Effect of Strains on Anisotropic Material Transport in Copper Interconnect Structures under Electromigration Stress

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We have analyzed the effect of strains on material transport in a typical dual damascene copper interconnect via under electromigration stress. The electromigration model 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 caused by the gradients of concentration, electrical potential, temperature, and mechanical stress is [5]

$$\vec{J}_v = -\mathbf{D}\left(\nabla C_v + \frac{Z^* e}{kT} C_v \nabla\varphi - \frac{Q^*}{kT^2} C_v \nabla T + \right.$$
$$\left. + \frac{f\Omega}{kT} C_v \nabla\sigma \right), \tag{1}$$

where C_v is the vacancy concentration, $Z^* e$ is the effective charge, Q^* is the heat of transport, $f\Omega$ is the vacancy volume relaxation, σ is the hydrostatic stress, k is Boltzmann's constant, and T is the temperature. We determine the diffusivity tensor $\mathbf{D}$ by [4]

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

where $\vec{R}^k$ 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]

$$\Gamma^k = \Gamma_0 \, exp\left[-\Omega\vec{\epsilon}_I \cdot (\mathbf{C}\,\vec{\epsilon})\right], \tag{3}$$

where $\vec{\epsilon}_I$ is the induced strain, $\vec{\epsilon}$ is the applied strain, and $\mathbf{C}$ 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 etch stop layers are 20 nm thick. In Fig. 2 the electric potential distribution is shown. Considering initially that the interconnect is free of strains, we obtained the vacancy distribution as shown in Fig. 3, 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 on the order of 0.5% to 1% are used. With $\epsilon_{xx} = 0.010, \epsilon_{yy} = 0.005$ and $\epsilon_{zz} = 0.001$, we have verified a very small increase in the vacancy concentration on the bottom of the via, as depicted in Fig. 4. In this case we have determined the off-diagonal components of the diffusivity tensor to be about 18% of the diagonal ones. Considering $\epsilon_{xx} = 0.008, \epsilon_{yy} = 0.015$ and $\epsilon_{zz} = 0.003$ the distribution of vacancies is significantly altered, although the change in the concentration values is still small, as Fig 5 shows. These higher strains increased 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.

Fig. 1. Interconnect via geometry.

Fig. 2. Electric potential distribution.

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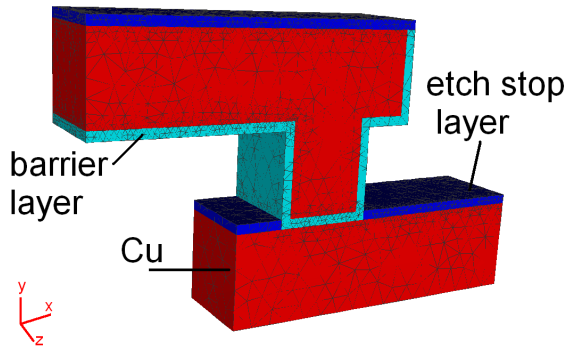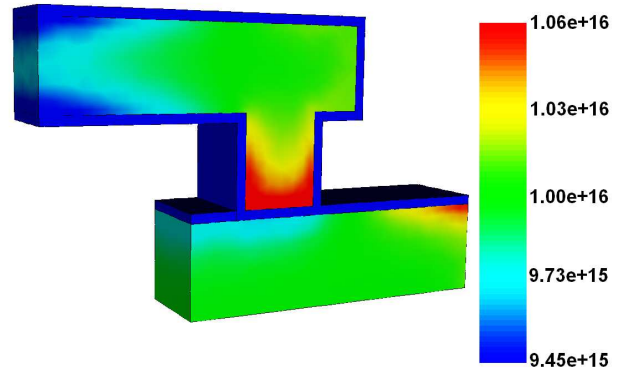

Fig. 4. Vacancy concentration for strains $\epsilon_{xx} = 0.010, \epsilon_{yy} = 0.005$ and $\epsilon_{zz} = 0.001$ (units in cm^{-3}).
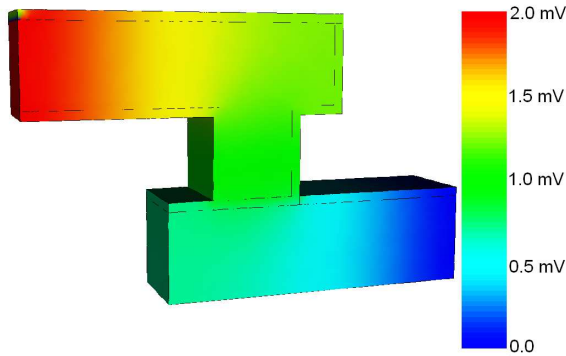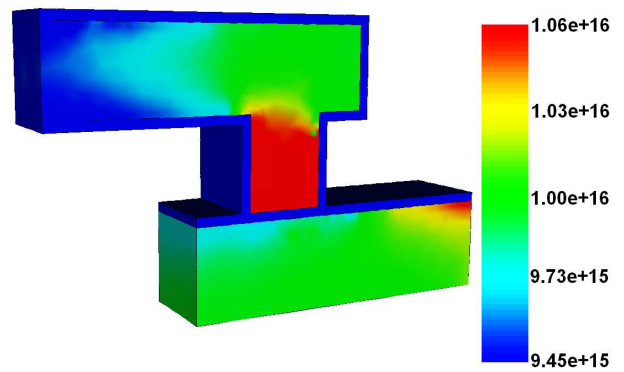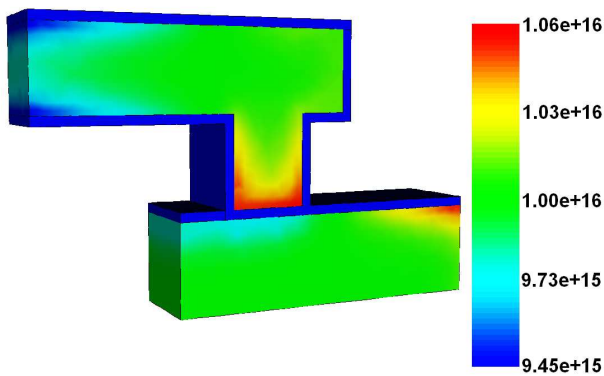

Fig. 5. Vacancy concentration for strains $\epsilon_{xx} = 0.008, \epsilon_{yy} = 0.015$ and $\epsilon_{zz} = 0.003$ (units in cm^{-3}).

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