Materials Science Forum Vol. 494 (2005) pp. 297-302
online at http://www.scientific.net

Neutralization of Ion Beams for Reduction of Charging Damage in Plasma Etching

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Keywords: Charging, Etching, Nanotechnology, Neutral Particle Etching, Neutralization Efficiency, Ultra Large Scale Integrated Technologies.

Abstract. Neutral beams were proposed for plasma etching in order to reduce damage due to charging. We analyzed the efficiency of neutralization in a system proposed recently where a beam of ions was neutralized in the gas phase and in a set of narrow tubes. We studied surface neutralization as well as collisions of ions in the gas. In the case of collisions of ions with aperture walls, efficiency of neutralization was assumed to be 100%. We also investigated the influence of various parameters such as aperture length, tube diameter and initial ion energy on the efficiency of neutralization using a Monte Carlo code for ion motion simulation. In our calculations we used a well-established set of cross sections for argon.

Introduction

Plasma etching of dielectrics poses a number of technological challenges. Because of a large number of interlayers, the number of steps that involve etching of dielectrics is the greatest in microchip production. At the same time, contact hole and via manufacturing, at current level of integration, involves high aspect ratios. This introduces further problems such as shadowing, Knudsen diffusion and charging of nanostructures. Charging becomes an issue only when the structures that were etched became smaller than 200 nm [1-3]. Several types of integrated circuit damages were shown to be associated with the charging of dielectrics [2,3].

Several techniques have been proposed to overcome charging problems. First, pulsed operation was analyzed as a way to avoid an increase in potential due to charging by allowing the free diffusion of electrons and negative ions to nanostructures during the afterglow period [2,4]. Another approach was to use fast neutrals rather than ions. It was first proposed by Petrović and Phelps [5] even when charging posed small problems and more explicitly later as a solution for charging problems [6]. The idea was to take advantage of charge transfer collisions to turn a large number of ions into fast neutrals. A grid would be used to isolate the remaining ions [7]. In this case the efficiency of fast neutral production would be the product of the gas phase neutralization efficiency and the transmitance of the grid. Samukawa and coworkers [8] and Economou [9] made a similar proposal but they have extended it by adding a set of narrow tubes and developed practical etching systems. While passing through the tubes ions could get further neutralized in collisions with the surface of the tube at low incident angles.

The efficiency of such a system is difficult to estimate. Gas phase collisions extend throughout the tubes and after leaving the tubes, if any ions are left they may suffer further collisions, produce fast neutrals. In this paper we have studied the efficiency of production of fast neutrals in a system identical to that proposed by Samukawa and coworkers [8] by considering both collisions in the gas phase and ion neutralization at the surface.

Neutralization on Wall Surfaces and Monte Carlo Procedure

In this paper we have considered two electron neutralization processes on the surface. For the particular problem, only very small incident angles (grazing incidence) were taken into account. We made calculations for argon ions. Standard formulae for the Auger like process of neutralization were used [10]. Probability that ion leaving the surface will be neutralized is:

$$P_\infty(v_n) = \exp\left(-\left(\frac{A}{a}\right)\left(\frac{1}{v_n}\right)\right) \quad . \ (1)$$

Here v_n is the normal component of velocity and A and a are the coefficients dependent on the surface material and the ion. If there is a penetration of the material, one needs to consider neutralization while approaching and while leaving the surface with corresponding velocities (v_{in} , v_{fn}). Then, the ionized fraction of the beam is equal to [10]:

$$f^+ = \exp\left(-\left(\frac{A}{a}\right)\left(\frac{1}{v_{in}} + \frac{1}{v_{fn}}\right)\right) \quad . \ (2)$$

Finally, if there is no penetration, then both ionization P_i and neutralization P_n on the surface are possible. As colliding particles leave the surface, the fraction of ions is determined by:

$$f^+ = (1 - P_i - P_n)\exp\left(-\left(\frac{A}{a}\right)\left(\frac{1}{v_{in}} + \frac{1}{v_{fn}}\right)\right) + P_i \exp\left(-\left(\frac{A}{a}\right)\left(\frac{1}{v_{fn}}\right)\right) \quad . \ (3)$$

It was difficult to find in literature the values for *A/a* ratio that would be valid for the situation of interest to us where presumably Ar^+ and CF_x^+ ions are to be used. If there is a penetration, then the values for hydrogen ions are: 1.6 10^4 – 2.2 10^6 m/s. If there is no penetration, the values for H^+ ions are: 2 – 9.7x10^4 m/s for the energy range: 0.6 – 2.4 keV, which is relevant to our applications [10]. In the 3 – 10 keV energy range, the values for He^+ are between 2x10^4 – 2x10^5 m/s. The range of the values of *A/a* found in literature is 10^4 – 10^7 m/s [10].

Normal velocity was defined in our calculations as a parameter and it may be associated with the total ion energy and the angular spread of trajectories. The available data for the spread of parameters were chosen in the worst-case scenario. Probability of the growth of neutrals f = 1- f^+ or the percentage of ions remaining in the beam was calculated. Results for angular dependencies of the ionic component of the beam are shown in Fig. 1. From the figure, one can see that a 100% efficiency of neutralization is achieved at small incidence angles for all values of parameters and that a significant number of ions are reflected only for small values of the parameter *A/a* and for angles of incidence greater than 10^o. Thus, we have concluded that the assumption of 100% efficiency of neutralization would be correct if the two electron Auger like neutralization was the dominant mechanism. One may expect a different efficiency in the case of resonant single electron neutralization process, but in that case the probability of neutralization would be even higher.

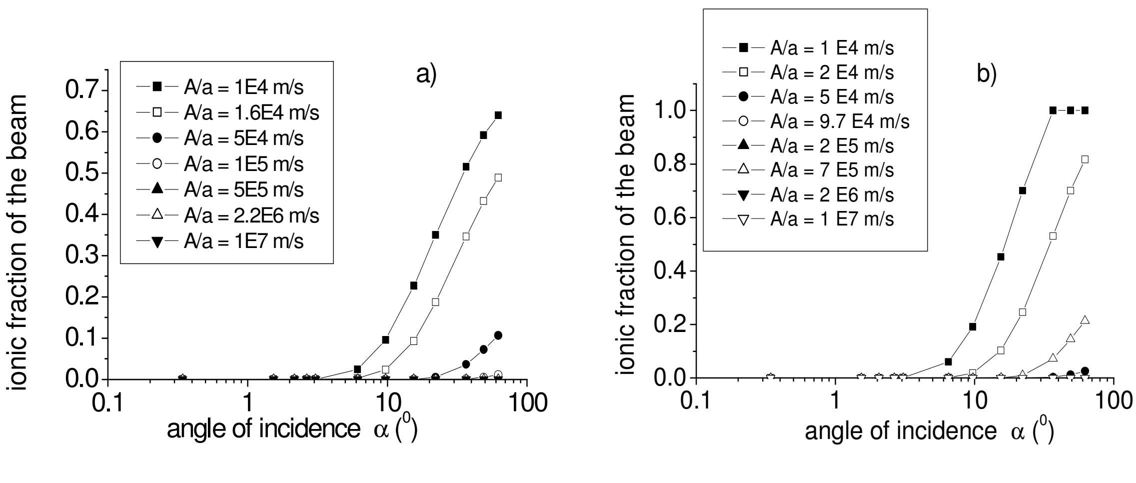


Fig. 1 Maximum content of ions in the beam reflected from the surface with (a) and without penetration (b).

Monte Carlo Simulation Technique and Calculation Procedure

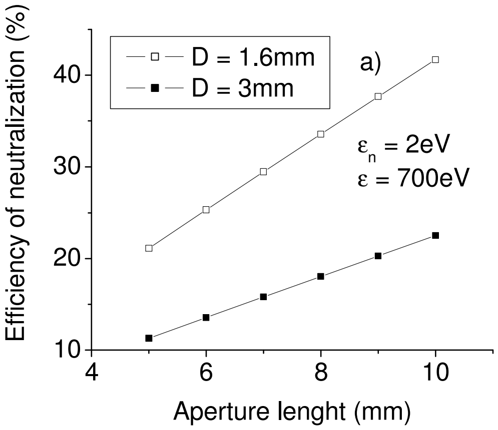
Monte Carlo simulation code was used to follow trajectories and take into account collisions. The code was tested both for the gas phase swarm transport [11] and for trajectories in essentially collisionless situations [12]. A small axial electric field (1 V/cm) was applied to bring the slow ions out of the system without giving them any significant energy. Calculations were made for argon ions in argon with a standard set of cross sections [6]. The gas phase collisions depend on the distance only.

Geometrical calculations were then made to establish the efficiency of neutralization on tube walls. Gas phase collisions as a function of distance were taken into account separately. Finally, we combined surface and gas phase neutralization and compared the results to the experimental data from [8].

Results and Discussion

Collisions with walls

Geometrical considerations are sufficient for taking into account surface neutralization when the efficiency for a single collision is 100%. Nevertheless, in order to allow a possibility of a less efficient process, we considered solid angles for multiple scattering on the surface. Results for the efficiency of neutralization are given in Fig. 2 as a function of geometrical parameters. The rise of efficiency with the length (*l*) of the tube is linear, while the decrease is observed with an increasing diameter (*D*). Axial and perpendicular velocities were taken as parameters. Realistic (experimental) values were chosen for the initial geometry [8], but the final over-all efficiency will depend on the diameter to length ratio, as well as the perpendicular to axial velocity ratio.



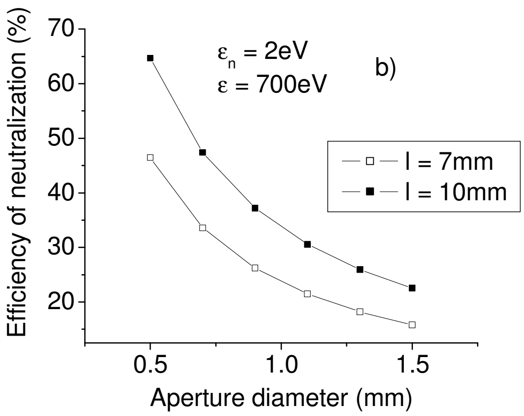
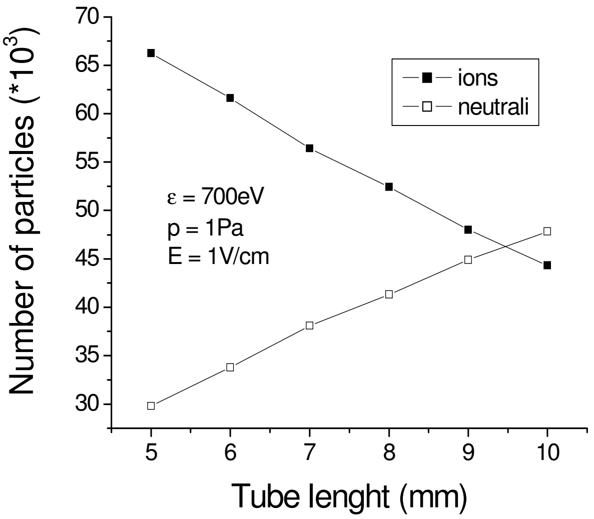


Fig. 2 Neutralization efficiency of the beam for 100% efficient collisions with the walls as a function of (a) length and (b) diameter. The total initial ion energy (ε) was 700 eV and the energy of the perpendicular velocity (ε_n) 2 eV.



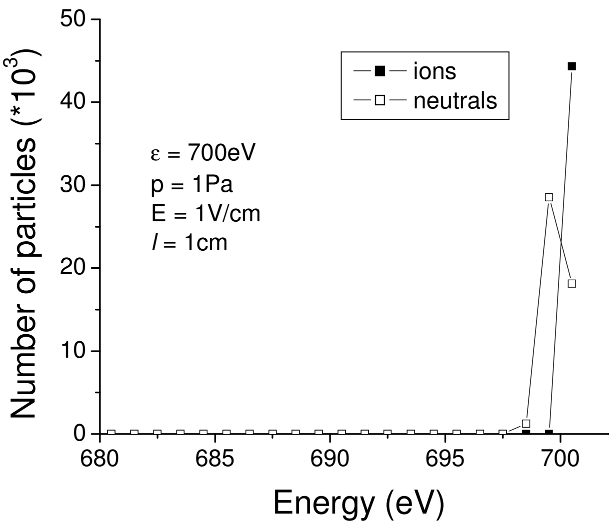


Fig. 3 Neutralization of the beam by collisions in the gas. Fig. 4 Energy distribution of high-energy particles.

Gas phase collisions

Ion neutral collisions, including charge transfer ones, in the gas phase leading to the formation of fast neutrals and slow ions were considered as a process that neutralizes the beam (of high energy particles). Only the total energy was taken as a parameter. Calculations were made for two pressures 0.1 and 1 Pa. In Fig. 3, we show the eutralization efficiency as a function of tube length at 1 Pa. 10,000 ions were released at the aperture of the tube with energy of 700 eV. A linear (or close to linear) decay of the number of high-energy ions and growth of neutrals is observed. The energy distribution function of particles is shown in Fig. 4. Distribution of neutrals (and low energy part of the ion distribution - not shown in the figure) is broader due to effect of elastic scattering and assumed angular distribution for charge transfer collisions. We can conclude that under conditions of the experiment the gas phase collisions may make a considerable contribution to the neutralization of the high-energy beam.

Combined neutralization of the beam

Finally, we calculated combined neutralization efficiency. Since in the sheath region before the tubes [8] there is a variable electric field dependent on plasma properties we limit ourselves to the length of tubes that may be filled with the background gas. The sheath neutralization may be easily added and in the case of [8] we subtracted its effect. The results on neutralization efficiency for two total energies and pressure of 1 Pa are shown in Fig. 5a as a function of tube length. The efficiency as a function of tube diameter at two pressures is shown in Fig. 5b.

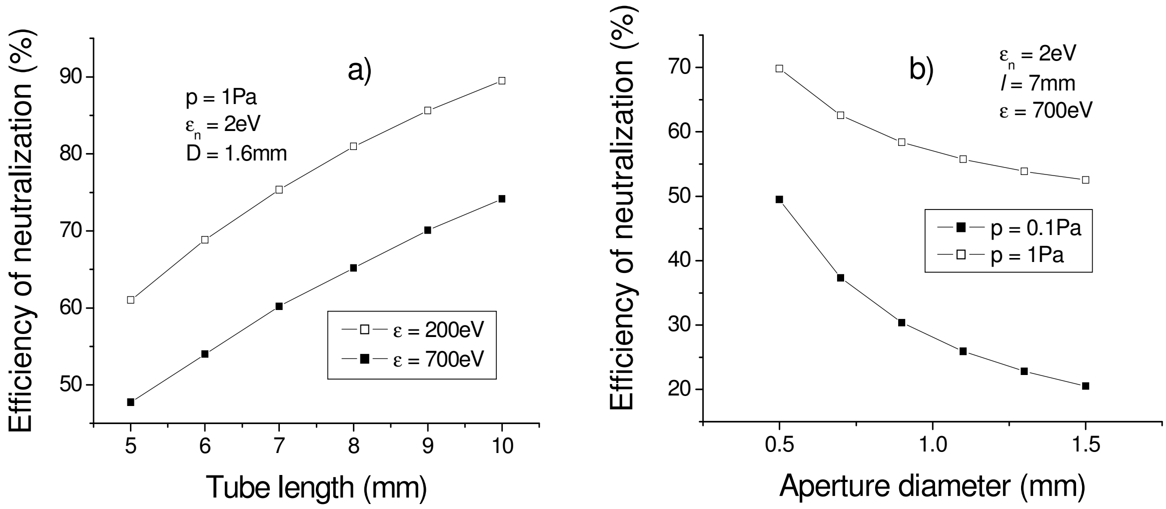


Fig. 5 Neutralization efficiency as a function of tube length for two initial energies (at 1 Pa) (a) and as a function of tube diameter for two pressures (b).

We see that the increase in efficiency with the tube length is almost linear and also that the contribution of the gas phase neutralization is considerable at 1 Pa, while at 0.1 Pa it is negligible under chosen conditions. Finally, in Fig. 6 we compare our calculations with the results obtained by Samukawa and coworkers [8]. A very good agreement has been reached with reasonable selection of the perpendicular velocity of the beam (angular spread).

Results and Discussion

Efficiency of neutralization was calculated for the neutral beam source proposed by Samukawa and coworkers [8]. First, we determined the worst-case surface neutralization efficiency and for angular spreads of less than 10^o it was shown that 100% efficiency might be a reasonable assumption. It turned out that the geometrical factor was critical, but the gas phase collisions made a significant contribution to the beam neutralization at 1 Pa. Efficiency was found to be determined mainly by the ratio of tube diameter to its length. However, one also has to take into account the overall transparency of the set of tubes and uniformity of etching at the surface of the wafer. These two considerations will limit the choice of geometrical parameters. Therefore we believe that the Scott-Phelps source [6,7] is also a very good option for neutral beam etching.

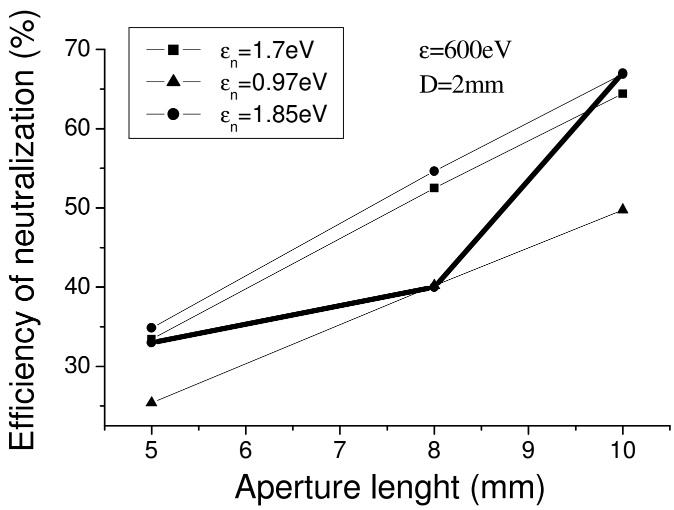


Fig. 6 Comparisons of calculations with the results from [8] for the identical conditions.

Acknowledgements

The work presented here was supported in part by Ministry of Science and Environmental Protection of the Republic of Serbia under Project 1478 and we are grateful to Prof. Toshiaki Makabe for useful suggestions.

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