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Modeling of a Plasma Etcher for Charging Free Processing of Nanoscale Structures

M. Radmilović-Radjenović[a], A. Stojković[b], A. Strinić[c], V. Stojanović[d], Ž. Nikitović[e], G.N. Malović[f] and Z.Lj. Petrović[g]

Institute of Physics, Belgrade, POB 68, 11080 Zemun, Serbia and Montenegro

[a]marija@phy.bg.ac.yu, [b]sandrast@phy.bg.ac.yu, [c]strinic@phy.bg.ac.yu, [d]stoyanov@phy.bg.ac.yu, [e]zeljka@phy.bg.ac.yu, [f]malovic@phy.bg.ac.yu, [g]zoran@phy.bg.ac.yu

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Abstract. Neutral beam etching is proposed as a candidate for reducing plasma-process-induced damage in nanoscale devices. In this paper, neutralization of ion beams due to both gas phase collisions and ion surface interactions based on a PIC (Particle in Cell) simulation of realistic Capacitively Coupled Plasma is presented. It was found that a satisfactory degree of neutralization might be achieved by a combined effect of charge transfer and surface collisions.

Introduction

Plasma etching is used in manufacturing of ultra large-scale integrated circuits [1,2]. Various plasma sources, such as capacitively coupled plasmas (CCP) [3,4], inductively coupled plasmas (ICP) [5,6], electron cyclotron resonance (ECR) plasmas [7,8] and helicon plasmas [9,10] have been considered in the past. Presently, ICPs are used for all processes except for the etching of dielectrics where CCPs are exclusively employed. However, plasma etching processes that use charged particles inevitably cause plasma-process-induced damage (PPID). Plasma charging damage was first reported by Yoshida in 1983 [11]. Hashimoto detailed its origin using the electron shading mechanism [12]. As the feature size decreases toward the nanoscale, the effect of PPID on the device characteristics becomes a more serious problem [13,14]. One of the most promising methods to overcome PPID and other charge-induced problems is using neutral beams for etching and deposition processes. Neutral particles can be created by a variety of methods, among which surface neutralization of ions is regarded to have the best properties [14].

Several techniques have been proposed to overcome charging problems. First, pulsed operation was considered as a possible way to avoid increase of the potential due to charging by allowing the free diffusion of electrons and negative ions to nanostructures during the afterglow period [15-17]. Neutral beam etching is being recognized as a new technique to reduce plasma-induced damage in materials processing. For that purpose, various neutral beams, such as hyper thermal atomic beam [18,19], neutral beam produced by ion-neutral scattering [20,21], neutral beam produced by ion-electron recombination [22] and fast neutrals created in charge transfer collisions [23] have been proposed. Of all these only the very energetic fast neutrals produced in charge exchange qualify for etching of dielectrics where solution for charging induced damage is critical.

In the investigation of the neutral beam etching, estimation of the neutralization efficiency represents a very important benchmark [14]. In this paper we have studied the efficiency of neutralization in a realistic system, similar to that proposed by Samukawa and coworkers [17], by considering collisions in the gas phase along with the ion neutralization at the surface. Surface neutralization of ions and collisions of ions in the gas were analyzed first separately and then their joint effect was determined. The gas phase neutralization for etching was first proposed by our group [23], but it was further extended by adding the idea of surface neutralization by Samukawa and coworkers [17,24] and by Economou and coworkers [25].

Simulation Procedure

Recently, simulation techniques have emerged as a very useful tool for predicting etch rates, evolving profiles of the micron-scale features fabricated in plasma-assisted processes, for modeling plasma etcher or for determining the influence of various plasma parameters on the ion-surface collisions. The studied system is the same as that already described in Ref. [14,17] and consists of a gas layer and a tube. The system for neutralization consists of thin tubes (diameter 1.4 mm and length 10 mm - 100 mm), which are parallel to the axis of the field. The tubes are made of reflecting walls and for the sake of simulation we assume 100% reflectivity. The initial beam consists of ions, which are gradually converted to fast neutrals in gas phase and ion-tube wall collisions at a grazing incidence. The probability of neutralization in ion-wall collision is 100% while the overall efficiency is less than 100% since all ions do not collide with walls or molecules. Ion energy distribution functions (IEDFs) and ion angle distribution functions (IADFs) corresponding to the RF discharges at 13.56 MHz were obtained by using Particle-in-cell/Monte Carlo collision code (PIC/MCC) (details about PIC/MCC code can be found in Ref. [26,27]). Calculations were carried out for two different values of the gas pressure of 1 and 10 mTorr of pure argon (for simplicity). The obtained distribution functions were applied as an input to Monte Carlo codes based on the null collision technique and a complete set of scattering cross sections that accurately represents collisions in argon [28]. Each of the processes has associated differential cross sections [28], which are used only to establish the angle of scattering. The probability of scattering, i.e. the free path is determined on the basis of the total cross section. Since, Monte Carlo collision modeling techniques have been well documented in our previous publications [14,28] only a brief description of the codes will be given here. The Monte Carlo codes used in this paper were developed to survey ion and fast neutral transport in parallel plate geometries with complex boundary effects under the influence of an electric field E. A small axial electric field (~1 V/cm) was applied to bring the slow ions out of the system without giving them any significant energy. Calculations for argon were performed for a wide range of conditions required in modeling.

We used another code that includes geometrical properties of the system to determine the neutralization efficiency as a result of collisions of ions with the aperture walls. Probabilities for neutralization in the gas phase collisions and on the walls were multiplied giving an overall neutralization efficiency and the corresponding distribution functions were established. We were especially interested in the influence of various parameters, such as the gas pressure, aperture length, and the diameter of the tube, on collisions of ions with the walls and overall probability of neutralization. In our previous studies [14] we have established that the probability of neutralization in a single collision of ions with the walls is equal to 1 for the conditions that are found in such discharges.

Results and Discussion

Ion surface collisions. The positive ions created in the plasma bombard the surface exposed to the plasma with energies typically of the order of tens to hundreds of eV. Plasma was used as a source of ions and the ions were accelerated by the sheath voltage and collected at the surface for realistic plasma conditions without additional bias. Due to ion surface collisions inside the apertures, some ions are converted into neutrals. The numbers of ions and neutrals that leave the tube were calculated for two different values of the pressure of 1 and 10 mTorr, the aperture length of 10 mm and the diameter of the tube of 1.4 mm. The obtained results are shown in Fig. 1. The obtained results are similar to the ion energy distribution at the boundary of the electrode, modified further but to a small degree by slightly energy dependent overall neutralization probability.

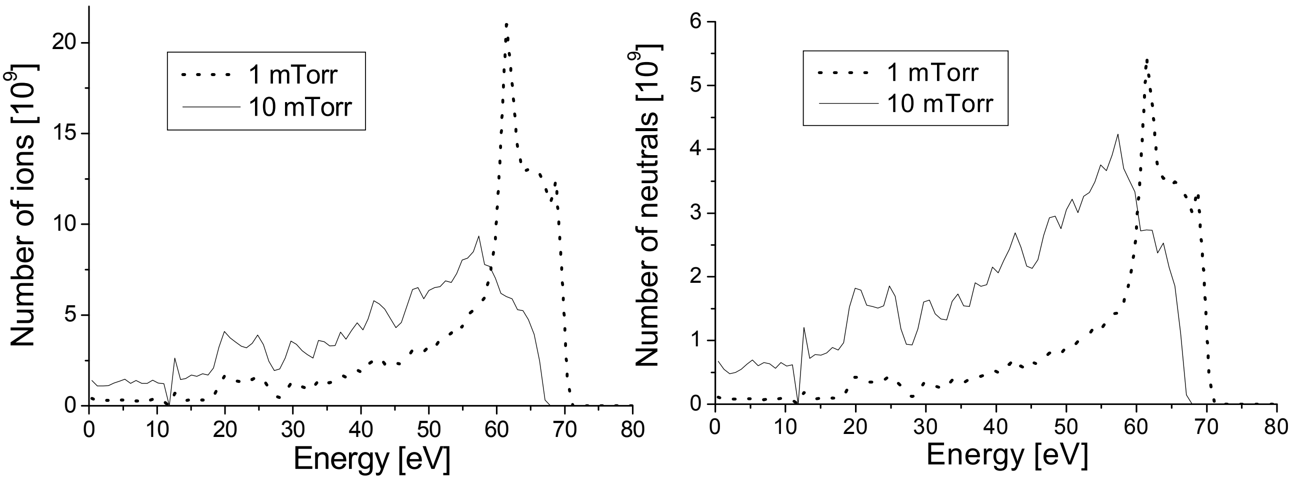

Fig. 1 The energy dependence of the number of ions and neutrals that leave the tube due to ion surface collisions. The results are presented for two values of the pressure of 1 mTorr (dashed lines) and 10 mTorr (solid lines).

It is important to note that in the case of collisions of ions with the aperture walls, probability of neutralization was assumed to be 100% in a single collision with walls of the tubes. The analysis of the results presented in Fig. 1 reveals that at a pressure of 1 mTorr, neutralization efficiency is around 21%, while at a pressure of 10 mTorr, this efficiency is higher and reaches 32%. This is merely due to the shape of the ion energy distribution function and its associated angular distributions.

Gas phase collisions. Ion neutral collisions (resonant charge transfer) in the gas phase that are responsible for the formation of fast neutrals have been considered by using the set of the Monte Carlo codes with parameters as previously specified. The obtained results for two different values of the aperture length are given in Fig. 2, just to illustrate the influence of the distance crossed by the beam on the neutralization efficiency. Gas phase collisions may occur within the tubes. After leaving the tubes, the residual ions can also suffer further collisions and produce fast neutrals. Consequently, the number of fast neutrals formed during gas phase collisions increases with increasing aperture length, as can be seen in Fig. 2. Fast neutral energy distribution has a similar shape to the ion energy distribution.

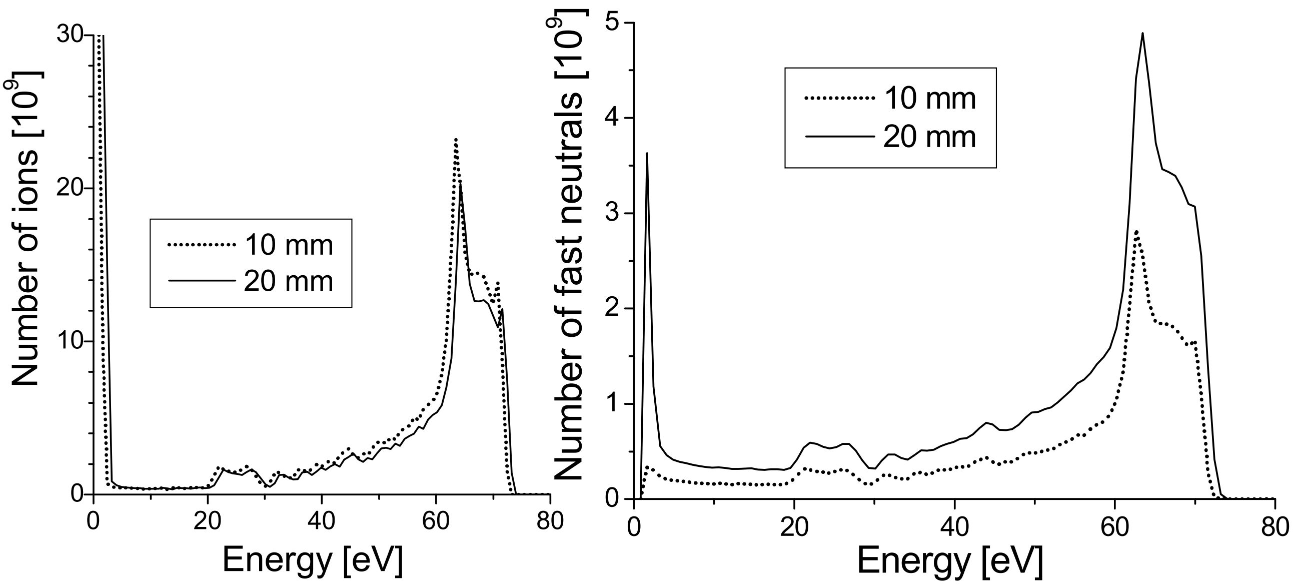

Fig. 2 Number of ions and neutrals as a function of particle energy. Calculations were performed for two different values of the length of the tube of 10 mm (dash lines) and 20 mm (solid lines). The presented results for ions and for fast neutrals correspond to the pressure of 1 mTorr.

Combined gas phase and surface neutralization. Finally we have calculated the number and distribution functions of neutrals and the neutralization efficiency combining both gas phase neutralization and neutralization due to collisions of the ions with the aperture walls. The obtained results at pressures of 1 and 10 mTorr can be observed in Fig. 3. As expected, the neutralization efficiency is higher at the higher pressure as a consequence of a larger number of collisions. Satisfactory neutralization is achieved at the higher pressure mostly due to gas phase collisions which is seen from the difference between the neutralization efficiencies at two different pressures. The outcome will definitely change as the geometry of the tubes and the pressure change. While the efficiency is better at the higher pressure of the two used here, the shape of the energy distribution is not as good. The lower pressure leads to a better shape of the energy distribution of ions arriving from the plasma sheath and consequently to a better suited energy distribution of fast neutrals.

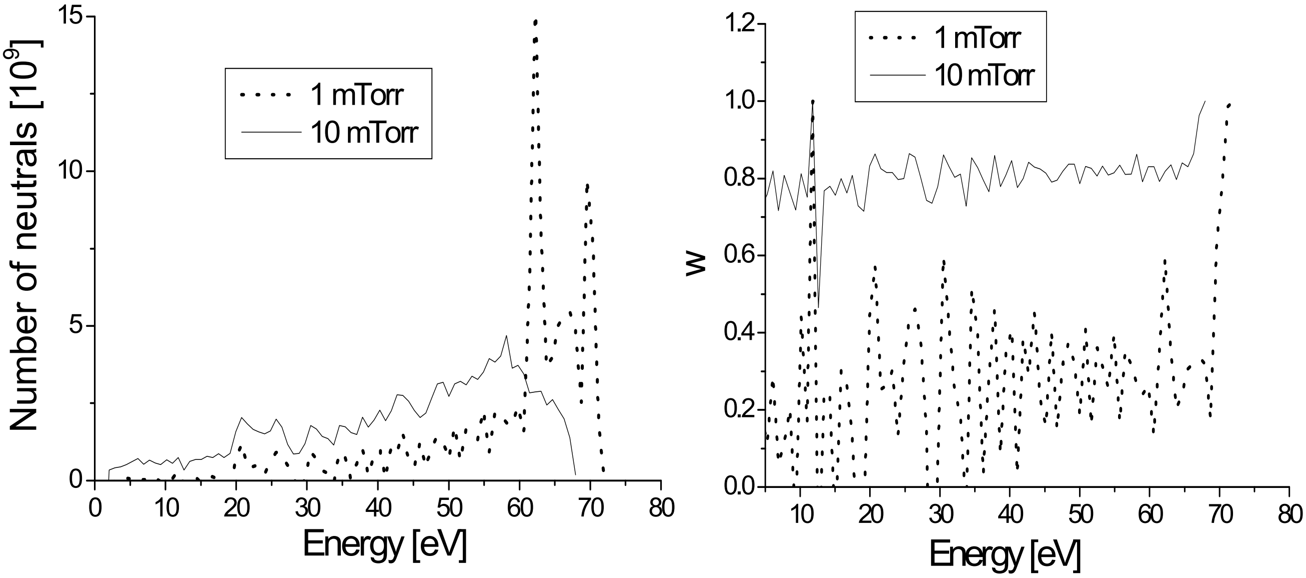

Fig. 3 The energy distribution of neutrals and the neutralization efficiency (W) determined by taking into account both gas phase neutralization and ions surface collisions.

Conclusion

Plasma processing is indeed one of the crucial modern technologies that has made a significant impact on the fabrication of integrated circuits (IC) and consequently on electronics and consumer goods in general. The challenges that remain to be solved include the ability to deposit and pattern new materials at nanometer scales that are needed in new generations of microlectronics fabrication. Damage to ICs during manufacturing as a result of charging of the dielectrics during finalization of interconnects reduces both the profitability and the ability to reach large sizes of microchips and make complete integration of a computer or digital TV on a single chip. The damage includes both the processing problems such as etch stop associated with charging [15], and the breakdown of the FET dielectric, which may occur due to lower and lower deposited charge as the dimensions are reduced.

Simulation results presented here were obtained for realistic geometries and realistic energy distributions obtained from a plasma. In that sense they are an extension of the previous results obtained for a monoenergetic beam. We have shown previously that the geometrical properties of the tube such as length and diameter ratio are very important in determining the efficiency, but gas phase collisions also give a significant contribution to the ion beam neutralization even under relatively low pressure conditions as used by Samukawa and coworkers [24]. The PIC code used here with the added interface of Monte Carlo codes and calculations of geometrical factors are sufficiently detailed description to analyze the realistic processes in plasma tools.

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