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Study of the Beam Extraction System of a Negative Ion Source with a C12A7 Electride Plasma Electrode

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Abstract. Key issues to fabricate a beam extraction system of a H^- source with a plasma electrode (PE) made from C12A7 electride which has low work function were studied. Preliminary study of the H^- extraction using a compact ECR ion source reveals, that high H^- current can be extracted from a source without PE bias of high voltage. A bucket type with ECR source is being designed. Beam simulation for the extraction through the designed electrodes has been carried out using the OPERA code. It predicts that the optimum perveance is 0.6 mA/kV$^{1.5}$, optimum acceleration to extraction voltage ratio V_{acc}/V_{ext} is 4, with the minimum beam divergence of 9 mrad, which are enough to demonstrate the capability to produce a high H^- current density.

INTRODUCTION

In order to enhance the negative hydrogen ion (H^-/D^-) surface production yield, alkali metal vapor such as cesium has been used to cover a PE of an ion source [1]. Accumulation of Cs in the source, however, shortens the maintenance cycle of the apparatus and causes Cs contaminations to downstream components. Alternative materials, such as carbon materials have been studied expecting a high negative ion production yield from the surface for a cesium-free plasma electrode (PE) [2,3]. Recently, a new inorganic material, C12A7 electride [4,5] having the low work function and sufficient electrical conductance, has been experimentally studied as a candidate material for it. In our previous work [6], an energetic atomic hydrogen (H^0) bombardment together with measurement of the work function was carried out. The photoelectric current from the C12A7 electride under irradiations with 325 nm He-Cd laser or 405 nm, 450 nm, 532 nm diode lasers showed that the measured work function was less than 2.7 eV. Exposure to the C12A7 electride to an atomic hydrogen (H^0) flux produced electric current corresponding to negative hydrogen ion (H^-) current from the surface. Similar characteristics were obtained for a low-work-function bi-alkali material covered molybdenum surface (~2.3 eV). Nearly the same magnitude of negative current signals was observed under the same exposure condition of atomic hydrogen flux. Recently, direct measurement of hydrogen isotope negative ions (H^-/D^-) has been carried out using an experimental apparatus in Aix-Marseille University [7]. A high production rate of negative hydrogen ion (H^-) was observed from a C12A7 electride surface immersed in hydrogen/deuterium low-pressure plasmas. The target was biased from 20 to 130 V negative with respect to the plasma for bombarding the target surface by H_3^+ ions from the plasma. The production rate was compared with that from a clean molybdenum surface. Using a pseudo exponential work-function dependence of the H^- production rate, the total H^- yield from a C12A7 electride surface bombarded at 80 V was evaluated to be 25 % of that from a cesiated molybdenum surface of the lowest work-function.

C12A7 electride is stable in ambient atmosphere, mechanically robust and machinable. These experiments indicated that it has potential to be used as production surface of cesium-free negative ion sources for accelerators, neutral beam injectors, and surface modification. In the present work, key issues to build a PE made from C12A7 electride are studied, and show a design of a proto-type beam extraction system of an ion source.

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KEY DESIGN ISSUES FOR A C12A7 ELECTRIDE PLASMA ELECTRODE

It was found by Hosono et al, that a refractory oxide $12CaO.7Al_2O_3$ (C12A7) can be transformed to an electride of low work function [4,5,8], by removing of clathrate oxygen ions from the positively charged crystallographic cages of C12A7 leading to formations of high-density electrons in the cages. Because the low work function is realized by connected cages forming a new conduction band called "cage conduction band" (CCB), impurities accumulation on the surface should be avoided. Meanwhile Kitano et al. reported that hydrogen negative ions are trapped in cages when the surface is exposed to hydrogen atmosphere [9].

An ion source with a C12A7 electride PE should be designed considering these specific surface properties. For example, an ECR plasma source might be favorable than an arc plasma source with tungsten filaments that should contaminate the electride surface due to tungsten evaporation. Moreover, an in-situ annealing and temperature control system of the PE under high vacuum is preferable. For an initial conditioning, annealing at temperature over 700° C is required, and integration of a conventional heating system is not enough because the system design to reach to this temperature is difficult.

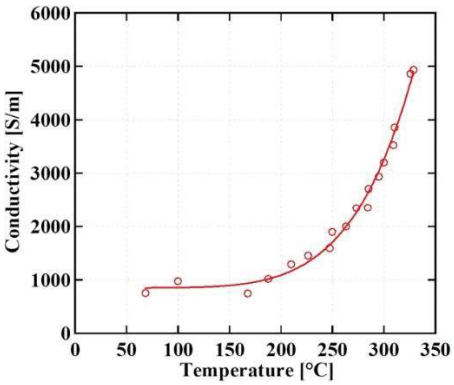


FIGURE 1. Measured conductivity of C12A7 electride during ohmic heating test of rectangular parallelepiped electride sample.

In this work we tested ohmic heating of electride by applying a voltage between the two longer ends of a 30 mm x 10 mm x 2 mm rectangular parallelepiped electride. As is shown in Fig. 1, the electrical conductivity increased with increasing temperature, as is reported before [4]. The sample heating up to 328 °C caused non-uniform temperature distribution, and the material became fragile. This can be the results of non-uniform current distribution in the sample. Other annealing methods, such as microwave heating, or infrared irradiation will be tested.

EXTRACTION OF H^- CURRENT FROM A COMPACT ECR SOURCE WITH A C12A7 PLASMA ELECTRODE

Although high H^- yields from a C12A7 electride surface were reported, it is not certain whether a H^- current can be extracted from an ion source using electride PE. Here, we constructed a small ECR test source of plasma size about 10 cm^3. Schematic diagram of experimental setup is shown in Fig. 2. An ECR plasma is excited by a helical antenna connected to a 2.45 GHz microwave source of 50 W(max) (Tamaoki Electronics Co. LTD), and it is diffused toward the PE. A plasma electrode of C12A7 electride and that of molybdenum of the same shape, same size of 16 mm diameter, 2 mm thick were fabricated. The extraction hole is 2 mm in diameter with a 45° cone shape. For the pretreatment of C12A7 electride PE, it was annealed at ~520◦C for 2 hrs., taken-out to air (dry) after cooling and installed to the ion source. A H^- beam was extracted from a single-stage-extraction electrode of 6 mm φ, and the beam current was measured by a Faraday Cup (FC) equipped with a pair of permanent magnets.

Fig. 3a shows the H^- current measured by FC as a function of the extraction voltage, under the experimental condition of gas pressure of 1.0 Pa measured in the FC chamber, and the maximum microwave input power under negligible power reflection. The H^- current with an electride PE is higher, than that with a clean Mo, by a factor of 80 – 100, as expected from the experimental results at Marseille [7, 8, 9]. It is known that there are two processes of H^- production on a surface in a plasma; desorption by sputtering, and charge transfer reflection.
The experimental results at Marseille [7, 8, 9] indicated that the latter has steep dependence upon the target bias

voltage, while the former shows much less dependence, and results there showed that the desorption process is dominant for the electride. Present results are consistent with these results of Marseille experiments. Dependence of H^- current on the microwave power was measured as well, and clear dependence was not observed when the forward wave amplitude was increased almost to the double and the reflected wave amplitude was kept at almost zero, as is shown in Fig. 3b. Here, the dependence of the floating potential of the plasma electrode is shown, as well, indicating that plasma parameters are not affected much. This means that the injected microwave power was not used efficiently. Further work on plasma parameters measurement is now under preparation.

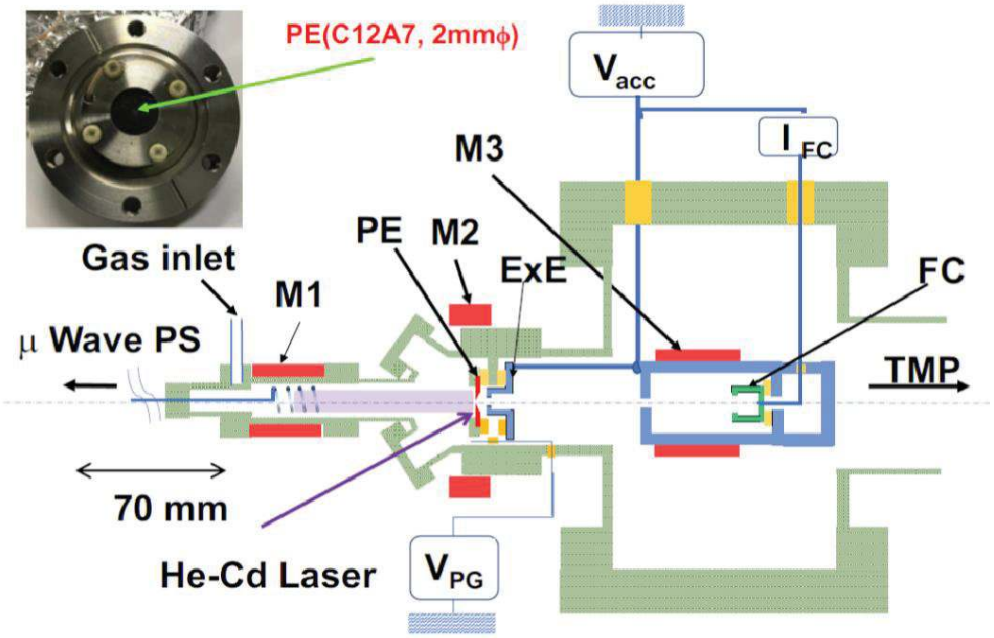


FIGURE 2. Schematic diagram of the experimental setup to measure the extracted negative current (H^-) from a small ECR source. PE and ExE denote the plasma electrode (electride or Mo) and the extraction electrode respectively. M1, M2, M3 denote pairs of permanent magnet for ECR, electron suppression near PE, and electron suppression in the Faraday Cup (FC). Both the extraction electrode and FC are on the high voltage stage against the ion source and vacuum chamber which are grounded. Bias voltage can be applied on PE independently.

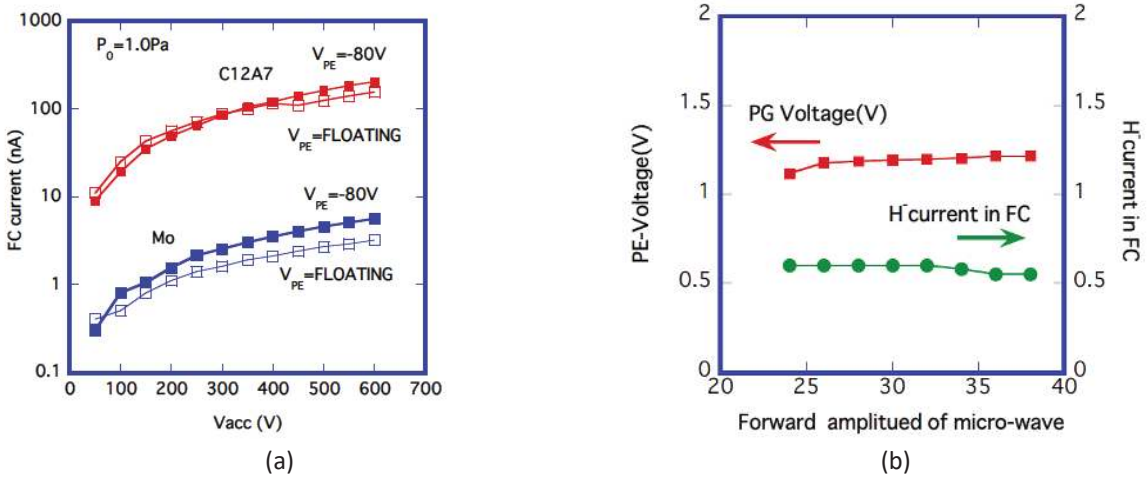


FIGURE 3. (a) Dependence of H^- current upon the extraction voltage. The current with an electride PE (in red) is higher than that with a clean Mo (in blue), by a factor of 80 – 100. (b) Dependence of the H^- current and floating potential of the plasma electrode upon microwave power.

DESIGN OF BEAM EXTRACTION SYSTEM

We design a bucket type negative ion source having an ECR plasma source and a three-stage-extractor electrode: plasma electrode, extraction and acceleration electrodes of 6 mm diameter each. The gap between the PE and extraction electrode (EE) is 8 mm, and that between EE and acceleration electrode (AE) 6 mm (case1) and the gaps can be exchanged (case 2). The electride PE will be heated by infrared irradiation or/and microwave heating. Another choice is pre-annealing in a separate vacuum chamber. Fig. 4 shows the cross-section view of the electrodes.

A calculation of beam optics of this three-stage electrode has been carried out using simulation software OPERA [9]. Fig. 5 shows the model of this calculation of case 1. In order to find the optimum perveance, at a fixed voltage combination of V_{acc} = 10 kV, and V_{ext} = 2 kV, beam trajectories and beam divergence were calculated, where V_{acc} and V_{ext} denote the voltage between AE and EE, and that between EE and PE, respectively. Optimum perveance was 0.6 mA/kV$^{1.5}$, as shown in Fig. 6a. Under this condition, the calculation to find out the optimum voltage ratio V_{acc}/V_{ext} was carried out (Fig. 6b). It was found that the optimum voltage ratio is 4, and the minimum beam divergence is 9 mrad, which is rather large compared with present H$^-$ beam sources for nuclear fusion and those for accelerators. However, these values of divergence and beam size are enough to demonstrate the capability to produce high H$^-$ current density.

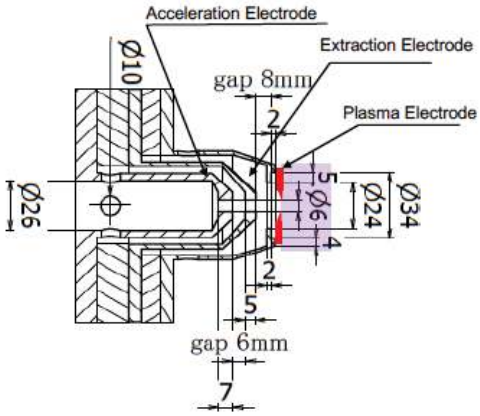


FIGURE 4. The cross-section view of the electrodes

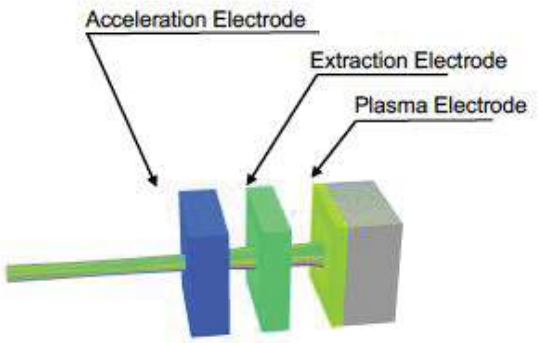
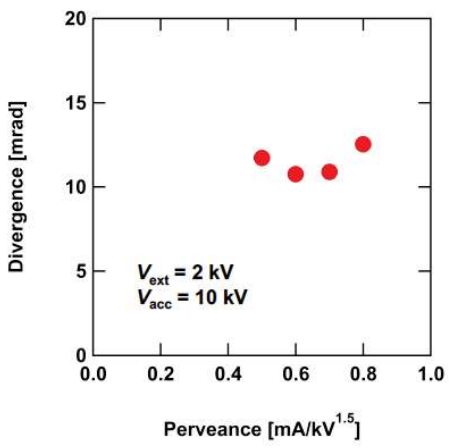
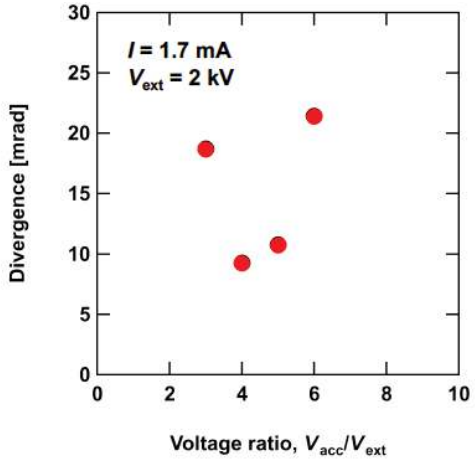


FIGURE 5. Simulation calculation model of beam optics



(a)



(b)

FIGURE 6. (a) The beam divergence dependence upon the perveance under fixed V_{acc} = 10 kV, and V_{ext} = 2 kV. (b) The beam divergence dependence upon the voltage ratio, $V_{acc}/V_{ext,}$ at optimum perveance condition.

CONCLUDING REMARKS

Key issues to fabricate a beam extraction system of a H^- source with a plasma electrode made from C12A7 electride which has low work function were studied. A trial of pre-treatment by direct ohmic exhibited a non-uniformity problem, but off-site heating worked and a sufficient H^- current for preliminary study was produced. The H^- extraction from C12A7 electride PE using a compact ECR ion source reveals, that high H^- current can be extracted from a source without PE bias of high voltage. Higher extraction voltage and higher plasma density are needed to demonstrate the full capability to produce higher H^- current and current density.

A bucket type ECR source is being designed. Beam Simulation for the extraction through the designed electrodes has been carried out using the OPERA code. It predicts that optimum perveance is 0.6 $mA/kV^{1.5}$, optimum voltage ratio V_{acc}/V_{ext} is 4, and the minimum beam divergence is 9 mrad.

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