# MEASUREMENT OF PLASMA TEMPERATURE WITH ELECTRIC PROBE UNDER FLOATING POTENTIAL

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One of the possible ways to determine electron temperature from two measurements of probe current on the electron part of *I-V* characteristic is discussed. In this case an alternating voltage of fixed amplitude is applied to the probe under floating potential via decoupling capacitor. It is shown that the probe bias voltage of magnitude $\sim\kappa T_e$ is enough to measure electron temperature and to calculate ion saturation current. The results of control experiment on measuring of plasma parameters in magnetron gas discharge are in good agreement with calculations.

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The classical method of measurement of the plasma parameters is based on analysis of exponential part of probe's *I-V* characteristic [1]. It allows in principle to determine temperature and relative density of plasma electrons as a result of probe current measurement only in two points of the probe characteristic. One of the possible way to determine electron temperature from two measurements of probe current on the electron part of *I-V* characteristic was realized by *Kaya* [2]. In this paper the electron temperature

$$kT_e = \frac{V_2 - V_1}{ln\dfrac{I_{e2}}{I_{e1}}}$$

was calculated after measuring the probe currents $I_{e2}$, $I_{e1}$ under probe potentials $V_2$, $V_1$.

However, such a method has several restrictions. These arise owing to the fact that the measured probe currents $I_{e1,2}$ must greatly exceed the ion saturation current. It doesn't always work due to increasing of power dissipated by probe with increasing of $I_e$ current. Furthermore the magnitude of current depends not only on electron temperature and probe voltage $V_{1,2}$, but also on plasma potential. The method's ability can be substantially widened, if amplitude of alternating probe current is measured under average value of current on the probe $\overline{I_e} = 0$, i.e. when probe is under floating potential.

At $\overline{I_e} = 0$ with zero initial bias on the probe the total flow of particles on the probe $\overline{n} = \overline{n_e V_e + n_i V_i}$ is essentially reduced. It leads to noticeable diminution of heat load on the probe and consequently to increasing measurement range of plasma density $n_e$ and electron temperature $T_e$. Our evaluations of thermal design show that in the floating potential mode it is possible to measure electron temperature and plasma density of hydrogen up to the value of about $10^{14}$ $cm^{-3}$ with $T_i$, $T_e \approx 30 \div 40$ $eV$ without necessity to take in account an effects concerned with occurrence of ion-electron emission.

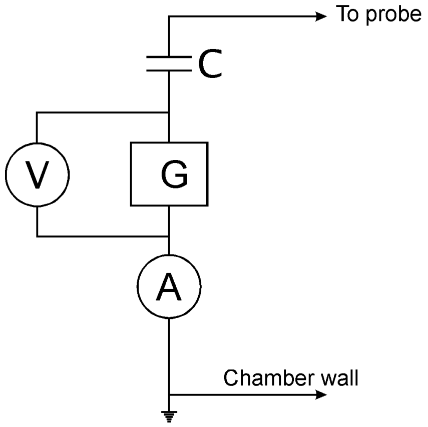

*Fig. 1. Measuring circuit*
*C – blocking capacitor; G – voltage pulse generator; V – voltage pulse meter; A – current pulse meter*

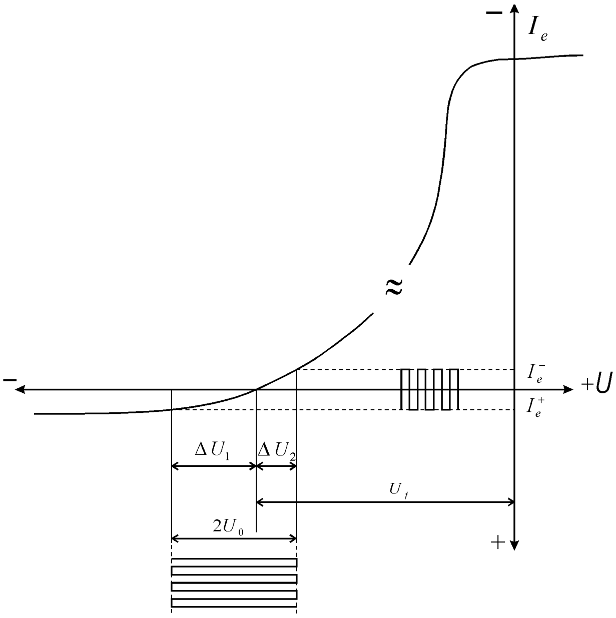

*Fig. 2. Current-voltage characteristic for the probe under alternating voltage*
*$U_f$ – probe voltage at $U_0=0$; $U_f - \Delta U_1$ - probe voltage at negative half-cycle of $U_0$; $U_f + \Delta U_1$ - probe voltage at positive half-cycle of $U_0$; $I_e$ – probe current*

Lets consider the operation principle of measuring circuit shown in fig.1. The probe is connected in series with square shape voltage pulse generator *G* and gauge of alternating current *A* through the blocking capacitor *C*. Under zero value of alternating voltage, the blocking capacitor is charged up to voltage of the floating potential $U_f=U+U_p$. $U_f$ – voltage between the probe and common electrode of the measuring circuit (for example the wall of vacuum chamber); $U$ – voltage between the probe and plasma; $U_p$ – voltage between plasma and common electrode of the measuring circuit.

When an alternating voltage with amplitude $U_0$ is applied the blocking capacitor $C$, which is charged up to the potential $U_f$, change its charge so that average value of current flowing through the capacitor kept zero value (Fig. 2):

$$\overline{I_e} = \overline{I_e^+ + I_e^-} = 0 \cdot$$

$I_e^+$ - probe current at negative half-cycle of $U_0$; $I_e^-$ - probe current at positive half-cycle of $U_0$.

Lets equate current balance for both half-cycles $U_0$ of alternating voltage and for the case when $U_0 = 0$

$$I_0^i + I_0^e \exp\left( -\frac{U}{kT_e} - \frac{\Delta U_1}{kT_e} \right) = I_e^+ \tag{1}$$

$$I_0^i + I_0^e \exp\left( -\frac{U}{kT_e} + \frac{\Delta U_2}{kT_e} \right) = I_e^- \tag{2}$$

$$I_0^i + I_0^e \exp\left( -\frac{U}{kT_e} \right) = 0 \tag{3}$$

$$\Delta U_1 + \Delta U_2 = 2U_0 \tag{4}$$

$$I_e^+ = -I_e^- = I_e \tag{5}$$

$I_0^i$ – ion saturation current;
$I_0^e$ – electron saturation current;
$I_e^+$ – probe current at negative half-cycle $U_0$;
$I_e^-$ – probe current at positive half-cycle $U_0$;
$I_e$ – amplitude value of alternating probe current;
$U_0$ – amplitude alternating voltage;
$U$ – voltage between the probe and plasma under $U_0$=0.

The solution of combined equations (1-5) gives

$$kT_e = \frac{2U_0}{ln\dfrac{I_0^i + I_e}{I_0^i - I_e}} . \tag{6}$$

One can measure $I_{e1}$ and $I_{e2}$ under two values of alternating voltage $U_{01}$, $U_{02}$ and therefore to calculate $I_0^i$, i.e. the magnitude which is proportional to plasma density

$$\frac{U_{01}}{U_{02}} = \frac{ln\dfrac{I_0^i + I_{e1}}{I_0^i - I_{e1}}}{ln\dfrac{I_0^i + I_{e2}}{I_0^i - I_{e2}}} . \tag{7}$$

At fixed ratio $\dfrac{U_{01}}{U_{02}} = 2$

$$I_0^i = I_{e2}\sqrt{\frac{I_{e1}}{2I_{e2} - I_{e1}}} ; \tag{8}$$

$$kT_e = \frac{2U_{02}}{ln(A + \sqrt{A^2 - 1})} = \frac{U_{o1}}{ln(A + \sqrt{A^2 - 1})} ;$$
$$where \ A = \frac{I_{e2}}{I_{e1} - I_{e2}} \tag{9}$$

If keeping the ratio $\dfrac{U_{01}}{U_{02}}$ constant to adjust the amplitude $U_{01}$ to such value that the ratio of measured currents would be equal to $\dfrac{I_{e1}}{I_{e2}} = \dfrac{(1+e)^2}{1+e^2} = 1{,}648$; then $kT_e = U_{01}$, $I_0^i = 1{,}313 I_{e1} = 2{,}184 I_{e2}$.

At fixed ratio $\dfrac{U_{01}}{U_{02}} = 3$

$$I_0^i = I_{e2}\sqrt{\frac{3I_{e1} - I_{e2}}{3I_{e2} - I_{e1}}} . \tag{10}$$

$$kT_e = \frac{2U_{02}}{ln(B + \sqrt{B^2 - 1})} = \frac{2U_{01}}{3\,ln(B + \sqrt{B^2 - 1})} ;$$
$$where \ B = \frac{I_{e1} + I_{e2}}{2(I_{e1} - I_{e2})} \tag{11}$$

In this case, under condition the ratio of measured currents is equal to

$$\frac{I_{e1}}{I_{e2}} = \frac{e^{\frac{4}{3}} + e^{\frac{2}{3}} + 1}{e^{\frac{4}{3}} - e^{\frac{2}{3}} + 1} = 2{,}369 ;$$

$$kT_e = U_{01}, \ I_0^i = 1{,}105 I_{e1} = 2{,}164 I_{e2} .$$

Thus for measuring electron temperature and ion saturation current it is possible to use alternating voltage with amplitude $\sim kT_e$. This method gives clear advantages when studying dense plasma and plasma with relatively high electron temperature.

Schematic diagram of experimental circuit that allow to determine $kT_e$ and $I_0^i$ from two measuring of probe current $I_{e1}$ and $I_{e2}$ under two values of alternating voltage $U_{01}$ and $U_{02}$ is shown in fig. 3.

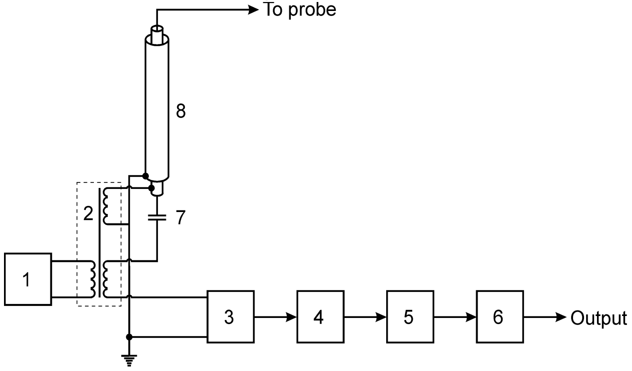

*Fig. 3. Schematic diagram of experimental circuit: 1) voltage pulse generator with controlled amplitude; 2) blocking transformer; 3) integrating amplifier of probe current; 4) detector; 5) switch generator; 6) output amplifier; 7) blocking capacitor; 8) connecting cable with double core screen*

The squared shape voltage pulse generator with variable amplitude (1) is loaded on blocking transformer (2). The first out secondary winding is connected to the probe through the blocking capacitor (7). Another one is connected to the input of the measuring amplifier (3) of probe current which output signal comes to full-wave rectifier. Working frequency of generator is in the range of 20...100 *kHz*. Since measured probe current is periodic and its average value is equal to zero, a probe current amplifier is realized as an integrating amplifier circuit. This gives an opportunity to efficiently suppress the noise component of probe current keeping total sensitivity high enough. After detection, the measured signal is additionally integrated by switch integrator (5) operating on frequencies, which corresponds to 2, 4, and 8 periods of alternating voltage. It leads to increasing of circuit sensitivity in 2, 4, 8 times and respectively to further decreasing the noise level of the probe current. After second integrating, a signal comes through the repeater (6) to the recording device.

To decrease the entry level of measured alternating current that is flow parallel to the probe current through the capacitor of the connecting cable, the circuit of cable capacity neutralization is used. It consists of additional winding of blocking transformer and connecting cable with double core screen connected each other as shown in fig. 3.

Neutralization of connecting cable capacity with length of about 2 *m* allow to decrease an entry level of measured current down to ≈1,5 *μA* at $2U_0$=4 *V* under working frequency 50 *kHz*. Time sequence of measuring circuit operation is shown in fig.4.

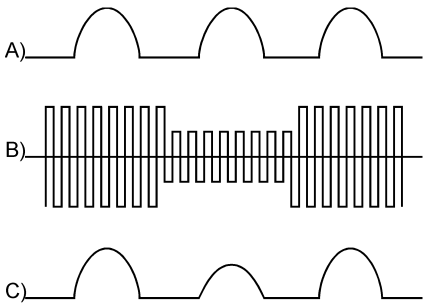

*Fig. 4. Time sequence of measuring circuit operation: A) discharge current; B) $U_0$ – generator output voltage; C) $I_e$ – measured probe current*

Results of calculations were proved with the help of above-mentioned measuring device when measuring plasma parameters in magnetron discharge. The works were carried out on the experimental setup described in details elsewhere [3]. Discharge parameters were following: working gas *Ar*, pressure $3\cdot10^{-3}$ *Torr*, discharge current $I_d$=2,5...3,5 A, voltage on the discharge gap $U_d$=460…480 *V,* pulse time of discharge current 6 *ms*, pulse rate 100 *kHz* (fig.4a). *Cu* cathode with diameter 190 *mm* was used.

The cylindrical probe of tungsten (length 5 *mm*, diameter 0,5 *mm*) was placed on the axis of discharge chamber at a distance 80 *mm* from the cathode. Results of measuring plasma parameters are shown in fig. 5

At different values of $2U_0$ the probe currents $I_e$ were measured. Then $I_0^i$ (formulas 8 and 10) and $kT_e$ (formulas 9 and 11) were calculated from two values of probe current $I_{e1}$ and $I_{e2}$ obtained at fixed ratio $\frac{U_{01}}{U_{02}}$ and then further were used to calculate $I_e = I_o^i \dfrac{exp\left(\dfrac{2U_0}{kT_e}\right)-1}{exp\left(\dfrac{2U_0}{kT_e}\right)+1}$.

Results of these measurements are shown in fig.5.

The offered measuring device allows determining plasma parameters with the help of electric probe under floating potential of any magnitude without using constant bias potential on the probe.

Because the measuring was carried out on plasma with small density ($n_e$~$10^9$ cm $^{-3}$) and therefore high relative level of probe current fluctuations, the major attention was given to the technique of measured information averaging (double integration of probe signals). With increasing the plasma density, the relative level of probe current fluctuations is decreased $\sim(n)^{-\frac{1}{2}}$. It allows increasing the measurement accuracy and time resolution, which depends on working frequency of voltage pulse generator.

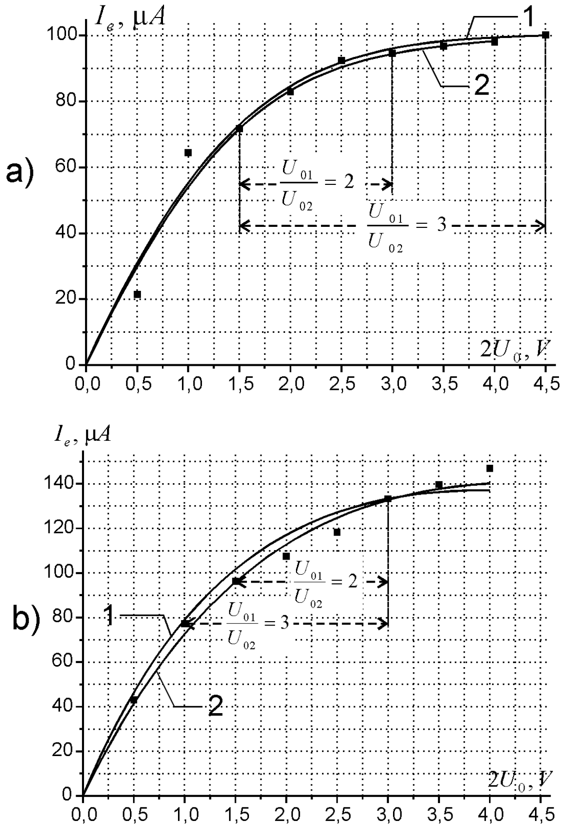

*Fig. 5. Dependence* $I_e = I_0^i \dfrac{\exp(\frac{2U_0}{kT_e})-1}{\exp(\frac{2U_0}{kT_e})+1}$:

*a) discharge current* $I_p$=2,5 *A*;

1) $\frac{U_{01}}{U_{02}} = 3$; $I_0^i = 101{,}5\,\mu A$; $kT_e = 0{,}82\,eV$.

2) $\frac{U_{01}}{U_{02}} = 2$; $I_0^i = 98{,}9\,\mu A$; $kT_e = 0{,}79\,eV$.

*b) discharge current* $I_p$=3,5 *A*;

1) $\frac{U_{01}}{U_{02}} = 3$; $I_0^i = 137{,}2\,\mu A$; $kT_e = 0{,}75\,eV$.

2) $\frac{U_{01}}{U_{02}} = 2$; $I_0^i = 141{,}5\,\mu A$; $kT_e = 0{,}89\,eV$.

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# ВИМІРЮВАННЯ ТЕМПЕРАТУРИ ПЛАЗМИ ЕЛЕКТРИЧНИМ ЗОНДОМ ПІД ПЛАВАЮЧИМ ПОТЕНЦІАЛОМ

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У статті запропоновано один з можливих методів визначення електронної температури за двома вимірюваннями зондового струму на електронній гілці вольт-амперної характеристики. У цьому випадку змінна напруга постійної амплітуди прикладається до зонда через розв'язуючий конденсатор. Показано, що потенціал зонда ~*к*$T_e$ достатній для вимірювання електронної температури та обчислення іонного струму насичення. Результати контрольних експериментів з визначення плазмових параметрів у магнетронному розряді добре узгоджуються з розрахунками.

# ИЗМЕРЕНИЕ ТЕМПЕРАТУРЫ ПЛАЗМЫ ЭЛЕКТРИЧЕСКИМ ЗОНДОМ ПОД ПЛАВАЮЩИМ ПОТЕНЦИАЛОМ

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В статье предложен один из возможных методов определения электронной температуры по двум измерениям зондового тока на электронной ветке вольт-амперной характеристики. В этом случае переменное напряжение постоянной амплитуды прикладывается к зонду через развязывающий конденсатор. Показано, что потенциал зонда ~к$\mathrm{T_e}$ достаточен для измерения электронной температуры и вычисления ионного тока насыщения. Результаты контрольных экспериментов по определению плазменных параметров в магнетронном разряде хорошо согласуются с расчетами.