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Numerical Simulation of Discharge Processes in DBD Plasma Actuator
DBD プラズマアクチュエータにおける電離過程の数値シミュレーション

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We have developed a numerical code based on PIC-MCC method to study flow generation mechanism in a dielectric barrier discharge (DBD) plasma actuator. Two-dimensional simulations of unsteady discharge processes were conducted with constant applied voltages. When a exposed electrode is negatively biased against a buried electrode, charged particles are generated on the dielectric surface because of electron avalanche, distort electric potential distribution, and spread as surrounding the exposed electrode. In the case of positively biasing, an ion cloud is generated on the exposed electrode and spreads to a direction of the buried electrode followed by the plasma. The momentum coupling between ions and neutrals primarily generates the force.

1. Introduction

Recently, applications of plasma flow have been studied for flow control and development of propulsion technique. A dielectric barrier discharge (DBD) plasma actuator is one of the most popular applications and consists of two electrodes placed parallel to each other [1–3]. One electrode is covered with a dielectric while the other is exposed to the flow. When a sufficiently high voltage is applied between two electrodes, electrons are accelerated and affect the surrounding electric field because of their charge. If the accelerated electrons collide with sufficient energy, activated neutrals can release new free electrons. The newly created electrons are accelerated in the electric field and lead further ionization, so-called electron avalanche. A considerable number of ions are created through the above process and also are accelerated.

The ions transfer their momenta to the neutrals through elastic collisions, and the flow is induced. However, some characteristics in the discharge processes have not been cleared completely yet. So, we aim to find a dominant factor in the discharge processes in the DBD plasma actuator. In this paper, we have numerically analyzed plasma formation process and force generation mechanism.

2. Numerical Methods

In order to estimate a plasma flow in the DBD plasma actuator, we should properly model the discharge processes with elastic and inelastic collisions. Generally, the assumption of thermal equilibrium or chemical equilibrium does not work out in the flow of the plasma actuator. Therefore, we employ Particle-In-Cell (PIC) method to estimate the interaction between plasma and electric field, and simultaneously, Monte Carlo Collision (MCC) method to estimate the interaction between plasma and neutrals. In the PIC method, motions of charged particles which are located in each computational cell are solved with some cell-assigned quantities representing electric field. The governing equations are as follows:

$$m\frac{d\mathbf{x}}{dt} = q\mathbf{E}, \quad (1)$$

$$\nabla \cdot \mathbf{D} = -\rho, \quad (2)$$

$$\mathbf{D} = \varepsilon\mathbf{E}, \quad (3)$$

where m is the mass of particle, q is the particle charge, and ρ is the charge density. In the present paper, the electrostatic field is only considered, so we solve Poisson equation for the electric potential. The charge density is calculated with the particle position and the particle charge. In the MCC method, many sample particles are used, and the change of particle velocity through collisions are estimated at each time step in a stochastic manner.

3. Simulation Conditions and Results

We have performed particle dynamics in the DBD plasma actuator using the developed two-dimensional code. The plasma actuator is modeled in a rectangular domain. It consists of two electrodes separated by a dielectric. The exposed electrode is 0.5-mm thickness and 0.25-mm length, and the buried electrode is 0.2-mm thickness and 1.25-

mm length. 600×600 computational cells are used for covering this domain. The buried electrode is set to be ground, while on the exposed electrode, constant voltage is applied. Since the buried electrode is covered with the dielectric, electrons are accumulated on it. The relative permittivity of the dielectric layer is set as 2.7 of the value of Kapton. Secondary electron emission coefficient is set to be 0.3. The exposed electrode assumed as the complete absorption boundary on which all electrons are absorbed, and all ions become neutrals.

In order to study the discharge processes, we simulate direct current discharge in nitrogen gas using our code. When −3000 V is applied as a negative constant voltage input on the exposed electrode, a large number of electrons are created and accumulated on the dielectric. The electric potential is distorted due to the high net charge density on the dielectric surface. The distorted potential generates high electric field intensity at the edge of the plasma. Electrons can be accelerated by the generated high electric field intensity. Since the electron avalanche is easily caused in the region of the high electric field, the plasma spreads as surrounding the exposed electrode (Fig. 1). Since it is one of the characteristics of glow discharge, the discharge process in the case of negative voltage is considered as glow-type discharge.

Next, on the exposed electrode, +3000 V is applied as a positive constant voltage input. In this case, electrons are accelerated to the exposed electrode with leading the electron avalanche. On the exposed electrode, the electrons are absorbed, so the ion-rich region is generated on the surface of the exposed electrode. This ion-rich region is called as ion cloud and distorts the electric potential. The region of high electric field intensity moves with the ion cloud toward the right side of Fig. 2, and the plasma spreads by following the ion cloud. Since it is one of the characteristics of streamer discharge, the discharge process in the case of positive voltage is considered as streamer-type discharge.

The charged particles transfer their momenta to the neutrals via elastic collisions. In force generation process, ion-neutral momentum coupling is dominant because of larger mass of the ion relative to the electron.

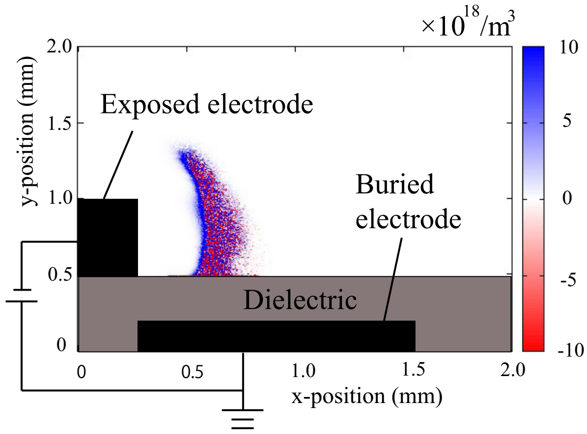

Fig. 1 Net charge density at t =1.0 ns in the case of negative voltage input.

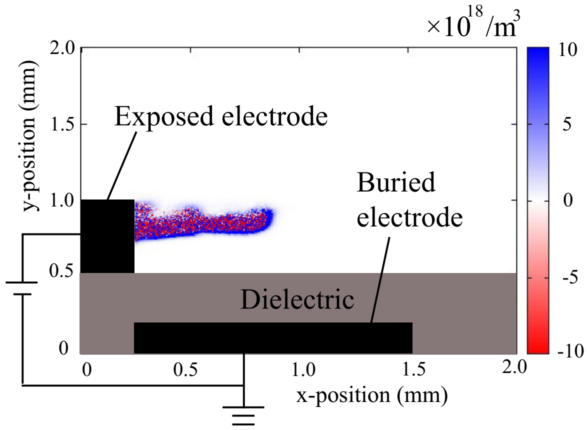

Fig. 2 Net charge density at t =1.0 ns in the case of positive voltage input.

4. Summary

We have modeled a DBD plasma actuator with some representative reactions and developed a two dimensional numerical code to examine discharge dynamics in it. Discharge processes were performed for the case of negative and positive voltages applied to the exposed electrode. In the negative voltage case, though the region of high net charge density spreads due to the electron avalanche, high electric field intensity in the vicinity of the exposed electrode is maintained. On the other hand, in the positive voltage case, after the ion cloud is generated in the vicinity of the exposed electrode, the region of high electric field intensity moves with the ion cloud. The momentum coupling between ions and neutrals primarily generates the force.

References

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