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RESEARCH REPORT

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Development of the Work Function Monitoring Method for a Converter of a Negative Ion Source

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Abstract

A method to monitor the change in the work function of the converter surface in a self-extraction negative ion source is developed. The photoelectron emission from the Cs-Mo surface in a plasma is detected by irradiating surface with laser lights. Negative ions produced at the surface shows a strong correlation with the photoelectron current from the surface in hydrogen and helium discharges. The photoelectron current induced by the Ar^+ laser is used to detect the change in the cesium coverage, or the work function, while that by the dye laser is found to be suitable to confirm the region of the work function minimum.

§1 Introduction

Surface conversion negative ion sources have been given attention for a long time, especially as an efficient H^-/D^- source for neutral beams in the fusion program [1] and as a good beam quality injector of an accelerator for high energy physics experiments. Recently, Mori et al. have found that this type of sources can also produce a beam of negative heavy ions with a remarkably high intensity [2]. Here, negative ions are produced on the converter surface which is negatively biased and immersed in a plasma. The rate of producing negative ions at the converter surface depends strongly on the work function of the surface [3], [4]. Therefore, alkali metals are usually introduced to keep the low work function converter surface. However, the work function of the converter is dynamically changing in a plasma due to the sputtering by plasma particles and the contamination by impurities. Thus the way to monitor the work function of the converter is necessary to control the converter surface condition appropriate to produce negative ions.

Wada studied the correlation of H^- production and the work function in a hydrogen plasma by measuring the photoelectron current from the cesiated metal surface [5]. The method is based on Fowler's theory [6]. He succeeded to measure the work function of a target in a small magnetic line cusp plasma by minimizing the plasma noise and employing a phase sensitive detection. Although this method can determine the absolute value of the work function, it is not necessarily convenient as a monitor of the work function, since the method requires more than ten kinds of light of different wave length. A way that quickly gives a measure of work function is more favorable, since the surface condition in a plasma often changes with a small time constant. When photoelectric measurement is chosen as the way to monitor the work function since it little disturbs a plasma, a high power light source is necessary to insure a good signal to noise ratio in a plasma.

In this paper we describe a simple method to monitor the work function with a good S/N ratio by using laser lights. The experiments to measure productions for H^- and He^- are perfomed. We obtain the strong correlation between the photoelectron current induced by laser and the negative ion production from the surface, the condition of which is dynamically changing in a plasma.

§2 Physics of photoelectron emission

2.1 *Change in the work function of the Cs-Mo surface*

An important consequence of Cs adsorption on Mo metal surface is to lower the surface work function. Near the work function minimum, the probability of forming negative ions takes the maximum value. The work function on a Mo-converter surface immersed in a plasma is shown in Fig.1 as a function of Cs coverage, as an example. The open and closed circles correspond to the value measured by Wada [5] and the one quoted from reference [7], respectively. Cesium on the surface is the fractional monolayer coverage at the work function *minimum* [3]. The coverage of cesium is also a function of temperature and incident atomic species.

Therefore, we must carefully control the cesium vapor pressure through adjusting oven temperature and monitor the change in the work function of the surface due to the change in the cesium coverage.

2.2 *Quantum efficiency of photoelectron emission*

The basic theory of photoelectron emission for clean metals at various temperature was studied by Fowler [6]. When the energy of the incident photon is close to the work function of the surface which is a function of cesium coverage, the photon energy is absorbed by electrons near the surface and they escape from the metal with a kinetic energy which is the difference between the potential and the incident photon energies. Here, the quantum efficiency Y is defined as the number of emitted electrons divided by the number of absorbed photons

$$Y=\frac{(photoelectron\ number)}{(absorbed\ photon\ number)}\ . \tag{1}$$

A gas of electrons in the conduction band of the metal follows the Fermi-Dirac statistics and the number of electrons per unit volume n is given by the following formula

$$n=\frac{2\sqrt{2}\pi m^{3/2}}{h^3}\frac{k^2T^2}{(U_0-h\nu)^{1/2}}\int_0^\infty \log[1+\{-y+(h\nu-\psi_w)/kT\}]dy\ , \tag{2}$$

where m, U_0, $h\nu$ and ψ_w are the electron mass, the potential step at the boundary, the incident photon energy and the work function, respectively [6]. The logarithm is expanded and integrated term by term with the limit of $T \to 0$. The formula gives the following one for the quantum efficiency

$$Y \propto \frac{(h\nu-\psi_w)^2}{(U_0-h\nu)^{1/2}}, \qquad h\nu>\psi_w$$

$$Y=0 , \qquad h\nu<\psi_w. \tag{3}$$

If we assume the absorptivity at the surface to be nearly constant, the square root of the quantum efficiency has almost a linear relation with the work function. This is shown in Fig.2. Here we must note that the theory is not necessarily a good approximation at higher value of μ, where $\mu=(h\nu-\psi_w)/kT$. If the surface temperature is not too high compared with the room temperature, we can use the formula to determine the work function. For a wider range of incident photon energy the formula (2) is theoretically more accurate.

When the monochromatic light like laser is injected on the Cs-Mo converter surface, and if the work function is lower than the incident photon energy, we can observe the photoelectron emission signal from the surface as a function of Cs coverage, that is as a function of the work function. One of the problems of the above formula (3) is the change in the absorptivity when cesium coverage becomes thick. However in the region of thin cesium thickness the photoelectron emission may correspond to the work function.

§3 Experimental setup and monitoring method of the photoelectron current

A schematic diagram of the experimental setup is shown in Fig.3. The ion source chamber of 20cm in diameter and 25cm long is surrounded by ten columns of the Samarium-Cobalt magnets (magnetic field strength at the pole of 3k Gauss). A tungsten filament of 0.1cm in diameter is used as an electron emission source to generate primary ionizing electrons. The filament is negatively biased with respect to the chamber wall and the arc discharge is maintained between the filament and the chamber wall. The plasma is confined along the multiline magnetic cusp geometry. A concave molybdenum converter of 6cm in diameter and 15cm in focal length is immersed into the center of the chamber to produce negative ions. The converter is negatively biased with respect to the plasma potential so that the positive ions are accelerated through the converter sheath. The negative ions are formed and they are accelerated back from the surface. Temperature control is possible from 10℃ to 80℃ for the chamber wall and from -10°C to 30℃ for the converter within an accuracy of ±1℃. Thus we can control the cesium recycling from the wall. Cesium oven is used to deposit cesium atoms on the Mo converter surface. In this experiment temperatures are set to 60°C for the wall and 5°C for the converter, respectively.

As a monitor of the condition of cesiated Mo surface, two lasers are used. One is an Ar^+ ion laser (Coherent Innova 100) which is oscillated with multi-lines (mainly 514.5nm (2.41eV) and 488nm (2.54eV)) and has power of 60-200mW. Another is a single-mode cw ring dye laser (CR 699-21) pumped by the Ar^+ laser which has the wavelength of 650nm (1.91eV) and the power of 20-100mW at the injection port of the ion source. These energies of the laser lines are illustrated in Fig.1. From the formula (3) if the work function of the surface is lower than the incident photon energy, the photoelectron current is observed as a function of the work function. From Fig.1 the photon energy of the Ar^+ laser is almost higher than the work function except the region of thin cesium coverage. On the other hand that of the dye laser is near the region of the minimum value of the work function. Therefore Ar^+ laser is used to observe the overall change in the surface work function due to the cesium coverage, and the dye laser is used to confirm if the surface has the work function near the minimum value. These laser lights are coupled into an optical fiber (50μm in diameter), and the output is collimated into the plasma chamber. The ratio of the photoelectron current induced by the laser to the converter current is estimated to be less than of the order of 10^{-4}. Furthermore, when the surface is immersed into a plasma, the plasma noise is superposed on the converter current. To obtain the photoelectron emission signal from a surface in a plasma with a good accuracy, we must consider the following items: (i) suppression of the plasma noise, and (ii) signal detection system to discriminate the photoelectron current from the plasma noise. The intensity of the photoelectron current is proportional to the incident photon flux. When the ordinary lamp is used, we must increase the ratio of the diameter of the light injection port to the size of the ion source, to obtain a large photon fluence on the converter. A laser light is more suitable to increase the fluence since its power density at the position far from the light source is higher compared with the other light sources such as an arc lamp. To discriminate from the plasma noise, the laser light is modulated by using a mechanical chopper system (about 40Hz). The induced photoelectron current which is modulated with the same frequency as the laser light is detected through the transformer by the Lock-In amplifier system. To reduce the plasma noise we operate the ion source plasma at the low arc power (40-70V, 0.3-0.5A). A multiline cusp plasma source is suitable since it produces and confine a plasma quietly [8].

§4 Results and discussion

4.1 *Hydrogen discharge*

Figure 4 shows the induced photoelectron emission by Ar^+ laser and H^- current as a function of time. As soon as cesium oven is open, H^- current increases and it reaches the first peak. On the other hand there is a time lag between the time of opening the cesium oven and the time that the photoelectron current starts to increase. This is because the photoelectron current is only observed when the work function becomes less than the incident photon energy. After the photoelectron current reaches the first peak it starts to decrease until the cesium oven is shut. This means that in this region the coverage of the cesium becomes thicker than the coverage of the work function minimum. If the supply of the cesium from the oven is stopped, the cesium on the converter surface is sputtered out by the plasma particles and the photoelectron emission retraces the time history as shown in Fig.4. The extracted H^- current with cesium (t>0) is about a hundred times larger than the current without cesium (t<0).

4.2 *Helium discharge*

In this experiment helium arc discharge is performed to see if He^- ions can be extracted from a surface plasma source. Results for this experiment will be published elsewhere by Sasao et al. Here we describe the results for the photoelectron emission from the Cs-Mo converter in a helium plasma. Figure 5 shows the discharge for the case of low oven temperature. In this case, Cs coverage does not seem to reach the work function minimum. When the valve of cesium oven is closed, the photoelectron current decreases more rapidly due to the larger sputtering rate of helium compared with hydrogen.

To confirm whether the work function reaches the minimum value or not, we use the dye laser which has energy of 1.9eV. Firstly the photoelectron emission induced by the Ar^+ laser is measured according to the same manner as that in the experiment in Fig.4. Secondly by using the dye laser the same experiment is performed. These are shown in Fig.6 (a) and (b). Comparing these figures, we conclude that in Fig.6 (a) the third peak corresponds to the work function minimum. The first small peak is also assumed to indicate the minimum, but the increase of the cesium coverage on the surface is too fast for the Lock-In amplifier to follow the exact change in the work function. The work function change in this experiment is faster than that in Fig.5 because of the high Cs flux to the converter due to high oven temperature. The second peak indicates a thick cesium coverage region, and the photoelectron current does not correspond to the change in the work function. The possible explanation of this behavior is the change in the absorptivity in accordance with the coverage of cesium. We can observe the sizable mass analyzer signal corresponding to the negative ion species with $e/M=1/4$, when the photoelectron current is detectable as shown in Fig.6 (b).

4.3 *Estimation of quantum efficiency*

The photoelectron current becomes of the order of a few μA at the point of the work function minimum when the Ar^+ laser is used to monitor. By using the experimental values of the photoelectron current of a few μA, the Ar^+ laser power of 0.18W and the incident photon energy of about 2.5eV, the quantum efficiency is estimated to be $\sim 4\times10^{-5}$ from the equation (1). In the Cs-Mo surface it is less than 10^{-4} experimentally [5]. The estimated value has a good agreement with the previous experimental ones.

4.4 *Impurity effect*

If there exist some impurities like hydrogen or oxygen, the work function changes compared with the pure cesium coverage [9], [10]. These effect would be reported elsewhere in detail. Here we describe briefly. We find that as increasing the cesium density in the ion source, the maximum current of the photoelectron emission decreases gradually. This means the increase of the work function. Meanwhile, the base pressure after shutting off the discharge has also decreased. The improvement of the base pressure is probably due to the adsorption of residual gas by Cs covering the chamber wall. After the discharge cleaning of the chamber wall, the maximum negative ion current and the photoelectron emission increase compared with the current before cleaning. The change in the oxygen current detected by the mass analyzer agrees with that in the negative ion current. It is concluded that the oxygen in the ion source plays an important role for the change in the work function.

§5 Conclusion

By using two kinds of lasers, which are the Ar^+ laser and the dye laser, the change in the work function on the Cs-Mo converter surface is studied. We succeed to measure the photoelectron current and monitor the surface condition with a simple photoelectric method. This can be done even when there is a plasma noise, because of the sufficient S/N ratio due to the high power laser light compared with other light sources. The photoelectron current induced by the Ar^+ laser gives the overall behavior of the change in the work function. The dye laser is more appropriate to find the work function minimum.

The experiments are performed for hydrogen and helium discharges to see the correlation between the negative ion yield and the photoelectron current. The behavior of the photoelectron current matches well with the extracted H^- current when the amount of Cs is small in the plasma. For helium discharge, signal from the mass analyzer behaving as He^- current is observed only near the region of the work function minimum and the cesium coverage on the converter surface seems to be stripped faster compared with the hydrogen discharge due to a larger sputtering yield.

Only results for the measurement of the photoelectron emission using Ar^+ and the dye lasers are reported here, but one may utilize the more convenient one like a He-Ne laser (632.8nm, 1.96eV) to confirm if the ion source is operated near the work function minimum of the converter.

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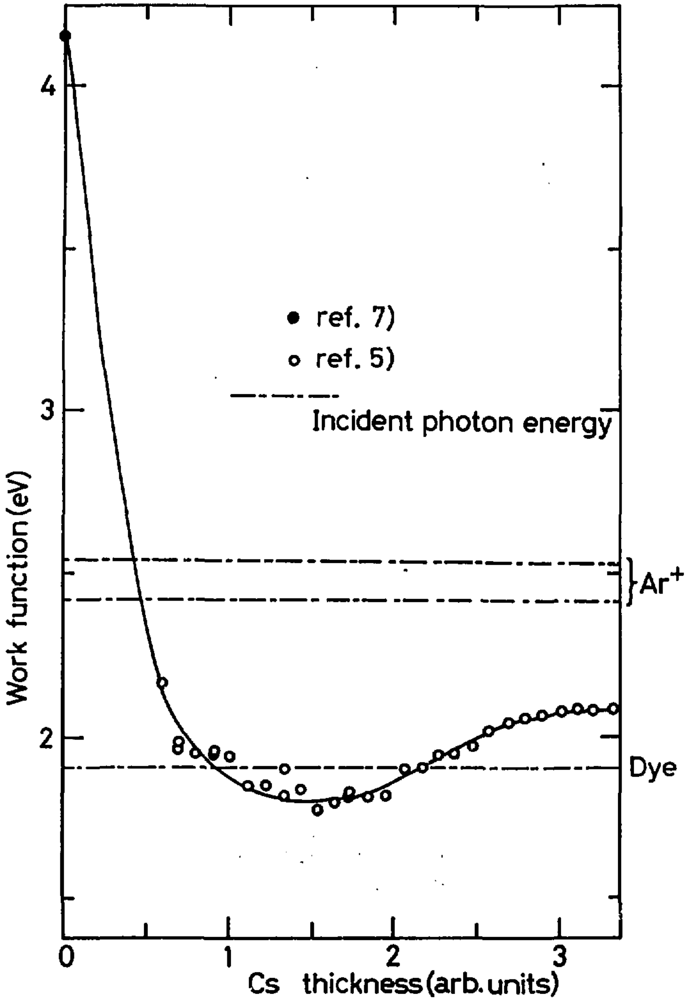

Fig. 1 Change in the work function of Mo covered with Cs. The open circle was the work function measured by Wada [5] and the closed circle is quoted from the table [7]. The photon energies of the Ar^+ (multi-lines oscillation) and the dye (single line) lasers are also presented.

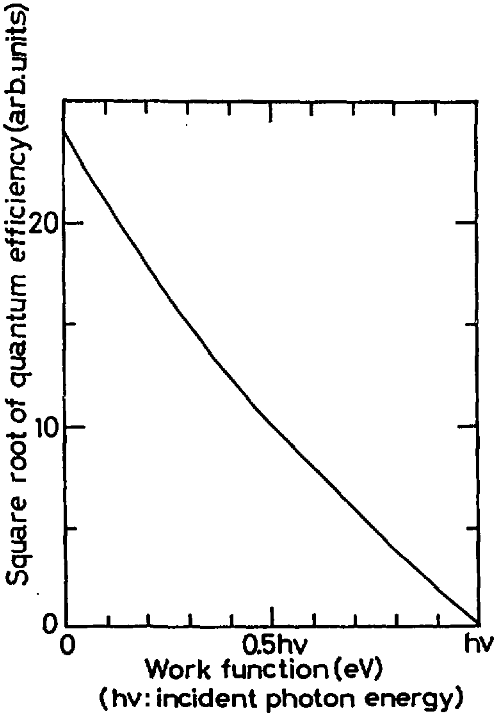

Fig.2 Square root of the quantum efficiency based on Fowler's theory as a function of the work function. The incident photon energy $h\nu$ is chosen to be 2.54eV which is the photon energy of the Ar^+ laser light.

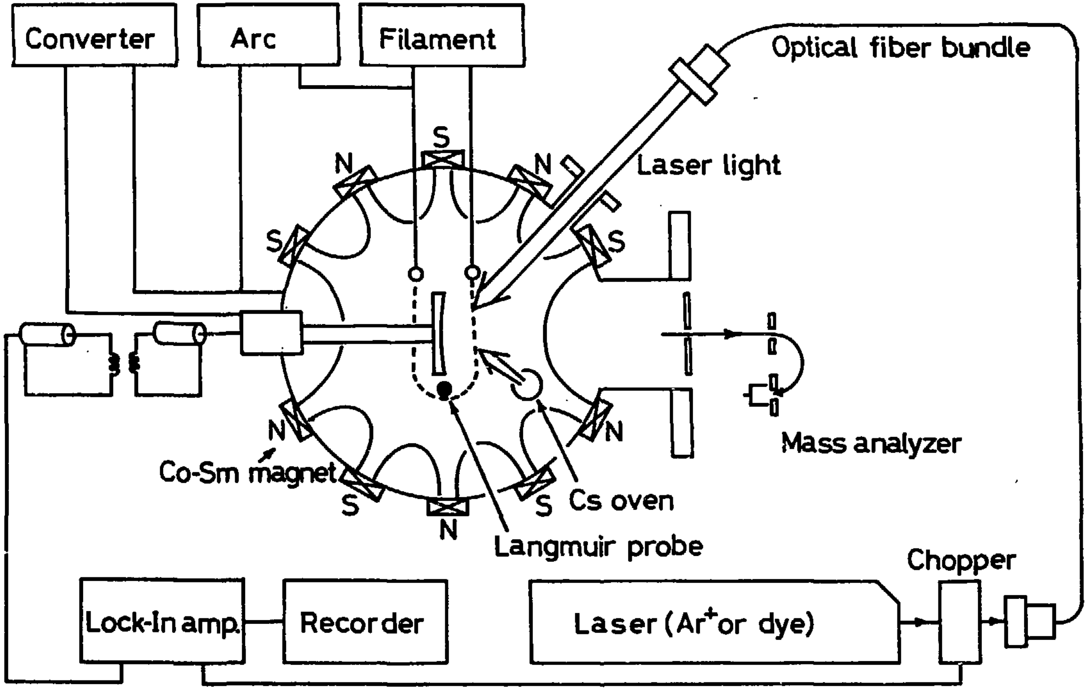

Fig.3 Schematic diagram of the experimental setup.

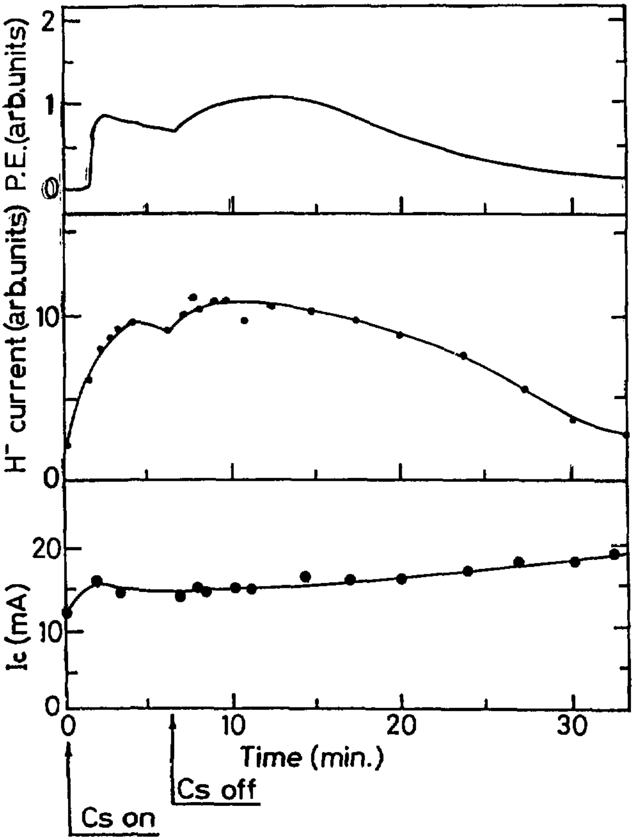

Fig.4 Induced photoelectron emission (P.E.) by the Ar^+ laser, H^- current and the converter current I_c as a function of the time in a hydrogen discharge with operating parameters as the arc power of 0.2A and 60V, the converter potential of -150V and the gas pressure of 0.87mTorr.

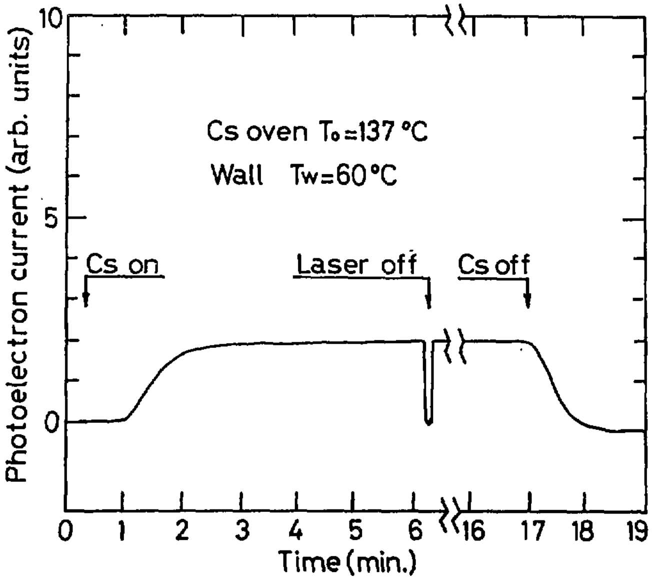

Fig.5 Photoelectron emission current for the lower oven temperature of about 137°C in a helium discharge under the condition as the arc power of 0.25A and 50V, the converter potential of -200V and the gas pressure of 2.5mTorr.

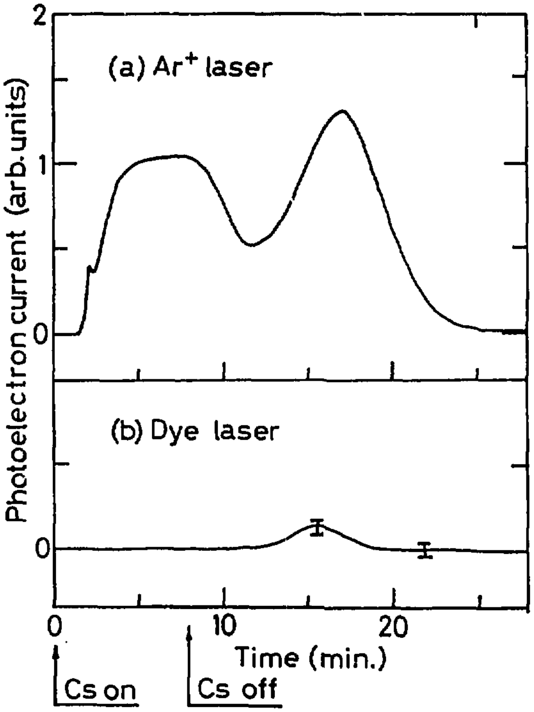

Fig.6 Comparison of the photoelectron current signals between the Ar^+ laser (a) and the dye laser (b) in a helium discharge under the condition as the arc power of 0.2A and 60V, the converter potential of -150V, the gas pressure of 2.3mTorr and the oven temperature of about 167°C.