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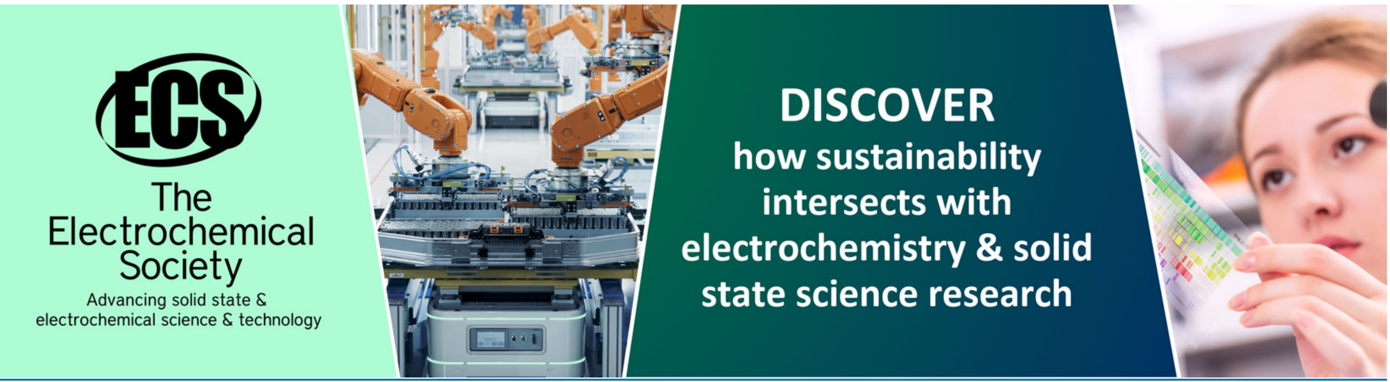

Development and applications of electron beam ion source for nanoprocesses

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Abstract. An electron beam ion source (EBIS) was developed and applied to create nanostructures. The EBIS uses a commercial superconducting magnet (3T) with vacuum system independent from another vacuum system which comprises all of the ion source constituents except the magnet. The attained parameters of electron beam are emission current of 180mA and acceleration voltage of 20kV. The EBIS creates HCIs in nA region (e.g. 2nA for Ar^{12+}). Higher charge states are suppressed by residual gases. The HCIs were irradiated to HOPG and the structure of irradiated surface was observed by STM, and the image indicates the fluence as much as 10^{13}ion/cm^2 is accessible with the present EBIS.

1. Introduction

The interaction of slow highly charged ions (HCIs) with solid surfaces is useful for ‘nanoprocess’; the modification, activation, machining and analysis in nanometer scale. The most serious problem in the application of HCIs for nanoprocesses is the limited intensity of HCI beam per specific area in nanometer size. Since the emittance of EBIS is not sufficiently small to focus the beam into nanometer size, screening aperture has to be used to create nano-beam. Assuming that the typical beam size of EBIS is 0.1mm in diameter, the beam intensity must be as high as 10^8 ion/s in order to inject an ion over 10x10 nm^2 area every second. An electron beam ion source, ‘Kobe EBIS’ has been developed to improve the beam intensity problem [1-3]. In the present paper, the final design after several remodeling and the present performance of the EBIS is described and some data of applications for irradiation of samples by HCIs are presented.

2. Kobe EBIS

In order to reduce the running cost and simplify the operational procedure, the Kobe EBIS uses a commercial superconducting magnet (3T) with a bore of 180 mm in diameter cooled by a

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closed-cycle refrigerator. The schematic diagram of the EBIS after the remodeling is shown in figure 1. The detail of the original design including electron beam and ion beam simulation is described on the literature [1,2]. All the components except the magnet are made bakable up to 250 deg C in order to minimize the contribution of background pressure when the EBIS is in operation. Electron gun and collector, which are operated on high voltage, are cooled by circulating coolant during operation, while the coolant has to be removed (not stick to apparatus) during the bakeout procedure. So, we used Vertrel XF (DuPont-Mitsui Fluorochemicals) as coolant because of its high vapor pressure and high electric resistivity. Prior to the operation, discharge cleaning of the drift tubes is also necessary, and is performed applying high voltage (5kV) to drift tubes under the maximum magnetic field.

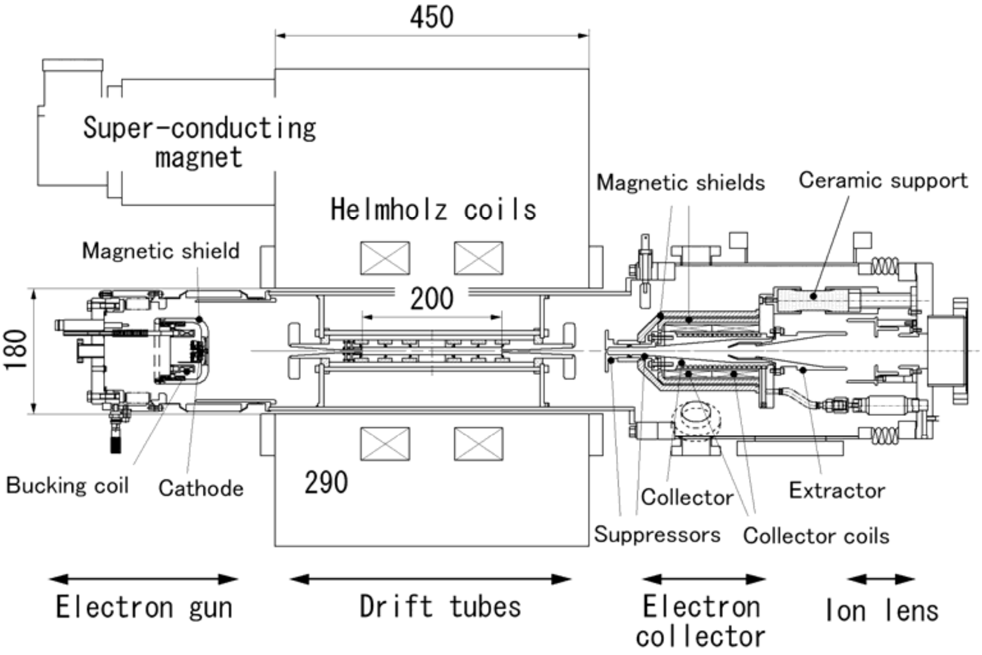

Figure 1. Schematic diagram of Kobe EBIS

After the initial operation, we found some errors in the calculation of the magnetic field distribution revealing that magnetic shields at the electron gun and collector were not efficient enough. The electron beam current was limited to less than 20 mA due to the return current of electrons (going back to the electron gun), which was not collected by the collector. To solve this problem, the electron gun has been moved away from the superconducting magnet by 9 cm and the magnetic shield at collector has been reconstructed with thicker shield structure. The pair of solenoid coils has been inserted inside the shield envelope and the ceramic supports have been reinforced [3]. The present device has been designed to perform degassing treatment thoroughly. Consequently, the maximum electron current has been increased up to 180mA. The acceleration voltage has been set to 20kV to insure stability of the whole system.

We have measured the charge state distribution of extracted ions introducing Ar gas at 5×10^{-8} Pa over a base pressure of $\sim1\times10^{-7}$Pa, as shown figure 2. The base pressure of the ion source in the presence of electron beam is $5\text{x}10^{-8}$ Pa $\sim1\text{x}10^{-7}$ Pa. The electron beam current was 150mA and acceleration voltage was 18kV. The potential of the drift tubes was 3kV. The ion current was measured by a Faraday cup located just after the exit slit of an analyzing magnet as a function of the current of the analyzing magnet. In order to maximize the ion currents, the slits were fully open. This leads to a low mass resolution in the spectrum of figure 2 where peaks of Ar^{q+} ($q\leq12$) can be identified. The peak intensities of Ar^{12+}, Ar^{11+} and Ar^{9+} ions are 2.0, 3.9 and 9.4nA, respectively. An adjustment of the magnetic field axis and the electron beam direction within an error of 0.1 mm is mandatory to reach such current intensities of the extracted ions. The peaks of ions which are ascribed to residual gas elements exist, and get dominant at lower m/q region. By the measurement with higher resolution (narrower slit width), the peak of Ar^{16+} was observable. It is essential to improve the vacuum for producing higher charge states abundantly. The charge state distribution strongly depends on the vacuum inside the drift tubes, and the most effective measure to improve the vacuum is to cool the drift tubes down to cryogenic temperature. The main residual gases under operation are H_2, CO and CO_2. Especially the partial pressure of CO and CO_2 increases during the presence of electron beam. So it is desirable to cool the drift tubes lower than 20K where the vapor pressure of CO is sufficiently low.

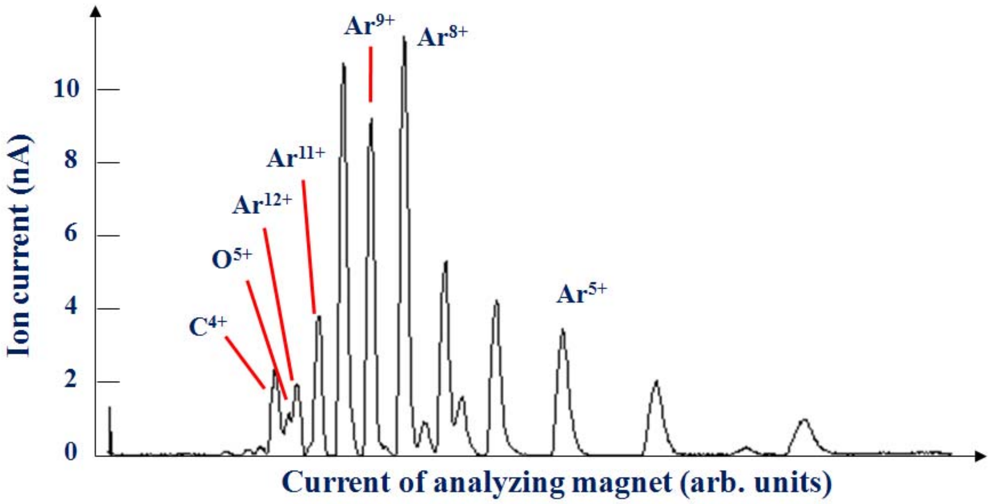

Figure 2. Charge state distribution of extracted Ar HCIs. For detailed description of the running conditions of the EBIS, see text.

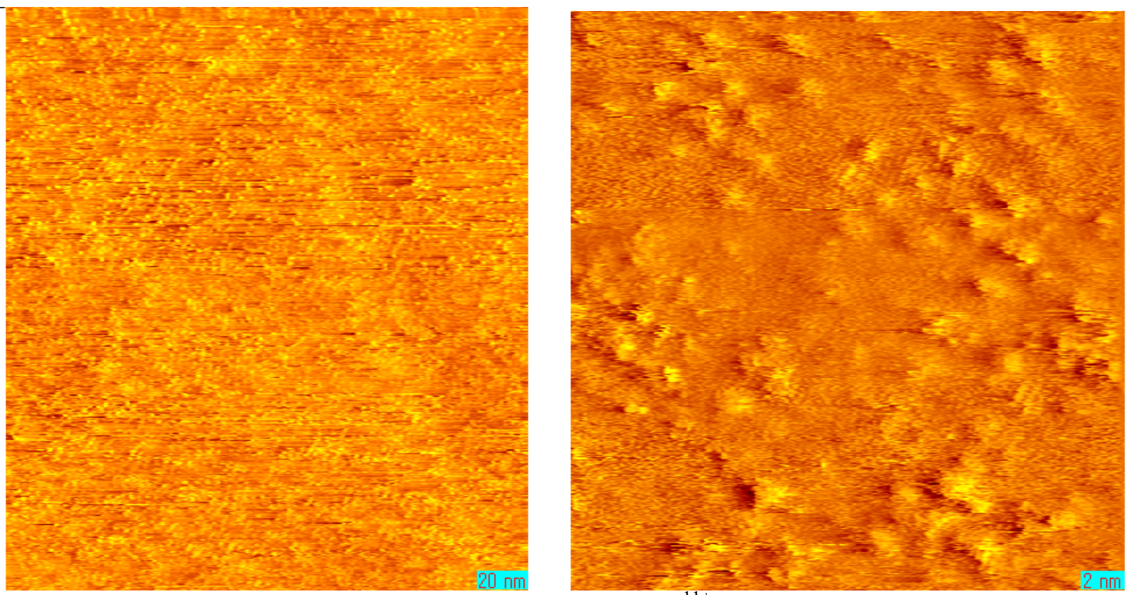

Figure 3. STM image of the HOPG surface irradiated with Ar^{11+} ions. The fluence of irradiated HCIs is estimated at $10^{13}/cm^2$.

3. Irradiation experiments

The irradiation experiments were performed using Ar^{11+} ions. Concerning the experimental setup, mass separated HCIs are focused through an electrostatic lens system and introduced to an experimental chamber equipped with a precise sample holder [4]. The irradiated sample was transferred to a STM system keeping UHV environment. Target of highly oriented pyrolytic graphite (HOPG) was used and the surface images after irradiation were measured by a scanning tunneling microscope (STM). The STM images of HOPG surface irradiated with Ar^{11+} ions for about 1 hour are shown in figure 3. The ion current from the sample was 0.3 nA. The images exhibit many protruded structures which are typical as irradiation traces on HOPG [5]. The fluence of irradiated HCIs is estimated at $10^{13}/cm^2$ which corresponds to an irradiation density of 10 traces per $100nm^2$ area. For future applications of nanoprocesses induced by HCIs, the flux of the beam must be sufficiently high in order to irradiate nm size regions within a realistic time. There should be some application with the present status, however, further improvement of the beam flux at the sample by 1~2 orders magnitude is necessary for the general use of HCI for nanoprocess applications.

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