CYLINDRICAL PROBE IN THE NITROGEN PLASMA OF A GLOW DISCHARGE AT AVERAGE PRESSURES

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The results of a study of the nitrogen plasma of a stabilized glow discharge ($I_t = 40-80$ mA, $p = 1-7$ mm Hg) using Langmuir probes 0.004 and 0.03 mm in diameter are presented. Considerable disagreement is found in the plasma parameters n and $f(\varepsilon)$ (electron concentration and energy distribution function of electrons) obtained by measurement with probes of $\phi = 0.004$ and 0.03 mm. An analysis of the experimental data made it possible to conclude that the measurements made using the probe of $\phi = 0.004$ mm are correct, and to show the magnitudes of the systematic distortions of the plasma parameters occurring in work with a probe of $\phi = 0.03$ mm.

Interest in the operation of a Langmuir probe in a glow discharge plasma at average pressures ($p \sim 10$ mm Hg) has intensified in connection with studies of the physical processes in the plasma of a CO_2 laser [1].

The difficulties connected with the use of the probe method for $p \gtrsim 1$ mm Hg have been indicated in the literature [2]. The theory describing the operation of probes at low pressures implies that the inequality d, D $\ll \lambda$ is satisfied (d is the diameter of the probe, D is the thickness of the space charge layer, and λ is the free path length of the electrons). Because the indicated dimensions are comparable in the region under consideration it can be expected that the plasma parameters measured by the probe will be distorted. The qualitative nature of the distortions arising in this case is clear: if the probe is at the space potential the current in it becomes so great that the influx of electrons from the plasma into the region of localization of the probe through diffusion is not able to restore the electron density n to the level n_0 in the undisturbed plasma. As a result, as noted in [2, 4] the probe method leads to an understated electron concentration n and to an overstated mean electron energy $\langle\varepsilon\rangle$.

A method of recovering the electron energy distribution for the case of a spherical probe comparable to the electron path length is proposed in [3]. The analogous problem for the case of a cylindrical probe is solved in [4]. Unfortunately, the method is rather cumbersome because of the dependence of the parameters D and λ which enter into the theory on the electron velocity distribution function $f(v)$; in addition, the assumption that the space charge layer has a small thickness is not always satisfied at $p > 1$ mm Hg.

A comparison of the characteristics of "thick" ($d = 30\ \mu$) and "thin" ($d = 4\ \mu$) probes in the plasma of a stabilized glow discharge in N_2 is made experimentally in the present report.

The degree of distortion of the plasma parameters by a probe at different gas pressures and discharge points was determined by the following system:

1) the electron distribution functions with respect to energy $f(\varepsilon)$ and velocity $f(v)$ at different points along a radius r of the gas-discharge tube were found by the second derivative method. Then the dependence of the mean electron thermal velocity

$$\langle v_T\rangle = \int f(v)\, v\, dv \left[\int f(v)\, dv\right]^{-1}$$

was calculated at different r;

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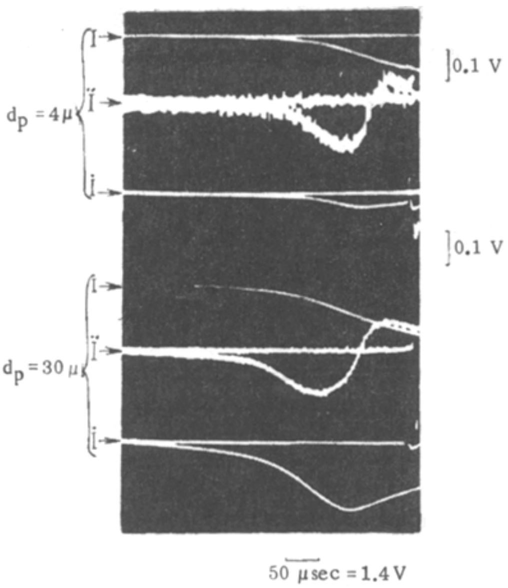

Fig. 1

2) the electron concentration n(r) for different distances from the axis of the tube was calculated from the probe currents at the space potential and the value $\langle v_T(r) \rangle$;

3) the electric field strength E was determined using a double probe;

4) the radial temperature distribution T(r) of the gas was determined from thermocouple measurements analogous to [5].

Since NT = const across the tube, the thermocouple measurements made it possible to obtain the dependence N(r) of the concentration of gas molecules for different experimental conditions;

5) the dependence $v_g(r)$ of the electron drift velocity was constructed from the known N and E, after which the radial dependence of the discharge current density $j(r) = en(r) v_g(r)$ was determined.

To test the correctness of the probe operation a comparison was made of the total current I_t in the gas-discharge tube measured with a milliammeter and the current reduced by the indicated method

$$I = 2\pi \int_0^R j(r)\, r\, dr$$

for pressures of $p \leq 7$ mm Hg and currents of $I_t = 40$, 60, and 80 mA. The electron energy distribution functions $f(\varepsilon)$ measured by the two probes under these same conditions were compared.

Probes of two types were mainly used in the experiments: d = 30 μ (platinum) and d = 4 μ (tungsten). Each probe consisted of a long quartz capillary (~100 μ in diameter) through which a wire of one of the indicated types was drawn. The length of the open part of the probe was l ~3 mm. The two probes (thick and thin) prepared in this way were mounted in a pair with a distance of ~3 mm between them. The probes were inserted into an uncooled gas-discharge tube (inner diameter 36 mm, length 750 mm) across its axis 12 cm from the anode and could be shifted radially without disturbing the vacuum. The flow velocity of gas in the tube was ~1 m/sec.

The measurements were made in the following way. The probes were at a floating potential and were alternately switched into the measuring circuit using a relay at 2 msec. At the moment of switching the probe was blocked with respect to electron flow, although the probe potential, which was set from a reference source connected between the anode and the probe, was close to the floating potential. The sequence of subsequent operations was as follows: the triggering voltage was supplied to the probe from a sawtooth pulse generator (amplitude of sawtooth pulse 50 V, duration ~1 msec, nonlinearity 2%). The voltage, proportional to the probe current I_p, was taken from the load impedance and was fed to one of the beams of an S1-33 oscillograph.

After differentiation of this signal using an RC circuit and amplification, a signal proportional to the first derivative of the probe current was viewed on the second beam. Finally, after redifferentiation and amplification the second derivative signal was fed to the third beam. After some fixed time (10 msec) the second probe was turned on according to an analogous program.

Oscillograms obtained by the system described above are presented in Fig. 1.

Each measurement was preceded by conditioning of the probe surface by ion bombardment. To determine such characteristics as the mobility, drift velocity, and free path length of the electrons in the gas it was necessary to know the concentration N of the neutral gas. The latter was measured indirectly from the measured pressure p and temperature T of the gas in the discharge. The gas temperature measurements were made using a platinum (ϕ = 30 μ) and copper (ϕ = 15 μ) thermocouple. The thermocouple was constructed analogously to a probe. The thermocouple was calibrated with respect to Rayleigh scattering of ruby laser light (V. N. Luk'yanov and G. I. Shu'zhenko took part in the light scattering experiments). The essence of the calibration consists in the following. Observation of the scattered radiation in the discharge

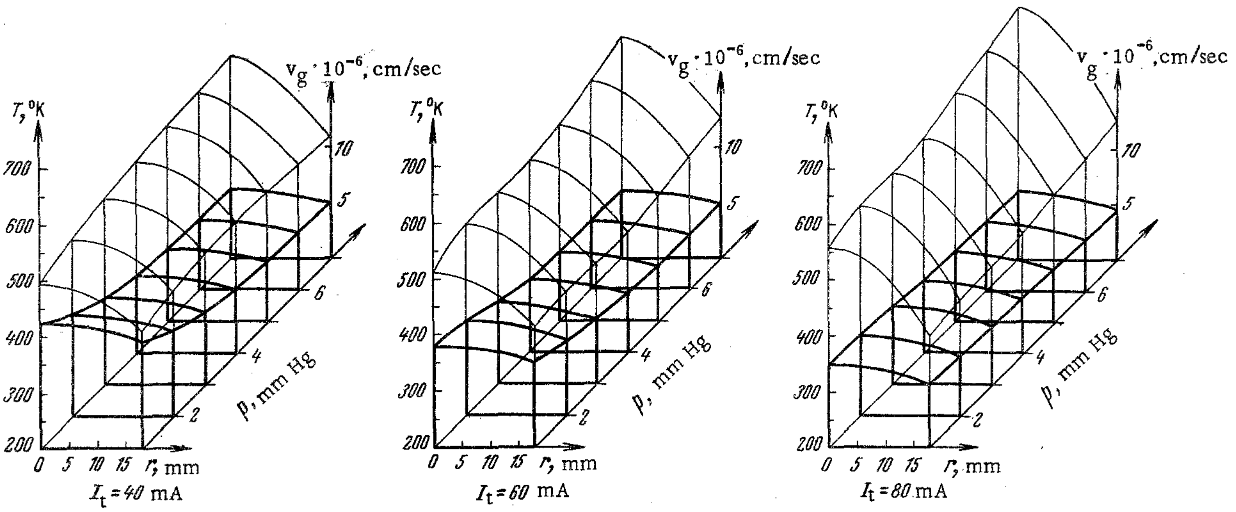

Fig. 2

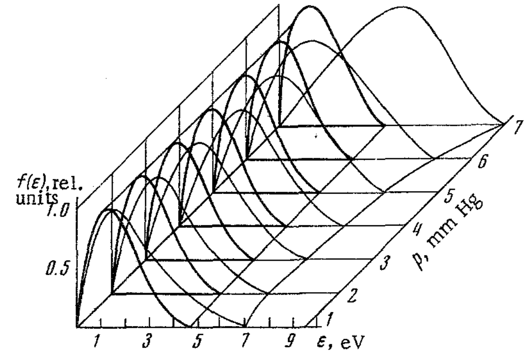

Fig. 3

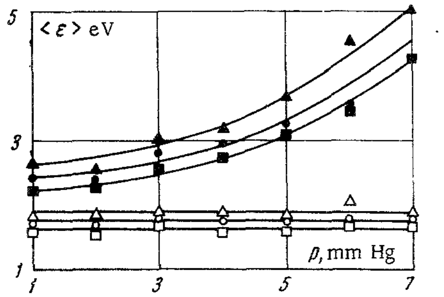

Fig. 4

and in cold gas at the same pressure makes it possible to determine $N/N_0 = T_0/T$. This ratio was then compared with the temperature ratio obtained from the thermocouple measurements. In the temperature and pressure range of interest to us the disagreement did not exceed 10%.

The gas temperature distributions (fine lines) along the radius in the pressure interval of p = 1-7 mm Hg are presented in Fig. 2 for three currents: I_t = 40, 60, and 80 mA. Measurements of the electric field strength E were made for these experimental conditions. In conjunction with the temperature measurements this makes it possible to determine the electron drift velocity from the dependence $v_g = F(E/N)$ which is known for nitrogen. Families of $v_g(r)$ curves are presented in Fig. 2 (heavy lines).

Electron energy distribution functions $f(\varepsilon)$ obtained from an analysis of the second derivatives of probe currents for different pressures and a discharge current of I_t = 80 mA are shown in Fig. 3. The curves shown by fine lines refer to the probe with d = 30 μ. The corresponding families of $f(\varepsilon)$ curves for currents of I_t = 40 and 60 mA have an analogous form. The mean electron energy functions

$$\langle\varepsilon\rangle = \left[\int f(\varepsilon)\,d\varepsilon\right]^{-1}\int f(\varepsilon)\,\varepsilon\,d\varepsilon$$

obtained from families of the type presented in Fig. 3 are illustrated in Fig. 4.

The magnitude of the measured electron concentration and the form of the distribution functions obtained from the probe characteristics depend essentially on the choice of the space potential point. In the literature this point is connected both with the null of the second derivative of the probe current [6, 7] and with its maximum [8]. The authors of the present report, based on the results of [6], took the null of the second derivative as the space potential.

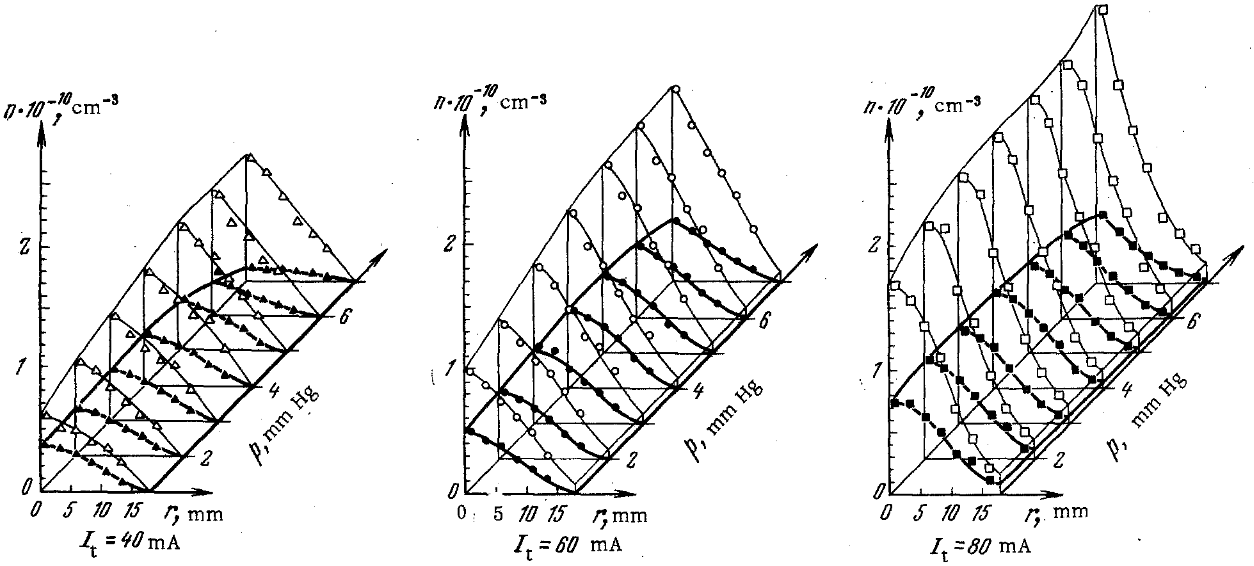

Fig. 5

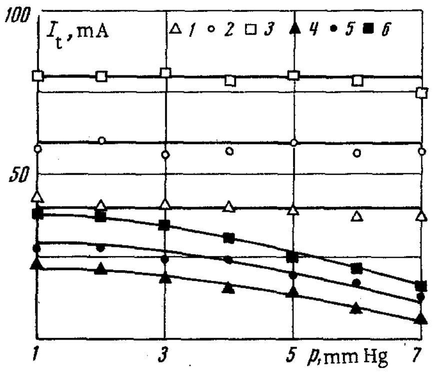

Fig. 6

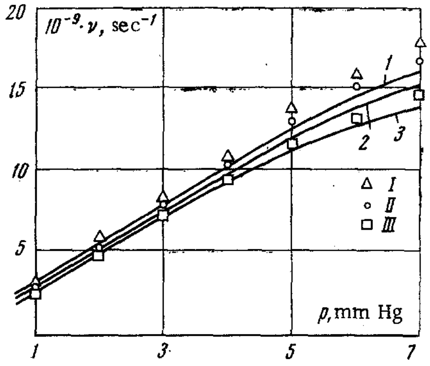

Fig. 7

Electron concentration functions for different pressures and discharge currents are presented in Fig. 5. The electron density was determined from the equation for the current at the probe at the space potential:

$$I_p = \frac{ne\langle v_T\rangle}{4}\pi l d \qquad \left(\langle v_T\rangle = \left[\int f(v)\,dv\right]^{-1}\int f(v)\,v\,dv\right)$$

where $f(v)$ is the velocity distribution function obtained from $\ddot{I}_p$ of the corresponding probe. Values of the discharge current through the tube for different experimental conditions can be reduced with the help of the equation

$$I = 2\pi e\int_0^R n(r)\,v_d(r)\,r\,dr$$

from the distributions n(r) and $v_g(r)$ obtained.

The results are presented in Fig. 6. Points 1, 2, and 3 refer to the thin probe and 4, 5, and 6 to the thick probe. The current reduced from the data obtained using the thin probe corresponds with good accuracy to the current measured by a milliammeter in the discharge circuit in the entire interval of experimental parameters. Since the error in determining the electron drift velocity is small it can be stated that the correctness of the determination of the electron concentration by the thin probe follows from the coincidence of the values of the reduced current and the discharge current measured by an instrument. The experimental results do not prove the correctness of the electron velocity and energy distribution functions found. However, in the case of the thin probe the existing facts confirm the correctness of the probe's operation. Let us present some of them.

1. As seen from Figs. 3 and 4, $f(\varepsilon)$ actually does not depend on the pressure. On the other hand, it is known that $\langle\varepsilon\rangle$ is proportional to $(\lambda E/v_g)^2$. An exact calculation shows that $\langle\varepsilon\rangle \simeq$ const in the pressure interval p = 1-7 mm Hg.

2. The effective frequency of collisions between electrons and molecules can be found through the reliably determined parameters

$$\nu_{\text{eff}} = eE / mv_g$$

and is independent of the distribution function used

$$\nu'_{\text{eff}} = \left[\int f(v)\,dv\right]^{-1} N \int \sigma(v) f(v)\,v\,dv$$

The appropriate calculation showed that the maximum difference between ν_{eff} and ν'_{eff} does not exceed the limit of 10% over the entire range (see Fig. 7). Points I, II, and III designate ν'_{eff} for discharge currents of 40, 60, and 80 mA, while curves 1 (40 mA), 2 (60 mA), and 3 (80 mA) correspond to $\nu_{\text{eff}} = eE/mv_g$.

3. Since as follows from Fig. 5 the electron concentration n found from the probe current at the space potential was correct, the value $\langle v_T\rangle$ calculated through $f(v)$ is also correct.

On the basis of the above it can be assumed with a high degree of reliability that the electron velocity distribution function is reproduced without distortions by the thin probe.

If the readings of the thin probe are taken as "absolute," the results obtained from the thick probe can be analyzed. The nature of the deviations is well seen in Figs. 3, 4, and 5. A rather significant broadening of the distribution function is primarily observed.

It is interesting to observe that the distribution function $f(\varepsilon)$ is even broadened at p = 1 mm Hg, where $d/\lambda \sim 0.1$. The distortion occurs because the thickness of the double layer, whose size in this case can be estimated at 75 μ, is comparable with the probe diameter.

The greatest error is observed in the electron concentration determination. At $I_t = 80$ mA and p = 1 mm Hg ($N = 1.67 \cdot 10^{16}$ cm^{-3}) n is understated twofold, and at p = 7 mm Hg 4.5-fold.

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LITERATURE CITED

1. M. Z. Novgorodov, A. G. Sviridov, and N. N. Sobolev, "Electron energy distribution in discharges used for CO_2 lasers," Zh. Prikl. Spektr., 13, No. 6 (1970).
2. V. M. Zakharova, Yu. M. Kagan, K. S. Mustafin, and V. I. Perel', "Probe measurements at average pressures," Zh. Tekhn. Fiz., 30, No. 4 (1960).
3. J. D. Swift, "Effects of finite probe size in the determination of electron energy distribution functions," Proc. Phys. Soc., 79, Part 4, No. 510 (1962).
4. A. I. Lukovnikov and M. Z. Novgorodov, "Distortion of electron energy distribution function measured by a cylindrical probe," Kratkie Soobshcheniya po Fizike, No. 1 (1971).
5. A. V. Eletskii, L. G. Mishchenko, and V. P. Tychinskii, "Thermal mode of the positive column of a gas discharge," Zh. Prikl. Spektr., 8, No. 3 (1968).
6. V. M. Milenin, "Determination of space potential using second derivative of probe current from a potential probe," Zh. Tekhn. Fiz., 41, No. 4 (1971).
7. M. Z. Novgorodov, A. G. Sviridov, and N. N. Sobolev, "Electron energy distribution in discharges used for CO_2 lasers," ZhÉTF Pis. Red., 8, No. 7 (1968).
8. N. A. Vorob'eva, Yu. M. Kagan, and V. M. Milenin, "Electron energy distribution function in the positive column of a mercury discharge," Zh. Tekhn. Fiz., 33, No. 5 (1963).