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Effect of strains on anisotropic material transport in copper interconnect structures under electromigration stress

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Abstract We 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. 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. We have obtained off-diagonal components of the diffusivity tensor up to 30% of the diagonal ones and a different distribution of vacancies due to electromigration.

Keywords Electromigration · Interconnect · Dual damascene

1 Introduction

Electromigration is the transport of material caused by the momentum transfer between conducting electrons and metal atoms [1]. With the continuous shrinking of the dimensions of modern integrated circuits the interconnects become subjected to higher current densities. In addition, the interconnect structure can be arranged in up to ten levels of wiring with thousands of interlevel connections such as vias. Hence, failure of metallic interconnect caused by electromigration is a key issue for reliability in microelectronics and the prediction of the long term interconnect behavior has become a major issue. The theoretical models of electromigration have gone through a long evolution starting with the early works of Black [1], Rosenberg and Ohring [2], Blech et al. [3–5], Kirchheim et al. [6], Korhonen et al. [7], Lloyd et al. [8, 9], and Clement [10], to the more general contemporary models of Sarychev et al. [11] and Sukharev [12].

Electromigration can be viewed as a multi-physics phenomenon, once the material transport is caused by several driving forces, such as concentration gradient, electric field, temperature gradient, and mechanical stress [11]. Residual mechanical stresses are introduced on interconnect lines as a result of the fabrication process flow [13]. Copper interconnects are typically produced by a dual damascene process, for which surrounding cap and barrier layers are mandatory. The choice of passivating film material together with the corresponding technology process produce tensile or compressive stresses in the interface between the passivating film and the interconnect metal. These stresses can be very high [14] leading to a significant anisotropic diffusion of the metal atoms [15].

In this work we evaluate the changes in the electromigration material transport in three-dimensional typical copper interconnect structures due to the anisotropic diffusivity of vacancies produced by residual strains, taking into account all relevant driving forces for atom migration.

2 Electromigration modeling

The total vacancy flux caused by the gradients of concentration, electrical potential, temperature, and mechanical stress,

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respectively, is given by [11]

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

where $\mathbf{D}$ is the diffusivity tensor, 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.

In conjunction with (1) the dynamics of the vacancies is obtained by solving the mass balance equation

$$\frac{\partial C_v}{\partial t} = -\nabla \cdot \mathbf{J}_v + G(C_v), \tag{2}$$

with

$$G(C_v) = -\frac{C_v - C_v^{eq}}{\tau}, \tag{3}$$

where $G(C_v)$ is a source function introduced by Rosenberg and Ohring [2], which models the vacancy annihilation and generation processes, and τ is the characteristic relaxation time [12].

The diffusivity tensor $\mathbf{D}$ is calculated by [15]

$$D_{ij} = \frac{1}{2}\sum_{k=1}^{12} R_i^k R_j^k \Gamma^k, \tag{4}$$

where $\vec{R}^k$ is the jump vector for a site k and Γ^k is the jump rate. The impact of the strains is a change of the jump rate through [16]

$$\Gamma^k = \Gamma_0 \exp\left[-\Omega\vec{\epsilon}_I \cdot (\mathbf{C}\,\vec{\epsilon})\right], \tag{5}$$

where $\vec{\epsilon}_I$ is the induced strain, $\vec{\epsilon}$ is the applied strain, and $\mathbf{C}$ is the elasticity tensor of the interconnect material. Due to the symmetry of a vacant point defect the induced strain is determined by

$$\epsilon_I = -\frac{1-f}{3}, \tag{6}$$

and the final induced strain vector is determined by

$$\vec{\epsilon}_I = \epsilon_I \mathbf{r}^k, \tag{7}$$

where $\mathbf{r}^k$ is a unit vector in the jump direction for a site k.

The simulation procedure is shown in Fig. 1. First, the electro-thermal problem determines the electric potential and the temperature distribution in the interconnect geometry, which are transfered to the electromigration model. Due to the fabrication process it is expected that anisotropic strains in the order of 0.1% to 1% [14, 17] have developed in the interconnects. We have set similar strains into $\vec{\epsilon}$ in (5) to reproduce the expected anisotropy. Therefore, the solution of the electromigration problem provides the vacancy distribution for each specific set of strains. Both the electro-thermal problem and the electromigration model are solved numerically by the finite element method [18] implemented in an in-house code.

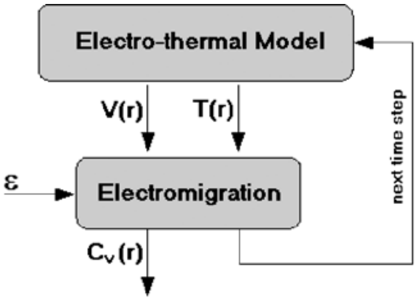

Fig. 1 The simulation procedure

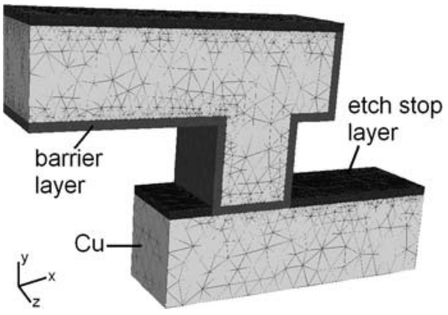

Fig. 2 Interconnect via geometry showing the metal line, capping layer, and barrier layer

3 Simulation results

The interconnect geometry analyzed by fully three-dimensional simulation is given in Fig. 2. The structure is an idealized via as produced by a dual damascene process for copper as interconnect metal. In order to avoid the copper to move into the interlevel passivation (not shown in figure), a capping layer is used, typically of SiN. The barrier layer serves also as a redundant path for electrical conduction. The line and via have a cross section of 0.2 × 0.2 μm^2, the tantalum barrier and capping layers are 20 nm thick. For the electromigration calculation we have assumed that the vacancy flux vanishes at the anode and cathode end of the interconnect structure, which corresponds to a blocking boundary condition.

In Fig. 3 we show the electric potential distribution. The applied current density is 2 MA/cm^2 in the x direction, i.e. the electrons flow from the bottom line up to the via and the upper line.

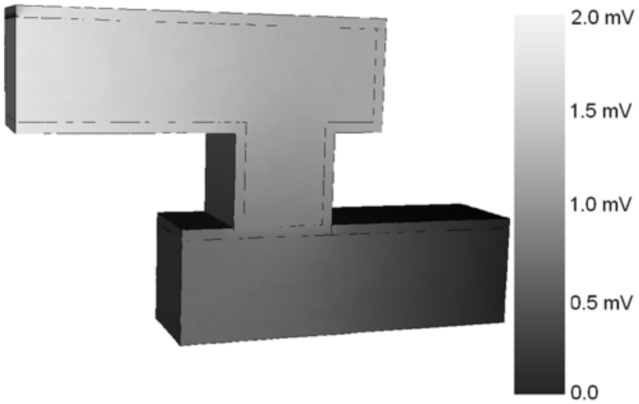

Fig. 3 Electric potential distribution

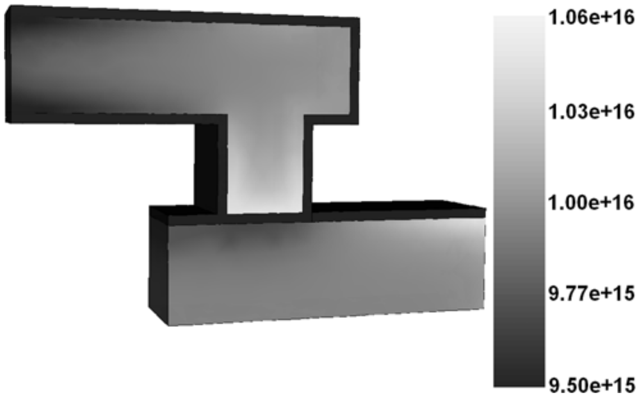

Fig. 4 Vacancy concentration for the interconnect without strains (units in cm^{-3}). The higher vacancy concentration on the interface between the bottom copper line and the etch stop layer occurs due to the increased interfacial diffusion coefficient

Considering initially that the interconnect is free of strains, i.e. $\vec{\epsilon}$ in (5) vanishes, we obtained the vacancy distribution as shown in Fig. 4, with 10^{16} cm^{-3} used as the initial vacancy concentration for copper [7]. This corresponds to the case of isotropic diffusion and the diffusivity tensor is a diagonal matrix with equal entries. 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.

It is well known that the interface between the copper and capping layer can act as a fast diffusivity path for atom migration. In order to consider that in our simulations we have increased the diffusion coefficient in this region, following the same approach as made by Sukharev [12]. The result is also a higher vacancy concentration in the cathode on the interface between the bottom metal line and the capping layer.

Applying the strains $\epsilon_{xx} = 0.010$, $\epsilon_{yy} = 0.005$ and $\epsilon_{zz} = 0.001$, we have verified only a very small increase in the vacancy concentration on the bottom of the via, as depicted in Fig. 5. The maximum vacancy concentration increased to 1.07×10^{16} cm^{-3}. In this case we have determined the off-diagonal components of the diffusivity tensor to be about 18% of the diagonal ones.

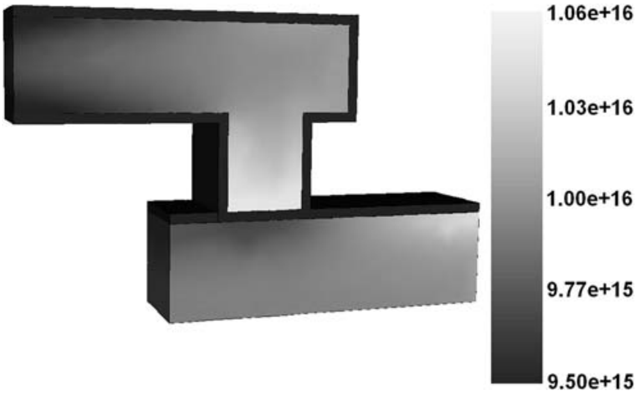

Fig. 5 Vacancy concentration for the residual strains $\epsilon_{xx} = 0.010$, $\epsilon_{yy} = 0.005$ and $\epsilon_{zz} = 0.001$ (units in cm^{-3})

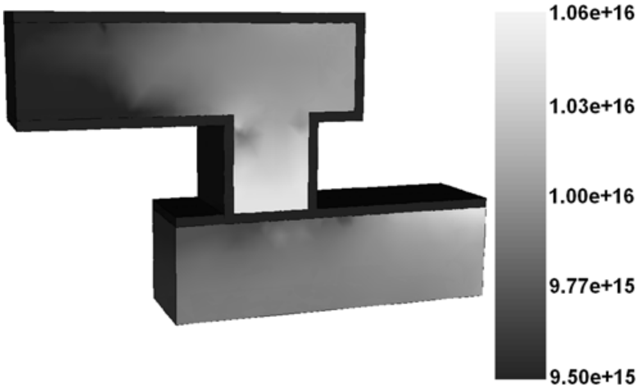

Fig. 6 Vacancy concentration for the residual strains $\epsilon_{xx} = 0.008$, $\epsilon_{yy} = 0.015$ and $\epsilon_{zz} = 0.003$ (units in cm^{-3})

Considering $\epsilon_{xx} = 0.008$, $\epsilon_{yy} = 0.015$ and $\epsilon_{zz} = 0.003$ the distribution of vacancies is significantly altered, as Fig. 6 shows, although the change in the maximum concentration to 1.08×10^{16} cm^{-3} is still small. We have observed a drift of vacancies in the z direction and, consequently, an accumulation to the right edge of the interconnect in relation to the direction of the electric current. The higher strains applied in (5) increased the off-diagonal diffusion coefficients in relation to the diagonal values. According to (4), we have determined $\frac{D_{ij,i\neq j}}{D_{ii}}$ to be about 30%.

The differences in the material distribution presented by the previous pictures is more easily seen in Fig. 7, which shows the vacancy concentration along a cut line from top to bottom in the upper interconnect line at the center region of the via.

4 Conclusion

The effect of strains on material transport in a typical dual damascene copper interconnect via under electromigration

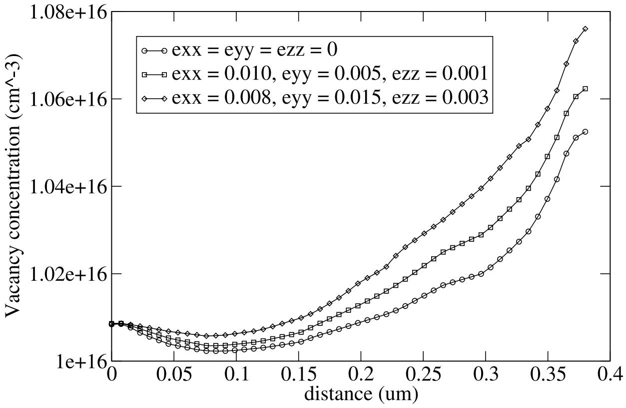

Fig. 7 Vacancy concentration as a function of the distance from top to bottom of the upper metal line at the center of the via

stress has been analyzed. The model incorporates all important driving forces for atom migration. Although in a fcc metal, like copper, the diffusivity is isotropic, the residual strains affect the jump rate of atoms to a vacant point defect producing an anisotropy in the diffusion. A diffusivity tensor in the transport equation takes into account this anisotropy generated by the applied strains. No change is observed in the vacancy distribution, until strains on the order of 0.5% to 1% are used. The maximum vacancy concentration cannot increase so much in relation to the equilibrium value, although the higher strains result in significant changes in the off-diagonals components of the diffusivity tensor. This can lead to significant anisotropy of material transport in an interconnect line under electromigration stress and this effect must be taken into account for a rigorous analysis of the electromigration problem.

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