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# STATE OF THE ART AND APPLICATIONS OF LOW-PRESSURE HF DISCHARGE PHYSICS

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UDC 537.523.74

*Features are examined for a high-frequency discharge between planar electrodes as widely used in plasma etching in microelectronics. Averaging in space and time over the fast electron motions enables one to simplify the discharge description considerably. The discharge can be analyzed for elevated pressures, when the electron distribution is determined by the instantaneous local electric field, by solving the equation of motion for the ions in the average fields. At low pressures, allowance must be made for the fact that the electron energy distribution is nonlocal. A simple kinetic equation is derived for that case. The effects of the nonlocality on the discharge parameters have been examined.*

By high-frequency HF low-pressure discharge is usually meant a discharge at 1-100 MHz and pressures below 1 torr. We restrict consideration to a capacitative discharge, which is formed when a high-frequency voltage is applied to planar electrodes. The latter may be metallic or be coated with insulator. We consider the particle motion in the alternating electric field. Figure 1a shows the electron paths in the x−t plane. The electrons move along periodic paths in the bulk of the plasma. The paths to the right of boundary B reach the electrode, so electrons are absent from them in the absence of emission. Near the electrode, there is a layer of thickness L in which electrons are absent for part of the period. The displacement of the ions during the period is much less, so their paths in Fig. 1 would be vertical lines. Phases of positive space charge (to the right of curve B), when the mean electric field accelerates the ions to the electrode, and the plasma phases alternate in the electrode layers, with $n_e \approx n_i$ in the latter. If $4\pi\sigma_i| < \omega < |4\pi\sigma_e|$, in which $\sigma_{e,i} = ne^2/m(\nu_{e,i} + i\omega)$, the current in the plasma is a conduction current, while that in the space-charge phase is a displacement current. The electric field here considerably exceeds the field in the plasma and most of the potential drop is localized there if the gap between the electrodes is not too large. The electrode layers determine the characteristic features of the HF discharge and most of the applications, so HF discharge physics is in essence the physics of the electrode layers.

In [1] we find the first simple model that describes the current transport in the layers; there it was assumed that the ion concentration in a layer is constant and is equal to the concentration in the bulk of the plasma, without allowance for the distribution of the ionization sources or the ion drift in the mean electric field. A theory for the electrode layers has been constructed [2] for conditions where the characteristic dimensions of the plasma and layer exceed the electron energy relaxation length $\lambda^*$, which involved solving the equation of motion for the ions in the mean field:

$$\frac{d}{dx}\left[-(D_a + D_{hf})\frac{dn}{dx} + Vn\right] = I_1 + I_2. \quad (1)$$

St. Petersburg Technical University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 5, pp. 717-719, May, 1992. Original article submitted November 12, 1991.

 1062-0125/92/6205-0512$12.50 

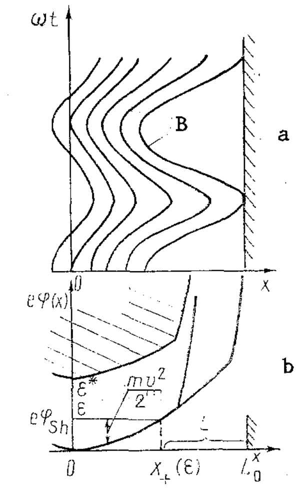


Fig. 1. Electron paths in a high-frequency field (a) and potential distribution in an HF discharge (b).

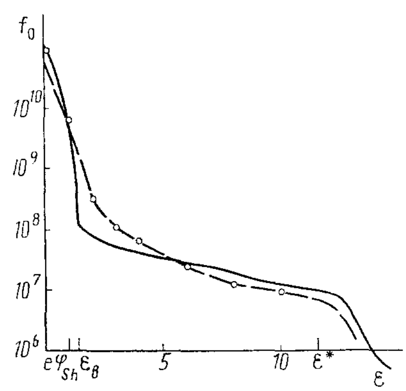


Fig. 2. Electron distribution in an HF discharge: solid line from calculation, dashed line from experiment [7]; Ar, $p = 0.1$ torr, $j_0 = 2.7$ mA/cm$^2$, $L_0 = 1$ cm, $f = 13.56$ MHz, $n_0 = 3.7 \cdot 10^8$ cm$^{-3}$, $L = 0.26$ cm, $n_{sh} = 0.66 \cdot 10^8$ cm$^{-3}$, $T_e = 0.42$ eV, $e\varphi_{sh} = 1.40$ eV, $f_0$, eV$^{-3/2}$/cm$^{-3}$; $\varepsilon$, eV.

Here $D_a$ is the ambipolar diffusion coefficient; $D_{hf}$ the effective diffusion coefficient, which describes the motion in the electric field averaged over the plasma phase; V the coherent velocity acquired in the mean field in the space-charge phase; $I_1$ the plasma-electron ionization; and $I_2$ the ionization in the space-charge phase produced by electrons ejected from the electrode. If $I_1$ predominates (so-called $\alpha$ discharge [1]), the ion concentration does not fall very greatly from the plasma to the layer because the current density should be conserved, while the ionization increases exponentially with the field. If $I_2$ predominates ($\gamma$ discharge), the concentration in the layer may exceed that in the plasma. This corresponds to higher current densities and smaller layer thicknesses than in an $\alpha$ discharge. The transition from an $\alpha$ discharge to a $\gamma$ one has been examined by experiment [1, 3, 4]. It is not difficult to obtain a numerical solution to (1), and the results agree with Monte Carlo simulation incorporating the electron motion [5, 6]. Approximate solutions have also been given [2] that enable one to determine major layer characteristics.

The situation is more complicated at low pressures, when the characteristic dimensions of the layer become less than $\lambda^*$. The ion motion is then described by an equation analogous to (1), but when one calculates the ionization sources, one must incorporate the nonlocality in the electron distribution. If $\lambda^* < L_0$, the electrons move with conservation of the total energy $\varepsilon = 1/2(m/v^2) + e\varphi(x)$ in the potential well shown in Fig. 1b. The $e\varphi(x)$ distribution is a slowly varying ambipolar potential with a sharp step at the moving boundary of the space-charge region. For $\omega > \nu^*$ ($\nu^*$ is the inelastic collision frequency), one can average the kinetic equation over the period T and the discharge cross section and derive an equation for the isotropic part of the distribution analogous to that obtained for the local case:

$$\frac{d}{d\varepsilon}\langle vD_\varepsilon(\varepsilon)\rangle\frac{df_0(\varepsilon)}{d\varepsilon}=\langle v\nu^*(\varepsilon)\rangle f_0(\varepsilon), \tag{2}$$

in which

$$\langle vD_\varepsilon(\varepsilon)\rangle=\frac{1}{2L_0T}\int_0^T\int_{x_-(\varepsilon,t)}^{x_+(\varepsilon,t)}vD_\varepsilon(\varepsilon-e\varphi(x))\,dxdt \tag{3}$$

is the averaged energy diffusion coefficient:

$$D_\varepsilon=\frac{e^2v^2\nu\langle\tilde{E}^2\rangle}{3(\omega^2+\nu^2)}, \tag{4}$$

with $x_-$ and $x_+$ the boundaries of the region accessible to an electron with energy $\varepsilon$ (Fig. 1b). Those boundaries are stationary for an electron with energy $\varepsilon < e\varphi_{sh}$, while the positions are dependent on time for $\varepsilon > e\varphi_{sh}$. Excitation and ionization may be produced by electrons with kinetic energy exceeding (in the hatched region in Fig. 1b); the ionization is localized in the central part of the discharge, where the electric field is minimal, in contrast to the local case. There is virtually no ionization in the layers, so the ion concentrations there are much less than in the plasma. High-energy electrons attain the edge of the plasma, where the alternating electric field is maximal. Consequently, the energy diffusion coefficient for them is larger, which reduces the slope of $f_0(\varepsilon)$. Figure 2 shows the distribution calculated from (2) together with the [7] measurements, which agree well. The fast electrons ($\varepsilon > \varepsilon\varphi_{sh}$) collide with the moving boundary and may be subject to stochastic heating if $\omega > \omega_b > \nu$ ($\omega_b^{-1}$ is the time of flight of an electron across the discharge gap). This also leads to a rise in the tail of the distribution.

The $\gamma$ electrons in a low-pressure discharge have long mean free paths and the main ionization is produced in the plasma, not in the layers.

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