Anomalous dissipation in KTaO$_3$ (111) interface superconductor in the absence of external magnetic field

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Abstract

Understanding the nature of dissipation mechanisms in two-dimensional (2D) superconductors under applied perpendicular magnetic field ($B_\perp$) using very small current ($I$) excitations has been a subject of huge interest in the last two decades. However, dissipation mechanisms at large $I$ drive remain largely unexplored. We investigate this fundamental question for a newly fabricated KTaO$_3$ (111)-based interfacial superconductor, which lies in the intermediate disorder regime. We demonstrate two distinct regimes of dissipation across the Berezinskii Kosterlitz Thouless phase transition temperature ($T_{\text{BKT}}$). Below $T_{\text{BKT}}$, $I$ driven breaking of vortex-antivortex pairs and superconducting weak links are found to be the major sources of dissipation. Most importantly, we uncover a new source of dissipation arising from large electric field driven electronic instability in the temperature range $T_{\text{BKT}} < T < T_C$ (where $T_C$ is superconducting transition temperature), leading to a rare observation of clockwise hysteresis loop in $I$-$V$ curve. While such behavior had been reported earlier in type II superconductors in the presence of $B_\perp$, experimental demonstration in the absence of external $B$ remains elusive so far. Our results not only reveal the microscopic structure of 2D superconductors close to BKT transition, but also deepens the understanding of how a BKT system is ultimately transferred to a normal state by increasing $I$. 

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Answering how robust is the superconducting condensate against external perturbation requires an intense knowledge about the role of disorder and dimensionality of the system [1]. With the recent advent of high quality sample fabrication techniques, there has been a surge of activity in the field of two dimensional (2D) superconductors in recent times [2, 3]. These systems undergo Berezinskii Kosterlitz Thouless (BKT) type of phase transition [4, 5]. In a pure BKT system, current ($I$) driven unbinding of thermally generated bound vortex-antivortex pairs is the major cause of dissipation under zero magnetic field ($B$) below $T_{\text{BKT}}$ [5–7]. This phenomenon happens over small $I$ drive and has been thoroughly investigated. Beyond this limit, there exists a large region in the $I$-$T$ phase space below $T_{\text{BKT}}$, which is characterized by a dilute plasma of vortices and antivortices. This region is microscopically similar to the regime of proliferated free vortices in temperature range $T_{\text{BKT}} \leq T \leq T_C$ [8]. Unfortunately, studying dissipation in these two regimes of free vortices has been highly challenging due to non-trivial dynamics of massively generated non-equilibrium quasi particles from the collapse of ultra fast moving vortices under large $I$ drive [9, 10].

The presence of disorder in samples, which is inevitable in reality, further complicates this problem by turning BKT system inhomogeneous. Such inhomogeneities might range from atomic level point defects to macroscopically phase separated regions [11–14]. While the former determines the vortex pinning strength, the latter very often leads to a network of superconducting puddles joined by weak superconducting links. Such weak links are very fragile under large electric field and are another competing source of dissipation under large $I$ in the absence of $B$ [15]. In the past, much of the attention has been paid to understanding the dissipation in either very clean or dirty system. Notably, all of these measurements have been primarily performed in the presence of $B$ (under very small $I$) and very little is known about the nature of dissipation under large $I$ [16, 17]. Further, what happens in the intermediate disordered regime also remains an open question. Understanding dissipation in such unexplored regimes is not only critical to answering some of the fundamental questions about BKT phase transition in inhomogeneous system but will also be pivotal in realizing next generation applications such as superconducting digital memory, cavities for particle accelerators and THz radiation sources [18–21].

Oxide heterostructure based interfacial superconductor turns out to be a promising platform for such an investigation as they intrinsically lie near the intermediate disorder regime and hence would allow for simultaneous investigation of dissipation pertaining to a pure BKT system and also arising from the inhomogeneous electronic structure using a single sample [23]. Recently, super-
FIG. 1. Device geometry and transport behavior of 2DEG at AlO\(x\)/KTO (111) interface

a. In a pure ionic picture, (111) oriented KTaO\(_3\) can be considered as a sequence of alternating [KO\(_3\)]\(^{5−}\) and Ta\(^{5+}\) planes. Arrangement of Ta\(^{5+}\) ions in two adjacent (111) planes (labelled by Ta-I and Ta-II) has been shown in the upper panel [22]. (Lower panel) Schematics of two Hall bars made on a AlO\(x\)/KTO (111) heterostructure.

b. Temperature-dependent \(R_S\) of 2DEG for the two Hall bars for a 7 nm AlO\(x\)/KTO (111) sample. Inset shows a magnified view around the superconducting transition temperature. Interestingly, the normal state \(R_S\) (\(T\)) shows a non Fermi liquid behavior \((R_S \propto T^\alpha\) where \(\alpha < 2\)) in a broad range of temperatures from 75 K to 300 K with \(\alpha = 1.5\) and 1.3 for current along [11\(\overline{2}\)] and [1\(\overline{1}\)0] respectively. This behavior is in sharp contrast with the \(T^3\) behavior observed in bulk electron doped KTO, where no superconductivity has been observed (see supplementary Fig. 2). Low temperature variation of \(R_S\) under \(B_\perp\) has been shown in c. (from 0 T to 0.1 T) and d. (from 0.2 T to 9 T) for the Hall bar along [11\(\overline{2}\)]. Dotted lines in (d) show logarithmic dependence of \(R_S\) with the temperature near the avoided SIT transition.
conductivity (SC) has been discovered at the interface and surface of (111) oriented KTaO$_3$ (KTO) with $T_C \sim 1.5$-$2.2$ K [24–27]. This $T_C$ is one order of magnitude higher than any STO based heterostructure [28] and hence has generated tremendous excitement in the field of interfacial SC. Most importantly, these samples are a bit cleaner compared to STO based superconducting interfaces. As a result, KTO (111) based superconductors lie exactly at the boundary between clean and dirty limits, making it a unique system for investigating dissipation in 2D superconductors. Interestingly, SC was also found to be strongly influenced by the choice of over-layer grown on KTO (111) substrate. For example, the presence of a magnetic element in the overlayer could lead to a stripe order near superconducting transition [24]. Such a situation would lead to additional directional anisotropy apart from the anisotropy arising from the two inequivalent crystallographic directions $[1 \bar{1} 2]$ and $[1 \bar{1} 0]$ for (111) oriented KTO (Fig. 1a).

In order to avoid the additional influence of overlayer on nature of dissipation, we have fabricated a new superconducting interface by ablating non-magnetic Al$_2$O$_3$ on KTO (111) substrate [dimension $5 \text{ mm} \times 5 \text{ mm} \times 0.5 \text{ mm}$] by pulsed laser deposition technique (see Methods and Supplementary Fig. 1). The resultant film is amorphous. For electrical transport measurements, two Hall bars were patterned along two in-equivalent crystallographic directions : $[1 \bar{1} 2]$ and $[1 \bar{1} 0]$ (Fig. 1a) by selective scratching of film deep into the substrate [32]. Fig. 1b shows the sheet resistance ($R_S$) vs. temperature plot of a 7 nm AlO$_x$/KTO (111) sample. As evident, the interface exhibits metallic behavior up to low temperature confirming the formation of two dimensional electron gas (2DEG). The origin of the 2DEG is connected to the creation of oxygen vacancies (OVs) [33] within the KTO substrate. Further, a clear superconducting transition is observed with little anisotropy e.g. $T_C = 1.55$ K and $1.51$ K for current along $[1 \bar{1} 2]$ and $[1 \bar{1} 0]$ respectively (inset of Fig. 1b) ($T_C$ is estimated from the condition $R_S(T_C) = 0.5 \times R_S(5 \text{ K})$). While the value of $T_C$ is very similar to the previous reports [24, 25], the observation of little anisotropy is in sharp contrast with the observation of large in-plane anisotropy in EuO/KTO (111) near the superconducting $T_C$ [24].

To further probe the nature of this new superconducting system, temperature dependent measurements of $R_S(T)$ under perpendicular ($B_\perp$) and parallel ($B_\parallel$) magnetic fields have been carried out. Fig. 1c shows one representative set of data for $I \parallel [1 \bar{1} 2]$ under low $B_\perp$ [$R_S(T)$ under $B_\perp$ for $I$ along $[1 \bar{1} 0]$ has been shown in Supplementary Fig. 3]. Clearly, the SC is disrupted at very low $B_\perp$, which can be attributed to the low pinning of vortices in 2D superconductors. Upon increasing the $B_\perp$, the sample undergoes an avoided superconductor to insulator transition (SIT) around $R_S$
Critical field, weak anti-localization, and the extent of disorder

- **Figure 2a**: Temperature dependence of upper critical field ($B_{C\perp}$) under $B_{\perp}$ for $I$ along [11\(\bar{2}\)] and [1\(\bar{1}\)0]. The solid line denotes fitting with Ginzburg-Landau theory.

- **Figure 2b**: Temperature dependence of upper critical field ($B_{C\parallel}$) under $B_{\parallel}$ for $I$ along [11\(\bar{2}\)] and [1\(\bar{1}\)0]. Further, $B$ is parallel to the current direction. The solid line denotes fitting with Tinkham’s model.

- **Figure 2c**: Sheet conductance difference ($\Delta\sigma=\sigma(B)-\sigma(B=0)$, $\sigma=1/R_S(B)$) in the units of $e^2/\pi\hbar$ for the Hall bar with $I$ along [11\(\bar{2}\)]. The black solid curves show the fitting with ILP (Iordanskii, Lyanda-Geller, and Pikus) theory [29, 30] (without considering linear Rashba term) including a classical $B^2$ term (also see Supplementary note S7 for fitting details).

- **Figure 2d**: Phase diagram of several superconducting compounds categorized by their extent of 2D character and cleanliness. 2D character is resembled by the anisotropy of critical field defined by ($B_{C\perp}/B_{C\parallel}$) and extent of disorder is quantified by the ratio between phase coherence length and electronic mean free path ($\xi_0/l_mfp$). Assuming a single isotropic band in 2D, $l_{mfp}$ is given by $l_{mfp}=\hbar/(e^2k_F R_S)$, where $k_F=(2\pi n_s)^{1/2}$ is the Fermi wave vector and $n_s$ is the sheet carrier density. From the measured $n_s$ (at 5 K) and $R_S$ (at 5 K), the $l_{mfp}$ is estimated to be $\sim 12$ nm for the present case. The value of all the parameters for other compounds have been largely taken from the reference [23] except for the LaTiO$_3$/STO interface which has been taken from [31]. AlO$_x$/KTO (111) is located very near to the boundary between clean and dirty limits, denoted by a horizontal solid line.
~ 1 kΩ/sq. (see Fig. 1d). This result is markedly distinct from the conventional theoretical framework that predicts a direct transition to an insulating state when the normal state $R_S$ approaches the quantum of resistance $h/4e^2 = 6.4$ kΩ/sq. in the limit $T \to 0$ ($h$ is the Planck’s constant and $-e$ is the electron’s charge) [34, 35]. Such avoided SIT is generally observed in 2D superconductors with relatively less disorder and has proven monumental in studying phases beyond the Landau Fermi liquid theory [36]. Interestingly, at higher $B_\perp$ and lower $T$, our sample exhibits a logarithmic dependence of $R_S$ on $T$. This logarithmic divergence is incompatible with the prediction of weak localization correction in 2D or Kondo effect [36] and is ultimately connected with the emergent granular nature of our conducting interface [37, 38]. In the later part of this article, we will establish the microscopic origin behind such a granular structure and further study about its impact on dissipation under large $I$.

Fig. 2a shows the temperature dependence of upper critical field ($B_{C_\perp}$), obtained by tracking the evolution of $T_C$ with $B_\perp$ in $R_S$ vs. $T$ plot. An appreciable difference in magnitude of $B_{C_\perp}$ is observed for $I$ along [11 2] and [11 0]. Higher value of $B_{C_\perp}$ along [11 2] is consistent with the observation of higher $T_C$ for $I \parallel$ to [11 2]. The solid line shows fitting with the Ginzburg-Landau (G-L) theory which predicts linear $T$ behavior of $B_{C_\perp}$ given by

$$B_{C_\perp} = \frac{\Phi_0 (1 - T/T_C)}{2\pi (\xi_0)^2} \quad (1)$$

where $\Phi_0$ is the magnetic flux quantum and $\xi_0$ is the G-L coherence length at $T = 0$ K. $\xi_0$ from fitting is found to be $\sim 23.4$ nm and 21.4 nm for $I$ along [11 2] and [11 0], respectively.

To determine the thickness of the superconducting region, upper critical field ($B_{C_\parallel}$) has also been determined under $B_\parallel$ with two different configurations: $I \parallel$ $B$ and $I \perp B$. Fig. 2b shows the temperature dependence of $B_{C_\parallel}$ for the case with $I \parallel B$ (see Supplementary Fig. 4 to Fig. 6 for raw $R_S$ vs. $T$ plot at different fixed $B$ and $B_{C_\parallel}$ vs. $T$ plot for $I \perp B$). Similar to the out of plane measurement, the magnitude of $B_{C_\parallel}$ is found to be larger for the Hall bar with $I$ along [11 2]. The temperature dependence of $B_{C_\parallel}$ shows a characteristic square-root dependence (shown by the solid lines in Fig. 2b). This is consistent with the Tinkham’s model [41] with

$$B_{C_\parallel} = \frac{\Phi_0 [12 (1 - T/T_C)]^{1/2}}{2\pi d \xi_0} \quad (2)$$

where $d$ is the effective thickness of the superconducting region. The estimated $d$ ($\sim 5$ nm) is much less than $\xi_0$, signifying 2D nature of the SC at the AlO$_x$/KTO (111) interface. Interestingly, the extrapolated value of $B_{C_\parallel}$ to 0 K ($\sim 10$ T) is much larger than Clogston Chandrasekhar (CC)
limit [42, 43]. Such a large value of $B_{C\parallel}$ is generally expected in systems with a strong spin orbit coupling (SOC) [44] and the observation of weak antilocalization (WAL) characteristics in longitudinal magnetoconductance data within the normal phase (see Fig. 2c) demonstrates the importance of SOC in the present case.

In order to examine the extent of disorder in our system, we have estimated the ratio of $\xi_0$ and the electronic mean free path $l_{mfp}$. The ratio is close to 2, emphasizing that the SC at AlO$_x$/KTO (111) interface falls in the intermediate disorder regime (see Fig. 2d, which summarizes several superconductors on the basis of disorder and 2D character). The presence of OVs within KTO in the present heterostructure are natural source of inhomogeneities. Clustering of OVs can also lead to a very local inhomogeneous electronic structure in the real space [45]. Apart from such local inhomogeneities, there is another source of inhomogeneity, which happens at a much larger scale, known as electronic phase separation (EPS) [11–14]. EPS has been routinely observed in STO based 2DEGs and is very often associated with the presence of multi carriers at the interface. The observation of two types of electrons with densities $n_1$ and $n_2$ with mobility $\mu_1$, and $\mu_2$, respectively ($n_1 >> n_2$ and $\mu_1 < \mu_2$) in our Hall effect measurements (see Supplementary note S8-S10) strongly suggests that a similar scenario might also be applicable in our samples as well. As a general consequence of this, superconducting puddles (joined by weak links) would emerge naturally in real space [46], making the SC strongly inhomogeneous. We believe this is the dominant cause for the observed granular nature of our system. We also note that EPS could also arise due to the Rashba SOC [11] which is also quite generic to our system.

Having established the nature of inhomogeneities in our 2D superconducting system, we explore the nature of dissipation under current bias in the absence of $B$. For this, comprehensive $I$-$V$ measurements have been performed. Fig. 3a shows the $I$-$V$ curves (in the positive quadrant) taken in forward and backward sweeps at several fixed temperatures from 1.26 K to 10 K for $I$ along [112] (see supplementary Fig. 12 for data of $I$ along [110]). All data (except the curve of 1.26 K) has been shifted vertically upwards for visual clarity. Broadly four distinct regimes can be identified in the $I$-$V$ curve at the lowest temperature (1.26 K) of our measurements: (1) At small currents (up to 60-70 $\mu$A), voltage drop is almost independent of $I$ signifying a dissipation-less regime. (2) Above this, a non-linear behavior appears in a very short window from $\sim$80 $\mu$A-110 $\mu$A. (3) This regime then translates into a region (from 110 $\mu$A to 175 $\mu$A), where the majority of the dissipation happens as observed by a large change in the voltage drop. (4) Above 175 $\mu$A, the magnitude of $V$ grows almost in proportion to the applied $I$ and finally enters into the regime
FIG. 3. **Current voltage (I-V) characteristics and determination of $T_{\text{BKT}}**

a. Temperature dependent $I-V$ curves measured in current bias mode for the Hall bar along [11\(\bar{2}\)]. Solid and dotted curves denote forward and backward sweeps, respectively. Curves have been shifted upward for visual clarity.

b. $I-V$ curves in logarithmic scale during the forward sweep. The solid black line shows the fit with the power law given by $V \propto I^\alpha$. A dotted gray line corresponds to $\alpha = 3$ where the BKT transition takes place.

c. Temperature dependence of $\alpha$ for $I$ along [11\(\bar{2}\)] and [1\(\bar{1}\)0]. A dotted green line shows a constant line for $\alpha = 3$.

d. To estimate $T_{\text{BKT}}$ using the Halperin-Nelson model [39, 40], $[\text{dln}(R_S)/dT]^{-2/3}$ has been plotted as a function of $T$, near the superconducting transition temperature. By finding the $x$ axis intercept of this plot, we find $T_{\text{BKT}} \sim 1.51$ K and 1.43 K for the Hall bar along [11\(\bar{2}\)] and [1\(\bar{1}\)0], respectively. These values are very close to the $T_{\text{BKT}}$, obtained in (c).

e. Temperature dependent $I-V$ curves measured in current bias mode for another sample with 14 nm AlO$_x$ thickness. Solid and dotted curves denote forward and backward sweeps, respectively. Curves have been shifted upward for visual clarity.
of ohmic dissipation. All these different regions in \( I-V \) characteristics are strongly \( T \) dependent. The first and fourth regimes are well understood [1] and are skipped from further discussions for the sake of brevity.

We first discuss the origin of non-linear \( I-V \), observed just above the dissipation less regime. Notably, this regime corresponds to the intrinsic dissipation of a BKT system which is characterized by power law behavior \((V \propto I^\alpha)\) arising from \( I \) driven unbinding of thermally generated vortex-antivortex pairs near the BKT transition [6, 7]. This behavior becomes much more evident in the logarithmic plot (Fig. 3b), where power law translates into a linear behavior. The value of \( \alpha \) becomes exactly 3 at the \( T_{\text{BKT}} \) (shown by a dotted gray line \((V \propto I^3)\) in Fig. 3b) and is routinely used to trace out BKT phase transition in 2D superconductors. Fig. 3c shows the temperature dependence of \( \alpha \) obtained from the linear fit in Fig. 3b. From the crossover of \( \alpha \) around 3, \( T_{\text{BKT}} \) is found out to be 1.39 K and 1.30 K for the Hall bar along [11\( \bar{2} \)] and [1\( \bar{1} \)0], respectively. These values of \( T_{\text{BKT}} \) are also very close to the estimated values (see Fig. 3d) using the Halperin-Nelson model \( (R_S=R_0\exp[-b/(T-T_{\text{BKT}})^{1/2}] \) where \( b \) is the vortex-antivortex interaction strength) [39, 40].

We next focus on the nature of dissipation beyond power law regime. At the lowest temperature of our measurement 1.26 K, which is below \( T_{\text{BKT}} \), dissipation happens via several discrete jumps in voltage during the forward sweep. This is much more evident from the \( dV/dI \) plot shown in supplementary Fig. 11. Such discrete behavior reminds us of phase slip events, which are generally observed in one dimensional (1D) superconducting wire [1]. We attribute discrete jumps in our sample to the breaking of quasi 1D superconducting weak links joining superconducting puddles [15]. Weak links are very fragile under electric field and break at a much lesser current density than the required amount to break the global SC. However, such discrete voltage jumps could also arise from the movement of free vortices across the sample boundary. Interestingly, an anticlockwise hysteresis is observed upon backward \( I \) sweep. This could be understood from the thermal effect argument wherein the local temperature of the sample goes higher (due to Joule heating) than the thermal bath, once it’s driven into the normal state [15, 47]. Since the critical current \( (I_c) \) of superconductors decreases with an increase in \( T \) (supplementary Fig. 11), sweeping back \( I \) immediately would lead to a shift of \( I-V \) curve towards left, leading to anticlockwise hysteresis. With the increase in \( T \), the position of the hysteresis is also found to shift towards lower \( I \). Surprisingly, the nature of hysteresis changes completely from anticlockwise to clockwise above a certain temperature (highlighted by arrows in Fig. 3a). Fig. 3e shows the \( I-V \) curves (in the positive quadrant) at several fixed temperatures for another sample with 14 nm AlO\(_x\) thickness (for \( I \)
FIG. 4. Sign change of hysteresis across BKT transition a. Maximum width of hysteresis ($\Delta I_c = (I_c)_{\text{forward}} - (I_c)_{\text{backward}}$) for 7 nm AlO$_x$ film on KTO (111). The upper and lower panels correspond to $I$ along [11\bar{2}] and [1\bar{1}0]. b. Similar data for another sample with double the thickness (14 nm) of AlO$_x$ along [11\bar{2}]) exhibiting similar clockwise hysteresis above a certain temperature. Such clockwise hysteresis is extremely rare [10] and has never been observed in any interfacial superconductors to the best of our knowledge.

To visualize this drastic change in $I$-$V$ hysteresis, we further plot the maximum width of hysteresis, defined as $\Delta I_c = (I_c)_{\text{forward}} - (I_c)_{\text{backward}}$ [$((I_c)_{\text{forward}}$ and $(I_c)_{\text{backward}}$ are the values of critical current in the middle of hysteresis in the forward and backward sweep, respectively] as a function of $T$ (Fig. 4a and Fig. 4b). The upper and lower panels in Fig. 4a correspond to $\Delta I_c$ for $I$ along [11\bar{2}] and [1\bar{1}0], respectively. Fig. 4b contains a similar set of data for another sample with AlO$_x$ thickness $\sim$14 nm (other characteristics of this sample have been shown in Supplementary note S14-S16). As clearly evident, hysteresis always changes its sign around the $T_{\text{BKT}}$ and vanishes around $T_C$ in all the four Hall bars, that we have investigated in this work. Such a peculiar behavior goes beyond the Joule heating argument and strongly emphasizes presence of an additional dissipation mechanism in the temperature range $T_{\text{BKT}} \leq T \leq T_C$ at large $I$ drive.

In order to understand such rare clockwise hysteresis, we consider Larkin and Ovchinnikov’s (LO) model of non-linear $I$-$V$ [9], which was originally formulated to deal with a highly non-
equilibrium problem of ultra-fast moving vortices under large $I$ drive in the mixed state of type II superconductors. It was predicted that, at large vortex velocities, quasiparticles at the core of the vortex can reach energies above the superconducting energy gap and ultimately diffuse away from the core, resulting in an electronic instability. Such a situation would lead to a non-linear $I$-$V$ characteristics [10, 48], which would be the strongest at temperatures close to the $T_C$ in the presence of very weak $B$ ($B \ll B_{C\perp}$). It is well known that even in the absence of $B$, 2D superconductors in the temperature range $T_{BKT} \leq T \leq T_C$ are known to be microscopically similar to a type II superconductor in the mixed state owing to the presence of thermally generated free vortices above $T_{BKT}$ [8]. This immediately suggests an exciting possibility of observing LO type of electronic instability in 2D superconductors close to $T_C$ even in the absence of externally applied $B$. We also emphasize that while all of our $I$-$V$ measurements have been performed in the absence of $B$, the self field from the applied $I$ in the sample should be sufficient to meet the criteria for the weak $B$ limit of LO model. Under these circumstances, functional form for non-linear $I$-$V$ is given by

$$I - I_c = \left[ \frac{V}{1 + (V/V^*)^2} + V \left( 1 - \frac{T}{T_C} \right)^{1/2} \right] \frac{1}{R_f}$$

(3)

where $R_f$ is the flux flow resistance and $V^*$ is the critical voltage given by

$$V^* = \frac{D^{1/2}[14\xi(3)]^{1/4}(1 - T/T_C)^{1/4}BL}{(\pi\tau_e)^{3/2}}$$

(4)

Here $D$ is the diffusion coefficient, $\tau_e$ is the inelastic electron scattering time, $\xi$ is the Riemann zeta function and $L$ is the length between voltage probes. It was further proposed that, once the system is driven into the normal resistive state in the forward sweep, the electron-electron (inelastic) scattering rate is higher (smaller $\tau_e$) [10]. This would mean that during the backward sweep the value of $V^*$ will be higher ($V^* \sim \tau_e^{-1/2}$) than that of the forward sweep. This would automatically pull the $I$-$V$ curve towards the right leading to a clockwise hysteresis. We believe such a hysteretic $\tau_e$ is the dominant cause behind the observation of clockwise $I$-$V$ in our samples. What remains unclear at this stage is the in-plane anisotropy observed in the onset of clockwise hysteresis e.g., there is a delay in the onset of clockwise hysteresis for $I$ along [110]. This could arise from the in-plane anisotropy of critical vortex velocity for the onset of electronic instability. Such an observation is beyond the LO theory and calls for further investigations in the future. Since the vortex structure in BKT system is strongly influenced by the presence of strong SOC [49], an extension of LO theory in presence of SOC and finite heating effects will be essential to understand
FIG. 5. **Current temperature (I-T) phase diagram at $B = 0$** $I$-$T$ phase diagram constructed using the parameters for Hall bar along [112] for 7 nm AlO$_x$/KTO(111) sample. Below the BKT transition, the sample is characterized by randomly distributed superconducting puddles joined by weak superconducting links. Increasing $I$ first lead to unbinding of vortex-antivortex pairs. This transition is shown by the square symbol. Further increase in $I$ leads to breaking of weak links. Diamond symbol marks the locus of current just before the closure of hysteresis in the forward sweep and triangle symbol defines the onset of clockwise hysteresis above $T_{\text{BKT}}$.

such non-trivial feature. In Fig. 5 we show a detailed $I$-$T$ phase diagram describing various active dissipation mechanisms in the absence of the $B$.

In conclusion, we have demonstrated a new route to achieve 2D superconductivity in (111)-oriented KTO substrate by ablating Al$_2$O$_3$ using pulsed laser deposition. The underlying interface is found to be intrinsically inhomogeneous in nature, which is attributed to the presence of two types of carriers. Interestingly, one of the bands is extremely dilute ($n_2 \sim 10^9\text{cm}^{-2}$) in nature. While, it remains unclear at this stage whether electrons in such a dilute band take part in SC or not, such a possibility would point towards an unusual pairing mechanism beyond BCS theory. Scanning tunnelling spectroscopy measurements will be monumental in understanding the exact nature of inhomogeneous SC.

Further, we uncover a rich variety of dissipation mechanisms close to the BKT transition. Ob-
servation of electronic instability induced dissipation (between $T_{\text{BKT}} \leq T \leq T_C$) could be ultimately traced back to the presence of proliferated free vortices above $T_{\text{BKT}}$, which is quite generic to the BKT phase transition [50]. Future studies will focus on measurements beyond the intermediate disorder regime under simultaneous top and bottom gate, which will provide an independent investigation of the role of disorder and carrier density in determining the nature of dissipation under large $I$ drive. We believe that the observation of electronic instability near the $T_C$ is not particularly limited to the oxide interfaces and it would be interesting to explore this highly non-equilibrium phenomenon in other 2D superconducting platforms, e.g. transition metal dichalcogenides, twisted bilayer graphene etc.

[1] Tinkham, M. *Introduction to superconductivity* (Courier Corporation, 2004).
[2] Saito, Y., Nojima, T. & Iwasa, Y. Highly crystalline 2d superconductors. *Nature Reviews Materials* 2, 16094 (2016). https://doi.org/10.1038/natrevmats.2016.94.
[3] Qiu, D. *et al.* Recent advances in 2d superconductors. *Advanced Materials* 33, 2006124 (2021). https://doi.org/10.1002/adma.202006124.
[4] Berezinskii, V. Destruction of long-range order in one-dimensional and two-dimensional systems having a continuous symmetry group i. classical systems. *Sov. Phys. JETP* 32, 493–500 (1971).
[5] Kosterlitz, J. M. & Thouless, D. J. Ordering, metastability and phase transitions in two-dimensional systems. *Journal of Physics C: Solid State Physics* 6, 1181–1203 (1973). https://doi.org/10.1088/0022-3719/6/7/010.
[6] Beasley, M. R., Mooij, J. E. & Orlando, T. P. Possibility of vortex-antivortex pair dissociation in two-dimensional superconductors. *Phys. Rev. Lett.* 42, 1165–1168 (1979). https://link.aps.org/doi/10.1103/PhysRevLett.42.1165.
[7] Epstein, K., Goldman, A. M. & Kadin, A. M. Vortex-antivortex pair dissociation in two-dimensional superconductors. *Phys. Rev. Lett.* 47, 534–537 (1981). https://link.aps.org/doi/10.1103/PhysRevLett.47.534.
[8] Resnick, D. J., Garland, J. C., Boyd, J. T., Shoemaker, S. & Newrock, R. S. Kosterlitz-thouless transition in proximity-coupled superconducting arrays. *Phys. Rev. Lett.* 47, 1542–1545 (1981). https://link.aps.org/doi/10.1103/PhysRevLett.47.1542.
[9] Larkin, A. & Ovchinnikov, Y. Nonlinear conductivity of superconductors in the mixed state. *Sov. Phys.*
JETP 41, 960–965 (1975).

[10] Samoilov, A., Konczykowski, M., Yeh, N.-C., Berry, S. & Tsuei, C. Electric-field-induced electronic instability in amorphous mo 3 si superconducting films. Physical review letters 75, 4118 (1995).

[11] Caprara, S., Peronaci, F. & Grilli, M. Intrinsic instability of electronic interfaces with strong rashba coupling. Phys. Rev. Lett. 109, 196401 (2012). https://link.aps.org/doi/10.1103/PhysRevLett.109.196401.

[12] Caprara, S. et al. Inhomogeneous multi carrier superconductivity at laxo3/srtio3/srtio3 interfaces. Superconductor Science and Technology 28, 014002 (2014). https://doi.org/10.1088/0953-2048/28/1/014002.

[13] Caprara, S. et al. Multiband superconductivity and nanoscale inhomogeneity at oxide interfaces. Phys. Rev. B 88, 020504 (2013). https://link.aps.org/doi/10.1103/PhysRevB.88.020504.

[14] Ariando et al. Electronic phase separation at the laalo3/srtio3 interface. Nature Communications 2, 188 (2011). https://doi.org/10.1038/ncomms1192.

[15] Likharev, K. K. Superconducting weak links. Rev. Mod. Phys. 51, 101–159 (1979). https://link.aps.org/doi/10.1103/RevModPhys.51.101.

[16] Benyamini, A. et al. Fragility of the dissipationless state in clean two-dimensional superconductors. Nature Physics 15, 947–953 (2019). https://doi.org/10.1038/s41567-019-0571-z.

[17] Saito, Y., Itahashi, Y. M., Nojima, T. & Iwasa, Y. Dynamical vortex phase diagram of two-dimensional superconductivity in gated Mos2. Phys. Rev. Materials 4, 074003 (2020). https://link.aps.org/doi/10.1103/PhysRevMaterials.4.074003.

[18] Embon, L. et al. Imaging of super-fast dynamics and flow instabilities of superconducting vortices. Nature Communications 8, 85 (2017). https://doi.org/10.1038/s41467-017-00089-3.

[19] Devoret, M. H. & Schoelkopf, R. J. Superconducting circuits for quantum information: An outlook. Science 339, 1169–1174 (2013). https://www.science.org/doi/abs/10.1126/science.1231930. https://www.science.org/doi/pdf/10.1126/science.1231930.

[20] Gurevich, A. & Ciovati, G. Dynamics of vortex penetration, jumpwise instabilities, and nonlinear surface resistance of type-ii superconductors in strong rf fields. Phys. Rev. B 77, 104501 (2008). https://link.aps.org/doi/10.1103/PhysRevB.77.104501.

[21] Welp, U., Kadowaki, K. & Kleiner, R. Superconducting emitters of thz radiation. Nature Photonics 7, 702–710 (2013). https://doi.org/10.1038/nphoton.2013.216.
[22] Xiao, D., Zhu, W., Ran, Y., Nagaosa, N. & Okamoto, S. Interface engineering of quantum hall effects in digital transition metal oxide heterostructures. *Nature Communications* **2**, 596 (2011). https://doi.org/10.1038/ncomms1602.

[23] A., D. *et al.* Clean 2d superconductivity in a bulk van der waals superlattice. *Science* **370**, 231–236 (2020). https://doi.org/10.1126/science.aaz6643.

[24] Changjiang, L. *et al.* Two-dimensional superconductivity and anisotropic transport at ktao3 (111) interfaces. *Science* **371**, 716–721 (2021). https://doi.org/10.1126/science.aba5511.

[25] Zheng, C. *et al.* Electric field control of superconductivity at the laalo3/ktao3(111) interface. *Science* **372**, 721–724 (2021). https://doi.org/10.1126/science.abb3848.

[26] Ren, T. *et al.* Two-dimensional superconductivity at the surfaces of ktao3/sub3/s/la/gated with ionic liquid. *Science Advances* **8**, eabn4273 (2022). https://www.science.org/doi/abs/10.1126/sciadv.eabn4273. https://www.science.org/doi/pdf/10.1126/sciadv.eabn4273.

[27] Mallik, S. *et al.* Superfluid stiffness of a ktao3-based two-dimensional electron gas. *arXiv preprint arXiv:2204.09094* (2022).

[28] Reyren, N. *et al.* Superconducting interfaces between insulating oxides. *Science* **317**, 1196–1199 (2007).

[29] Iordanskii, S., Lyanda-Geller, Y. B. & Pikus, G. Weak localization in quantum wells with spin-orbit interaction. *ZhETF Pisma Redaktsii* **60**, 199 (1994).

[30] Ojha, S. K. *et al.* Oxygen vacancy-induced topological hall effect in a nonmagnetic band insulator. *Advanced Quantum Technologies* **3**, 2000021 (2020). https://doi.org/10.1002/qute.202000021.

[31] Biscaras, J. *et al.* Two-dimensional superconductivity at a mott insulator/band insulator interface latio3/srktio3. *Nature Communications* **1**, 89 (2010). https://doi.org/10.1038/ncomms1084.

[32] Cui-Zu, C. *et al.* Experimental observation of the quantum alous hall effect in a magnetic topological insulator. *Science* **340**, 167–170 (2013). https://doi.org/10.1126/science.1234414.

[33] Ojha, S. K. *et al.* Electron trapping and detrapping in an oxide two-dimensional electron gas: The role of ferroelastic twin walls. *Phys. Rev. Applied* **15**, 054008 (2021). https://link.aps.org/doi/10.1103/PhysRevApplied.15.054008.

[34] Goldman, A. M. & Markovi ´c, N. Superconductor-insulator transitions in the two-dimensional limit. *Physics Today* **51**, 39–44 (1998). https://doi.org/10.1063/1.882069.

[35] Haviland, D. B., Liu, Y. & Goldman, A. M. Onset of superconductivity in the two-dimensional
limit. Phys. Rev. Lett. 62, 2180–2183 (1989). https://link.aps.org/doi/10.1103/PhysRevLett.62.2180.

[36] Kapitulnik, A., Kivelson, S. A. & Spivak, B. Colloquium: Anomalous metals: Failed superconductors. Rev. Mod. Phys. 91, 011002 (2019). https://link.aps.org/doi/10.1103/RevModPhys.91.011002.

[37] Beloborodov, I. S., Lopatin, A. V., Vinokur, V. M. & Efetov, K. B. Granular electronic systems. Rev. Mod. Phys. 79, 469–518 (2007). https://link.aps.org/doi/10.1103/RevModPhys.79.469.

[38] Zhang, X., Hen, B., Palevski, A. & Kapitulnik, A. Robust anomalous metallic states and vestiges of self-duality in two-dimensional granular in-inox composites. npj Quantum Materials 6, 30 (2021). https://doi.org/10.1038/s41535-021-00329-2.

[39] Halperin, B. I. & Nelson, D. R. Resistive transition in superconducting films. Journal of Low Temperature Physics 36, 599–616 (1979). https://doi.org/10.1007/BF00116988.

[40] Minnhagen, P. The two-dimensional coulomb gas, vortex unbinding, and superfluid-superconducting films. Rev. Mod. Phys. 59, 1001–1066 (1987). https://link.aps.org/doi/10.1103/RevModPhys.59.1001.

[41] Tinkham, M. Effect of fluxoid quantization on transitions of superconducting films. Phys. Rev. 129, 2413–2422 (1963). https://link.aps.org/doi/10.1103/PhysRev.129.2413.

[42] Chandrasekhar, B. S. A note on the maximum critical field of high-field superconductors. Applied Physics Letters 1, 7–8 (1962). https://doi.org/10.1063/1.1777362.

[43] Clogston, A. M. Upper limit for the critical field in hard superconductors. Phys. Rev. Lett. 9, 266–267 (1962). https://link.aps.org/doi/10.1103/PhysRevLett.9.266.

[44] Werthamer, N. R., Helfand, E. & Hohenberg, P. C. Temperature and purity dependence of the superconducting critical field, $H_{c2}$, iii. electron spin and spin-orbit effects. Phys. Rev. 147, 295–302 (1966). https://link.aps.org/doi/10.1103/PhysRev.147.295.

[45] Ojha, S. K. et al. Oxygen vacancy induced electronic structure modification of ktao3. Phys. Rev. B 103, 085120 (2021). https://link.aps.org/doi/10.1103/PhysRevB.103.085120.

[46] Chen, Z. et al. Carrier density and disorder tuned superconductor-metal transition in a two-dimensional electron system. Nature Communications 9, 4008 (2018). https://doi.org/10.1038/s41467-018-06444-2.

[47] Gurevich, A. V. & Mints, R. G. Self-heating in normal metals and superconductors. Rev. Mod. Phys.
METHODS

**Sample growth and characterization:** AlO\(_x\)/KTO(111) samples were fabricated by ablating a single crystalline Al\(_2\)O\(_3\) target on (111) oriented KTO substrate using a pulsed laser deposition system (Neocera LLC, USA) equipped with a high pressure reflection high energy electron diffraction setup (Staib instruments, Germany). A KrF excimer laser (Coherent, Germany) operated at a repetition rate of 1 Hz (\(\lambda=248\) nm) and an energy density \(\sim 1\) J/cm\(^2\) (on the target) was used for ablating the target. Target to substrate distance was fixed at 5.6 cm. The substrate was heated using a resistive heater whose temperature was maintained at 560 °C during the growth. The growth chamber pressure was \(5 \times 10^{-6}\) Torr during the deposition. Immediately after the ablation, the sample was cooled to room temperature at a rate of 15°C/min under the vacuum. The surface morphology of the as received substrate and the film was monitored by performing atomic force microscopy (AFM) in non-contact mode using a Park AFM system. The thickness of the films was determined from X-ray reflectivity measurement performed in a lab based Rigaku Smartlab diffractometer. For more details, see supplementary note S1.

**Transport Measurements:** All the transport measurements were performed in an Oxford Integra LLD system using the standard four probe method in the Hall bar geometry. Ohmic contacts were made by ultrasonically bonding Al wire. Electrical resistance was measured using a dc delta mode with a Keithley 6221 current source and a Keithley 2182A nanovoltmeter and also using standard low-frequency lock-in technique. For \(I-V\) measurements a Keithley 2450 source meter was used.
in current bias mode with a sweep rate of 10 $\mu$A/sec.

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COMPETING INTERESTS

The authors declare no competing interests.
Supplementary Material

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S1. Growth and characterization of AlO$_x$/KTO (111) sample

FIG. S1. a. RHEED image of KTO (111) substrate. b. The intensity of the specular RHEED spot during the growth of the film. c. RHEED image just after the deposition of the film. d. AFM image of the substrate. e. AFM image of the film. f. X-ray reflectivity pattern of the heterostructure along with the simulation.

Fig. S1a shows the reflection high energy electron diffraction (RHEED) image of as received KTO (111) substrate. Observation of intense diffraction spots along with Kikuchi lines establishes the flat and single crystalline nature of the surface and further excludes the possibility of faceting [1, 2]. This is further evident from the atomic force microscopy (AFM) image of the substrate, which exhibits a very smooth surface morphology with mean roughness ($R_q$) $\sim$ 100 pm (Fig. S1d). Fig. S1b shows the temporal evolution of the intensity of the specular RHEED spot
during the film deposition. As evident, intensity decreases gradually during the growth. This is due to the amorphous nature of the film which is evident from the absence of any diffraction spots in the RHEED image after the deposition (Fig. S1c). The resultant film has very flat surface morphology (Fig. S1e) with $R_q \sim 175$ pm. In order to determine the thickness of the films, X-ray reflectivity measurements have been performed. Fig. S1f shows the measured data along with the simulation (using GenX [3]) for two representative samples with thicknesses $\sim 7$ nm and 14 nm.
S2. $R_S$ vs. $T$ data of the bulk oxygen deficient KTaO$_3$ (001) single crystal.

FIG. S2. Sheet resistance vs. temperature plot for three bulk oxygen deficient (001) oriented KTO single crystal with sheet carrier densities $2.2 \times 10^{15}$ cm$^{-2}$, $1.6 \times 10^{15}$ cm$^{-2}$ and $8.4 \times 10^{14}$ cm$^{-2}$ measured at room temperature. The solid black line denotes fitting with $T^3$. Data have been reproduced with permission from references 30 and 45 of the main text.
S3. $R_S$ vs. $T$ data under perpendicular $B$ for Hall bar along [1\bar{1}0]

FIG. S3. Low temperature variation of $R_S$ under $B_\perp$ for the Hall bar along [1\bar{1}0] has been shown in a. (from 0 T to 0.1 T) and b. (from 0.2 T to 9 T) for 7 nm AlO$_x$/KTO (111) sample. Similar to the Hall bar along [11\bar{2}], an avoided SIT is observed around $R_S \sim 0.9 \text{k}\Omega/\text{sq}$. A logarithmic dependence is also observed at higher $B$ and low $T$. 
S4. $R_S$ vs. $T$ data under in-plane $B$ for Hall bar along [112] for two configurations ($B \parallel I$ and $B \perp I$)

FIG. S4. Low temperature variation of $R_S$ under $B \parallel$ (for 7 nm AlO$_x$/KTO (111) sample) when $I \parallel [11\bar{2}]$ and $B \parallel I$ has been shown in a. (from 0 T to 4 T) and b. (from 5 T to 9 T). Plots for the case when $I \parallel [11\bar{2}]$ and $B \perp I$ has been shown in c. (from 0 T to 3.25 T) and d. (from 5 T to 9 T).
S5. $R_S$ vs. $T$ data under in-plane $B$ for Hall bar along [110] for two configurations ($B \parallel I$ and $B \perp I$)

FIG. S5. (a) Low temperature variation of $R_S$ under $B\parallel$ (for 7 nm AlO$_x$/KTO (111) sample) when $I \parallel [1\bar{1}0]$ and $B \parallel I$ have been shown in a. (from 0 T to 3.25 T) and b. (from 5 T to 9 T). Plots for the case when $I \parallel [11\bar{2}]$ and $B \perp I$ has been shown in c. (from 0 T to 4 T) and d. (from 5 T to 9 T).
S6. Temperature dependent upper critical field under in-plane $B$ for both the Hall bars for two configurations ($B \parallel I$ and $B \perp I$)

FIG. S6. Temperature dependent upper critical field ($B_{C\parallel}$), obtained by tracking the evolution of $T_C$ with $B_{\parallel}$ in $R_S$ vs. $T$ plot for all the four configurations discussed in sections S4 and S5. For the case of Hall bar along $[1\bar{1}2]$, $B_{C\parallel}$ is found to be lower for the case when $B \parallel I$ (configuration 1) than $B \perp I$ case (configuration 2). Interestingly, this trend is completely opposite for the Hall bar along $[1\bar{1}0]$ where $B_{C\parallel}$ for the case when $B \parallel I$ (configuration 3) is found to be higher than $B \perp I$ case (configuration 4). Such a behavior could arise from a small $p$-wave component in the superconducting order parameter as proposed recently [4].
S7. Fitting of weak-anti localization (WAL) data with Iordanskii, Lyanda-Geller, and Pikus (ILP) theory

FIG. S7. a. Temperature dependence of the phase coherence time ($\tau_{\phi}$) and spin precession time ($\tau_{SO}$) obtained from the fitting for both the Hall bars. b. Temperature dependence of the number of independent channels contributing to WAL.

As shown in the main text, ILP theory (with only cubic Rashba term) along with a small Kohler $B^2$ term provides an excellent fit at all temperatures. In the absence of linear Rashba term, the correction to the sheet conductance ($\Delta \sigma$) is given by

$$\Delta \sigma(B) = N \frac{e^2}{\pi \hbar} \left[ \Psi\left(\frac{1}{2} + \frac{B\phi}{B} + \frac{B_{SO}}{B}\right) - \frac{1}{2} \Psi\left(\frac{1}{2} + \frac{B\phi}{B}\right) \right. + \frac{1}{2} \ln \frac{B\phi + B_{SO}}{B}$$

$$\left. + \frac{1}{2} \ln \frac{B\phi + 2B_{SO}}{B} + \frac{1}{2} \ln \frac{B\phi}{B} \right]$$

where $N$ is the number of independent interference channels [5], $\Psi$ is the digamma function, $B\phi=\frac{\hbar}{4e^2}l_{\phi}$ ($l_{\phi}$ is the phase coherence length) and $B_{SO}=\frac{\hbar}{4e^2l_{SO}}$ ($l_{SO}$ is the spin-precession length) where $\hbar$ is the reduced Planck’s constant. Associated characteristics time scales, phase coherence time ($\tau_{\phi}$) and spin precession time ($\tau_{SO}$) are given by $\tau_{\phi}=\frac{\hbar}{4eDB\phi}$ and $\tau_{SO}=\frac{\hbar}{4eDB_{SO}}$ where $D$ is the diffusion coefficient given by $D=v_f^2\tau/2$ ($v_f$ is the Fermi velocity and $\tau$ is the elastic scattering time).
$v_f$ and $\tau$ were estimated assuming a single band having parabolic dispersion with effective mass $m^* = 0.3m_e$ [6]. Fig. S7a shows the temperature dependent $\tau_\phi$ and $\tau_{SO}$ obtained from the fitting for both the Hall bars along [112] and [1\overline{1}0]. As evident, $\tau_{SO}$ is smaller than $\tau_\phi$ satisfying the criteria for WAL [7, 8]. Temperature dependence of the number of independent channels has been plotted in Fig. S7b.
S8. Transverse resistance ($R_{xy}$) as a function of the out-of-plane magnetic field at different temperatures

FIG. S8. Antisymmetrized transverse resistance as a function of the magnetic field measured at various temperatures in the metallic phase for 7 nm AlO$_x$/KTO (111) sample. The direction of $I$ is along the crystallographic axis [112].

Fig. S8 shows $R_{xy}$ vs. $B$ curves recorded at several fixed temperatures. To eliminate the longitudinal component of resistance ($R_{xx}$), the data has been antisymmetrized with respect to $B$. As clearly evident, the slope $R_{xy}/B$ increases with the decrease in temperature. Assuming single band transport, the Hall coefficient is given by $R_H = -1/ne$ (where $n$ is the carrier density and $-e$ is the electron’s charge). Since, $R_{xy}/B = R_H$, an increase in slope $R_{xy}/B$ with lowering of temperature immediately suggests decreasing $n$ with lowering of temperature. A similar trend has also been observed for other Hall bar along [110]. In sections S9 and S10, we discuss the origin of the nonlinear Hall effect in the present case.
S9. Non-linear Hall effect and evidence for two-band transport

FIG. S9. The Hall coefficient $R_H$ as a function of out-of-plane magnetic field at 5 K and 50 K for both the Hall bars along [11$\bar{2}$] and [1$\bar{1}$0] has been shown in a and b. c. Linear fitting of $R_{xy}$ vs. $B$ data at 5 K for $I$ along [11$\bar{2}$]. To visualize the presence of little non-linearity in $R_{xy}$, the residual ($R_{xy}$-Fit) is multiplied by 50. d. $R_{xy}$ vs. $B$ data at 5 K (for $I$ along [11$\bar{2}$]) along with fitting using two band model.

To extract the value of $n$, we have tried to fit the data with a straight line assuming one band model. Interestingly, we find that, below 20 K, $R_{xy}$ vs. $B$ can not be captured using one band approximation due to the presence of a little non-linearity. This is clearly evident in the $R_H$ vs. $B$ plot shown in Fig. S9a and b for both the Hall bars. Fig. S9c shows the failure of one band model in describing our Hall data at 5 K. Such nonlinear effects in $R_{xy}$ could arise from the presence of multi carrier transport at the interface. In order to verify this, we have considered a minimal two
band model where $R_{xy}$ is given by

$$R_{xy} = -\frac{1}{e} \frac{\left( \frac{n_1 \mu_1^2}{1+\mu_1^2 B^2} + \frac{n_2 \mu_2^2}{1+\mu_2^2 B^2} \right) B}{\left( \frac{n_1 \mu_1}{1+\mu_1^2 B^2} + \frac{n_2 \mu_2}{1+\mu_2^2 B^2} \right)^2 + \left( \frac{n_1 \mu_1}{1+\mu_1^2 B^2} + \frac{n_2 \mu_2}{1+\mu_2^2 B^2} \right)^2 B^2},$$

with the constraint $(eR_S)^{-1} = n_1 \mu_1 + n_2 \mu_2$. Here, $n_1$, $n_2$ and $\mu_1$, $\mu_2$ are the sheet carrier densities and mobilities of the two types of electrons. As evident from the Fig. S9d, two band model provides an excellent fit to our Hall data in the whole range of $B$ strongly indicating the presence of two types of carriers in the system. Such a two band transport has not been demonstrated so far for KTO (111) based superconductors.
S10. Temperature dependent sheet carrier density ($n_S$), mobility ($\mu$) and evidence for carrier freezing effect

**Fig. S10.**

**a.** Temperature dependent $n_S$ (for Hall bar along [112] and [110]) obtained from fitting of anti-symmetrized $R_{xy}$. $n_1$ and $n_2$ are the density of electrons confined to the lower and upper band, respectively.

**b.** Temperature dependent mobility ($\mu$) for Hall bar along [112] and [110]. $\mu_1$ and $\mu_2$ are electron’s mobility confined to the lower and upper band, respectively.

**c.** The Arrhenius plot of $\ln(n_1)$ for the temperature range 100 K − 175 K for both the Hall bars.

Fig. S10a shows temperature dependent $n_1$ and $n_2$ obtained for $I$ along [112] and [110]. Surprisingly, $n_2$ is found out to be $\sim 10^9$/cm$^2$ which is 5 orders of magnitude lower than $n_1$. Fig. S10b shows the corresponding variation of mobility. The mobility of low density carriers ($\mu_2$) is found to be higher than that of high density carriers ($\mu_1$). Interestingly, a prominent carrier freezing effect [9] is observed below 175 K down to 100 K. This is evident from the Arrhenius plot of $\ln(n_1)$ vs. $1/T$ shown in the figure Fig. S10c. A linear fit results in a very shallow defect state, which would be just 3.6 meV below the conduction band.
S11. Temperature dependent $I$-$V$ characteristics and critical current ($I_C$) for Hall bar along [11\bar{2}]

FIG. S11. a. Temperature dependent full cycle $I$-$V$ curves measured in current bias mode for the Hall bar along [11\bar{2}] on 7 nm AlO$_x$/KTO (111) sample. For full cycle measurement, the current was swept from 0 $\mu$A$\rightarrow$200 $\mu$A$\rightarrow$200 $\mu$A$\rightarrow$0 $\mu$A. For the sake of clarity, 0 $\mu$A$\rightarrow$200 $\mu$A and 200 $\mu$A$\rightarrow$0 $\mu$A branches have not been shown in the plot. 200 $\mu$A$\rightarrow$200 $\mu$A branch is denoted as backward sweep and -200 $\mu$A$\rightarrow$200 $\mu$A branch is denoted as forward sweep. b. $dV/dI$ plot at 1.26 K for $I$ along [11\bar{2}]. Several spikes in the derivative above certain current correspond to several discrete jumps in the voltage drop. d. Temperature dependence of critical current ($I_C$).
S12. Temperature dependent $I$-$V$ characteristics and observation of clockwise hysteresis for Hall bar along [110]

FIG. S12. a. Temperature dependent full cycle $I$-$V$ curves measured in current bias mode for the Hall bar along [110] on 7 nm AlO$_x$/KTO (111) sample. For the sake of clarity, 0 $\mu$A→200 $\mu$A and 200 $\mu$A→0 $\mu$A branches have not been shown in the plot. Fig. b shows the same plot with all the curves (except at 1.26 K) shifted vertically for visual clarity. Similar to $I$ along [112], clockwise hysteresis appears above a certain temperature.
S13. $R_S$ vs. $T$ data of another sample with 14 nm AlO$_x$ thickness.

FIG. S13. Temperature dependent $R_S$ of another sample with 14 nm AlO$_x$ thickness. Similar to 7 nm AlO$_x$/KTO (111) sample, a little anisotropy is observed between Hall bars made along [11\bar{2}] and [1\bar{1}0]. $T_C$ is found to be 1.57 K and 1.51 K for current along [11\bar{2}] and [1\bar{1}0], respectively.
S14. Temperature dependent $I$-$V$ characteristics of another sample with 14 nm AlO$_x$ thickness for $I$ along [112]

FIG. S14. Temperature dependent full cycle $I$-$V$ curves measured in current bias mode ($I \parallel [11\bar{2}]$) on another sample with 14 nm AlO$_x$ thickness. For the sake of clarity, 0 $\mu$A}$→200 $\mu$A and 200 $\mu$A}$→0 $\mu$A branches has not been shown in the plot.
S15. Temperature dependent \( I-V \) characteristics and observation of clockwise hysteresis on another sample with 14 nm AlO\(_x\) thickness for \( I \) along [1\(\bar{1}0\)]

![Graph showing temperature dependent full cycle \( I-V \) curves measured in current bias mode for the Hall bar along [1\(\bar{1}0\)] on another sample with 14 nm AlO\(_x\) thickness. For the sake of clarity, 0 \( \mu \)A→200 \( \mu \)A and 200 \( \mu \)A→0 \( \mu \)A branches have not been shown in the plot. Fig. b shows the same plot with all the curves (except at 1.26 K) shifted vertically for visual clarity. Similar to \( I \) along [11\(\bar{2}\)], clockwise hysteresis appears above certain temperature.]

[1] Ichimiya, A., Cohen, P. I. & Cohen, P. I. *Reflection high-energy electron diffraction* (Cambridge University Press, 2004).

[2] Middey, S. *et al.* Epitaxial growth of (111)-oriented laalo3/lanio3 ultra-thin superlattices. *Applied Physics Letters* **101**, 261602 (2012). [https://doi.org/10.1063/1.4773375](https://doi.org/10.1063/1.4773375).

[3] Björck, M. & Andersson, G. Genx: an extensible x-ray reflectivity refinement program utilizing differential evolution. *Journal of Applied Crystallography* **40**, 1174–1178 (2007).

[4] Zhang, G. *et al.* Spontaneous rotational symmetry breaking in ktao \( _3 \) interface superconductor. *arXiv*
preprint arXiv:2111.05650 (2021).

[5] Nakamura, H. et al. Robust weak antilocalization due to spin-orbital entanglement in dirac material sr3sno. Nature Communications 11, 1161 (2020). https://doi.org/10.1038/s41467-020-14900-1.

[6] Bareille, C. et al. Two-dimensional electron gas with six-fold symmetry at the (111) surface of ktao3. Scientific Reports 4, 3586 (2014). https://doi.org/10.1038/srep03586.

[7] Bergmann, G. Weak localization in thin films: a time-of-flight experiment with conduction electrons. Physics Reports 107, 1–58 (1984). https://www.sciencedirect.com/science/article/pii/0370157384901030.

[8] Caviglia, A. D. et al. Tunable rashba spin-orbit interaction at oxide interfaces. Phys. Rev. Lett. 104, 126803 (2010). https://link.aps.org/doi/10.1103/PhysRevLett.104.126803.

[9] Liu, Z. Q. et al. Metal-insulator transition in srtio3−x thin films induced by frozen-out carriers. Phys. Rev. Lett. 107, 146802 (2011). https://link.aps.org/doi/10.1103/PhysRevLett.107.146802.