Evaluation of radioactivity in semiconductor samples by Kr-ion beam irradiation

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On the basis of a fee-based facility-sharing program, RIKEN provides heavy-ion beams from RIKEN Ring Cyclotron (RRC) to private companies for the irradiation of semiconductor devices to be used in satellites. By using the accelerated heavy ions, the clients simulate the single-event effects (SEEs) of the devices caused by heavy-element components of cosmic rays. The samples are irradiated at the E5A beamline[1] in the atmosphere, and the linear energy transfer (LET) of the beam can be adjusted with an energy-degrader system. During the irradiation, the samples become radioactive through two processes: (1) nuclear reactions in the sample induced by the beam and (2) the injection of secondary nuclides produced in upstream materials. The secondary nuclides contaminate the beam and affect the LET distribution, while the nuclear reactions in the sample may contribute to SEEs. To assess the beam contamination and to understand the irradiation effects in industrial utilization, we studied the radionuclides in the irradiated samples by employing a radiochemical method.

In March 2017, during beam preparation and characterization for a client's beam utilization, we irradiated test samples with a ^{84}Kr beam under the same condition as the client's irradiations. A 70-MeV/nucleon ^{84}Kr beam from the RRC passed through a 50-μm-thick Au foil as a scatterer, a Kapton window separating vacuum and the atmosphere, an ionization chamber, a 0.1-mm-thick plastic scintillator, an energy degrader consisting of a 586-μm-thick aluminum layer, and an approximately 305-mm-thick atmosphere, following which it impinged a test sample of Si wafers (100-mm diameter and 0.5-mm thickness) or acrylic plates (75 mm × 80 mm, 1-mm thickness), where two identical plates were stacked for each material. The Si test sample was selected to simulate the clients' sample of semiconductor devices, and the acrylic resin was used to distinguish different activation processes. The yield of the secondary nuclides from the upstream materials should be independent of the sample materials, whereas that of the reaction products in the samples should be dependent. The number of the ions was approximately 4.5×10^{10} for the Si wafers and 5.5×10^{10} for the acrylic plates during irradiation for 10 min. According to SRIM calculation,[2] the ions impinged the sample at 25 MeV/nucleon, which corresponded to an LET of approximately 19 MeV/(mg/cm^2) in Si, and the primary ^{84}Kr ions stopped in the first plate of the stack. In the following, we report the analyses of the first plate, which had most of the radioactivity.

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We measured the gamma rays from the irradiated samples with Ge detectors; for the Si wafer, we performed measurements 9 times from 7 min to 91 days after the irradiation, and for the acrylic plate, we performed measurements 9 times from 10 min to 106 days. We analyzed the observed gamma-ray peaks according to the transition energies, lifetimes, and branching ratios, and we identified 61 radionuclides from ^{24}Na to ^{104}Ag in the Si wafer and 49 nuclides from ^{24}Na to ^{93m}Mo in the acrylic plate. Subsequently, we extrapolated the decay curves of radioactivity to the end of the irradiation time to obtain the production rates of the nuclides and deduced their production probabilities normalized to one incident ^{84}Kr ion.

Figure 1 shows some of the obtained nuclide-production probabilities. Nuclides with atomic number $Z \leq 36$ have similar production probabilities between the Si and acrylic samples, except for a few small-Z nuclides, which indicates that these consist mainly of secondary nuclides produced in the upstream materials. The production probabilities of nuclides with $37 \leq Z \leq 42$ are similar or higher in the acrylic sample compared with the Si sample; in particular, those of ^{83}Rb and ^{84}Rb are three to four times higher. Nuclides with $Z > 42$ are found only in the Si sample, which indicates that these nuclides are only produced by nuclear reactions in the Si sample.

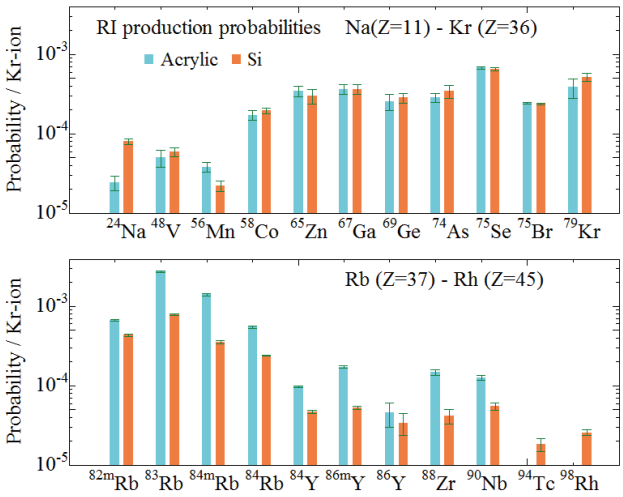

Fig. 1. Production probabilities of nuclides from ^{24}Na to ^{98}Rh obtained by the gamma-ray measurements.

References

1) T. Kambara, A. Yoshida, RIKEN Accel. Prog. Rep. **48**, 239 (2015).
2) J. F. Ziegler, `http://www.srim.org`.