Strain-Induced Anisotropy of Electromigration in Copper Interconnect

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Modern interconect represents a complex mechanical system where stress sources determined by the fabrication process influence electromigration. Due to geometry and material composition of a typical interconnect this stress is non-hydrostatic and causes a general anisotropy of material transport.
The electromigration model used in this work incorporates all important driving forces for atom migration coupled with the solution of the electrical and thermal problems [1]. Our approach differs from others by considering a diffusivity tensor in the transport equation taking into account the diffusion anisotropy generated by the applied strains.
Residual mechanical stresses are introduced on interconnect lines as a result of the fabrication process flow [2]. These stresses can be very high [3] leading to a significant anisotropic diffusion of the metal atoms [4]. The total vacancy flux is caused by the gradients of concentration, electrical potential, temperature, and mechanical stress [5].
We determine the diffusivity tensor **D** by [4]

$$D_{ij} = \frac{1}{2}\sum_{k=1}^{12} R_i^k R_j^k \Gamma^k$$

where R^k is the jump vector for a site k and Γ^k is the jump rate. The impact of the strains/stresses is a change of the jump rate through [6]

$$\Gamma^k = \Gamma_0 \exp[-\Omega\varepsilon_I \cdot (C\varepsilon)],$$

where ε_I is the induced strain, ε is the applied strain, and **C** is the elasticity tensor.

The interconnect geometry analyzed by fully three-dimensional simulation is given in Fig. 1. The line and via have a cross section of 0.2 x 0.2 μm^2 , the tantalum barrier and the etch stop layers are 20 nm thick. Considering initially that the interconnect is free of strains, we obtained the vacancy distribution as shown in Fig. 2, with 10^{16} cm^{-3} used as the initial vacancy concentration for copper [7]. As expected, the vacancies concentrate “downstream”, mainly in the via region, where the copper meets the barrier layer, with a small increase above the initial concentration. No change is observed in the vacancy distribution, until strains in the order of 0.5 % to 1 % are used.
With ε_{xx} = 0.01, ε_{yy} = 0.005, and ε_{zz}= 0.001, we have verified a very small increase in the vacancy concentration on the bottom of the via, as depicted in Fig. 3. In this case we have determined the off-diagonal components of the diffusivity tensor to be about 18 % of the diagonal ones. Considering ε_{xx} = 0.008, ε_{yy} = 0.015, and ε_{zz}= 0.003 the distribution of vacancies is significantly altered, although the change in the concentration values is still small, as Fig. 4 shows. These higher strains increase the off-diagonal diffusion coefficients to about 30% of the diagonal values.
In conclusion, we have shown that high strains, and consequently stresses, can lead to significant anisotropy of material transport in an interconnect line under electromigration stress. This effect must be taken into account for a rigorous analysis of the electromigration problem.

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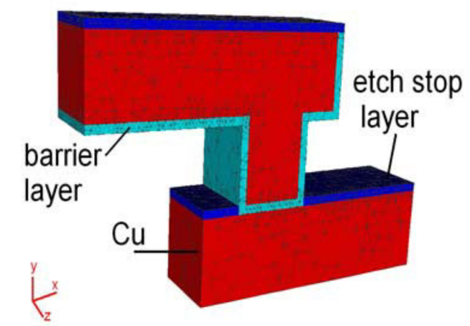

Fig.1: Interconnect via geometry.

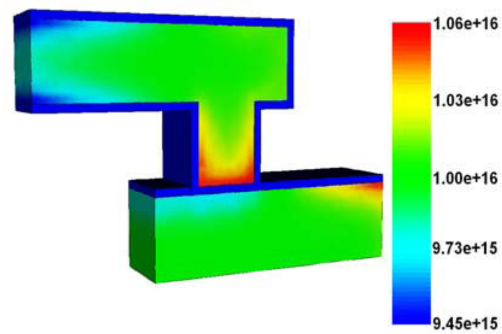

Fig.2: Vacancy concentration for the interconnect without strains (units in cm $^{-3}$) . The higher vacancy concentration on the interface between the bottom coper line and the etch stop layer occurs due to increased interfacial diffusivity.

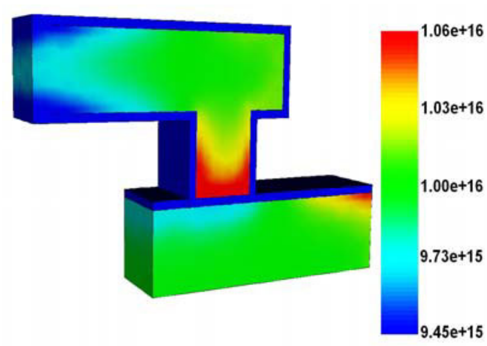

Fig.3: Vacancy concentration for strains $\varepsilon_{xx} = 0.01$, $\varepsilon_{yy} = 0.005$, and $\varepsilon_{zz} = 0.001$, (units in cm $^{-3}$) .

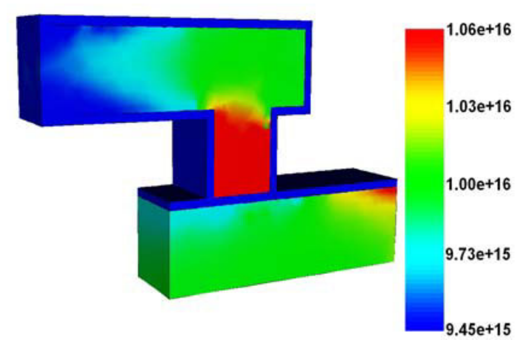

Fig.4: Vacancy concentration for strains $\varepsilon_{xx} = 0.008$, $\varepsilon_{yy} = 0.015$, and $\varepsilon_{zz} = 0.003$, (units in cm $^{-3}$) .

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