Report of RCNP International Joint Usage/Joint Research

1. Title of research

- Radioactivity analysis for the research of radiation response of semiconductor quantum devices

2. List of collaborators (Name; Position; Affiliation; E-mail)

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3. Period of research

- From August 2021 to March 31st, 2022

4. Method and location of collaboration implementation (remote, or any place in case in person)

- Double Beta Decay experiment room, Kamioka Underground Laboratory

5. Publication list (Articles, Talks, Theses)

Articles

- No articles

Talks

- 「量子ポイントコンタクトの放射線応答の調査」，湯田　秀明，吉田　斉，大塚　朋廣，岸本 康宏，2022年3月，日本物理学会 第77回年次大会
- “Basic Research on Radiation Response of Semiconductor Quantum Devices”, H. Yuta, Y. Kishimoto, T. Ohtsuka, S. Yoshida, Feb.17, 2022, FY2021 RIEC Annual Meeting on Cooperative Research Projects

Theses

- No Theses

6. Description of the results and outputs(*)

We investigate the resistance of semiconductor quantum dots (semiconductor QDs) to ionizing radiation and their potential use as sensors for radiation detectors. Semiconductor QDs, together with superconducting qubits, are promising as the core quantum devices for quantum computers. Quantum coherence is essential for quantum computers. Ionizing radiation from semiconductor QDs and their surroundings deteriorates this coherence, and may be one of the factors that hinder the realization of a quantum computer with many bits in particular. In this study, we investigate the response of semiconductor QDs to radiation and study this problem.

If semiconductor QDs show a sensitive response to radiation, we intend to explore the application to a high-sensitivity radiation sensor that actively utilizes this point.

Since semiconductor QDs operate at cryogenic temperatures in a vacuum, it is not easy to set up a radiation source in the vicinity of the cryostat. If a radiation source is installed outside the cryostat, it requires a very strong gamma-ray source, which is impractical. We therefore focused on the fact that the substrate of the quantum QD is GaAs, and decided to use the neutron capture reaction of Ga and As followed by a beta decay event. As shown in the table1, both Ga and As have large capture cross sections and half-lives exceeding 10 hours. Therefore, the number of radioactive nuclei produced by the neutron capture reaction in the substrate is large, and the time required for cooling the substrate after neutron irradiation is sufficient. Moreover, since the nuclei decay and lose their radioactivity in a few days, it is expected that the changes over time can be followed to clearly see the effects of radioactivity.

Table1: Radioactivity produced by neutron irradiation of GaAs substrate

Nuclide	Natural Abundance(%)	Cross section (barn)	Radio-nuclide	Half-life	Q-value (MeV)
^{69}Ga	60.2	1.9	^{70}Ga	21.1 m	1.66
^{71}Ga	39.8	5.0	^{72}Ga	14.1 h	3.99
^{75}As	100	4.5	^{76}As	26.3 h	2.97

For the activation of this substrate, a neutron source at the underground experimental facility in Kamioka, Gifu Prefecture, was used, and for the measurement of radioactivity after activation, an ultra-low background HPGe detector installed in Lab-D was used. In addition, quantum point contacts (quantum PCs) were used instead of quantum QDs for the illustration study. The reason for this is that quantum PCs have a highoperating temperature and can start experiments in a short time.

In the Kamioka underground, a GaAs substrate was activated near a 252Cf neutron source (1.1 MBq) surrounded by a polyethylene moderator and graphite neutron reflector, followed by measurements using a low-background HPGe detector. As a result, 198Au (144 keV) and 187W (685 keV) were observed in addition to the expected 72Ga and 76As. Since tungsten (W) is not present in the GaAs substrate but only in the surrounding package, this nucleus is not available. On the other hand, gold (Au) is used as an electrode on the substrate (about 1% of the total) and is also used as plating on the periphery of the substrate, so this nucleus can be used to study the radiation response to quantum devices.197Au has a natural abundance ratio of 100% and a reaction The cross section is very large (98.65 barn) and the half-life is long (64.66 h), so it can be used very effectively.

The above results, i.e., the effect of ionizing radiation by activating the substrate Ga, As, Au as wiring material, etc., was investigated in Quantum PC. The quantum PC substrate was irradiated with neutrons for 7 days, half of which was used to measure the radioactivity with HPGe detector, and the other half was placed in a cryostat to measure the current value of the quantum PC. The produced radioactivity in the GaAs substrate was evaluated as in Table2.

Table2: Produced radioactivity in the GaAs substrate.

Product nuclide	Radioactivity（Bq）	Half-ife
^{72}Ga	$(1.3 \pm 0.3) \times 10^{-2}$	14.1 h
^{76}As	$(2.6 \pm 0.5) \times 10^{-2}$	26.24 h
^{198}Au	1.64 ± 0.06	64.66 h

It is known that the current value of the quantum PCs changes in a short time in a spike manner. This spike-like change is thought to be caused by the transition of a charge trapped near the quantum PC, which in turn causes a change in the electrostatic field of the quantum PC. In this study, we investigated the frequency of the spike phenomenon, based on the idea that the ionizing effect of radiation may affect this spike phenomenon.

In contrast, the frequency of quantum PC spike events was compared in two cases, one about 30 hours after the end of neutron irradiation, and the other after one month had passed since the end of neutron irradiation and the radioactivity had ceased. The results are summarized as follows

- Measurement from 20 to 170 hours after the end of activation

A sharp decrease in the frequency of spikes was observed at a time constant of about 50 hours after the end of activation. After 100 hours, the frequency of spikes showed a constant value of about 0.5 to 1.0 spikes per hour.

- Measurement of samples after one month of activation

After the start of the measurement, the frequency of spikes was high, but it suddenly decreased (time constant of about 10 hours), and a frequency of 3 to 8 spikes per hour was observed.

Although the decrease in spike frequency immediately after the end of activation is consistent with the half-life of 198Au, a decrease from the beginning of the measurement was also observed in the sample taken one month after the end of activation, and the spike frequency after settling to a constant value was greater than that immediately after the end of activation. These data strongly suggest the need to conduct experiments at higher radiation intensities. We plan to increase the radiation intensity and investigate radiation effects in detail.

7. Amount of budget implemented and used

- No budget requests

8. Requests or comments for improvement of the COREnet program