Formation of Quantum Dots in ZnO Heterostructures and Observation of Kondo Effect

K. Noro[1, 2], Y. Kozuka[3], K. Matsumura[1, 2], T. Kumasaka[1], Y. Fujiwara[1, 2], A. Tsukazaki[4, 5], M. Kawasaki[6, 7] and T. Otsuka[1, 2, 5, 7, 8]

[1]*Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan*

[2]*Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, Sendai 980-0845, Japan*

[3]*Research Center for Materials Nanoarchitectonics (MANA), National Institute for Material Science (NIMS), Tsukuba 305-0044, Japan*

[4]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

[5]*Center for Science and Innovation in Spintronics, Tohoku University, Sendai 980-8577, Japan*

[6]*Department of Applied Physics and Quantum-Phase Electronics Center (QPEC), University of Tokyo, Tokyo 113-8656, Japan*

[7]*Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan*

[8]*WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

tomohiro.otsuka@tohoku.ac.jp

High-quality two-dimensional electron gas (2DEG), mainly made from GaAs and Si semiconductor heterojunction, has been used to observe quantum phenomena. With the recent development of growth technology, producing high-quality zinc oxide (ZnO) heterostructures has become possible. High mobility 2DEG is created in the structures, and Quantum Hall Effect [1][2] and Quantum Point Contacts (QPC) [3] have been observed. Here, we demonstrate the formation of quantm dots and measure the electron transport properties of the dots in ZnO heterostructure devices.

We fabricated gate-defined quantum dot devices and measured the conduction of the devices in the cryogenic environment using a dilution refrigerator. We observed Coulomb oscillations in the current through the devices by applying negative voltage to gate electrodes to adjust tunnel barriers and energy of the quantum dot. Also, Coulomb diamonds were observed as shown in the figure. These results indicate the formation of quantum dots in ZnO heterostructure devices.

We also observed conductance peaks in Coulomb diamonds at V_{sd} = 0, corresponding to Kondo effect. This Kondo effect is different from the Kondo effect observed in GaAs quantum dots because the zero bias peaks are observed in neighboring Coulomb diamonds: the even-odd effect is broken. It indicates that the Kondo effect occurs with the even number of electrons in quantum dots. We analyzed the temperature dependence of the zero-bias peaks in the different number of electrons. Moreover, we studied the magnetic field dependence of the zero-bias peaks, and observed complicated peak splitting not seen in the normal Kondo effect. These characteristic properties may be caused by the Kondo effect including multiple orbits caused by strong electron correlation in ZnO [4]. These will be useful for future quantum devices utilizing electron correlation in ZnO.

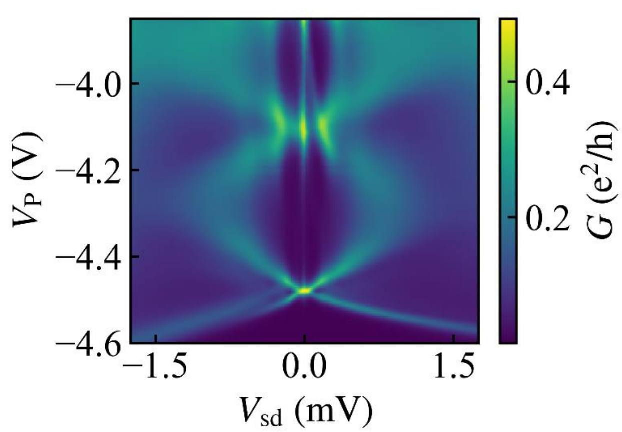

Fig.1. Coulomb diamonds with zero-bias peaks caused by Kondo effect

Reference

[1] A. Tsukazaki *et al.*, Science **315**, 1388 (2007).

[2] A. Tsukazaki *et al.*, Nat. Mater. **9**, 889 (2010).

[3] H. Hou *et al.*, Physical Review B **99**, 121302 (2019).

[4] K. Noro *et al.*, arXiv:2311.12508.