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# Effect of Ag-alloying addition on the stress–temperature behavior of electroplated copper thin films

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**Abstract**

The effect of Ag-alloying on the microstructural and thermo-mechanical properties of electrochemically deposited Cu thin films was investigated using the focused ion beam technique, scanning electron microscopy and the electron back scatter diffraction (EBSD) technique as well as the substrate curvature method to study their stress–temperature and stress relaxation behavior. The results show that the linear elastic behavior of 1 μm thick Cu films is significantly improved by alloying. Additionally, after annealing such films have an excellent low electrical resistivity of 1.9–2.0 μΩ cm, which meets the requirements of the roadmap ITRS [International Technology Roadmap for Semiconductors, Edition 2003, part: interconnect, available at http://public.itrs.net/].


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## 1. Introduction

The ongoing trend of reducing the cross-sectional dimensions of interconnects in microelectronic devices resulted in the replacement of Al-based metallizations by copper. Copper-metallization thin films typically have a lower resistivity (approximately 2 μΩ cm) and a higher resistance against electromigration than Al films; that is the reason why Cu interconnects meet the current criteria in microelectronics as to signal speed, power consumption and reliability. The application of Cu films was primarily prompted by their material properties as higher melting point and yield stress, and therefore a higher activation energy for the drift-diffusion process of electromigration, where microstructural features and stress behavior of Cu films on barrier layers are of fundamental relevance [2]. When atomic flux occurs, a stress gradient is formed which superimposes the residual stress inside the interconnect line [3]. Such a stress gradient is the origin of mass backflow, which opposes the electromigration flux. Therefore, a suppression of electromigration by an

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advancement of the Cu films due to alloying is expected [4–6], in accordance with results obtained by other groups [7,8]. Since atomic transport takes place predominantly via interfaces with a low activation energy (e.g. the surface or special high-angle grain boundaries), precipitation or segregation effects are of interest for the development of advanced metallizations.

## 2. Experimental

Cu(0–5 at% Ag) alloy films were electrochemically deposited (deposition rates 2–5 nm/s) using a $CuSO_4$ based electrolyte which also contains additives and $AgNO_3$ for Ag-alloying addition. Films with a thickness of 1 μm were deposited onto thermally oxidized 3–4 in. Si(1 0 0) wafers using a dc current density of 5–15 mA/cm$^2$. Before the electroplating procedure, wafers were covered by magnetron sputtering of a β-Ta(30 nm)/TaN(50 nm) barrier system and a 100 nm Cu seed layer.

Thin film stress $\sigma_f$ develops when the film dimension varies relative to the substrate due to both the changes of the microstructure and the development of thermal stresses during heating or cooling because of a misfit in their thermal expansion coefficients [9]. The stress development results in a bending of the film (f) and the substrate (s). $\sigma_f$ can be calculated for $d_f \ll d_s$ using the Stoney equation [10]. To study the stress–temperature behavior of Cu(Ag) films from RT up to 500 °C, a vacuum apparatus (<$10^{-3}$ Pa) for a sensitive laser-optical determination of the substrate curvature of beam-shaped samples (6 mm × 59 mm) was used, which allows stress measurements with a deviation of ±(10–25 MPa). Initial stress was calculated from the difference in curvature of the uncoated substrate and the coated one. The film thickness was determined using FIB cross-sections where the standard deviation of the thickness was found to be about 3–5% along the wafer diameter.

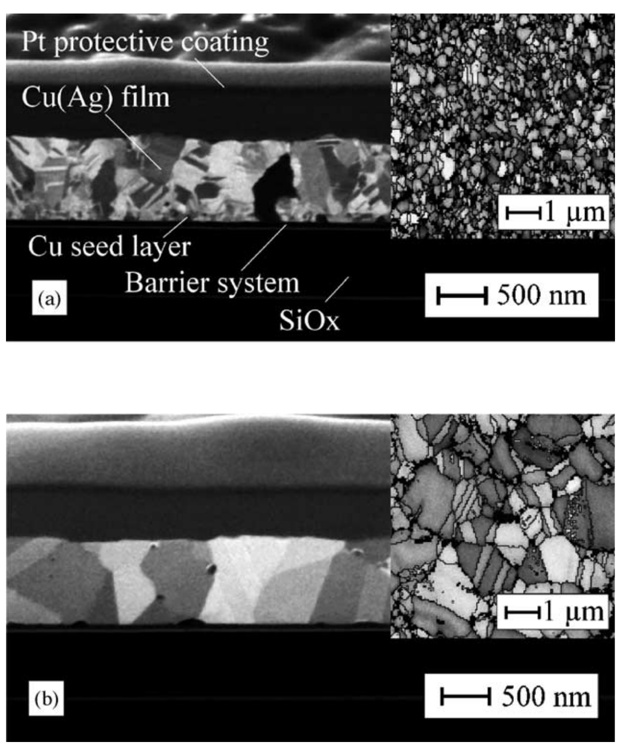


Fig. 1. FIB cross-sections (tilted by 45°) and SEM/EBSD maps (top view) of microstructural evolution of Cu(0.6 at% Ag) layers (a) as-deposited, and (b) after the third thermal cycle up to 500 °C [6].

## 3. Results and discussion

As an example, the microstructural evolution of an electroplated Cu(0.6 at% Ag) film during the first three thermal cycles up to 500 °C (heating and cooling rate 4 K/min) is demonstrated in Fig. 1. In the as-deposited state the individual layers are well separated (Cu(Ag) film, Cu seed layer). Grains are randomly distributed with respect to their crystal orientation. After the first cycle the film microstructure is almost stabilized. A significant grain growth as well as an assimilation of the Cu seed layer into the Cu(Ag) film is obtained. After the third cycle a weak (1 1 1)-fiber texture was detected. A self-annealing effect as known for electroplated pure Cu films could not be observed. Some voids generated by vacancy agglomeration are observed predominantly at grain boundary triple junctions and at the interface. To visualize only the stress–temperature behavior of the Cu(Ag) film without any influence of the barrier system, the $\sigma(T)$-curve of the Ta/TaN bilayer on the substrate was measured at first to correct the stress–temperature curves of the complete layer stack. The thermoelastic region of the Cu films was increased due to Ag-alloying addition (Fig. 2), but the electrical resistivity of 1.9–2.0 $\mu\Omega$ cm was close to the Cu film value. Consequently, electroplated Cu(Ag) films meet the resistivity requirements of the roadmap ITRS 2003 [1] of $\leq$2.2 $\mu\Omega$ cm. Differences between the curves of the second and the third cycles were not observed. In other words, irreversible plastic effects do not occur between RT and 500 °C.

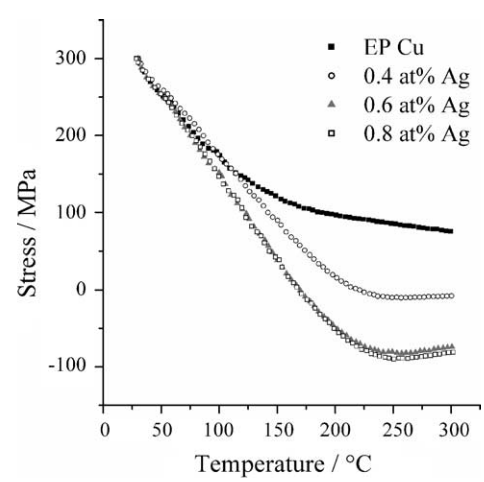


Fig. 2. Heating parts of stress–temperature curves up to 300 °C of electroplated Cu films with different Ag contents (EP Cu: without Ag). Curves are normalized to 300 MPa at RT for comparison.

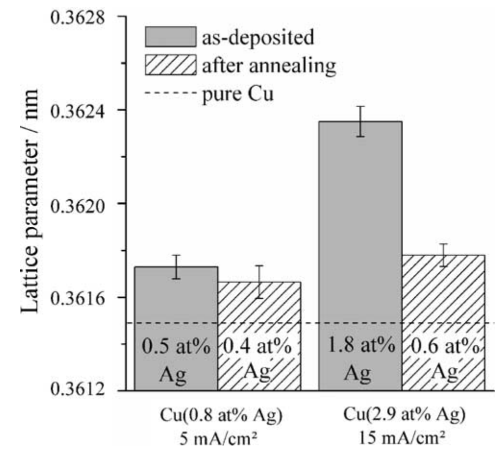


Fig. 3. Lattice parameters for two different Ag contents in the as-deposited state and after annealing at 500 °C, heating and cooling rates 4 K/min. The amount of Ag which is incorporated in the Cu matrix was calculated using Vegard's law.

Fig. 3 shows a variation of measured lattice parameters (by XRD) of as-deposited and annealed Cu(Ag) films for two different Ag contents. In annealed films, the strain of the copper lattice due to Ag solid solution formation was found to be decreased. With respect to their low solubility in copper, Ag atoms probably segregate to interfaces like grain boundaries and surfaces. XRD results also indicated Ag precipitation clusters after annealing. But, further investigations are necessary to give well-founded evidence. Segregation kinetics of Ag can influence the stress relaxation behavior and, subsequently, also the electromigration behavior of such films. However, alloying atom clusters could act as obstacles to dislocations or atomic flow at grain boundaries and triple junctions suppressing the electromigration mass transport.

## 4. Conclusions

Advanced Cu metallizations were developed by Ag-alloying addition. Such films show an increased thermo-mechanical behavior as well as a low electrical resistivity, which is close to that of pure

Cu films. Therefore, Cu(Ag) alloy films seem to be a candidate for the next interconnect generation with increased resistance against electromigration failure.

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