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The reliability of measurements on electron energy distribution function in silane rf glow discharges*

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Electron energy distribution function (EEDF) is a key parameter of plasmas, which is directly proportional to the second derivative of the probe I-V characteristics. Because of an amplifying effect of unavoidable noises in the experimental probe I-V curves during the derivation process, the experimental I-V curves should be smoothed before performing the numerical derivation. This paper investigates the effect of adjustable factors used in the smoothing process on the deduced second derivative of the I-V curves, and an optimum group of the adjustable factors is selected to make the rms deviation of the smoothed I-V curves from the measured curves less than 1%. A simple differentiation circuit is designed and used to measure the EEDF parameter straightforwardly. It is the first time, so far as we know, to measure the EEDF parameters simultaneously by means of both numerical and circuit derivative methods under the same discharge conditions and on the same discharge equipment. The deviation between two groups of mean electron energy E and electron density n_e obtained by the above different methods is within about 7%. This apparently improves the reliability of the measurements of the EEDF parameters.

Keywords: Langmuir probe, reliability, numerical derivation, circuit derivation
PACC: 5270, 5280, 0260

1. Introduction

Plasma-enhanced chemical vapour deposition (PECVD) in parallel-plate silane radio frequency (rf) glow discharges is the most widespread method in deposition of silicon-based thin films. To a large extent, the relation between plasma properties and material properties is still unknown. There is not a commonly accepted model on the deposition mechanism yet. Electron energy distribution function (EEDF) in silane rf glow discharges is a key parameter for studying the spatial reaction process in a plasma and the surface reaction process on the substrate. For these reasons, there have been extensive studies of EEDF in capacitively coupled rf glow discharge plasma.[1−5]

Langmuir probe is the most commonly used diagnostic tool in the measurement on the EEDF of the plasma. The EEDF $f(\varepsilon)$ is directly proportional to the second derivative $\mathrm{d}^2I/\mathrm{d}V_\mathrm{p}^2$ of the probe I-V characteristic[6]

$$[f(\varepsilon)]_{(\varepsilon=-eV)} = -\frac{4}{A_P e^2}\sqrt{\frac{-m_\mathrm{e}V}{2e}}\frac{\mathrm{d}^2I}{\mathrm{d}V_\mathrm{p}^2}, \qquad (1)$$

where I and V_p are the collection current and bias voltage of the probe, respectively. A_p is the probe surface area exposed to the plasma. V is the probe potential relative to the plasma potential. m_e and ε are the mass and energy of the electron, respectively.

The mean electron energy E and electron density n_e can be evaluated from the normalized EEDF.

$$E = \int_0^\infty \varepsilon^{\frac{3}{2}} f(\varepsilon)\mathrm{d}\varepsilon, \qquad (2)$$

$$n_\mathrm{e} = \frac{4I_\mathrm{e,sat}}{eA_\mathrm{p}v_\mathrm{e}}, \qquad (3)$$

$$v_\mathrm{e} = \left(\frac{2E}{m_\mathrm{e}}\right)^{1/2}. \qquad (4)$$

Here $I_\mathrm{e,sat}$ is the saturated current of the probe, v_e is the mean electron velocity.

The second derivative of the probe I-V curve can be either obtained by numerical treatments or straightforwardly measured by a differentiation circuit.

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The measured probe I-V curves may be distorted, and deviate from the probe intrinsic characteristics because of both rf interference and contamination effects on the probe characteristics. A tuned and heating Langmuir probe has been used to restrain both effects successfully,[7,8] to provide an accurate measurement of the probe I-V characteristic. Even so, there are unavoidable statistic noises in the measured I-V characteristic, and an amplifying effect of these noises on the derivative of the I-V curves.[5] Therefore, the experimental I-V curve should be smoothed before carrying out the derivation of the I-V curve in numerical treatments. The second derivatives of the I-V curve may change with the selected adjustable factors in the smoothing process for the experimental I-V curve. This causes an uncertainty of the EEDF parameters obtained from the smoothed I-V curves. The unreliability of the measurement on EEDF parameters may appear in the derivative-circuit method also due to the existence of statistic noises.

In order to improve the accuracy and reliability of the measurement on EEDF parameters, a key problem is to restrain the amplifying effect of the statistic noise during the derivation process of the experimental probe I-V curves. This is the main subject of this paper.

Until now, the reported EEDF parameters of the plasma in a certain discharge equipment have been obtained by only one of the above methods, either numerical or circuit-derivative method. Therefore, these measured results cannot be compared with each other. In this paper, both the above differentiation methods are, for the first time so far as we know, used to measure the EEDF parameters of the plasma on the same discharge equipment under the same discharge situation simultaneously. Both the measured results are compared and agreed with each other well; therefore, the reliability of the measurements on EEDF parameters in silane rf glow discharges is apparently improved.

2. Experimental set-up

The probe diagnostic system in the capacitively rf glow discharge equipment is shown schematically in Fig.1. In the discharge room V, discharge is generated using a rf (13.56MHz) power supply P_{rf} fed through a matcher M and a capacitor C. W is the observation window of the discharge room. The probe P is positioned between the grounded up-electrode E_1 and the powered bottom-electrode E_2. The bias voltage V_{p} and the collected current I of the probe are fed to and measured by a source meter Keithley 617 simultaneously.

The probe is made of a tungsten filament with a diameter of 0.45mm. The probe tip of a 5mm length is exposed to the plasma, the other part of the probe is electrically shielded by a thin glass sleeve. The parallel circuit of L_1, C_1 in Fig.1 is tuned at 13.56MHz for restraining the rf interference on the probe which is heated by thermal radiation from the heater H placed in the up-electrode E_2 for restraining the contamination effect of the probe.

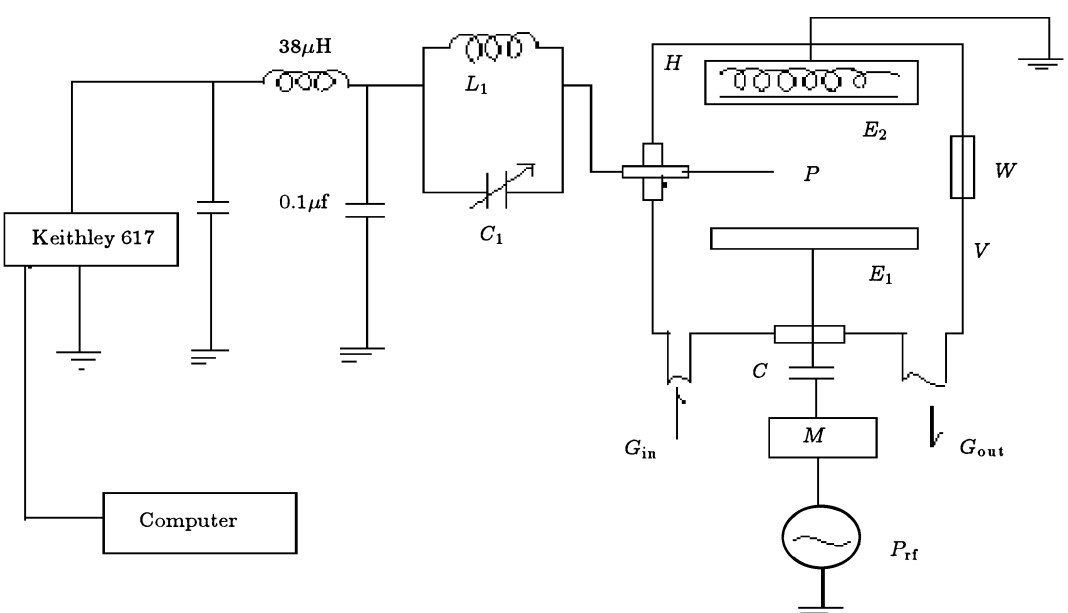


Fig.1. Schematic of the probe diagnostic system.

All of the experimental I-V characteristics are measured using this tuning and heating probe diagnostic system to restrain both effects of rf interference and contamination on the probe.

3. Numerical differentiation method

Numerical differentiation of the probe I-V characteristic is an important method for measurement on the EEDF parameters of the plasma. Various numerical differentiation methods have been carried out, and a comparison between them has been made.[3−5,9]

In this section, we briefly introduce a smoothing method for the experimental I-V characteristics, which was developed by Hayden.[10] The basic problem is to describe the effect of the selected adjustable factors on the numerical differentiation of the probe I-V characteristics in order to search an optimum group of the adjustable factors in the smoothing process and improve the reliability of the measurement on the EEDF parameters of the plasmas.

If we measure a function $y(x)$, what we really measure is not such a function but its convolution product with the instrument function of the experimental system

$$h(x) = y^* g = \int_{-\infty}^{\infty} y(t)g(t-x)\mathrm{d}t, \qquad (5)$$

where $h(x)$ is the measured function and $g(x)$ is the instrument function, which is normalized to unit. Let us write the measured function as follows

$$h(x) = h_n(x) + N(x), \qquad (6)$$

where $h_n(x)$ is the nth approximation to the smoothed function and $N(x)$ is the noise.

$$h_n(x) = h^* g_n, \qquad (7)$$

where $g_n = 1-(1-g)^{(n)}$, and the product $g^{(n)}$ means the convolution of g with itself n-1 times.

In most cases, the instrument function g can be approximated by a Gaussian distribution function with a standard deviation of σ, the function g_n is given by

$$g_n(x) = \sum_{k=1}^{n} \left(\frac{n}{k}\right)(-1)^{k+1}\frac{1}{\sqrt{2\pi k}\sigma}\mathrm{e}^{-\frac{x^2}{2\sigma^2 k^2}}, \qquad (8)$$

where n is the number of iterations.

The $h(x)$ and x correspond to the experimental collected I and bias voltage V of the probe, respectively. So $h_n(x) - x$ corresponds to the nth approximation of the smoothed probe I-V characteristic.

The measured probe I-V characteristic in the silane rf glow discharges was smoothed by the Hayden method using a different group of the adjustable factors n and σ. The measured and its smoothed I-V characteristics are shown in Fig.2(a) for n=1,3,5 at fixed σ=2, and in Fig.2(b) for σ=2,4,6 at fixed n=2, respectively. These curves demonstrate that the deviations between the measured and its smoothed I-V characteristics are sensitive to n at fixed σ=2, but less sensitive to σ at fixed n=2.

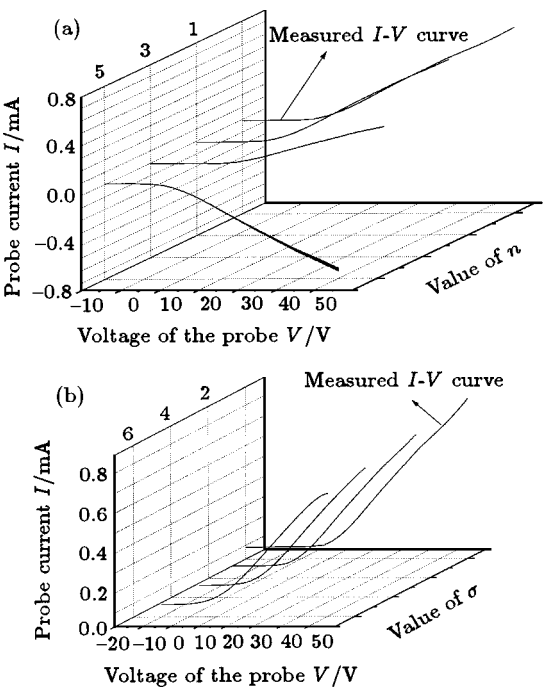


Fig.2. Plots of the measured and its smoothed probe I-V characteristics. (a) Corresponding to the adjustable factors: n=1, 3, 5 at fixed σ= 2; (b) corresponding to the adjustable factors: σ=2, 4, 6 at fixed n=2.

The second derivatives of the measured and its smoothed I-V characteristics have been worked out. The values of the second derivative of the measured characteristics are some mixed and disordered data.[5] The second derivatives $(\mathrm{d}^2I/\mathrm{d}V_\mathrm{p}^2)$ of the characteristics smoothed by using a group of the adjustable factors of n=1,3 at fixed σ=2 and σ=2,4,6 at fixed n=2 are shown in Figs.3 and 4, respectively. In Fig.3, the curve of $(\mathrm{d}^2I/\mathrm{d}V_\mathrm{p}^2) - V_\mathrm{p}$, corresponding to n=3, σ=2, appears severely oscillated because the probe I-V characteristic is distorted in the smoothing process.

A group of the plasma parameters E and n_e evaluated from the data of the $(\mathrm{d}^2I/\mathrm{d}V_\mathrm{p}^2) - V_\mathrm{p}$ curves shown in Fig.4, are listed in Table 1. These evaluated plasma

parameters are quite different, and closely related to the selected adjustable factors σ and n used in the smoothing process of the measured I-V characteristics. The rms deviations between the measured and its smoothed I-V characteristics are 0.7%, 1.2% and 2% corresponding to a group of adjustable factors σ=2,4,6 at fixed n=2, respectively. An optimum group of the adjustable factors is selected as σ=2 and n=2, depending on a minimum rms deviation (less than 1%) between the smoothed and its measured probe I-V characteristics, and the corresponding evaluated plasma parameters are E=4.2eV and n_e=7.5×10^{14}m^{-3}.

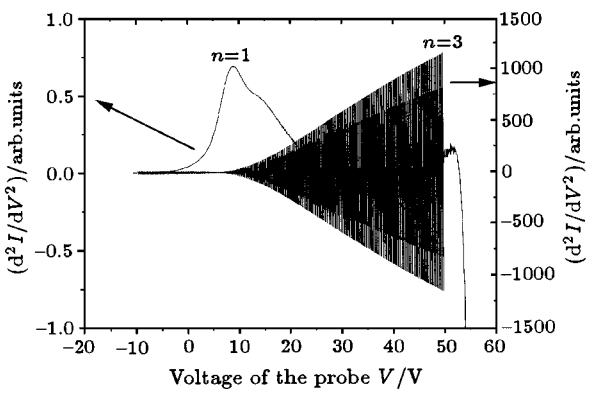


Fig.3. Plots of the second derivatives of the smoothed probe I-V characteristics for n=1, 3 at fixed σ=2.

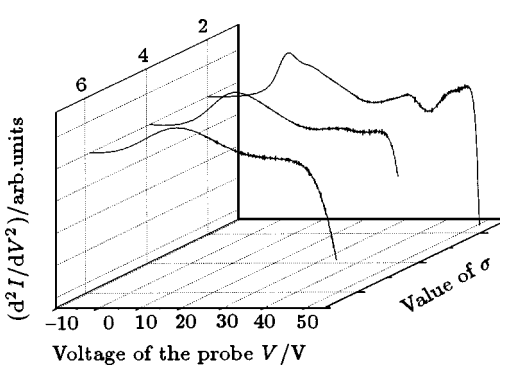


Fig.4. Plots of second derivatives of the smoothed probe I-V characteristics for σ=2, 4, 6 at fixed n=2.

Table 1. The mean electron energy E and electron density n_e for σ=2, 4, 6 at fixed n=2.

σ	2	4	6
E/eV	4.2	6.1	8.4
$N_e/10^{14}$m^{-3}	7.5	12.8	13.5

In order to prove the reliability of the measurement of the EEDF parameters obtained from the smoothed probe I-V characteristics using the optimum group of adjustable factors in the numerical differentiation method, it is necessary to measure the EEDF parameters by a circuit differentiation method and make a comparison between the EEDF parameters obtained by the two different measurement methods.

4. Circuit differentiation method

Goyak[11] has used a differentiation circuit to measure the second derivative of the probe I-V characteristic successfully. A rapid scanning voltage 20V·ms^{-1} was biased on the probe to avoid the contamination effect of the probe and reduce the phase retardation effect of the circuit. We design a more simple differentiation circuit consisting of two operation amplifiers, because both of the rf interference and contamination effects on the probe have been restrained by using a tuned and heating probe diagnostic circuit. The designed differentiation circuit is shown in Fig.5, and joined to the tune unit consisting of L_1 and C_1 in the probe diagnostic system in Fig.1. The output voltage V_{out} of the differentiation circuit is directly proportional to $\mathrm{d}^2I/\mathrm{d}V_p^2$,

$$V_{out} = KR_3^2C_3^2R_y\mathrm{d}^2I/\mathrm{d}V_p^2, \qquad (9)$$

where K is a constant, the ratio of the voltage increment to the time increment biased on the probe.

The sampling resistance R_y (2kΩ) is a voltage divisor, which provides a sufficiently large input signal for the differentiation circuit, but does not affect the measurement accuracy of the circuit, because R_y is much smaller than the resistance of the probe sheath in the plasma. The series circuit of R_3 (2kΩ) and C_3 (4700μF) and the parallel circuit of R_4 (10kΩ) and C_4 (100PF) are the input and feedback units of the operation amplifiers, respectively. The amplifying effect of the noises on the measured EEDF functions is very weak, because $R_3 \ll (\omega C_3)^{-1}$, $R_4 \ll (\omega C_3)^{-1}$ in the normal operation situation. With the increase in frequency ω, the input and feedback units consisting of such component parameters will reduce the amplification of the closed differentiation circuit, and therefore, restrain the effect of high-frequency noises, and improve the stability of the circuit operation.

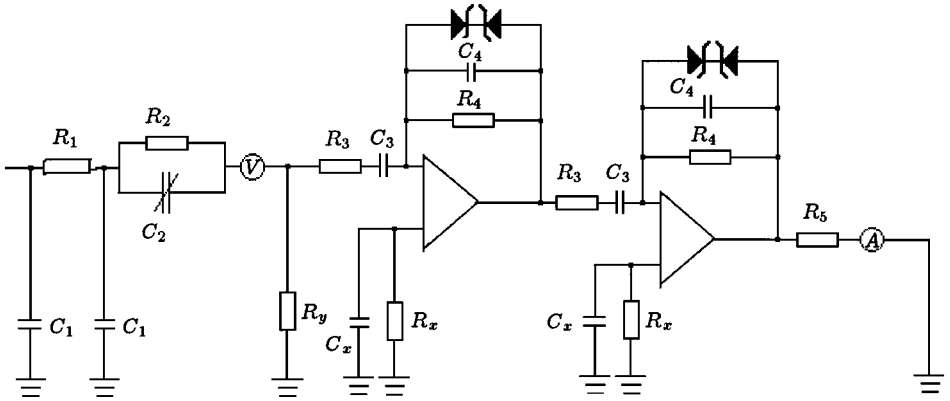


Fig.5. The differentiation circuit.

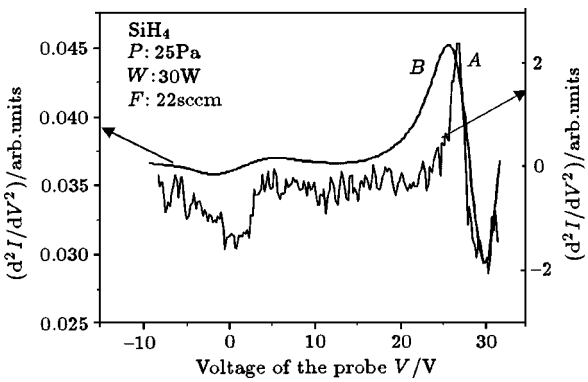


Fig.6. Plot of the second derivatives of the probe I-V characteristics. Curve A measured by the differentiation circuit; curve B obtained using the numerical differentiation method.

The second derivative of the I-V probe characteristic was straightforwardly measured by using the differentiation circuit. A plot of the second derivative obtained is shown in Fig.6 curve A.

In order to make a comparison, another plot of second derivative of an I-V probe characteristic smoothed using the optimum group of the adjustable factors is shown in Fig.6 curve B. Both curves A and B are measured on the same discharge equipment and under the same discharge conditions: operation pressure P=25Pa, rf power W=30W, flow rate of silane F=22 sccm.

The parameters of mean electron energy E and electron density n_e evaluated from the EEDF straightforwardly measured by using the differentiation circuit are 4.4 eV and $8.1\times10^{14}\mathrm{m}^{-3}$ respectively, which are a little difference from the parameters of 4.2eV and $7.5\times10^{14}\mathrm{m}^{-3}$ evaluated from the EEDF obtained by using the numerical differentiation method. The deviation between the two groups of parameters is less than 7%.

5. Conclusions

Because the amplifying effect of unavoidable noises, which exist in the measured probe I-V characteristics, on the derivative of the probe characteristics, the measured probe I-V characteristics should be smoothed before the derivation.

The second derivative of the smoothed characteristics changes with the group of the adjustable factors used in the smoothing process. The basic problem is to select an optimum group of adjustable factors by making the smoothed probe I-V characteristic fit to the measured well, and the rms deviation between the measured one and the smoothed characteristics should be less than 1%.

In the differentiation circuit, the operation amplifier input and feedback units consisting of an optimum group of component parameters can restrain the effect of noises on the measured EEDF functions, and effectively improve the stability of the circuit operation.

The two groups of parameters of the mean electron energy and electron density evaluated from the EEDF functions agree well with each other. These EEDF functions were measured using the circuit and numerical differentiation methods, respectively, in the same discharge equipment and under the same discharge conditions; therefore, this apparently improves the reliability of the measurement on EEDF parameters.

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