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Feasibility study on high current ion beam extraction from anode spot plasma for large area ion implantation

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In this paper, we have investigated the feasibility of the high current beam extraction from anode spot plasma as an ion source for large area ion implantation. Experiments have been carried out with the ambient plasma produced by inductive coupling with radio-frequency (RF) power of 200 W at the frequency of 13.56 MHz. Anode spot plasmas are generated near the extraction hole of 2 mm in diameter at the center of a bias electrode whose area exposed to the ambient plasma can be changed. It is found that the maximum ion beam current is extracted at the optimum operating pressure at which the area of bias electrode exposed to ambient plasma is fully covered with the anode spot plasma whose size is dominantly determined by the operating pressure for given gas species. It is also observed that the extracted ion beam current increases nonlinearly with the bias power due to the changes in size and shape of the anode spot plasma. With the well-established anode spot plasma operating at the optimum gas pressure, we have successfully extracted high current ion beam of 6.4 mA (204 mA/cm^2) at the bias power of 22 W (~10% of RF power), which is 43 times larger than that extracted from the plasma without anode spot. Based on the experimental results, criteria for electrode design and operating pressure for ion beam extraction from larger extraction aperture are suggested. In addition, the stability of anode spot plasma in the presence of ion beam extraction through an extraction hole is discussed in terms of the particle balance model.

1. Introduction

Extraction of high current ion beam from plasma sources is essential for the enhancement of productivity in ion implantation technique. In conventional ion implantation equipment, a source plasma is produced in a source chamber by the emission of primary electrons for direct-current (DC) source or radio-frequency (RF) heating of electrons for RF source [1]. The ion beam is extracted from the source plasma through an extraction hole by applying a negative potential with respective to the plasma to an extraction electrode located in the downstream of the plasma. In such configuration, higher ion beam current has been achieved by increasing the electrical power fed to the source chamber through the increase of the number density of the source plasma. However, it is noticed that heating the entire volume of the source plasma is very inefficient to obtain the higher ion beam current. Instead, it is easily recognized that increasing the plasma density only in the vicinity of the extraction hole is obviously more power-efficient. In this manner, the implementation of an anode spot plasma [2], which is capable of generating a dense plasma near the extraction hole as schematically shown in Fig. 1, seems to be very suitable for the enhancement of ion beam current in ion implantation technique.

An anode spot plasma is a localized high density plasma which is generated in front of a small electrode biased positively with respect to the ambient plasma. It is well known that the anode spot plasma is generated when the potential difference between the small electrode (bias electrode) and the ambient plasma exceeds the ionization potential of the working gas [2]. Due to its capability for the generation of high density plasma at localized regions with relatively small additional power, the anode spot plasma has been successfully utilized as a high brightness plasma ion source for nano-applications such as focused ion beam (FIB) and nano-medium energy ion scattering (nano-MEIS) [3,4].

In the previous studies [3–6], the diameter of an extraction hole denoted as a_{ext} in Fig. 1 was much smaller than the length of the

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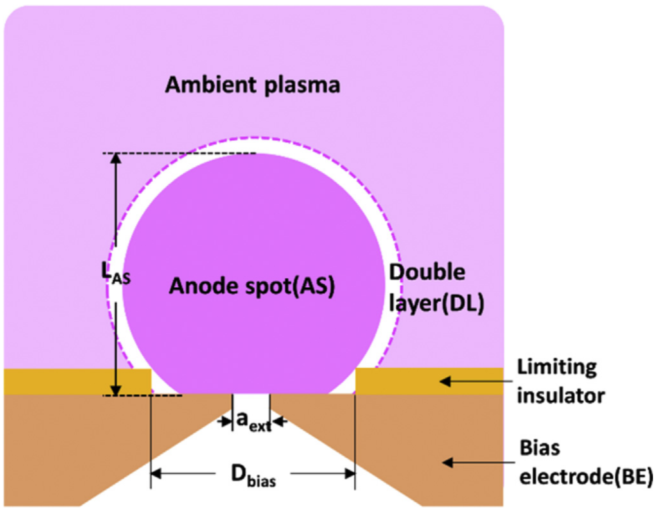

Fig. 1. Schematic diagram of anode spot plasma generated near the bias electrode with an extraction hole.

anode spot plasma (L_{AS}) and the amount of ion beam current extracted from the anode spot plasma was as low as a few hundred microamperes. Hence, the formation of anode spot plasma was observed not to be affected by the presence of the extraction hole. However, for the application of the anode spot plasma to large area ion implantation, the extraction hole needs to be enlarged so as to increase the amount of ion beam current. When the hole size is increased, it is easily predictable that the stable formation of anode spot plasma becomes more difficult. Therefore, sustaining anode spot plasmas in the presence of large extraction hole is important for the application of anode spot plasma in large area ion implantation technique.

In the present work, we have studied the characteristics of anode spot plasma produced in front of a bias electrode with an extraction hole larger than that used in the previous work [6] in order to obtain ion beam current order of mA. We investigate the changes in size and shape of anode spot plasma formed near the extraction hole and also consider to correlate them with the amount of ion beam extracted from anode spot plasma. Effects of the operating pressure and the area of bias electrode exposed to ambient plasma on the beam extraction are also examined. The detailed description of experimental setup and procedure is given in Section 2. Sections 3 and 4 are devoted to the experimental results and discussion for the characteristics of anode spot plasma in front of a bias electrode and the ion beam characteristics extracted from the extraction hole, respectively. The stability of anode spot plasma in the presence of the ion beam extraction through an extraction hole is discussed in terms of the particle balance equation in Section 5. Finally, conclusion and outlook are drawn in Section 6.

2. Experimental detail

Fig. 2 shows the schematic diagram of a plasma ion source used in the present study. The basic structure is the same as that used in our previous work [6], but the beam extraction aperture is enlarged to extract higher ion beam current through it. Argon is chosen as a working gas and the operating pressure inside a plasma chamber made of fused silica is adjusted in the range of 10–100 mTorr, while the gas pressure in the extraction region is maintained below 1.7×10^{-4} Torr. The ambient plasma is generated by inductive coupling with fixed RF power of 200 W at the frequency of 13.56 MHz. An extraction hole of 2 mm in diameter ("a_{ext}" in Fig. 1) is drilled at the center of a bias electrode which is located underneath the lower plasma electrode. The area of the bias electrode exposed to the ambient plasma is defined by an inner diameter ("D_{bias}" in Fig. 1) of a limiting insulator made of Al_2O_3. As depicted in Fig. 2, three kinds of the limiting insulators with different inner diameters of 3, 4, and 5 mm are prepared to control the electrode area exposed to the ambient plasma. Therefore, outer diameter of the bias electrode exposed to the ambient plasma is also changed to be 3, 4, and 5 mm. It is noted that the electrode area exposed to the ambient plasma plays an important role for the formation of stable anode spot plasma [5]. A DC voltage up to +250 V is applied to the bias electrode for generating anode spot plasma and the current is measured with a current-limiting resistor of 100 Ω. Then, the current–voltage characteristics of anode spot plasma can be easily determined [6].

Ion beam extraction from the anode spot plasma has been performed by applying a high voltage to the plasma electrodes up to +15 kV with respect to the ground. The diameter of a hole located at the center of the ground electrode is 3.3 mm and the distance between the bias electrode and the ground electrode is 3.5 mm. The extracted ion beam current is measured with a Faraday cup located at 55 mm away from the ground electrode. Besides, the ion current flown to the ground electrode is also measured to determine the optimum beam optics. Visual observations with a digital camera are also carried out to examine the changes in size and shape of the anode spot plasma.

3. Formation and characteristics of anode spot plasma without beam extraction

Fig. 3 shows the typical current–voltage curve and pictures of the anode spot plasma generated in front of a bias electrode with beam extraction hole of 2 mm in diameter. In this case, the operating pressure is 50 mTorr and the bias electrode is covered with a limiting insulator with inner diameter of 4 mm. The bias current stays as low as ~100 mA until the breakdown of an electron sheath [7], or equivalently the onset of anode spot plasma, occurs at ~17 V. Even after the onset of anode spot plasma, the bias current is still low when the bias voltage is low, showing that the anode spot plasma is small and covers only partial region of the bias electrode (see points "B" and "C" in Fig. 3). However, as the bias voltage is increased, the bias current rapidly increases because the anode spot expands and covers the area of the bias electrode ("D" → "F"). After the anode spot plasma fills the entire area of the bias electrode, the bias current saturates and the stable anode spot plasma forms (see point "G"). Note that the amplitude of the saturated bias current is observed not to be changed with the outer diameter of the bias electrode. Since the bias current is roughly proportional to plasma density in front of the bias electrode, it is easily recognized that the plasma density increases around 15 times than that without anode spot plasma when the anode spot plasma operates at the saturated region.

Previously, we reported that the magnitude of the saturated bias current was not affected by the gas pressure at a given RF power for the anode spot plasma in the operating pressure range of 50–150 mTorr [6]. However, in the present experiments, it is found that the saturated bias current decreases when the gas pressure is further reduced to below ~25 mTorr, as shown in Fig. 4(a). A simple global discharge model explains that the reduction in the saturated bias current is related with the rapid increase of the electron temperature of ambient plasma at low pressure regime [8]. The increase of the electron temperature enhances the particle loss to walls across the sheath, hence lowers the plasma density at the same absorbed power. Fig. 4(b) shows the change in shape of anode spot plasma at the saturated region with the gas pressure. The