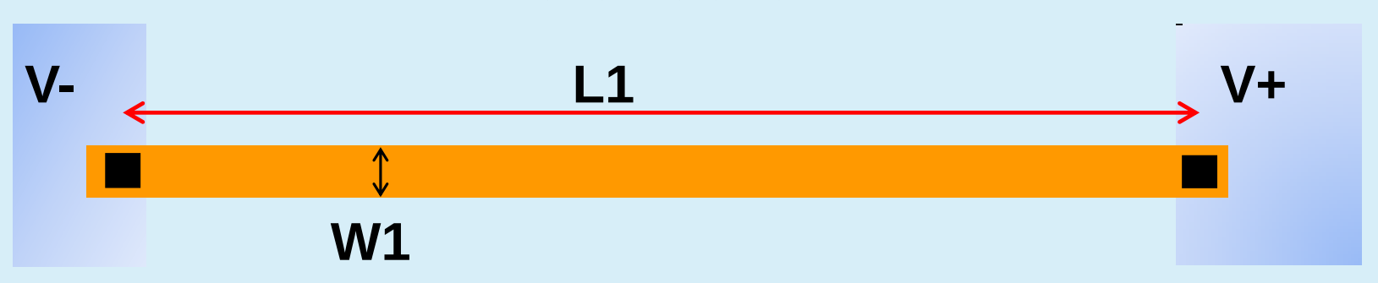
Stress evolution due to EM in metal line confined: Model and Correlation with experiments

G. Marti[1,2], L. Arnaud[1, 3] and Y. Wouters[2]

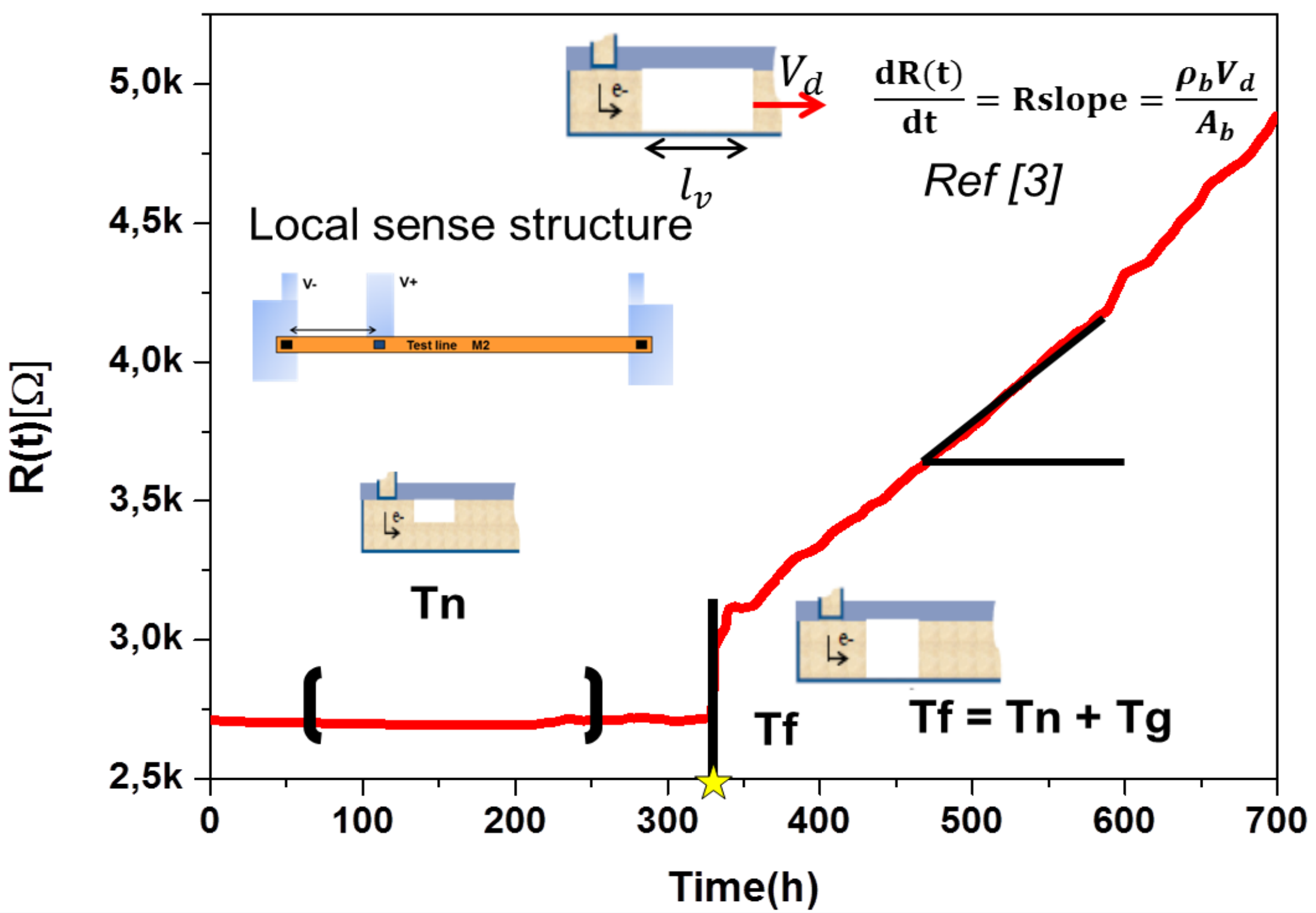
[1]STMicroelectronics, 850 rue Jean Monnet, 38926 Crolles Cedex France
[2]SIMaP UMR5266 CNRS/UJF/Grenoble-INP, 1130 rue de la piscine, BP 75, 38402 St-Martin-d'Hères Cedex France
[3]CEA-Leti Minatec, 17 rue des martyrs, 38054 Grenoble Cedex09 France
Email: giulio.marti@st.com

Electromigration (EM) is one of the main reliability failure mechanism of integrated circuit interconnects. The continuous scaling of the interconnect dimensions leads to higher operating current densities and temperatures, which accentuates the electromigration failure. Electromigration modelling becomes an important tool for explaining several experimental observations and can provide a stronger basis for design and fabrication of reliable metallization. The main challenge is the diversity of the relevant physical phenomena to take into account and the correlation with experiments.



EM standard test consists in elementary structures that are stressed under accelerated conditions (high current and temperature) until degradation occurs.

Examples of EM degradation depends also on the wire topological parameters and the interconnection network configuration

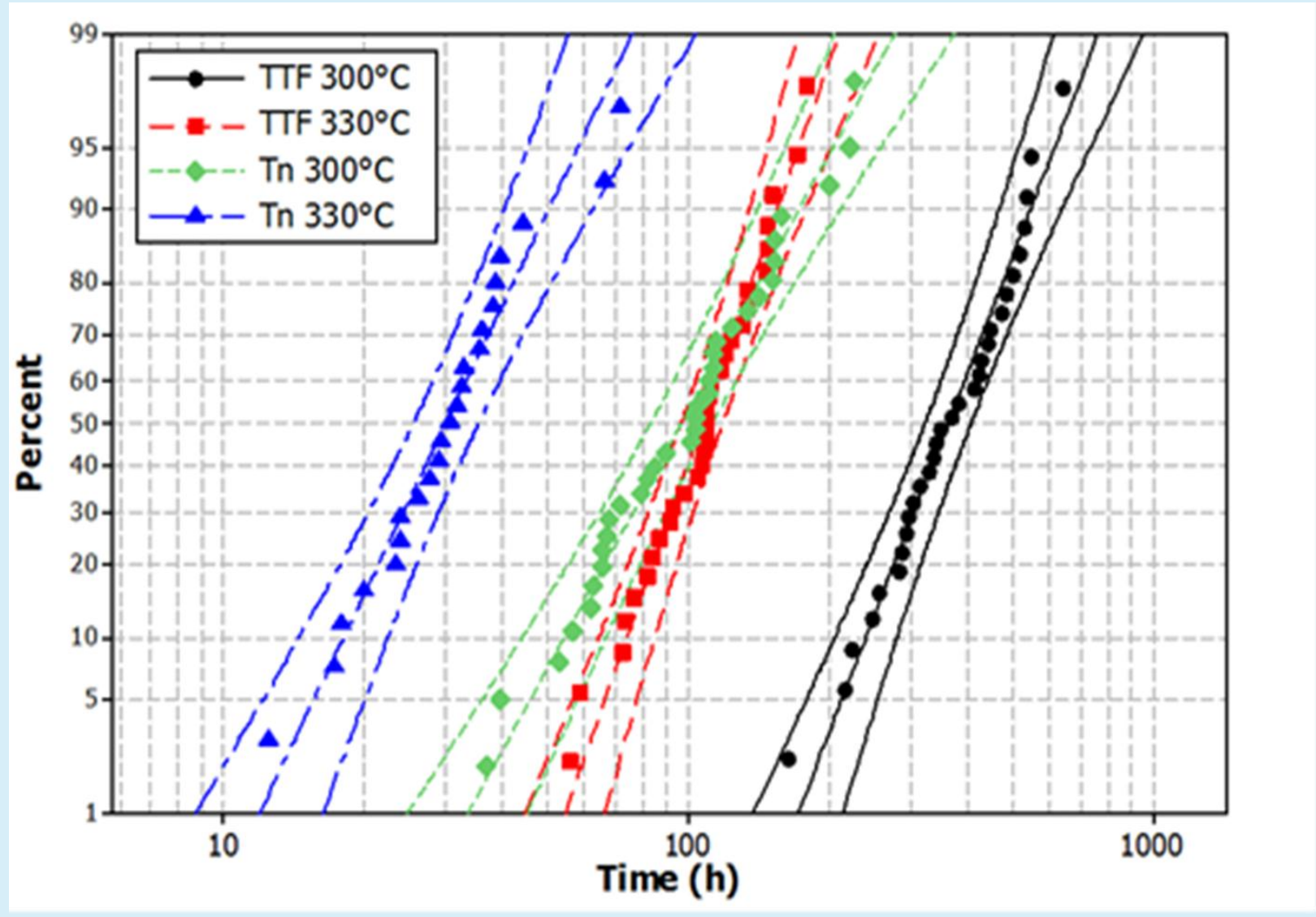


Resistance versus time curve of CS that is subjected to electromigration stress. Different phases of the degradation process representing the evolution of the degradation of the test line

As a consequence of accelerated tests, extrapolations from EM stressing conditions to operating conditions according to the following equation are necessary

Black's Law

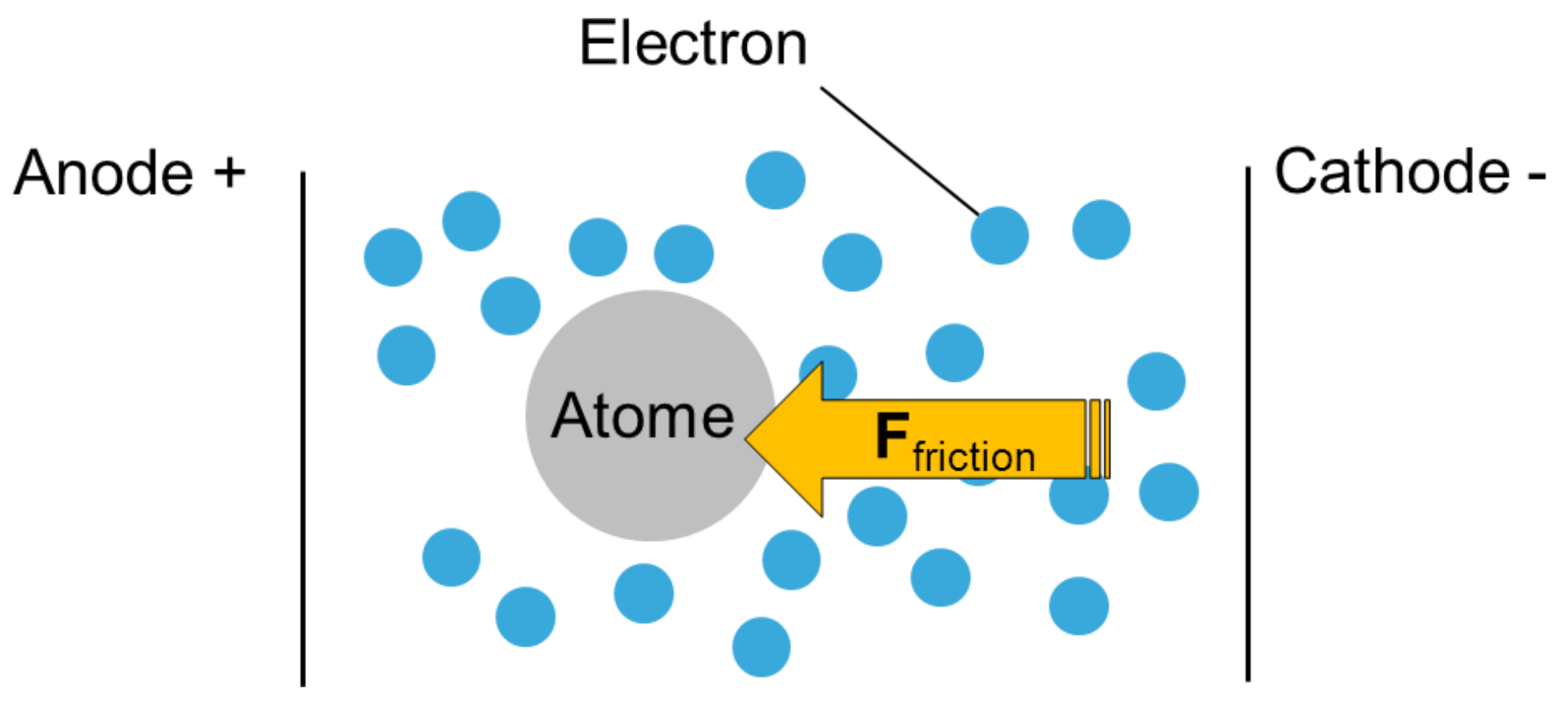
$$Tf_{oper} = MTf_{stress}\left(j_{stress}/j_{oper}\right)^{n} exp\left[\frac{Ea}{k}\left(\frac{1}{T_{oper}} - \frac{1}{T_{stres}}\right)\right]$$



Black JR, Proc. of phys. symposium (1966), p 148

Time to failure (TTF) and Time of Nucleation (Tn) calculated respectively with the SSV and LSS at accelerated conditions

Electromigration modelling becomes an important tool for explaining several experimental observations and can provide a stronger basis for design and fabrication of reliable metallization. The main challenge is the diversity of the relevant physical phenomena to take into account. Indeed, the material transport is driven by the vacancy concentration, mechanical stress and temperature gradients, and electrical potential.



j et T, acceleration factors

$$F_{friction} = Z^{*} e \rho j$$

$$D = D_0\, exp(-E_a/kT)$$

Metallic material migrates due to a vacancy exchange mechanism

$$\dot{C}v = -\nabla q + G$$

Vacancy nets flux

$$q = \sum_i q_i \quad \begin{cases} q_1 = -D_v \nabla C_v & \longrightarrow \textbf{Vacancy concentration} \\ q_2 = -\dfrac{D_v C_v}{kT} Z^{*} e \nabla V & \longrightarrow \textbf{Potential} \\ q_3 = -\dfrac{D_v C_v}{kT} f \Omega \nabla \sigma_h & \longrightarrow \textbf{Hydrostatic stress} \\ q_4 = -\dfrac{D_v C_v}{kT} \dfrac{Q^{*}}{T} \nabla T & \longrightarrow \textbf{Temperature gradient} \end{cases}$$

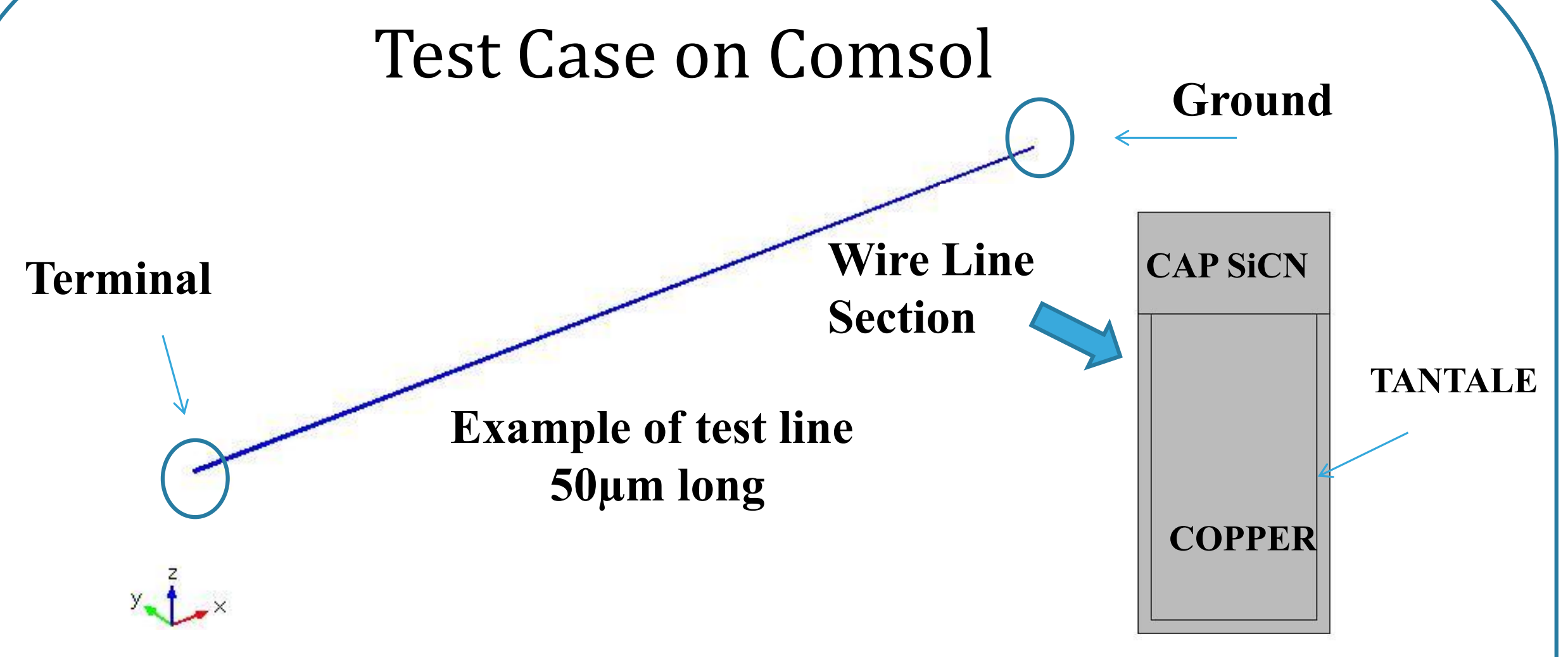
$$G = -\frac{C_v - C_{v0} e^{\frac{(1-f)\Omega\sigma_h - E_v}{kT}}}{\tau_v}$$

source/sink term describes the production/annihilation of vacancies

$$\dot{\underline{\varepsilon}}_{ij}^{em} = \Omega\left[f \nabla q + (1-f) G\right] \underline{\delta}_{ji}$$

Sarychev and Zhinikov approach

Strain rate term: difference between the volume of an atom and the volume of a vacancy generates volumetric strain



Test Case on Comsol

Ground

Terminal

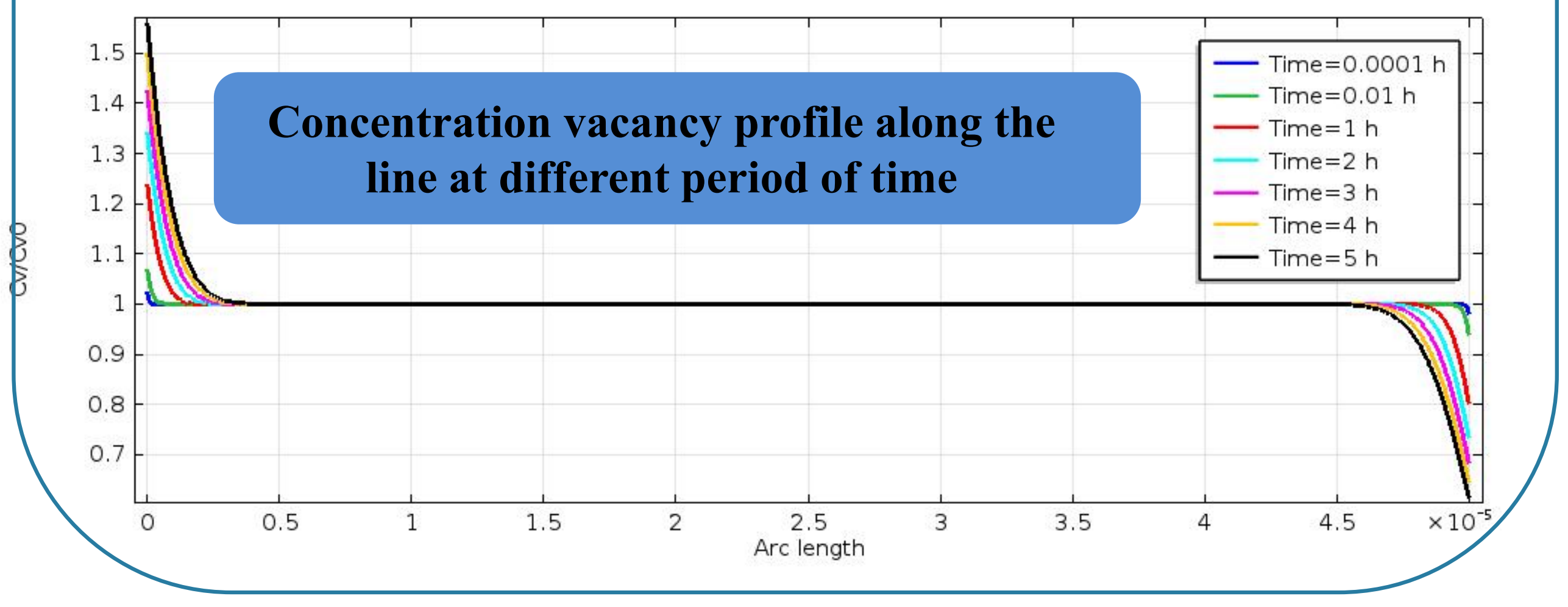
Wire Line Section

Example of test line 50μm long

CAP SiCN

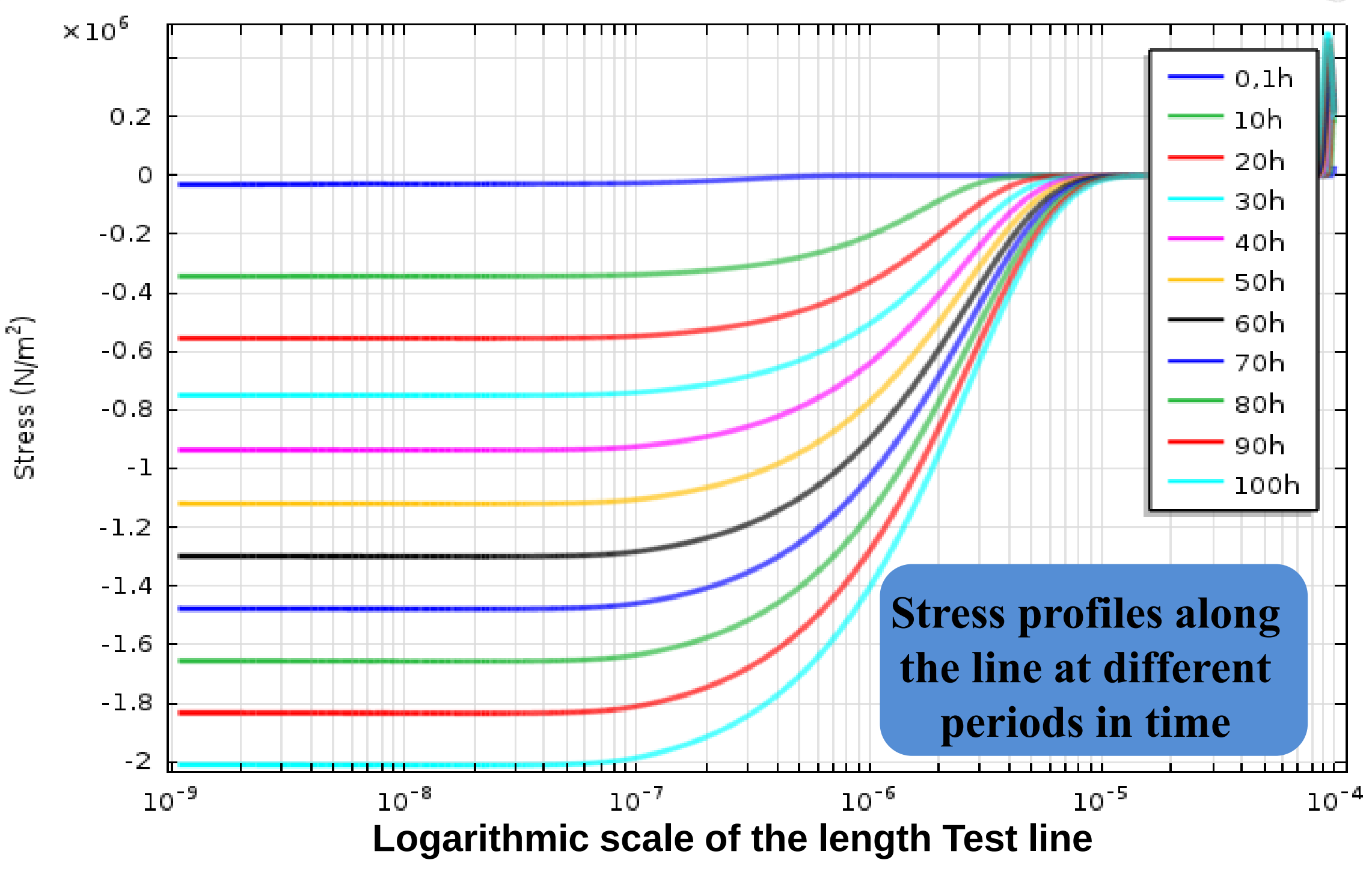
TANTALE

COPPER



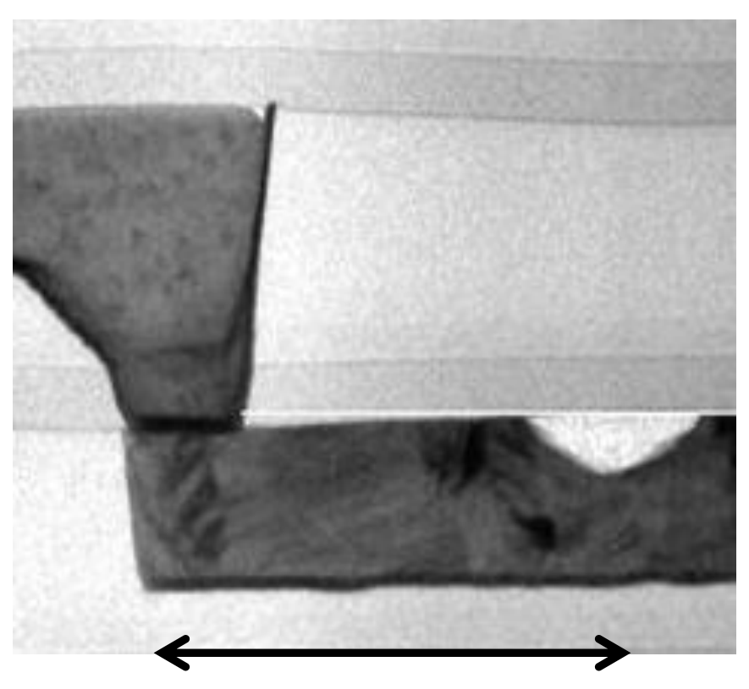
Concentration vacancy profile along the line at different period of time

The degradation of the electrical resistance of interconnect segment can be derived from the solution of the kinetics equation[3] which describes the time evolution of vacancy's concentration (Cv) and stress (σ). Then, the evolution of stress could be correlated with the experimental data with the purpose to find the critical stress necessary to nucleate a void.



Stress profiles along the line at different periods in time

Logarithmic scale of the length Test line



Distance of the void from the cathode

1. **Knowing the distance of nucleation with morphological analyses**
2. **Stress profile at different time with simulations**

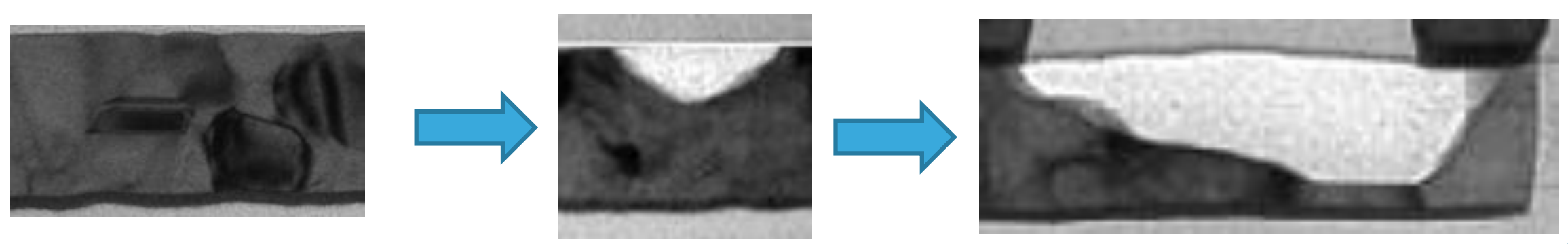
Allowed us to define a critical stress for the nucleation

Conclusions

- **Model of electromigration was reproduced simplified and adapted to the technology dual damascene Cu line embedded in low-k dielectric of the C028 technology process**
- **Time nucleation can be used now to calibrate existing models based on the critical mechanic stresses to have more realistic predictions**
- **Critical stress for the nucleation (calculated just approximately until now) can be evaluated more precisely**

Perspectives

Void growth model and correlations with experiments



References

[1] J.R. Lloyd, Black's law revisited: nucleation and growth in electromigration failure Microelectronics Reliability (2007), p 1468-1472

[2] G. Marti et al., Study of EM void nucleation and mechanic relaxation effects, Microelectronic Engineering 54 (2014), p1692-1696

[3] F. Cacho et al., Electromigration Induced Failure Mechanism: Multiphysics Model and Correlation with Experiments, IEEE-Euro SimE (2008)

[4] L. Arnaud et al., Study of void formation in Cu interconnects using local sense and standard singlevia structure Proc. of ADMETA (2012), p 54-55

[5] L. Doyen et al., Extensive analysis of resistance evolution due to electromigration induced degradation J. Appl. Phys. 104 (2008), 123521-1

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