FLUID MODEL OF PLASMA IN MAGNETRON SPUTTER DEVICE

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1. Introduction

Magnetron sputtering is widely used in industry and research for etching and thin film deposition [1-2]. In all types of magnetrons a specific configuration of an external magnetic field, applied to trap electrons in a region close to cathode (see Fig.1), allows the magnetron operation at lower pressures and voltages than within the other devices.

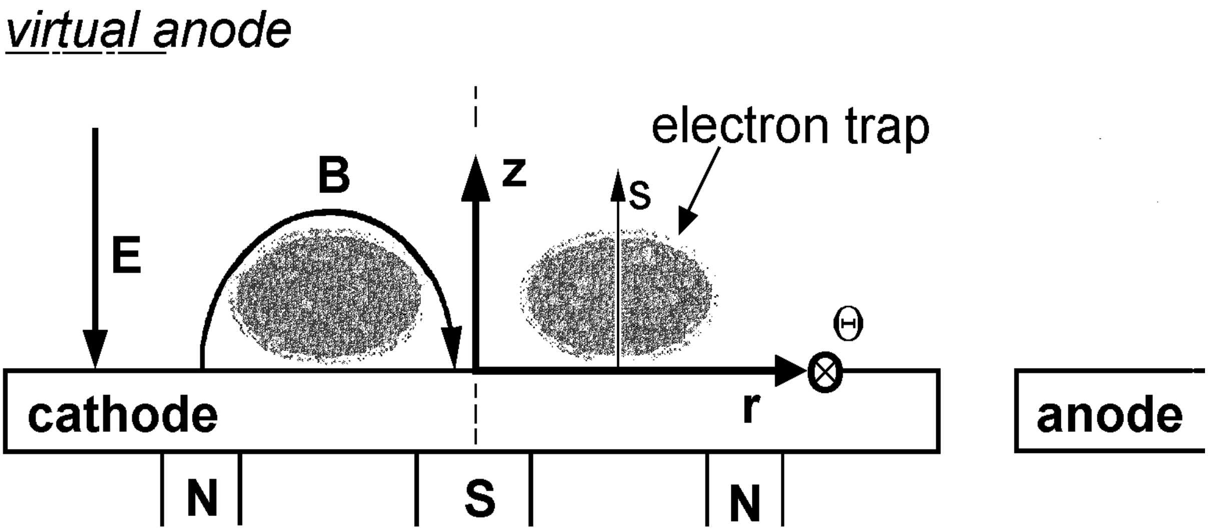

Fig. 1. Schematic of magnetron sputter device.

Investigation of a magnetron discharge spatial structure is a way to understanding transport processes and has important implications for controlling nonuniformity of a target sputtering. Since a principal virtue of the magnetron is its ability to operate effectively at low pressures and voltages, it is worthwhile to study mutual relations of discharge phenomena and plasma transport. Numerical models commonly use one of two basic approaches: a kinetic or fluid one. Kinetic particle-in-cell (PIC method) Monte Carlo simulations require considerable computer time and memory. Most of this time is consumed by determining particle motion and collisions with neutral species. Hydrodynamic models significantly reduce computational cost of numerical simulations. At the shorter time a better understanding of the phenomena may be achieved.

This paper introduces a one-dimensional three-fluid model developed for the modelling of plasma behaviour in magnetron. For ions and two kinds of electrons (cold & hot) the model takes into account continuity, momentum transfer and energy balance as well as the Poisson equation for potential. Reasons for introducing two-temperature electrons are also presented.

2. Fluid model of magnetron sputter source

In the following analysis, idealised slab geometry is considered. The origin of coordinate system is placed in the centre of a cathode crater. Plasma transport between the cathode and virtual anode is described by the one-dimensional model, based on the Braginskii equations

$$\frac{\partial n_k}{\partial t} + \frac{\partial}{\partial s}(n_k v_k) = S_{n_k} \tag{1}$$

$$\frac{\partial}{\partial t}(m_k n_k v_k) + \frac{\partial}{\partial s}\left\{m_k n_k v_k^2 + n\kappa T_k \mp \frac{\partial \Psi}{\partial s} - \pi_k\right\} = S_{p_k} \tag{2}$$

$$\frac{\partial}{\partial t}\left\{\frac{3}{2} n_k \kappa T_k + \frac{1}{2} m_k n_k v_k^2\right\} + \frac{\partial}{\partial s}\left\{\left(\frac{5}{2}\kappa T_k + \frac{1}{2} m_k v_k^2 - e\Psi\right) n_k v_k + q_k\right\} - \pi_k\left(\frac{\partial v_k}{\partial s}\right) = \\ = - v_k \frac{\partial}{\partial s}(n_k \kappa T_k) + Q_{ei} + W_k \tag{3}$$

with Poison equation for potential

$$\epsilon \frac{\partial^2 \Psi}{\partial s^2} = e\left(n_{e_c} + n_{e_h} - n_i\right) \tag{4}$$

where:

subscript $k = e_c, e_h, i$ denotes cold electrons, hot electrons and ions, respectively,

- s - coordinate along the direction of electric potential, measured from the crater region at the cathode surface to virtual anode on magnetic field surface,
- n - concentration,
- v - flow velocity along the s coordinate,
- T - temperature,
- Ψ - potential,
- κ - Boltzmann constant,
- π - longitudinal viscous stress,
- q - heat flux,
- ε - permittivity,
- e - particle charge,
- m_e, m_i - electron and ion masses, respectively.

S_{n_k}, S_{p_k}, W_k are the density, momentum and energy source terms from the interaction with neutrals and due to the perpendicular inflow of plasma,

$$Q_{ei} = \frac{3 m_e n}{m_i \tau_{ei}} \kappa \left(T_e - T_i \right) \quad (5)$$

$Q_{e\,i}$ - electron-ion energy equilibration term due to the Coulomb collisions.

The discharge in magnetron chamber is weakly ionised. Since the ions exchange energy efficiently with the neutrals, the ion temperature is nearly the same as the background gas. At very low pressures, however, T_i may be higher than T_n. That is the reason why for the model selfconsistency ion temperature is treated as independent variable. Electron-ion collision term could be neglected as well as electron viscosity.

3. Two-temperature electrons

It has been found [3] that in the outer regions over the magnetic trap electrons are characterised by two temperatures. In the electron trap one can find a single, hot electron component, while outside a confinement there are both, hot and cold, components. The hot electron density is higher in the trap and decreases outside. On the contrary, density of the cold electrons is higher outside the trap and negligible inside.

The overall electron energy distribution function (EEDF) in the system appears like the sum of two Maxwellian energy distributions. The assumption of Maxwellian distribution in the fluid model does not take into account the rising high-energy tail when the electrons approach the sheath boundary. Because of the high energy threshold of the ionisation, particularly these high-energy electrons are involved in ionisation. Using the average kinetic energy the fluid model will therefore underestimate the ionisation rate and overestimate the electron temperature. EEDF in the magnetised region is largely non-Maxwellian with an extended tail of energetic electrons. The thermal part of the EEDF is Maxwellian due to the generally high degree of ionisation.

The idea of taking into account two-temperature electrons has been analysed. Although this approach seems to be unusual, it is possible to introduce two fluids for the description of hot and cold electrons. Fluid models are successfully used even for the phenomena within the regions where validity of hydrodynamic approximation is violated. Therefore, two-temperature (bi-Maxwellian) approach for electrons seems to be acceptable.

4. Numerical solution

Numerical solution of model equations is difficult because of high nonlinearity and strong coupling. The partial differential equations describing the transport model in question have been solved on a nonuniform staggered mesh. An implicit method [4] developed for the quasilinear parabolic equations has been employed while the convective terms have been discretized according to the upstream scheme of donor cell type [5]. For nonlinear terms, the first order Taylor expansion has been used to accelerate the convergence. The applied numerical method is linear according to the i-th approximation of the variable at a new time step, therefore the obtained tridiagonal matrix equations could be solved successively by the highly efficient computational technique. Numerical schemes and elements of GRAD_1D [6] computational package for tokamak edge plasma transport have been applied to accelerate the code evaluation.

5. Comparison with experiment

For comparison of theoretical predictions with experimental results a project of cooperation with Institut für Plasmaforschung (IPF) - Universität Stuttgart has been developed. Results obtained with plane and cylindrical Langmuir probes are predicted as parameters for model validation. The two groups of electrons already found in IPF experiment correspond strictly with the presented approach of two-temperature electron fluids.

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