

DESIGN-SPECIFIC VARIATIONS IN VIA-CONTACT ETCH - FULL CHIP ANALYSIS

V. Sukharev, A. Markosian, N. Khachartyan, L. Manukyan, and J. H. Choy

Ponte Solutions Inc., Mountain View, CA 94040, USA,

E-mail: Valeriy.Sukharev@ponte.com

1. Introduction

Via-contact etch process step is traditionally considered as one of the most technically difficult steps in semiconductor processing. A variety of via patterns characterized by different densities are used as test structures to reach a targeted etch rate, targeted feature profile (sidewall slope, bottom flatness, corner rounding, etc.) and electrical as well as reliability targets. One of the most serious problems is determination of the process recipe window, which covers all issues associated with the pattern density variations. A cause of this problem is in well-known microloading phenomenon [1] (MP), which is an across-layout steady state variation in concentration of neutral species participating in etching reactions. This variation is caused by a variation in pattern density which generates a variation in radical consumption. MP manifests itself when neutral diffusion is not fast enough to alleviate concentration gradients. Etch rate of any arbitrary via is characterized by a global pattern density (PD), i.e., a number of vias belonging to the layout segment of the size of the mean free path λ of gas species, as well as by a local PD. While the former factor is responsible for the global radical density variation across the layout the last one, determined by the feature aspect ratio (AR), introduces an additional variation in radical flux numbers consumed by etch reactions inside via.

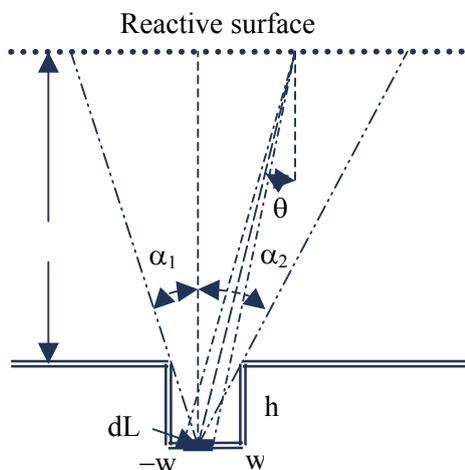


Fig. 1. Schematic for determination of the reflected radical flux unit.

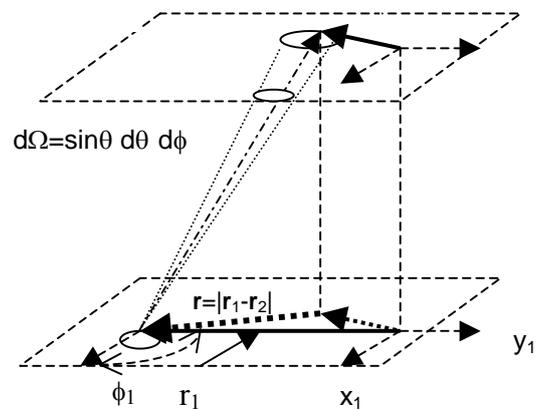


Fig. 2. A radical flux supplied by the "effective reaction surface" per unit area, per unit time, per solid angle in a direction θ .

Plasma assisted dielectric etch of silicon, silicon dioxide as well as low-K carbon doped silica is the processes characterized by very complex mechanisms. They involve different type of reactive species and different type of surface phenomena such as radical generation, polymer formation and etch ion energy transfer through the polymer layer, physical sputtering, etc. (see, for example, review [2] and the reference there). The importance of understanding and addressing the effect of PD non-uniformity on etch rate of the patterned wafer was realized at the early time of the planar technology development. Since then, many attempts have been undergoing to capture the microloading effects at the chip design stage or in other word to take into account the process-induced critical dimension (CD) variations caused by the PD heterogeneity. The linked multi-scale simulations were employed to address this complex problem. A reactor scale model provides the flux distributions of all important species. When implemented in the feature scale simulations, the results of the linked multi-scale simulations provide the capability to capture the process related and topography related effects. It should be noted that while the robust simulation models for all considered scales have been developed and widely used, the proper link between them has not been developed yet. All existing examples of the linked plasma etch models have a sequential character and cannot address the etch-induced CD variations caused by PD heterogeneity.

In order to address the PD effect in via etch rate variation an approximate model taking into account both the effects have been developed.

2. Model synopsis

The developed model and calculation algorithm for etch rate and etched profile variations across the chip consists of the following segments:

- determination of the across-die concentration distributions for all neutrals participated in etch reactions by means of solution of the corresponding diffusion (diffusion-convection) equations with the flux boundary conditions (BC) describing the PD-dependent consumption of the neutrals at the die surface
- addressing the inside feature transport resistance for the radical fluxes in order to converge the radical flux coming from the plasma to the surface into the flux of this radical reaching the feature bottom
- development of the etch rate formalism as a function of the flux-numbers of neutrals and the ion energy flux
- development of the etch stop criterion for determination of etched profile.

Fluxes of different radicals coming from plasma impinge a wafer surface. We assume that depending on the nature of i -th radical the fluxes impinged a surface covered by photo-resist

(PR) are reflected with a probability χ_{PR}^i . A probability to be consumed by the etch reactions inside etched feature is χ^i (χ^i is AR-dependent parameter). Spatial variation in neutral flux consumed by the etch reactions results in variation in neutrals concentration in the near-surface area. Diffusion of radicals works against this variation trying to level its concentration. As a result the steady state distribution of radicals is developed. Continuum models of chemical species transport are not applicable in the scales below λ . To avoid this problem an effective “reaction surface”, located above real wafer surface at a distance λ , should be introduced. A flux BC at the “reactive” surface (Fig. 1), which is introduced for the accounting of the consumed radicals, takes the following form:

$$\Gamma_{ds2}^C = \frac{N_i(\vec{r})c_i}{4} \frac{h^2}{\pi} \int_0^{2\pi} \int_0^\infty (\chi_{PR}^i (1 - \rho(r_1, \phi_1)) + \chi^i(AR)\rho(r_1, \phi_1)) \frac{r_1 dr_1 d\phi_1}{(h^2 + |\vec{r}_1 - \vec{r}|^2)^2}. \quad (1)$$

Here, $\rho(x_1, y_1)$ presents a number either 1 or 0, representing a pattern of PR openings at the die surface, c_i is the gas thermal velocity and N_i is the concentration of the i -th radical. Similarly, to Stenger, by solving the diffusion equations averaged along the plasma thickness, with the flux BC, given by (1), we obtain the $N_i(\vec{r})$ distributions at the “reactive surface”.

Fluorocarbons plasmas are able to supply both the ions and radicals necessary for SiO₂ etch. Fluorocarbon radicals (CF, CF₂, CF₃, etc.) produced in a plasma form fluorocarbon films on all the surfaces exposed to the plasma. These layers can protect the surfaces against the interactions with the plasma. Fluorocarbon ions deliver the energy needed for activation of the SiO₂ etch reactions. Mutual actions of these radicals and ions result in the SiO₂ etch. The thickness of a fluorocarbon layer (C-F) determines the etch rate of underlying SiO₂. A balance between deposition and etching of carbon atoms on the surface determines the thickness of the C-F layer. Hence, the reaction scheme for the SiO₂ etch by the fluorocarbon plasmas can be described as follows:

- CF_x radical fluxes result in C-F polymer deposition.
- O-atom flux is a major cause of the polymer removal.
- Precursors for the etch-related reactions are formed at the polymer-SiO₂ interface by ion-induced energy transfer: “-Si-O-” + E = “Si-” + “O-”. Energy flux is controlled by the polymer thickness.
- Surface reactions between “activated” Si- and O- from SiO₂ and F- and C- from an adsorbed layer (thin C-F) and solid state chemical reactions between these “activated” Si- and O- from SiO₂ and F- and C- from reactions polymer (thick C-F) are responsible for the silicon oxide etch and the polymer thickness reduction.

Regarding the radical transport inside feature, we assume that oxygen atoms are characterized by the sticking coefficient close to one because of their very high reaction ability with carbon. In this case, any particular point at the feature bottom can be reached by only those atoms whose velocity vectors are oriented along the lines of sight, i.e., inside the solid angle of visibility of the plasma (Fig. 2). AR-dependent variation in the visibility across the feature bottom and variation in oxygen concentration at the reactive surface are responsible for the O-flux variation at the feature bottom. Contrary, the CF_2 radicals almost do not react with the sidewall covered by the C-F polymer. Polymer surface should be activated by the low-energy ions to be able to adsorb the CF_x radicals. Because of the almost vertical orientation of the sidewalls, as well as the direction of the ions, not many ions can impinge the sidewalls. Hence, CF_2 radicals are characterized by almost zero sticking coefficients and the Knudsen transport approximation can be applied. CF_x flux is constant across the bottom.

On the final step we substitute the calculated flux-number for CF_x and O-radicals coming to the point of the feature bottom characterized by a (x,y) coordinate to the equation which provides the relation between the flux-numbers and the value of the impinging ion energy when the etch is stopped. This equation generates a 2D curve describing the bottom contour of the etch profile.

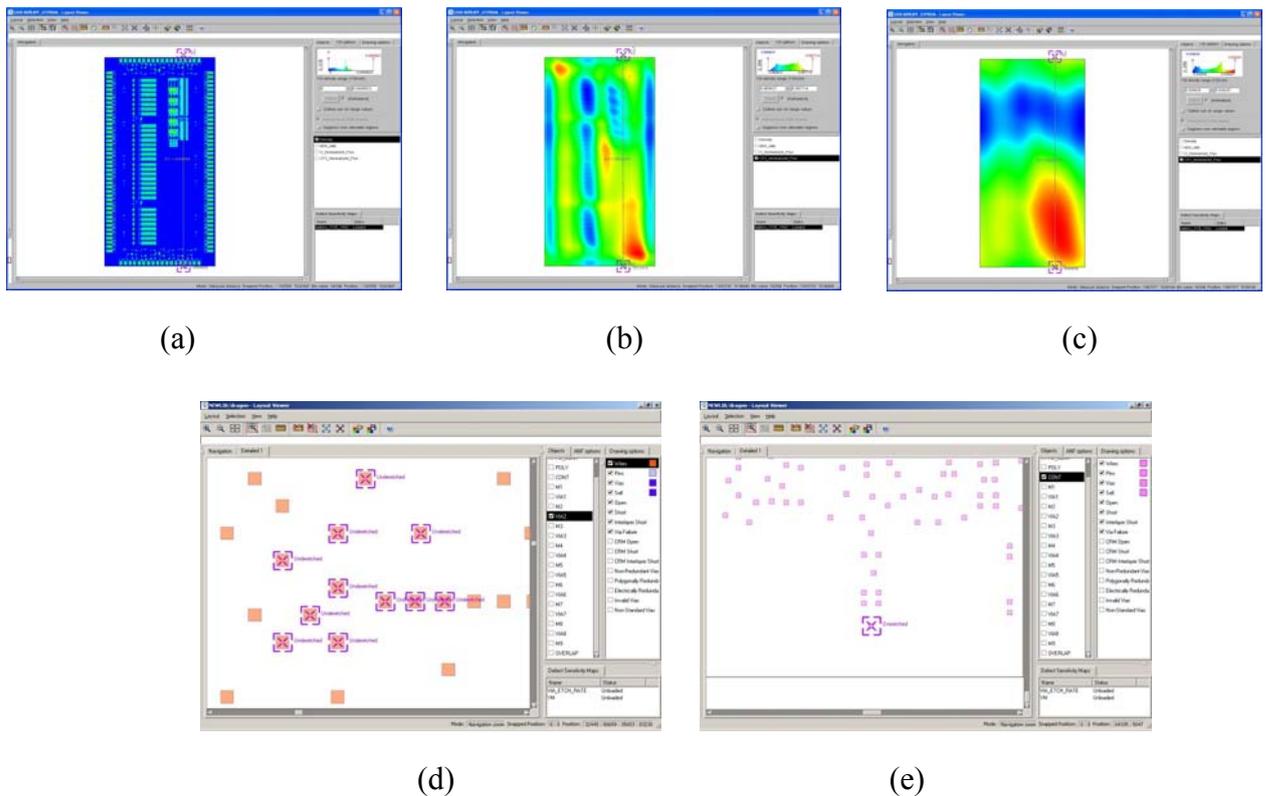


Fig. 3. ER variations across a die with the PD shown in (a) for high (100 mTorr)–(b) and low (10 mTorr)–(c) gas pressures. Under-etched (d) and over-etched (e) bias.

3. Conclusions

Implementation of mask correction steps for compensation of the process-induced variations drives the development of new design tools. EDA tool developed on the basis of described PD-dependent etch model is an example of this kind of tools. A model-based mask correction and a “dummy”-via fill generated by this tool provide the process optimization speed-up, which is critical at the initial stages of advanced technology ramp-up.

REFERENCES

1. C.J. Mogab. *J. Electrochem. Soc.*, v. 124, 1262 (1977).
2. R.A. Gottscho, C.W. Jurgensen, and D.J. Vitkavage. *J. Vac. Sci. Technol. B*, v. 10, 2133 (1992).