Advanced Device Laboratory（2022）
Chief Scientist: Koji Ishibashi (D.Eng.)

(0) Research fields

CPR Subcommittee**:** Engineering, Physics

Keywords: Quantum Nanoscale devices, Carbon nanotube nanostructures, superconductor/topological insulator hybrid structures, Nanofabrication Nanoscale Si-based transistors

(1) Long-term goal of laboratory and research background

We explore functional nanoelectronics that is complementary to the Silicon electronics. We try to make use of various quantum objects such as an electron charge/spin, an exciton, Cooper pairs et al. that can be controlled in a single particle level and could be used in quantum computing devices and other functional quantum devices. To realize these devices in nanoscale dimensions, we not only use conventional semiconducting materials (such as Si-MOS structures), but also use carbon nanotubes and semiconductor nanowires that have extremely small dimensions which are difficult to realize with conventional lithography technique. Topological insulators could be explored by combining them with superconductors, where a unique quantum state of the Majorana zero mode is expected. We also study atom manipulation techniques for the ultimate small structures as well as inspection techniques for functional nanostructures. New physics or new functionalities that appear in the nanoscale devices and new functional materials are also our interests.

(2) Current research activities (FY2022) and plan

1) Nanoscale Si transistors for single spin control

Continuing from last year, we worked on the application of room temperature Pauli spin blockade to magnetic sensors. By optimizing the device structure and device operating conditions, we achieved a signal ratio of up to 9% and a magnetic field sensitivity of 20 microTesla. In a joint research project with Teikyo University and Kioxia Corporation, we confirmed single-electron transistor operation at 1.5 Kelvin electrical conduction in the device. Furthermore, by using the device as a highly sensitive charge system, we performed precise measurements of charge traps around the device.

Future plan, We will try to increase device performance at room-temperature as a magnetic sensor and explore a possibility for scaling.

2) Coherent control of excitons in carbon nanotube quantum dots

We have developed and demonstrated unique potential control in the individual single-wall carbon nanotubes by putting molecules at the both ends (Fig.1(a)). Formation of the coupled quantum dots have been demonstrated. In this year, we have operated the double dots as an exciton qubit by coherently controlling the quantum states. In the system, the |0> state corresponds to “no exciton” in the dot, and the |1> state corresponds to “single exciton” in the dot. The readout is carried out by measuring photoluminescence from each dot which has different emission wavelength. The important ingredient for the conditional quantum gate is an interaction between the excitons in the different dots. The CNOT

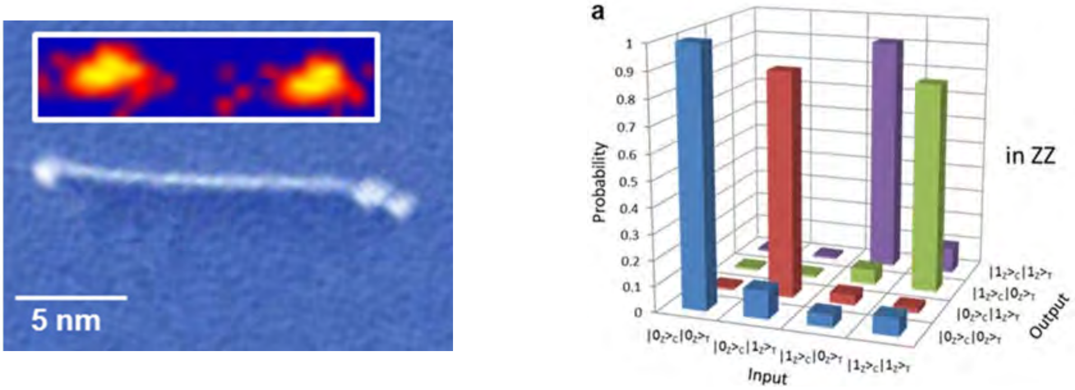

Fig (left): Scanning tunneling microscope image of the SWCNT double quantum dots and density of states in the structure. (right) Output probability of each quantum state after the CNOT operation.

(Controlled-NOT) gate operation is demonstrated in Fig.1(b) where the output state probability is measured after the CNOT operation to the coherently prepared initial states.

__Future plan__, The developed technique will be applied for the quantum emitters. We also try to develop an integration technique of the devices for practical applications.

3) Superconductor/semiconductor hybrid structures

Andreev bound states are unique quantum states formed at the interface between a superconductor and a metal. When the metal is replaced by the on-dimensional semiconductor nanowires or topological insulators, even more interesting quantum states, such as Majorana bound states, are predicted to appear. That could be used for the robust topological qubit. In our study, we use InAs based semiconductor nanowires or WTe$_2$ which is an experimentally demonstrated 2-dimensional topological insulator in a monolayer form. In this year, we have succeeded in making good superconducting contacts to the multi-layer WTe$_2$, where we found the annealing process improve the contact quality dramatically. With the process, we have demonstrated a formation of the Josephson junction (The junction showed standard JJ behaviors).

The work on the semiconductor nanowires has been carried out in collaboration with Thomas Scheapers's group in Julich Research Center in Germany, and the work on WTe$_2$ have been carried out in collaboration with Dr. Masayuki Hosoda and Dr. Kenji Kawaguchi of Fujitsu Research.

__Future plan__, A difficulty in this study lies on the material and device processing as the material easily degrades in air. We still pursue fabricating Josephson junctions with a monolayer WTe$_2$, as well as search for now material that is more robust in air and easier to handle, to achieve topological Josephson junctions.

(3) Members

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Masashi Nantoh
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Patrick Zellekens
Michael Randle
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Yoriko Asano and Yoko Sakai

(4) Representative research achievements

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2. Manabu Ohtomo, Russell Deacon, Masayuki Hosoda, Naoki Fushimi, Hirokazu Hosoi, Michael Randle, Mari Ohfuchi, Kenichi Kawaguchi, Koji Ishibashi, Shintaro Sato, "Josephson junctions of Weyl semimetal WTe2 induced by spontaneous nucleation of PdTe superconductor", Appl. Phys. Express **15**, 075003 (2022)
3. Akira Hida and Koji Ishibashi, "Exciton Controlled-NOT Gate Using Coupled Quantum Dots in Carbon Nanotube", ACS Photonics, 9, 3398-3403 (2022)
4. Patrick Zellekens, Russell Deacon, Pujitha Perla, Detlev Grützmacher, Mihail Lepsa, Thomas Schäpers, and Koji Ishibashi, "Microwave spectroscopy of Andreev states in InAs nanowire-based hybrid junctions using a flip-chip layout", Communications Physics, **5**, 267 (2022)
5. Yoshisuke Ban, Kimihiko Kato, Shota Iizuka, Shigenori Murakami, Koji Ishibashi, Satoshi Moriyama, Takahiro Mori and Keiji Ono, "Introduction of deep level impurities, S, Se, and Zn, into Si wafers for high-temperature operation of a Si qubit", Jpn. J. Appl. Phys. 62, SC1054 (2023)

Laboratory Homepage

http://www2.riken.jp/lab/adv_device/en/index.html