Non-Uniform Temperature Distribution in Interconnects and Its Impact on Electromigration

Ali Abbasinasab, Malgorzata Marek-Sadowska

ECE Department, University of California, Santa Barbara, Santa Barbara, CA 93106

{ali, mms}@ece.ucsb.edu

ABSTRACT

We investigate the effect of electrically induced thermal load on interconnect reliability and aging. We propose new models for uniform and non-uniform temperature evolution and its steady state distribution in interconnects considering Joule heating and heat convection. The models are verified by comparing the results against those of finite element experiments. We apply our models to study material migration induced aging and failures. We discuss how different non-uniform temperature profiles affect interconnect lifetime. We propose new formulas for accurate temperature aware assessment of the mortality of interconnects. We demonstrate that neglecting thermal effects in modern technologies may lead to incorrect conclusions about interconnect mortality. We also provide a method for modeling the true mean time to failure based on underlying physics.

KEYWORDS

Aging, lifetime, reliability, interconnect, electromigration, thermomigration, stress migration, EM

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1. INTRODUCTION

Many papers are devoted to studying temperature distribution of conductors in VLSI chips. They mostly present analytical models that consider the effect of ohmic heating generated in wires by electric current [1-3]. However, most of them only consider this single source of heating without correctly considering the effects of vias and miscellaneous heat distributions and transfers due to various external settings. In reality, temperature is not distributed uniformly along the wire. Vias play the role of heat sinks or heat sources, transferring the heat between the layers. Assuming, in a common case, that vias transfer heat from the layers closer to device to the layer closer to the heat sink (ambient temperature), the temperature profile measured in the experiments are usually of upside-down shape (i.e. n). [2] takes the effect of via into account and proposes an

analytical model for a single end-to-end wire. However, they assume that the temperatures at both ends are the same, which might not be true especially for long wires passing over several blocks. More advanced works such as [1] present a similar idea. However, their model cannot be readily incorporated into the aging problem due to their assumption on substrate temperature. Our novel model is later used for interconnect aging due to mass transport. The model considers Joule heating and heat convection with respect to arbitrary external settings.

The effect of temperature rise produces temperature gradients which generate thermomigration affecting other failure mechanisms namely electromigration and stress migration [22][23]. There are some similar efforts on modeling thermal effect and electromigration such as [24]. However, to our knowledge, the mutual interaction between them has not been discussed. Since the thermal effect on aging can no longer be neglected for modern technologies [4-6], we present novel formulas for mortality of interconnects under thermal load. We provide a comprehensive study using our models to see how various thermal profiles influence material migration through hydrostatic stress analysis. Many interesting and useful conclusions are drawn on any specific non-uniform temperature distribution. We also propose a set of useful tools for designer to potentially exploit the design opportunities provided by thermal effects. We perform extensive experiments to verify the correctness of our models by comparing them against detailed finite element experiments.

There are orthogonal works [1][7], that due to lack of correct physics-based models, use empirical external data and large-scale statistical analysis methods under various experimental temperatures and apply a corrective constant fixed temperature increase or fluctuation (ΔT) to the average operating temperature or attempt to fit an exponent in Black's MTF equation [8]. We also present a method for calculating the true interconnect mean time to failure.

2. TEMPERATURE IN INTERCONNECTS

The evolution and steady state of temperature in interconnects has been studied very well. The existing models, however, are developed based on simplified initial and boundary conditions. In the well-known and widely adopted model in [1][2][9] the temperature distribution and evolution of temperature is studied only for uniform external temperatures and a specific boundary condition. In other words, they assumed that temperatures at both ends are the same, which is invalid for long wires with different layers of metal and devices underneath. We revisit the heat conduction in metallic interconnects and solve the heat equation for arbitrary shape interconnects and all possible boundary conditions.

Given by the first law of thermodynamics, the transient thermal behavior of a solid in a given region over time is [10]:

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$$\rho_m c_p \frac{\partial T}{\partial t} + \nabla q = Q \quad (1)$$

where ρ_m and c_p are the mass density and specific heat, respectively, $q = -k\nabla T$ is due to the heat flux described by the Fourier's law, $Q = Q_{jh} + Q_{con}$ is due to various heat generation processes including Joule heating ($Q_{jh} = j^2 \rho = \Delta V^2 / \rho L^2$) and heat convection $Q_{con} = k(T_0 - T)/\Gamma^2$ where Γ is the thermal characteristic length determined by the geometry and topology of surrounding interconnects. In this paper we use the model in [9] for Γ which matches perfectly with FEM experiments. It can be shown that Γ can be properly approximated by:

$$\Gamma^2 = t_{cu} t_{ILD} \frac{k_{cu}}{k_{ILD}} \quad (2)$$

where t_{cu} and t_{ILD} are the thickness of the wire and the dielectric and also k_{cu} and k_{ILD} are thermal conductivity of the wire and dielectric, respectively.

Note that Γ can be modeled differently depending on layout topology. While we used the model in [2][9], the proposed model is not limited to Γ as stated in (2) – any other model for the thermal characteristic length can be plugged into and handled by our new models.

Under stationary condition the solution to (1) for a wire ($-L/2 < x < L/2$) with initial conditions of $T(-L/2) = T_1$ and $T(+L/2) = T_2$ is obtained as:

$$T(x) = T_0 + T_m \left[1 - \frac{\cosh\left(\frac{x}{\Gamma}\right)}{\cosh\left(\frac{L}{2\Gamma}\right)} \right] + T_n \left[\frac{\sinh\left(\frac{x}{\Gamma}\right)}{\sinh\left(\frac{L}{2\Gamma}\right)} \right] \quad (3)$$

where $T_0 = (T_1 + T_2)/2$, $T_n = (T_1 - T_2)/2$ and $T_m = j^2 \Gamma^2 \rho / k$ is the maximum temperature rise. For the simple case where the anode and cathode have the same temperature (T_0), (3) matches the solutions in [2][3][9].

To verify the correctness and accuracy of the model proposed in (3), we compared it against detailed finite element experiments. Not only the model can be used for a single end-to-end wire, it can readily be used for any complex structure with given initial conditions (e.g. external temperatures). Figure 1 (a), for example, demonstrates the application of the new model to a complex structure. In principle, the model presented in (3) is solved for all individual node to node segments. The complicated multi-branch structure shown in Fig 1 is a small part of a large intermediate-length net from IBM benchmark [11]. The entire circuit is analyzed using SPICE which provides the corresponding current density to our FEM experiments. Branches carry current densities of the order of 1MA/cm². The segment is then properly constructed in COMSOL Multiphysics [12]. The values for geometrical, electrical, mechanical and

Figure 1: Distribution of (a) temperature (b) stress in a complex net

Figure 2: Effect of current, width and technology scaling on (a) temperature rise; (b) The TM flux to EM flux ratio.

thermal properties of technology are obtained from various recent reports of major foundries for 10nm [4-6][13-17]. Via effect which explains the inter-layer heat transfer is also employed for realistic and accurate modeling [1][9]. The external ambient temperatures for surrounding layers 4, 5 and 6 are assumed to be 373.15K, 376.65K and 379.65K, respectively. The temperature evolution due to Joule heating and heat convection is obtained by detailed finite element methods. The temperature distribution is depicted for the steady state in Fig 1 (a) which agrees with the results obtained by the model proposed in (3).

The proposed model is independent of the underlying technology (geometry and material properties) or external settings. In other words, any arbitrary electrical and thermal settings can be properly fed to and accommodated by (3).

Fig. 2 shows the significance of temperature in contemporary technologies. In Fig 2 (a), the temperature rise is shown versus technology scaling (which includes all enforced factors: such as thickness, aspect ratios, minimum pitch, thermal and electrical properties) and design elements (such as current and width). Current density is not directly employed as it is partially technology dependent (through thickness) and thus is non-distinguishable in terms of design and technology. However, the corresponding current and the interconnect width are used appropriately. The mean values for the parameters are obtained from recent experimental reports on modern manufacturing processes of major foundries [4-7][13-17]. Due to the space limit, the effects are shown for local interconnects only; similar observations can be made for other layers. present a method for calculating the true interconnect mean time to failure.

3. MATERIAL MIGRATION

A metallic line is considered reliable if material concentration is almost constant across the wire within a specific period of time (i.e. several years). The change of atom concentration C due to atomic fluxes is described as follows:

$$\frac{\partial C}{\partial t} = -\nabla \cdot \vec{J} \quad (4)$$

where $J = \vec{J}_{EM} + \vec{J}_{TM} + \vec{J}_{SM}$ is the atomic flux composed of several different fluxes due to electromigration, stress migration, and thermomigration (left to right) described as:

$$\vec{J} = -\frac{DC}{kT} (eZ\nabla V + \Omega \nabla \sigma - QT^{-1} \nabla T) \quad (5)$$

where D is the diffusivity, k is Boltzmann's constant and T is the temperature, e is the fundamental electron charge, Z is the effective charge ρ is the resistivity and j is the current density, σ is the hydrostatic stress and Ω is the atomic volume and Q represents the specific heat of transport of metal. [18] presents an analytical model that eliminates the intangible concentration quantity based on a relationship between hydrostatic stress and concentration (using $\delta\sigma/B = -\delta C_a/C_a$ where B is the bulk modulus):

$$\frac{\partial \sigma}{\partial t} = B \nabla \cdot \left(-\frac{D}{kT} eZ\rho j + \frac{D}{kT} \frac{Q}{T} \nabla T - \frac{D}{kT} \Omega \nabla \sigma \right) \quad (6)$$

As a result, studying concentrations of atoms can be done by analyzing stress evolution. The presented model is similar to the one proposed in [19]. The distinction, however, is that the current model captures all material migration factors whereas the model in [19] assumes fixed temperature and no TM.

Fig 2 (b) shows the relative significance of thermomigration flux w.r.t. electromigration flux which has roughly the same order of magnitude and can no longer be ignored. It confirms that impact of thermal effect compared to electromigration and stress migration on the overall material migration process is not negligible. Such overall effect is aggravated by technology scaling and larger current density. The mean values for the parameters are obtained from recent experimental reports on modern manufacturing processes [4-7]. This model confirms that for novel technologies [12-17], neglecting the temperature evolution and its impact on interconnect reliability and their lifetime may lead to wrong conclusions or catastrophic failures.

The steady state of a system under material migration is achieved when all atomic fluxes cancel each other out (i.e. $J_{EM} + J_{SM} + J_{TM} = -\frac{eZ}{\Omega} j\rho + \nabla \sigma - \frac{Q}{\Omega T} \nabla T = 0$). By integration, the steady state of model in (4) can be described as follows:

$$\sigma(x) = \frac{eZ\rho}{\Omega} jx + \frac{Q}{\Omega} \ln T(x) + c \quad (7)$$

where constant c is readily obtained by boundary conditions.

4. ACCURATE CRITERIA FOR RELIABILITY DUE TO MATERIAL MIGRATION UNDER NON-UNIFORM TEMPERATURE

Having (5) and the principle of atom conservation (i.e. $\int_{-L/2}^{+L/2} \Delta C dV = -\frac{C_0 HW}{B} \int_{-L/2}^{+L/2} \sigma dx = 0$) [20], yields:

$$\sigma_c - \sigma_a = \frac{eZ\rho}{\Omega} jL + \frac{Q}{\Omega} \Delta \ln T \quad (8)$$

$$\sigma_c + \sigma_a = -\frac{eZ\rho}{\Omega} j^2 \mathcal{L}^2 \quad (9)$$

where $\mathcal{L}^2 = \frac{2Q}{eZk} \left(\frac{T_0}{T_a T_c} - \frac{2\Gamma}{T_0 L} \tanh\left(\frac{L}{2\Gamma}\right) \right) \Gamma^2 \approx \frac{2QT_0 \Gamma^2}{eZkT_a T_c}$.

These criteria capture the effect of temperature, stress and current density for assessing the mortality of a wire. Having the critical stresses for voiding and hillock, σ_{crit}^v and σ_{crit}^h , we can define new critical terms including temperature effects $\tau_{crit}^v = \frac{2\Omega}{eZ\rho} \sigma_{crit}^v - \frac{Q}{eZ\rho} \Delta \ln T$ and $\tau_{crit}^h = \frac{2\Omega}{eZ\rho} \sigma_{crit}^h + \frac{Q}{eZ\rho} \Delta \ln T$. Solving (8) and (9), the conditions for immortality under non-uniform temperature distribution can be stated as:

$$jL - j^2 \mathcal{L}^2 < \tau_{crit}^v \quad (10)$$

$$-jL - j^2 \mathcal{L}^2 > \tau_{crit}^h \quad (11)$$

This model is similar to Blech's conditions [3][21], yet it considers the effect of thermal load. The new model offers various extended criteria. The maximum current density for a wire with given length and initial temperatures is obtained by:

$$j_{max}^v = \frac{-L + \sqrt{L^2 - 4\mathcal{L}^2 \tau_{crit}^v}}{2\mathcal{L}^2} \quad (12)$$

$$j_{max}^h = \frac{+L - \sqrt{L^2 + 4\mathcal{L}^2 \tau_{crit}^h}}{2\mathcal{L}^2} \quad (13)$$

Also, the model implies more precise length criteria reflecting the effect of temperature and does not suffer from pessimistic voiding and optimistic hillock predictions of other models. Defining a relative temperature rise, $\theta = T_m/T_0$, yields useful tools for guiding physical design as follows:

$$L_{max}^v = \left(1 + \frac{Q}{\Omega \sigma_v} \theta \right) L \quad (14)$$

$$L_{max}^h = \left(1 - \frac{Q}{\Omega \sigma_h} \theta \right) L \quad (15)$$

The models presented in (14-15) imply that taking the temperature effect into account for any current density j , the maximum length for void-immune and extrusion-safe wire can be relaxed or tightened by $Q\theta/\Omega\sigma$, respectively. This also means designers can take advantage of a more accurate short length effect and apply significantly larger current densities.

4.1 Extrema

A metallic line The models presented in (10)-(15), in their core, check the hydrostatic stress against the critical stress on the end points of a wire where stress have the extreme values (i.e. the max tensile and compressive stresses occur in the cathode and anode, respectively). However, the exact positions of the extrema depend on temperature profile and may no longer happen in the wire ends. The maximum stress can be found by solving the following equation:

$$\frac{\partial \sigma}{\partial x} = \frac{eZ}{\Omega} j\rho + \frac{Q}{\Omega T} \frac{\partial T}{\partial x} = 0 \quad (16)$$

Plugging equation (3) into (15), yields a very accurate approximation for the maximum stress as follows:

$$x_s = \Gamma \cosh^{-1} \left(\frac{eZT_0 k}{Qj\Gamma} \cosh\left(\frac{L}{2\Gamma}\right) \right) \quad (17)$$

where t_{cu} and t_{ILD} are the thickness of the wire and the surrounding dielectric and also k_{cu} and k_{ILD} are thermal conductance of the wire and the dielectric, respectively.

The location for maximum stress under EM, TM and SM can be found based on the geometrical, electrical and thermal characteristics of a wire and dielectric which are readily available. The stress distribution under temperature effect for a complex net is shown in Fig 1 (b). The maximum stress within two end points may not necessarily occur at ends.

4.1 Mean Time to Failure

A metallic line The models The mean time to failure of an interconnect is often evaluated by the well-known Black's equation [8] as follows:

$$MTF = Aj^{-n} e^{\frac{E_a}{kT}} \quad (18)$$

where A is a constant and n is a model parameter which are obtained empirically. Yet, determining the current density exponent is a critical task which may vary for interconnects with different electrical, thermal and mechanical loads. We propose to determine a true mean time to failure based on the atomic flux divergences. In other words, the parameters in Black's model can be determined readily by the following method.

As it was discussed before, the key to determine the depletion or accumulation of atoms in a region is to look at the overall intake and outtake of atoms due the multiple fluxes. This quantity can be measured accurately by atomic flux divergence. Therefore, it can be stated that

$$MTF \propto \frac{1}{\nabla \cdot \vec{J}} \quad (19)$$

It can be shown that the total flux divergence presented in (2) can be written as follows:

$$\nabla \cdot \vec{J} \approx \left[\frac{E_a}{kT} \frac{\nabla T}{T} + \frac{\nabla^2 V}{\nabla V} \right] \cdot \vec{J}_{EM} + \left[\frac{E_a}{kT} \frac{\nabla T}{T} + \frac{\nabla^2 T}{\nabla T} \right] \cdot \vec{J}_{TM} + \left[\frac{E_a}{kT} \frac{\nabla T}{T} + \frac{\nabla^2 \sigma}{\nabla \sigma} \right] \cdot \vec{J}_{SM} \quad (20)$$

Plugging the fluxes due to EM, TM and SM and writing (20) quantitatively from (2) yields:

$$MTF \propto \frac{1}{D(\alpha j^2 + \beta j^3 + \gamma j^4)} \approx Aj^{-n} e^{\frac{E_a}{kT}} \quad (21)$$

where α , β and γ are determined by the parameters in experiments or equivalently the ones in previous equations. The rightmost-hand side equation is the well-known Black's equation where A is a pre-exponential constant factor and n is an empirically found parameter. As it can be seen there is an intuitive agreement between flux divergence with Black's equation where the current density exponent n and constant A are traditionally determined empirically. In other words, flux divergence analysis can enrich Black's empirical equation by explaining the model parameters. Empirical extractions of n usually set it to be between 2 to 4 – depending on which terms are more dominant.

5. EXPERIMENTS: VARIOUS THERMAL PROFILES

Extensive experiments have been performed to verify the validity of our findings and models. Table 1 shows the application of our model to intermediate-length interconnects in 10nm technology under various thermal profiles (due to Joule heating). The values for geometrical, electrical, mechanical and thermal properties of technology are obtained from [1-3][15-19].

Table 1: Stress evolution and violation checking under different temperature distributions

L	J	Temperature	Finite Element Methods		Models	
			Blech [3]	New	Extrusion	Voiding
1003	-1	T_{high}			✓	✓
		T_{low}			✓	✓
		T_{high}			✓	✓
		T_{low}			✓	✓
		T_{high}			✓	✓
	506	T_{high}			✓	✓
		T_{low}			✓	✓
		T_{high}			✓	✓
		T_{low}			✓	✓
		T_{high}			✓	✓

Units: L: um, J: MA/cm², T: K, Stress: MPa. Temperature and stress ranges: $T_{low} = 374$ to $T_{high} = 383$ and -800 to 800 MPa. Critical stresses=500MPa (dotted lines). Anode: $-l = -50$, Cathode: $l = 50$. ✓: violated, ✗: not violated, ✓: aggravated

The experimental results in Table 1 present the experiments on two similar wires with lengths of 50um and 100um. Current density of 3×10^{10} A/m² and 6×10^{10} A/m² are applied with different boundary conditions to cover several nonuniform solutions of the heat equation. We use common structures which can be adjusted by any technology. Readers may note that the presented model is technology independent and universal. It can accommodate any wiring configuration and technology through different values for material, electrical and thermal properties of

Figure 3: Left column: Applied electric potential, temperature rise (Joule heating) and evolving stress (top to bottom, respectively). Right column: normalized fluxes due to EM, TM and SM (top to bottom, respectively). The experiment shows stress evolution from a no-stress state ($t = 0$ s) to the steady state ($t = 7e7$ s = 2.2 years).

components. As it can be seen in Table 1 there are considerable differences in terms of violations predicted by the proposed model and the existing ones. They are caused by not considering TM in existing models.

In particular, when the temperature gradients are negative towards the cathode and from the anode, such gradients alleviate the tensile and compressive stresses. This can be exploited by designers to have a greater reliability margin in terms of the maximum length or current density as temperature, indeed, increases the resilience of interconnect. On the other hand, positive temperature gradients towards the cathode and from the anode, aggravate the tensile and compressive stress. Table 1 demonstrates a comprehensive scheme for the impact of different temperature distributions on immortality conditions. The conventional Blech based EM rules may assess the EM violations incorrectly (last columns in Table 1). Such effects are severer for larger current density (compare cases $3 \times 10^{10} \text{ A/m}^2$ vs $6 \times 10^{10} \text{ A/m}^2$).

In general, two situations may occur: (1) in some cases, the existing models may wrongly scrutinize reliability in unfailing parts and consequently impose unnecessary design tightening and (2) in some other cases, they may underestimate serious problems causing unpredicted behaviors or catastrophic failures to occur. The existing models for reliability evaluation are usually pessimistic in case of interconnect voiding and optimistic when extrusion occurs. Without loss of generality and for the sake of discussion, the absolute values of the corresponding critical stress are assumed to be 500MPa [3][21]. The wires therefore are assumed to just violate the critical threshold.

Figure 4: The permissible values for j and L under different thermal load. Contour lines correspond to different values of normalized thermal effect (Joule Heating) (a) $L=0$, (b) $L=2$, (c) $L=4$ and (d) $L=8$.

Table 1 demonstrates that Blech based models relying on jL product can wrongly evaluate the health of interconnects. In all cases the products of current density and length are the same and thus they are assessed to have the same reliability and lifetime. However, the proposed model distinguishes these cases properly. Indeed, the immortality of a wire should be evaluated by $jL - j^2 L^2$ rather than jL . The results are in a strong agreement with detailed FEA experiments.

For a detailed discussion on how temperature evolution and stress evolution are mutually related, case 1 in Table I is discussed in detail using the stress evolution model. The results are presented in Fig 3. For ease of discussion, the flux values are normalized by their common factor (i.e. BD/kT). Application of current density results in EM. As a side effect, a temperature rise occurs through Joule heating process. The temperature gradient produces atomic flux and consequently causes TM. While current is applied and temperature raises, stress develops simultaneously. These three fluxes compete against each other and reconcile in a steady state.

The new model confirms that thermomigration usually (i.e. for the thermal profile of $\cap$) tends to aggravate compressive stress and potentially exacerbate the risk of extrusion or shorts. On the other hand, thermomigration mitigates tensile stress and possibly alleviates the risk of voiding or opens. Indeed, atoms tend to migrate from hot to cool areas. Since the hottest location is usually towards the center of the interconnect line, some atoms travel to anode and increase the compression, and some atoms move back to cathode and compensate depletion and consequently reduce the tensile stress. Intuitively, increasing temperature usually mitigates shrinkage and intensifies expansion. This may cause serious effects (i.e. stress aggravation Thermomigration interacts with electromigration and stress migration, it may result in (1) asymmetric stress distribution, (2) early hillock formation (shorter lifetime), (3) late voiding (longer lifetime) and (4) non-end failures. The experimental results indicate that due to such effects many expected failures may not occur or some new may occur.

The proposed model also explains several experimental observations that may have been inexplicable before such as some unexpected failure locations. For instance, our experiments reveal that having temperature effect included in aging process

can be exploited intentionally to gain more design flexibility and freedom in physical design. For instance, Fig 4 illustrates the admissible values for the current density and length of an interconnect under different thermal load. The thermal load is presented in terms of $\mathcal{L}$ which indicates the heat generation due to Joule heating. The highlighted regions show the permissible combination of jL for a wire to be mortal due to voiding with respect to the thermal load. As it can be seen when $\mathcal{L}$ is zero, i.e. Joule Heating is negligible, the space for safe values of j and L can be estimated and verified by Blech's model (i.e. the outer region of 1/xy-like curve). However, for non-negligible Joule heating effect, i.e. $\mathcal{L} \neq 0$ (e.g. cases (b), (c) and (d)), term $j^2 \mathcal{L}^2$ in $jL \pm j^2 \mathcal{L}^2$, allows having larger current density without experiencing voiding violations for the same length. Similar analysis can be performed for hillock violations under different distributions. It implies increasing thermal load may loosen design rules in terms of max current density and increase design flexibility.

6. CONCLUSION

In summary, depending on the temperature evolution due to the Joule Heating and heat convection, the admissible space for values of j and L can no longer be explained by Blech's model yet our novel model captures it correctly.

The evolution of temperature within metallic interconnect due to Joule heating is studied in detail. A new model is presented to provide a steady state temperature profile under any arbitrary non-uniform conditions. The model is then incorporated in models for material migration. The stress development and aging process were investigated considering the Joule heating induced thermomigration. It was shown that neglecting such effects during reliability assessment of interconnects may lead to wrong evaluation for modern interconnect technologies. New criteria, as a result, are developed to check the immortality of wires under any thermal, electrical and mechanical conditions. These criteria do not suffer from common problems of Blech-based methods (i.e. pessimistic void predication and optimistic hillock estimation).

Various temperature profiles have been investigated in detail. It was shown, depending on the steady state profile of temperature, the voiding and hillock potential appearance will be affected, and therefore Blech based method cannot be trusted. The new models confirm that thermomigration usually (i.e. for the thermal profile of $\cap$) tends to aggravate compressive stress and potentially exacerbate the risk of extrusion or shorts. On the other hand, thermomigration mitigates tensile stress and possibly alleviates the risk of voiding or opens. In general cases, when the temperature gradients are negative towards the cathode, such gradients alleviate the tensile and compressive stresses. This can be exploited by designers to have a greater reliability margin in terms of the max length or current density as temperature. On the other hand, positive temperature

gradients towards the cathode, aggravate the tensile and compressive stress.

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