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Pressure Measurement Using Field Electron Emission Phenomena

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Adsorption of residual gas molecules damped the emission current of a W (310) field electron emission (FE) emitter. The damping speed was linearly proportional to the pressure gauge readings at pressure ranging from $\sim 10^{-8}$ Pa to $\sim 10^{-9}$ Pa, and the proportionality constant was employed to measure pressure in the 10^{-10} Pa range. A time plot of FE current revealed the existence of an "initial stable region" after the flash heating of W(310) FE, during which the FE current damps very slowly. The presence of non-hydrogen gas removed this region from the plot, supplying a means of qualitatively analysing the gas species.

Keywords : Pressure, Field electron emission, Adsorption, Work function, Extreme high vacuum

I. Introduction

Pressure is defined as force per unit area applied to the surface of an object. In a low or medium vacuum range of pressure higher than 0.1 Pa, the force per unit area can be directly measured using a force collector such as a diaphragm, piston, etc. In high vacuum (HV) or ultra-high vacuum (UHV) systems in which the pressure is lower than 10^{-3} Pa, however, the force is too small to be measured directly. Various physical phenomena, e.g. thermal conduction, resonance, friction, etc., are used for measuring the pressure. The pressure in modern HV or UHV systems is mainly measured by reading the ionization current of residual gas, which is equivalent to counting the approximate number of ambient gas molecules.

Pressure measurement in an extreme high vacuum (XHV) range of pressure $P < 10^{-9}$ Pa is challenging, because the ionization pressure gauge is often the largest outgassing source in XHV systems [1]. The ionization gauge emits several watts and accelerates hot electrons of mA order, while the ionization current is on the order of < 1 pA in an XHV range of pressure, $P < 10^{-9}$ Pa. The consumption of a large amount of power is the origin of the large outgassing and it leads to misreading of the gauge. Several kinds of XHV gauges have been developed with special attention paid to the suppression or separation of background current signals [1-3]. However, the developed XHV gauges are quite complicated and measurements are not based on a simple mechanism, making them expensive and prone to false signals.

When a high electric potential is applied to a sharp metal tip, the potential barrier, which keeps electrons inside the solid, is narrowed by the high electric field around the tip apex; the height of the barrier is the work function. The electrons tunnel quantum mechanically through the narrowed potential barrier at the apex into the vacuum. This phenomen-

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on is called field electron emission (FE) and the sharp metal tip is called a field emitter [4].

The surface of a field emitter, i.e. the tip, is covered with gas molecules. In a vacuum, flash heating of a tip at ＞2,000 K causes the molecules to desorb from the tip surface. However, residual gases, mostly hydrogen in the UHV or XHV range, adsorb on the clean surface and raise the surface work function. The FE current therefore starts to decrease immediately after the tip cleaning, which is done by flash heating. Because the adsorption rate of residual gas is proportional to the pressure, the decreasing rate of the FE current is also proportional to the pressure. Therefore the damping speed of the FE current has often been used to estimate the pressure [5]. Cho et al. measured pressure using the FE current from a W tip oriented in the (111) direction with a measuring time of a few minutes in the 10^{-10} pa range [6].

Here, we show that the damping behaviour of the FE current from a W tip oriented in the (310) direction can also be exploited for pressure measurement in the XHV range. The adsorption effect of non-hydrogen gas molecules on the damping behaviour of the FE current is discussed as a way of analysing residual gas components qualitatively.

II. Experimental Apparatus

Fig. 1 provides a schematic illustration of the FE system used to investigate the emission characteristics of the W(310) FE sources. The system is evacuated using an ion pump (ULVAC Inc., PST-400AX2, nominal pumping speed 400 ℓ/s) and a non-evaporable getter (NEG) pump (Saes Getters, Capacitorr D-400). All the parts were degassed in a vacuum furnace at temperature of ＞300°C.

W (310) wires were electrochemically sharpened in a polishing solution. During the sharpening process, the surface of the FE tips is oxidized and contaminated by impurities in the solution. The surface oxide layer and impurities must be removed for stable FE operation, usually by flash heating at ＞2,000 K in vacuum. FE tips were spot welded onto a W polycrystal wire loop and indirectly heated by resistively heating the wire. The total emission current I_E from the FE tip was measured using a current meter in the line supplying acceleration voltage to the cathode. The current Ip of the electron beam measured using a faraday cup passes through a small aperture of 0.5 mm diameter. The current Ip originates from the (310) surface on the FE tip apex, and this is usually called the probe current. To measure probe current Ip of nanoampere range, a pico-ammeter was connected

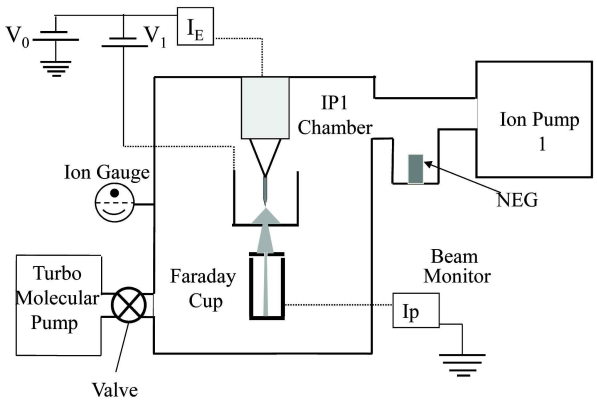

Figure 1. Schematic diagram of the experimental setup.

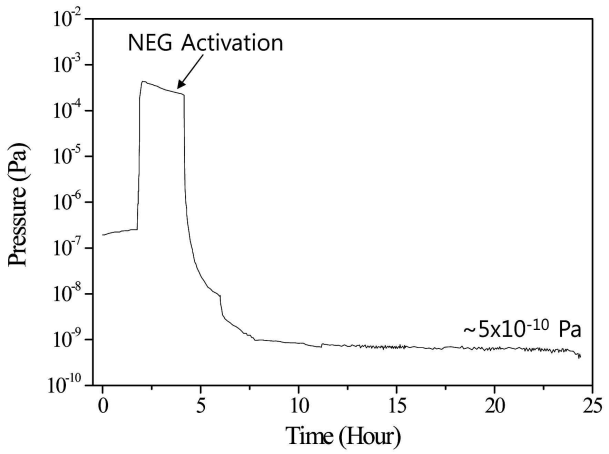

Figure 2. A pumping curve of the XHV FE system.

to the faraday cup.

Fig. 2 shows a pumping curve of the chamber in which the W(310) FE tips operated. The pressure was measured using an extractor ionization gauge (Leybold Inc., IM 540), which was installed near the NEG and the ion pump. The measured pressure is denoted by P_G. The FE system was baked for 48 hours and the pressure P_G gradually fell to 2×10^{-7} Pa. The NEG pump was activated for the last 2 hours during the bakeout and P_G rose to 4×10^{-4} Pa. After turning off both the baking and the NEG activation, P_G dropped rapidly to $\sim5\times10^{-10}$ Pa in 24 hours.

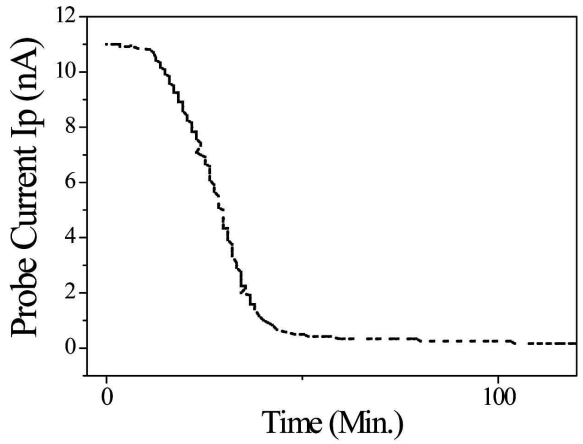

Figure 3. A typical damping curve of the W(310) FE probe current Ip under the UHV pressure range of 10^{-8} Pa.

III. Experimental Results and Discussion

Fig. 3 shows a typical plot of the probe current Ip from a W(310) FE tip under UHV of the low 10^{-8} Pa range. After tip cleaning, the probe current decreased quite slowly until it reached about 90% of the initial value. We denote the 90% damping time by τ_{90}, which normally corresponds to the point where the slope of the probe current Ip plot changes. The 90% damping time τ_{90} will be used to indicate the duration of "the stable region". The stable region lasted about 10 minutes, and then the FE current started to drop rapidly to a few % of the initial value; which has been called "the ever decreasing region" [7]. The rate of decrease of the FE current slowed with time and finally reached "the non-decreasing region", indicating saturation of the initially clean surface.

Decrease of pressure P_G to the 10^{-8} Pa range prolonged τ_{90} greatly, but the overall shape of the Ip trace did not change. Fig. 4 shows Ip plots of a W(310) FE tip under pressure ranging from 10^{-8} to 10^{-10} Pa. The total emission current I_E did not show "the stable region", revealing that this region is inherent only to the (310) surface of tungsten. The values of τ_{90} were 15, 105, and 450 minutes under P_G of 2×10^{-8} Pa, $2\sim3\times10^{-9}$ Pa, and $6\sim8\times10^{-10}$ Pa, respectively. As denoted by the dotted lines in Fig. 4, the 50% damping time τ_{E50} of the total emission cur-

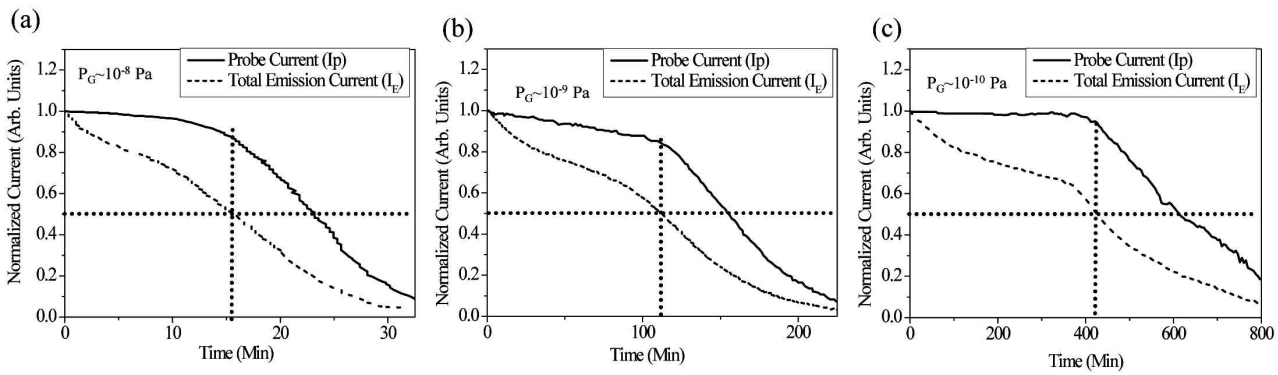

Figure 4. Damping curves of FE current at pressure (P_G) ranging from $\sim3\times10^{-8}$ Pa to $\sim8\times10^{-10}$ Pa. The probe and total emission currents are denoted by Ip and I_E, respectively.

rent I_E coincided with the point where the slope of the Ip current plots changed, which normally corresponds to the 90% damping time τ_{90} of the probe current Ip. The probe current always started to damp rapidly at around τ_{90}.

Oshima et al. showed that the product of the pressure P_{CH} and the damping time τ of the FE current is constant. The inverse of τ can be taken as the damping rate of the FE current, and the pressure should be proportional to $1/\tau$, which can be expressed as

$$P_{CH} \cdot \tau = \mathrm{C}_{CH} \Leftrightarrow P_{CH} = \mathrm{C}_{CH} \cdot \frac{1}{\tau} \quad (1)$$

where C_{CH} is proportionality constant.

We then compared $1/\tau_{E50}$ with the pressure gauge reading. The pressure was raised by heating the NEG modules. Residual gas analysis revealed that the outgassing from the heated NEG consisted of more than 99% hydrogen, as shown in Fig. 5. Because the NEG does not pump methane, the second highest component in the residual gas spectra was CH_4. The damping rate rose rapidly with an increase of pressure.

The plot of $1/\tau_{E50}$ as a function of the measured pressure P_G presented an almost complete linear dependence at pressure ranging from $\sim 10^{-8}$ Pa to $\sim 10^{-9}$ Pa, as indicated by the dotted line in Fig. 6(a). At pressure in the 10^{-10} Pa range, however, the pressure reading deviated from the dotted linear line, indicating the pressure gauge had read values higher than the real values. The plot was thus fitted with a straight line only in the pressure range from 10^{-8} Pa to 10^{-9} Pa, as in Fig. 6(b), yielding a proportionality constant C_{CH} of 1.93×10^{-7} (Pa·min). The measured

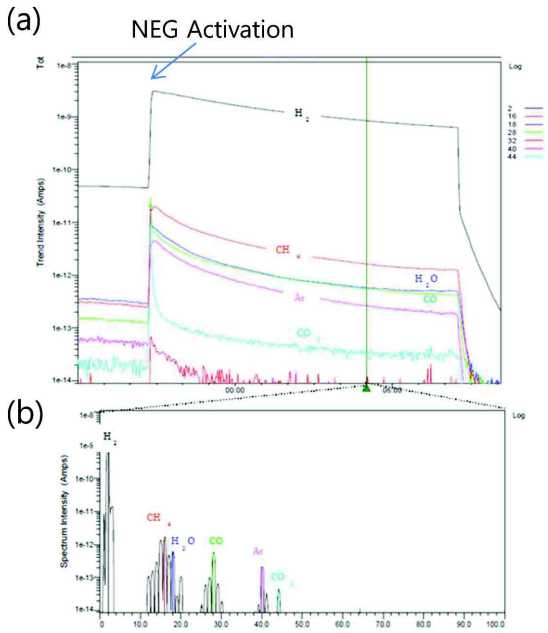

Figure 5. Plot of residual gas ion current (a) and a residual gas spectrum during NEG activation (b). NEG activation started at the time indicated by the arrow in (a).

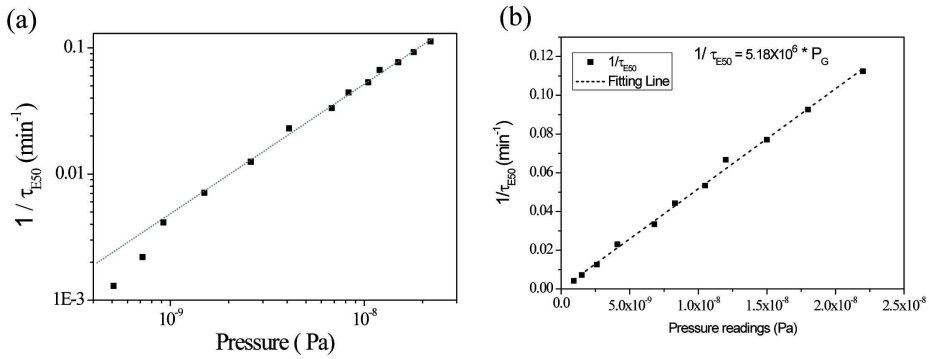

Figure 6. The inverse values of the damping time τ_{E50} of the FE current were plotted in a log-log scale at pressure (P_G) ranging from 2.2×10^{-8} Pa to 5.1×10^{-10} Pa (a) and in a linear scale at a pressure range from $\sim 2.5\times10^{-8}$ Pa to $\sim 1\times10^{-9}$ Pa (b). The data was fitted with a straight line in (b).

damping times of 770 and 450 minutes can then be converted to pressure values of 2.5×10^{-10} Pa and 4.2×10^{-10} Pa, respectively, using C_{CH}. The half year operation of our FE system increased the damping time τ_{E50} to more than 1,000 minutes, which corresponds to a P_{CH} of $< 1.9\times10^{-10}$ Pa.

The FE current damps due to an increase in the work function induced by gas adsorption. The work function changes differently depending on the kinds of surface and gas. The damping behavior of FE current is normally governed by the adsorption of hydrogen under UHV or XHV. If an electron beam strikes the extractor anode, it causes desorption of a large amount of gas molecules. This is known as Electron Stimulated Desorption (ESD) [8]. ESD outgassing often governs the pressure P_{CH} around cathodes, in particular for large emission current. If there remains a large amount of non-hydrogen gas, in particular on the extractor anode, ESD generates a large amount of non-hydrogen gas. We have developed several kinds of extractor anodes made of low-outgassing material. Nevertheless, we have occasionally observed the disappearance of 'the initial stable region' of W(310) FE current when a significant amount of non-hydrogen gas molecules appeared to remain.

Fig. 7(a) shows an I_p plot of a W(310) FE source obtained 1 day after the termination of a system bakeout. Although the measured pressure was in the range of 10^{-10} Pa, the stable region completely disappeared and the initial damping speed was rather high. Consequently, the 90% damping time τ_{90} of the probe current Ip shortened relative to τ_{50}. Normally, the 90% damping time τ_{90} is about half that of τ_{50}. However, Fig. 7(a) yields a ratio τ_{90}/τ_{50} of ~0.2. A maximum of two days of FE operation with an I_E of 10 μA returned the value of the ratio τ_{90}/τ_{50} to >0.5, as shown in Fig. 7(b). This demonstrates the cleaning effect on the extractor anode by the electron beam bombardment. When the anode is contaminated due to certain factors, e.g. outgassing from the electric discharge during high voltage operation, leakage, etc., the electron beam cleaning of the extractor anode takes more time. Fig. 8 shows the evolution of the ratio τ_{90}/τ_{50} with FE operation when the extractor anode was contaminated by outgassing from an electric discharge test. It took about 20 days for the value of τ_{90}/τ_{50} to return to its normal value of >0.5 for an I_E of 10 μA. For an I_E of 2 μA, τ_{90}/τ_{50} usually remained higher than 0.5, showing that the ESD-induced outgassing rate was reduced by lowering the emission current, I_E.

All the above observations revealed that the presence of non-hydrogen gas removes the 'the initial stable region' of the Ip trace of the W(310) CFE sources. This may explain why "the initial stable region" of the W(310) FE current has seldom been observed in any of the studies reported in the literature

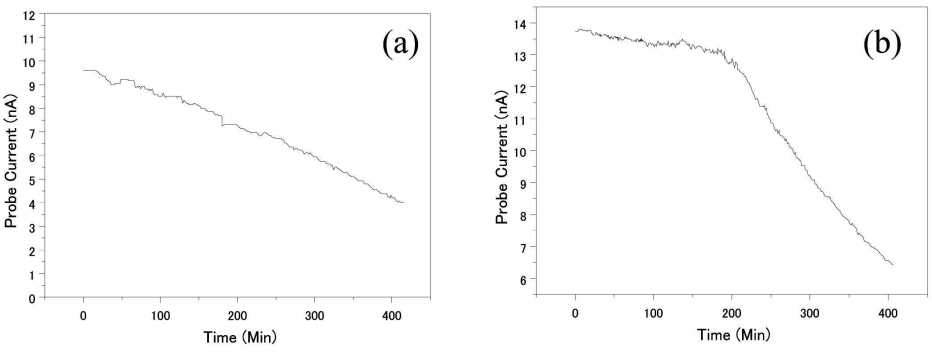

Figure 7. Damping plot of the probe current Ip from a W(310) tip one day (a) and three days (b) after a system bakeout.

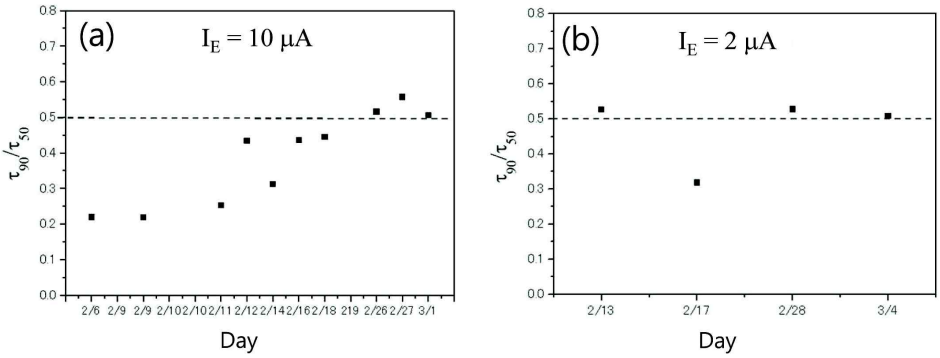

Figure 8. Evolution of the values of the ratio of damping time τ_{90} to τ_{50} for total emission current I_E of 10 μA (a) and 2 μA (b). Before the measurement, the extractor anode was contaminated by an electric discharge.

[9]; the appearance of "the initial stable region" requires the complete removal of non-hydrogen residual gas. We propose that monitoring the ratio τ_{90}/τ_{50} could reveal the presence of gas species other than hydrogen.

IV. Summary

A thoroughly degassed FE system was constructed and the emission current from W(310) FE sources was used to characterize the vacuum around the CFE source. After flash heating the W tip, the FE current damped quite slowly until the probe current reached 90% of the initial value, indicating the presence of a "stable region". The damping time of the FE current was inversely proportional to the operating pressure of the W(310) electron sources. The proportionality constant C_{CH} between the inverse of the damping time and the pressure was determined. If a field emitter is installed in a UHV or XHV system, one can measure the operating pressure by monitoring the damping time of the FE current and multiplying its inverse by C_{CH}. The presence of non-hydrogen gas removed the 'stable region' from the FE current plot, indicating that the shape of the time-plot of the FE current can be used to roughly estimate the main residual gas components.

Acknowledgments

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