INTEGRATED SIMULATION OF DISCHARGE AND LASER PRODUCED PLASMAS IN EUV LITHOGRAPHY DEVICES

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Abstract

Both Laser and Discharge produced plasma are being used as a light source for EUV lithography. A key challenge for Discharge Produced Plasma (DPP) devices is achieving sufficient brightness to support the throughput requirements of High-Volume Manufacturing lithography exposure tools. One method for improving source brightness is to simulate the source environment in order to optimize the EUV output. An integrated model for the description of hydrodynamics and optical processes in a DPP device has been developed and integrated into the HEIGHTS–EUV computer simulation package. Model development consisted of several main tasks: plasma evolution and magnetohydrodynamic (MHD) processes; detailed photon radiation transport, and physics of plasma/electrode interactions in DPP devices. Advanced numerical methods for the description of magnetic compression and diffusion in a cylindrical geometry are used in the HEIGHTS package. HEIGHTS can also study detailed hydrodynamic and radiation processes in various laser produced plasma (LPP) devices. Radiation transport of both continuum and lines is taken into account with detailed spectral profiles in the EUV region. Radiation transport is solved using two different methods, i.e., by direct integration of the transport equation and by 3-D Monte Carlo techniques. Discharges using Xenon and Tin gasses are simulated and compared.

1. Introduction

The EUV lithography community has made several important contributions to improving the radiation source device. Recent advances in laser and discharge systems with high repetition rate and high average power suggest the feasibility of modular, flexible, and relatively inexpensive microelectronic production facilities based on laser and discharge plasma sources. However, several challenges remain. Modern projection lithography systems require /1/ as a minimum 1% conversion efficiency of laser light into soft X-rays within a 2% bandwidth at 13.5 nm, where multilayer reflectivity of more than 60% can be routinely achieved by Mo-Si mirrors. Final in-band power must be obtained, with an intermediate focus over 120 W. These requirements necessitate investigation and optimization not only of power sources but also plasma irradiation parameters, plasma energy deposition, target material, device design, etc. In this work, we present our simulation model of the MHD and optical processes that occurs in DPP and LPP devices.

1. Mathematical model

We consider the general set of three-dimensional (3D) resistive MHD equations /2/ expanded with heat transport fluxes, radiation fluxes, electron-ion interaction term, and laser absorption source term. The general set of equations is presented in two-temperature approximation model:

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0\\
&\frac{\partial \rho\mathbf{v}}{\partial t} + \nabla\cdot\left(\rho\mathbf{v}\mathbf{v} + p_{tot} - \frac{\mathbf{B}\mathbf{B}}{4\pi\mu}\right) = -\frac{1}{4\pi\mu}\mathbf{B}(\nabla\cdot\mathbf{B})\\
&\frac{\partial e_{tot}}{\partial t} + \nabla\cdot\left[\mathbf{v}(e_{tot}+p_{tot}) - \frac{1}{4\pi\mu}(\mathbf{v}\cdot\mathbf{B})\cdot\mathbf{B} + \frac{c^2\eta}{16\pi^2\mu^2}(\nabla\times\mathbf{B})\times\mathbf{B} - \lambda_e\nabla T_e - \lambda_i\nabla T_i - \mathbf{S}_{rad}\right] =\\
&\qquad\qquad\qquad\qquad = Q_{las} - \frac{1}{4\pi\mu}(\mathbf{v}\cdot\mathbf{B})\cdot(\nabla\cdot\mathbf{B})\\
&\frac{\partial e_i}{\partial t} + \nabla\cdot\left[\mathbf{v}(e_i+p_i) - \lambda_i\nabla T_i\right] = 3\frac{m_e n_e}{m_i\tau_e}(k_B T_e - k_B T_i)\\
&\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) + \frac{c^2}{4\pi\mu}\nabla\times(\eta\nabla\times\mathbf{B}) + \frac{ck_B}{en_e}\nabla n_e\times\nabla T_e = -\mathbf{v}(\nabla\cdot\mathbf{B})
\end{aligned}
\tag{1}
$$

Here, e_{tot} – total energy that includes the hydrodynamic part, $e_h = e_e + e_i + e_{kin}$, and the magnetic part $e_m = \frac{B^2}{8\pi\mu}$; e_e – electronic component of the plasma energy that includes thermal energy of electron and ionization energy; e_i – ion component of the plasma energy; and $e_{kin} = \frac{\rho v^2}{2}$ – kinetic energy of the plasma. Analogous to energy, pressure has hydrodynamic and magnetic parts: $p_{tot} = p_e + p_i + \frac{B^2}{8\pi\mu}$. Magnetic diffusion processes are taken into account as the Joule heat term, $\frac{c^2\eta}{16\pi^2\mu^2}(\nabla\times\mathbf{B})\times\mathbf{B}$, in the total energy equation and as the diffusion term, $\frac{c^2}{4\pi\mu}\nabla\times(\eta\nabla\times\mathbf{B})$, in the magnetic field equation, where η is resistivity, and μ is magnetic permeability. In the calculations we assumed $\mu = 1$ for the plasma. The thermal conduction in the plasma is the combined result of the electron $\lambda_e \nabla T_e$ and ion $\lambda_i \nabla T_i$ activity, where λ is the conductivity coefficient and T is the temperature. The radiation transport process is represented here as flux $\mathbf{S}_{rad}$ and the laser heating source as Q_{las}. Also taken into account is the energy interchange between electrons and ions in the form $3\frac{m_e n_e}{m_i \tau_e}(k_B T_e - k_B T_i)$ /3/ and the thermally generated magnetic field $\frac{ck_B}{en_e}\nabla n_e \times \nabla T_e$ /4,5/. Here m is the mass; n_e and τ_e are electron concentration and the relaxation time; $c-$ speed of light; e – electron charge; and k_B- Boltzmann constant. To complete this full set of MHD equations, functions for the thermodynamic pressure of electrons $p_e = p(e_e, \rho)$, resistivity $\eta = \eta(e_e, \rho)$, and thermal conductivity $\lambda_{e/i} = \lambda(e_{e/i}, \rho)$ are determined from the equation of state, discussed in /6/. Equation (1) constitutes the initial set of equations used for modeling laser generated plasma processes. The conditions of a particular problem and a specific geometry will lead to the transformation of the main equations. If the EUV device and plasma motion does not have symmetry, we expressed Eq. (3) in the 3-D Cartesian coordinate system otherwise, the 2D cylindrical coordinate system can be used. Since the final set of the transformed equations has convective terms (hydrodynamic flux) and dissipative terms (heat conduction, laser heating, radiation transport, and electron-ion interaction), we used splitting of physical processes in our numerical algorithm to separate the hyperbolic and parabolic parts /2/. The conservative form of the initial equations allows the use of the TVD method in the Lax-Friedrich formulation (TVD-LF) for solution of the convective stage /7/. An implicit numerical scheme with sparse matrix linear solvers is used for calculating the heat conduction and magnetic diffusion terms /2,8/. The Monte Carlo methods are used for modeling the radiation processes: laser heating, photon radiation transport in the plasma, and the EUV output /2,6,8/.

3. Results and discussion

To validate our model and benchmark HEIGHTS package, we solved several problems and compared our results with known analytical and experimental results. The calculation blocks (MHD, thermal conduction, radiation transport, etc.) were tested separately and in various combinations /2,6,8/.

Several of DPP devices were simulated and compared with experimental EUV output parameters /9/. Good agreement between numerical calculations and data from device operations and the directions for optimization of DPP devices and external power sources was identified.

We carried out numerical experiments to study the influence of the thermally generated magnetic field on the plasma parameters and the EUV output in the lithography energy range /2/. Simulations of the LPP device with droplet and planar targets showed little dependence of plasma parameters from the thermomagnetic source for radiation power density of $10^{10} - 10^{11}$ W/cm^2. The theoretical model and HEIGHTS package allowed investigating the influence of complex spatial effects of plasma motion on the final conversion efficiency of the LPP devices and will be reported in future publications.

Theoretical models developed and integrated HEIGHTS package showed wide capabilities and flexibility. The models and code can therefore be used for optimization of obtained data, investigation of LPP devices with complex geometry and structure targets, study of combined influence of spatial effects and target composition on the final EUV output, and EUV source size and form.

Acknowledgments

Major part of this work was supported by the Intel Corporation. Argonne National Laboratory is operated by the University of Chicago for the U.S. Department of Energy under contract W-31-109-ENG-38.

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