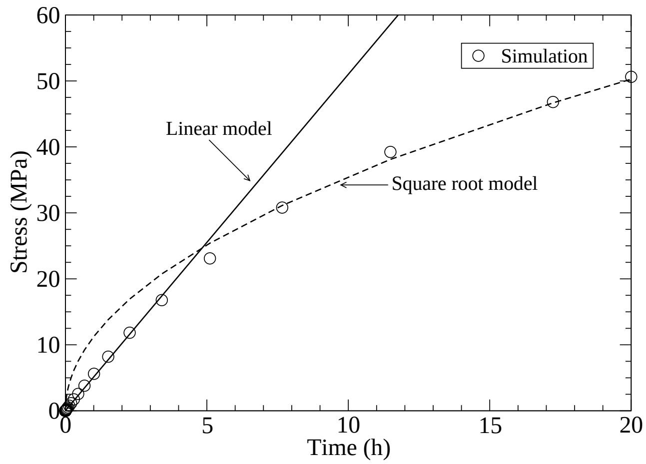

Figure 4. Fitting of a numerical solution using a linear and a square root model.

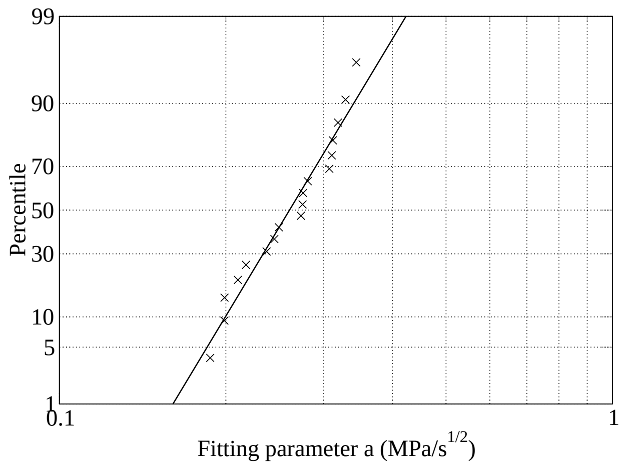

Figure 5. Distribution of the square root model fitting parameter.

square root increase with time. This is shown in Figure 4 for a typical stress curve. The portion of linear stress increase was first explained by Kirchheim (10) and the square root stress increase was obtained by Korhonen's solution, given in Eq. [4]. Thus, the stress increase at a grain boundary obtained from numerical simulations with a rather complete model and for fully three three-dimensional structures can be conveniently described by simple analytical solutions.

Since void nucleation is expected to occur at the higher stress magnitudes, the second part of the stress curve is fitted by the square root model given in Eq. [4], where *a* is a fitting parameter. By fitting the stress curves of all simulated structures, the distribution of the parameter *a* is determined, as shown in Figure 5. It is well described by lognormal statistics, where the mean and the standard deviation are 0.23 $MPa/s^{1/2}$ and 0.19, respectively.

Applying Eq. [5] with the obtained parameter distribution, the distribution of times to void formation is readily obtained, as shown in Figure 6. Due to the lognormal statistics of *a*, the void formation time also follows a lognormal distribution, where the mean and standard deviation are 8.5 h and 0.38, respectively.

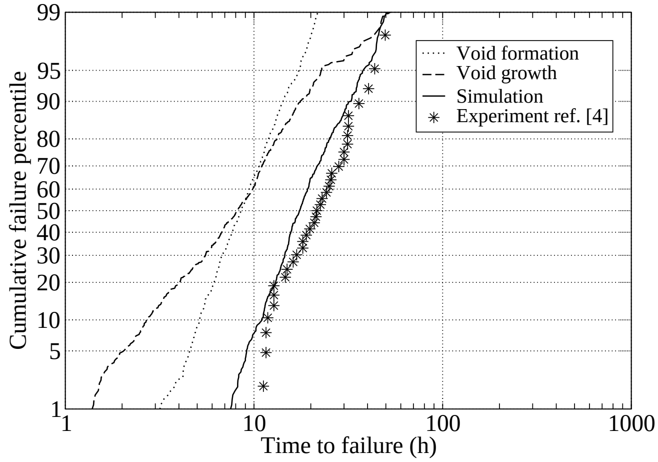

Figure 6. Early EM lifetime distribution.

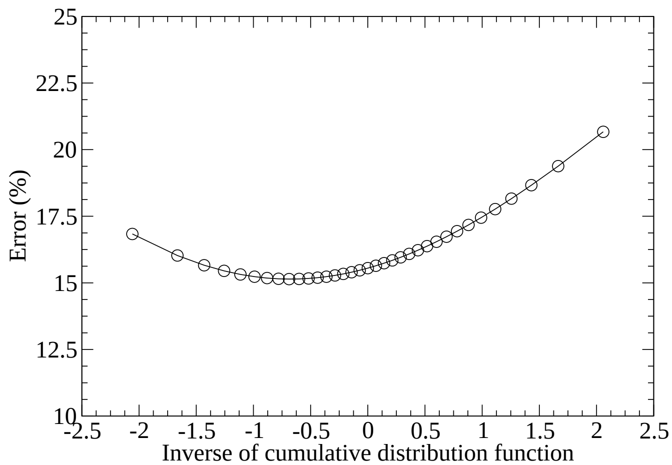

Figure 7. Error between the simulation and the experimental results.

The void growth time is determined by Eq. [8]. Choi *et al.* (9) obtained an activation energy for surface diffusivity of 0.45±0.11 eV from EM tests carried out with clean copper surfaces. Thus, it is expected that their measurement delivers a more precise copper surface diffusivity than the typical ones performed on oxidized surfaces and, therefore, we have used their estimation for the activation energy in the simulations. Furthermore, we have assumed that the activation energy follows a normal distribution (11). This leads to a lognormal distribution for the surface diffusivity and, consequently, for the void growth time. The resulting distribution of the void growth time is shown in Figure 6. The mean and the standard deviation are 8.0 h and 0.7, respectively. It should be pointed out that the void formation time and the void growth time are of the same order of magnitude, which highlights the importance of considering both contributions.

The total early EM lifetime distribution, shown in Figure 6, is obtained by summing up the nucleation and growth contributions, where the lognormal mean and standard deviation are 17.5 h and 0.41, respectively. Figure 6 also shows the experimental results obtained from Filippi *et al.* (4).

The relative difference between the simulated and experimental lifetimes for the same failure percentile varies between 15 % and 20 %, as shown in Figure 7. The difference is smaller for shorter lifetimes, since the proposed slit void growth model is more accurate for very early failures, where the void volumes are smaller. This error magnitude is reasonable, considering the assumptions made for the model parameters and the simplicity of the model. Therefore, we can say that the simulation results provide satisfactory estimates for the early EM lifetimes.

Conclusion

A compact model for estimation of the early EM lifetime distribution of copper dual-damascene interconnects was developed. A key feature of the model is that it consists of a physical model based on simple analytical expressions, nevertheless providing a satisfactory description of the complex physics of EM phenomena in fully three-dimensional interconnects. The model accounts for both, the void formation and the void growth kinetics. Moreover, it can take into account the statistical distribution of physical parameters and is thus able to deliver a distribution of EM lifetimes. The simulations yield a reasonable estimation for the early EM lifetimes in comparison to published experimental results.

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