Finite-element simulation of process gas dissociation and plasma production in inductively coupled plasma for dry etching applications

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Abstract: User-friendly finite element (FE) partial differential equation (PDE) solvers are now-a-days commercially available and permit plasma simulation towards the design of plasma-processing equipment to concentrate on adequate physics modeling with very little to no effort going into computer coding. Here we use this approach to investigate the spatial distribution of active species in a generic inductively coupled plasma (ICP) chamber used for nanopattern etching for nanodevice manufacturing applications.

Keywords: inductively coupled plasma, multi-fluid model, chlorine, oxygen, argon

1. Introduction

Multi-fluid models provide less detail than particle-in-cell codes, but require much less computation time. The underlying PDEs are numerically solved using FE method PDE solvers, difficult to code, but available as easy-to-use commercial software packages. The latter are usually limited to specific physics, but more flexible packages, such as COMSOL®, allow changing the underlying PDEs up to re-writing from scratch, while providing collection of ready-to-use blocks, such as Poisson and fluid solvers. In this contribution we apply this approach to get insight into the factors influencing the spatial distributions of active argon, chlorine and oxygen species in low-temperature low-pressure processing plasma.

2. Model

The model includes continuous transport equations for the main species involved (Ar/O/Cl atoms, O_2 /Cl_2 molecules, both in ground and excited states, electrons, several types of atomic and molecular ions, both positive and negative. Convection, diffusion, and electrostatic drift are accounted for. Production/loss of individual species are governed by the respective collision rates, taken as functions of gas temperature and average electron energy, the latter computed assuming Maxwellian or any other chosen electron energy distribution function. The average electron energy is obtained from transport equation with the elastic and inelastic collisions mostly responsible for the electron heating and cooling in the bulk. To get the electron heating the RF electric field is needed, so that a frequency-domain Maxwell equation solver is included. The time averaged plasma potential profile is solved for by a Poisson solver with a source term reflecting the imbalance between positive ions and negatively charged particles (negative ions and electrons). The gas flow has little influence on electron and ion distributions in electropositive plasmas/regions, due to ambipolar diffusion being much faster than gas flow at such low pressure. However, uncharged active species are not subject of ambipolar diffusion and thus diffuse about two orders of magnitude slower, so that the gas flow must be taken into account for them.

Steady state cannot be directly computed due to difficulties to guess an initial state realistic enough to lead to convergence, so instead we solve a transient problem starting from conditions where the initial state can be somehow guessed (e.g. very low power and only argon at the inlet) and then change the conditions gradually until a steady state for the conditions of interest is reached.

3. Results

Figure 1 shows the steady-state atomic chlorine density distribution in a cylindrical 13.56 MHz ICP processing chamber with one-turn ICP antenna at 20 mTorr argon/oxygen/chlorine gas mixture. At the gas inlet atomic chlorine is not present (all chlorine is still in molecular state) which quickly changes to almost only atomic chlorine at a few centimeters from the inlet. Decreasing the atomic chlorine improves the etching anisotropy, while in atomic-chlorine rich plasmas isotropic chemical dry etching prevails. Figure 1 indicate that at this particular conditions there will be significant isotropic etching.

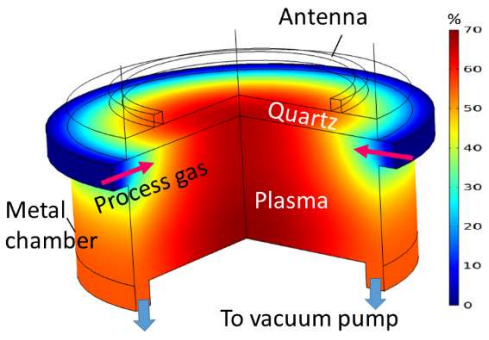

Fig. 1. Degree of dissociation of chlorine in high-density low-temperature low-pressure ICP.