Demonstration of Metal–Insulator Transition Induced by Resonant Tunneling in Double Quantum Well Structures of Strongly Correlated Oxides

The metal–insulator transition (MIT), a fascinating phenomenon occurring in some strongly correlated materials, is of central interest in modern condensed-matter physics. Controlling the MIT by external stimuli is a key technological goal for applications in future electronic devices. However, the standard control by means of the field effect faces severe difficulties when applied to the MIT. We have developed an alternative method based on resonant tunneling in a double quantum well structure of strongly correlated oxides, which offers practical advantages over conventional methods. Our work opens avenues for realizing the Mott transistor based on the wave-function engineering of strongly correlated electrons.

Controlling the quantum ground state of a system is essential for applications. The best-known example is semiconductor technology, where the state (conductive or not conductive) of a semiconductor is driven by the so-called field-effect transistor (FET). In the FET, the number of electric charge carriers is controlled by an external voltage.

Some strongly correlated electron materials naturally show a metal-to-insulator transition (MIT) [1, 2]. It is thus highly desirable to control such a MIT in the same way as is done for semiconductors. However, despite intensive effort, FET control of the MIT in strongly correlated materials has so far been unsuccessful owing to fundamental difficulties.

According to the Mott–Hubbard theory [3], a ground state in strongly correlated materials is described by the ratio of the Coulomb interaction (U) to the bandwidth (W). When $U < W$, the material is metallic, but it becomes insulating when $U > W$. Therefore, tuning the U/W ratio by some external perturbation would enable the MIT to be controlled, and so the practical realization of this idea has been one of the central goals in modern condensed matter physics.

Here, we propose a new approach for tuning the U/W ratio, and thus controlling the MIT, using the resonant-tunneling (RT) effect [4] in double quantum well (QW) structures of strongly correlated oxides [5]. The concept is schematically illustrated in Fig. 1. The double QW structure consists of two strongly correlated oxide layers and a barrier layer (insulator). The top QW is a "marginal" Mott insulator, i.e., a material in the insulating Mott phase but in close proximity (U slightly larger than W; $U \gtrsim W$) to the metallic one, while the bottom QW is a correlated metal. In the marginal Mott-insulating QW, the quantized electron states are localized due to $U \gtrsim W$, leading to a Mott-insulating state, but the QW exhibits a transition to a metallic state upon applying a small external stimulus. If the RT occurs between the marginal Mott-insulating QW and metallic QW states, the QW states that are energetically close to each other are hybridized. As a result, the marginal Mott insulator is expected to be metallized owing to U becoming smaller than W.

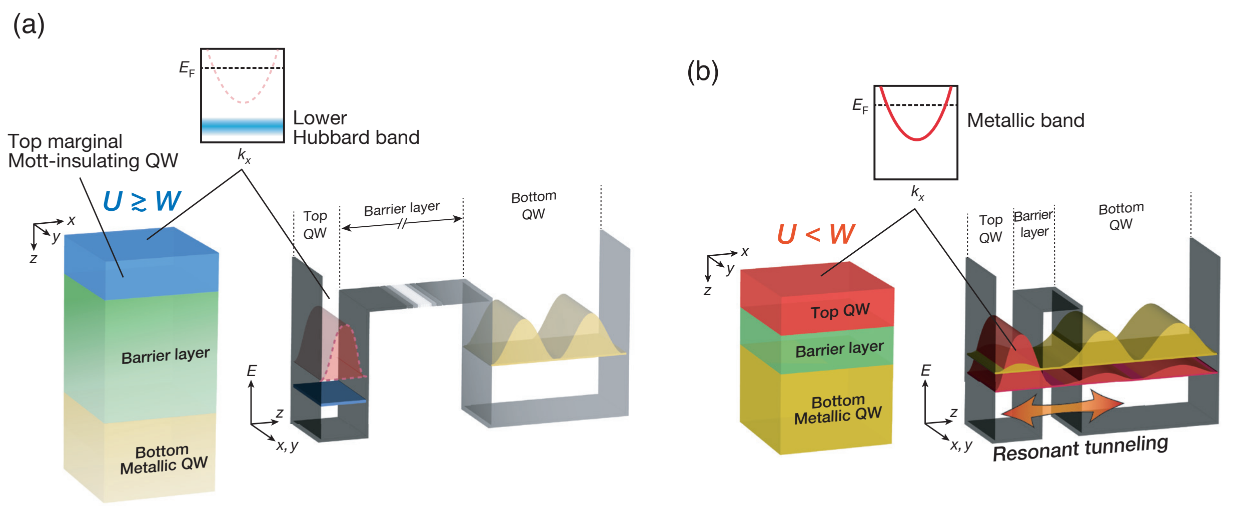

Figure 1: Schematic illustration of MIT induced by the RT effect. (a) Before switching on the RT effect. Owing to the marginal Mott-insulating nature of top QW states, the strongly correlated electrons in the original top QW states become localized, resulting in a localized state (lower Hubbard band) presented in blue. (b) After switching on the RT effect. Owing to the hybridization between the top and bottom QW states, bonding (red curve) and antibonding (yellow curve) states are formed.

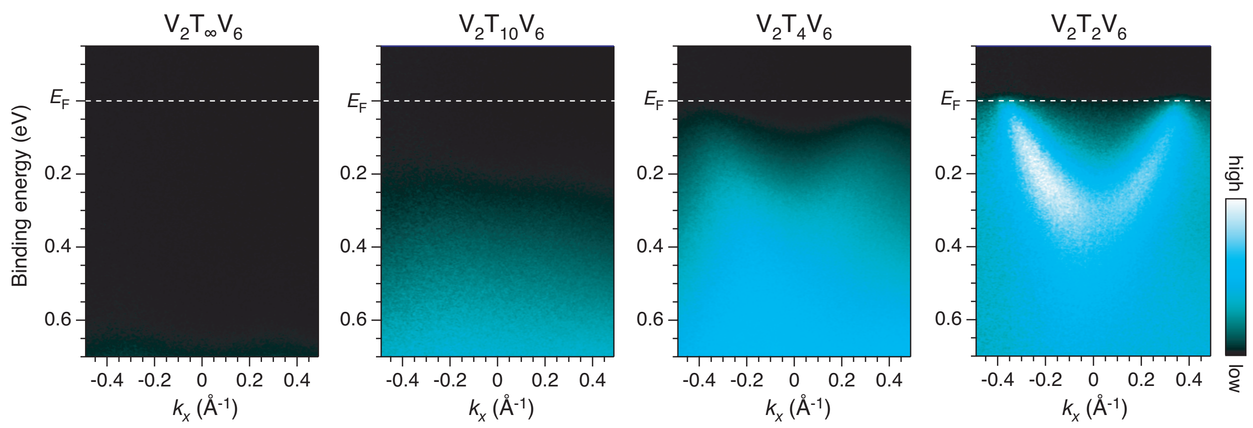

Figure 2: Visualization of the MIT induced by RT in double QW structures of strongly correlated oxides.

To demonstrate the MIT driven by the RT effect, we fabricated double QW structures where layers of the strongly correlated conductive oxide $SrVO_3$ (SVO) sandwich a barrier layer of $SrTiO_3$ (STO), a band insulator. A recent theoretical study predicted that the 2 ML of SVO is at the verge of the Mott insulator, and it can easily become a metal by applying a small perturbation [6].

Thus, as the top marginal Mott-insulating QW, we used a 2-ML SVO layer. As a counterpart, we used a 6-ML SVO for the bottom metallic QW layer, so as to induce the RT effect between two energetically close QW states [7]. Based on the previously reported structure plot of quantization energies as a function of SVO layer thickness, the first quantization level of the top (2-ML SVO) QW states matches the second quantization level of the bottom (6-ML SVO) QW [8]. Thereafter, the (2-ML SVO)/(L-ML STO)/(6-ML SVO) double QW structure is denoted as $V_2T_LV_6$.

The transition from the marginal Mott-insulating QW states to the metallic QW states induced by the RT effect was visualized by *in situ* angle-resolved photoemission spectroscopy (ARPES). As can be seen in Fig. 2, there are no discernible states near the Fermi level (E_F) in the ARPES images of the $V_2T_\infty V_6$ structure, reflecting the Mott-insulating nature of the 2-ML SVO films. As the STO barrier layer becomes thinner, a faint dispersive feature emerges near E_F. Eventually, a metallic band whose dispersion crosses E_F is clearly visible in the $V_2T_2V_6$ double QW structures.

The present study demonstrates that the MIT can be controlled by the RT effect in double QW structures of strongly correlated oxides. Our observations offer valuable insight into the quest for novel quantum phenomena using oxide heterostructures since the U/W ratio can be controlled by designing the wavefunction of their strongly correlated electrons. The present demonstration also paves the way for creating Mott-transistor operation based on the quantum RT effect between designed wavefunctions of strongly correlated electrons.

REFERENCES

[1] A. Georges, G. Kotliar, W. Krauth and M. J. Rozenberg, *Rev. Mod. Phys.* **68**, 13 (1996).
[2] M. Imada, A. Fujimori and Y. Tokura, *Rev. Mod. Phys.* **70**, 1039 (1998).
[3] J. Hubbard, *Proc. R. Soc. A Math. Phys. Eng. Sci.* **276**, 238 (1963).
[4] S. M. Sze and K. K. Ng, "*Physics of Semiconductor Devices*", 3rd edn (Wiley-Interscience press, Canada, 2006).
[5] R. Yukawa, M. Kobayashi, T. Kanda, D. Shiga, K. Yoshimatsu, S. Ishibashi, M. Minohara, M. Kitamura, K. Horiba, A. F. Santander-Syro and H. Kumigashira, *Nat. Commun.* **12**, 7070 (2021).
[6] Z. Zhong, M. Wallerberger, J. M. Tomczak, C. Taranto, N. Parragh, A. Toschi, G. Sangiovanni and K. Held, *Phys. Rev. Lett.* **114**, 246401 (2015).
[7] M. Kobayashi, K. Yoshimatsu, T. Mitsuhashi, M. Kitamura, E. Sakai, R. Yukawa, M. Minohara, A. Fujimori, K. Horiba and H. Kumigashira, *Sci. Rep.* **7**, 16621 (2017).
[8] K. Yoshimatsu, K. Horiba, H. Kumigashira, T. Yoshida, A. Fujimori and M. Oshima, *Science* **333**, 319 (2011).

BEAMLINE

BL-2A

R. Yukawa[1], M. Kobayashi[1], T. Kanda[2], D. Shiga[1, 2], K. Yoshimatsu[2], S. Ishibashi[3], M. Minohara[1], M. Kitamura[1], K. Horiba[1], A. F. Santander-Syro[4] and H. Kumigashira[1, 2]
([1]KEK-IMSS-PF, [2]Tohoku Univ., [3]AIST, [4]Univ. Paris-Saclay)