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Reduction of the divergence angle of an incident beam to enhance the demagnification factor of a two-stage acceleration lens in a gas ion nanobeam system of several tens of keV

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ABSTRACT

The demagnification factor of a two-stage acceleration lens in a gas ion nanobeam system that produces ion beams with energies in the order of 10 keV was enhanced in this study so that a hydrogen ion beam with a diameter of 115 nm could be produced. The reduction of the divergence angle of the incident beam into the two-stage acceleration lens is the effective method for enhancing the demagnification factor. The divergence angle has been gradually reduced by firstly introducing the preacceleration electrodes to control the divergence angle, namely divergence-angle-control electrodes, and secondly replacing an anode with a modified anode that possesses a Pierce electrode, both of which were in an ion source directly connected to the lens. In this study, the divergence angle of less than 3.6×10^{-4} rad that was previously used to produce a 160-nm hydrogen ion beam with the energy of 46 keV by the above procedure was numerically determined using an ion beam extraction simulation code. The determined minimum divergence angle of the incident ion beam was calculated to be 2.0×10^{-4} rad, which was about half of the previously obtained divergence angle; this was used to experimentally form a hydrogen beam with a diameter of 115 ± 10 nm and the energy of 47 keV. The demagnification factor was estimated to be 1,739 using the newly formed hydrogen beam, which was similar to the simulation result.

1. Introduction

Focused metal ion beams with energies in the range of several tens of kiloelectronvolts and full width at half maximum (FWHM) beam diameters ranging from several nanometers to several hundred nanometers have mainly been used to modify the photomasks that have insufficient properties in semiconductor manufacturing processes [1–3] and study microelement distribution in a measurement sample [4–6]. Such focused ion beams (FIBs) can be produced by commercially available focused ion beam systems, which typically consist of either a liquid metal ion source (LMIS) or a gas field ion source (GFIS) and a conventional focusing lens such as a magnetic quadrupole lens [7] or an einzel lens [8]. These lenses generally exhibit the demagnification factor up to the order of 10^2. The Ga^+ and He^+ beams mainly generated by LMIS and GFIS, respectively, exhibit the energies in the order of 10 keV. Each source consists of a sharp needle with a tip diameter in the range of 10 nm, and this source results in producing ion beams with a small diameter and a small divergence angle via the field emission effect. In addition, the tip is an object in beam trajectory calculations in an FIB system. The demagnification factor by the conventional lenses is, therefore, sufficient for the forming of focused Ga^+ or He^+ beam with energies in the order of 10 keV and the diameters of 10^0–10^1 nm; such ion beams are referred to as nanobeams in this paper. However, there are two disadvantages of using a Ga^+ nanobeam for measurement purposes. First, they cause a high sputtering effect, which can damage the surface of the measurement sample. Second, the samples get contaminated by Ga^+s in many cases. Using He^+ nanobeams for reliable microfabrication is difficult because they possess small and unstable currents. These problems could be solved if a plasma-type ion source was used to form a gas ion nanobeam.

A gas ion nanobeam system that is capable of producing ion beams in the order of 10 keV was developed by combining a duoplasmatron-type ion source that generated low-energy stable gas ion beams [9] and a compact two-stage acceleration lens with a high demagnification factor, referred to as nanobeam system herein. The two-stage acceleration lens has two main functions; namely, the acceleration and focusing of ion beam, both of which can be done simultaneously. The improvement of the demagnification factor of the two-stage acceleration lenses has so far been studied to produce a 100-nm-diameter hydrogen ion beam of about 50 keV, this beam will hereafter be referred

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to as a 100-nm hydrogen beam. In the nanobeam system the object for the ion beam trajectories is set to a 200-μm-diameter through-hole of an anode in the ion source, this anode hole hereinafter referred to as a 200-μm object, the plasma-type ion source utilized by this system generates the ion beam using this hole. Although the diameter of 200-μm object is one order of magnitude smaller than that typically used in conventional plasma-type ion sources, it is nevertheless more than 10,000 times larger than the tip of the needle of a FIB. A demagnification factor of around 2000, which is more than 10 times greater than that of a FIB's lens, is therefore necessary if the two-stage acceleration lens is to be used to form 100 nm hydrogen beams.

In order to obtain a demagnification factor of 2000 for a two-stage acceleration lens, the balance between two intrinsic properties of the two-stage acceleration lens had to be considered during the design of the nanobeam systems; namely, that demagnification factor is inversely proportional to a divergence angle of an incident beam, and that demagnification factor is proportional to the square root of the acceleration ratio (which is the ratio of an accelerated beam energy to an incident beam energy). In a beam trajectory calculation for the two-stage acceleration lens, a demagnification factor of 2000 was numerically obtained using the lens parameters computed by a calculation code [10] for an electrostatic lens under the use of an incident beam that had an energy on 100 eV, a divergence angle of 1×10^{-3} rad, and an accelerated beam by an energy in the order of 10 keV [11]. Several experimental preliminary studies have been performed to achieve the required demagnification factor of 2000.

In the beginning of these studies, a hydrogen ion beam of about 30 keV with a diameter of a few μm was experimentally produced from a 100-eV incident beam extracted from the ion source and measured by a beam size measurement system to which we applied a knife-edge method [12] placed with a working distance of 60 mm. The working distance was kept constant throughout the study. The results from these experiments showed that the demagnification factor was roughly estimated to be about 100 that is equal to the diameter of the 200-μm object was divided by the experimentally obtained beam diameter. This demagnification factor was also calculated from a simulation of the ion trajectories in a nanobeam system that utilized the incident beam with the divergence angle of 10^{-2} rad emitted from a geometrical position of an extraction electrode in the ion source. In addition, the results also indicated that the main aberrations of two-stage acceleration lens, namely the spherical and chromatic aberrations, were practically negligible, and the beam diameter depended solely on the demagnification factor of the two-stage acceleration lens [13]. The demagnification factor of this lens was determined to be about 100, which was smaller than the assumed 2000 and was therefore insufficient for the production of a 100-nm diameter beam. The obtained small demagnification factor was attributed to the incident beam with the large divergence angle of the order of 10^{-2} rad that was one order of magnitude larger than the assumed one. The reduction of the incident divergence angle was found to be more effective than the increasing the acceleration ratio of the two-stage acceleration lens from the intrinsic property of the two-stage acceleration lens, and it was studied for the enhancement of the demagnification factor step by step as follows;

(1). In this study, the incident beam for the two-stage acceleration lens was controlled by the divergence-angle-control electrodes introduced between the extraction electrode in the ion source and the two-stage acceleration lens. A 280-nm diameter hydrogen ion beam was then experimentally formed at 32 keV [13]. Using the experimentally obtained beam diameter and the lens parameters computed by the calculation code, the divergence angle was roughly estimated to be 3.6×10^{-3} rad, which was about one order of magnitude smaller than the previously obtained angle in the order of 10^{-2} rad. The result from this study showed that the injection of an incident beam that has a smaller divergence angle into the two-stage acceleration lens can reduce the beam diameter to 100 nm.

(2). In addition to the procedure outlined in (1), a direct anode extraction (DAE) method was introduced in the ion source to further reduce the beam diameter, and it was tested in experiments. The DAE method comprised a modified anode on the basis of Pierce extraction electrode with a tip of 67.5 degrees [14] and the short distance between the anode and the extraction electrode in order to extract a beam with a smaller divergence angle without significantly increasing the beam energy largely by applying several hundred volts to the extraction electrode in the ion source. Using the DAE method, the initially assumed incident beam with the about 100 eV and 1×10^{-3} rad was changed with the incident ion beam in the order of 10^2 eV and the divergence angle in the order of 10^{-4} rad. The DAE method enabled us to produce a smaller beam divergence angle than in the procedure (1), and a 160-nm hydrogen ion beam was produced at 46 keV in this experiment [15], this study is hereinafter referred to as "Improvement #2." From the beam diameter, the demagnification factor was estimated to be 1250. The diameter and the demagnification factor were improved from the previous study, but still they were insufficient for our goal.

In this study, the result obtained in Improve #2 was used to improve the demagnification factor of two-stage acceleration lens; in particular, the lens parameters based on the result were employed to help produce a smaller divergence angle for the incident beam than that of procedure (2), so that a 100-nm hydrogen beam could be experimentally produced. This was attempted through the theoretical and experimental examinations. To begin with, the divergence angle of the incident ion beam for the first acceleration lens of the two-stage acceleration lens was theoretically estimated using the experimental parameters provided by the Improvement #2; the reduction in the divergence angle was then studied on the basis of calculations carried out for the ion beam trajectories from the anode in the ion source to the entrance of the first acceleration lens using a beam ion extraction simulation code. Then a hydrogen ion nanobeam was experimentally produced by applying the voltages obtained by the beam trajectory calculation to the electrodes in the ion source. Consequently, a 47-keV hydrogen ion beam with a diameter of 115 ± 10 nm was experimentally produced by the nanobeam system; this was in good agreement with the 109.5-nm diameter that had been calculated on the basis of lens parameters that corresponded to both the smallest divergence angle given by the results of the simulation (2×10^{-4} rad) and the estimated demagnification factor of 1739.

2. Relationship between the divergence angles of the incident beam and outgoing beams in the first acceleration lens of the two-stage acceleration lens

A schematic of the two-stage acceleration lens used in the present study is shown in Fig. 1; it consists of the first and second acceleration lenses that are similarity shapes. The second acceleration lens is 5 times larger than the first one. The two-stage acceleration lens voltages obtained in Improvement #2 are listed in Table 1. The lens parameters were calculated by the calculation code; these parameters are also listed in Table 1. The electrostatic potentials along the central axes of each of the two acceleration lenses, which were used in the calculation code, were computed using an ANSYS code [16] for a finite element method.

The relationship between the angles of the incident and outgoing beam in the present study was numerically obtained using the voltages applied to the electrodes in Improvement #2 and the lens parameters listed in Table 1. The beam diameter, Φ_I, at the image (image diameter) used to determine this relationship is shown in Fig. 2 and is represented by the following equation:

$$\Phi_I = \sqrt{\left(\frac{\Phi_O}{D}\right)^2 + \Phi_{Sh}^2 + \Phi_{Ch}^2} \quad (1)$$