Self-Consistent Analysis of a Helium Plasma in a Cylindrical Hollow Cathode

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The helium plasma in a cylindrical, axially symmetric direct current hollow cathode discharge is theoretically investigated. A self-consistent hybrid method is used to describe the radial behavior of the plasma components and the electric field around the axial center of the discharge. The hybrid method includes the solution of an equation system consisting of Poisson's equation and fluid equations for electrons, ions, and excited helium atoms. Using the electric field and excited atom densities obtained in this system, the space-dependent transport and collision rate coefficients of the electrons are obtained by a kinetic treatment of the electrons. This treatment is based on a powerful multi-term method for solving the inhomogeneous Boltzmann equation in cylindrical coordinates. The theoretical results obtained for a discharge current of some mA and a pressure of few Torr are compared with available experimental ones.

KEY WORDS: Hollow cathode; self-consistent hybrid method; spatially inhomogeneous Boltzmann equation; multi-term expansion.

1. INTRODUCTION

In a large variety of technical and scientific applications the advantages of hollow cathode arrangements are exploited. Such discharge types are used, e.g., for etching, thin-film deposition (1) and surface treatment (2, 3) as well as for lasers, (4, 5) spectral line sources and radiation standards (6) and for ion sources. (7) The advantages of the hollow cathode discharge result mainly from their special geometry. The closed form of the cathode leads to a large ionization efficiency. In planar discharges this efficiency is limited because of the charge carrier loss which is caused by diffusion in transversal direction and recombination at enclosing walls. Compared with planar discharges this loss is strongly reduced in hollow cathode discharges. Nearly all ions which are produced in the volume reach the cathode and contribute there to the charge carrier production by secondary reactions.
electron emission. Fast electrons can pass the negative glow and oscillate between the opposite cathode falls. These pendulum electrons have already been predicted by G"unter-Schulze (8) and experimentally verified. (9, 10) If the negative glow regions of opposite cathode sides overlap, the ionization efficiency becomes very pronounced and the so-called 'hollow cathode effect' emerges.

Various theoretical approaches are reported in the literature. The appropriate description of the electron component requires special attention because of their active role with respect to the charge carrier production and their strongly non-local behaviour. Approximate solutions have been applied which are based on multi-temperature models, (11) or (semi-) analytic solutions for electrons in different energy ranges (12, 13) and simplified considerations of the collision processes. Monte Carlo calculations have been extensively performed to describe the fast electrons, and a theoretical study of a micro hollow cathode discharge based on the solution of the spatially averaged Boltzmann equation and an assumed monoenergetic electron beam has recently been reported. (19)

For a self-consistent description Poisson's equation and at least a model for the ions must be included in the theoretical approach. During the last years, hybrid methods have been developed which couple fluid models for slow electrons and ions with the solution of Poisson's equation and Monte Carlo calculations for the fast electrons. Recent extended approaches also include a fluid description of excited atoms (26) or Monte Carlo simulations of fast ions and atoms. (5, 27)

This paper reports a new self-consistent description of the helium plasma in a cylindrical, axially symmetric hollow cathode discharge. A hybrid method is used which combines a fluid description of electrons, ions, and excited atoms with the solution of Poisson's equation. Furthermore, the non-local behaviour of the electrons is taken into account by solving their space-dependent Boltzmann equation. This kinetic treatment of the electrons yields spatial profiles of transport and rate coefficients which are required within the fluid description. An advantage of the kinetic approach in comparison with Monte Carlo-hybrid methods consists in the fact that an artificial separation between electrons in different energy ranges can be avoided. In this manner, not only the rate coefficients of inelastic collisions of the electrons with the helium atoms in the ground and excited states but also their transport coefficients can be determined. The solution of the electron Boltzmann equation in the strongly