Temperature-dependence of Threshold Current Density-Length Product in Metallization Lines: A Revisit

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Abstract. One of the important phenomena in Electromigration (EM) is Blech Effect. The existence of Threshold Current Density-Length Product or EM Threshold has such fundamental and technological consequences in the design, manufacture, and testing of electronics. Temperature-dependence of Blech Product had been thermodynamically established and the real behavior of such interconnect materials have been extensively studied. The present paper reviewed the temperature-dependence of EM threshold in metallization lines of different materials and structure as found in relevant published articles. It is expected that the reader can see a big picture from the compiled data, which might be overlooked when it was examined in pieces.

1. Introduction

Electromigration (EM) is a complex current-induced mass transport phenomenon in metallic interconnecting lines. The phenomenon had been recognized as one of the most significant factors in the failure of electronic circuits and hence become the central issue in reliability. Many efforts have been done to understand the underlying physics and describe the mechanisms of EM. The earliest theoretical study of EM was known to be established by Fiks[1] and Huntington and Grone[2] whereas the simple semi-empirical description of EM phenomena was attributed to Black[3] based on the established theory. A comprehensive review on the theoretical frameworks was presented by Sorbello[4] starting from very general phenomenological equations of irreversible thermodynamics ended up with the dynamical non-adiabatic considerations. A recent introductory review on the physically-based models of EM was written by Orio et.al.[5]. It is generally known that the established models was developed based on a general assumption that EM is a Diffusion-Convection Problem in which the transport phenomena is dictated by several driving forces. Two boundary problems are introduced to provide a simple solution of EM-induced mass transport equation that has a practical use[6]. The first boundary condition refers to a metallic line connecting two infinite vacancies reservoir subjected to an electric current. The second one was derived from a line packed in two diffusion barriers (perfectly blocking boundary condition). Such a model considering vacancy accumulation due to the flux divergence of EM-induced flux and normal Fickian diffusion flux was proposed by Shatzkes and Lloyd[7]. The examination of the model solution from the second boundary value has lead to two main deficiencies involving a very short time scale to reach the maximum vacancy supersaturation and a very low value of it. In line with Rosenberg and Ohring[8] who revealed that the lifetime is mainly dictated by the void growth mechanism. Orio et.al.[5] revealed
that it will prevent vacancy condensation-aided void formation so that a critical vacancy concentration cannot be employed to predict the interconnect failure. It was assumed that the situation can only be resolved by introducing the mechanical stresses into the equation[5].

The existence of mechanical stresses in EM dated back to the Blech Experiment on EM in thin Aluminum films on Titanium Nitride. Blech[9] proposed that the deceleration of EM in the experiment was associated with the generation of compressive stress around the anode alligned with the possible explanation of EM retardation in Al suggested by Ainslie et.al.[10]. The presence of the stress was experimentally proven by the crack of the overlying SiN as well as the formation of long aluminum extrusion through etched holes in the area of cathode. Similar to the pressure effect investigated in SiN-covered film, it was also assumed to operate in uncovered Al having only their nature oxide.

Referring to Blech[9], the retardation effects took place when the electrical driving force was counter balanced by mechanical driving forces associated with the stress gradient. Since the event cannot be exist at any current, it was assumed that there must be a critical stress the film can withstand before permanently deforming as manifest by the formation and growth of hillocks. Moreover, it was also assumed that the super-saturation of vacancies or deficiency of atoms might decrease the chemical potential resulting in the chemical potential difference. The average chemical potential gradient opposing the EM then was calculated by dividing it with the stripe line.

Applying Ainslie et.al.[10] assumption that the free energy difference between the both ends of the stripe is proportional to the product of atomic volume and the normal stress difference between stripe ends and neglecting any other chemical potential gradients, Blech[9] proposed a threshold equation involving the stress. The equation, however, cannot be used to differentiate the relative contribution of anode and cathode area to the free energy difference between the both ends of the stripe. The effect of strain rate was not studied as the equation was developed based on the assumption that the materials behave plastically ideal. The temperature-dependence of the threshold-length product revealed from the experiment was qualitatively assumed to be associated with the temperature-dependence of Aluminum flow stress.

![Figure 1](image1.png)

**Figure 1.** Schematic Illustration of Blech Experiment as Explained in Ref.[9]

2. Stress and Electromigration

More quantitative discussion of the stress and EM in metallization lines were presented by Tu[11], Ross[12], Kirchheim[13], and Korhonen et.al.[14]. Tu[11] has employed the thermodynamic of irreversible process to analyze the interaction of stress and EM, assuming that it is basically a creep process. Ross[12] developed a numerical model for the formation of EM damage in thin metallization which was able to calculate stress developed around the EM flux divergence sites and also to predict time to failure. Physical-based model of the transient stress build up during EM was developed by Kirchheim[13] who calculated for the first time time-dependence tensile and compressive stresses. A pair of partial differential equation for vacancy concentration and stress was developed from the physical basis, employed to solve the problem numerically and, for 3 limiting cases, analytically, and compared with the experimental results. One of the significant drawbacks of the model came from the approach that neglects the direct contribution of the vacancy flux to the stress development as
discussed later by Sarychev et.al.[14]. The second physically-based analytical model was developed by Korhonen et.al.[15]. Despite the model was proposed to improve previous works and provide a closed analytical solution, it contains such important flaws as revealed later by Llyod[16] and Sarychev et.al.[14]. The major limitations came from the abandonment of vacancy relaxation and the assumption of vacancy equilibrium. Clement and Thompson[17] re-examined the formulation of Korhonen model comprising the assumptions and approximations in the Korhonen treatment and was able to show that the analytical solution for a semi-finite line with a blocking boundary condition only provide a good approximation when the stress build up is small. More accurate analytic formulation was derived to express the maximum stress evolution in the confined interconnect. Sarychev et.al.[14] proposed a new model using an approach similar to that used for thermal stress model. The key different of the approach compared to that of the established models[13,15,17] is the comprehensive consideration of the total deformation at given position $(x_1,x_2,x_3)$. Employing this approach, the entire stress tensor evolution can be described and related to the boundary value of the line. By doing so, a general 3D equation linking the transport phenomena and stress evolution had been derived to describe the distribution of mechanical stress within the metallization line attached on the surface and confined by passivation layer. Prior to Sarychev et.al.[17], Gleixner and Nix[18] had proposed a physically-based model of EM and stress-induced evolution in realistic microstructures. Unlike Sarychev et.al.[14], the model to solve diffusion-stress equations was developed in 2D while taking into account the 3D effects of passivation constraints. Sukharev, Zschech, and Nix[19] made an improvement by involving mass transport along the grain boundary in addition to that along the interface. It was assumed that the mass transport path was depending on the competing activation energy along it.

3. Blech Effect

One of the important phenomena in EM is the existence of the threshold current density-length product. The existence EM Threshold or Blech Product had been proven and well accepted. The threshold was able to be quantified by measuring drift velocity and explained by the opposing gradient caused by the accumulation and depletion of atoms at the strips end.

Drift velocity was formerly defined by Huntington and Grone[2] as:

$$v_d = \frac{D_o |Z^*| e \rho j}{kT} \ \ \ \ (1)$$

where:

- $v_d$ = drift velocity
- $eZ^*$ = effective charge of ion
- $\rho$ = electrical resistivity
- $j$ = electrical current density
- $D_o$ = diffusion coefficient
- $\Delta H$ = activation energy
- $k$ = Boltzman’s constant
- $T$ = temperature

Blech[9] designed an edge displacement experiment from which drift velocity was measured by observing the movement of strips end. The threshold was able to be determined by assuming that the net drift velocity of EM becoming zero whenever the value was reached.

The varying drift velocity is caused by diffusional back flows during EM associated with the free energy different of moving species between the strip ends. The backflow is hence proportional free
energy gradient and reciprocally proportional to the length. The net drift velocity can also be expressed in term of EM velocity and backflow velocity[20].

\[ v = v_{EM} - v_{BF} = \frac{D}{kT} Z^* \rho_0 \frac{\Delta G}{kT} \frac{1}{l} \]  

(3)

where:

- \( v \) = net drift velocity
- \( v_{EM} \) = EM drift velocity
- \( v_{BF} \) = backflow drift velocity
- \( \Delta G \) = free energy different
- \( l \) = length of strip

When the net drift velocity is zero, then:

\[ \frac{D}{kT} Z^* \rho_0 \frac{\Delta G}{kT} \frac{1}{l} = \rho_* \]  

(4)

Re-arranging the equation will result in:

\[ \left( j/l \right)_c = j_c l = j_l = \frac{\Delta G}{Z^* \rho_0} \]  

(5)

where:

- \( \left( j/l \right)_c \) is a constant at any given temperature known as “threshold current density-length product” or simply “Blech product”.

The threshold current density-length product has a significant technological importance as the sub-threshold line will not suffer EM because of the zero net flux. As the Blech product is constant and stress current densities are typical for any given applications, the critical length \( l_c \) is known as the Blech length. Both Blech product and length has a significant role in the design and manufacture of electronic circuits and testing structure.

One of the particular interests in electronic packaging is the dependence of Blech product on the temperature. Temperature-dependence of Blech product was firstly established from Blech experiment[9]. The phenomenological equations for EM threshold as a function of temperature can be derived from the effective charge number of an ion in EM, \( Z^* \), that consist of two parts [1,2,4,11]:

\[ Z^* = Z_{ed}^* + Z_{wd}^* \]  

(6)

Referring to Tu[11], \( Z_{ed}^* \) can be recognized as the nominal valence \( Z \) of the metal while ignoring the dynamical screening effect around the ion. \( Z_{wd}^* \), on the other hand, corresponds to the momentum change effect between the carriers and the ions.

Huntington and Grone[2] expressed \( Z_{wd}^* \), in terms of specific resistivity ratio.

\[ Z_{wd}^* = -Z \frac{\rho_d}{N_d} \frac{m_0}{m^*} \]  

(7)

where:

- \( \frac{\rho_d}{N_d} \) = specific resistivity of a diffusing atom
\( \frac{\rho}{N} \) = specific resistivity of a normal atom
\( m_0 \) = free electron mass
\( m^* \) = effective electron mass

Assuming the specific resistivity of an atom in a metal is proportional to the scattering elastic cross section, which is then proportional to the average square displacement from equilibrium or \( \langle x^2 \rangle \), Einstein’s model of atomic vibration can be employed to estimate the cross section of normal atom[11].

\[
\frac{1}{2} m \omega^2 \langle x^2 \rangle = \frac{1}{2} kT
\]  

(8)

where:
\( m \) = atomic mass
\( \omega \) = angular vibrational frequency

Assuming that the atom and its surrounding has acquired the temperature-independence kinetic energy of diffusion \( \Delta H_m \), Tu[11] was able to specified the cross section of scattering of the diffusing atom \( \langle x_d^2 \rangle \) as:

\[
\frac{1}{2} m \omega^2 \langle x_d^2 \rangle = \Delta H_m
\]

(9)

The ratio of equation (8) and (9) was obtained as:

\[
\frac{\langle x_d^2 \rangle}{\langle x^2 \rangle} = \frac{2 \Delta H_m}{kT}
\]

(10)

It can be seen from this ratio that the resistivity of a normal metal changes reciprocally with temperature. This change is attributed to the equation (8) reflecting the well-established findings that the resistivity of normal metal varies linearly with temperature above Debye temperature.

Substitution of (10) to (7) and (6) will result in:

\[
Z^* = -\frac{\Delta H_m m_0}{kT m^*} - 1
\]

(11)

Assuming 12 \( \langle 110 \rangle \) paths in FCC lattice, the factor of \( \frac{1}{2} \) was cancelled out (see Fig.2).

Using available data of \( \Delta H_m \), Tu[11] was able to show the agreement between calculated and measured data. Furthermore, the calculated \( Z^* \) for Au was also found to agree well with the measured \( Z^* \) from Huntington and Grone[2] as depicted in Fig. 3.

The temperature dependence of Blech Product, therefore, can be generally examined by combining equation (11) with (5).

\[
(jl)\epsilon = \frac{\Delta G}{-Z \left[ \frac{\Delta H_m m_0}{kT m^*} - 1 \right] \rho}
\]

(12)
Having examined the temperature-dependence of Blech Product thermodynamically, we can always assume that the EM Threshold is a function of temperature. The relationship, however, is not straight forward, as there exist in the equation other factors that are also temperature-sensitive. Therefore, it is important to study the real temperature-dependence characteristics of EM threshold in common interconnect materials. The present paper reviews the temperature-dependence of EM threshold of different interconnect materials and structures as found in relevant publications. It is expected that the reader can see the entire perspective on the compilation of scattered data, which might be overlooked when it was examined separately in more details.
4. Temperature-Dependence of EM Threshold

Temperature-dependence of EM Threshold in various metallization lines had been studied extensively since Blech’s Edge Displacement Experiment in 1976\[9\] and the results had been published accordingly. It was revealed in this remarkable paper that, along with $v/j$, $(ji)_c$ of thin Al films on Titanium Nitride (Ti-N) were temperature-dependence. Furthermore, it was also learned from Blech’s Experiment that the drift velocity increased with temperature rise whereas the threshold-length product decreased with temperature. Blech\[9\] speculated that the increase of the threshold with the decrease of temperature might be related to the increase of Al flow stress. In addition to this common sense, it was assumed that there could be further increase in stress gradient due to the tensile stress near the cathode. Of the important phenomena in EM is the existence of the threshold current density-length product. The existence of the EM Threshold or Blech Product had been soundly proven and well accepted. The threshold was able to be quantified by measuring drift velocity and explained by the opposing gradient caused by the accumulation and depletion of atoms at the strips end.

Temperature-dependence characteristics of Al, Au, and Cu based metallization lines had been studied extensively. The edge displacement method and its variants had been long established in the studies of EM Threshold in thin film metallization lines\[9,21-27\]. Important modifications of this method were introduced by Ogawa et.al.\[28\]. Technologically more realistic methods were developed in the integration package level starting from single inlaid to three levels of interconnect structure. Various structure and configurations of line, via, and contact had been developed to study EM phenomena of metals and alloys at various temperature \[28-32\]. Studies were typically performed in the range between room temperature and 550°C.

Dual Damascene Cu structures had become a field of interest since early 2000s\[25-37\]. In 2003s, the effects of porous low-k on the temperature-dependent EM Threshold had also become an attractive area\[32,34,36,37\]. In addition to the key interconnect materials, solder materials including the lead free ones were also studied\[38,39\]. Edge displacement test was nevertheless used in the latest study\[39\]. Optical and electron microscopy methods had been long established in characterizing the product. The use of such a non-conventional characterization method as AFM in the area was also introduced. Figure 4 summarizes the experimental data on the temperature-dependence of EM threshold since Blech’s experiment in 1976\[9\].

The linear temperature-dependence of the EM Threshold had been clearly shown by Blech and his co-workers \[9,21\]. Linear dependency of EM Threshold with temperature can be derived from Equation (12). Similar with the argument found in Tu\[11\], Equation (12) can be simplified if $\Delta H_m$ is much larger than $kT$. Then the equation is simplified and the relationship is made clear.

\[
(ji)_c = \frac{\Delta G}{-Z} \frac{\Delta H_m}{m^*} \frac{m_0}{e\rho} \tag{13}
\]

\[
(ji)_c \propto -T \tag{14}
\]

Based on such assumptions, the only factor that is temperature-sensitive is electrical resistivity, $\rho$. Provided the temperature is below Debye Temperature, in which the electrical resistivity does not increase with temperature, the linear relationship is maintained. Blech experiment on Al and Au in the selected range of temperature seems to follow this assumption very well. This simple linear relationship, however, is not always maintained.
Figure 4. Plot of EM Threshold (A/cm) vs. Temperature (°C) Experimental Data[9,21-36,38]
Brief analysis on most of data obtained from Schreiber[22] has shown that there is a transition temperature at which the EM Threshold is no longer sensitive to the temperature change. Furthermore, the characteristic curve of EM Threshold vs. Temperature can be generally divided into two region i.e. (1) the region where the product is constant with the temperature increase (time independent region), and (2) the region where the product is decreasing with the increase of temperature (time dependent region).

Similar phenomena was found in many experiment with Cu-based interconnect as shown in Fig. 6. The two regions and transition temperature for example had been clearly seen in Frankovic and Bernstein[23,24]. Different assumptions, however, were proposed to explain such similar phenomena. Frankovic and Bernstein[22] assumed that $Z^*$ to be inversely proportional to $\rho$ and therefore the product of $Z^*\rho$ is temperature-independence. It was proposed that the gradient should be responsible for any variations of Blech Product. Blech[9], like many others[11-18], assumed that there exists the gradient of stress corresponding to chemical potential. Moreover, in line with Blech[9] who assumed the temperature-dependence behavior is related to temperature-dependence flow stress as well as Tu[11] who stated that EM is essentially a creep problem, Frankovic and Bernstein[23] suggested to use Ashby Deformation Map to explain transition temperature.
Other lessons learned from the big picture of EM Threshold vs. Temperature are the influence of initial material structure, geometry and surrounding as well as testing structure and condition on the temperature-dependence behavior. It can be learned from the map that different initial structure of material, which is also related to the fabrication or assembling process. The difference between annealed/un-annealed, bamboo/polycrystalline, and Reactive Ion Etched/Damascene, dielectric constant, for instance, were well recognized. Effect of surroundings such as encapsulation, cover, capping layer, passivation layer were also be recognized. The variation of testing structures and conditions may also affect the product. There existed edge displacement and via testing of many variants. Most of them are self-made. As the testing system is not well standardized, it is not a simple task (if not impossible) to compare data from different experiments apple to apple. Idealized curve and effect of initial materials and surroundings is depicted in Fig. 6 and Fig. 7.

**Figure 6.** Idealized Curve of \((j\ell)_c\) vs. \(T\)

**Figure 7.** Idealized Effect of The Initial Material (Process History, Structure and Properties) (Left) and Its Surrounding (Right)
5. Concluding Remarks

Temperature-dependence of EM-threshold has been revisited. Phenomenological threshold equation had been derived from the velocity drift and examined thermodynamically to find a constitutive law for temperature-dependence of EM threshold. Experimental data from relevant publication had been reviewed and studied. The plot in general can be idealized into (a) temperature-independent region and (b) temperature-dependent region within it a temperature transition may exist. This temperature may be related to either competing temperature-sensitive thermodynamic factor or deformation mechanisms map based on established assumptions.

General effects of initial materials (process history, geometry, and structure) and surroundings (cover, encapsulation, capping layer, passivation layer) were generalized and idealized despite of the fact that not all of the available data can be compared apple to apple due to variations in testing structure and condition. Since EM threshold and its temperature-dependence has significant implications on design, manufacture, and testing of electronics, it is suggested to develop a more general and well standardized testing system that is able to produce comparable and more reliable EM Threshold Data at various temperatures.

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