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Measurement of lifetimes of thin carbon stripper foils produced by ion-beam sputtering

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ABSTRACT

Thin carbon stripper foils used in high-intensity proton accelerators and heavy-ion accelerators must have long lifetimes. Thin carbon foils were fabricated by ion-beam sputtering using reactive and inert gas ions. The lifetime of the foils was measured using a KEK 650-keV high-intensity DC H^- (negative hydrogen ion) beam; changes in the foil thickness and surface deformations during irradiation were investigated. The lifetime of a typical stripper foil fabricated by heavy-ion-beam (Ar and Kr) sputtering was 60–70 times longer than that of the best commercially available foils. This paper reports a fabrication method for carbon stripper foils, along with an investigation of their lifetimes and changes in foil thickness during beam irradiation.

1. Introduction

Recent improvements in the design and operation of ion sources and related devices used in accelerators have enabled the realization of high-intensity ion-beam currents. However, these currents cause radiation damage to thin carbon stripper foils and thus decrease their lifetime. The operational efficiency of Pelletron-type tandem, cascade-type proton, and heavy-ion accelerators strongly depends on the lifetime of the stripper foils [1–3]. Replacing damaged foils with new ones would cause beam stop and radiation hazards to maintenance personnel. At the Japan Proton Accelerator Research Complex (J-PARC), a foil lifetime longer than 300 h is required to minimize these effects.

The lifetime of a stripper foil depends on the preparation method, electron beam evaporation, glow discharge technique, CW and pulsed-laser technique, and arc discharge. For example, a 40 μg/cm^2 carbon foil can be prepared in only a few minutes by the arc discharge method and in roughly 1 h by the electron beam evaporation method; however, almost 10 h are required by the ion-beam sputtering method. On the other hand, it is known that carbon foils produced by heavy-ion-beam sputtering have long lifetimes against the bombardment of 3.2-MeV DC Ne^+ beams, as reported in Refs. [4,5]. In order to understand the behavior of these foils upon irradiation by light ions generated by high-intensity DC H^- beams, we measured the lifetime of the foils produced by ion-beam sputtering using reactive (H_2, O_2, N_2) and inert (Ne, Ar Kr) gases.

2. Foil preparation

Carbon foils (thickness: 30–40 μg/cm^2) were produced by ion-beam sputtering using H_2, O_2, N_2, Ne, Ar, and Kr as the source gases (Table 1). The source gas passed through a flow meter and was fed to a duoplasmatron ion source. The ion beam was extracted at 10 kV and used to bombard the carbon target (high purity graphite, Japan Carbon Co., Ltd.). Because the arc voltage is very low, the charge state is 1 in most cases. The sputtered carbon was deposited on the surface of three glass slides (dimensions: 26 × 32 mm^2 each), which were coated with a release agent (Creme-Coat, By J. Varley and Sons, St. Louis, Missouri). An aluminum foil (dimensions: 26 × 32 mm^2; thickness: 15 μm) positioned near the glass slides was weighed before and after the sputtering to determine the thickness of deposited carbon (Fig. 1).

The weight of the aluminum foil was measured using an electronic microbalance (Mettler UM-3). Because the carbon foils were to be self-supporting, they were carefully peeled off after the glass substrates were immersed in pure water. All the foils were then mounted on stainless steel holders (dimensions: 17 × 14 mm^2)

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Table 1
Typical parameters for ion-beam sputtering.

Ion species	H_2, O_2, N_2, Ne, Ar, Kr
Source gas	>99.99% purity
Vacuum pressure	2×10^{-3} Pa
Filament material	Ta, $\phi = 1.5$ mm
Filament current	40–80 A
Extraction voltage	10 kV
Focus voltage	~1 kV
Ion current	2–3 mA
Beam spot upon carbon target	$\phi = 1$–3 mm
Charge state	+1 for atomic beam

having a 13-mm-diameter aperture. The carbon foils produced using Kr gas were highly fragile.

We observed the foil surfaces under a microscope at a magnification of 800 times. Fig. 2 shows the photographs of the carbon foils before they were peeled off the glass substrates.

Table 2 lists the thickness and numbers of produced foils. Four (two each of thickness 22 μg/cm^2 and 50 μg/cm^2) commercially available foils (CM; Arizona Co., Ltd., USA) were used as a reference for lifetime comparison.

3. Beam experiments

We observed the behavior of the carbon stripper foils during bombardment with a 650-keV H^- beam at the KEK Cockcroft-Walton electrostatic accelerator. High-power 650-keV H^- beam can simulate high-energy deposition on carbon stripper foils at the J-PARC. The stripper foils were irradiated by a high-current beam up to a temperature of 1300 K. The experimental setup is shown in Fig. 3 [6]. The area of the beam spot formed on a thick carbon foil (thickness: 250 μg/cm^2) was monitored and adjusted using the upstream quadrupole magnets. The beam current was measured using a Faraday cup. The lifetime of the foil was defined as the integrated charge that passed through the foils until they ruptured or that produced large holes at the beam spot.

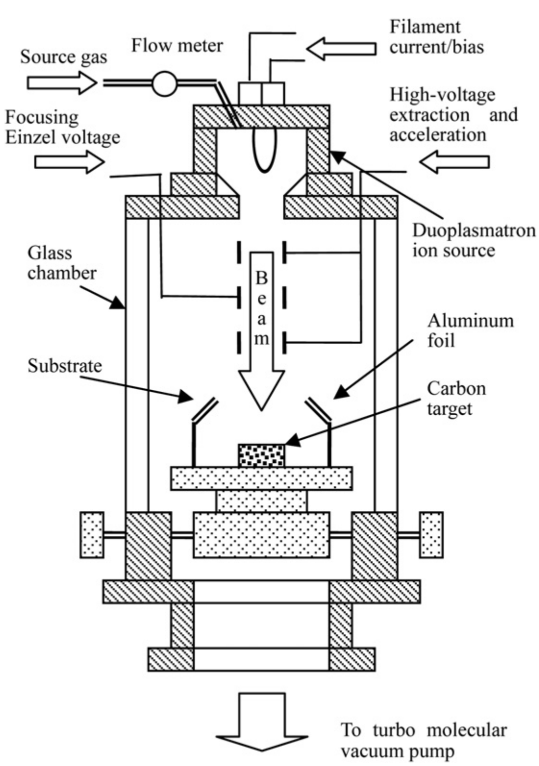

Fig. 1. Ion-beam sputtering apparatus. Source gas passes through a flow meter and is fed to a duoplasmatron ion source. Ion beam is extracted at 10 kV to bombard the carbon target.

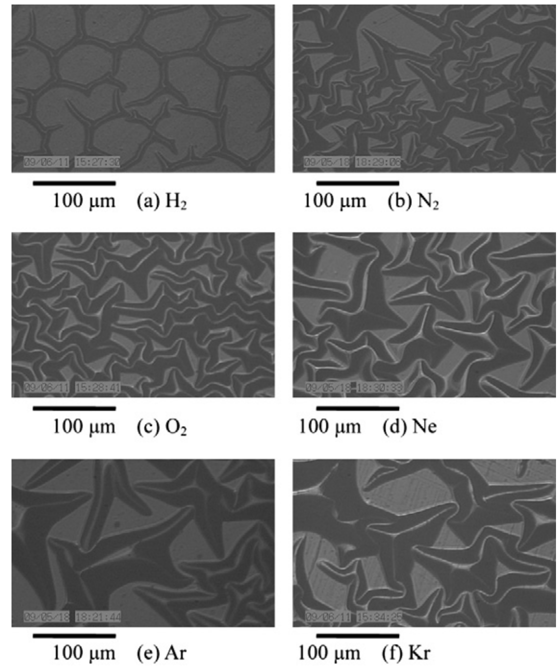

Fig. 2. Microscopic observation of surface of carbon stripping foils produced using ion-beam sputtering methods. Wrinkles show peeling from the glass slide.

The H^- beam current and dimensions of the ellipsoidal beam spot were 190–210 μA and $\sim 1.5 \times 2.5\pi$ mm^2, respectively. The carbon stripper foils are locally heated to a temperature of 1300–1500 K by energy deposition from the injected H^- beam. The pressure in the scattering chamber was maintained at $\sim 1 \times 10^{-4}$ Pa.

The carbon stripper foils were video monitored during irradiation and photographed at regular intervals; the foil temperatures were measured using a radiation thermometer (Wavelength: 0.8–1.6 μm; Japan Sensor Co., Ltd.; FTK9-P300R).

4. Results

4.1. Lifetime

Fig. 4 shows the results of the experiments. All commercial (CM) foils ruptured after irradiation of ~614 mC. The foils produced using H_2 ruptured quickly (78 mC). Grooves were formed on the foil surface upon irradiation, and then the foil was broken to draw surface inside. In the case of other foils, pinholes were formed at the beam spot. The average lifetimes of the foils produced using O_2, N_2, Ne, Ar, and Kr were 19,778 mC, 24,415 mC, 26,515 mC, 39,400 mC, and 34,349 mC, respectively. These carbon stripper foils had much

Table 2
Tested foils.

Source gas	Thickness (μg/cm^2)	Grain size (μm)
H_2	33.3, 35.5, 35.5	<0.001
O_2	34.2, 34.2	0.001–0.005
N_2	30.0, 30.7	0.001–0.005
Ne	31.6, 38.7	0.005–0.01
Ar	37.5, 36.4	0.01–0.2
Kr	33.7, 33.7, 34.0, 34.0, 34.0	0.01–0.2