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Precision Control for Beam Irradiation Dose by Developing a Real-time Dose Monitoring System

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We have developed a real-time dose monitoring system for a low-energy ion-beam facility. Before we developed the monitoring system, the system had given a substantial error of ±23% when we irradiated an ion beam with a dose as much as 3.0×10^{16} cm^{-2} on the Si substrate. Moreover, a low irradiation dose as small as 10^{13} cm^{-2} was scarcely able to be controlled because of a too short irradiation time of several seconds, producing a greater dose error. To develop a real-time dose monitoring system, in this work, we employed a current integrator in conjunction with a beam stopper, by which a dose of 3.0×10^{16} cm^{-2} can be exactly irradiated on the sample with less than ±6% error, which was ensured by the measurements of Rutherford backscattering spectroscopy.

Keywords: Real-time dose monitoring system, Ion-beam facility, Rutherford backscattering spectroscopy
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I. INTRODUCTION

The gas ion beam facility installed at the Korea Multipurpose Accelerator Complex (KOMAC) has been providing various kinds of ion beam outputs, such as H^+, N^+, Ar^+, and He^+, for many scientific users [1]. Moreover, more kinds of gas ions have been developed in this facility. For reliable beam irradiation effects on matter by using this facility, precision irradiation doses as one intends should be made [1–3]. Previously, however, from a scientific point of view, we often encountered unacceptable beam-irradiation effects on matter. In many cases, due to a greater dose uncertainty, a low irradiation dose may frequently invoke some deviation from the irradiation dependence. Thus, exact control of beam irradiation doses is essential if accurate beam irradiation effects on matter are to be obtained [2,3].

Before we had developed a real-time dose monitoring system, we used a digital oscilloscope to estimate the dose irradiated [4], the current coming from Faraday cups being converted to a voltage signal and then being integrated. It took a long time to analyze the total charge because of the big data size recorded at a rate of ∼1Mb/sec wasting much memory space, thus making estimates of the irradiation doses difficult. In this older system, we needed to keep monitoring doses irradiated and stopped the irradiation by pushing a button manually when the irradiating dose seems to be consistent with the intended dose. This method frequently led to an unwanted error in controlling the irradiation dose. In this work, we have developed a real-time beam monitoring and control system, for which we employed a digital current integrator and counter. The irradiated doses obtained using the dose-estimating systems before and after development were compared by using Rutherford backscattering (RBS) spectroscopy [5,6]. We found the dose accuracy to be highly enhanced in the recently developed system compared to the older system, even for high-dose beam-irradiation experiments.

II. EXPERIMENT

We have employed an Ortec 439 digital current integrator (AMETEK Inc., USA) to integrate the beam currents obtained from the two Faraday cups. The two Faraday cups are used for measuring the beam currents on the right and the left sides, enabling us to enhance beam irradiation uniformity by controlling the beam direction. The data obtained were transferred into an Ortec 928 counter (AMETEK Inc., USA), in which the counter measures the beam currents on both sides, and the timer activates the beam stopper when the accumulated current corresponds to an intended value. After the real-time dose monitoring system had been developed, we performed beam-irradiation experiments on Si wafers to assess the developed system. We used an Ar^+ ion beam to irradiate Si wafers with a dose of 3.0×10^{16} cm^{-2}. The dose irradiating Si was estimated by using RBS spectroscopy [5,6] and was compared with the data obtained from the older system.

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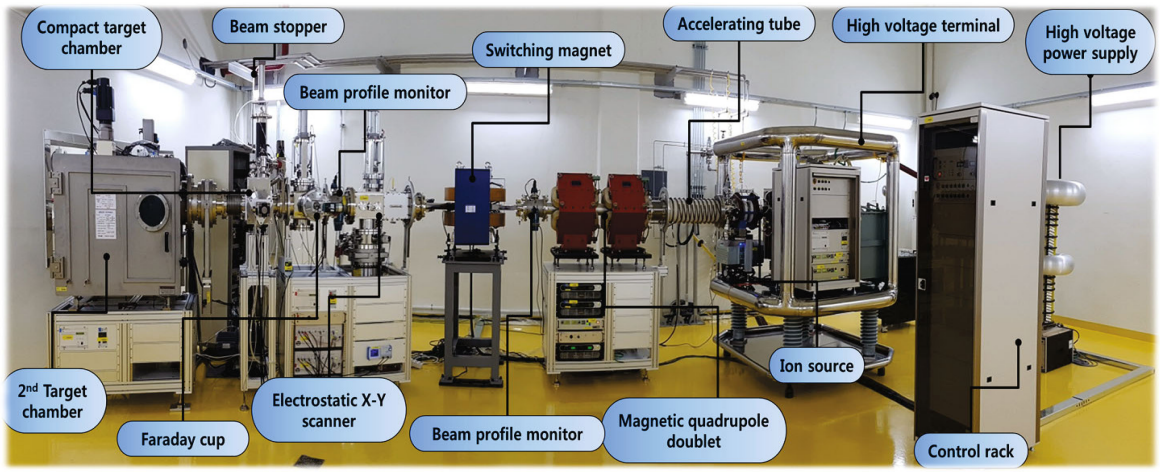

Fig. 1. Whole view of a gas ion facility, for which each part is indicated in this figure. To make a real-time dose monitoring system, we attached a beam stopper in front of the compact target chamber.

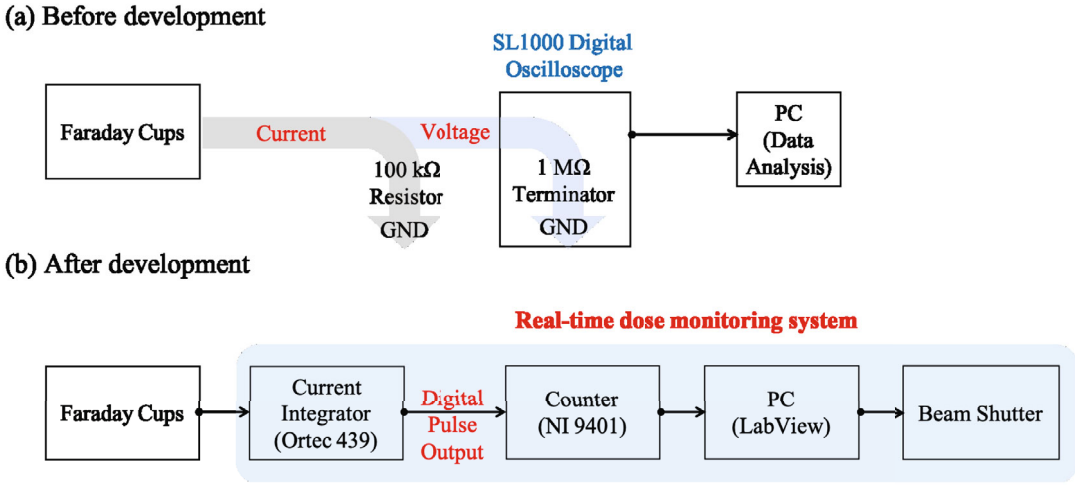

Fig. 2. (a) The currents from the Faraday cups were measured by using a digital oscilloscope. The charge was converted to a voltage signal by using a 100 ± 1 kΩ resistor. Then, the voltage signal was integrated, taking a long time to analyze the total charge, as well as using consuming much memory. (b) A digital current integrator and counter were used for real-time control of the beam fluence. The currents from the Faraday cups were measured by using a digital current integrator that digitizes the input current, producing output pulses for three specific different input charges: 10^{-6}, 10^{-8}, or 10^{-10} C. The digitizing rates of the integrator were specifically in the range from 0 to 10 kHz.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the gas-ion-beam facility, which has been providing beams for scientific users studying material science and surface engineering [1]. The principal parts of the facility are noted in Fig. 1. As a part of the development, an automatic plasma-generating method in the ion source has been developed. Before the development, the manual procedure for plasma generation was as follows: the filament power should be turned on to heat the filament, followed by gas flowing and then the arc power being turned on. In this procedure, we should turn them on in order after ensuring each procedure had properly worked. During the beam extraction, the filament power can also be changed; thus, we should manually control it to have a stable beam [4]. However, in the real-time monitoring system after the development, all the processes mentioned above work automatically, enabling an automatic adjustment of the extracted beam current via a proportional-integral-differential control of the filament input current. A beam stopper was installed to prohibit further beam irradiation on the sample after an intended dose had been achieved.

In Fig. 2, two different methods for charge accumulation are displayed. Before the development, we used the digital oscilloscope for the irradiated dose estimate, as shown in Fig. 2(a). The charges coming from the Faraday cups are converted to a voltage signal in this os-

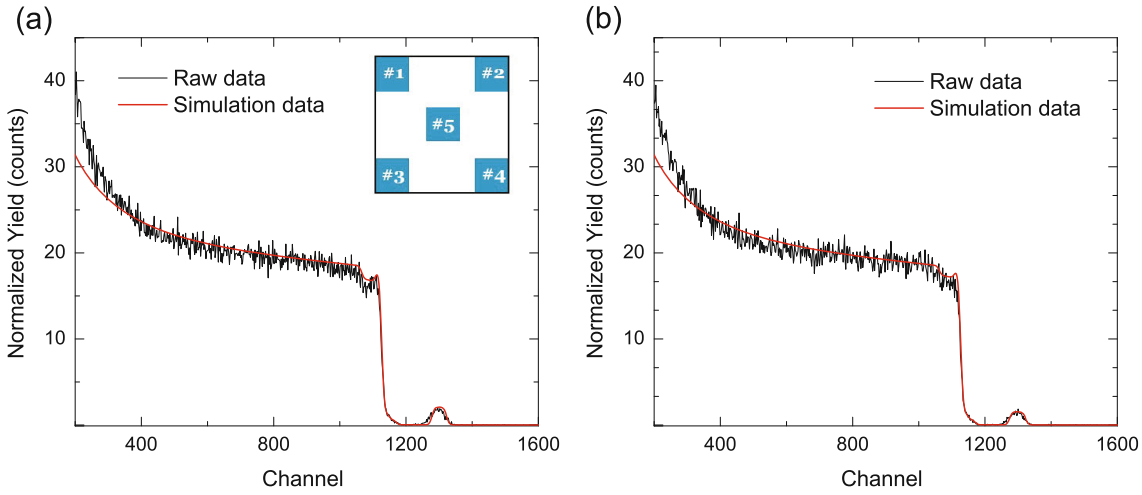

Fig. 3. RBS spectra (a) before and (b) after developing the system. Inset of (a) shows the different positions of the five samples for beam irradiation, providing data on beam uniformity. All samples are 1 cm × 1 cm in size, the entire area being 4 cm × 4 cm. The detailed doses and their errors obtained by analyzing the spectra are summarized in Table 1.

cilloscope [4]. The data, however, consume much storage because they are accumulated as fast as ∼1 Mbyte/sec. Then, to estimate the accumulated charge, we should integrate the voltage signal, although it takes a longer time as the number of data is greater. In the end, we cannot estimate the beam current and the accumulated charge in real-time. Therefore, we have a great error when the intended dose is as small as 10^{13} cm^{-2} because of the irradiation time being too short as small as several seconds when dealing with the data. In Fig. 2(b), the new method is conceptually much different from the older one. We employed a current integrator and counter, which can quickly digitize the input current. When the charge piles up to the limit of capacitors being able to store as much as 10^{-6}, 10^{-8}, or 10^{-10} C, the integrator creates an output pulse with 500-nm width and a maximum frequency of 10 kHz, emptying the accumulated charge in the capacitors. This method, thus, measures the charge and accumulates the beam current in real-time. Finally, the timer stops the beam from irradiating on the sample by making the stopper work when the charge accumulates as much as the intended value.

Figure 3 shows the RBS data and the simulated spectra for Ar^+-ion-implanted Si measured before and after the development. Fitting to the model as shown in Eq. (1), which was generated using the RUMP software, reveals the numbers of Ar^+ ions, *i.e.*, the Rutherford cross-section for backscattering (σ_R), in each sample at different positions [5–7]:

$$\sigma_R(E,\theta) = \left(\frac{Z_1 Z_2 e^2}{8\pi\varepsilon_0 E}\right)^2 \times \frac{1}{\sin^4\theta}\frac{\left[M_2\cos\theta + (M_2^2 - M_1^2\sin^2\theta)^{1/2}\right]^2}{M_2 \times (M_2^2 - M_1^2\sin^2\theta)^{1/2}}, \quad (1)$$

Table 1. The irradiated doses and their errors estimated from the RBS spectra for Ar^+ ions in Si before and after developing a real-time dose monitoring system. The intended dose was 3.00 × 10^{16} cm^{-2}.

Faraday cup	Digital oscilloscope (old)		Current integrator (new)	
	Dose [× 10^{16} cm^{-2}]	Error [%]	Dose [× 10^{16} cm^{-2}]	Error [%]
No. 1	3.55	+18	2.81	−6
No. 2	3.55	+18	2.92	−3
No. 3	3.45	+15	2.97	−1
No. 4	3.55	+18	3.08	+3
No. 5	3.70	+23	2.92	−3

where θ is the scattering angle, Z_1 and M_1 are the nuclear charge and mass of the projectile, respectively, and Z_2 and M_2 are the nuclear charge and mass of the target atom, respectively. The beam uniformly irradiated five samples positioned at different areas, as shown in inset of Fig. 3(a). The irradiated total dose for singly charged ions reads as

$$\text{Dose } \Phi = \frac{\left(\dfrac{\text{Ion beam current in amps}}{Q}\right)\cdot(\text{Irradiated time})}{\text{Ion beam scanning area}}. \quad (2)$$

In Table 1 are summarized the irradiated doses and their errors for these samples obtained by using the RBS analysis. With the developed system, the dose error decreases to less than ±6% from ±23%, proving that the developed real-time monitoring system is a good method

for controlling the irradiation dose. We note that, in the older system, we manually activated the stopper when reaching an intended irradiation dose with an error of less than ±1%. The discrepancies between the doses acquired from the system and those from the RBS data may come from a deviation of the offset value in the digital oscilloscope. Even a slight offset value can lead to a large discrepancy when the accumulated data becomes large, *i.e.*, a high irradiated dose.

IV. CONCLUSIONS

In summary, we have developed a real-time dose monitoring system and have compared the irradiated doses acquired before and after the development, and the data being observed using Rutherford backscattering spectroscopy. In the developed system, the dose error decreases to less than ±6%, giving a substantially enhanced accuracy as compared to the older system. The developed system will be helpful in understanding the beam irradiation effects on various types of matter, prohibiting unwanted experimental errors due to the radiation.

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