The Influence of Adsorption Kinetics on Copper Superfilling for Dual Damascene

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The proceeding scaling in microelectronic devices requires smaller and smaller copper wires for energy transfer in integrated devices. Voids in the copper wires lead to a resistance increase and damage of the wiring. Copper wires are fabricated by electrochemical deposition as it enables a bottom-up, void free copper growth, so-called superfilling. The present work focuses on the mechanism of the electrochemical deposition with the goal of understanding and describing the superfilling. Electrochemical measurements and partial fill experiments under production-like conditions are carried out to study the effects of bath additives. The co-adsorption theory is adopted to explain additive interaction which is presumed to be the key for superfilling. It is shown that superfilling is a result of the synergistic adsorption behavior of at least two organic additives and a kinetic balancing between additive accumulation and copper deposition rate.

The electrochemical processes in copper plating have been studied in great detail.1–3 Tremendous efforts were taken to characterize chemical reactions on copper surfaces.4–7 The results answer fundamental questions about reaction paths of the stepwise copper ion reduction and they explain the chemical behavior of various additive molecules.8–11 However, the applicability to real copper plating processes and the phenomenon of superfilling is limited. So far, chemical explanations fail to answer one basic question: Why does superfilling requires at least two additives?

Studying the real copper plating process is quite difficult for two reasons. First, the time scale on which superfilling occurs is very short. It is known that the bottom-up fill is more severe the smaller the structure dimensions get. SEM cross sections show that the best bottom-up filling results occur at structures below 100 nm width. However, the filling process for such small structures takes only a few seconds, too fast to be observed by any measurement method requiring quasi steady-state conditions. Second, the chemical environment makes it challenging to investigate the deposition process. The sulfuric acid attacks all involved metals, e.g. barrier materials like TaN/Ta as well as copper seed layers. The only way to prevent etching is to apply a cathodic potential to the substrate. The cathodic potential immediately starts the copper deposition process when electrolyte and substrate are brought together. This prevents corrosion, but it also prevents wetting measurements at copper/electrolyte interfaces.

In the presented paper, observations from wafer-level copper plating experiments are shown. The used electrolyte is a commercially available high acid copper bath with two additives that can be added separately. The exact chemical compositions of the additives are proprietary, but it is well known that one additive contains sulfonate or thiolate groups and the other one is based on a long-chained polyglycol. The sulfonate or thiolate based additive is often referred as sulfonate or thiolate groups and the other one is based on a long-chained polyglycol. The long-chained polyglycol additive has the property to increase the polarization resistance for metal deposition and is therefore referred as suppressor. Since our intention is not the chemical nature of interactions and reactions, but the copper deposition behavior depending on the presence or absence of those additives, we will keep the common names accelerator and suppressor for simplicity.

We derive the superfilling phenomenon in terms of co-adsorption kinetics which is based on the fundamental work of Frumkin and Damaskin.14–16 They investigated that the presence of a second additive species leads to completely different adsorption behaviors than in the case of a single additive. The adsorption can either be enhanced or suppressed by the presence of another additive species (Figure 1). Plating baths represent complex systems containing typically more than one surface active components.

In an earlier study the authors of this paper observed the following:20

- Small amounts of chloride are essential to achieve strong and compact suppressor adsorption.
- The accelerator does not work as a catalyst during copper plating. Both, accelerator and chloride show depolarization effects at an electrode, which have only little impact on copper deposition rate.
- Using a combination of accelerator and suppressor leads to superfilling, which is a synergetic interaction based on suppressor displacement.
- There exists a minimum amount of suppressor for sufficient superfilling. Lower suppressor concentration leads to voids, higher suppressor amounts have no impact.

Additives are forming wetting layers by adsorption. The formation process of those adsorption layers is considered to be reversible.

In liquid electrolytes, electrodes' surfaces are always occupied by electrolyte species. Additive molecules from the bulk electrolyte, \(A_{\text{bulk}}\), compete with adsorbed electrolyte species, \(S_{\text{ads}}\), for surface sites (Eq. 1).21

\[
A_{\text{bulk}} + S_{\text{ads}} \rightleftharpoons A_{\text{ads}} + S_{\text{bulk}}
\]  

\[\text{[1]}\]

The equilibrium constant of the adsorption reaction is defined as adsorption constant \(k\), indicating the ratio of adsorption and desorption rate. Together with the additive bulk concentration \(c\), the adsorption constant determines the liquid/surface additive interactions. Lateral additive interactions affect the distribution of adsorbed molecules on the surface. Attractive lateral interactions enhance additive adsorption which leads to the formation of adsorption layers. Repulsive lateral interactions disturb additive adsorption, which leads to a lower additive surface coverage.

Frumkin’s adsorption isotherm (Eq. 2) gives a mathematical relationship for the lateral interaction parameter \(\alpha\), bulk concentration \(c\), adsorption constant \(k\) and surface coverage \(\theta\). 14

\[
k c = \frac{\theta}{1 - \theta} \cdot \exp(-2\alpha c)
\]  

\[\text{[2]}\]

An expansion of the Frumkin’s isotherm was derived by Damaskin for the presence of a second additive (Eq. 3). It describes adsorption isotherms for the coadsorption of two additives with the subscripts 1 and 2. Here, the parameter \(a_{12}\) is introduced, which describes the

\[
a_{12} = \frac{\kappa_{12}}{\kappa_{11} + \kappa_{22}}
\]  

\[\text{[3]}\]
Figure 1. Schematics of the adsorption of two additive species demonstrating that the individual adsorption behavior does not allow conclusions on the co-adsorption behavior. In case of positive interaction between two additive species, co-adsorption can lead to an enhanced adsorption with increased surface coverage compared to the individual state of additive 1. In case of negative interaction, a reduced adsorption evolves resulting in a lower surface coverage for additive 1.

\[
k_{1c1} = \frac{\theta_1}{1 - \theta_1 - \theta_2} \cdot \exp \left[ -2(2a_{11}\theta_1 + a_{12}\theta_2) \right]
\]

\[
k_{2c2} = \frac{\theta_2}{1 - \theta_1 - \theta_2} \cdot \exp \left[ -2(2a_{22}\theta_2 + a_{12}\theta_1) \right]
\]

The formation of a stable adsorption layer comprising of surface areas \(\theta_1\) consisting of additive 1 and surface areas \(\theta_2\) consisting of additive 2 can be achieved, when the free energy of adsorption \(F_{ads}\) reaches a minimum. A thermodynamic expression for calculating \(F_{ads}\) according to Damaskin is given in Eq. 4.

\[
F_{ads}(\theta_1, \theta_2) = -a_{11}\theta_1^2 - a_{22}\theta_2^2 - 2a_{12}\theta_1\theta_2 + \theta_1 \ln \left( \frac{\theta_1}{k_{1c1}} \right) + \theta_2 \ln \left( \frac{\theta_2}{k_{2c2}} \right) + (1 - \theta_1 - \theta_2) \cdot \ln(1 - \theta_1 - \theta_2)
\]

At a minimum of \(F_{ads}\), the total surface coverage \((\theta_1 + \theta_2)\) covers values between 0 (no adsorption) and 1 (compact monolayer). The adsorption equilibrium and the corresponding surface coverage of both additives strongly depend on their bulk concentrations, adsorption constants and interaction parameters.

Figure 2 exemplarily shows the impact of the interaction parameter \(a_{12}\) on the coadsorption of two additives. The interaction parameter \(a_{12}\) has a significant effect on the total surface coverage \(\theta_1 + \theta_2\) and the equilibrium state of the adsorption free energy. Negative feedback on adsorption occurs if \(a_{12}\) assumes values equal or less than zero. That means, no interaction or even repulsive forces between the additives are observed. In those cases the local minima for the adsorption free energy appear near the corners of the diagrams. Positive feedback on adsorption occurs in case of attractive interactions between the additives. Then, the tendency for complete surface coverage is high and the adsorption layer can contain both additive species. For moderate attraction \((a_{12} = 1)\) the sum of \(\theta_1 + \theta_2\) is less than one, meaning that no complete surface coverage is reached.

Another way to influence the surface coverage of the additives is shifting the applied potential. The relationship between electrode potential \(E\) and surface coverage \(\theta\) is given in Eq. 5.

\[
q = \int i(t)dt = (C_0 + C_1)E = q_0(1 - \theta) + q_1\theta
\]

In this equation, \(i\) stands for the applied current, \(q\) is the exchanged charge and \(C\) the capacity of the electrochemical double layer at the electrode. The indexes 0 and 1 correspond to an electrode free of additive coverage \((\theta = 0)\) and a completely covered electrode \((\theta = 1)\), respectively. Eq. 5 can be used to determine surface coverage by...
measuring the charge transfer for a constant potential (Eq. 6).

\[ \theta = \frac{q - q_0}{q_1 - q_0} \]  

[6]

A shift in the applied potential causes a change of the adsorption constant, which leads to a reorientation of the adsorbed molecules.\(^{17,20}\)

Eq. 7 shows the potential dependence of the adsorption constant \( k \), illustrated by index \( E \).\(^{21,22}\) Here, \( E_S \) is the additive dependent shift of the open circuit potential for \( \theta = 1 \).

\[ k_E = k \cdot \exp \left( \frac{q_0 E + q_1 (E_S - E/2)}{RT} \right) \]  

[7]

Experimental

Our study focuses on the influence of a two-component additive system containing accelerator and suppressor. The behavior of the single components in terms of adsorption behavior and influence on structure filling is studied, as well as the synergetic interaction impacting the surface occupation and copper deposition processes. The results are interpreted according to the presented adsorption considerations.

The starting point for our investigation is a pre-optimized plating process yielding very good superfilling profiles. From that starting point, additive amounts and electrical plating parameters are varied to figure out their influence on superfilling.

We carry out our experiments from a commercial available virgin make-up solution containing 168 g/L CuSO_4·5H_2O (40 g/L Cu), 100 g/L H_2SO_4 and 50 ppm Cl^-. The additives, which are added to the electrolyte individually, are commercial solutions containing sulfonate/thiolate and polyglycol groups. Their exact formulations and molar concentrations are proprietary, so the additive concentrations are given as mL_additive/L_el. Our investigations are performed with a PAR potentiostat/galvanostat under cleanroom conditions (22.5°C ± 0.1°C).

Superfilling experiments are executed galvanostatically on patterned wafer coupons (28 nm node) in a beaker containing 250 mL of the electrolyte. The coupons with an area of 7.5 cm × 10 cm are cut from a 300 mm patterned wafer. Before, the wafers were coated with a conventional PVD TaN/Ta barrier/liner stack and a PVD copper seed layer. In our plating experiments the wafer coupons are set as cathode and a pure copper plate is used as anode. A deposition current of 600 mA was applied, which corresponds to a current density of 8 mA/cm² on unstructured samples.

In order to characterize structure filling behavior SEM cross-section images of the processed samples were taken. For preparation, the coupons were cleared along specific test structures and coated with carbon subsequently. Then, a platinum layer was deposited on top and the breaking edge was milled by a gallium focused ion beam.

Based on the deposition experiments, cyclovoltammetric and potentiostatic experiments were carried out to investigate the additives adsorption behavior more in detail. These measurements were set up using a three electrode composition. A rotating disk electrode of platinum with a diameter of 5 mm was used as working electrode (WE) with a fixed rotation rate of 100 rpm. The measurement potentials were applied with respect to a KCl saturated Ag/AgCl reference electrode having a defined potential of +0.197 V vs. standard hydrogen electrode. For counter electrode a copper rod was used.

Cyclovoltammetric scans were conducted to characterize the quasi-static adsorption behavior of the additives within a potential range between −0.5 V and 1.6 V. Potential sweeps with a rate of 100 mV/s were performed three times and the last cycle was used for analysis in order to achieve steady state conditions. The presented plots only show the cathodic trends of the scans in the potential region where the copper deposition reaction takes place.

To distinguish the additives adsorption kinetics potentiostatic experiments were performed at a fixed potential of −0.1 V for 600 s. In order to achieve comparable conditions all measurements were started in an additive-free electrolyte. After stabilization of the current density-time-curve for about 60 s, additives are injected into the electrolyte. The tip of the pipette for injection was fixed in the reactor and the distance between the outlet and the working electrode was 5 cm.

Results and Discussion

Structure filling experiments.—Plating experiments expose the tremendous impact of the additives. The often described superfilling occurs when both additives, accelerator and suppressor, are present. A time-resolved plating series (Figure 3) shows that the very first step in the plating process is a conformal deposition. After 5 seconds, enhanced bottom-up filling starts inside the trenches. During superfilling especially the small structures are filled very rapidly, while wide structures are filled more slowly. After the trenches are completely filled with copper an overburden arises.

The conformation that superfilling is an effect of the synergetic additive behavior is demonstrated by repeating the plating experiments in absence of one additive (Figure 4). For baseline comparison a deposition from a pure additive free electrolyte is performed.

The fill behavior of a solution containing only accelerator looks similar to that of using an additive-free electrolyte. In both cases the copper deposition occurs non-isotropic on horizontal areas leaving the sidewalls uncoated. This indicates that accelerator alone has no remarkable influence on the filling performance. Using only suppressor, in contrast, results in a conformal fill profile. The copper deposition rate is equal for all surface sites concluding that suppressor leads to a uniform wetting of all surface areas without getting poor inside the structures.

The conformal copper deposition in presence of suppressor is further investigated by varying the suppressor concentration (Figure 5). Conformal deposition only takes place at high enough suppressor concentrations. For too low suppressor concentrations sidewall voids evolve (red circles).
Figure 4. (a) Fill behavior in absence of additives: The deposition takes place at the structure bottom and at the top bars. No copper deposition is observed on sidewalls, (b) fill behavior in presence of accelerator only: The deposition is similar to that from pure electrolyte. Accelerator alone does not influence the copper filling, (c) fill behavior in presence of suppressor only: A very conformal copper deposition arises with equal deposition on bottom, sidewalls and bars.

Figure 5. Effect of suppressor concentration on conformal film deposition. Below a threshold concentration, a non-conformal deposition with sidewall voids evolves. For sufficient suppressor concentrations >0.5 ml/l a voidfree and conformal deposition is obtained.

**Single additive effects.**—Cyclovoltammetric measurements can be described as a non-static method. A cathodic potential is applied, which induces the reduction of copper ions. The copper reduction and associated deposition results in a faradaic current which is measured by a potentiostat. Sweeping the voltage from a cathodic to an anodic range keeps the system in motion. Fast and significant changes are detected, while time-consuming processes are neglected. Another advantage of cyclovoltammetry is its reproducibility. By sweeping the voltage back and forth between $-0.5$ V and $+1.6$ V, stable overlaying plots are achieved. This indicates the reversibility of the copper deposition/dissolution reactions and thus a physical dominated nature of the additive adsorption processes that take place at the electrode surface.

When accelerator is added to a base electrolyte, only minor changes in the cyclovoltammograms are detected. Even with very high accelerator concentrations of 10 ml/l, which is much more than it is used in common plating processes, there is no severe impact on the current-potential behavior (Figure 6). The effect of suppressor on the current potential behavior is severe. For an extended potential range up to $-0.2$ V the current is remarkably suppressed, which corresponds to a low charge exchange at the surface. We interpret that effect by the formation of a suppressor containing adsorption layer that physically blocks the copper ions from reduction.

Based on the cyclovoltammograms, adsorption constants for accelerator and suppressor are estimated. Taking into account that literature values for adsorption rates and maximum surface coverages can
deviate strongly from our system, the plots in Figure 7 reflect only tendencies for potential dependent adsorption constants. The adsorption constants for both, suppressor and accelerator decrease strongly with the cathodic potential. However, the adsorption constant of suppressor is more than two orders of magnitude higher than the adsorption constant of accelerator.

Another way to show the impact of accelerator and suppressor on the copper plating is to carry out potentiostatic measurements. There, a small cathodic potential is applied to a copper substrate which is mounted in electrolyte. After a delay of 60 s, an additive is injected and the current change is detected (Figure 8).

In case of accelerator a slight increase of the cathodic current is recorded. This corresponds to the results of the cyclovoltammetric scans (Figure 6), where the same effect around the potential value of −0.1 V is observed. In the literature this phenomenon is often interpreted as a catalytic effect of the accelerator, which enhances the copper deposition rate by compact chemisorption.2,10 This mechanism seems to be questionable, since chemisorption basically means irreversible occupation of free surface sites. This would constrain the copper deposition and stands in contrast to an acceleration effect for irreversible occupation of free surface sites. This would constrain the mechanism seems to be questionable, since chemisorption basically means irreversible occupation of free surface sites. However, the adsorption constant of suppressor does not show significant adsorption behavior in terms of blocking free surface sites from copper deposition.

When suppressor is injected into the electrolyte, the current density immediately drops until nearly no copper deposition takes place anymore. This may be caused by a strong adsorption of suppressor molecules occupying free surface sites and preventing copper ions from reduction. The fast and instantaneous current decrease right after injection shows that the adsorption process is driven by a fast kinetics. After a few seconds nearly the whole surface is covered by suppressor.

interaction of accelerator and suppressor.—The severe inhibition of the current flow in presence of suppressor can be significantly reduced by adding accelerator into the same system (Figure 9). The cathodic current increases as a function of the accelerator dose.

Based on the coadsorption theory of Frumkin and Damaskin this phenomenon is regarded as a repulsive interaction between both additives. The strongly adsorbed suppressor molecules are displaced effectively in the presence of accelerator, while accelerator itself possesses no remarkable adsorption capability. As a result more non-occupied surface sites arise, which are available for copper deposition. The higher the accelerator concentration the more suppressor desorbs. Due to that it is possible to adjust the surface coverage by regulating the amount of accelerator.

Potentiostatic measurements show the kinetics behind the repulsive interaction more in detail (Figure 10). Again, a small cathodic potential is selected and both additives are injected simultaneously.
after a stabilization delay. Once injected, an instantaneous decrease of the cathodic current can be seen similar to the results of suppressor only (see Figure 8). As time proceeds, the current density increases again until the initial value before injection is reached. Analyzing these results we can determine that the initial state right after injection is dominated by the fast and strong suppressor adsorption, while the final state is more affected by the influence of accelerator. The time in-between is dedicated to the suppressor desorption process caused by the repulsive interaction with accelerator. The kinetics of this process is much slower than the initial suppressor adsorption, but strongly depends on the additive concentrations. Doubling the amount of the injected additives leads to a faster desorption of suppressor. This is especially driven by the addition of accelerator, whereas the additional suppressor doesn’t show a remarkable effect. This can be explained by analyzing is the initial suppressor adsorption. Due to the high velocity of this process, the surface is saturated by suppressor very rapidly within a few seconds. An additional amount of suppressor does not affect the surface coverage any further. Once the surface is saturated by suppressor, only the amount of accelerator predicts desorption velocity. The more accelerator, the faster the suppressor desorption process.

**Correlation between additive adsorption behavior and superfilling.**—The results of the deposition experiments show that superfilling requires a combination of accelerator and suppressor. Within the first seconds of the electrochemical deposition (t ≤ 5 s) a conformal copper layer is formed. That is caused by the fact, that all additives are distributed homogeneously across the surface. The fast physisorption of suppressor leads to an energetic equalization of each surface site by generating a high overall charge transfer resistance. Thus a conformal copper deposition arises within the initial plating state.

Besides adsorption, fluid dynamics must be taken into consideration during the copper filling. Small copper lines with widths below 100 nm are filled within seconds (Figure 11). During that time enough copper ions must be transported from the bulk electrolyte into the trenches. For our electrolyte the initial amount of electrolyte copper ions inside a trench is approx. by factor 10^3 times smaller compared to the required amount for complete trench fill with solid copper. Contrary to the copper ion flux toward the structures, the electrolyte and additive species must leave the structure rapidly due to the growing copper.

The supply of copper ions from the bulk electrolyte is driven by the concentration gradient and the voltage drop across the electrolyte/copper interface. Migration velocities in the range of 100 nm/s are possible. The opposing movement of electrolyte species out of the structure is caused by the volume reduction of the filling structure. Within structures with widths below 100 nm molecule movement is assumed to be driven by diffusion. A mathematical formulation for diffusion processes is given by Wilke and Chang (Eq. 8). This empirical correlation is based on the Stokes-Einstein equation and describes diffusion coefficient D in dependence of molecule size (molar volume \( V_b \)), where \( T \) is the temperature, \( \eta_s \) the dynamic viscosity, \( M \) the molar mass and \( \Phi \) the association factor of the solvent (water). The smaller the electrolyte species the more easily they can escape from the decreasing cavity. Big and slow molecules like additive species are left behind, which leads to a concentration increase of additives inside the trenches.

\[
D = 7.4 \times 10^{-8} \frac{T(\phi M)^{0.5}}{\eta_s V_b^{0.6}}
\]

![Figure 11](image_url) The copper ion flux during copper filling must deliver \( 10^3 \) times of the initial copper amount into a trench. While copper ions are entering the trench, the electrolyte and additive species are forced out of the filling structure.
Based on Eq. 8 the diffusion coefficients for the common components contained in plating solutions are calculated and listed in Table 1. Bigger electrolyte species exhibit lower diffusion coefficient and lower diffusion velocity. While the diffusion of small ions and molecules (H$_2$O, SO$_4^{2-}$, Cl$^-$) proceeds fast, the bigger additive molecules need more time for diffusion. Hence, an accumulation of both suppressor and accelerator takes place within the metallization structures during structure filling leading to a higher additive concentration inside the structures compared to the outside.

At the same time the additive agglomeration inside the structures is more pronounced at the structure bottom, because of the concave shape. As a result an additive concentration profile inside the trenches arises with higher additive concentrations toward the bottom.

For the filling process, the accumulation of suppressor has no effect on the copper deposition, as long as the initial concentration is high enough to lead to a complete and conformal adsorption. The accumulation of accelerator, however, has a strong impact on the charge transfer when suppressor is present.

While accelerator on its own has no significant effect on the copper deposition, it can reverse the inhibiting effect of suppressor leading to a higher additive concentration inside the structures compared to the outside. As a result the charge transfer and the copper deposition rate increases. This is especially the case at the structure bottom, where the additive accumulation is highest. As a result, along the additive concentration profile inside the structures different local copper growth rates arise. With the highest growth rate at the bottom and lower growth rates toward the top the typical bottom up filling behavior of the superfilling process develops. Figure 12 shows the mechanism of superfilling schematically.

Furthermore, it is evident that the volumes to be filled with copper decreases more rapidly for narrow lines than for wide lines, as it is shown in Figure 13. The faster the volume shrinks, the more additives accumulate. Thus, narrow lines, which are more affected by the volume decrease, show a better superfill behavior than wide lines. That is in accordance with partial fill experiments, which reveal that superfilling is more evident the narrower the structures are. Thus, a rapid decrease of volume promotes superfilling.

### Conclusions

The presented work focuses on the kinetics of the synergetic adsorption/desorption interactions between two organic additives, accelerator and suppressor, in sub-100 nm structures. The impact on the copper deposition process is discussed. It is found out, that the copper deposition process is driven by an additive accumulation which influences adsorption/desorption velocities and copper deposition rate. During copper deposition both additives accelerator and suppressor accumulate near the growing surface. Within the initial phase, the surface is majorly occupied by suppressor due to a fast adsorption velocity. This results in an increased surface wetting, which is mandatory for the superfilling. Due to diffusion limitations inside narrow features a higher additive concentration evolves compared to blank surface areas. In this phase, the suppressor desorption takes place due to a repulsive interaction with accelerator. This process is a function of the accelerator concentration only. Although suppressor accumulation takes place simultaneously, it has no effect on the overall adsorption process. The reason is that the surface is already saturated by suppressor molecules proven by the formation of a conformal copper layer in the first phase of the copper deposition. Superfilling is a result of the accumulation of accelerator. The more accelerator is present, the faster the blocking adsorption film removes leaving free surface sites for copper deposition. The different additive concentrations inside and outside the features induce different local copper growth rates along the concentration profile. As a result superfilling with a bottom-up filling behavior is achieved.

### Table 1. Molar volume $V_b$ and diffusion coefficient D of the plating electrolyte species ($T = 295.7$ K, $M = 22.2$ g/mol, $\Phi = 2.6$, $\eta_{vis} = 1.67 \times 10^{-2}$ g/(cm s)$^{27}$).

| Species                  | $V_b$ (cm$^3$/mol) | D ($10^{-6}$ cm$^2$/s) |
|-------------------------|--------------------|------------------------|
| H$_2$O                  | 14.8               | 19.8                   |
| Cl$^-$                  | 24.6               | 14.6                   |
| SO$_4^{2-}$              | 58.8               | 8.7                    |
| Accelerator (e.g. MPS)  | 142.7              | 5.1                    |
| Suppressor (e.g. PEG)   | 882                | 1.7                    |
| $M_w = 1000$ g/mol       |                    |                        |

**Figure 12.** Schematics showing the proposed mechanism of superfilling based upon an accumulation of suppressor and accelerator during the copper deposition.

**Figure 13.** Calculated volume decrease for a 200 nm high interconnect line in dependence of the line width during the deposition of conformal copper films of various thicknesses.
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