Enormous thermoelectric power factor of ZrTe2/SrTiO3 heterostructure

Chun Hung Suen
Hong Kong Polytechnic University
Songhua Cai
Nanjing University
Hui Li
The Hong Kong University of Science and Technology
Xiaodan Tang
College of Physics, Chongqing University
Huichao Wang
Peking University
Mingquan He
College of Physics, Chongqing University
Yisheng Chai
Chongqing University https://orcid.org/0000-0003-0034-7488
Kai Zhou
College of Physics, Chongqing University
Chi Man Wong
The Hong Kong Polytechnic University
Jiannong Wang
Hong Kong University of Science and Technology https://orcid.org/0000-0002-6133-6371
Xiaoyuan Zhou
Chongqing University
Jiyan Dai (jiyan.dai@polyu.edu.hk)
Hong Kong Polytechnic University

Article

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Enormous thermoelectric power factor of $ZrTe_2/SrTiO_3$ heterostructure

Chun Hung Suen[1+], S.H. Cai[1+], Hui Li[2+], Xiaodan Tang[3], Huichao Wang[4,], M.Q. He[3], Y.S. Chai[3], K. Zhou[3], Chi Man Wong[1], Jiannong Wang,[2,*] X. Y. Zhou[3,*] and Ji-Yan Dai[1,*]*

[1] Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

[2] Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

[3] College of Physics, Chongqing University, Chongqing 401331, China

[4]School of Physics, Sun Yat-sen University, Guangzhou 510275, China

Abstract

Achieving high thermoelectric power factor in thin film heterostructures is essential for integrated and miniaturized thermoelectric device applications. In this work, we demonstrate a mechanism to enhance thermoelectric power factor through coupling the interfacial confined two-dimensional electron gas (2DEG) with thin film conductivity in a transition metal dichalcogenides-$SrTiO_3$ heterostructure. Owing to the formed conductive interface with two-dimensional electron confinement effect and the elevated conductivity, the $ZrTe_2/SrTiO_3$ (STO) heterostructure presents enormous thermoelectric power factor as high as $4 \times 10^5\ \mu W cm^{-1}K^{-2}$ at 20 K and $4800\ \mu W cm^{-1}K^{-2}$ at room temperature. Interfacial reaction induced degradation of Ti cations valence number from Ti^{4+} to Ti^{3+} is attributed to be responsible for the formation of the quasi-two-dimensional electrons at the interface which results in very large Seebeck coefficient; and the enhanced electrical conductivity is suggested to be originated from the charge transfer induced doping in the $ZrTe_2$. By taking the thermal conductivity of STO substrate as a reference, the effective zT value of this heterostructure can reach 15 at 300 K. This superior thermoelectric property makes this heterostructure a promising candidate for future thermoelectric device, and more importantly, paves a new pathway to design promising high-performance thermoelectric systems.

Keywords: Thermoelectric; $ZrTe_2$ thin film; high mobility; interface; transition metal dichalcogenides

[+] These authors contribute equally

[*]corresponding contact:

Jiyan.dai@polyu.edu.hk; xiaoyuan2013@cqu.edu.cn; wanghch26@mail.sysu.edu.cn; phjwang@ust.hk

Introduction

Seeking high performance thermoelectric thin films is a hot topic in condensed matter physics and materials science and is attracting growing interests recently[1-6]. The development of micro-cooling devices and miniaturized self-powered devices is technically important for improvement of large-scale integrated circuits, which drives the study of thermoelectric thin films. For example, in microprocessors, the "hot spot" regions with higher power density frequently cause the fatal thermal failure, and thin film-based thermoelectric device can be a potential solution for in-demand cooling of circuits. Furthermore, high-performance thermoelectric thin films are also essential to build micro-power generators for self-powered devices in environments where a thermal gradient exists; this is significant for power engineering and management in future electronics.

The performance of a thermoelectric material can be evaluated by a dimensionless figure of merit $zT = S^2\sigma T/(\kappa_e + \kappa_l)$, where S, σ, T, κ_e, and κ_l represent Seebeck coefficient, electrical conductivity, absolute temperature, electronic thermal conductivity and lattice thermal conductivity, respectively[7,8]. To enhance the figure of merit, numerous efforts have been devoted to improve the power factor (power factor = $S^2\sigma$)[9-13] or reduce the thermal conductivity[14-18]. Among those methods to realize large thermoelectric power factor in a thin film/substrate heterostructure, interface engineering has been proven to be an effective approach to enhance Seebeck effect of the heterostructure. Especially, the presence of quasi-two-dimensional electron gas (quasi-2DEGs) at the interface is a dominant factor to the enhancement of |S|[1,19-22]. As an ideal substrate with unique physical and chemical properties, $SrTiO_3$ (STO) has been widely applied in thin film growth as well as the exploration of novel low-dimensional physics[1,23-28]. For example, the unique electronic phenomena generated from the heterointerface between epitaxial oxide layer and the STO substrate such as the very intriguing $LaAlO_3/SrTiO_3$ system has raised much attention. However, although the LAO/STO interface generally shows enhanced |S|, itself has not been found to exhibit an outstanding thermoelectric power factor mainly due to the limitation of its low conductivity at room temperature. For designing a viable high-performance thermoelectric system, it is necessary to couple both high conductivity and the enhanced thermoelectricity on a single hetero-interface.

Here, we demonstrate the realization of giant thermoelectric power factor in $ZrTe_2/SrTiO_3$ heterostructure, which mainly attribute to the coupling between interfacial quasi-2DEG generated on STO surface and the high conductivity of transition metal dichalcogenides (TMDs) film. An interfacial reaction between the pulsed-laser deposition (PLD) grown layered $ZrTe_2$ thin film and STO substrate leads to the appearance of quasi-2DEG which results in a great enhancement of the Seebeck coefficient. Meanwhile, the conductivity is also dramatically enhanced which may result from the doping effect of TMD film induced by charge transfer from the interface. Combining both the high Seebeck coefficient and electrical conductivity, this heterostructure system eventually presents an outstanding thermal power factor as well as thermoelectric figure of merit zT value. This work provides a promising

pathway for designing of high-performance thermoelectric systems, and opens up new possibilities for exploration and development of intriguing thermoelectric materials, structures as well as thin film-based thermoelectric devices.

Methods

In this study, PLD was used to grow $ZrTe_2$ films using an alloy target with Zr:Te=1:5 on the (100) STO substrates. The substrate-target distance during the deposition was 5 cm, with the base pressure of around 5×10^{-5} Pa, and the films were grown at optimized substrate temperature (T_s) of 550 ºC. To prevent the $ZrTe_2$ film from oxidation in air, an amorphous AlN capping layer of ~ 70 nm thick was deposited on top of the $ZrTe_2$ film at 200 ºC. The laser source was a KrF excimer laser with a wavelength of 248 nm. $ZrTe_2$ films with different thicknesses from 5 nm to 10 nm, 35 nm and 60 nm were deposited on STO substrates.

X-ray Diffraction (XRD) with Cu Kα_1 source was used to determine the orientation and crystallinity of $ZrTe_2$ film. To determine the microstructure and thickness of $ZrTe_2$ film, transmission electron microscope (TEM) was used for cross-sectional characterization. High-resolution TEM (HRTEM) images were acquired on JEOL 2100F TEM, operated at 200 kV. Scanning TEM (STEM) images were acquired on Thermofisher Titan G2 60-300 aberration corrected S/TEM. The accelerating voltage of electron beam is 300 kV. The convergence angle of electron probe for STEM-HAADF imaging is 22.5 mrad and the collection angle of annular detector is 79.5-200 mrad. A Gatan dual-EELS system was used for STEM-EELS data acquisition. For EELS line scan, the acquisition time per pixel is 1 s. The acquisition energy range is 420 to 720 eV with 0.1 eV dispersion, including the major or minor edges of oxygen and Ti. A 16T-PPMS (Physical Properties Measurement System) was utilized to measure the Seebeck coefficient and electrical conductivity at a temperature range from 0.5 K to 300 K. The measurement of Seebeck coefficient and electrical conductivity in the range from 300 K to 600 K was carried out on Joule Yacht MRS-3 thin film thermoelectric parameter test system.

Results and discussion

The microstructure and composition of all samples were firstly investigated using various methods. Figure 1(a) shows the cross-sectional HRTEM image of a 35 nm-thick $ZrTe_2$ film grown on STO substrate with a AlN capping layer. As it can be seen, between the STO substrate and AlN capping layer most parts of film clearly show (0001) $ZrTe_2$ lattice fringes parallel or nearly parallel to the substrate. This result is consistent with the expected layered structure of $ZrTe_2$ as shown schematically in Figure 1(b). $ZrTe_2$ has a hexagonal close-packed crystal structure with space group of $P\bar{3}m1$, and its 1T structure has an octahedral coordination of metal atoms[29] that can be illustrated as a CdI_2-type structure[30]. A unit cell of $ZrTe_2$ is denoted by a cyan rectangle in Figure 1(b) and can also be identified in the magnified HRTEM image. The crystal structure of our $ZrTe_2$ film was also characterized by XRD. Figure 1(c) presents the XRD pattern of the sample with 60 nm-thick film, where peaks at 2θ

= 13.3 °, 26.9 °, 40.8 ° and 55.4 ° correspond to the *c*-axis (0001), (0002), (0003) and (0004) diffraction peaks of hexagonal $ZrTe_2$ (*a* = 0.395 nm, *c* = 0.663 nm, JCPDS #54-560), respectively. These results imply that the $ZrTe_2$ film is preferentially grown along *c*-axis, which is consistent with the HRTEM observations. However, it should be pointed out that, besides the dominating *c*-axis orientation peaks, other orientation peaks are also found in XRD, suggesting that the growth of $ZrTe_2$ film on STO is non-epitaxial.

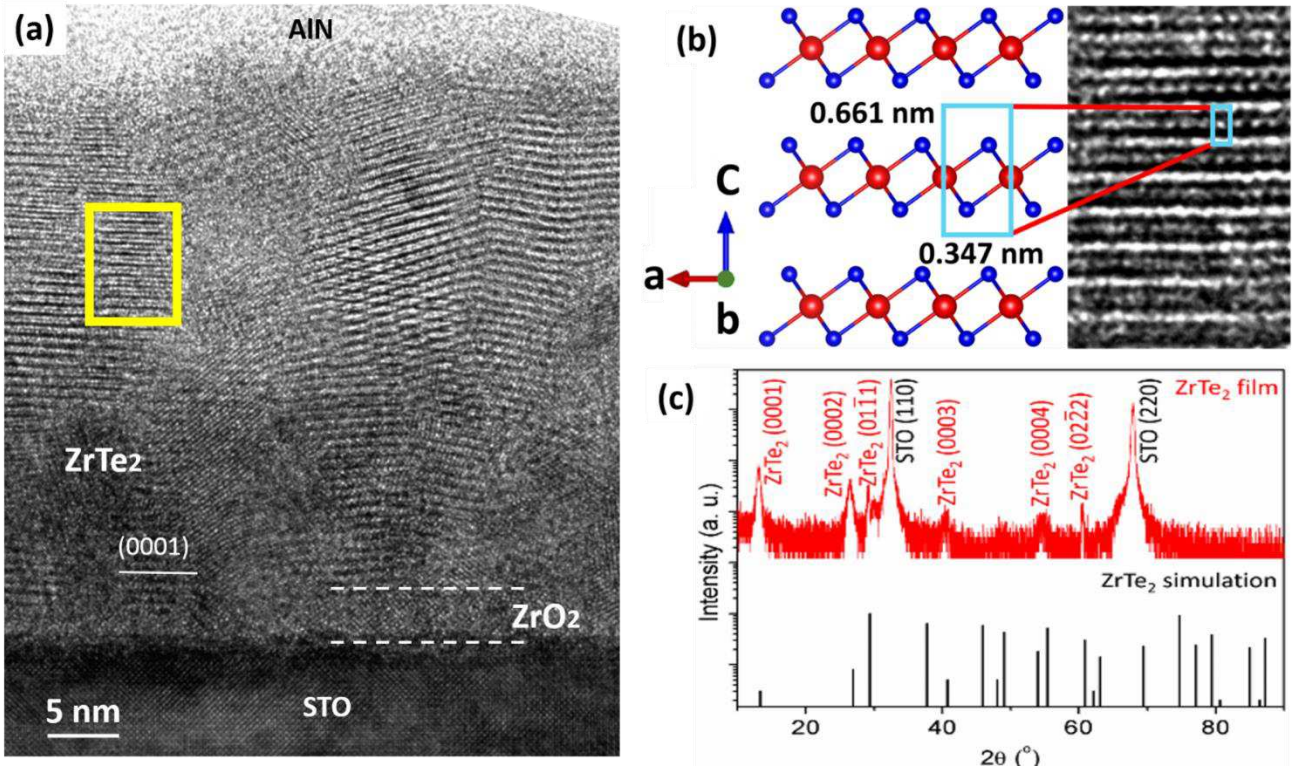

Figure 1 Crystal structure characterizations. (a) High-resolution TEM image of the $ZrTe_2$ film on STO substrate, where an interfacial layer of ZrO_2 reaction phase can be identified between the STO substrate and the $ZrTe_2$ film. (b) Magnified image of yellow rectangle region in (a) showing the correspondence of real unit cell with the crystal structure model of $ZrTe_2$. The unit cell is denoted by a rectangle to compared with magnified high-resolution TEM image of the $ZrTe_2$ film. (c) Typical XRD patterns of 60 nm $ZrTe_2$ film. The $ZrTe_2$ simulation pattern (JCPDS #54-560) is also illustrated for comparison.

It is worth noting that between the layered $ZrTe_2$ and the STO substrate, there exists a ~5 nm thick interfacial layer with a different lattice structure to $ZrTe_2$. A detailed analysis of the lattice spacings and their angles suggests that this interfacial layer is ZrO_2 (See Figure S1). This implies that interfacial reaction occurs between the deposited $ZrTe_2$ film and the STO substrate, and the interfacial characteristic has remarkably influenced the physical properties of both the $ZrTe_2$ film and the STO substrate. This can be revealed by the STEM energy disperse x-ray (EDX) spectroscopy element

mapping and the electron energy loss spectroscopy (EELS) analysis of the interfacial region as shown in Figure 2. A sample with relatively thin $ZrTe_2$ film (10 nm thick) was selected to reveal the overall elemental distribution of the whole sample. It is apparent in EDX mapping results shown in Figure 2(a), that the distributions of O and Te are not uniform along the thickness direction, i.e., the signal intensity of Te increases near the interface with a decrease of O signal. It is surprising to see that O even exists in the whole film, suggesting an out diffusion of O from STO which can be proven by EELS line-scan analysis across the interface as shown in Figure 2(b) and (c). By extracting the signals of Ti and O edges from the EELS spectrum, the energy loss near edge structures (ELNES) reveals that the 4 unit cells of STO from interface exhibits a different chemical state with bulk STO. From the 4th layer of STO up to the interfacial layer, the valence state of Ti cations degrades from Ti^{4+} to Ti^{3+} (peak shift and shape variation in Figure 2(b) with a corresponding change of O K-edge fine structure (Figure 2(c)). The interfacial characteristics imply a conductive STO surface, which is analogous to the similar situation in the oxide heterostructures such as LAO/STO.

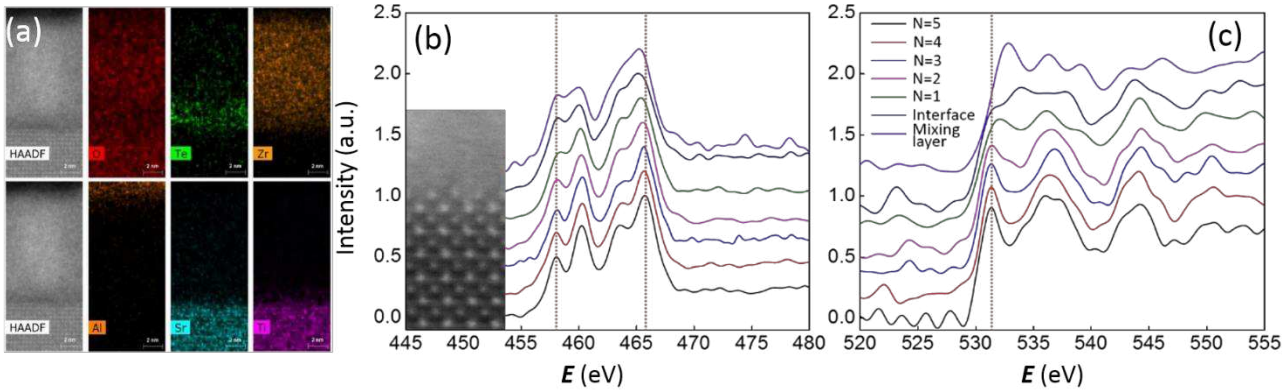

Figure 2 Elemental mapping and interfacial valence states of Ti and O ions. (a) STEM-EDS element mapping across the interface, (b) EELS results of Ti-3d L edge shift peaks, and (c) O-2p K edge fine structure across the interface.

We have carried out thermoelectric and electron transport properties measurements to different thicknesses of samples at temperatures ranging from 2 K to 600 K. The $ZrTe_2$/STO heterostructures exhibit negative Seebeck coefficient throughout the whole temperature range, indicating a n-type conducting characteristic; and the general trend is that the thicker films show relatively lower Seebeck coefficient but with high electrical conductivity, while very thin films present highly fluctuated Seebeck coefficient and high resistance. Figure 3(a) shows the temperature-dependent Seebeck coefficients of the $ZrTe_2$/STO heterostructures with 35 nm and 60 nm-thick $ZrTe_2$ films from 2 K to 600 K. The Seebeck coefficient in the sample with a 35 nm-thick $ZrTe_2$ generally increases with the temperature increases from 2 K and finally reaches the maximum value of about 530 μV/K at 440 K, above which the Seebeck coefficient begins to decrease. The sample with 60 nm-thick $ZrTe_2$ film shows a similar trend while the maximum Seebeck coefficient appears at 111 K with a value of 368

μV/K. The temperature-dependent electrical conductivity of both samples are shown in Figure 3(b), which confirms that these heterostructures are highly conductive. The electrical conductivity can reach a remarkable value up to 10^7 S/cm at low temperature state (2 K). The coexistence of both very large Seebeck coefficient and very high electrical conductivity of the $ZrTe_2$/STO heterostructure consequently leads to enormous thermoelectric power factor. As shown in Figure 3(c), the thermoelectric power factors monotonically increase with the decreasing of temperature in both samples and finally achieve a colossal value even exceeds $3 \times 10^5\ \mu W cm^{-1}K^{-2}$ at 20 K.

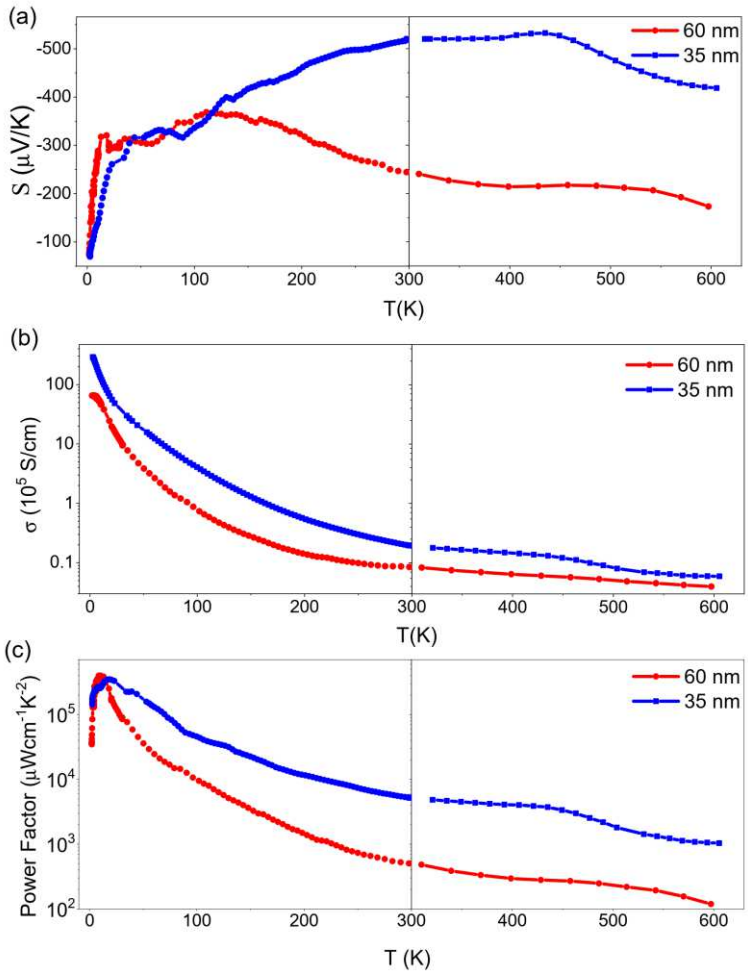

Figure 3 Thermoelectric and electrical conductive properties. (a) Seebeck coefficients, (b) electrical conductivities, and (c) thermoelectric power factors, of the $ZrTe_2$/STO heterostructures with 35 nm and 60 nm-thick $ZrTe_2$ films.

As well known, quasi-2DEG can exist in the conductive STO interface and its presence can be a prime factor for triggering intriguing thermoelectric properties. To clarify the contribution of the possible interfacial effect to the outstanding thermoelectric properties, we further conducted systematic electron transport measurements on the heterostructure. As a follow-up to our previous work[29], in these high quality heterostructures, we observed obvious Shubnikov–de Haas (SdH) oscillations superimposed

on the large magnetoresistance at low temperatures below 4 K. Figure 4(a) shows the oscillations after subtracting a smooth background from the measured magnetoresistance of a typical 60 nm-thick $ZrTe_2$ film on STO. The periodicity in the reciprocal of magnetic field (1/B) demonstrates that the SdH effect is the origin. Fast Fourier Transform (FFT) results further reveal that the oscillating frequency peak is about 29.5 T as shown in Figure 4(b). By analyzing the temperature dependence of the oscillations using the Lifshitz-Kosevitch formula, we obtain an effective mass of $1.3m_0$ where m_0 represents the rest mass of an electron (Figure 4(c)). In addition, the Dingle temperature is calculated as 1.4 K based on the measured quantum oscillations. It is interesting to find that the microscopic parameters of the quantum oscillations actually agree well with those acquired in conductive STO surfaces[31-38]. Thus, we believe that the interfacial effect between the $ZrTe_2$ thin film and the STO substrate plays a significant role for presenting the very exotic transport properties in our observation[29].

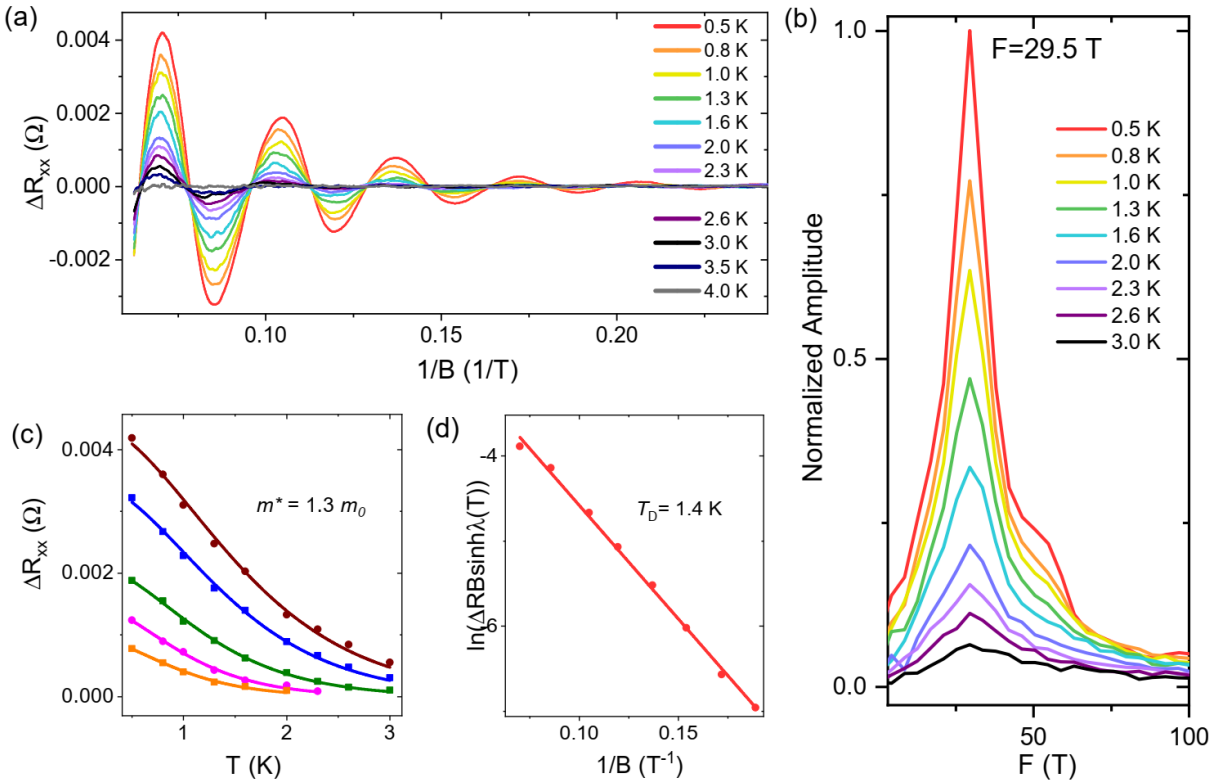

Figure 4 Quasi two-dimensional transport characteristics of the heterostructure. (a) SdH quantum oscillations in the $ZrTe_2$/STO, and (b) FFT results of the oscillations revealing a frequency peak of 29.5 T. (c) and (d) are calculated effective mass and Dingle temperature based on the Lifshitz-Kosevitch formula.

Our previous study on the $ZrTe_2$/STO heterostructures has revealed a quasi-2D transport characteristic of the hybrid heterostructure, within which the electrons exhibit a high mobility of about $1.8 \times 10^4\ cm^2V^{-1}s^{-1}$ at 2 K[29]. The quasi-2D transport feature is consistent to the layered structure

of $ZrTe_2$ and the property of quasi-2D electrons in the STO interface as well. These characteristics are supposed to be responsible for the observed enormous Seebeck coefficient and power factor. Similar findings also exist in TiO_2/STO, LAO/STO and FeSe/STO heterostructures[1,39,40]. In the TiO_2/STO heterostructure, with the presence of 2DEG, the room temperature (300 K) Seebeck coefficient is as large as 1050 $\mu V/K$; while our $ZrTe_2$/STO heterostructures show a value of $|S|_{300K}$ smaller than 500 $\mu V/K$ (Figure 3(a)). It is worth noting that the Seebeck coefficient of the heterostructure shows obvious dependency with the thickness of the TMD film that a thicker $ZrTe_2$ film leads to the decrease of |S|. Figure S2 shows comparison of our results to reported Seebeck coefficients from other 2D systems. In fact, a control sample with only the ZrO_2/STO interfacial contribution shows much higher Seebeck coefficient with a value of about 750 μV/K at 300 K, well consistent with the result in the TiO_2/STO heterostructure[1] (see Figure S3(b)) . Meanwhile, the electrical conductivity is also found to be thickness dependent; while this dependence is opposite to that of the Seebeck coefficient. The control sample with only ZrO_2/STO shows a much higher resistance, making the Seebeck coefficient measurement fluctuate vigorously and also prevents the system achieving a higher power factor. As a conclusion, the deposition of TMD $ZrTe_2$ thin films on the top of the quasi-2D system results in slight decrease of the Seebeck coefficient of the system due to its relatively lower Seebeck coefficient, but it contributes very high conductivity to the system. With the coupling between the thin $ZrTe_2$ film and the STO-based interface, the largest thermoelectric power factor can be achieved in the $ZrTe_2$/STO heterostructure.

However, it should be noted that for a much thinner thickness, the interface is not well conductive and EELS results show that the valence state of Ti cations at the interfacial region is still Ti^{4+} instead of Ti^{3+} (see Figure S4). Therefore, we come to the conclusion that the interfacial state for forming a confined 2D conductive interface is essential for achieving the outstanding thermoelectric properties in this system. On the other hand, the extremely high conductivity is another crucial factor for realization of the giant thermopower factor. We also prepared a $ZrTe_2$ thin film on the insulating Al_2O_3 (Figure S5) to clarify the origin. It can be found that the $ZrTe_2$ thin film is indeed metallic with a high conductivity but still lower than the value achieved in the $ZrTe_2$/STO system; this also suggests a modulation effect to the $ZrTe_2$ film from the interface. As a reference, the FeSe/STO is a well-explored metal/STO heterostructure system due to the interface-enhanced high temperature superconductivity [41,42]. Strong evidences have shown that the interfacial electron-phonon coupling as well as the electron doping on the FeSe layer should be responsible for the high temperature superconductivity of the FeSe/STO system[43-47]. In particular, the electron doping to the film through the thermal annealing generally decreases the resistance of the system and thus enhances the conductivity[48]. We suggest that similar mechanism may also exist in the metallic $ZrTe_2$/STO heterostructure that the electron doping from the substrate to the TMD film determines the very high conductivity of the system. More efforts are needed to further demonstrate the underlying physical origins.

It is noticeable that there exists a small peak in the Seebeck coefficient at about 20 K (Figure 3(a)), and this can be explained by the phonon-drag effect[49-51] originated from the STO (100) substrate. One study that related to the thermal transport of STO[52] exhibits a thermal conductivity peak close to 20 K. When a thermal gradient is applied to the thin film and substrate, nonequilibrium phonons will be generated and transfer their momentum to the carriers; as a result, an additional electric field is formed in the film, thus enhance the Seebeck coefficient. The characteristic of phonon-drag effect is that, it is more effective at temperatures where the substrate attains its maximum thermal conductivity; this is the reason why the peak of Seebeck coefficient, as shown in Figure 3(a), is near the temperature where the substrate exhibits its peak thermal conductivity.

For thin films, the substrate thermal conductivity dominated the thermal transport, so we estimate the effective thermoelectric figure of merit zT mainly based on the value of thermoelectric power factors of the film and the reported thermal conductivity values of STO single crystal[53]. For the 35 nm $ZrTe_2$/STO sample, the effective zT value at 300 K is about 15, which is extremely higher compared to most of the reported works according to the best our knowledge[3,54]. Even for the 60 nm thick $ZrTe_2$ film sample, the effective zT is about 1.5 at 300 K and increases to 13 at 18 K. This superior thermoelectric property makes this heterostructure a promising candidate for future thermoelectric device.

Conclusion

In summary, we demonstrate that the $ZrTe_2$/STO heterostructure possesses colossal thermoelectric power factor at both low temperature and room temperature. The excellent thermoelectric properties can be attributed to the formation of two-dimensional electrical transport property as well as the enhanced conductivity due to charge transfer occurs in the interface. This study reveals the promising thermoelectric properties of $ZrTe_2$/STO heterostructure and provides a new pathway for development of thermoelectric materials and structures. Furthermore, the mechanism exploration is of fundamental importance for both thermoelectric physics and possible application on thin film-based electronic devices.

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Supporting Information for

Enormous thermoelectric power factor of $ZrTe_2/SrTiO_3$ heterostructure

Chun Hung Suen[1+], S.H. Cai[1+], Hui Li, [2+] Xiaodan Tang,[3] Huichao Wang[4], M.Q. He[3], Y.S. Chai[3], K. Zhou[3], Chi Man Wong[1], Jiannong Wang,[2,*] X. Y. Zhou[3,*] and Ji-Yan Dai[1,*]*

[1] Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

[2] Department of Physics, Hong Kong University of Science and Technology, Hong Kong, China

[3] College of Physics, Chongqing University, Chongqing 401331, China

[4] School of Physics, Sun Yat-sen University, Guangzhou 510275, China

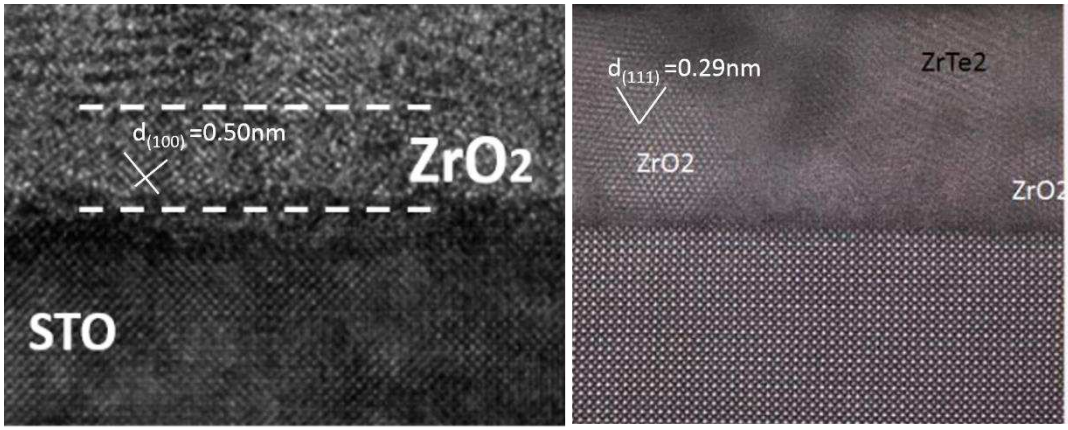

Figure S1 Detailed microstructure of the interface. (a) HRTEM, and (b) STEM, images of the interfacial structure. ZrO_2 becomes the dominant component near the interface area.

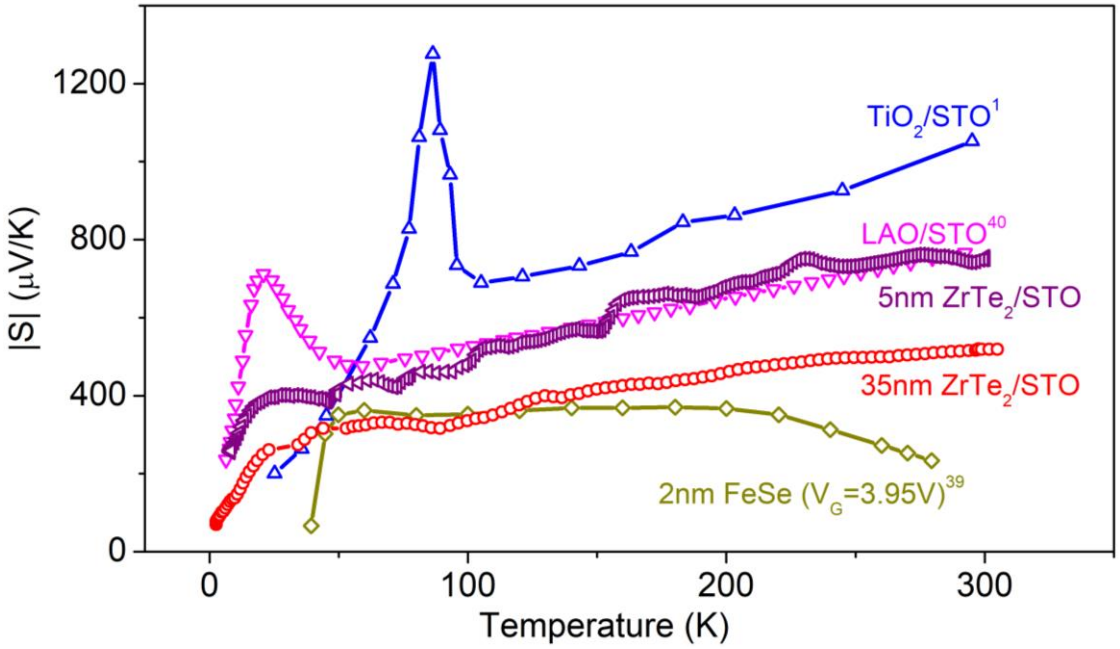

Figure S2 Comparison of temperature-dependent Seebeck coefficients with literatures among 2D systems.

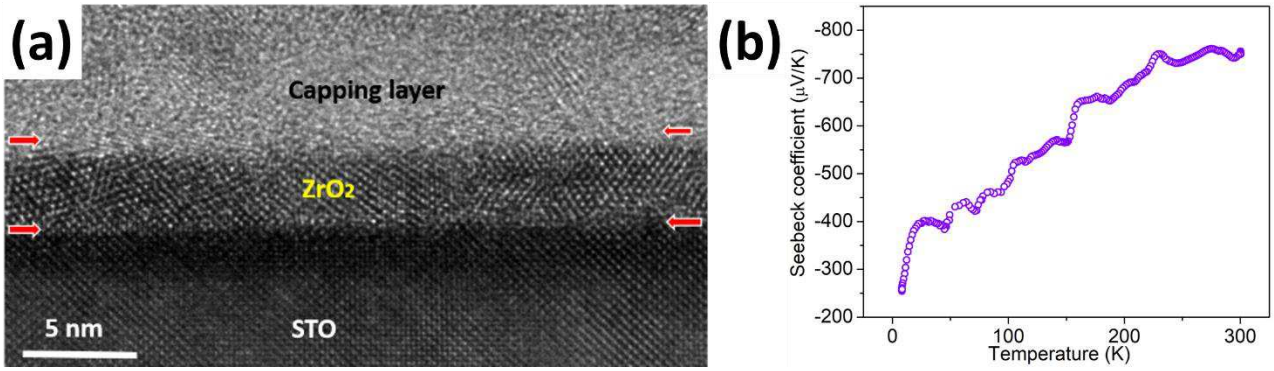

Figure S3 Microstructure and Seebeck coefficient of control sample (only 5nm-thick ZrO2 film on STO). (a) HRTEM image, and (b) the Seebeck coefficient showing that the control sample has much larger Seebeck effect but unstable due to its high resistance. This ZrO_2/STO heterostructure was formed by PLD sputtering of Zr target at the same condition of $ZrTe_2$ film growth.

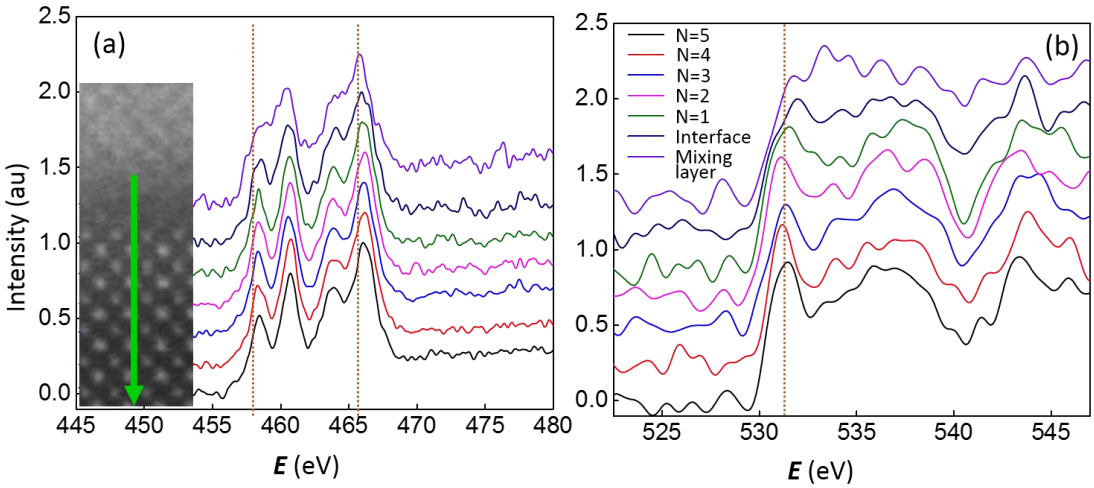

Figure S4 Interfacial valence states of Ti and O ions in thinnest control sample (5nm-thick ZrO_2 film on STO). (a) EELS results of Ti-3d L edge shift peaks, and (b) O-2p K edge fine structure across the interface.

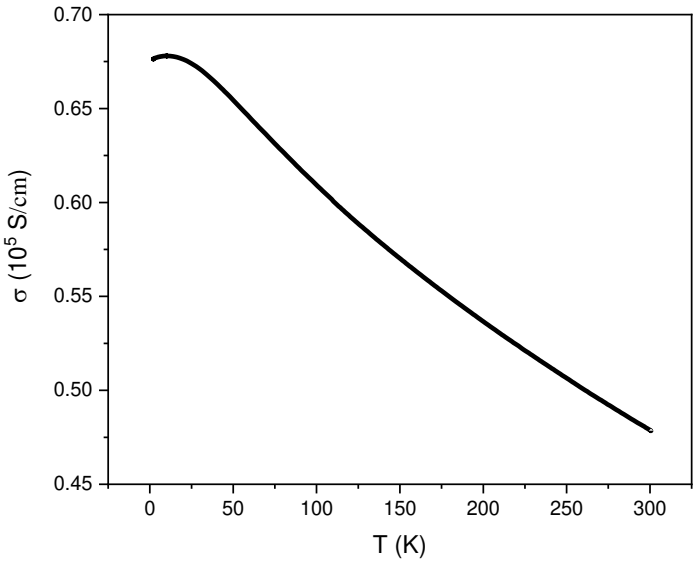

Figure S5 Conductivity-temperature relationship of the $ZrTe_2$ thin film on Al_2O_3 substrate.

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Figures

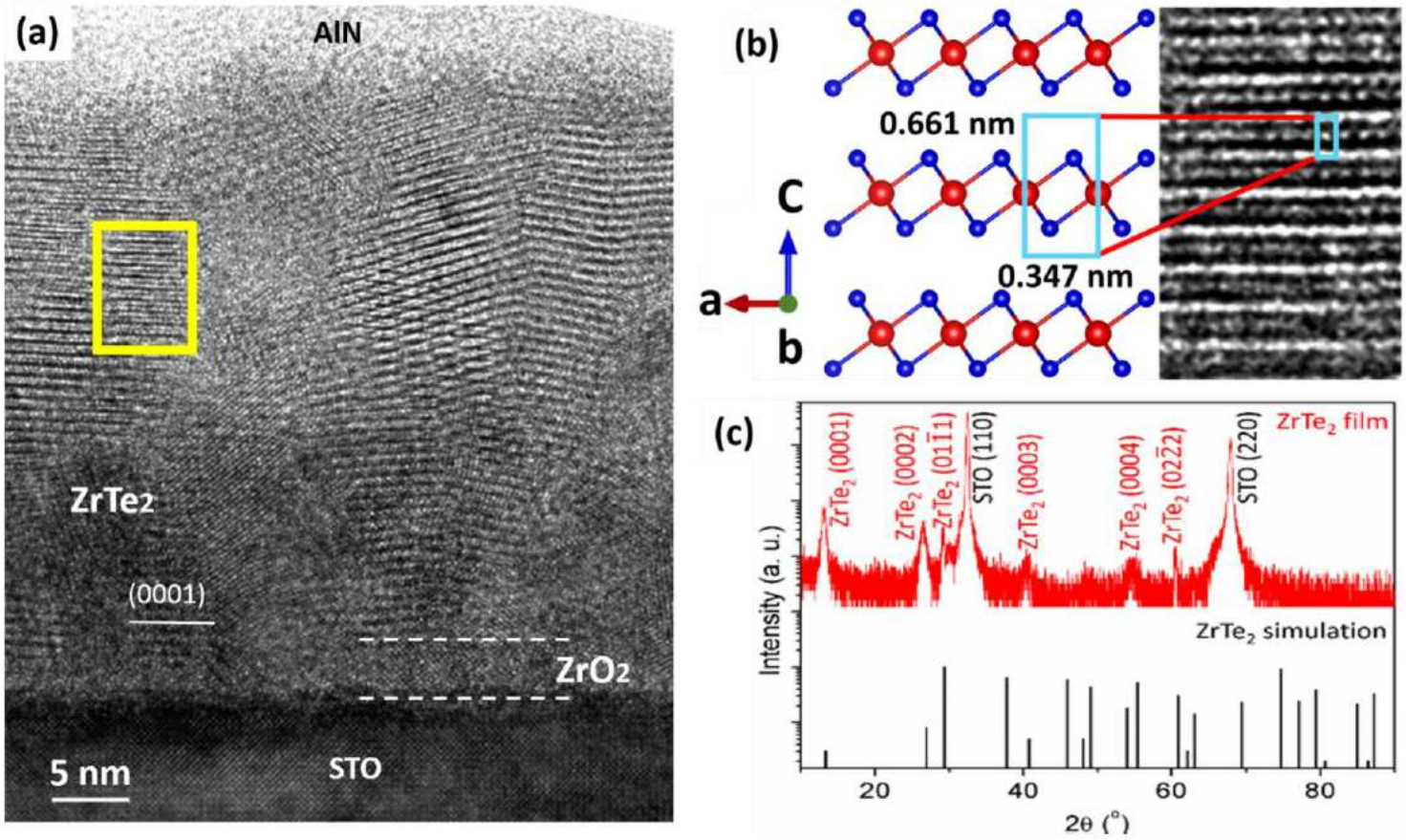

Figure 1

Crystal structure characterizations. (a) High-resolution TEM image of the ZrTe2 film on STO substrate, where an interfacial layer of ZrO2 reaction phase can be identified between the STO substrate and the ZrTe2 film. (b) Magnified image of yellow rectangle region in (a) showing the correspondence of real unit cell with the crystal structure model of ZrTe2. The unit cell is denoted by a rectangle to compared with magnified high-resolution TEM image of the ZrTe2 film. (c) Typical XRD patterns of 60 nm ZrTe2 film. The ZrTe2 simulation pattern (JCPDS #54-560) is also illustrated for comparison.

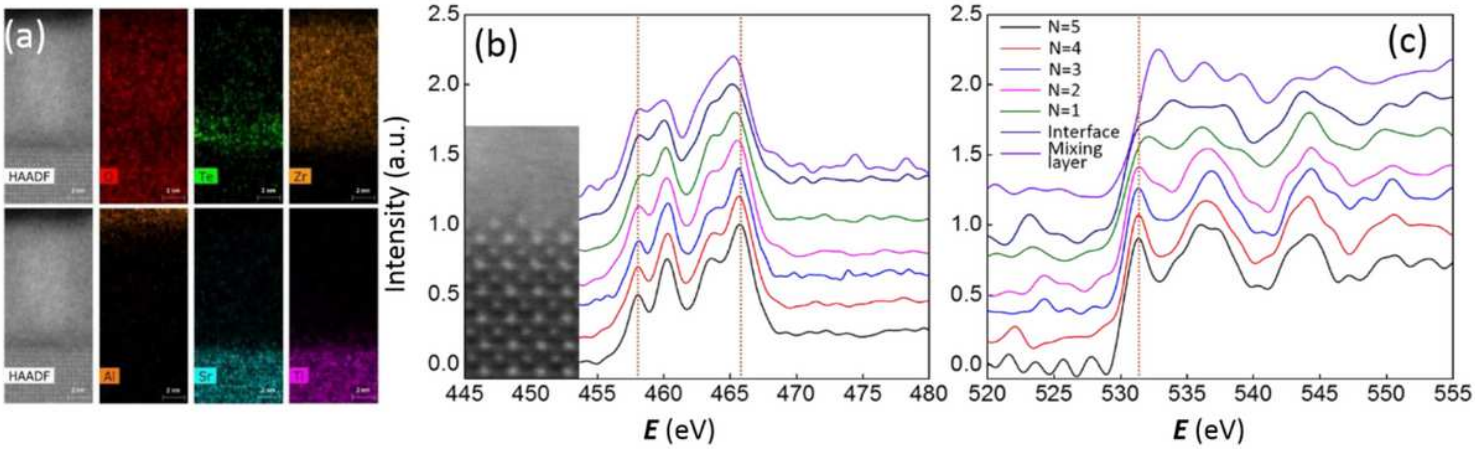

Figure 2

Elemental mapping and interfacial valence states of Ti and O ions (a) STEM-EDS element mapping across the interface, (b) EELS results of Ti-3d L edge shift peaks, and (c) O-2p K edge fine structure across the interface.

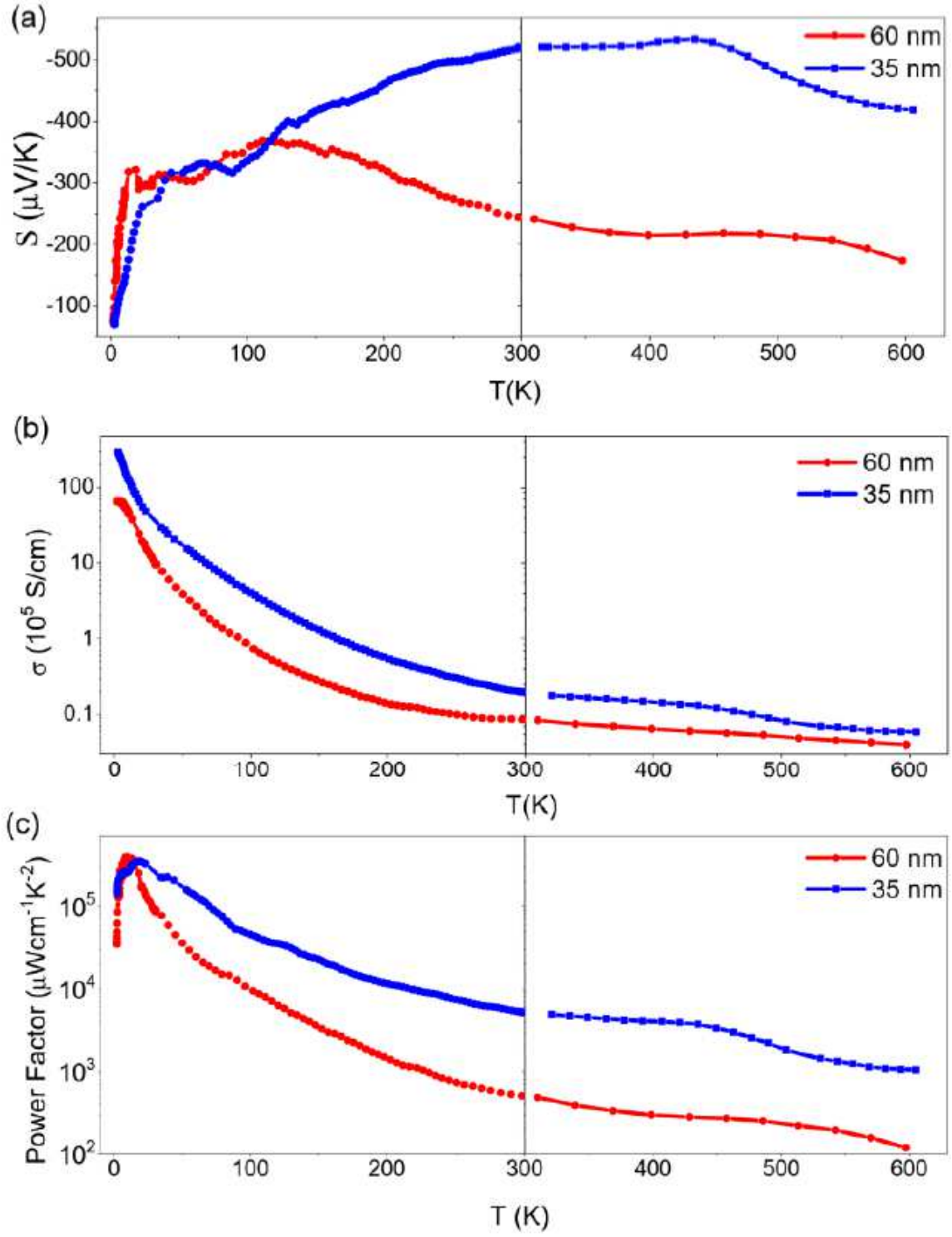

Figure 3

Thermoelectric and electrical conductive properties. (a) Seebeck coefficients, (b) electrical conductivities, and (c) thermoelectric power factors, of the ZrTe2/STO heterostructures with 35 nm and 60 nm-thick ZrTe2 films.

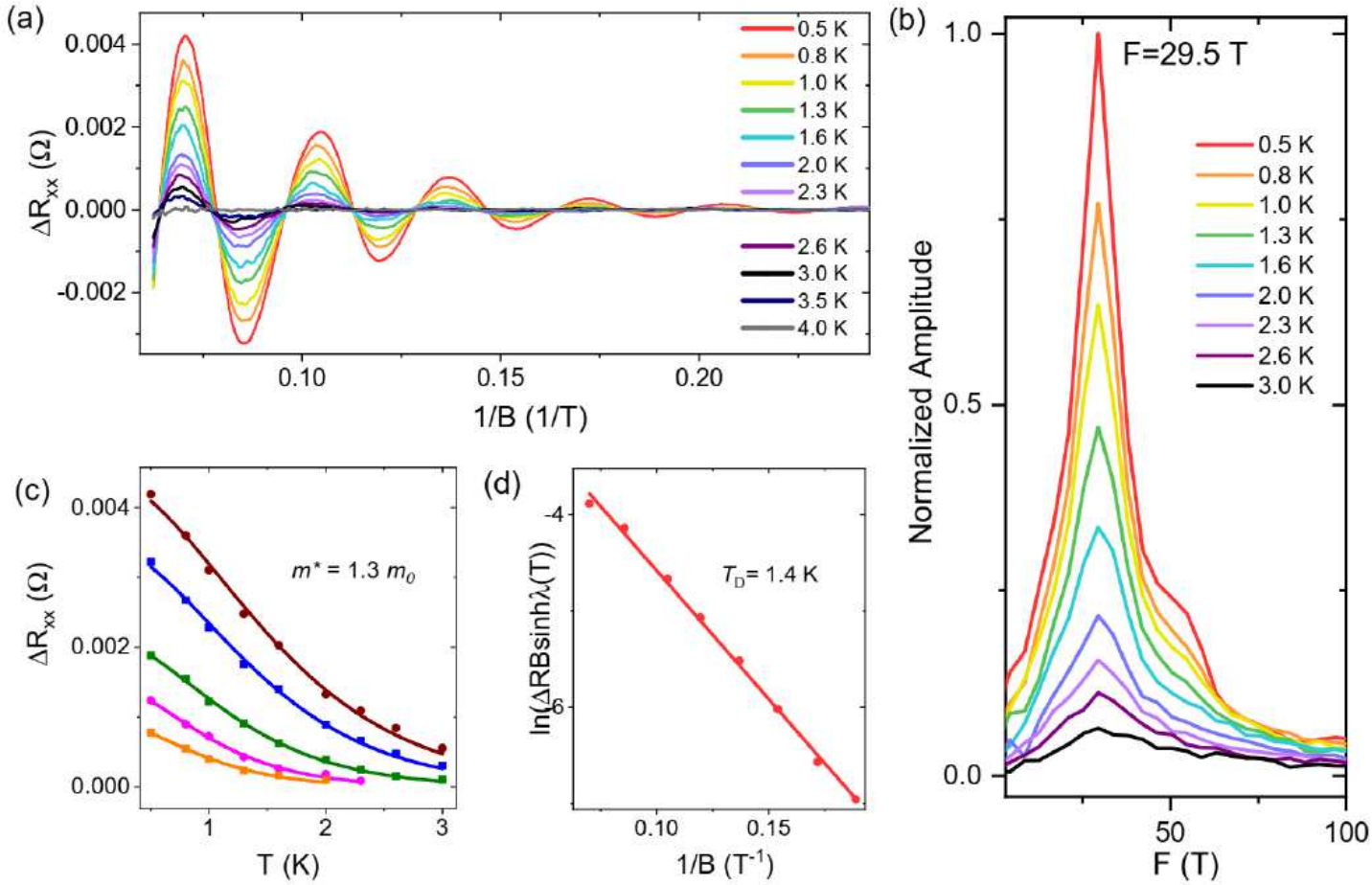

Figure 4

Quasi two-dimensional transport characteristics of the heterostructure. (a) SdH quantum oscillations in the ZrTe2/STO, and (b) FFT results of the oscillations revealing a frequency peak of 29.5 T. (c) and (d) are calculated effective mass and Dingle temperature based on the Lifshitz-Kosevitch formula.