures. This is consistent with our measured slope of $n = 4.5$ [30–34]. This mechanism has also been proposed within the rigid band model [34].

For the [001] direction, we extract $n = 2.98$, which roughly spans the entire temperature range (5–400 K). However, a deviation occurs between 9 and 50 K, where $n = 3.56$. Given the narrow temperature range of this deviation, further measurements may be necessary to confirm a more monotonic trend. The $n = 3$ behavior was previously observed and attributed

TABLE I. Summary of transport parameters along the [010] and [001] current directions.

Axis	ρ_{300} (μΩ cm)	ρ_0 (μΩ cm)	RRR	T_C (K)	T_L (K)	T_H (K)	$n(T_L)$	$n(T_H)$
[010]	237	26.4191 ± 0.0004	16	397	56	112	4.52	2.44
[001]	303	14.1752 ± 0.0010	45	396	9	50	2.98	2.98

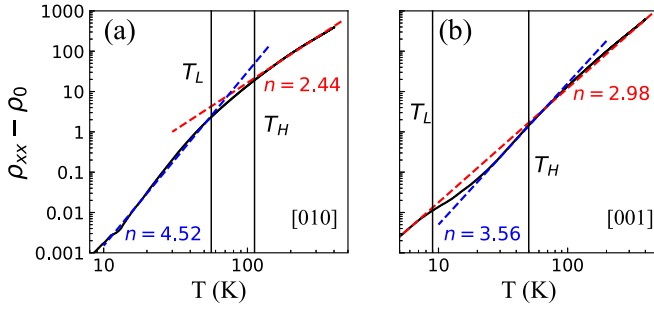


FIG. 2. Logarithmic fit of ρ_{xx} . Low- (blue) and high- (red) temperature regimes indicated by vertical lines labeled T_L and T_H , respectively. Dashed lines are linear fits along (a) [010] and (b) [001] with corresponding slopes denoted by n .

to nonrigid band behavior [35], likely driven by unconventional one-magnon scattering [31]. The weak temperature dependence suggests a more uniform magnetic structure and interactions along the [001] direction.

Since half-metals exhibit 100% spin polarization at the Fermi level with a gap in the minority spin channel, their scattering behavior is highly sensitive to spin-dependent effects and band anisotropy. Directional coupling between spin, charge, and lattice dynamics is a defining feature of many half-metallic ferromagnets. The anisotropy observed in ρ_{xx} suggests variations in band curvature and dispersion along [010] and [001] near the Fermi energy. Figure 3 illustrates the crystallographic anisotropies in both real and reciprocal space.

Previous works reported significant band crossings along [001] [19,36], including the presence of two degenerate triple points (TPs). Although these TPs are not located exactly at the Fermi level, they are both less than 0.5 eV from the Fermi energy, and we predict they can shift under the presence of external stimuli and contribute to the transport properties.

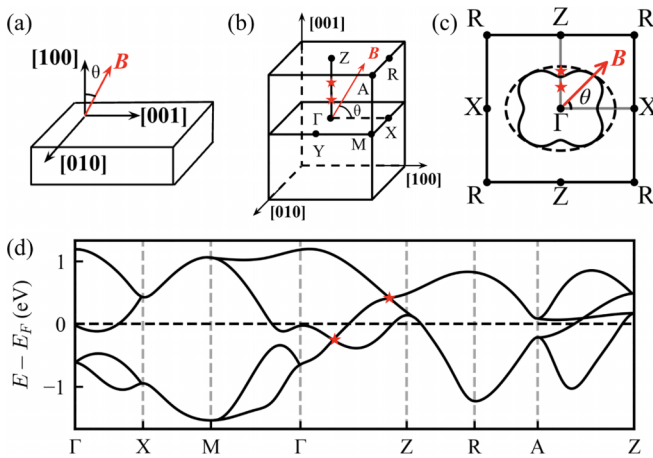


FIG. 3. Electronic structure of CrO_2 . (a) Schematic of sample orientation used for measurements, with magnetic field B applied at angle θ from the surface normal. (b) Reciprocal space bulk Brillouin zone of CrO_2 with high-symmetry points labeled. (c) Cross-sectional rendering of the Fermi surface from [19,36] along the $k_x k_z$ plane. (d) Band structure of spin majority carriers in CrO_2 near the Fermi level [37]. Triple-point crossings are indicated as red stars.

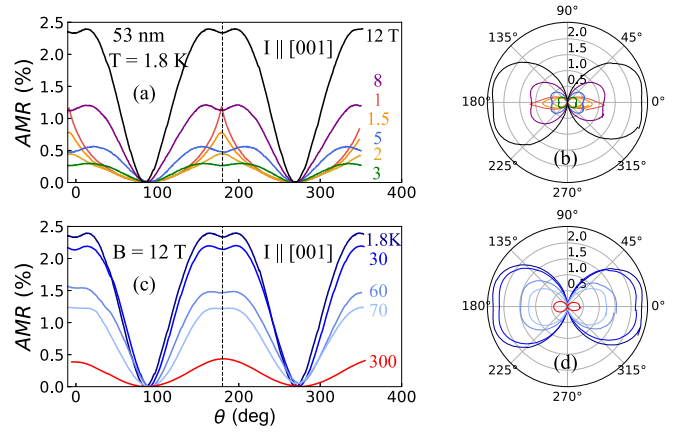


FIG. 4. Anisotropic magnetoresistance (AMR) along [001]. (a) Field-dependent AMR at 1.8 K and (b) the corresponding polar plot representation. (c) Temperature-dependent AMR at 12 T and (d) the corresponding polar plot. Dashed lines are at $\theta = 180^\circ$.

Renormalization effects from the double-magnon scattering we observe at low temperatures can modify the properties of these spin wave interactions, affecting their energies and potentially lowering the energy of the electronic states near the Fermi level [3,38]. Additionally, asymmetric Zeeman splitting between spin channels from large applied magnetic fields along with large spin-orbit coupling (SOC) [39] may also lift the degeneracies in the TPs and lead to sizable energy shifts.

B. Anisotropic magnetoresistance measurements

We performed angle-dependent ρ_{xx} measurements to investigate the effects of temperature and magnetic field on the 53 nm sample with current applied along the [001] and [010] directions. In particular, we examined the out-of-plane angular variation in the anisotropic MR (AMR), defined as $\text{AMR}(\theta) = \frac{\text{MR}(\theta) - \text{MR}(90^\circ)}{\text{MR}(90^\circ)}$, where θ is the angle between the applied magnetic field B and the sample's surface normal.

As we rotate B from an in-plane orientation parallel to the current direction to an out-of-plane configuration perpendicular to the current at 1.8 K, the AMR in Fig. 4(a) peaks at 2.4% near 0° , 180° , and 360° , with minima at 90° and 270° , forming a four-lobed bow-tie pattern. This AMR magnitude is among the highest reported for epitaxial CrO_2 films, reinforcing the role of spin-dependent scattering in this highly spin-polarized system [24].

The transition from a sharp, cusplike feature at low fields below 2 T in the AMR to the double-hump shape at high fields likely reflects the strong magnetic anisotropy between the in-plane [010] and [001] and out-of-plane [100] directions. We performed vibrating sample magnetometry (VSM) measurements of the bulk 53 nm film along these directions; they are included in Fig. S2 in Sec. II of the Supplemental Material to illustrate this anisotropy when tilting the field out of the plane of the sample. The low-field VSM results along these orthogonal directions portray the magnetic anisotropy of this CrO_2 film and the differences in the density of states (DOS) and scattering pathways along these directions.

The AMR dependence on the applied field is further illustrated in the polar plot in Fig. 4(b). At low fields below 2 T, AMR primarily reflects magnetic anisotropy, which is

dictated by crystal symmetry. This is shown by the sharp, elongated teardrop-shaped AMR at low fields, which is highly anisotropic. At higher fields above 3 T, the AMR is increasingly governed by electronic structure effects. The electron Fermi surface of CrO₂ forms a pillbox around the zone center [3,4,19,36]. As observed, the $k_x k_z$ cross section of the electron Fermi surface shown in Fig. 3(c) closely resembles the bow-tie-like AMR pattern we observed experimentally above 3 T. Deviations from this rendering can be explained by the fact that applying a magnetic field warps the Fermi surface in plane and thereby modifies the electronic structure.

In CrO₂, the [001] direction exhibits enhanced spin-dependent scattering, which can be attributed to the higher projected DOS (PDOS) along this axis. The larger AMR effect observed along [001] points to electronic states being more densely packed along this direction. Theoretical calculations, as well as our own experimental data, have shown that CrO₂'s easy magnetization direction is along [001], correlating with a higher PDOS at the Fermi level [40]. This leads to a greater number of available electronic states for enhancing spin-dependent scattering.

TPs can enhance magnon-mediated scattering events by increasing the PDOS at specific energy levels and thereby resulting in more frequent scattering events. They can also significantly influence SOC by enhancing orbital hybridization. This enhancement leads to anisotropic spin-dependent scattering, directly impacting the AMR. Single-crystalline CrO₂ has been shown to exhibit strongly anisotropic SOC along the [010] and [001] directions [39]. The interplay between SOC and magnon scattering, influenced by the presence of TPs near the Fermi level, plays a crucial role in this temperature-dependent resistivity [41].

A temperature-dependent AMR scan at 12 T is shown in Fig. 4(c) and reveals that AMR is strongest at low temperatures, where conduction electron spin polarization is more robust. As expected, the AMR magnitude decreases with increasing temperature due to weakened spin-dependent scattering. Similar butterflylike AMR patterns have been observed in type-II Weyl semimetals, which also exhibit highly anisotropic electron Fermi surfaces [42].

We repeat these angle-dependent AMR measurements along the orthogonal [010] direction. As illustrated in Fig. S3 in Sec. III of the Supplemental Material, the AMR along [010] is at maximum $\sim 0.7\%$, which is only about one third of that measured along [001]. The general trends and shapes of the polar plots, however, are consistent with the results in Figs. 3(b) and 3(d), although with significantly lower amplitude. This suppression can be attributed to resistivity minimization when $\mathbf{B}$ aligns with low-PDOS directions, reducing available scattering sites. Here, a low-PDOS direction refers to bands that are steeply dispersing, meaning that for a given energy range, fewer states are available along [010] compared to the [001] direction. A lower PDOS leads to weaker scattering, which may explain the smaller AMR response along [010].

C. Background magnetoresistance

Field-dependent ρ_{xx} measurements were performed on the 53 nm film at 1.8 K across a wide range of magnetic fields and

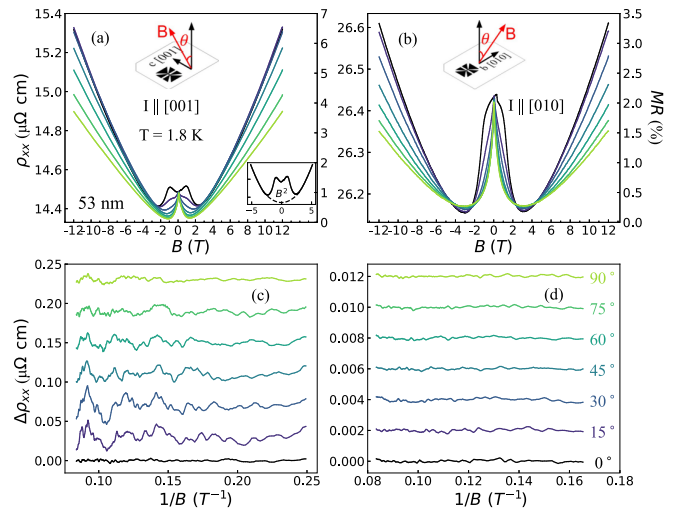


FIG. 5. Angle-dependent magnetoresistance (MR) of bulk CrO₂. MR measurements collected at 1.8 K along (a) [001] and (b) [010]. The dashed line in the inset of (a) is the quadratic fit to the $\theta = 0^\circ$ data. (c) and (d) illustrate underlying quantum oscillations $\Delta\rho_{xx}$ after subtracting the smoothly varying polynomial background from data in (a) and (b).

tilt angles. The Hall bar configurations enabled measurements along both the b [010] and c [001] crystallographic axes, as illustrated in the insets in Figs. 5(a) and 5(b), respectively. The MR was quantified as $MR(B) = \frac{R_{xx}(B) - R_{xx}(0)}{R_{xx}(0)}$. The extended field range explored in this study allows access to higher MR values than previously reported [23,24,30,43]. A second-order polynomial fit was applied to the high-field regime for $\theta = 0^\circ$ and extrapolated to zero field [dashed line in the inset of Fig. 5(a)]. This analysis reveals an MR as large as 6.58%, the highest reported for CrO₂ epitaxial thin films to date [30,44,45].

The observed MR exhibits contributions from both classical and quantum mechanisms. At high fields, the MR follows a quadratic field dependence (B^2) as the cyclotron radius shrinks below the mean free path between collisions. This is characteristic of classical transport dominated by the Lorentz force which arises due to the cyclotron motion of charge carriers, leading to a nonsaturating orbital MR effect.

At low fields, quantum contributions to MR manifest as quantum interference corrections in the presence of SOC. The initial “positive” MR observed only along the [001] current direction can be attributed to weak localization effects due to time-reversal symmetry breaking from the applied magnetic field. This effect is small, on the order of 1%–2%, and is gradually suppressed at higher fields. This is consistent with spin-dependent weak antilocalization effects observed in other half-metallic ferromagnets [46,47].

D. Emergent oscillatory phenomena at high field

After the smoothly varying polynomial background is subtracted from the high-field MR, periodic oscillations in the longitudinal resistivity $\Delta\rho_{xx}$ emerge as a function of inverse magnetic field, as shown in Fig. 5(c). These oscillations along [001] correspond to SdH oscillations, a hallmark of

quantum oscillatory behavior in high-mobility electron systems. Although elusive, SdH oscillations were theorized to manifest in CrO₂ due to its high carrier mobility and low carrier number [30].

Despite the typically large Fermi surfaces in CrO₂, which can short out quantum oscillations, we successfully resolve an oscillatory component, likely facilitated by the high quality of our samples and extreme measurement conditions. Figure 5(c) presents the SdH oscillations along [001] at various magnetic field tilt angles ($0^\circ \leq \theta \leq 90^\circ$). As θ increases, the oscillation amplitude monotonically decreases, with pronounced suppression near 0° and 90° . Although the suppression at 90° is expected in most thin film systems due to minimized Lorentz force and insufficient orbital motion, the obstruction of oscillations at 0° is interesting. This points to transport that is dominated by high-mobility pockets away from 0° . In anisotropic Fermi surfaces, the extremal orbits responsible for SdH oscillations appear only when the magnetic field is tilted from the symmetry axis. If the relevant orbits vanish at 0° or become nonextremal, meaning the cross-sectional area is not a minimum or maximum, we may not observe SdH oscillations even if Landau levels are forming.

The MR effect is related to the anisotropy of various scattering mechanisms which, as indicated by the distinct angular dependence and nontrivial behavior of ρ_{xx} , may be sensitive to extremal Fermi surface orbits. The high quality of our samples combined with the large magnetic fields and low temperatures employed enables the detection of these oscillations. Further increasing the field strength or reducing the temperature could amplify these oscillations, making them even more pronounced.

Notably, this study represents an experimental observation of SdH oscillations in a half-metallic ferromagnet. The observation of well-defined SdH oscillations confirms the presence of Landau quantization, indicating a quantum contribution to the MR. The persistence of oscillations up to 12 T suggests that carriers experience field-dependent quantization of states, highlighting the unique quantum transport properties of CrO₂.

Interestingly, the SdH oscillations are significantly suppressed along [010], underscoring a highly anisotropic and warped Fermi surface in CrO₂. This anisotropic Fermi surface structure results in direction-dependent effective masses, influencing electron dynamics along different crystallographic axes. The conditions required to observe such oscillations imply that transport along [001] is characterized by a smaller effective mass, higher carrier mobility, and lower scattering rate compared to [010]. Moreover, the presence of a subtle subharmonic background even after background subtraction further supports a highly anisotropic and potentially warped Fermi surface. These findings align with theoretical band structure calculations and Fermi surface reconstructions for rutile CrO₂ [36,48].

E. Analysis of quantum oscillations

We apply a fast Fourier transform (FFT) to the oscillatory component of the $\Delta\rho_{xx}$ data presented in Fig. 5(c) to identify the dominant SdH oscillation frequencies. The FFT spectrum for $\theta = 30^\circ$, shown in the inset of Fig. 6(a), reveals a single dominant frequency of $f = 48 \pm 6$ T, as indicated by the

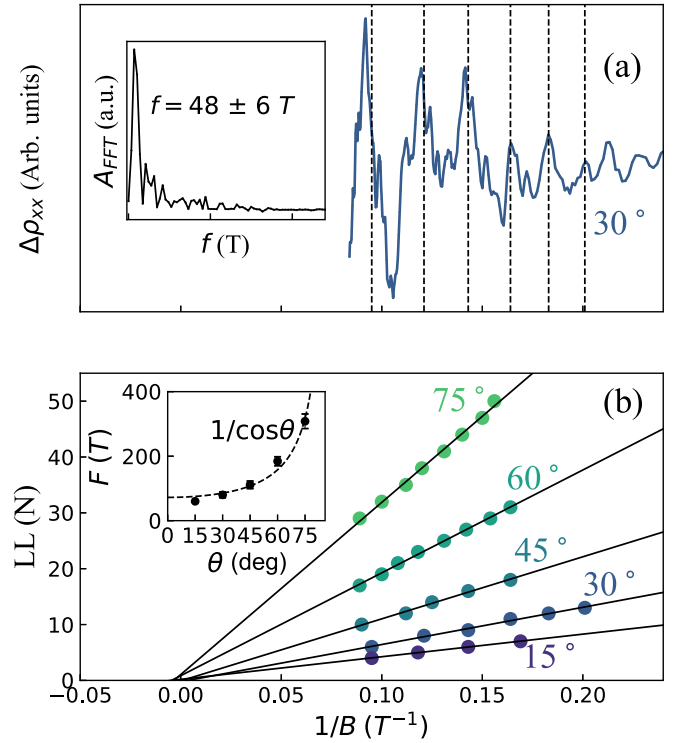


FIG. 6. Analysis of Shubnikov-de Haas oscillations. (a) Data along [001] after background subtraction at $\theta = 30^\circ$. The inset shows the corresponding FFT spectrum. (b) Landau level fan diagram of peak positions [indicated by dashed lines in (a)] at various tilt angles. Linear fits with slopes F plotted as a function of tilt angle are given in the inset of (b).

dashed guidelines. Since each extremal cross section of the Fermi surface corresponds to a distinct oscillation frequency, the more complex Fermi surface theoretically predicted for CrO₂ should, in principle, produce multiple frequencies. Here, we resolve a single distinct frequency, with seemingly multiple components in Fig. 6(a) that are difficult to resolve. We attribute the lack of any clear secondary frequencies primarily to the limitations in our experimental setup. We believe that further reductions in temperature below 1.8 K and application of fields above 12 T will make these SdH oscillations even more pronounced and reveal additional secondary frequencies.

In a magnetic field, electron energy levels quantize into discrete Landau levels (LLs). To analyze these states, we plot the peak positions of $\Delta\rho_{xx}$ as a function of $1/B$ to construct a LL fan diagram at various tilt angles, as shown in Fig. 6(b). The data are fit with

$$N = \frac{F}{B} + \delta, \quad (2)$$

where F is the SdH oscillation frequency in teslas, N is the LL integer index, δ is the phase shift correction factor, and B is the magnetic field strength. Well-defined LLs are typically observed in high-purity metals where weak electron scattering preserves the sharpness of the LLs. The observation of clear LL quantization in CrO₂ further confirms its high sample quality, low impurity concentration, and robust transport properties, even in the bulk regime of the 53 nm film.

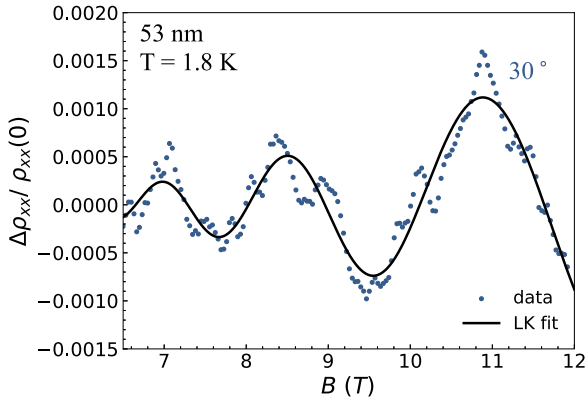


FIG. 7. Magnetic-field-dependent data along [001] at $\theta = 30^\circ$ fit to the Lifshitz-Kosevich (LK) model described by Eq. (3).

We analyze the evolution of the oscillation frequency F as a function of θ , as shown in the inset of Fig. 6(b). The slopes range from 41 ± 3 T at $\theta = 15^\circ$ to 308 ± 22 T at $\theta = 75^\circ$. The data follow a $1/\cos\theta$ trend within error margins. These frequency trends align well with those extracted from the SdH oscillation periodicity in $1/B$. At larger tilt angles, the SdH oscillation amplitude drops. At $\theta = 90^\circ$, where the magnetic field is parallel to the sample, $F(\theta)$ theoretically diverges. This fit suggests quasi-two-dimensional-like magnetotransport which depends on the perpendicular component $B_\perp = B \cos\theta$.

The angular dependence of SdH frequencies can be understood in the context of its highly anisotropic Fermi surface. In strongly anisotropic three-dimensional (3D) materials, the electronic structure can exhibit quasi-two-dimensional (quasi-2D) behavior along certain crystallographic directions. CrO_2 possesses elongated Fermi surface pockets, particularly along the [001] direction, which can give rise to quasi-2D behavior in the quantum oscillations that are further enhanced when the magnetic field is rotated away from this principle axis. Although the film is thicker than the typical quantum confinement length scales, partial confinement cannot be ruled out entirely, and it may contribute to the quasi-2D-like angular dependence. The dominant factor, however, is likely the intrinsic Fermi surface anisotropy rather than true quantum confinement or surface states. Notably, the SdH signal persists over a wide angular range and maintains a strong bulk character, which argues against a surface-state origin. Additionally, the small residual nonzero oscillations persisting at 90° are a signature of 3D bulk Fermi surface contributions [49,50].

In addition to the angular dependence of ρ_{xx} , we also attempt to examine the temperature dependence of the SdH oscillations. While oscillations are clearly evident at low temperatures, they fade rapidly and become indistinguishable above 1.8 K. Even with advanced signal processing techniques, we could not track clear oscillatory behavior at high temperatures (see the Supplemental Material, Sec. IV [22]). We attribute the suppression of oscillations above 1.8 K to the effects of thermal broadening. Figure 7 plots the normalized oscillatory component $\Delta\rho_{xx}/\rho_{xx}(0)$ for $\theta = 30^\circ$ along [001] at 1.8 K, where $\rho_{xx}(0)$ is ρ_{xx} measured at $B = 0$ T.

To analyze the temperature dependence, we apply a modified thermodynamic Lifshitz-Kosevich (LK) fit [50–53],

given by

$$\frac{\Delta\rho_{xx}}{\rho_{xx}(0)} \propto \sqrt{\frac{B}{2F}} \frac{\alpha T m^*}{m_0 B \sinh\left(\frac{\alpha T \mu}{B}\right)} \exp\left(\frac{-\alpha T_D m^*}{B m_0}\right) \times \cos\left(\frac{\alpha g m^*}{2m_0}\right) \cos(2\pi N), \quad (3)$$

where the temperature T is fixed at 1.8 K. Here, $\alpha = \frac{2\pi^2 k_B m_0}{e\hbar}$, where e is the elementary charge, m_0 is the free electron mass, m^* is the effective cyclotron mass, k_B is the Boltzmann constant, and $\hbar$ is the reduced Planck's constant. In Eq. (3), g is the g factor, with B , F , and N as previously defined.

The LK fit enables us to extract several key material parameters, including the scattering time $\tau = \frac{\hbar}{2ek_B T_D}$, as well as the carrier mobility $\mu = \frac{e\tau}{m^*}$ and the mean free path $l = \tau v_F$. Additionally, we extract Fermi surface properties, including the Fermi wave vector $k_F = \sqrt{\frac{2eF}{\hbar}}$, the Fermi velocity $v_F = \frac{\hbar k_F}{m^*}$, and the cross-sectional Fermi pocket area $A_F = \pi k_F^2$. The extracted values of these parameters are summarized in Table II.

Because the LK analysis requires temperature dependence to deduce conclusive material parameters, we provide these results only for reference purposes, with the caveat that they correspond to a single set of fitting parameters and therefore should not be taken to be exact because a temperature-dependent LK fit could not be performed due to experimental limitations.

The Dingle temperature T_D accounts for damping effects due to scattering and provides insight into the effective thermal broadening of the LLs. Relative to other materials that exhibit SdH oscillations [49,51,52], the low Dingle temperature of CrO_2 indicates minimal thermal expansion over a wide temperature range, which is advantageous for applications requiring thermal stability such as optical and electronic devices. The extracted mean free path at 1.8 K is consistent with previous experimental measurements at 2 K [6,16,24,44,45] and theoretical estimates for single-crystal CrO_2 at 0 K [3].

The scattering time falls within the expected range of 10^{-14} to 10^{-12} s for transition metal oxides [25]. Similarly, the electron effective mass agrees with theoretical calculations at high-symmetry points on the Fermi surface [16,26,36,58]. To further analyze quantum transport, we compute the dimensionless parameter $\omega_c = \frac{eB}{m^*}$, which characterizes electron orbits and their contributions to SdH oscillations. When $\omega_c \tau \gg 1$, electrons complete multiple cyclotron orbits before scattering, signifying the quantum limit. Given the presence of discrete SdH oscillations, we expect $\omega_c \tau > 1$, which is, indeed, the case.

Finally, the carrier mobility of half-metallic states in bulk CrO_2 thin films has been reported as being on the order of a few hundred $\text{cm}^2/\text{V s}$ at low temperature [16,25,30]. The carrier density value we report was extracted assuming a single-band model using the standard expression given by $n = k_F^3/3\pi^2$, where k_F was determined from the SdH frequency assuming a spherical Fermi surface. This model neglects potential complexities such as anisotropic Fermi surface geometry, which is known and also shown in this work to exist in CrO_2 . We highlight that our value represents an

TABLE II. Summary of extracted material parameters for CrO₂ from the Lifshitz-Kosevich fit.

Parameter	Symbol	Measured value	Value from the literature	Units	Ref.
Oscillation frequency	f_{sdH}	48 ± 6		T	
Effective mass	m^*	0.53 ± 0.05	0.48–0.58	m_0	[36]
Scattering time	τ	$(3.3 \pm 0.8) \times 10^{-13}$	1.3×10^{-14}	s	[25]
Dingle temperature	T_D	3.6 ± 0.5		K	
Carrier mobility	μ	0.12 ± 0.02	0.0125	$\text{m}^2/\text{V s}$	[30]
3D carrier density	n_{3D}	$(2.8 \pm 0.4) \times 10^{23}$	$(1.04\text{--}1.3) \times 10^{22}$	cm^{-3}	[54,55]
Fermi wave vector	k_F	1.21 ± 0.08	1.00	$\text{\AA}^{-1}$	[56]
Fermi velocity	v_F	$(0.82 \pm 0.13) \times 10^5$	$(1.38\text{--}3.8) \times 10^5$	m/s	[45,57,59]
Fermi pocket area	A_F	4.6 ± 0.6	0.23–0.26, 8.86	$\text{\AA}^{-2}$	[3,36]
Mean free path	l	27 ± 8	30–115	nm	[16,24,44,45]
Cyclotron parameter	$\omega_c \tau$	1.31 ± 0.34			

upper bound under this simplified approximation and that a direct quantitative comparison to two-band-derived values [30] should be made carefully.

IV. SUMMARY AND CONCLUSIONS

We reported an experimental observation of Shubnikov–de Haas oscillations in the half-metallic oxide CrO₂, providing key insights into its quantum transport properties beyond the ultrathin limit. Notably, we detect oscillations in bulk films, establishing CrO₂ as a viable system for exploring quantum phenomena in half-metallic ferromagnets.

Our study also revealed temperature-dependent double-magnon scattering and strongly axis-dependent anisotropic magnetoresistance. These results are well supported by theoretical models, including the thermodynamic Lifshitz-Kosevich formalism and Landau level indexing, offering a deeper understanding of CrO₂'s band structure and intrinsic properties. Furthermore, we extracted key material parameters that align with previous studies, reinforcing the nontrivial oscillatory behavior in ρ_{xx} . These findings position CrO₂ as an intriguing exotic half-metallic system with unique electronic and spin-dependent properties, making it a promising candidate for spintronic applications and the study of novel half-metallic materials.

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All authors contributed to the study of magnetotransport properties in spintronic oxides. V.S.B. conceptualized the research, prepared samples, conducted measurements, analyzed data, and drafted the manuscript. B.J.B. and H.M.C. assisted with sample fabrication. D.T.P., X.W., and J.Q.X. performed RSM and XRD analyses and contributed to sample preparation. G.X. supervised the project, coconceptualized the study, analyzed data, contributed to manuscript preparation, and secured funding.

DATA AVAILABILITY

The data that support the findings of this study are openly available in the Brown Digital Repository [60].

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