Electronic band structure of (111) SrRuO$_3$ thin film—a\ angle-resolved photoemission spectroscopy study

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We studied the electronic band structure of pulsed laser deposition (PLD) grown (111)-oriented SrRuO$_3$ (SRO) thin films using in situ angle-resolved photoemission spectroscopy (ARPES) technique. We observed previously unreported, light bands with a renormalized quasiparticle effective mass of about 0.8$m_e$. The electron-phonon coupling underlying this quasiparticle mass renormalization manifests a characteristic kink at the binding energy of 44 meV, which is lower than the values reported for the (001)-oriented SRO films. Furthermore, the quasiparticle spectral intensity at the Fermi level is considerably suppressed, and two prominent peaks appear at binding energies of 0.8 eV and 1.4 eV, respectively. We discuss the possible implications of these observations. Overall, our work demonstrates that high-quality thin films of oxides with large spin-orbit coupling can be grown along the polar (111) orientation by the PLD technique, enabling in situ electronic band structure study. This could allow for characterizing the thickness-dependent evolution of band structure of (111) heterostructures—a prerequisite for exploring possible topological quantum states in the bilayer limit.

Perovskite transition metal oxides (TMOs) encompass a wide variety of properties like high-temperature superconductivity, magnetism, ferroelectricity, metal-insulator transition, colossal magnetoresistance, and multiferroic.$^{[12]}$ The plethora of physical properties in these materials originates from the subtle interplay among the charge, lattice, spin, and orbital degrees of freedom. Tweaking this interplay via epitaxy or heterointerfacing, furthermore, allows manipulating these properties and even designing novel phenomena or functionalities, which are unattainable by the bulk solid-state synthesis route. Examples include strain-induced enhancement of ferroelectricity and superconductivity,$^{[13]}$ high-mobility conducting interface,$^{[14]}$ interface ferromagnetism, polar skyrmion.$^{[15]}$ While the majority of these works have been carried out using heterostructures that are grown along the crystallographic [001] direction, their (111)-oriented counterparts are gaining considerable attention recently.$^{[16,17]$

Perhaps the biggest motivation to study (111)-oriented TMO heterostructures stem from the prediction of stabilizing novel topological phases in the bilayer limit.$^{[18,19]}$ Specific to this orientation, the trigonal crystal field symmetry, together with a sizable spin-orbit coupling, is argued to open topologically protected energy gaps in an otherwise topologically trivial band structure. The strong electronic correlation that is inherent to the TMOs is further expected to enrich their topological properties. An important step in this direction, is to first comprehensively understand the band structure of thicker (111) TMO films, and subsequent characterization with thickness scaling. Thus, in situ angle-resolved photoemission spectroscopy (ARPES) studies could be highly beneficial, which however requires overcoming difficulties involved growing high-quality thin films on the polar (111) surfaces. Besides, the requirement of strong spin-orbit coupling (SOC) strength further narrows the choice of materials to the TMOs that contain heavier elements. Accordingly, to our best knowledge, ARPES studies on (111) thin films are limited to the 3$d$ Nickelates,$^{[20,21]}$ where the SOC strength is expected to be weak. It is, therefore, instructive also exploring TMOs with larger SOC.

In this regard, SrRuO$_3$ (SRO)—a 4$d$ TMO is of particular interest since both the SOC strength (0.1-0.15 eV) and electronic correlation are rather sizeable.$^{[22]}$ In the bulk, SRO is an itinerant ferromagnet (below 165 K) and exhibits a Fermi-liquid behavior below 40 K.$^{[23]}$ Thin films of SRO that are grown along the [001] direction have been extensively studied as a model system in the context of anomalous Hall effect originating from the magnetic monopole in the momentum space.$^{[24,25]}$ Recently, it has gained renewed interest due to the observation of the topological Hall effect.$^{[26]}$ Besides, they are commonly used as metallic electrodes-thanks to the feasibility of growing atomically smooth films with high crystalline quality. The electronic band structure of (001) SRO films is relatively well understood both on the theoretical$^{[26,27]}$ and experimental fonts.$^{[28,29]}$

In contrast, the (111)-oriented SRO films have received moderate attention. Notably, (111) SRO thin films have been shown to exhibit anomalously enhanced magnetism (compared to the bulk), and conductivity compared to (001) SRO thin films.$^{[30,29]}$ It is also proposed that (111) SRO heterostructures could support half-metallic ground state at room temperature, and upon electron doping, a
quantum anomalous hall state could arise in the bilayer limit. Both of these properties are highly relevant for spintronic applications. Despite these intriguing electronic properties, the electronic band structure of (111) SRO films has not been studied experimentally.

In this communication, we report the electronic band structure of (111) SRO thin film probed by means of in situ APRES technique. We find the existence of a novel light band with a characteristic renormalized quasiparticle effective mass of 0.8m_e. Further, we show that this mass renormalization can be attributed to the electron-phonon mode coupling, which manifests as a kink in the dispersion at a binding energy of 44 meV. Both the renormalized effective mass and the position of the kink differ from the values previously reported on SRO, thereby underscoring the unique electronic property of (111) SRO film.

SRO thin films were grown on the B-site terminated (111) oriented SrTiO_3 (STO) substrates using the pulsed laser deposition technique (KrF laser, λ = 248 nm). During the growth, the substrate temperature and the background oxygen partial pressure were set to 680 °C and 100 mTorr, respectively. Meanwhile, the laser fluence and repetition rate were fixed to 1.1 J/cm² and 1 Hz, respectively. The growth dynamics were monitored by the reflection high energy electron diffraction (RHEED) technique. After growth, samples were cooled down to room temperature, and the oxygen flow was stopped for achieving a high vacuum, ~5×10⁻¹⁰ Torr. After growth, the samples were transferred to the preparation chamber and post-annealed in 1×10⁻⁹ Torr oxygen partial pressure at 510 °C for 30 minutes to achieve a clean surface. Films were subsequently transferred in situ to the angle-resolved photoemission spectroscopy (ARPES) chamber, which is equipped with VG Scienta DA30 analyzer and ultraviolet light source and monochromator from Fermi instrument. During the ARPES measurement, the base pressure in the chamber was better than 8×10⁻¹¹ Torr, and the sample temperature was 10 K. For the ARPES measurement, we employed HeI (21.22 eV) light. X-ray photoemission spectroscopy (XPS) measurement was performed using Al Kα (1486.6 eV) at room temperature in the XPS analyzer chamber equipped with SPECS XR50 X-ray photon source (Fig. S1 in Supplemental Material). After the ARPES and XPS measurements, the samples were characterized by low energy electron diffraction (LEED). Electrical transport measurement was performed by ultrasonically bonding gold wires on to the film in four-terminal configuration and using a Quantum Design PPMS. The surface morphology was probed using an Asylum Cypher atomic force probe microscope (AFM).

Figure 1 (a) displays the characteristic RHEED intensity profile of the specular [00] Bragg reflex (inset of Fig. 1 (a)) during SRO thin film growth. The specular RHEED intensity exhibits clear oscillations, reflecting the layer-by-layer growth of SRO film. The RHEED intensity oscillations enable us to precisely controlling the film thickness, which we varied between 7-30 unit cells (u.c.). As a representative figure, here, we have shown the RHEED intensity profile and pattern taken during and after the growth of a 15 u.c. thick SRO film. As shown in the inset of Fig. 1 (a), the RHEED pattern of the SRO film consists of sharp diffraction spots forming a Laue circle, which suggests coherent growth of crystalline domains with long-range ordering. This conjecture is further supported by the observation of sharp LEED pattern (Fig. 1 (b)), which following the six-fold symmetry of the
(111) surface, forms hexagonal motifs. In addition to intense principal spots, relatively weaker non-integer peaks are also discernable in the LEED image, which suggests presence of surface reconstruction. AFM characterization further reveals that the film surface is atomically flat (Fig. 1 (c)) and consists of well-defined step-terrace structure with a nominal step height of 0.23 nm that amounts to the one-unit cell of SRO along the [111] direction. Transport measurement shows a metallic behavior (Fig. 1 (d)) down to 2 K, along with a kink at 127 K that is characteristic of the onset of ferromagnetic phase transition. The residual resistivity ∼200 μΩ cm (at 2 K) compares well to the values reported for SRO (001) films of similar thicknesses. Overall, the structural and electrical characterization demonstrates that high-quality SRO films can be grown on the (111) STO substrate.

Next, to probe the electronic band structure of (111) SRO films, we measured APRES on SRO films with thicknesses varying from 7 u.c., 15 u.c., and 30 u.c.. While the thinnest film turns out to be insulating, ARPES measurements on the other two samples reveal a metallic nature with a sharp Fermi cutoff (Fig. S2 (a) in Supplemental Material). Furthermore, the 15 u.c. thick SRO film exhibits relatively sharper bands and clear Fermi surface compared to the 30 u.c. thick film. In the main text, we, therefore, limit our discussion to the ARPES measurement performed on the 15 u.c. thick SRO film.

Figure 2 (a) and 2 (b) show the ARPES intensity plot along the high symmetry Γ−K direction of the Brillouin zone (BZ) (Fig. 3 (a)) and the corresponding angle-dependent energy distribution curves (EDC), respectively. The valence band spectra show weak dispersion along this high symmetry direction. Nonetheless, the characteristic features associated with the O 2p non-bonding and bonding states between -3 eV and -7 eV are discernable (Fig. S3 in Supplemental Material). Meanwhile, between -2 eV and the Fermi level, EDC displays two unconventional peaks centered around -1.4 and -0.8 eV (marked by the triangles), alongside a considerably suppressed quasiparticle (QP) peak at the Fermi level. We found these features are common to all (111) SRO films, irrespective of their thicknesses (Fig. S2 in Supplemental Material).

To comprehend the origin of the suppressed QP intensity and the -1.4 eV peak, we additionally studied an SRO film that was identically grown on the (001) STO substrate. The valence band spectrum of this (001) SRO film exhibits a sharp QP peak, and void of any additional peaks down to 2 eV from the Fermi level (Fig. S3 in Supplemental Material). This rules out the excessive Ru deficiency in our film as the origin. Next, we consider disorders and enhanced electronic correlation, which can transfer spectral weight from the Fermi level to the so-called in-gap states and lower Hubbard band, respectively—yielding an incoherent peak around -1.3 eV. It is reasonable to expect that structural or compositional disorders could be present on the polar (111) surface as a means of compensating its polar charge. The single peak structure of the O 1s XPS spectrum (Fig. S1 (a) in the Supplemental Material), however, suggests that the contribution from the com-
The Fermi surface consists of pairs of hotspot around \( k \) (Fig. 3 (b)) indicated the surface projected BZ. As evident from the curvature plot (Fig. 4 (b)), with the increasing \( k \) point that vertically disperses before merging with six bands near \(-0.8\) eV. This vertical band merges with three pairs of waterfall-like bands near the \(-0.8\) eV. While the origin of the vertical feature remains unknown, from Fig. 3, it is clear that the intensity of the six dispersive bands passes through a dip at \(-0.5\) eV before peaking at \(-0.8\) eV. This implies that the peak at \(-0.8\) eV in the valance band spectra (Fig. 2 (b)) corresponds to the bottom of these six bands.

Next, to gain insight into the many-body interactions, we further analyzed the strongest band. In Fig. 4 (a) we show the corresponding energy versus momentum dispersion along the cut indicated by the white line in Fig. 3 (b). As evident from the Fig. 4 (b), with the increasing binding energy, the hotspot pairs shift towards the center of the BZ \((\bar{\Gamma})\) forming six bands, which are dispersive down to about \(-0.6\) eV before merging around \(-0.8\) eV. In addition, we observed a relatively weaker feature at the \( \bar{\Gamma} \) point that vertically disperses before merging with six bands near \(-0.8\) eV. This vertical band merges with three pairs of waterfall-like bands near the \(-0.8\) eV. While the origin of the vertical feature remains unknown, from Fig. 3, it is clear that the intensity of the six dispersive bands passes through a dip at \(-0.5\) eV before peaking at \(-0.8\) eV. This implies that the peak at \(-0.8\) eV in the valance band spectra (Fig. 2 (b)) corresponds to the bottom of these six bands.

Having examined the valance band of the (111) SRO film, we turn our attention to the fermiology and band dispersion. Figures 3 (a) and (b) display the 3D ARPES image and iso-energy surfaces measured within the energy window of \(-0.8\) eV from the Fermi level. The iso-energy momentum surfaces in Fig. 3 (b) are surfaces summed ranging \pm 10 meV at corresponding binding energies. The white dashed lines in Fig. 3 (a) and 3 (b) (Fermi level) indicated the surface projected BZ. The Fermi surface consists of pairs of hotspot around the \( M \) points exhibiting a three-fold symmetry. The three-fold symmetry of the Fermi surface possibly originates from sampling the bulk Fermi surface away from the high-symmetry points \((\bar{\Gamma}, \bar{Z})\) along the \( k_z \) axis. Assuming a nominal inner potential value of about 14 eV\(^{15}\), we estimate that with the photon energy of 21.2 eV, we slice at \( k_z \sim 0.15 \pi / c \), where \( c = \sqrt{3}a_0 \) with \( a_0 = 3.93 \) Å being the pseudo-cubic lattice parameter of SRO. Another salient feature of the (111) SRO fermiology concerns the strong azimuthal-angle dependence of the hotspot-intensity (Fig. S4 in Supplemental Material\(^{11}\)). This could imply an orbital selective occupation of the band\(^{19,20}\) that is possibly stemming from the degeneracy-lifting of the Ru \( t_{2g} \) states under the trigonal crystal field imposed by the (111) heterostructuring\(^{10}\). Nonetheless, we chose the azimuthal configuration that yields the clearest Fermi surface and robust dispersion.

As evident from the Fig. 3 (b), with the increasing binding energy, the hotspot pairs shift towards the center of the BZ \((\bar{\Gamma})\) forming six bands, which are dispersive down to about \(-0.6\) eV before merging around \(-0.8\) eV. In addition, we observed a relatively weaker feature at the \( \bar{\Gamma} \) point that vertically disperses before merging with six bands near \(-0.8\) eV. This vertical band merges with three pairs of waterfall-like bands near the \(-0.8\) eV. While the origin of the vertical feature remains unknown, from Fig. 3, it is clear that the intensity of the six dispersive bands passes through a dip at \(-0.5\) eV before peaking at \(-0.8\) eV. This implies that the peak at \(-0.8\) eV in the valance band spectra (Fig. 2 (b)) corresponds to the bottom of these six bands.

Next, to gain insight into the many-body interactions, we further analyzed the strongest band. In Fig. 4 (a) we show the corresponding energy versus momentum dispersion along the cut indicated by the white line in Fig. 3 (b). As evident from the curvature plot (Fig. 4 (b)), which magnifies the dispersion between 0.4 to 0.52 Å\(^{-1}\) (blue dashed box in Fig. 4 (a)), the band meets the Fermi level at the Fermi wave vector, 0.51 Å\(^{-1}\). For quantifying the quasiparticle mass renormalization, we extracted the momentum distribution curves (MDC) of the band and derived peak position of each MDC by the Lorentzian fitting. The derived peak positions are plotted in Fig. 4 (c) with red circles showing a clear dispersion. The solid blue line is a quadratic polynomial fit to the dispersion yielding a bare band mass, \( m_b = 0.41 \pm 0.02 m_e \). The MDC peak dispersion shows a "kink" at -44 meV (marked by a triangle) and deviates from the quadratic behavior. Fitting the renormalized part of the band, we obtained the renormalized QP mass \( m^* = 0.76 \pm 0.04 m_e \).
which translates into a corresponding renormalization factor \( m^*/m_b = 1.85 \). Interestingly, the renormalized QP mass is much lower than the values previously reported for (001) SRO films or layered \( \text{Sr}_2\text{RuO}_4 \), which nominally lie in the range 4-16\( m_e \), and known to be strongly band dependent\(^{23,35,47} \). Recently, both light and heavy bands with \( m_b \) values of 1\( m_e \) and 14\( m_e \), respectively, have been found to coexist in \( \text{CaRuO}_2 \); these numbers are still larger than the band mass we obtained in this study. Although the extremely light band observed in (111) SRO films is surprising, it could be a natural consequence of probing a specific part of BZ. This limitation perhaps also hinders observing other heavier bands.

The kink in the MDC dispersion, which is considered to arise from the electron-phonon coupling, typically found in the energy range -60 to -70 meV in (001) SRO film\(^{23,17} \), now appears at lower binding energy in our (111) SRO film. To crosscheck the kink energy in Fig. 4 (d), we show the real part of the self-energy (\( \Re \Sigma(\omega) \)) and full width at half maximum (FWHM) extracted from the MDC. The FWHM is linearly proportional to the imaginary part of the self-energy (\( \Im \Sigma(\omega) \)) that can be expressed as,

\[
\Delta k = 2 \Im \Sigma(\omega)/v_0
\]  

(1)

Here \( \Delta k \) and \( v_0 \) are FWHM and the bare velocity, respectively.\(^{32} \) \( \Re \Sigma(\omega) \) increases from Fermi energy, reaches its maximum value around -44 meV, and gradually decreases. Meanwhile, FWHM of the MDC peaks starts to drastically increase around -44 meV, indicating the sudden increase of the scattering rate induced by electron-phonon coupling.\(^{23,40,47} \) Overall, both fitting MDC dispersion and analysis of real and the imaginary part of the self-energy consistently points towards the existence of a kink around -44 meV. Remarkably, the position of this kink is comparable to the energy of the \( B_{2g} \) phonon mode (354 cm\(^{-1} \) = 43.9 meV) that corresponds to the motion of apical oxygen ions.\(^{21} \) Meanwhile, in (001) SRO films, the kink is attributed to the coupling between electron and in-plane oxygen vibration-driven \( A_g \) (540 cm\(^{-1} \) = 67 meV) mod.\(^{23} \) These considerations, thus, suggest that changing the growth orientation also alters the electron-phonon mode coupling. Yet, the corresponding renormalization factors \( (m^*/m_b) \) for both orientations are comparable.\(^{17} \)

In summary, we have demonstrated that high quality SRO film can be grown along the polar (111) direction using the PLD technique. \textit{In situ} ARPES study reveals the existence of light bands in the (111) SRO film. The effective mass analysis yields a renormalized quasiparticle effective mass of \( \sim 0.8m_e \), which is lowest among the Ruthenates. The band dispersion shows a prominent kink at -44 meV, suggesting the origin of mass renormalization is electron-phonon coupling, albeit the phonon mode that couples to electrons in the (111) SRO film is different than its (001) counterpart. Also, we found that the quasiparticle spectral weight is suppressed at the Fermi level, and an incoherent peak appears at -1.4 eV, which we suggest possibly originating from the structural disorders that could be present on the polar (111) surface.

This work also leaves some open questions and scope for future studies. For example, we could not identify the orbital character of the observed bands, nor we could clarify the origin of the vertical feature at the Brillouin zone center. Synchrotron-based ARPES measurements with variable polarization and photon energies, complemented by theoretical calculations, could allow comprehensively understanding the overall band structure, including the orbital character of the band and the vertical feature. Nevertheless, we hope that our work would further stimulate studies on (111) thin films of correlated oxides with strong spin-orbit coupling strength and eventually pave the way towards realizing novel topological quantum phases.

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Y.I., and C.K. discussed and interpreted the result. H.R. and Y.I. analyzed the data. H.R., S.D., and B.K. studied the optimized sample cleaning condition. H.R. performed the ARPES measurements. H.R., S.D. and B.K. studied the optimized sample cleaning condition. H.R. performed the ARPES and XPS measurements under the supervision of C.K. and with assistance from I.S., M.K., S.H., J.J., S.H. and W.K. H.R. and Y.I. analyzed the data. H.R., S.D., Y.I., and C.K. discussed and interpreted the result. H.R. and S.D. wrote the manuscript with inputs from all the authors.
SUPPLEMENTARY INFORMATION

Figure S1 shows the core-level spectra of the 15 unit cells (u.c.) thick (111) SRO film measured at room temperature. In Fig. S1 (a), O 1s spectrum shows a clear and sharp single peak centered around 529 eV, and the overall line shape is slightly asymmetric due to metallic screening. Absence of shoulder peaks on the high binding side of the O 1s peak indicates the film surface is free from contamination such as hydroxide, carbonate, water, and also the amount of compositional disorders is minimal. The core-level spectrum of Ru 3d and Sr 3p are shown in Fig. S1 (b). In Fig. S1 (c), we show the XPS spectrum covering the Ru 4p, Sr 4s, Sr 4p, O 2p, and Ru 4d peaks. The peak positions are consistent with the previous study. Please note that the energy resolution of the analyzer is \(\sim 1\) eV; this results in an enhanced broadening of the core level peaks.

Figure S2 shows the valence band spectra of the 7, 15, and 30 u.c. thick (111) SRO films taken at 20 K. For a clear comparison, the intensity of all three spectra is normalized with respect to the O 2p non-bonding peak intensity at binding energy 3 eV. Spectra of the 30 and 15 u.c. thick films show similar peak positions between the Fermi level and -8 eV. Both spectrum from 30 u.c. and 15 u.c. sample show sharp Fermi cutoff at the Fermi level (inset of Fig. S2), which is calibrated with reference to the poly Au spectrum. However, the spectrum of the 7 u.c. thick sample, plotted in green color, is blue-shifted to the higher binding region and does not exhibit a sharp Fermi cutoff. The inset of Fig. S2, which magnifies the spectra near the Fermi level, better describe this blue shift and the absence of the Fermi cutoff. These observations imply an insulating nature of the 7 u.c. (111) SRO film, \(\sim 1.6\) nm. This insulating nature is consistent with recently reported thickness-dependent transport study, which shows a metal-insulator transition in (111) SRO film below 2.7 nm.

In Fig. S3 (a), we represent the angle integrated valence band spectra from SRO (001) and (111) films. We integrated the energy versus slit angle spectrum along the slit angle direction. During the measurement, the slit sets to be parallel with \(\tilde{X}-\tilde{X}\) direction for (001) film and \(\tilde{X}-\tilde{K}\) direction for (111) film. Our SRO (001) spectrum well matches with reported results and there are some different aspects between (001) and (111) results. Please see the main text for the detailed description. In Fig. S3 (b), we plot the valence band spectra (within 2 eV from the Fermi level) that are summed over the momentum space covering \(k_x, k_y = -0.4\) to 0.4 Å\(^{-1}\). One can notice the two differences between (001) and (111) spectra. First, the intensity of the quasiparticle peak QP at the Fermi level of the (111) film is suppressed as compared to the (001) film. Second, while the (111) film exhibits clear peaks centered at -1.4 and -0.8 eV, the (001) SRO film does not show an enhanced spectral weight at higher binding regions. These observations allow us to rule out the possibility of excessive Ru deficiency in our samples and suggest the suppressed QP peak intensity and two peak structures in the (111) SRO film are of intrinsic origin.

We performed azimuthal dependent Fermi surface mapping and the results are displayed in Fig. S4. Figure S4 (a) and (c) is the Fermi surface measured after rotating the sample azimuthally by 5 and 40 degrees counterclockwise, respectively. In Fig. S4 (b) and (d), we show the intensity versus in-plane momentum plot extracted from (a) and (c), respectively. For a clear comparison, the maximum intensity is set to 1 in (b) and (d). In the case of 5 °, intensity along the A (C) and B (D) show very close value in all in-plane momentum. But, in the case of 40 ° rotation, the intensity of B is reduced by 20% compared to A. Also, C and D show a similar tendency with A and B. One can notice that the hotspot-intensity is inversely proportional to their distance from the \(k_y\) axis. This strong azimuthal angle-dependent intensity anisotropy or the so-called matrix element effect might imply an orbital selective occupation of the Ru 4d \(t_{2g}\) band.

Apart from extracting the bare band mass \((m_b)\) and renormalized band mass \((m^\ast)\), we also estimated the bare and renormalized velocities from the MDC dispersion. To calculate the renormalized band velocity at Fermi level, we performed the fitting with linear function at \(E_F \pm 8\) meV from MDC peak (red circles). The calculated renormalized band velocity at Fermi level \((v^\ast)\) is 1.76 ± 0.15 eV Å. The calculated bare band velocity at Fermi level \((v_b)\) obtained from the fitting is 2.77 eV Å. From these results, we estimate \(v_b/v^\ast = 1.59 \pm 0.13\), which compares fairly well to the renormalized factor, \(m^\ast/m_b = 1.85\).
FIG. S1. (Color online) (a) XPS spectrum of O 1s. (b) XPS spectrum around Ru 3d and Sr 3p peaks. (c) XPS spectrum showing the Ru 4p, Sr 4s, Sr 4p, O 2p peaks and valence band near the Fermi level. The Fermi level, which is calibrated using Au, is marked with a black dashed line.

FIG. S2. (Color online) Angle integrated valence band spectra from 7, 15, and 30 u.c. (111) SRO films. (inset) Magnified spectra between the Fermi level and 0.2 eV binding energy. The Fermi level that is calibrated using Au is marked with a black dashed line.
FIG. S3. (Color online) (a) Angle integrated valence band spectra up to 10 eV binding energy of (001) and (111) SRO films. Ru 4d-O 2p bonding and O 2p non bonding states are denoted by B and NB, respectively. (b) Angle integrated valence band spectra magnifying the Ru 4d t_{2g} dominated part of the valance band spectra within an energy window of 2 eV from the Fermi level. Please note that these spectra are extracted by summing over the whole momentum space, accessible in our experimental geometry. Black triangles mark the two peaks centered at -1.4 and -0.8 eV in the angle integrated spectrum of the (111) SRO film.

FIG. S4. (Color online) (a) Fermi surface measured after rotating the sample azimuthally by 5° counterclockwise. (b) (Left) Intensity versus momentum plot along the lines A and B in (a). (Right) Intensity versus momentum plot along the lines C and D in (a). (c) Fermi surface measured after rotating the sample azimuthally by 40° counterclockwise. (d) (Left) Intensity versus momentum plot along the lines A and B in (c). (Right) Intensity versus momentum plot along the C and D in (c).
FIG. S5. (Color online) The band dispersion near the Fermi level extracted from Lorentzian fitting of MDC curves is shown by red circles. The quadratic fitting, which we use to extract the bare band mass is shown by the solid blue line. The linear fitting in the energy range of -8 to 8 meV from our MDC peak (red circles) is shown by the dashed red line. The dashed blue line represents the linear contribution of the quadratic polynomial fitting, which we use to estimate the bare band velocity near the Fermi level ($v_b$).