2D model of a hydrogen inductive discharge with a planar coil

Ts Paunska\textsuperscript{1}, A Shivarova\textsuperscript{1}, Kh Tarnev\textsuperscript{2} and Ts Tsankov\textsuperscript{1,3}

\textsuperscript{1}Faculty of Physics, St. Kl. Ohridski University of Sofia
5 J. Bouchier Blvd., 1164 Sofia, Bulgaria
\textsuperscript{2}Department of Applied Physics, Technical University of Sofia,
8 Kl. Ohridski Blvd., 1000 Sofia, Bulgaria
E-mail: tsankov@phys.uni-sofia.bg

Abstract. Based on a two-dimensional (2D) fluid-plasma model of low-pressure hydrogen discharges sustained by rf power deposition of the type of inductive discharges with a planar coil, the study presents the spatial distribution of the plasma parameters and of the fluxes in the discharge and discussions outlining plasma maintenance in regions outside the rf power input.

1. Introduction
The use of inductively coupled plasmas with planar coils as reactors for processing in the microelectronics industry has stimulated since the 90’s of the last century active theoretical research on the source operation within 2D and 3D discharge modelling [1, 2]. Inductive discharges with hydrogen plasmas are currently also actively studied as sources of negative ions for the neutral beam injection heating in large Tokamak devices. However, in the latter case the source, performed as large scale experimental arrangements of a two-chamber source, has an inductive discharge with a cylindrical coil as a driver [3]. On the other hand, recent results for high negative ion density in smaller radius discharges [4] has traced out a suggestion for a design of the source as a matrix of small radius discharges [5]. Since an inductive discharge with a planar coil would be a technically better solution, this study is directed towards description of such small radius discharges, not yet studied in the literature on the microelectronics processing technology.

This study presents results from a 2D-model of small-radius hydrogen discharges with rf power deposition of the type of inductive discharges with a planar coil. Due to the small radius of the discharge compared to its length, remote plasma maintenance clearly shows evidence. The latter requires detailed analysis of the spatial distribution of the particle and electron-energy fluxes as shown by the results presented here. The model is a first step towards self-consistent description of a small-radius negative hydrogen ion source inductively driven by a planar coil and, therefore, rovibrational excitation, negative hydrogen ions and variation of the gas temperature are currently not accounted for.

2. Description of the model
Hydrogen discharge maintenance in a straight cylindrical metal discharge vessel and power deposition with a super-Gaussian shape along its axis located at one of its end plates (z = 0 in...
the figures further on) is described within the fluid plasma theory. The initial set of equations is based on the fluid-plasma theory. The continuity equations

\[ \frac{\partial n_\alpha}{\partial t} + \nabla \cdot \vec{\Gamma}_\alpha = \frac{\delta n_\alpha}{\partial t} \]

are solved for the electrons (\(\alpha = e\)), the three types of positive ions (H\(^+\), H\(_2^+\) and H\(_3^+\) denoted by \(\alpha = ij\), with \(j = 1, 2, 3\), respectively) and the hydrogen atoms (\(\alpha = a\)). Here \(n_\alpha\) and \(\Gamma_\alpha\) are, respectively, the particle densities and their fluxes and \(\delta n_\alpha/\partial t\) describes the production and the losses of the corresponding type of particles \(\alpha\). In the electron energy balance

\[ \frac{3}{2} \frac{\partial (n_e T_e)}{\partial t} + \nabla \cdot \vec{J}_e = P_{\text{ext}} - P_{\text{coll}} + P_{\text{dc}} \]

\(T_e\) is the electron temperature (in energy units), \(P_{\text{ext}}\) is the externally applied rf power density, \(P_{\text{dc}} = -\varepsilon \vec{E}_e \cdot \vec{E}_{dc}\) is the Joule losses/input related to the dc electric field \(\vec{E}_{dc}\), with potential \(\Phi\) (\(\vec{E}_{dc} = -\nabla \Phi\)) and \(P_{\text{coll}}\) summarises the electron energy losses in collisions with neutrals. The electron energy flux \(\vec{J}_e\) is with its two compounds, the conductive \(J_{e,\text{cond}} = -\chi_e \nabla T_e\) and convective \(J_{e,\text{conv}} = (5/2)T_e \Gamma_e\) fluxes; \(\chi_e\) is the thermal conductivity coefficient. The Poisson equation

\[ \Delta \Phi = -\frac{e}{\varepsilon_0} \left( \sum_{j=1}^{3} n_{ij} - n_e \right) \]

and the expression for the gas pressure \(p = \kappa T_g (n_a + n_m)\) complete the initial set of equations. Here \(e\) and \(\varepsilon_0\) are the elementary charge and the vacuum permittivity, \(T_g\) is the gas temperature, \(n_m\) is the density of the hydrogen molecules and \(\kappa\) is the Boltzmann constant. The boundary conditions [6] are for the fluxes and for the potential at the walls as well as for symmetry on the axis \((r = 0)\).

3. Results and discussions

The results discussed here (figures 1–3) are for two values of the total applied rf power \(Q = 250\) and 500 W and of the gas pressure \(p = 20\) and 50 mTorr. The mean free paths of the charged particles are such that the latter value of \(p\) is in the gas pressure range of diffusion-controlled discharges whereas the former is at the transition to the free-fall regime of discharge maintenance.

The contour plots of the plasma-parameter distribution and the arrow plots of the fluxes in figure 1 completed with the axial variations of the contributors to the electron balance and the electron-energy balance in figure 2 outline the following pattern of the discharge behaviour:

(i) The rf power deposition region, extended towards about \(z = 6\) cm (figure 2(b)), sustains high density plasma with high \(T_e\) and high dc potential (figure 1). The charged particle production there by ionization (atom ionization prevailing over that of the molecules (figure 2(a)) as confirmed also by comparing the density values of the atomic and molecular ions in figures 1(b)–1(d)) compensates the diffusion losses towards the side wall of the vessel (losses in the radial direction (figure 2(a))). An axial electron flux flowing into the on-axis region, due to the formation of a vortex type of an electron flux in the power deposition region, also aids the ionization to compensate the diffusion losses in the radial direction. Upstream axial flux towards the \((z = 0)\)-surface shows also evidence as particle losses. Charged particle losses through the fluxes strongly prevail over volume recombination (figure 2). Due to the radially homogeneous rf power deposition and the density drop towards the discharge walls, the highest values of \(T_e\) (figure 1(e)) are close to the walls and this drives a conductive flux directed to the on-axis region of the discharge. The latter aids the rf power deposition to compensate the electron energy losses.
in collisions (figure 2(b)). The dc electric field directed towards the walls drives the ion fluxes (which are, in fact, drift fluxes) straight to the walls (figures 1(f) and 1(b)–1(d)).

(ii) The region of a remote plasma maintenance (at about \( z \gtrsim 10 \text{ cm} \)) is characterized by low plasma density (figures 1(a)–1(d)), low \( T_e \) (figure 1(e)) and low dc potential (figure 1(f)). The electron energy input is via the conductive flux which compensates electron energy losses for maintenance of the dc electric field (figure 2(b)). Energy input via the convective flux also adds to the conductive flux. The electron energy losses in collisions, including collisions for ionization, are negligible. The existence of the remote plasma is due to an axial electron flux which compensates the particle losses to the side wall of the discharge vessel, i.e. the radial electron flux. In the remote plasma region the dc electric field is directed to the walls (figure 1(f)).
Figure 3. Axial variations at \( r = 0 \) of \( n_e \) (a), \( T_e \) (b) and \( n_a \) (c) for \( p = 20 \) and 50 mTorr, \( Q = 250 \) and 500 W.

like in the power deposition region and the ions drift along the field lines (figures 1(b)–1(d)).

(iii) The region \( 6 \text{ cm} \lesssim z \lesssim 10 \text{ cm} \) shows the transition between the region of a rf power input and the remote plasma region. In its on-axis region electron energy input via the conductive flux, slightly supported by a Joule heating in the dc field (the \( P_{dc} \)-term in (2)), compensates electron energy losses in collisions (figure 2(b)). Input of electrons via the radial flux compensates their losses via their axial flux.

Figure 3 shows the changes in the plasma parameters with varying \( p \) and \( Q \). The main trends are similar to those in the first chamber of the tandem source modelled in Refs. [6, 7].

4. Conclusions
The 2D fluid plasma model presented in the study, providing results for the structure of low-pressure rf discharges with inductive driving of the type of a planar coil, outlines remote plasma maintenance in one-chamber (straight tube) gas-discharge vessels: The plasma existence is due to an axial electron flux from the driver that compensates the diffusion losses to the walls and the electron energy input via the conductive flux compensates energy losses for the maintenance of the dc field that forms the fluxes. As it should be expected for sources with remote plasma maintenance, the fluxes are important. The latter shows similarities with the behaviour of the fluxes in two-chamber plasma sources with metal walls and a rf power deposition to the first chamber [6] that determines a discharge regime with a dc current in a rf discharge, due to different electron and ion fluxes.

Acknowledgments
The work is within project DO02-267 supported by the National Science Fund of Bulgaria. Support via project BUL/1026233 of the Alexander von Humboldt Foundation is also acknowledged.

References
[1] Kushner M J, Collison W Z, Grapperhaus M J, Holland J P and Barnes M S 1996 J. Appl. Phys. 80 1337–44
[2] Lymberopoulos D P and Economou D J 1995 J. Res. Natl. Stand. Technol. 100 473–94
[3] Speth E et al 2006 Nucl. Fusion 46 S220–38
[4] Paunska Ts, Schlüter H, Shivarova A and Tarnev Kh 2006 Phys. Plasmas 13 023504
[5] Paunska Ts, Shivarova A and Tarnev Kh 2009 J. Appl. Phys., submitted
[6] Paunska Ts, Shivarova A, Tarnev Kh and Tsankov Ts 2009 AIP Conf. Proc. 1097 12–21
[7] Paunska Ts, Shivarova A, Tarnev Kh and Tsankov Ts 2009 AIP Conf. Proc. 1097 99–108