RF 플라즈마 전산모사시 시간에 따른 주기적 정상상태 효율적 계산

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On Rapid Computation of Time Periodic Steady State for Simulation of RF Plasma

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서론

Plasma processing technology is currently utilized in the wide range of applications including advanced Integrated Circuit (IC) fabrication. In the fabrication of modern IC's, over 30% of entire processing steps implement the plasma process as a key technology. In spite of their extensive usage and technological importance in the microelectronic industry, plasma processing equipment have been empirically designed and statistically optimized at great expense of development time and cost. As processes and product complexity continue to increase for more advanced IC development, the performance of the plasma process need to be predicted at the process design stage to reduce the development cost. This requires the numerical simulation of an appropriate model of plasma temporally modulated with an externally imposed frequency.

In such plasma simulation, to reach ″Time Periodic Steady State″ with a typical operating condition, one needs to integrate plasma model equations over about 1500 RF cycles for electro-positive plasmas, and possibly much longer for electro-negative plasmas involving slow ion-ion recombination processes. When neutral chemistry and transport are coupled to the charged species behavior, asymptotic convergence may worsen due to the large disparity in time scales between neutral and charged species. The latter responds typically in nano-second time scales, while the former responds in milli-second time scales. Although the implicit scheme relaxes time step restrictions during simulation, it is still necessary to accurately resolve the time period of imposed RF modulation to capture the cumulative electron motion which significantly affects the behavior of ions and neutrals.

This paper proposes a methodology reducing the number of RF cycles necessary to reach time periodic steady state solutions for efficient plasma simulations. Our methodology employs a feedback control approach in conjunction with an implicit time integration scheme.

본론

Among various plasma modeling approaches depending on the level of complexity, this work utilizes a three moment plasma model derived by taking moments of the Boltzmann equation. The three moment model comprises continuity and momentum equations for both electron and ions, and an energy equation for electron. Greater depth, assumptions and justifications of the model together with boundary condition can be found elsewhere [1, 2]. The governing equations form a nonlinear system of hyperbolic partial differential equations, which can be decoupled through an eigenvalue decomposition utilizing the Jacobian matrices of spatial derivative terms. The decoupled partial differential equations are transformed to a series of nonlinear algebraic equations by a finite difference approximation, and spatiotemporal solutions are then found by iteratively marching them in time with a specified time step. Such a numerical method for the computation of time transient solutions can be also found elsewhere [1]. As described earlier, however, this method requires a large number of RF cycles to be simulated for the evaluation of time periodic steady state solutions.

To reduce the computation time required to reach the time periodic steady state, a feedback approach can be utilized with an appropriate gain. For the clarity of the proposed concept, consider a simple ordinary differential equation

$$\frac{dx(t)}{dt} = ax(t) + d(t) \tag{1}$$

of which the long term ("steady state") solution is time periodic with a period T. The simplest way to obtain a steady state solution is first representing the differential equation by an explicit finite difference approximation, and then iteratively solving the resulting algebraic equation as follows

$$\begin{array}{lcccc} & \mathrm{M} & & & \\ x_k & = & (1 + a\Delta t)x_{k-1} & + & d_{k-1}\Delta t \\ x_{k+1} & = & (1 + a\Delta t)x_k & + & d_k\Delta t \\ & \mathrm{M} & & & \\ x_{k+m} & = & (1 + a\Delta t)x_{k+m-1} & + & d_{k+m-1}\Delta t \\ & \mathrm{M} & & & \end{array} \tag{2}$$

where $\Delta t=T/m$, m is the number of time steps within one period, and x_k and x_{k+m} represent solutions at the beginning and end of the cycle respectively. Through a subsequent back-substitution, Eq. (2) can be represented, as shown in Fig. 1.(a), by

$$y_{k+1} = \alpha y_k + \delta_k \tag{3}$$

where $y_k=x_k$, $y_{k+1}=x_{k+m}$, $\alpha=(1+a\Delta t)^{m+1}$and

$$\delta_k = \sum_{i=k-1}^{k+m-1} (1 + a\Delta t)^{k+m-i-1} d_i \Delta t \tag{4}$$

If the value of a is close to unity, the system would reach the time periodic steady state slowly. To make the system quickly approach the steady state, a feedback signal with an appropriate gain K can be added such that

$$y_{k+1} = \alpha y_k + \delta_k + K(y_{k+1} - y_k) \tag{5}$$

as shown in Fig. 1(b). By taking a z transform, the transfer function of Eq. (5) becomes

$$Y = \frac{(1-K)y_0 + D}{(1-K)z - (\alpha - K)} \tag{6}$$

From Eq. (6), it is not difficult to show that the arbitrarily response can be obtained by setting the gain equal to a.

In plasma simulation, feedback signals multiplied by appropriate gains are added at the beginning of each cycle. The gain is rigorously evaluated by the analysis of the linearized model for each RF period. The added feedback terms are nothing more than the differences between current values and past values obtained one period before, which eventually vanish as solutions approach the steady state. Fig. 2. shows the number of cycles and corresponding CPU time required to reach the time periodic steady state in the one-dimensional simulation of a parallel plate, capacitively coupled RF argon plasma. Operating pressure was 300 *mTorr*, and applied volatge and frequency were 100 *V* and 13.56 *MHz*, respectively. Without feedback control approach, as shown in Fig. 2.(a), it took about 2000 RF cycles to reach the steady state where the L1 norm become less than 0.01. The corresponding CPU time took about 4000 seconds on a Compaq Alphastation. By imposing the feedback control after 100 RF cycles later, the system quickly approached its steady state within a few more cycle, as shown n Fig. 2.(b). The consequent CPU time reduced to more or less than 600 seconds, acquiring about sevenfold speedup in simulation time. Fig. 3. shows plasma properties, at the steady state, obtained with the application of the feedback control approach to the simulation. Plasma density, plasma potential and electron temperature were approximately 3.8e9 $\#/cm^3$, 40 *V* and 4 *eV*, respectively. Although not shown in the figure, the steady state plasma properties obtained without the implementation of the feedback control were almost identical to those shown in Fig. 3.

결론

This paper discussed the application of a feedback control approach to plasma simulation for the rapid evaluation of time periodic steady state solutions. The feedback gain was rigorously estimated during simulation by taking into account the previous plasma behavior. Through the one-dimensional simulation of a parallel plate, capacitively coupled RF argon plasma, the feedback control approach demonstrated its capability to dramatically reduce the number of RF cycles required to reach the time periodic steady state, resulting in several factors of speedup in simulation time.

후기

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참고문헌

[1] Heon Chang Kim and Vasilios I. Manousiouthakis, "Dually driven radio frequency plasma simulation with a three moment model", Journal of Vacuum Science & Technology A., 16(4), 2162-2172, 1998.
[2] Heon Chang Kim and Vasilios I. Manousiouthakis, "Simulation based plasma reactor design for improved ion bombardment uniformity", Journal of Vacuum Science & Technology B., 18(2), 841-847, 2000.

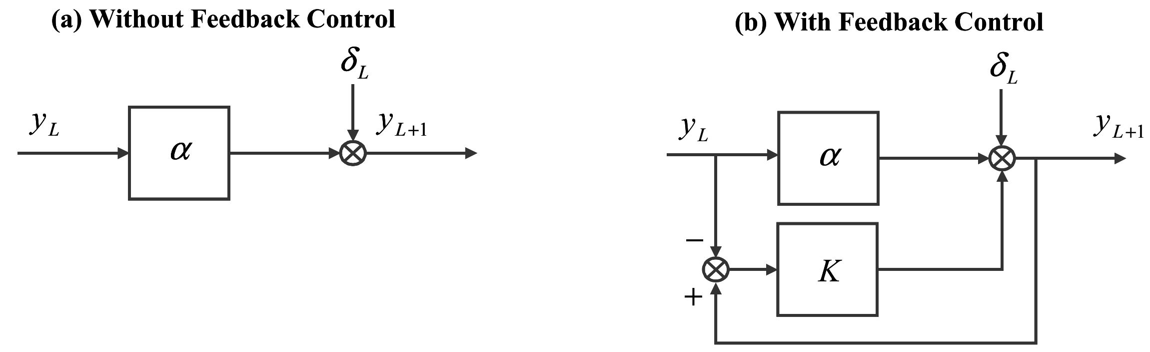

Fig. 1. Block diagrams of simulation schemes with and without feedback control approach.

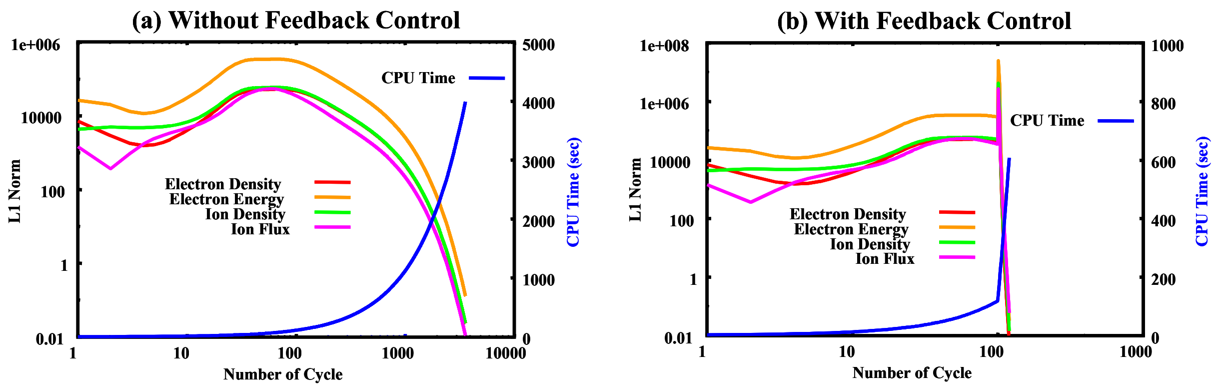

Fig. 2. Comparisons of simulation times required to obtain time periodic steady state solution.

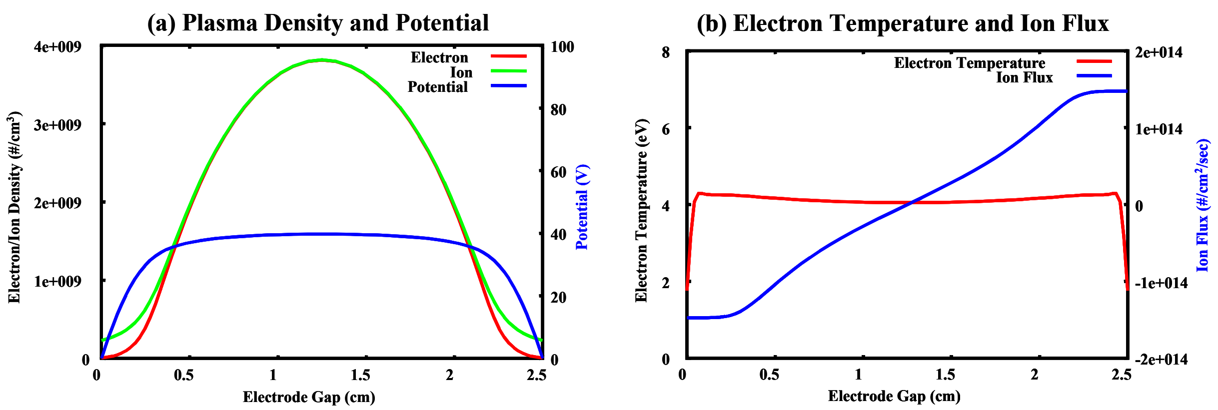

Fig. 3. Plasma properties at steady state obtained with feedback control approach.