Tunable two-dimensional superconductivity and spin-orbit coupling at the EuO/KTaO$_3$(110) interface

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Unconventional quantum states, most notably the two-dimensional (2D) superconductivity, have been realized at the interfaces of oxide heterostructures where the value of the zero-voltage superconducting critical temperature ($T_c(0)$) can be effectively controlled by the gate voltage ($V_G$). Here we report that the interface between high-quality EuO (111) thin film and KTaO$_3$ (KTO) (110) substrate shows superconductivity with onset transition temperature $T_{c\text{onset}} = 1.35$ K. The 2D nature of superconductivity is verified by the large anisotropy of the upper critical field and the characteristics of a Berezinskii–Kosterlitz-Thouless transition. By applying $V_G$, $T_{c\text{onset}}$ can be tuned from $~1$ to $1.7$ K; such an enhancement can be possibly associated with an increased spin-orbit energy $E_{so} = h/\tau_{so}$, where $\tau_{so}$ is the spin-orbit relaxation time. Further analysis of $\tau_{so}$ based on the upper critical field ($H_{c2}$) and magnetococonductance reveals complex nature of spin-orbit coupling (SOC) at the EuO/KTO(111) interface with different mechanisms dominating the influence of SOC effects on the superconductivity and the magnetotransport in the normal state. Our results demonstrate that the SOC should be considered an important factor in determining the 2D superconductivity at oxide interfaces.

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INTRODUCTION

Oxide heterojunctions are ideal platforms for exploring a remarkable variety of emergent phenomena. In particular, the superconducting electron gases residing at the interface between two insulators have attracted considerable attention. Previous studies have revealed that the conductive interfaces in the SrTiO$_3$ (STO)-based heterojunctions exhibit a surprisingly enriched cascade of unusual properties including the coexistence of superconductivity and ferromagnetism, and anomalous Hall effect. The more recently discovered KTaO$_3$ (KTO)-based heterojunctions also host two-dimensional (2D) superconductivity and anomalous Hall effect. Most interestingly, application of electric fields can effectively modulate the strength of spin-orbit coupling (SOC), carrier density and the disorder level, consequently it can control the $T_c$ and even lead to a superconducting-to-insulator quantum phase transition. Despite that KTO and STO are isostructural compounds with similar band structures, the two systems are distinct from each other in many aspects. The conductive electrons in STO and KTO are contributed by the Ti 3d and Ta 5d bands, respectively, thus the KTO-based superconducting interface (SI) should have a stronger SOC. Furthermore, whilst superconductivity has been realized at the (001)-, (110)- and (111)-oriented STO-based interfaces with comparable $T_c$, the KTO (001)-based interface is non-superconducting, whereas the KTO (110) and KTO (111)-based interfaces show superconductivity with $T_c$ around 1 and 2 K, respectively.

Several recent experimental observations, e.g., peculiar stripe phase in the normal state (although needs further confirmation) and unusual doping dependence of the upper critical field ($H_{c2}$), imply possible unconventional superconductivity at the KTO-based interface. Further evidence for the novelty of the superconductivity can stem from its responses to the external electric fields. It has been argued that the back gate voltage applied to the LaAlO$_3$/KTO(111) (LAO/KTO) interface predominantly controls the effective disorder (and consequently the electron scattering rate) rather than the carrier density. At the EuO/KTO(111) interface, both the $T_c$ and $H_{c2}$ are reported to be sensitive to the carrier density in the gating process. Under certain circumstances, the SOC effect can play an essential role in determining the physics in oxide heterostructures (most notably at LAO/STO interface close to the Lifshitz point), due to the inversion symmetry breaking at the interface. For these interfaces, the behaviors of both the normal and the superconducting states are to be understood only with the SOC taken into account. For instance, the magnetotransport properties of the normal state usually reflect the influence of SOC in terms of the weak localization or weak antilocalization effects, whereas the unusually high $H_{c2}$ and potential unconventional pairing in the superconducting state can be triggered by the complex contributions of SOC. Moreover, it has been shown that the SOC at the STO-based SIs can be effectively manipulated by the application of electric fields, leading to intricate evolution of physical properties as revealed experimentally. In this sense, it is important to explore the role of SOC at the KTO-based SIs and its influence on 2D superconductivity.

This work reports the growth of high-quality EuO (111) thin films on KTO (110) substrates. The interface between them is proved to host 2D superconductivity. Most intriguingly, we find a large tunability of $T_c$ and SOC at the EuO/KTO(110) interface by applying an electric field across KTO substrates. Based on these observations, we propose that in addition to carrier density and effective disorder, the SOC strength has a significant impact on $T_c$. This may be linked to the unconventional nature of the superconductivity at the KTO-based interface.
RESULTS AND DISCUSSION

Characterization of the EuO/KTO(110) heterostructures

High-quality EuO (111) thin films were grown on (110)-oriented KTO substrates using a molecular beam epitaxy (MBE) system (see Methods for details). Bulk EuO crystallizes in a cubic structure with lattice constant $a = 5.145$ Å. Stoichiometric EuO is an insulator with a band-gap of 1.12 eV at room temperature. Fig. 1a shows a schematic illustration for our EuO/KTO(110) heterostructure. To confirm the quality of films, we performed the scanning transmission electron microscopy (STEM) measurements. Figure 1b shows a cross-section with KTO [001] orientation in the plane (another direction along KTO [110] is shown in Supplementary Fig. 1a). Due to a certain lattice mismatch (∼5%) between EuO (111) and KTO (110) surfaces, the epitaxial EuO at the interface is distorted within a thickness of approximately 2 atomic layers (red square in Supplementary Fig. 2); single crystallinity is recovered beyond this region. Atomic-scale energy-dispersive x-ray spectroscopy (EDS) shows a relatively clear interface in which the diffusion of Eu exists in the superficial layer of KTO (the white dotted region in Supplementary Fig. 2). Electron energy loss spectroscopy (EELS) peaks of Eu also suggest that the Eu doping in KTO persists up to approximately 3 atomic layers crossing the interface (Supplementary Fig. 3). EDXRF pattern confirms that our samples have good single crystallinity (Fig. 1c). A fit using the angle of the Laue oscillation peaks yields the film thickness of about 7 nm (Supplementary Fig. 1b). The films also exhibit good surface flatness with a root-mean-square roughness around 0.343 nm (Supplementary Fig. 4).

The transport properties were measured using the Van der Pauw method (inset of Fig. 1d). The samples are metallic in the whole temperature ($T$) range as shown in Fig. 1d, indicating the formation of electron gases at the interfaces. Both samples undergo a superconducting transition at low temperatures. For sample #1, $T_{c}^{\text{onset}}$ is 1.35 K, and the zero resistance is observed at $T_{c}^{\text{zero}} = 1.06$ K (Fig. 1e). The magnetic-field ($H$)-dependent Hall resistance $R_{H}$ measured at $T = 2$ K confirms that the charge carriers are electron-type for both samples (inset of Fig. 1e). In Fig. 1f we plot the 2D Hall carrier density $n_s$ and the Hall mobility $\mu$ (extracted from the Hall and sheet resistance data) versus temperature. For sample #1 (2), $n_s$ is 8.6 (9.0) × 10^{13} cm^{-2} and $\mu$ is 86 (128) cm^{2} V^{-1} s^{-1} at 2 K. Compared to LAO/KTO(110) interface, both $n_s$ and $T_c$ in our samples are higher, consistent with the results for the (111)-oriented devices. During the growth process, Eu atoms have a strong capability to uptake oxygen from the surface layer of the KTO; this effect may cause the higher $n_s$ and consequently the enhanced $T_c$ in the EuO/KTO heterostructures.

2D superconductivity

We measured the $T$-dependent 2D sheet resistance $R_{\text{sheet}}$, under magnetic fields applied perpendicular and parallel to the interface to investigate the nature of this interfacial superconductivity. As shown in Fig. 2a and b, the superconductivity is remarkably suppressed by a magnetic field of ∼0.4 T and ∼6 T applied perpendicular and parallel to the interface, respectively. Such strong anisotropy indicates the 2D nature of superconductivity. To further verify this, we fit our data to the Ginzburg-Landau theory for a 2D superconductor:

$$
\mu H_{c2}(T) = \left[ \Phi_0 / 2n^2 \xi_{GL}(0) \right] \left[ 1 - (T/T_c) \right],
$$

$$
\mu H_{c2}(ab)(T) = \left[ \Phi_0 \sqrt{1/L_2} / 2n^2 \xi_{GL}(0) \right] \left[ 1 - (T/T_c) \right]^{1/2},
$$

where $\xi_{GL}$ is the Ginzburg–Landau coherence length, $\Phi_0$ is the flux quantum, and $d_{sc}$ is the superconducting layer thickness. The $T/T_c$
dependence of upper critical fields for H//ab (μBH//ab) and H//c (μBH//c) (Fig. 2c) are determined from the Rsheet-T curves shown in Fig. 2a, b, respectively. The fits to Eq. 1 yield the zero temperature limit values μBH//c(0) = 0.45 T and μBH//ab(0) = 6.65 T, corresponding to an anisotropic ratio of ~15; meanwhile, the fits also give χGL(0) = 27.03 nm and dnc = 6.35 nm. A similar analysis for sample #2 was shown in Supplementary Fig. 5. Since the growth conditions of #1 and #2 are different, μBH//c and dnc of these two samples also differ slightly. Nonetheless, dnc is smaller than χGL in both samples, confirming the 2D nature of the superconductivity in the EuO/KTO(110) interface. Besides, dnc is much larger than the diffusion depth (~0.5 nm) of Eu atoms (Supplementary Fig. 3). The mean free path of the conducting electrons can be estimated as lmpf = (h/e2)(1/kRsheet) in a single-band model (k = √2mni is the Fermi wave number, h is the Planck constant, e is the elementary charge)32. Using the measured Rsheet(2 K) and n(2 K), we estimated the lmpf of sample #1 to be 59.3 nm, which is larger than the χGL. We note that though our EuO/KTO(110) interfaces are much cleaner compared to the LAO/KTO(110) and EuO/KTO(111) interfaces wherein lmpf < χGL,8,9 these SIs are still in the dirty limit (Methods).

With solid evidence for 2D superconductivity, we further examine the expected behaviors of the Berezinskii-Kosterlitz-Thouless (BKT) transition in our devices.13 The BKT transition, a transition from unpaired vortex and antivortex pairs, can result in a VoS power-law dependence and can be characterized by a transition temperature T_{BKT} extracted from the 50% normal-state resistance out-of-plane and in-plane. The estimated Pauli paramagnetic limit (μ0H\text{P}) is marked with a blue dashed line in Fig. 2b. A linear extrapolation from the high-T linear section (red dashed line) crosses the T-axis at T_{BKT} = 1.17 K.

By fitting the I-V curve in the nonlinear range (Fig. 3b and c), we attain an exponent α approaching 3 at T_{BKT} = 1.01 K. Apart from the I-V method, the T_{BKT} can also be estimated from the formula Rsheet(T) = R0exp(-b(T/T_{BKT})^{-1/2}), where R0 and b are material parameters. Application of such fit to the measured Rsheet(T) yields T_{BKT} = 1.17 K (inset of Fig. 3c). T_{BKT} obtained from these two approaches appears to be close to T_{BKT} again pointing towards the 2D nature of the superconductivity.

For a 2D weak coupling BCS superconductor, the parallel critical field can be determined by the Chandrasekhar-Clogston limit (Pauli paramagnetic limit):35,36 $\mu_0H_B = 1.76k_BT_C/\sqrt{2}\mu_B$, where $k_B$ and $\mu_B$ are the Boltzmann's constant and Bohr magneton, respectively. Taking $T_C = T_{BKT} = 1.01 K$, we have $\mu_0H_B = 1.874 T$, which reaches only 28% of $\mu_0H_{ab}(0)$ (blue dashed line in Fig. 2c). Several factors can enhance the Pauli limit appreciably, such as strong-coupling superconductivity and many-body effects.37,38 In our samples, the most likely reason for the large $\mu_0H_c(0)$ could be the strong SOC originating from the inversion symmetry breaking at the interface and the relatively heavy tantalum ions.29,39 which can be verified by the electric-field manipulation that we will discuss in the following section.

Electric-field control of superconductivity

To explore the effect of electric fields, our samples were made into 20 × 100 μm² Hall bar devices (inset of Fig. 4a). A schematic diagram of the device (Supplementary Fig. 7) and the manufacturing process are presented in Methods. The superconductivity can be successfully tuned by applying a gate voltage (Vg) across KTO.
voltages can be estimated using the 3.8 K data of higher origin for the continuous increase of density and disorder suggests that there should be an alternative where \( n \) tuning effect of electric fields highly depends on the mobility \( \mu \) and Hall mobility \( \mu_H \), which directly affects spin-orbit coupling, whose strength directly affects the superconducting layer thickness \( d_{sc} \) in an effective model for 2D superconductor with strong SOC, we have:

\[
\mu_H^{\text{ab}}(T = 0) = -\frac{1.76h\kappa_c}{3\mu^2 r_{so} + D(d_{so}e)^2/3}
\]

where \( r_{so} \) is the spin-orbit relaxation time (\( \epsilon_{so} = h/r_{so} \)), \( D \) is the diffusion constant obtained from the slope of the out-of-plane upper critical field: \( \Delta(T) = h/(\mu^2 r_{so} + D(d_{so}e)^2/3) \) (we use the data in Supplementary Fig. 5c to fit \( D \) because sample #2 has similar \( \mu_H^{\text{ab}} \) with the gating sample). The fits of \( \mu_H^{\text{ab}} \) using Eq. 1 allow us to determine the evolution of \( \epsilon_{so} \) and \( d_{so} \) upon the continuous changing of \( V_G \) from 150 to \( -80 \) V (Fig. 4e). As \( V_G \) varies from 150 to \( -80 \) V, \( \epsilon_{so} \) decreases from 32 (14) to 22 (2.7) nm (an offset decrease of 12 nm) and \( d_{so} \) is shown in Supplementary Fig. 5d, \( d_{so} \) is much larger than \( d_{sc} \) at all \( V_G \), especially for \( V_G < 0 \), confirming the 2D nature of the superconductivity at EuO/KTO (110) interface in the gating process. Taking \( T = T_c^{\text{mid}} \), we also obtain the \( V_G \)-dependent \( \epsilon_{so} \) as plotted in Fig. 4d. With \( V_G \) ramping from 150 to \( -80 \) V, \( \epsilon_{so} \) increases from 1.2 to 21.1 meV with a large ratio of \( \Delta T \), revealing a strong tunability of the SOC at the EuO/KTO (110) interface. The plot of \( T_c^{\text{mid}} \) versus \( \epsilon_{so} \) (Fig. 4f) indicates that \( T_c^{\text{mid}} \) is predominantly controlled by different factors in two ranges of \( V_G \) separated by \( V_G = -80 \) V where \( T_c^{\text{mid}} \) exhibits a clear kink. From \( V_G = 150 \) to \( -80 \) V, \( T_c^{\text{mid}} \) rises rapidly with decreasing \( V_G \). Considering the increasing \( n_s \) with decreasing \( V_G \) in this range, the increase of \( T_c^{\text{mid}} \) is predominantly driven by the variation of carrier density. By contrast, as \( V_G \) is swept from \( -80 \) towards \( -180 \) V, \( T_c^{\text{mid}} \) increases linearly with \( \epsilon_{so} \) (Fig. 4f), whereas \( n_s \) gradually decreases. Therefore, we conclude that the increase of \( T_c^{\text{mid}} \) is directly related to the enhancement of spin-orbit scattering in the range of \( V_G \) from \( -80 \) to \( -180 \) V (Fig. 4b).

The present work is the first report on the electric-field-controlled SOC at the KTO-based SI. Here we briefly compare it with that in the STO-based SI. Distinct from the barely tunable SOC at the LAO/STO(110) interface, the tunability of SOC in our samples is considerably large. Nonetheless, a relationship between
Fig. 5  Spin-orbit scattering effect in magnetotransport. a The normalized transverse magnetoconductance \( \Delta \sigma(H) = 1/R_{\text{shee}}(H)-1/R_{\text{shee}}(0) \) measured at \( T = 3.8 \) K under different \( V_G \). \( H \) is applied perpendicular to interface. We ignore the Hall term due to its small amplitude (Supplementary Fig. 8). The curves are shifted vertically for clarity. The black solid lines are fits to the Maekawa-Fukuyama model (see text). b The \( V_G \)-dependent effective fields \( H_t \) and \( H_{so} \) (see text) extracted from the fitting in (a). c The evolution of the relaxation times for inelastic scattering (\( \tau_i \)), spin-orbit scattering (\( \tau_{so} \)), and elastic scattering (\( \tau \)) upon varying \( V_G \). d \( \tau \)-dependent \( 1/\tau_{so} \) determined from the magnetoconductance (MC) and \( \tau_{so} \) determined from the upper critical field. The dashed lines are linear fits to guide the eyes.

\[ \frac{\Delta \sigma(H)}{\sigma_0} = \Psi \left( \frac{H}{R_{\text{shee}}} \right) + \frac{1}{2\sqrt{1-x^2}} \Psi \left( \frac{H}{\hbar c + H_{so} (1 - \sqrt{1-x^2})} \right) \]

The SOC relaxation time in magnetotransport

The strength of SOC can also be evaluated from the normal-state perpendicular magnetoresistance. Here, we measured the magnetoresistance at \( T = 3.8 \) K under different \( V_G \) (Supplementary Fig. 14). In the diffusive regime, the field-dependent quantum correction to conductivity \( \Delta \sigma(H) \) can be described by the Maekawa-Fukuyama (MF) model:\(^{17,27}\)

where \( \sigma_0 = 2e^2/h \) is the quantum conductance, \( \Psi(x) = \ln(x) + \Psi[1/2 + (1/x)] \) [where \( \Psi(x) \) is a digamma function and \( \gamma = g_\text{\textsc{e}} H/4eD_n H_{so} \)], \( H_t \) and \( H_{so} \) are the inelastic and spin-orbit effective fields, respectively. The last term including parameters \( A \) and \( C \) is a Kohler term that originated from the classical orbital magnetoresistance. Combining the 2D nature of the superconductivity in the gating process, the diffusion coefficient \( D_n \) can be expressed as: \( D_n = v_F^2/\tau \) (\( v_F = \sqrt{2m^*}/m^* \) is the Fermi velocity, where \( m^* \) is the effective electron mass). The relaxation time \( \tau \) for elastic scattering can be extracted from \( R_{\text{shee}} \) based on the Drude model: \( \tau = m^*/e^2R_{\text{shee}} \). By applying the fits to the MF model (Eq. 3) to the magnetoconductance (Fig. 5a), we obtained the parameters \( H_{so} \) (Fig. 5b) and \( A/C \) (Supplementary Fig. 15) at different voltages by assuming \( g = 2 \) and \( m^* = m_e \). (the variation of \( m^* \) within the reasonable range (\(-0.5 \sim 1.0 m_e\)) does not change the qualitative conclusions, see Methods). \( H_{so} \) increases with \( V_G \) decreasing, in agreement with the \( V_G \) dependence of \( \epsilon_{so} \) shown in Fig. 4d and verifies the enhancement of SOC at large negative \( V_G \).

The evolution of spin-orbit relaxation time \( \tau_{so} \) and the inelastic relaxation time \( \tau_i \) can be further derived from the effective fields: \( H_{so} = gH_{so} \). In Fig. 5c we plot all three relaxation times \( \tau_i \), \( \tau_{so} \) and \( \tau \) against \( V_G \). \( \tau_{so} \) is the smallest among them, which means that the spin-orbit scattering in the KTO-based SI is strong and dominates the decoherence process. More intriguingly, as shown in Fig. 5d, we have \( \tau_{so} \propto 1/\tau \); this is consistent with the expectation for the \'D'yakonov-Perel' (DP) mechanism of spin relaxation.\(^{46}\) The DP scenario describes the spin precession around the spin-orbit field between scatterings that leads to the spin dephasing: such mechanism is consistent with Rashba-type SOC at the interface.\(^{46}\) However, we mention that whether we plot the \( \tau_{so} \) extracted from \( \epsilon_{so} \) (Fig. 4d) determined from \( H_{so} \) against \( \tau \) (Fig. 5d), it shows \( \tau_{so} \propto 1/\tau \), i.e., \( \tau_{so} \) obtained from \( H_{so} \) and the magnetoconductance exhibit distinct behaviors. The relationship of \( \tau_{so} \propto 1/\tau \) corresponds to the Elliott-Yafet (EY) mechanism\(^{47,48}\) describing spin-flip scatterings. Hence, the spin-orbit scattering that affects the pair-breaking effect of the Zeeman field and that contributes to the quantum correction of charge transport in the normal state are assigned to the EY and DP mechanisms, respectively. A possible explanation for this discrepancy is that Cooper pair formation and the normal-state electrical transport are dominated by electrons occupying different conduction channels or subbands at the interface. Similar behavior has also been observed for the LAO-STO system.\(^{41}\) More exotic probabilities, such as SOC-enhanced spin susceptibility in the superconducting state (which naturally enhanced the Pauli
limit critical field) or unconventional superconducting pairings\(^{49-51}\), are to be verified by future investigations.

To conclude, high-quality single-crystalline EuO (111) thin films have been grown on KTO (110) substrates. The large anisotropy of \(H_{c2}\) and the characteristics of a BKT transition show that the interface between them is a 2D superconductor. The remarkable response of \(T_c\) to the applied \(V_{AC}\) is proved to be predominantly linked to the high tunability of SOC strength under external electric fields. \(\tau_0\) obtained from \(H_{c2}\) and the magnetocconductance manifests the typical behaviors expected for the EY and DP spin-relaxation mechanisms, respectively, implying the complexity of the SOC effects at the EuO-KTO SIs. Our results demonstrate that the SOC should be considered as an important factor controlling the 2D superconductivity and might lead to unconventional superconductivity at the KTO-based interface. Further theoretical investigations are needed to elucidate such unusual interplay between the electric-field-control SOC and superconductivity.

**METHODS**

**Growth of EuO/KTO(110) heterostructures and device fabrication**

EuO (111) thin films were grown on (110)-orientated KTO single crystal using a molecular beam epitaxy system with a base pressure of \(4 \times 10^{-10} \) mbar. The samples size are 5 × 5 mm\(^2\). Before growth, the KTO substrates were pre-annealed at 600 °C for 1 h and then cooled down to growth temperature. The deposition rate of Eu was 0.2 Å/s, calibrated by a quartz-crystal monitor. The depositions were performed at 400 °C. The oxygen pressures during the growth of EuO films was \(\text{O}_2\) with no oxygen supply. A 3-nm-thick germanium was prepared on the KTO substrate to protect the sample from further oxidation when exposed to air.

**Scanning transmission electron microscopy (STEM) and transport measurements**

The slices for STEM were prepared from selected areas using Carl Zeiss Crossbeam 550 L and the high angle annular dark field (HADDF STEM) was obtained with no oxygen supply. A 3-nm-thick germanium was prepared to the applied \(V_{AC}\) field-control SOC and superconductivity.

**Verification of the dirty-limit scenario**

For a weak coupling BCS superconductor, the BCS coherence length \(\xi_{BCS} = (\hbar V_c)/(\pi n_{c} k_B T_c)\). In the negative \(V_c\) regime for our sample, \(I_{np} / \xi_{BCS} = (\pi n_{c} k_B T_c)/\hbar\) ranges from 0.05 to 0.07. Thereby, the condition \(I_{np} < \xi_{BCS}\) for the dirty-limit superconductors is still valid at our SIs. This result validates the application of Eq. 2 in the main text which describes the upper critical field of a 2D superconductor in the dirty limit.

**Effective mass of electrons**

Due to the relatively low mobility of our samples, our available experimental probes fail to resolve quantum oscillations in magnetoresistance down to 0.1 K (Supplementary Fig. 16). In ref. 45, the effective mass of electrons \(m^* = 0.62 m_e\) under high magnetic fields. To verify the influence of the effective mass of electrons on our data, as shown in Supplementary Fig. 17. All parameters \((H, H_{soc}, A, C)\) show the same magnitude and trend as the results obtained by assuming \(m^* = m_e\); the consistency is particularly good for \(V_{AC} < 0\).

Therefore, we propose that our fits do not strongly depend on the value of \(m^*\), and the variation of \(m^*\) within the reasonable range (−0.5–1.0 \(m_e\)) does not change the qualitative conclusions.

**DATA AVAILABILITY**

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

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**AUTHOR CONTRIBUTIONS**

X. H. and X. C. conceived the experiments; X. H., F. M., Z. L. and Z. H. prepared the interface samples and fabricated the devices; X. H. and Z. H. performed XRD and AFM measurements; X. H. performed the electrical transport measurements; S. W. and B. G. performed the STEM experiments; X. H., F. M., Z. X. and X. C. analyzed the data; X. H., Z. X. and X. C. prepared the manuscript. All authors contribute to editing the manuscript.

**COMPETING INTERESTS**

The authors declare no competing interests.

**ADDITIONAL INFORMATION**

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