Facility for Heavy-Ion Irradiation of Semiconductors at RIKEN RI-Beam Factory

Tadashi KAMBARA* and Atsushi YOSHIDA

RIKEN Nishina Center, Wako, Saitama 351-0198, Japan

Abstract

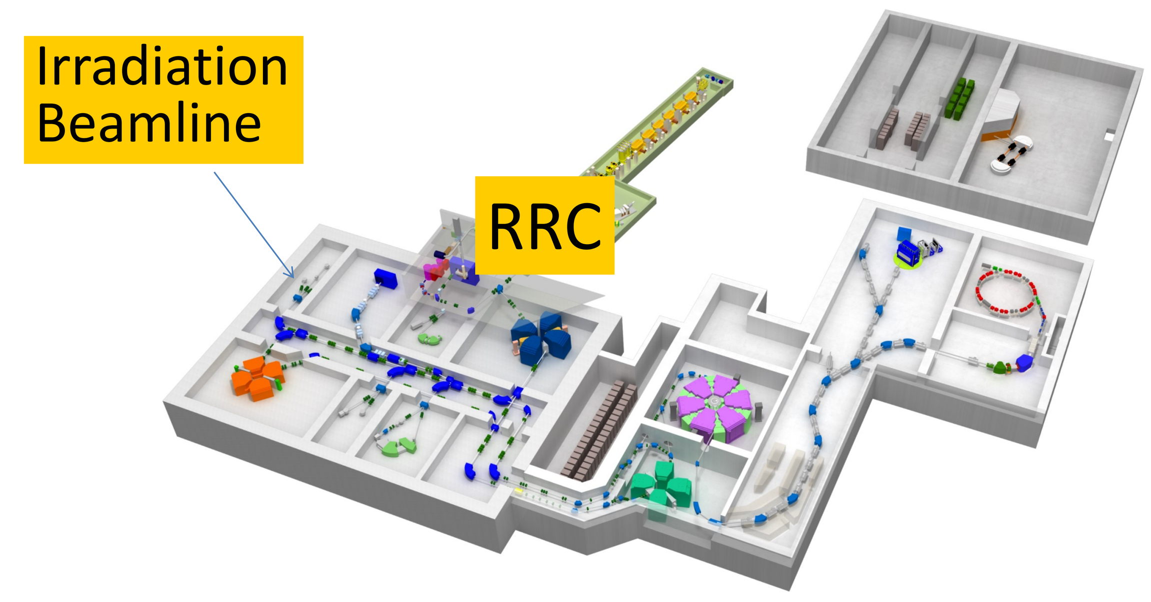
RIKEN RI-Beam Factory (RIBF) provides fast Kr and Ar ions to private companies in Japan for the SEE evaluations of space-use semiconductors.
The samples can be irradiated in the atmosphere, and LET and flux can be selected from wide range of values.
We present the irradiation facility and measurements of the beam characteristics, and discuss beam-impurity nuclides produced in the upstream materials through radiochemical analyses and ion-transport simulations.

RIKEN RI-Beam Factory (RIBF)

RIBF [1] is a heavy-ion accelerator facility which features high intensity beams of ions of all elements with energy up to 345 MeV/u and various radioactive isotope beams (RI beams).

RIBF is mainly used for experiments in nuclear physics, materials sciences, chemistry, and radiation biology.

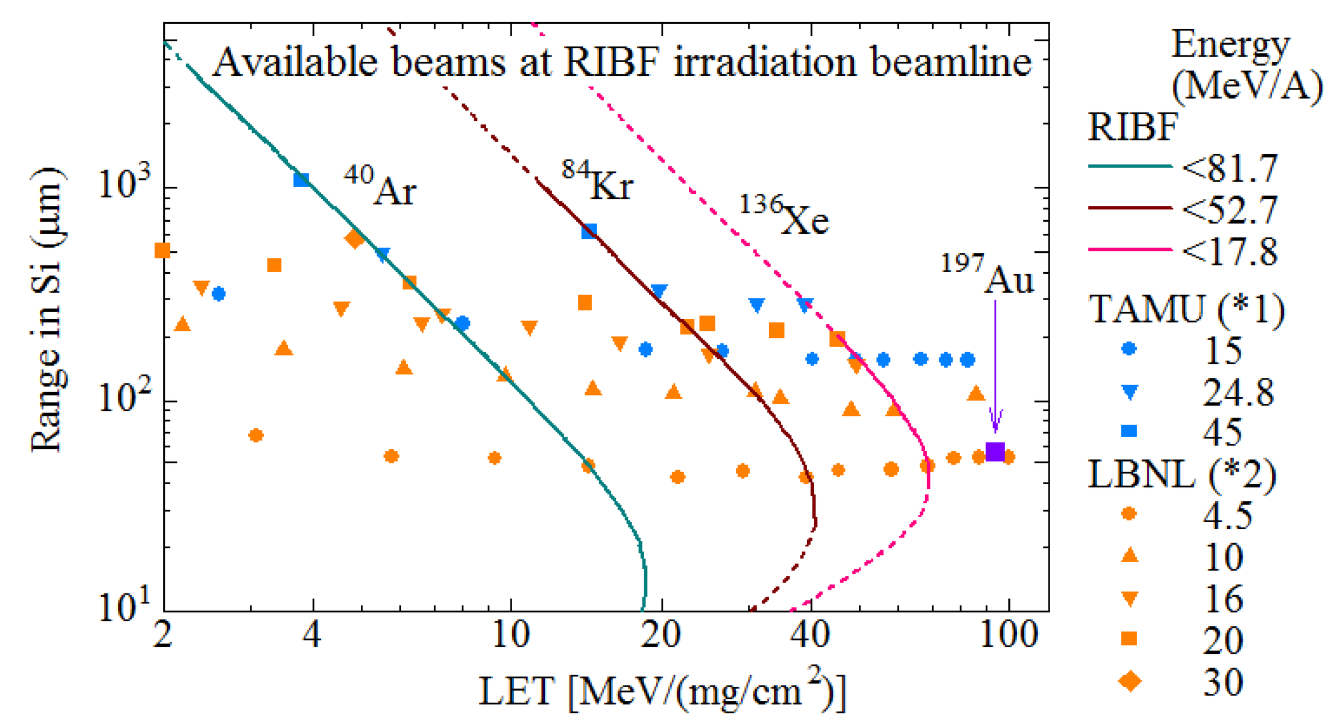
In 2014, RIBF started to provide fast heavy ions up to 95 MeV/u for fee to private companies which evaluate single-event effects (SEEs) of space-use semiconductors.



Beam and Facility for Semiconductor Irradiation

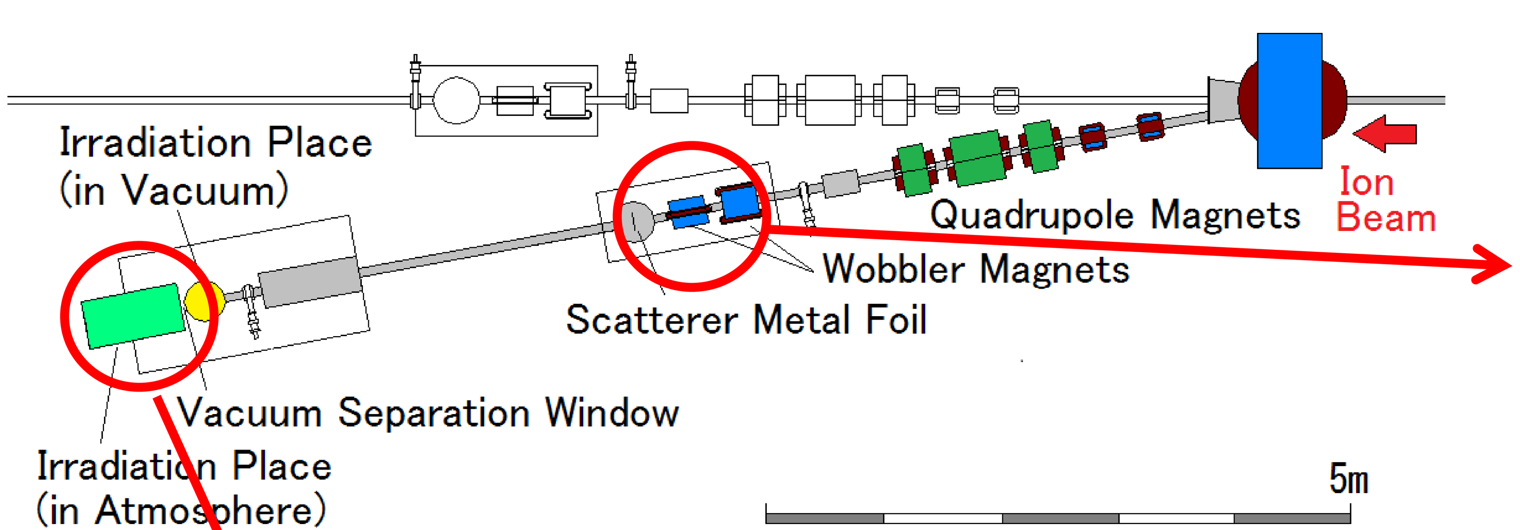
- **^{40}Ar and ^{84}Kr beams have been in practical use, while ^{136}Xe and ^{197}Au beams are being tested.**
- **Samples are irradiated in air: easy access, quick exchange and simple electric connections to the device under test.**
- **LET can be set between 2.2 and 41 MeV/(mg/cm^2) by selection of the ion species and with an energy degrader.**

Ions	Beam Energy (MeV/u)		LET in Si [MeV/(mg/cm^2)]	
	Accelerated by RRC	Max. at sample	Min. at sample	At Bragg peak
^{40}Ar	95	81.2	2.2	18.7
^{84}Kr	70	41.8	11.7	41
^{136}Xe	39	17.3	47.2	70
^{197}Au	18.4	4.6	94.1	95

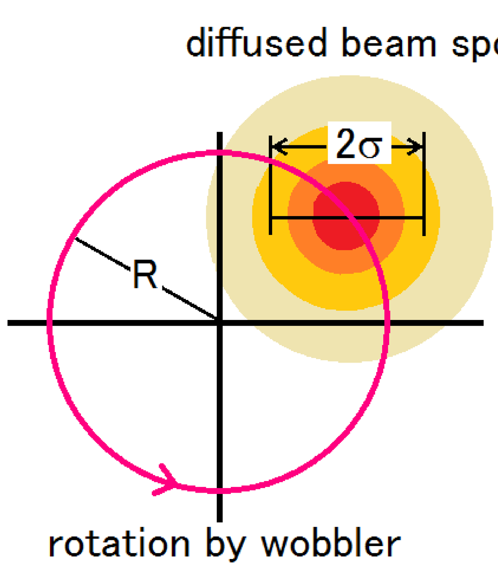


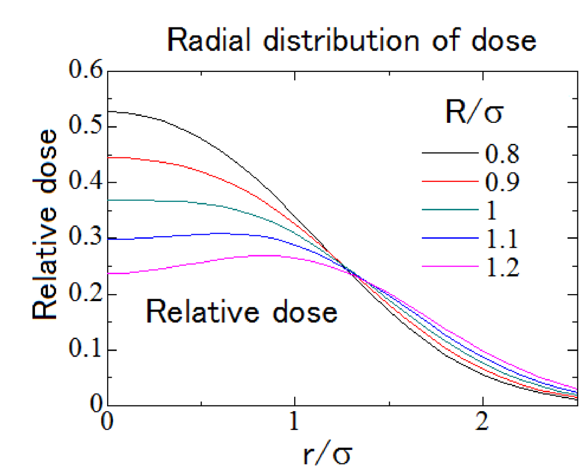
*1 https://cyclotron.tamu.edu/ref/beamlist.pdf
*2 http://cyclotron.lbl.gov/base-rad-effects/heavy-ions/cocktails-and-ions

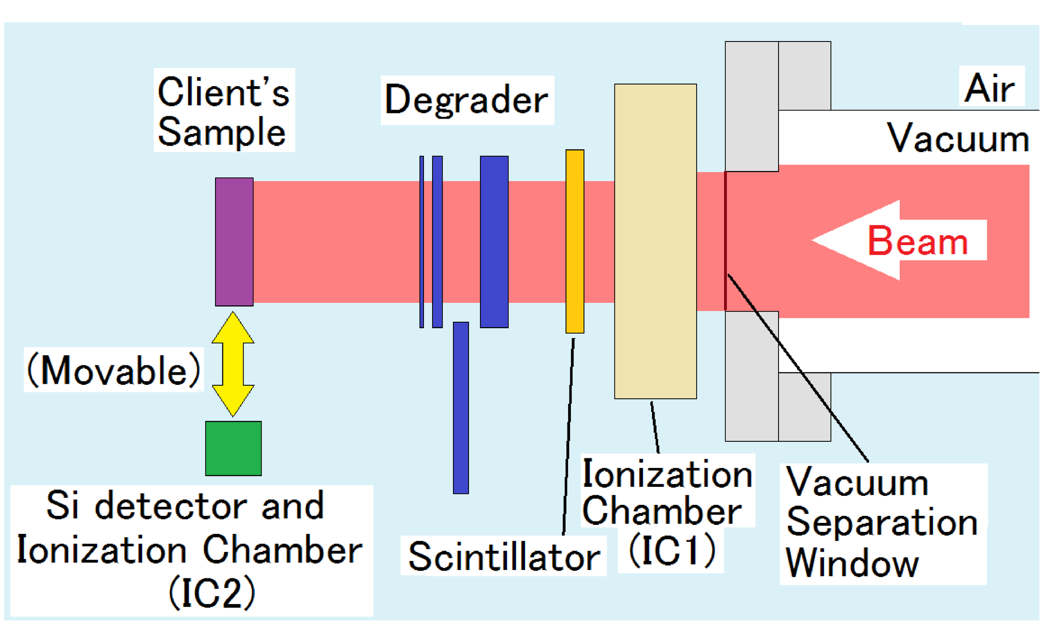
Beamline for material irradiation

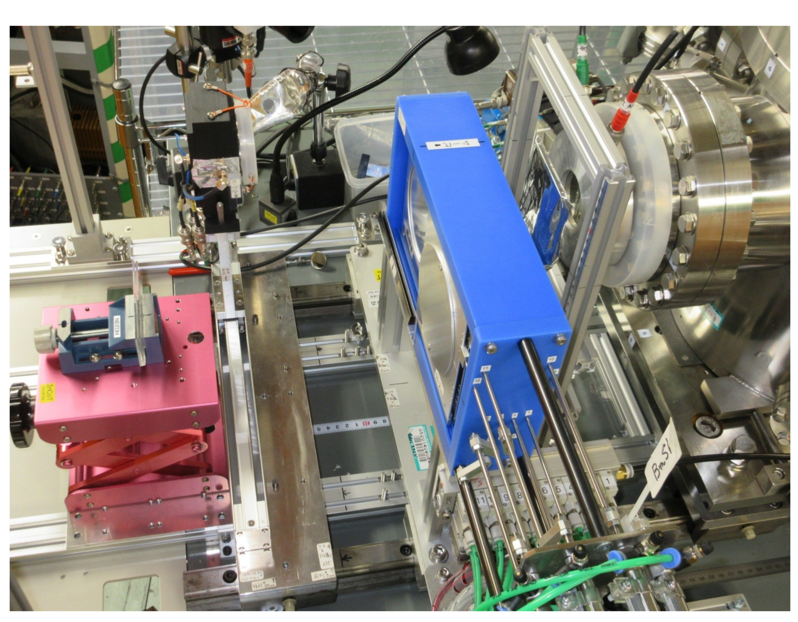


At about 4 m upstream, a gold foil diffuses the beam spot and a pair of wobbler magnets bend the beam at 60 Hz to trace a circle so that a uniform dose distribution is formed.









Before irradiation, the beam passes through

- **a vacuum separation window (60-mmφ, 75-μm thick Kapton) and**
- **two fixed transmission-type detectors to measure the beam flux:**
  (1) a plastic scintillator (100 mm x 100 mm, 0.5-mm or 0.1-mm thick) to count all ions, and
  (2) a parallel-plate ionization chamber (IC1: 50-mm diameter) for high flux.
- **LET is adjusted with energy-degrader (12 Al-foils, total thickness up to 3 mm by about 5-μm step).**

At the clients' irradiation position:
(1) Si ΔE-E detectors (total thickness 150 - 4000 μm) and
(2) a shallow ionization chamber (IC2: 14-mm diameter, 2-mm thick)
can be inserted for beam measurements.

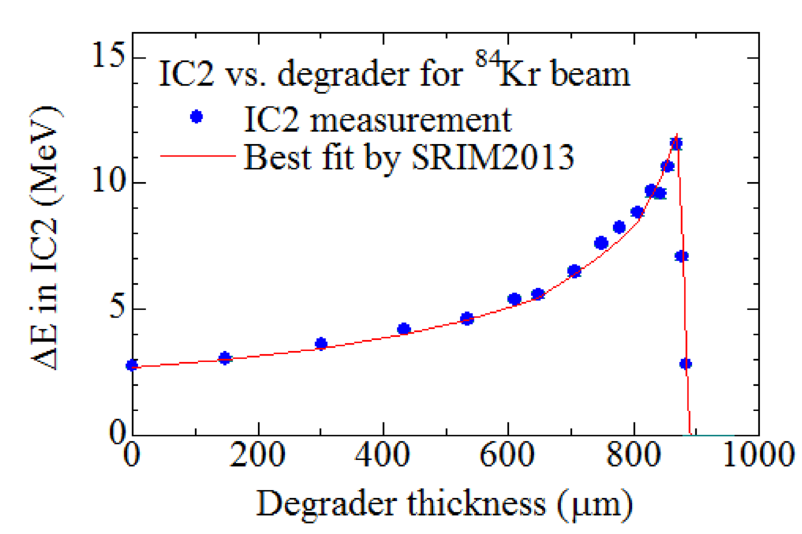
Clients control ion flux and LET from outside of the radiation controlled area via LAN

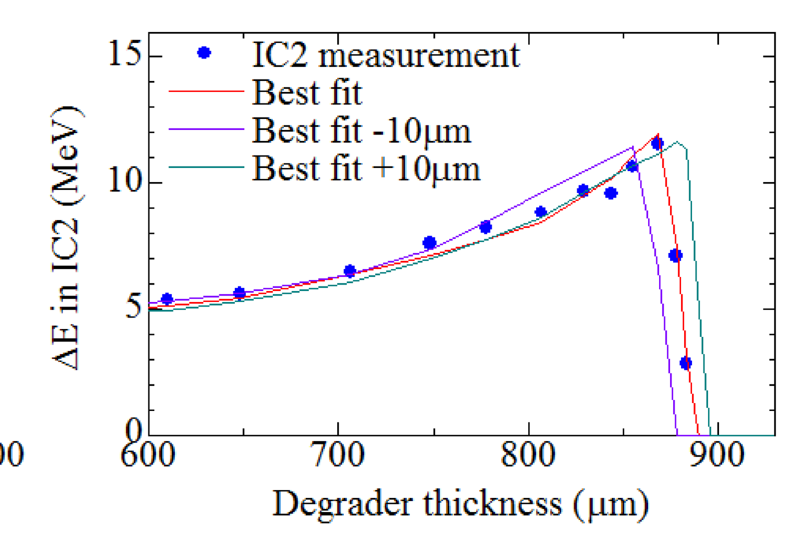
Determination of degrader thickness vs. LET

The degrader-thickness dependence of IC2 current is measured and fitted by calculations of SRIM-2013 [2].

Using the best-fit result to the Bragg-peak measurement, the beam energy at the sample is determined within 5um accuracy of the Al thickness.

The actual degrader thickness for the desired LET is then calculated with the SRIM code.



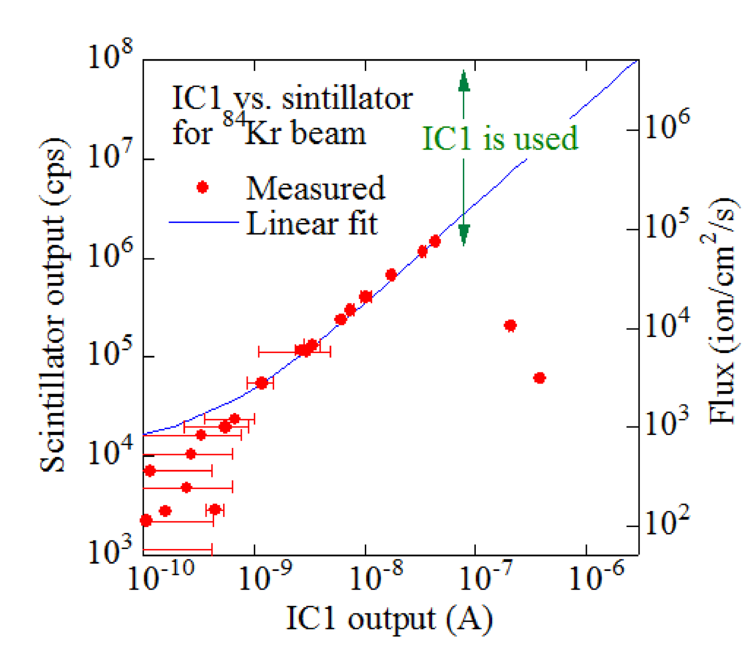


Beam flux calibration

IC1 output current is calibrated by the ion count rate of the scintillator.

Flux is continuously monitored during irradiation: scintillator is used below 7×10^4 ions/cm^2/s, and IC1 is used above it.

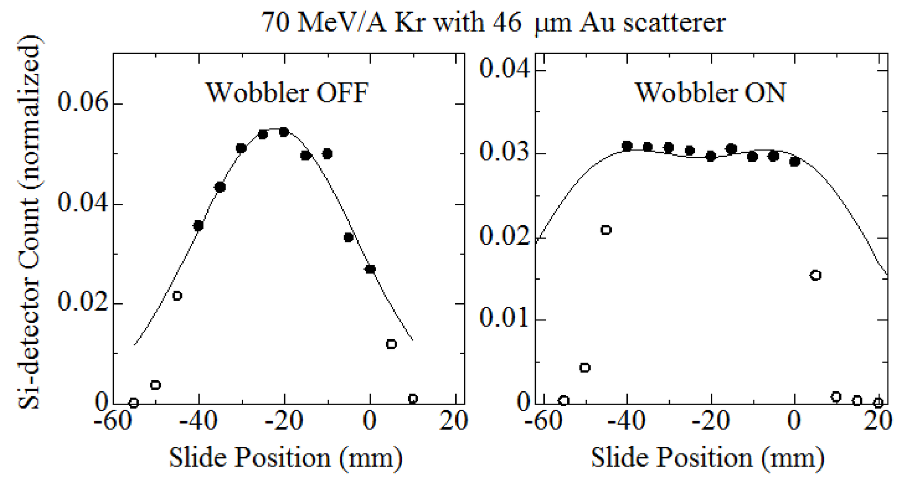
Clients can select ion flux between 10 to 10^7 ions/cm^2/s.



Uniformity of flux distribution

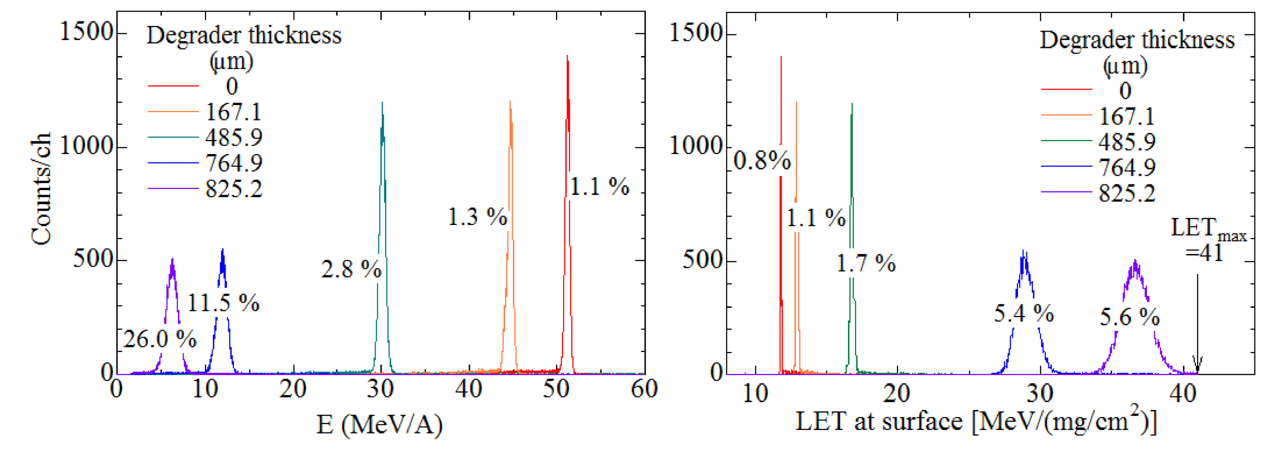
The beam is scanned by the Si detectors at the irradiation position.

The uniformity is within ±5% in a 5-cm diameter area and within ±1.8 % in a 3-cm diameter area.



Energy and LET distribution

Energy spectra of ions are measured by the Si detectors at different degrader thicknesses.

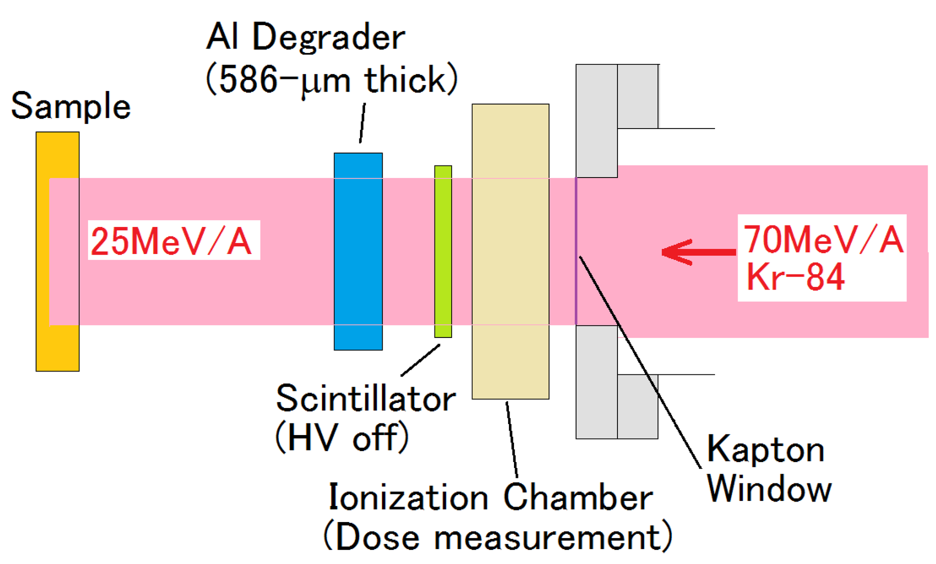


Beam Impurities Originating from Upstream Reactions

Nuclear reactions in the upstream materials, such as the window, the energy-degrader, the transmission-type detectors and air, produce fast nuclides that contaminate the beam and affect the LET distribution. We studied the production probabilities of impurity nuclides in the Kr beam by a radiochemical method and compared them with a simulation.

Irradiation of test samples

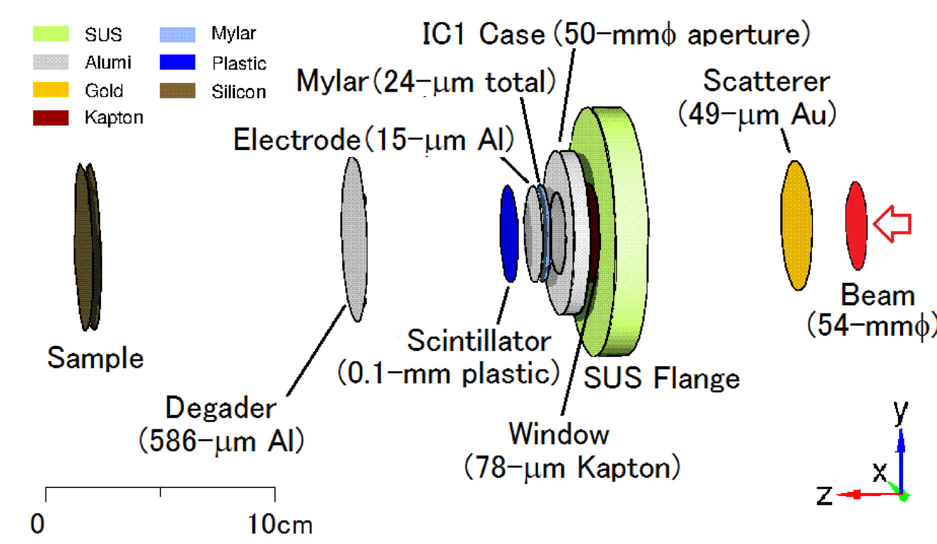
We irradiated Si wafer and acrylic plate with the ^{84}Kr beam at the clients' irradiation position. The two materials were selected to distinguish the radionuclides produced upstream from those produced in the sample. The degrader was 586-μm thick and the irradiation time was 10 min each.



Sample	Si-wafer	Acrylic plate
size	100 mmφ	75 mm ×80 mm
thickness	0.5 mm	1 mm
Number of Ions	4.5×10^{10}	5.5×10^{10}
Range	0.33 mm	0.5 mm

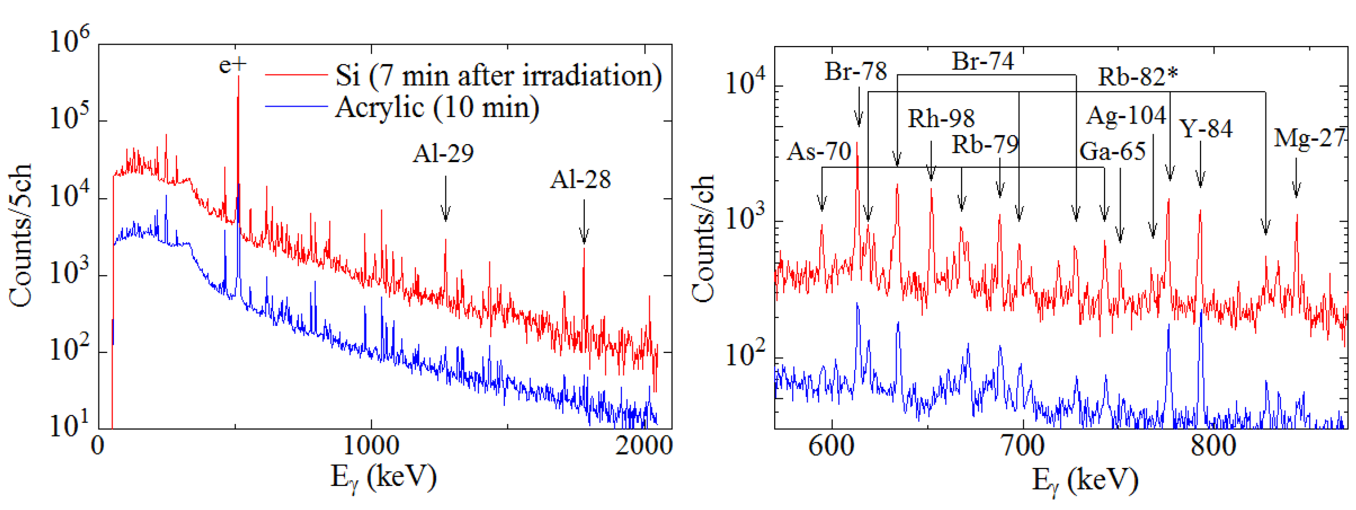
Simulation

We simulated the nuclear reactions in the irradiations with Particle and Heavy Ion Transport code System [3] (PHITS) which traced each resultant nucleus from its production to stopping, and compared the results with the gamma-ray measurements to evaluate the validity of PHITS.

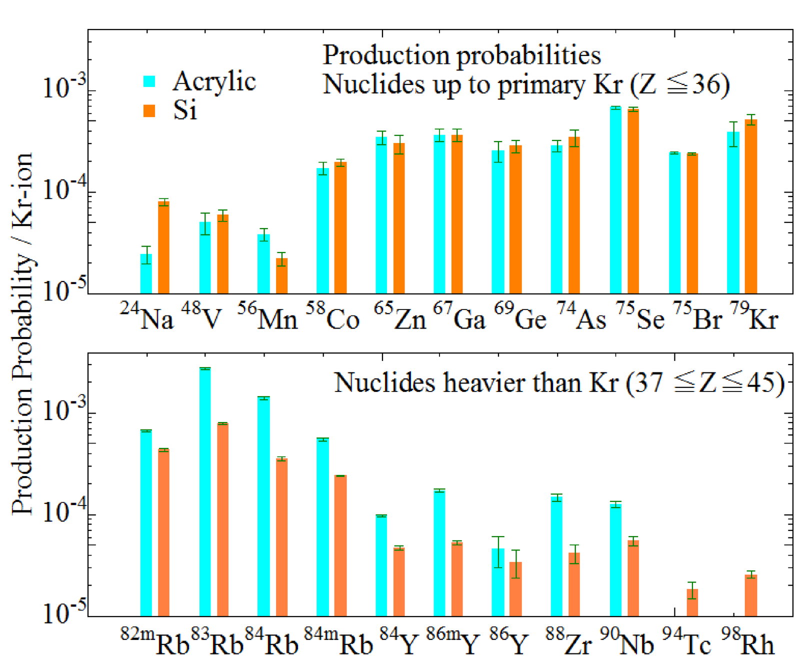


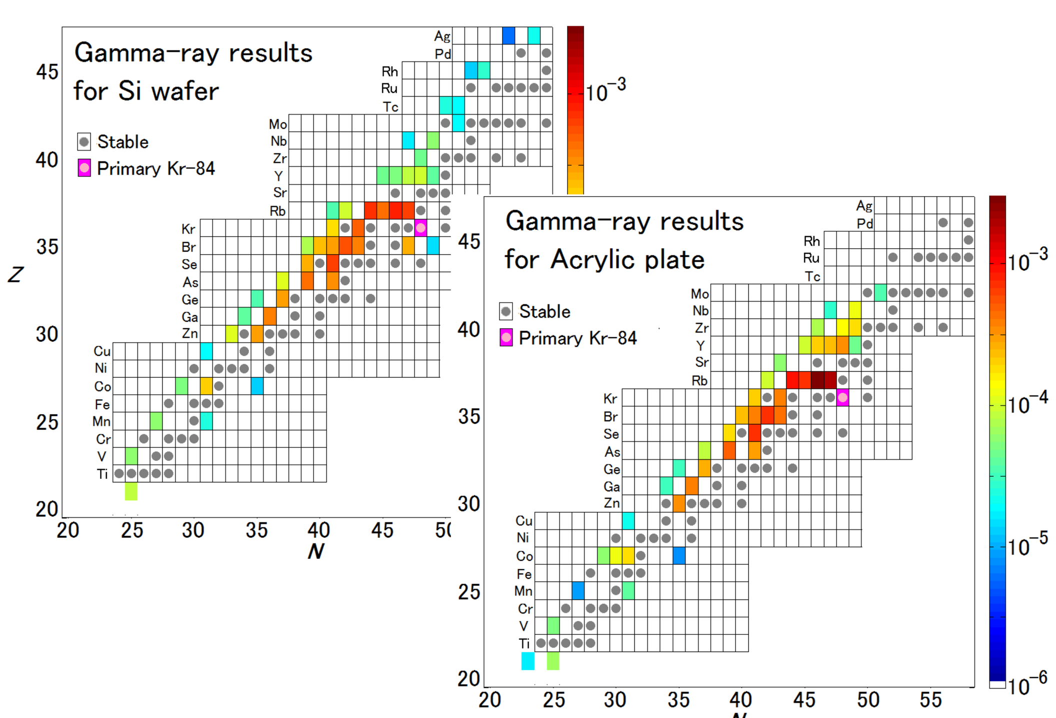
Gamma-ray measurements

Gamma-ray spectra of the samples were taken with the Ge detectors from 7 min to 3 mon after the irradiations.



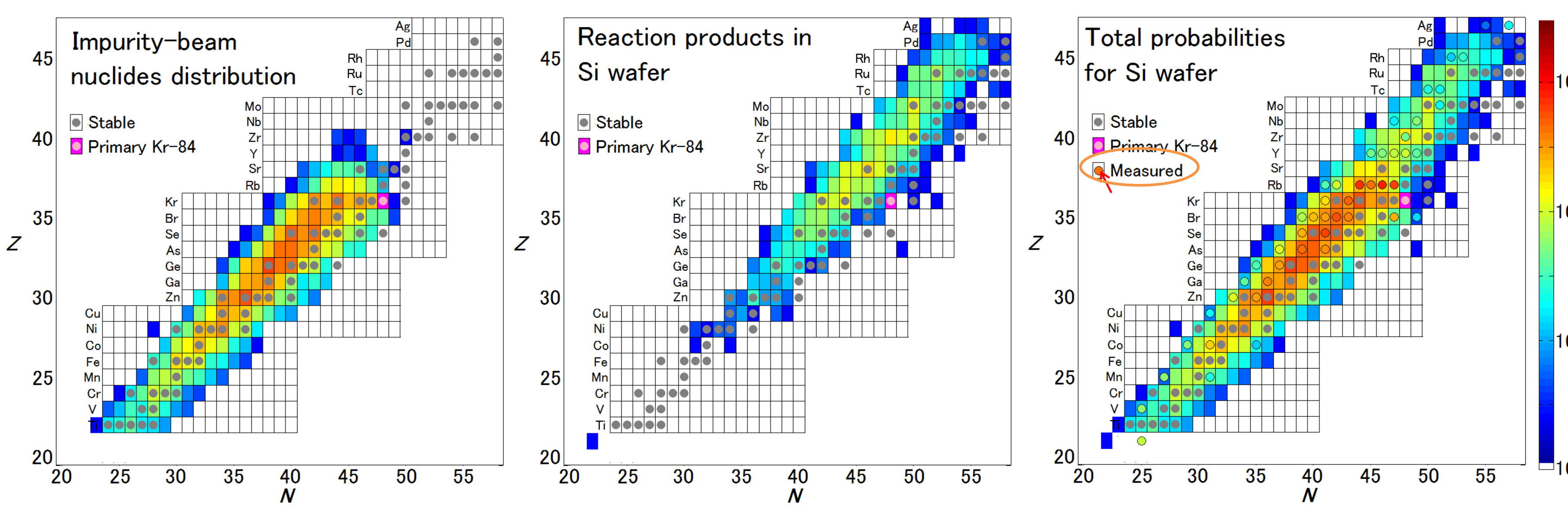
About 61 species (^{24}Na to ^{104}Ag) were identified in the Si wafer and 49 species (^{24}Na to ^{93m}Mo) in the acrylic plate.
Production probabilities were obtained from the radioactivity.





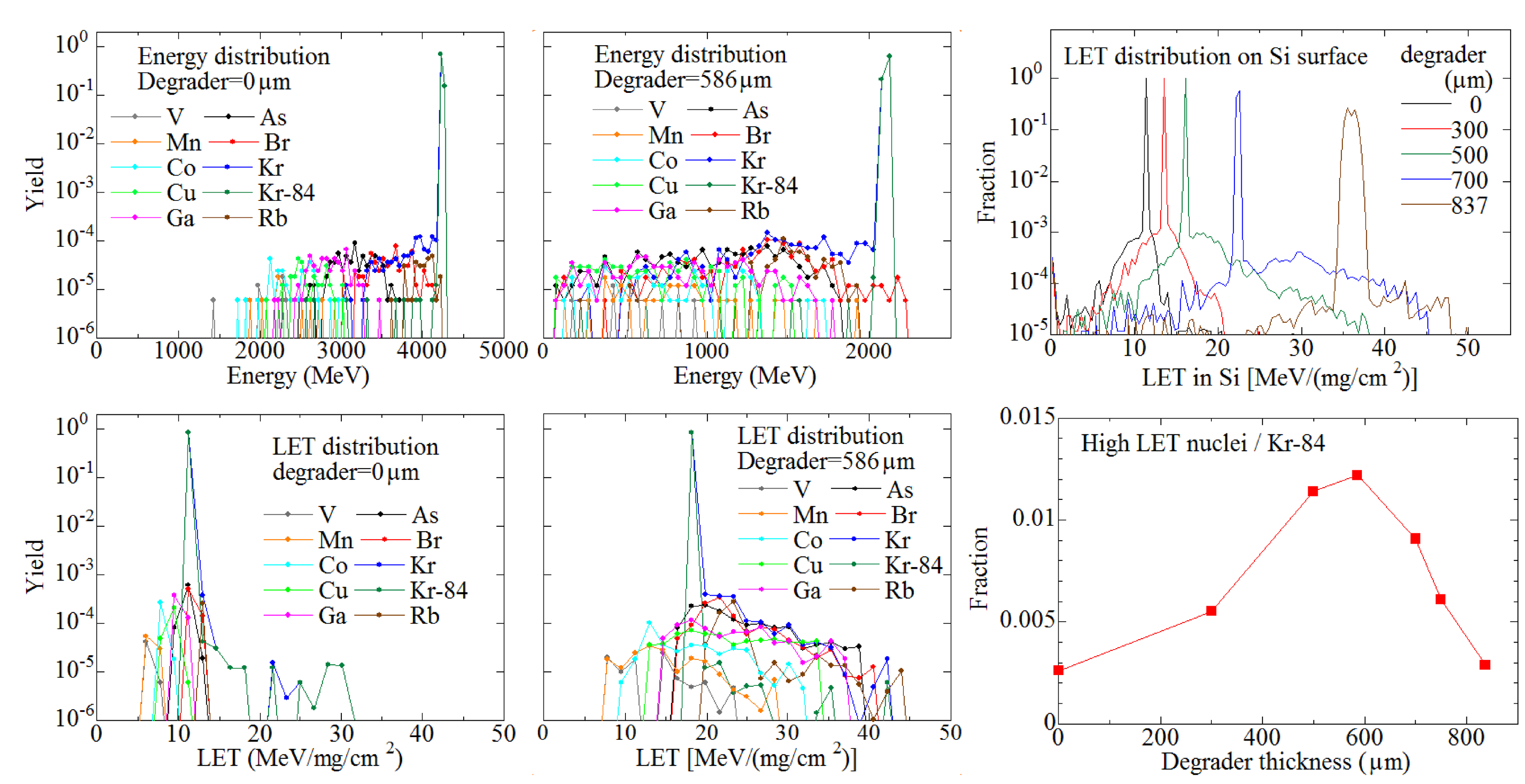
Z ≤ 36: similar between Si and acrylic, mainly impurity-beam nuclides
Z > 42: only nuclear reactions in the Si sample,
37 ≤ Z ≤ 42: similar or higher in the acrylic, both origins may contribute.

Probabilities of nuclides stopped in the sample



PHITS predicts that the impurity beam consists mainly of projectile-like nuclides with 20 < Z ≤ 39 , whereas those produced in the sample extend to higher Z, and reproduces the overall features of the measured probabilities of the RI nuclides in the samples. We think it validates the use of PHITS to simulate our beam and irradiation, and we go further into simulations with different thickness of degraders.

Degrader thickness dependence of LET distribution



According to PHITS, the high-LET impurity is degraded projectile-like nuclides and accounts for about 1 % of the beam at maximum for intermediate thicknesses of the degrader.

Summary

RIKEN RI Beam Factory provides fast heavy ions to private companies in Japan to simulate cosmic-ray induced SEE in space-use semiconductor devices.
Kr and Ar ions are in use with a uniform dose distribution in the 5-cm-diameter area and the LET selectable from 2.2 to 41 MeV/(mg/cm²).
Samples can be irradiated in air and the clients can control the LET and ion flux from outside of the radiation-controlled area.
Production probabilities of impurity-beam RI nuclides were measured by radiochemical analyses of irradiated test samples.
Heavy-ion transport simulations reproduced the overall features of the measured probabilities, and shows that high-LET impurity nuclides produced in the upstream materials accounts for about 1 % at maximum of the intensity of the Kr-beam.

References

1. H. En'yo, Nuclear Physics News, Vol. 25, No. 3 (2015) 5, http://www.rarf.riken.jp/index_e.html.
2. J. F. Ziegler: http://www.srim.org/.
3. T. Sato et al., "Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02", J. Nucl. Sci. Technol. https://doi.org/10.1080/00223131.2017.1419890, https://phits.jaea.go.jp/index.html.