Coupled Hydrodynamic and Electrodynamic Modelling of an Transformer Coupled Plasma (TCP) for Semiconductor Processing

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Abstract

A planar transformer coupled plasma source (TCP) as used for semiconductor processing was characterised theoretically and experimentally. In this paper the homogeneity of the plasma in dependence of process pressure and coil configurations was investigated. Simulations for noble gas discharges in a wide pressure range were compared with theoretical data from a reactor model. A 2D-fluid plasma model coupled self-consistently with an electrodynamic model was used to calculate the theoretical results. Experiment and simulation show very good agreement for a wide range of parameters.

1 Introduction

Using the same amount of RF-input power, the TCP-concept provides significantly higher plasma densities than capacitively coupled discharges. Therefore for technological applications, TCP discharges become more and more interesting.

From a technological point of view the homogeneity of the discharge is a crucial parameter. Process steps like plasma etching and chemical vapour deposition (PCVD) depend significantly on the local plasma parameters like the electron density or the electron energy distribution. In order to ensure this homogeneity over the whole wafer area within certain tolerance limits an increasing effort has to be spent with increasing substrate diameter.

In this paper, especially the influence of different coil geometries was investigated as well theoretically as experimentally. For this purpose, calculations with a two dimensional fluid plasma model were compared with measurements in an inductively coupled reactor as it is in use for diamond deposition experiments. The results show the dependence of the discharge homogeneity on the coil configuration as well as on the neutral gas pressure.

2 Experimental Setup

Experiments were carried out in a planar inductively coupled plasma source (TCP) [1] as displayed in Fig. 1. The stainless steel chamber (A) has a cylindrical geometry with $R = 10$ cm, $\mathrm{H} = 4$ cm. The upper boundary of the chamber is a quartz window (B).

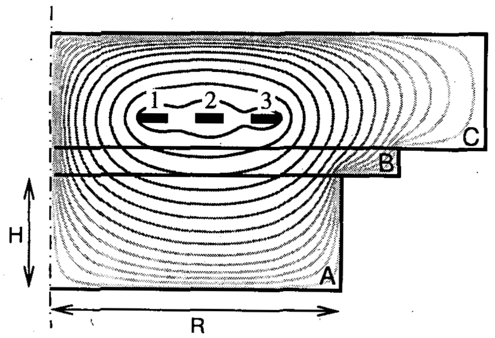


Fig. 1: TCP discharge vessel with planar coils. The simulation area consists of the discharge vessel (A), a quartz window (B) and the electrodynamic simulation domain (A + B + C). Contours show the intensity of the electric field lines induced by RF-currents in all three coils.

RF-power ($f = 27$ MHz) is transferred from three concentric coils $(1, 2, 3)$ through the quartz window to the plasma. In order to study the correlation beetween coil position and discharge properties like electron density and temperature the coils were powered separately. Coil positions were: $r_1 = 35$ mm, $r_2 = 55$ mm, and $r_3 = 75$ mm. A Faraday shield was mounted between the coils and the quartz window to minimize capacitive coupling. By grounding this shield, the energy of ions hitting the substrate can be reduced.

Diagnostics were performed by Langmuir probe measurements. The probe delivered local data of the electron density, plasma potential and electron energy distrution function. It was moved radially in a distance of 20 mm from the bottom of the reactor chamber.

3 Hydrodynamic Plasma Model

A hydrodynamic two fluid model including balance equations for ion mass and momentum was used. Electrons are described by a drift-diffusion approach and balance equations for mass and energy. The electrostatic interaction of positively and negatively charged carriers is incorporated by Poisson's equation. The heating of the plasma by externally applied RF-currents is taken into account by self-consistent coupling with an electrodynamic model [2], [3], [4]. The complete set of governing equations is:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}_i) = n_e \cdot \nu_{iz}(T_e), \tag{1}$$

$$\frac{\partial (n_i m_i \vec{v}_i)}{\partial t} + \nabla \cdot (n_i m_i \vec{v}_i \vec{v}_i) = e n_i \vec{E} - n_i m_i \nu_i \vec{v}_i. \tag{2}$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{j}_e = n_e \cdot \nu_{iz}(T_e), \tag{3}$$

$$\frac{\partial n_e \epsilon}{\partial t} + \nabla \cdot \vec{\Gamma}_e = -e\vec{E} \cdot \vec{j}_e - P_c + P_h. \tag{4}$$

$$\vec{j}_e = \frac{n_e e}{m_e \nu_e} \vec{E} - \frac{1}{m_e \nu_e} \nabla n_e k T_e, \tag{5}$$

$$\vec{\Gamma}_e = \frac{5}{2} k T_e \vec{j}_e - \frac{5}{2} \frac{k T_e}{m_e \nu_e} \nabla k T_e. \tag{6}$$

$$\nabla \cdot \left(\epsilon_0 \vec{E}\right) = e(n_i - n_e), \tag{7}$$

$$\Delta \underline{\vec{E}} + k \underline{\vec{E}} = i \omega \mu_0 \underline{\vec{j}} \tag{8}$$

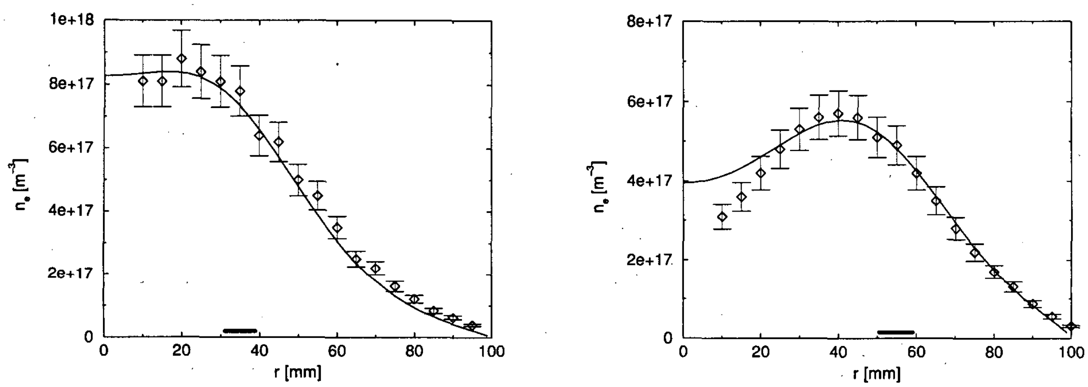
Here, n_i, $\vec{v_i}$ denote ion number density and velocity, respectively. Particle generation is given by $n_e \cdot \nu_{iz}(T_e)$, where n_e is the electron number density and ν_{iz} the ionisation frequency, which is a function of the electron temperature T_e. The ion mass is m_i, the electric field is $\vec{E}$ and ν_i is the frequency of inelastic collisions with neutral atoms. The electron particle flux $\vec{j_e}$ depends on the electron thermal energy kT_e and the electron-neutral collision frequency ν_e. The electron energy flux $\vec{\Gamma}_e$ is also dependent on the collision frequency ν_e. Heating by the RF-field is described by P_h, while power losses due to electron neutral collision are included by P_c. Heating is caused by the alternating, RF-induced azimuthal field $\underline{\vec{E}}$.

4 Results

Measurements and calculations were performed for the case that all three coils are powered separately. Fig. 2 shows measured and calculated radial electron density profiles for an argon discharge operating at a pressure of 10.0 Pa.

The different coil positions correlate with the maxima of the electron density. Theory and experiment are in good agreement.

In order to study the homogeneity for different pressure values coil "2" was powered and the gas pressure was varied. Results are shown in Fig. 3. For increasing neutral gas pressure the discharge becomes more localised in proximity to the powered coil. Again, theory and experiment are in excellent agreement.



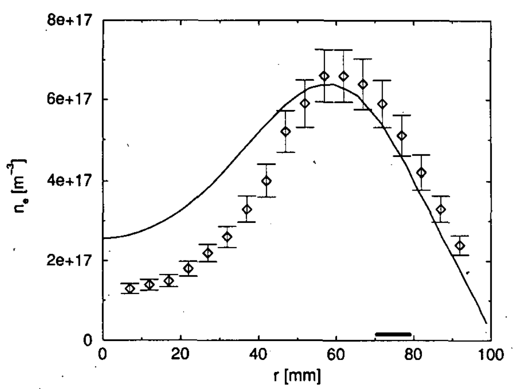
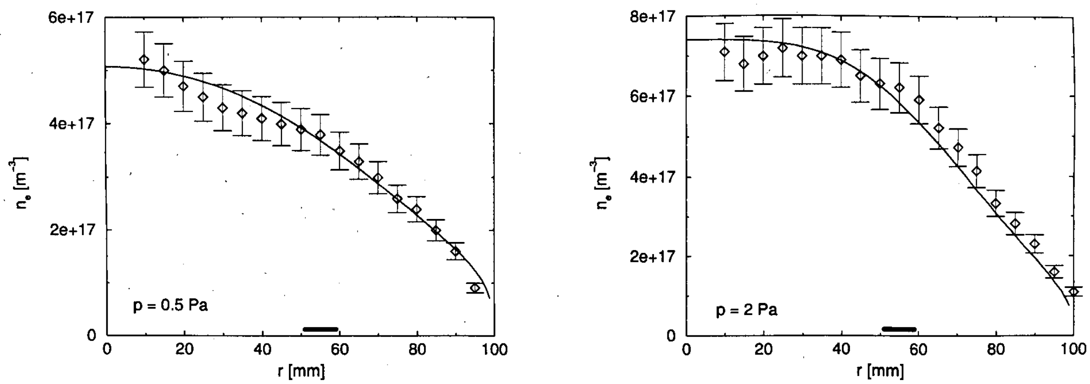


Fig. 2: Measured and calculated electron density profiles in radial direction for p_N = 10.0 Pa. All three coils were powered separately. The position of the powered coils are respectively displayed close to the r-axis.

Although the neutral gas pressure of 10 Pa is relatively low, the discharge tends to have a torus-shaped density distribution. The simulation seems to overestimate the electron density in the center of the discharge. Especially for the case the outermost coil

"3" is powered this difference becomes significant. It might be due to an overestimated thermal conductivity of the electrons in the model.



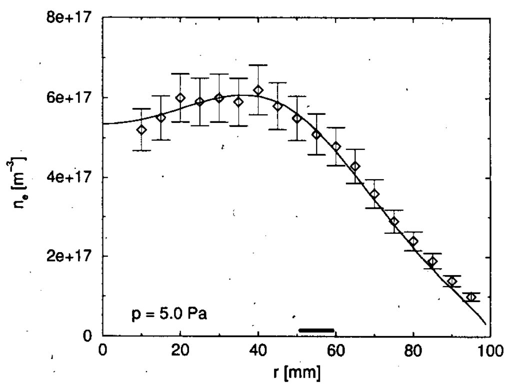


Fig. 3: Measured and calculated electron density profiles in radial direction for varying neutral gas pressure p = 0.5 Pa – 5.0 Pa.

References

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