DAMAGE MECHANICS OF LOW TEMPERATURE ELECTROMIGRATION AND THERMOMIGRATION

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ABSTRACT

Electromigration (EM) and thermomigration (TM) are processes of mass transport which are critical reliability issue for next generation nanoelectronics. The purpose of this project is to study influence of low temperature on EM and TM interaction. In this paper, a model for EM and TM process is proposed and has been implemented in finite element method. The governing equations include mass conservation, force equilibrium, heat transfer, and electricity conduction equations. A damage evolution model based on thermodynamics is introduced to evaluate the degradation in solder joints subjected to high current densities and high temperature gradients. The results are compared with experimental data to validate the model.

INTRODUCTION

Electromigration is a mass diffusion process which happens as a result of an exchange of momentum between charge carriers (free electrons) and the thermally activated ions of a metal conductor. The phenomenon of electromigration has been known for more than 100 years. But it has become a concern only when the miniaturization of integrated circuits and recently solder joints made it a significant reliability problem. Electromigration takes place at noticeable levels only when current density is higher than a critical value. For example electromigration is not a problem in our daily used electric current supply system. In bulk wires used for home circuitry, according to National Electrical Code (NEC)[1], the maximum allowed current density is in the magnitude of several hundred Amp/cm\textsuperscript{2} due to Joule heating.
Any current density exceeding this value will produce enough heat to melt an insulator metal wire. However current density in nanoelectronics is above $10^6$ Amp/cm$^2$ in interconnects and more than $10^4$ Amp/cm$^2$ in solder joints. Under such high a current density the driving force from scattering free electrons colliding into metal atoms is insufficient to make electromigration a significant problem. Because of low current density historically electromigration has not been a major problem in electrical systems. However, things changed in 1966 when the Integrated Circuits (IC) were commercialized. Electromigration went onto the stage in focus as a critical reliability issue in flip-chip technology[2, 3]. In ICs, electricity is conducted via thin Al or Cu film stripes that are in direct contact with an effective heat sink (Si). Because most of the heat generated in interconnects, transferred to the heat sink via Si chip, as a result thin film conductors can withstand current densities at least two orders of magnitude greater than traditional insulated bulk wires. This allows current densities of nearly $10^6$ Amp/cm$^2$ with minimal Joule heating. The increase of the operating current inevitably causes the current density to be carried by each solder bump to rise dramatically too. Therefore, electromigration has become an inevitably critical reliability issue for solder joints, too.

Moreover, Joule heating generated under the conditions of a high electrical current density is highly localized, especially in SiC power electronics devices. Thermal gradient is thus created in the medium, which leads to thermomigration(TM). TM is a mass migration of compound material caused by temperature gradient. If an initially homogeneous two phase alloy is placed within a temperature gradient, mass diffusion can lead to a disintegration of the components. One component diffuses preferentially faster to the cold end, and as a result the hot region becomes depleted in that component. This effect is called the Soret effect (also Ludwig-Soret effect) in fluids [4]. This resulting diffusion is known as thermomigration or thermal diffusion.

Almost all previous electromigration research works ignored the role of TM in EM induced failure. This is perhaps because thus far the magnitude of TM flux has been assumed to be much smaller than EM. Recently scientists theoretically deduced that when the thermal gradient is large enough, it can be the dominant driving force [5-7]. Additionally, some experimental work has been performed to show that indeed TM can play a significant role in EM-induced failure in thin film cracking[8]. Ye et al [7] was the first to show that TM forces under high current density can be larger than EM in flip chip solder joints.
PHYSICAL MODEL

Electromigration is a process in which many mechanisms work together. The major factors include, mass transportation, electrical conduction, heat transfer, and the corresponding mechanical stresses. A numerical model has been developed and implemented by FEM that accounts for all these mechanisms. In this model, vacancy diffusion governed by the vacancy conservation equation; mechanical deformation is governed by the force equilibrium equations, in which we considered the damage related viscoplasticity properties of the solder material; heat transfer is governed by the Fourier’s law; and electric field is governed by Maxwell’s equation of conservation of charge.

GOVERNING EQUATIONS

High current density and large temperature gradients create four distinct diffusion driving forces:

(1) Electrical current field forces, which include two driving mechanisms. One is the electrostatic force of the electric field. The other one is so called the electron wind force as originally suggested by Skaupy[9]. The electron wind force refers to the effect of the momentum exchange between the scattered moving free electrons and ionic atoms. This momentum exchange happens because of scattering of free valence electrons, which collide with metal atoms and push them in the direction of electron flow[10, 11].

(2) Thermal gradient is one of the strongest driving forces. Joule heating generated by high electricity current density is highly localized and consequently results in a large thermal gradient in the medium, which leads to thermomigration. The physical explanation behind thermomigration is not well understood. But recent literature shows that thermomigration could play a significant role in electromigration induced failure [6-8, 12, 13].

(3) Spherical stress gradient is another driving force. As mass transport happens from one side to the other, compressive stresses build in one side and tensile on the other. The gradient of these stresses usually counteracts other driving mechanisms [14-22].
The atomic vacancy concentration gradient, which is small compared to those induced by the former three items, initially, however, as vacancy concentration increases on one side and mass density increases on the other side, this force becomes critical.

Electromigration is a diffusion controlled mass transport process. It is governed by the following vacancy conservation equation, which is equivalent to mass conservation equation.

\[
C_{v_0} \frac{\partial c}{\partial t} + \nabla q - G = 0 \tag{1.1}
\]

Where

- \(C_{v_0}\) Equilibrium vacancy concentration in the absence of any stress field
- \(c\) Normalized vacancy concentration and \(c = \frac{C_v}{C_{v_0}}\)
- \(C_v\) Vacancy concentration
- \(t\) Time
- \(q\) Vacancy flux which is given by [23],

\[
q = -D_v C_{v_0} \left[ \nabla c + \frac{Z^* e}{kT} (\nabla \phi) c + \frac{c f \Omega}{kT} \nabla \sigma^p + c \frac{c}{kT} Q \nabla T \right] \tag{1.2}
\]

Where

- \(D_v\) Effective Vacancy diffusivity
- \(Z^*\) Vacancy effective charge number
- \(e\) Electron charge
- \(\phi\) Electrical potential
- \(j\) Current density (vector)
- \(f\) Vacancy relaxation ratio, ratio of atomic volume to the volume of a vacancy
- \(\Omega\) Atomic volume
- \(k\) Boltzmann’s constant
- \(T\) Absolute temperature
- \(\sigma^p\) Spherical part of stress tensor, \(\sigma^p = \text{trace}(\sigma) / 3\)
is heat of transport, the isothermal heat transmitted by moving the atom in the process of jumping a lattice site less the intrinsic enthalpy.

\[ G = -C_\text{eff} \exp \left( \frac{(1-f) GV_{\text{cr}}}{kT} \right) \]  

(1.3)

\( \tau_s \) is characteristic vacancy generation/annihilation time.

THERMODYNAMICS OF DAMAGE EVOLUTION DUE TO THERMOMIGRATION

It has been shown by Basaran et al [23-27] that the damage in solids can be quantified by the change in disorder parameter in Boltzmann equation which gives the relationship between entropy and disorder in a system. A variable \( D \) is defined as the ratio of the change in disorder parameters to the original reference state as follows:

\[ D = D_{cr} \left( 1 - e^{\frac{\Delta s}{kT}} \right) \]  

(2.1)

In this equation \( D_{cr} \) is the critical damage parameter used to define the failure for specific application. \( \Delta s \) is change in entropy with respect to a reference state. \( k \) is the Boltzmann’s constant. \( N_0 \) is Avogadro’s number. If \( D_{cr} \) is taken as 1, \( D \) starts from zero and reaches 1 at the end.

The entropy produced in an irreversible process caused by thermomigration can be expressed as

\[ \Delta S = \int_0^T \left( \frac{1}{2} \sigma \cdot \varepsilon_p + \frac{C_\text{f} D_{cr}}{kT^2} \sigma : F_k : F_k + \frac{1}{T} \sigma : \varepsilon_p' \right) \, dt \]  

(2.2)

Where

\[ F_k = - \left( Z^* \varepsilon_p \Phi + \frac{f_\text{cr} \sigma' \Phi'}{T} \nabla T + \frac{Q^*}{c} \nabla c \right) \]  

(2.3)

\( \sigma \) is deviatoric stress tensor,
\( \varepsilon_p \) is inelastic strain tensor.

The damage evolution formula can be given by plugging (2.2) into (2.1).
The test vehicle used in this study is a 27mm × 27mm × 0.97mm flip-chip package, which involves a 7.62mm × 7.62mm × 0.74mm silicon die interconnected to a 0.3mm thick two-layer substrate with 720 solder bumps shown in Figure 1 and Figure 2. The diameter of the solder bump is 140μm while the standoff is 100μm. The aluminum trace interconnect on the die is 1μm thick and the copper trace on the PWB substrate is 15μm thick. The solder alloy is 95.5Sn-4Ag-0.5Cu (SAC 405 in wt %) which is bonded with 96.5Sn-3Ag-0.5Cu (SAC 305) presolder.

The layout of circuits and solder joints on the flip-chip test vehicle is shown in Figure 1. Only a single daisy chain at the edge of the die on the encompassed region is electrified with a constant electric current of 2.5Amp. The configuration of the daisy chain, the path of the current and solder joint numbers are shown in Figure 2. During testing, the daisy chain shown in Figure 2, was connected to a constant DC power supply with the positive terminal connected to V1+, while the negative terminal to P-, as shown in Figure 1.

A series of specimens were tested in thermal chamber with ambient temperatures of -20°C, -30°C, -40°C, and -50°C. Thermal chamber used in this experiment has a 1m³ test compartment equipped with two 30-horsepower (22.4kW) compressors. Cooling performance, given by the manufacturer, to cool 113.4 kg of aluminum from +85°C to −54°C is 30°C/minute on average. Compared to the mass of our test vehicle, the test chamber capacity is very large in such a way the cooling of the die would be almost instantaneous. Failure is defined as when the system electrical resistance exceeds 1 ohm in all stressing cases, as to avoid melting of solder joint and consequently destroying the microstructure.

Thermal properties for the materials used in analysis are listed in Table 1[28]. In damage evolution analysis, the molar heat flux of SAC405 alloy is 22.16kJ/mole[29], and the temperature dependent diffusivity is using $D_v = 272e^{-\frac{48953}{RT}} (\times 10^8 \ m^2/s)$[30]. The rest material properties used in this paper come from Lin.[31]
DISSCUSSION OF RESULTS

Because of miniature size of the solder ball, it is not possible to measure the solder ball temperature directly. Instead we measured temperatures on top of the die and bottom of the substrate as reference temperatures. A 3D full finite element model (FEM) is employed to perform steady state Joule heating analysis. The difference between the measured and calculated temperature at top of die and bottom of substrate is fairly accurate for -40°C and -50°C ambient temperature, but FEM simulations predicts -20°C and -30°C, with some error exceeding 20%. This may results from the complexity of temperature dependent thermal properties of the system.

Figure 3 and Figure 4 show the current density map at the critical cross section of the solder joint when the ambient temperature is -50°C, of solder #7 and solder #10, respectively. These two solder joints have the maximum current density. From these figures we can see that the current distribution is not uniform across the section. Current crowding phenomenon is observed at the upper left corner in solder #7 and at the upper right corner in solder #10, respectively. The current density at these locations is $5 \times 10^4 \text{A/cm}^2$.

Because the aluminum interconnect on the die is very thin and current density is highly localized, high temperature gradients are observed in both solder #7 and solder #10. When ambient temperature is -50°C, in Figure 5 we notice that the maximum temperature gradient exists in solder #6, which is about 1700°C/cm, between top and bottom. In Figure 6 we see that 13°C temperature difference exists between the top and the bottom of the solder #7, which yields a temperature gradient of 1300°C/cm, between top and bottom; and 12°C temperature difference in solder #10, corresponding to 1200°C/cm in temperature gradient, from top to bottom.

In Figure 2 we notice that the current flow does not pass through solder #6. Therefore electromigration cannot happen in solder #6. Thermomigration dominates the mass transport process (TM only) in solder joint #6. In solder #7, current enters the solder bump from the copper trace in the base, passes through the solder ball, and flows out through the aluminum trace on the crown. The electrons move in the opposite direction to the current. Considering the downward temperature gradient, we conclude that the overall effect in solder #7 is the superimposition of thermomigration and electromigration in the downward direction (TM+EM). In solder #10, current flows from the top to the bottom. The electron flow
result in an electron wind force which is pushing mass upward. At the same time, thermal gradient drives atoms from top to bottom. Hence solder #10 experience thermomigration and electromigration in the opposite directions(TM-EM).

Figure 8 is a backscatter scanning electron microscope (SEM) picture for solder bump before testing. The brighter part of the solder ball is SAC405, the darker finger is Cu$_6$Sn$_5$ Inter Metallic Compound(IMC), which can be found in both the top side, Figure 8 (b), and the bottom side, Figure 8(c). After applying current for 68 hours at the ambient temperature of -50°C, we discovered that Cu$_6$Sn$_5$ become thinner in the top side, as can be seen in Figure 9(a). This may result from the disintegration of Cu$_6$Sn$_5$ under the thermal gradient force. Due to the higher diffusivity of copper than tin, copper atoms move faster than tin atoms to the cold side and leave tin behind. Because of the limit supply of copper atoms at the chip side, Cu$_6$Sn$_5$ cannot reform. Figure 10 shows normalized vacancy concentration in solder #6 at -50°C which is similar to SEM image of this joint in Figure 9, there is a large vacancy concentration at the top side of the joint. Similar thing happens in solder #7 with the presence of electromigration driving force. The movement of mass to the bottom side leaves behind vacancy at the top side (Figure 9(b) and Figure 11). In solder #10, the electromigration driving force overrides the thermal gradient force with an overall force upwards. From Figure 9(c) we cannot see any reduction in Cu$_6$Sn$_5$ IMC thickness in the top side or the bottom side.

Figure 13, Figure 14, and Figure 15 shows the damage contour as defined by (2.4) after 70 hours in solder #6, solder #7, and solder #10 respectively. In these simulations, damage parameter is normalized to $D_{cr} = 0.094$, in order to meet the failure criterion defined during the experiments, which is electrical resistance of 1 ohm. By comparing Figure 13, Figure 14, and Figure 15, it can be concluded that solder #7 is the most critical solder joint in the entire test vehicle. When solder #7 fails ($D = D_{cr}$), the damage parameters in solder #6 and solder #10 are still far below failure criterion. The comparison of 3 solder balls show that although TM alone (solder #6) does not produce damage as fast as EM, but it can slow down (solder #10) or hasten (solder #7) the EM process significantly, as seen in Figure 16.

Figure 17 shows the evolution of damage in solder #7 at different levels of ambient temperature, including -20°C, -30°C, -40°C, and -50°C. The mean time to failure is defined by the moment when $D = D_{cr}$. All the results from simulation are compared with experimental data, as is shown in Figure 18. From the comparison we can observe that the simulation predicts the MTTF for -40°C and -20°C pretty
well, but overestimates the case of -30°C, slightly. It is obvious that -30°C is a critical temperature, below which MTTF increases significantly.

CONCLUSION AND DISCUSSION

In this paper, a fully coupled temperature-diffusion-displacement damage model for electromigration and thermomigration process is presented. The model has been verified by experimental results. By investigating the damage evolution process in a flip chip package, some important findings are discovered. Performance of solder joint is very sensitive to the service temperature. In both our experiments and simulations as can be seen in Figure 18, when the ambient temperature increases, the MTTF drops down dramatically. Relation between MTTF and temperature is not linear. -30°C is a critical temperature.

Electromigration is a critical reliability issue for solder joints subjected to high current. Thermomigration due to Joule heating can significantly accelerate EM damage or can slow it down. Since electromigration is always accompanied with thermomigration process, the combined effect should always be taken into account.

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REFERENCES


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<td>Density</td>
<td>7.39×10^{-15} (kg/μm³)</td>
<td>8.92×10^{-15} (kg/μm³)</td>
<td>2.70×10^{-15} (kg/μm³)</td>
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<td>Thermal Conductivity</td>
<td>57.3×10^{-6} (W/μm.K)</td>
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<td>Electrical Conductivity</td>
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<td>Specific Heat</td>
<td>200 (J/kg. K)</td>
<td>385 (J/kg. K)</td>
<td>902 (J/kg. K)</td>
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