Mott gap engineering in $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ superlattices

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In recent years, iridium oxides have attracted intensive research interests both in experiments and theories due to their comparable energy scales of the Coulomb repulsion and strong spin-orbit coupling (SOC) [1,2], where a plenty of novel quantum states such as Weyl semimetal, topological insulator and quantum spin liquid have been studied [3–7]. Among the iridates, the layered-perovskite Sr_2IrO_4 (SIO) is a $J_{\text{eff}} = 1/2$ Mott insulating antiferromagnet caused by the interplay of the SOC and electronic correlations [8,9]. The crystal and electronic structures of SIO are similar to the high-temperature superconductor La_2CuO_4 , which gives a prospect of a new possible high-temperature superconductor [6,10]. In order to control its band structure, many efforts have been made to explore and engineer the electronic structures of SIO. Elemental substitution or chemical doping is always the popular way to tune the electronic structure of materials [11], whereas it is still difficult to reach the critical value of doping level in SIO without breaking its intrinsic phases [12–15]. Mechanical strain seems to be able to control the band structure of complex oxide, but it is also challenging to achieve the desired electronic structure in that those ceramic oxides cannot endure a super high stress [16–18]. Therefore, in order to manipulate the electronic structure of SIO-based materials effectively, it is highly desirable to find an alternative pathway to engineer the Mott gap in oxides.

Superlattice is a periodic building block of a few unit cells of two (or more) materials [19]. In artificially designed superlattices, the interface with broken symmetries couples the spin, lattice, orbit and charge degree of freedoms and plays a vital role in the emergent phenomena and functionalities by mismatch strain, charge transfer, proximity effect, etc. [20–22], which may be absent in their bulk crystals [23,24]. In this letter, we investigated

the electronic structures of SIO thin films and $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ (SIO/STO) superlattices. All the thin films have the same thickness of ~ 12 nm. The conduction mechanism of Mott variable range hopping (Mott-VRH) model was used to fit the temperature dependence of the resistivity of the SIO/SIO superlattices, which is different from the thermal activation model for the SIO thin films. Moreover, the band gap and the resistance of those superlattices are much lower than those of SIO bulks and thin films. In addition, with an increasing period, the band gap of the superlattices is further reduced mainly due to the contribution of the Ir–O–Ti interfaces.

$[(\text{SIO})_a/(\text{STO})_b]_c$ (I_a/T_b)_c superlattices and SIO thin films with the same thickness of ~ 12 nm were grown on the STO (001) substrates by laser molecular beam epitaxy (L-MBE) assisted by reflection high-energy electron diffraction (RHEED). For the subscript of the superlattices, *a* and *b* denote the stacking sequence of SIO and STO layers, respectively, and *c* represents the total amount of periods. Superlattices and thin films were deposited on the STO (001) substrates with an atomic smooth TiO_2 -terminated surface, which was obtained by thermal annealing after etching the commercial STO substrates with NH_4F -HF (buffered HF, BHF) at room temperature. The substrates were then heated to 800°C under a 0.02 mbar oxygen pressure. For all the samples' growth, a KrF excimer laser with a wavelength of 248 nm and energy density of $\sim 1 \text{ J cm}^{-2}$ was used, and the frequency was 2 Hz. Then the films were slowly cooled (5°C min^{-1}) to room temperature under an oxygen pressure of 100 mbar. The layer-by-layer growth was controlled by the *in-situ* monitoring of RHEED, and a typical oscillation of $(I_3/T_6)_2$ is shown in Fig. 1a. During the deposition, the RHEED pattern maintains a strip-like feature after the growth of SIO and STO layers (see Fig. 1b), indicating high-quality

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Figure 1 Epitaxial growth of the SIO/STO superlattices. (a) *In-situ* monitoring of RHEED oscillation, indicating the layer-by-layer growth of $(\text{I}_3/\text{T}_6)_2$ superlattice. (b) Stripe-like RHEED patterns of $(\text{I}_3/\text{T}_6)_2$ superlattice during the growth process, demonstrating the flat two-dimension interface and surface. (c) Topography of $(\text{I}_3/\text{T}_6)_2$ superlattice by AFM.

interfaces and surfaces. Moreover, based on the RHEED patterns, there is no strain relaxation during the growth. The topography with a clear step terrace was characterized by atomic force microscopy (AFM) as shown in Fig. 1c.

Synchrotron X-ray diffraction (XRD) measurements were carried out at room temperature at beamline 1W1A of Beijing Synchrotron Radiation Facility. The $\theta/2\theta$ X-ray diffractogram confirms the periodicity and high-quality epitaxy as shown in Fig. 2a. To further examine the interfaces' quality, high-resolution scanning transmission electron microscopy (STEM) measurements were performed by JEOL 2100F (JEOL, Tokyo, Japan) transmission electron microscope, which was operated at 200 keV and equipped with CEOS (CEOS, Heidelberg, Germany) probe aberration corrector, double spherical aberration (Cs) correctors. As schematically shown in Fig. 2b, the alternative SIO and STO layers with clear interfaces were obtained with artificially designed Ir–O–Ti bonds in $(\text{I}_3/\text{T}_6)_2$ superlattices. There is a tensile strain of $\sim 0.4\%$ in the SIO layers but a strain-free nature of the STO layers (Fig. 2a). Besides, no strain relaxation is observed for all samples on STO (001) substrates.

Fig. 3a shows electrical transport measurements for the superlattices and the SIO thin film by traditional four-point measurements using a Quantum Design Physical

Properties Measurement System (PPMS). A relatively small resistivity was observed in SIO/STO superlattices compared with that of the SIO thin film, especially below 200 K. In order to further study the electronic structures, the thermal activation model was used to fit the temperature-dependent resistivity of the SIO thin films [12,16]

$$\rho(T) = \rho_0 \exp\left(\frac{\Delta}{2k_B T}\right), \quad (1)$$

where ρ , ρ_0 , Δ , and k_B are the resistivity, resistivity coefficient, energy band gap, and Boltzmann constant, respectively. Fig. 3b depicts the fitting curves, and then the band gap is estimated to be 270.7 meV, comparable to the value reported elsewhere [16,18]. As for the SIO thin film, the fitting of thermal activation model indicates that the electrical transport properties could be described by a single band gap [25]. However, for the SIO/STO superlattices, the Mott-VRH model fits well to the measured resistivity as a function of temperature as seen in Fig. 3c, but not the thermal activation model (inset of Fig. 3b). Here, the Mott-VRH mode is expressed as the following equation [26,27]:

$$\rho(T) = \rho_0 \exp(T_M / T)^{1/4}, \quad (2)$$

Figure 2 (a) Synchrotron XRD of the SIO thin film and series of SIO/STO superlattices on the STO substrate, indicating the high quality and periodicity of our samples. (b) TEM cross-section image of the $(I_3/T_6)_2$ superlattice. The schematic shows the detail structure of the interface.

where T_M is the characteristic temperature and it has a relation with the Mott hopping energy (E_M) as [26,27]

$$E_M = \frac{1}{4} k_B T (T_M / T)^{1/4}. \quad (3)$$

According to Fig. 3c, the change of conduction mechanism suggests that the intrinsic band structure has been modified. Furthermore, it is also found that when SIO and STO layers in the superlattices get thinner, the fitting slope is smaller, which implies a smaller band gap. The fitting parameters (E_M , meV) for $(I_6/T_{12})_1$, $(I_3/T_6)_2$, $(I_2/T_4)_3$, and $(I_1/T_2)_6$ superlattices are $1.77T^{3/4}$, $1.23T^{3/4}$, $1.19T^{3/4}$, and $1.13T^{3/4}$, respectively. Then, the band gaps of the superlattices at 300 K are calculated to be 127.6, 88.7, 85.8 and 81.4 meV for $(I_6/T_{12})_1$, $(I_3/T_6)_2$, $(I_2/T_4)_3$ and $(I_1/T_2)_6$, respectively.

Fig. 3d gives a summary of the band gaps of the SIO/STO superlattices and the SIO thin film where the abscissa axis is defined by the number of the SIO layers in the superlattices (i.e., the number a in $(I_a/T_b)_c$, $a = \infty$ stands for the SIO thin film). It is noteworthy that the band gap of the SIO/STO superlattices is much smaller than that of the SIO thin film. The more the interfaces, the smaller the band gap. These observations reveal that the number of the interfaces could play a vital role in the tuning of the band structure; note that the macroscopic strain may not be the main mechanism in reducing the band gap since the superlattices almost possess the same strain. A possible origin is the reconstruction of the charge, spin and orbit at atomic scale across the interfaces [28–32]. Based on a comparison of the band gap of the I_a/T_b

superlattices with that of the interfacial STO (Fig. S1), the SIO near the interface may dominate the observed transport properties. The conduction mechanism of Mott-VRH model is usually utilized in doped SIO [33], indicating a possible charge transfer at the interface. In SIO/STO superlattices, the Ir–O–Ti bonds may result in a reconstruction of charge and orbit. Fig. 4a shows the spatially resolved electron energy loss spectroscopy (EELS) of Ti $L_{2,3}$ edge, the relative intensity change of t_{2g} and e_g compared with the STO implies the existence of Ti^{3+} [34–37], indicating a possible charge transfer from SIO to STO layer near the interface, achieving hole doping near the interfacial SIO layer. In addition, the $J_{eff} = 1/2$ bandwidth (W) of the SIO can be easily changed by the neighboring, doping and bond length [38,39]. Considering the short Ti–O bond compared with Ir–O bond [40,41], the Ir 5d electrons will be hybridized with the O 2p and Ti 3d orbits and become more delocalized than the one in SIO thin films, evidenced by the existence of Ti^{3+} near the Ir–O–Ti interface. Therefore, the delocalization of the Ir 5d electrons will broaden the bandwidth near the interface [39]. As shown in the Fig. 4b, the band structure of the bulk SIO is mainly determined by the combined effect of SOC (λ) and electron correlation (U) [38]. Since the energy scale of $J_{eff} = 1/2$ bandwidth is smaller than U , this band will be separated into the upper and the lower Hubbard band. Because of the Ir–O–Ti bonds, the increase of W will reduce the energy gap between the upper Hubbard band (UHB) and the lower Hubbard band (LHB), thus leading to the decrease of

Figure 3 (a) Temperature-dependent resistivity for the SIO thin film and series of SIO/STO superlattices. Inset shows the schematic of the four-point transport measurement. (b) Plots of $\ln \rho$ vs. $1000/T$ for the SIO thin film and the SIO/STO superlattices (inset). The nonlinearity of the curves in the inset shows that the thermal activation model cannot well fit the resistivities of SIO/STO superlattices. (c) Plots of $\ln \rho$ vs. $1/T^{1/4}$ for the SIO/STO superlattices and the SIO thin film (inset). The nonlinearity of the curve in the inset demonstrates that the transport in the SIO thin film cannot be attributed to VRH. (d) Band gaps of the SIO thin film and the SIO/STO superlattices, where the abscissa axis is defined by the number of SIO layers in the superlattices (i.e., the number a in $(I_a/T_b)_c$). Note that $a = \infty$ stands for SIO thin film.

Figure 4 (a) Spatially resolved EELS of $Ti L_{2,3}$ edge near the interface in the SIO/STO superlattice and the STO substrate. The relative peak intensity t_{2g}/e_g increase near the interface implies the existence of Ti^{3+} , indicating the delocalization of d electrons in the Ir-O-Ti bond. (b) Schematic band diagram of the SIO thin film and Ir-O-Ti interface in the SIO/STO superlattices.

band gap in the superlattices. It should be pointed out that the mechanism mentioned above could be the reasonable one. Additionally, some other factors, such as subtle strain without relaxation, may also contribute to the band structure.

In conclusion, the band structure of SIO has been tailored *via* the interfacial engineering in the SIO/STO superlattices. The reduced band gap in these superlattices inspires us that the construction of oxide superlattices may be an effective way to dramatically tuning the elec-

tronic structure of SIO-based materials. Advanced superlattice structures (with non-equivalent or polar interfaces, etc.) could be designed at atomic scale to manipulate the band structure of a broad range of Mott insulators, so that emergent physical phenomena such as unconventional superconductivity or topological order states may be achieved.

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- Witzak-Krempa W, Chen G, Kim YB, *et al.* Correlated quantum phenomena in the strong spin-orbit regime. *Annu Rev Condens Matter Phys*, 2014, 5: 57–82
- Rau JG, Lee EKH, Kee HY. Spin-orbit physics giving rise to novel phases in correlated systems: Iridates and related materials. *Annu Rev Condens Matter Phys*, 2016, 7: 195–221
- Wan X, Turner AM, Vishwanath A, *et al.* Topological semimetal and Fermi-arc surface states in the electronic structure of pyrochlore iridates. *Phys Rev B*, 2011, 83: 205101
- Carter JM, Shankar VV, Zeb MA, *et al.* Semimetal and topological insulator in perovskite iridates. *Phys Rev B*, 2012, 85: 115105
- Katukuri VM, Yadav R, Hozoi L, *et al.* The vicinity of hyperhoneycomb β - Li_2IrO_3 to a three-dimensional Kitaev spin liquid state. *Sci Rep*, 2016, 6: 29585
- Wang F, Senthil T. Twisted Hubbard model for Sr_2IrO_4 : Magnetism and possible high temperature superconductivity. *Phys Rev Lett*, 2011, 106: 136402
- Hao L, Meyers D, Suwa H, *et al.* Giant magnetic response of a two-dimensional antiferromagnet. *Nat Phys*, 2018, 14: 806–810
- Kim BJ, Jin H, Moon SJ, *et al.* Novel $J_{\text{eff}}=1/2$ Mott state induced by relativistic spin-orbit coupling in Sr_2IrO_4 . *Phys Rev Lett*, 2008, 101: 076402
- Kim BJ, Ohsumi H, Komesu T, *et al.* Phase-sensitive observation of a spin-orbital Mott state in Sr_2IrO_4 . *Science*, 2009, 323: 1329–1332
- Meng ZY, Kim YB, Kee HY. Odd-parity triplet superconducting phase in multiorbital materials with a strong spin-orbit coupling: Application to doped Sr_2IrO_4 . *Phys Rev Lett*, 2014, 113: 177003
- Song C, Malik IA, Li M, *et al.* Hidden metal-insulator transition in manganites synthesized via a controllable oxidation. *Sci China Mater*, 2019, 62: 577–585
- Ge M, Qi TF, Korneta OB, *et al.* Lattice-driven magnetoresistivity and metal-insulator transition in single-layered iridates. *Phys Rev B*, 2011, 84: 100402
- Yan YJ, Ren MQ, Xu HC, *et al.* Electron-doped Sr_2IrO_4 : An analogue of hole-doped cuprate superconductors demonstrated by scanning tunneling microscopy. *Phys Rev X*, 2015, 5: 041018
- Korneta OB, Qi T, Chikara S, *et al.* Electron-doped $\text{Sr}_2\text{IrO}_{4-\delta}$ ($0 \leq \delta \leq 0.04$): Evolution of a disordered $J_{\text{eff}}=1/2$ Mott insulator into an exotic metallic state. *Phys Rev B*, 2010, 82: 115117
- Wen F, Liu X, Zhang Q, *et al.* Interface-engineered hole doping in $\text{Sr}_2\text{IrO}_4/\text{LaNiO}_3$ heterostructure. *New J Phys*, 2019, 21: 103009
- Rayan Serrao C, Liu J, Heron JT, *et al.* Epitaxy-distorted spin-orbit Mott insulator in Sr_2IrO_4 thin films. *Phys Rev B*, 2013, 87: 085121
- Wang J, Huang H, He W, *et al.* Nanoscale bandgap tuning across an inhomogeneous ferroelectric interface. *ACS Appl Mater Interfaces*, 2017, 9: 24704–24710
- Nichols J, Terzic J, Bittle EG, *et al.* Tuning electronic structure via epitaxial strain in Sr_2IrO_4 thin films. *Appl Phys Lett*, 2013, 102: 141908
- Esaki L, Tsu R. Superlattice and negative differential conductivity in semiconductors. *IBM J Res Dev*, 1970, 14: 61–65
- Ramesh R, Schlom DG. Creating emergent phenomena in oxide superlattices. *Nat Rev Mater*, 2019, 4: 257–268
- Tian Y, Wei L, Zhang Q, *et al.* Water printing of ferroelectric polarization. *Nat Commun*, 2018, 9: 3809
- Bhandari C, Satpathy S. Spin-orbital entangled two-dimensional electron gas at the $\text{LaAlO}_3/\text{Sr}_2\text{IrO}_4$ interface. *Phys Rev B*, 2018, 98: 041303
- Matsuno J, Ihara K, Yamamura S, *et al.* Engineering a spin-orbital magnetic insulator by tailoring superlattices. *Phys Rev Lett*, 2015, 114: 247209
- Dasa TR, Hao L, Yang J, *et al.* Strain effects on structural and magnetic properties of $\text{SrIrO}_3/\text{SrTiO}_3$ superlattice. *Mater Today Phys*, 2018, 4: 43–49
- Lu C, Quindeau A, Deniz H, *et al.* Crossover of conduction mechanism in Sr_2IrO_4 epitaxial thin films. *Appl Phys Lett*, 2014, 105: 082407
- Mott NF. Conduction in glasses containing transition metal ions. *J Non-Crystalline Solids*, 1968, 1: 1–17
- Rosenbaum R. Crossover from Mott to Efros-Shklovskii variable-range-hopping conductivity in In_xO_y films. *Phys Rev B*, 1991, 44: 3599–3603
- Hwang HY, Iwasa Y, Kawasaki M, *et al.* Emergent phenomena at oxide interfaces. *Nat Mater*, 2012, 11: 103–113
- Reyren N, Thiel S, Caviglia AD, *et al.* Superconducting interfaces between insulating oxides. *Science*, 2007, 317: 1196–1199
- Tsukazaki A, Ohtomo A, Kita T, *et al.* Quantum Hall effect in polar oxide heterostructures. *Science*, 2007, 315: 1388–1391
- Yamada H, Kawasaki M, Ogawa Y, *et al.* Perovskite oxide tricolor superlattices with artificially broken inversion symmetry by interface effects. *Appl Phys Lett*, 2002, 81: 4793–4795
- Kida N, Yamada H, Sato H, *et al.* Optical magnetoelectric effect of patterned oxide superlattices with ferromagnetic interfaces. *Phys Rev Lett*, 2007, 99: 197404
- Qi TF, Korneta OB, Li L, *et al.* Spin-orbit tuned metal-insulator transitions in single-crystal $\text{Sr}_2\text{Ir}_{1-x}\text{Rh}_x\text{O}_4$ ($0 \leq x \leq 1$). *Phys Rev B*, 2012, 86: 125105
- Lodahl P, Floris Van Driel A, Nikolaev IS, *et al.* Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals. *Nature*, 2004, 430: 654–657
- Garcia-Barriocanal J, Cezar JC, Bruno FY, *et al.* Spin and orbital Ti magnetism at $\text{LaMnO}_3/\text{SrTiO}_3$ interfaces. *Nat Commun*, 2010, 1: 82
- Lee JS, Xie YW, Sato HK, *et al.* Titanium d_{xy} ferromagnetism at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nat Mater*, 2013, 12: 703–706
- Shah AB, Ramasse QM, Zhai X, *et al.* Probing interfacial electronic structures in atomic layer LaMnO_3 and SrTiO_3 superlattices. *Adv Mater*, 2010, 22: 1156–1160
- Moon SJ, Jin H, Kim KW, *et al.* Dimensionality-controlled insulator-metal transition and correlated metallic state in 5d transition metal oxides $\text{Sr}_{n+1}\text{Ir}_n\text{O}_{3n+1}$ ($n=1, 2$, and ∞). *Phys Rev Lett*, 2008, 101: 226402
- Souri M, Kim BH, Gruenewald JH, *et al.* Optical signatures of spin-orbit exciton in bandwidth-controlled Sr_2IrO_4 epitaxial films via high-concentration Ca and Ba doping. *Phys Rev B*, 2017, 95: 235125
- Meijer GI, Staub U, Janousch M, *et al.* Valence states of Cr and the insulator-to-metal transition in Cr-doped SrTiO_3 . *Phys Rev B*, 2010, 81: 115105

2005, 72: 155102

- 41 Kini NS, Strydom AM, Jeevan HS, *et al.* Transport and thermal properties of weakly ferromagnetic Sr_2IrO_4 . *J Phys-Condens Mater*, 2006, 18: 8205–8216

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Author contributions Zhang J, Xiong C, Liu X and Yang Y conceived the experiments and prepared the manuscript. Liu X and Yang Y prepared the samples and performed the electronic transport and synchrotron XRD measurements. Shi Y and Yan D synthesized the target. Lu J performed the AFM measurement. Gu L and Zhang Q performed the STEM and EELS measurements. Cheng R and Wang F were involved in the discussion of the manuscript. All authors were involved in the revision of this manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Supporting data are available in the online version of the paper.

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$\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ 超晶格中Mott能带结构的调控

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摘要 5d族过渡金属氧化物具有强自旋轨道耦合作用, 可以衍生出诸多量子现象, 例如, Sr_2IrO_4 是强自旋轨道耦合导致的Mott绝缘体。为了研究 Sr_2IrO_4 新奇的电子结构和伴随的功能性, 亟待调控其Mott能带。本文中, 我们利用激光辅助分子束外延, 在单晶 SrTiO_3 衬底上外延制备了高质量的 Sr_2IrO_4 薄膜和 $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ 超晶格。电输运测试表明, 热激发和Mott可变频跃迁两种传导机制分别适用于 Sr_2IrO_4 薄膜和 $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ 超晶格。这种传导机制的转变表明 $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ 界面电子结构发生了重构。此外, $\text{Sr}_2\text{IrO}_4/\text{SrTiO}_3$ 超晶格的带隙从270.7–81.4 meV的显著调控可能源自Ir–O–Ti界面电子去局域化导致的能带展宽。研究表明, 超晶格界面工程可在原子尺度上有效地调控强关联氧化物的电子结构。