Considerations for Copper Deposition for ULSI Interconnects

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Abstract

The extension of a leveling theory to account for multiple additives, such as accelerators and inhibitors, is discussed within the context of copper electrodeposition in submicron features. Agreement and discrepancy between theory and experiment are shown. The failure under certain conditions of an established leveling theory is discussed, and another postulated mechanism is presented. The application of copper-electrodeposition technology to sub-100-nm features may require direct deposition onto poorly conductive barrier materials. Some theoretical and practical considerations for the development of this next-generation technology are briefly discussed.

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Introduction

Reliable technologies exist for the electrodeposition of void-free copper films onto seed layers that have previously been deposited onto wafers patterned with submicron trenches and vias.¹⁻³ The development of a process requires the establishment of a range of practical operation parameters, such as the composition of the bath, the fluidflow conditions, and the current density. As feature size shrinks, and upstream and downstream integration requirements change, there exists an almost continuous need to refine the operating conditions. Optimization of the operating conditions by experiment requires a substantial and costly effort. The need therefore exists for a which methodology in important parameters are extracted from limited experimental data and subsequently used as inputs into a shape-change simulation tool, which can be used to significantly reduce the number of required fill studies

The heart of the simulation tool is the theoretical description of leveling. Leveling has been extensively studied for years.⁴⁻¹¹ The best demonstrated theory of leveling is based on a diffusion-adsorption mechanism.

Here, we summarize our recent efforts^{12,13} in extending such theories.

Results and Discussion

Two recent papers show that leveling theories can be extended to multicomponent additive cocktails common in practical applications.^{12,13} These papers treat an electrolyte containing the additive package: chloride ions, polyethylene glycol (PEG), bis (3sulfopropyl) disulfide (SPS), and Janus Green B (JGB). It is shown that, as long as sufficient quantities of JGB are present, the diffusion-adsorption mechanism can explain all of the fill results.

The model uses adsorption and kinetic parameters obtained by fitting theory to polarization measurements, leaving no free parameters to be fit by shape-change comparisons with experiments. A critical parameter $p = 100 \left(\frac{i_{bottom} - i_{top}}{i_{top}} \right)$ is used to characterize the initial current distribution inside the feature and predicts whether leveling is possible or not. We propose contour plots of *p* as a function of concentrations of accelerator and inhibitor as a concise method for summarizing practical ranges of operation.

The fill-study results obtained on wafer fragments that are mounted onto a rotating-disk assembly spinning at 200 rpm are superimposed onto the pcontour plot in figure 1. In this figure, the aspect ratio of the features is approximately four. The experimental results are consistent with the simulation, except when $c_{IGB} = 0$. It is probable that leveling under these conditions is achieved by another mechanism However, the present theory seems applicable whenever JGB For example, at low is present. concentration of SPS, leveling only occurs in the low concentration range of JGB, while the bath loses its leveling capacity as the inhibitor becomes abundant. The value of c_{JGB} at which voids occur is well predicted by simulation.

Perhaps most impressively, the simulations predict that, while operating at a concentration of JGB of 5 ppm, leveling is possible only at high SPS. This prediction requires the use of the JGB modeling parameters in a range of SPS that lies considerably outside the range of data used in the curve fitting. In short, we feel that the good agreement between the simulation and experiment of figure 1 is very promising, especially if it is recalled that the simulations were fit to electrochemical measurements and to no fill studies.

However, when JGB, the assumed leveling agent is absent, void-free deposits are observed under some conditions. Interestingly, bumps emerge from the feature.¹⁴⁻¹⁷ Established theories, which do not account for dynamic surface phenomena, cannot explain these observations even if the usual pseudo-steady-state assumption for the concentration fields of reactant and additives is relaxed. Apparently, another under prevails mechanism these conditions. We hypothesized one such mechanism and showed that numerical simulations are consistent with experiment.¹⁸ Moffat and co-workers have proposed similar mechanisms.¹⁹

Future Directions

Substantial progress in the development of simulation tools that can account for the influence of organic additives on current distribution when copper is electrodeposited onto copper seed layer has been made. However, future generation processes may require that copper be deposited directly onto barrier materials such as TaN, Ta, Ti, or TiN. This is major challenge because of poor adhesion between the copper film and the barrier. Furthermore, the nucleation and growth mechanisms of the copper onto the barrier materials are not well understood even in the absence of organic additives.

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Figure 1. Comparison between the fill-study results and *p*-contour plot. The symbols show the experimental filling situation of trenches with width of approximately 200 nm and an aspect ratio of approximately 4. The disk rotation speed for both experiments and simulation is 200 rpm.