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# Prediction of Solder Interconnects Wetting and Experimental Evaluation

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## Abstract

A new analysis methodology to predict solder interconnect wetting is developed to reveal the causes of poor wetting during flip chip assembly and to provide solutions. The analysis methodology characterizes solder wetting as two different processes: the wetting dynamics of the solder contact line and the generation of the minimum energy surface of the molten solder. Surface Evolver is implemented to generate the surface shape of solder during wetting. Since there are no quantified dynamics models for solder materials, a solder wetting dynamics model is developed based on former wetting models proposed for other materials. The contact angle relaxation of spreading over time is measured in specially designed experimental setup for model development. As a result of experiment and model evaluation, a best wetting dynamics model is developed and the development of analysis methodology is completed. The study of reflow process parameter effects is ongoing.

## Introduction

As the density of interconnects in electronics packaging increases and the size of microelectronic devices decreases rapidly, the formation of the solder joints during the assembly process becomes a more important issue. To make a robust interconnect, the solder bump must come into contact with the base metal where it wets the pad. Under ideal conditions, the molten solder spreads across the substrate surface and reacts with a metal substrate to form a good metallurgical bond. However, one hundred percent yields during assembly are not practically accomplished in the real world. The failure to achieve interconnect yield due to poor solder wetting leads to increased costs in electronics manufacturing. When faced with wetting problems in industry, the typical approach is to perform a repetitive experimental evaluation of the process parameters. Since this trial and error approach is not based on fundamental physics, the underlying causes for poor solder wetting are not discerned and tedious repetition of experimental work is needed to develop a solution for each specific case. Therefore, the development of solder interconnect wetting model is essential to overcome the shortcomings of current approaches.

In spite of the importance of solder interconnect wetting in electronics assembly, currently there is no quantified wetting model for solder materials based on physical principles. As a consequence, there has been no attempt to relate the chip assembly process parameters to the solder wetting behavior. In the field of wetting dynamics, a tremendous amount of fundamental studies have been performed. The majority of this work has involved simple systems, such as water or polymer on a non-reactive surface [1-7]. These non-reactive wetting studies are performed based on two different approaches: hydrodynamics [2, 3] and molecular kinetics [4]. The two approaches focused on different energy dissipation channels. The efforts to combine these two approaches were also performed [5-7]. Several researchers have studied the wetting dynamics of reactive materials [8-12]. Reactive wetting studies considered that reaction or diffusion drives wetting dynamics. But no wetting dynamics model was applied for tin-lead or lead-free solder materials due to the complexity of the solder wetting phenomena and experimental difficulties.

The first objective of this study is to determine a solder interconnect wetting dynamics model by performing the solder wetting experiment in specially designed setup. Former wetting dynamics models proposed for the other materials were evaluated by experiment and the most appropriate equation was selected. This theoretical model includes the impact of environmental temperature and geometry on solder wetting. Secondly, a new analysis methodology to predict solder interconnect wetting is developed based on solder interconnect wetting model and Surface Evolver, which finds equilibrium shape of the molten solder at any instant. The analysis methodology will reveal the causes of poor wetting during electronics assembly and to provide solutions, thereby reducing process design, development, and implementation time.

## Analysis Methodology

The analysis methodology characterizes solder wetting as two different processes: the wetting dynamics of the solder contact line and the generation of the minimum energy surface of the molten solder. Therefore, the analysis methodology consists of finding equilibrium shape of the molten solder at any instant, determining the wetting dynamics, and interfacing the two. Important assumption of the analysis methodology is that the transition speed to minimum energy shape is much faster than contact line wetting speed. Therefore, once the triple contact line coordinates of the solder sphere or bumps are determined by the wetting dynamics equation, the solder surface evolves toward minimal energy shape simultaneously. Surface Evolver is implemented to generate the surface shape of solder during wetting. The Surface Evolver is an interactive

program for the study of surfaces shaped by surface tension and other energies, subject to various constraints.

To determine the wetting dynamics, a C++ subroutine based on the previously developed wetting dynamics equation is used to calculate the solder evolution with time, and C++ is also used to develop the interface between the equilibrium solution and the wetting dynamics solution.

## Experiment

### Experimental

Wetting experiment was performed in specially designed setup for evaluating the wetting dynamics equations. Since solder wetting requires appropriate temperature environment, a temperature chamber, which can provide high temperature ramp rate, high temperature capacity, constant temperature maintenance, and gas input for environmental control, is developed. The chamber is fitted with two transparent windows for monitoring the wetting motion from outside of the chamber. A Redlake PCI-2000 color high-speed camera, which can capture up to 2000 frames per second, and a video acquisition system with 2 gigabytes video RAM were employed for monitoring the fast evolution of solder wetting motion. A 7X microscopic lens was attached to the camera to magnify the small solder drop. The chamber control and temperature acquisition during experiment were performed with the Labview program in the computer via RS232 communication. The schematic diagram of the experimental setup is shown in Figure 1.

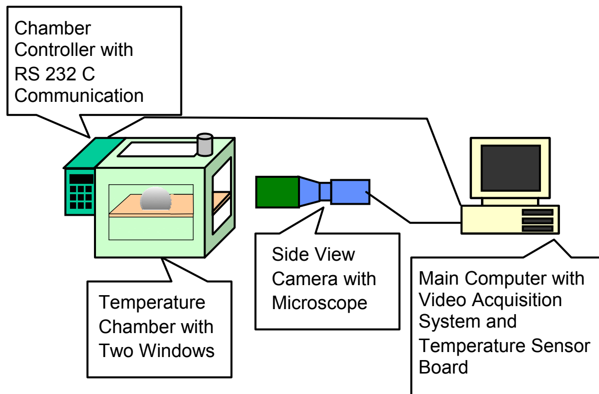


Figure 1: Schematic diagram of experimental setup

To evaluate the impact of temperature profile on solder wetting, isothermal wetting experiment is essential. For isothermal wetting experiment, solder sphere should be kept away from the wettable surface during temperature ramp, and then solder contacts the wettable substrate at desired temperature. Specially designed accessory containing vertical movement system and substrate holder was constructed. A glass slide is adopted as non-wettable substrate, which holds the solder sphere from upside by aid of flux before solder sphere contacts wettable surface. The schematic of this design is shown in Figure 2. The micrometer controls the position of solder sphere very accurately.

The captured images during wetting experiments were analyzed with the image processing software, Optimas™.

### Materials

Samples of 635μm diameter eutectic tin-lead solder spheres were employed for the first test. Gold-coated copper clad was used as a substrate. Before the experiments, the substrates were cleaned in HCl solution, rinsed in distillated water and then dried with purified air gun. Low residue flux (Alpha 9171) and Rosin flux were applied to the samples to remove the oxide from the solder and the substrate

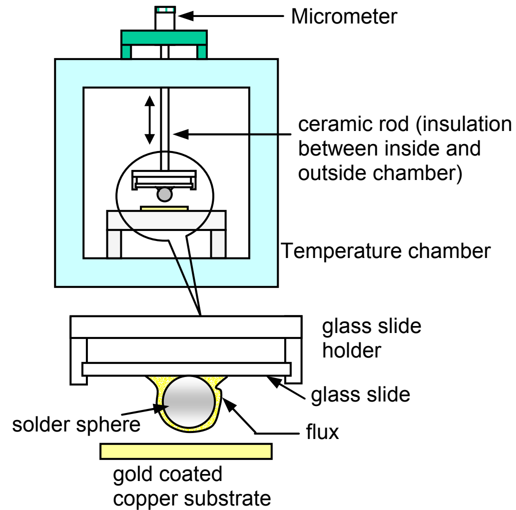


Figure 2: Schematic diagram of accessory design

## Results and Discussion

### Wetting dynamics model development

The procedure of wetting dynamics development is shown in Figure 3. In order to develop a solder interconnect wetting model and an analysis methodology, a solder interconnect wetting is simplified as a liquid solder droplet wetting on a substrate.

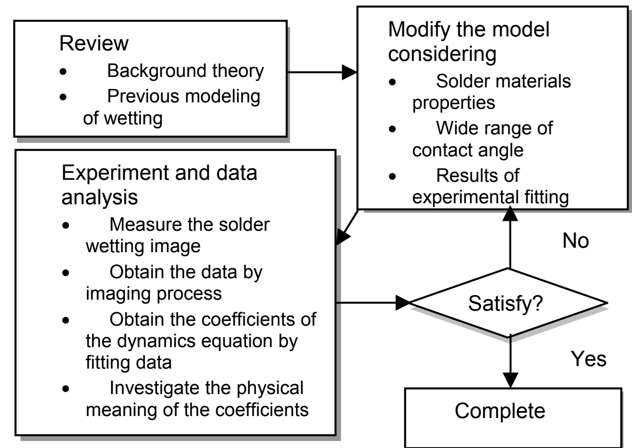


Figure 3: Procedure chart of wetting dynamics equation development

Surface tension, gravity, and chemical reaction are regarded as driving forces for solder wetting from the review of background theory and previous works. The gravity force is generally ignored in modeling the wetting of small solder spheres with high surface area to volume ratios. In the

assemblies considered in this research, the size of the solder interconnect is small enough to ignore gravity effects. A Bond number, $Bo = \frac{g(\rho_L - \rho_V)d^2}{\gamma_{LV}}$, where, $\gamma_{LV}$ is the liquid-vapor surface tension, $g$ is the gravitational acceleration, $d$ is the diameter of liquid sphere and $\rho_L$, $\rho_V$ are respectively the liquid and vapor density, represents gravitational force to surface tension force ratios. The value of Bond number with solder properties is 0.079, when the diameter of solder sphere is set to 635µm. This small value of Bond number validates the assumption.

The correlation between the driving force of wetting in reactive system and chemical reaction was investigated. Chemical reaction might be a factor to affect wetting dynamics and wetting angle. However, experiments with tin-lead solder materials with various tin contents shows the higher chemical activity was not directly correlated to higher wetting speed or smaller wetting angle [13]. A Study of the driving force of reactive wetting was performed for the system in which the formation energy varied, but the surface energy term kept constant. The result of this experiment showed that only the final interfacial chemistry of the system correlates the wetting in reactive system, not with the intensity of interfacial reactions [8,10]. Therefore, this study will not consider the chemical reaction as a dominant driving force for solder wetting specially, in high speed wetting stage. The surface tension imbalance, which usually considered as a driving force of droplet wetting, tends to be the dominant force in the solder wetting regime considered in this research.

As governing physical processes, molecular kinetics within the three-phase zone near the wetting line, and viscous dissipation inside bulk flow are investigated.

Molecular kinetic approach [4] assumes that the leading contribution to the dissipation during spreading is due to the adsorption and desorption of molecules within the three-phase zone near the wetting line. Considering a driving force as the imbalance of surface tension and adopting Eyring's molecular kinetic theory of liquid [14], the wetting velocity ν was given by:

$$v = 2K_{eq}\lambda \sinh\left(\frac{\gamma_{LV}\left(\cos\theta_{eq} - \cos\theta\right)}{2nk_B T}\right)$$

$$K_{eq} = \left(\frac{k_B T}{h}\right)\exp\left(\frac{-\Delta G^*}{Nk_B T}\right)$$

Where, $K_{eq}$ is equilibrium frequency of molecular displacement, $\Delta G^*$ is a molar activation free energy of wetting, $T$ is the absolute temperature and $N$ is the Avogadro number, $k_B$ is the Boltzmann constant, $h$ is the Plank constant, $\lambda$ is the length of each molecular displacement, $n$ is the number of adsorption sites per unit area, and $\theta_{eq}$ is the equilibrium contact angle.

For the hydrodynamic approach, which assumes dissipation during spreading was mainly due to viscous flow within the wedge, a simplified Cox model [3,5] was evaluated for solder material. The equation is simplified as:

$$v = \gamma_{LV}\frac{\theta^3 - (\theta_{eq})^3}{9\mu \ln\left(\frac{r}{s}\right)}$$

Where, µ is the viscosity of the liquid, $r$ is the characteristic macroscopic length for the flow occurring during wetting, and $s$ is the slip length, below which the continuum description is not valid.

Molecular kinetic approach and hydrodynamic approach satisfy the driving force defined in this study with different energy dissipation processes.

Experimental Results

Isothermal wetting experiments were performed at 193°C for wetting model evaluation and the examples of captured images are shown in Figure 4.

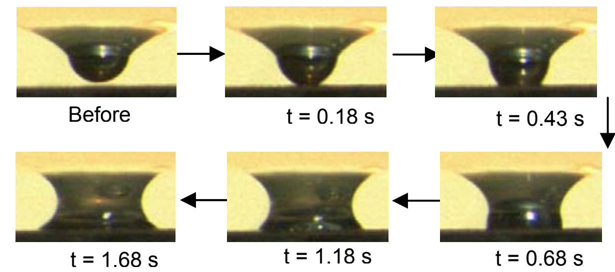


Figure 4: Wetting images captured in specially designed chamber.

Material properties for model evaluation are presented in Table 1. The value of $\gamma_{LV}$ at 193°C is approximated referring to former publications [13,15-18]. Equilibrium contact angles were measured at 193°C. The average value of the equilibrium contact angle was 7.2° for this configuration. For molecular kinetic model, $n$ is calculated using liquid solder density and λ is obtained from the relation of $n$ ($n = \lambda^{-1/2}$). Since the liquid density changes very slightly with temperature, $n$ and λ are assumed to be constant value with temperature.

Two wetting models were fitted to experimental data with fitting parameters of $K_{eq}$ for the molecular kinetic equation and $s$ for the hydrodynamic equation. Curve fitting was performed by modifying a nonlinear fitting solver, MINPACK, which was developed by Argon National Laboratory.

| Properties | Eutectic Solder |
|---|---|
| Liquid Density, $\rho_L$ | 8.4g/cm$^3$ |
| Melting points, $T_m$ | 183 °C |
| Surface tension with flux, $\gamma_{LV}$ | 420mN/m |
| Equilibrium contact angle, $\theta_{eq}$ | 7.2° |
| Number of adsorption sites per unit area, $n$ | 5.5 x 10$^{22}$ atoms/m$^2$ |
| Length of each molecular displacement, λ | 4.3 x 10$^{-12}$ m |
| Viscosity, µ | 2.2 mPa s |

Table 1: Material properties of eutectic solder at 193°C

Figure 5 shows the contact angle relaxation of eutectic tin-lead solder with low residue flux at 193°C and best fits of molecular kinetics model and hydrodynamics model. Dashed curve and Solid curve are obtained by fitting hydrodynamic model and molecular kinetic model respectively Molecular kinetics model shows good agreement with contact angle relaxation, when the fitting parameter $K_{eq}$ is 6.65 x $10^{10}$. However, hydrodynamics model shows a different trend with the experimental data. The parameter value of $s$ from curve fitting is order of $10^{-100000}$. This value does not have any physical meaning.

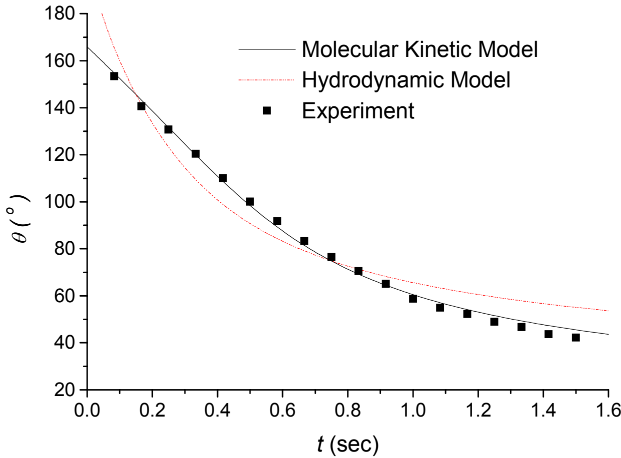


Figure 5: Contact angle vs. time at 193°C with low residue flux

The evaluation of wetting models indicates that energy dissipation occurring near triple contact line due to the molecular kinetic motion is the dominant process during solder wetting. The hydrodynamics model that assumes the viscous dissipation due to the flow is dominant is not applicable for solder wetting because the viscosity of molten solder is very low and surface tension is very high. Therefore, molecular kinetic model was chosen for solder wetting dynamics. Originally, molecular kinetic model was developed for non-reactive wetting system. However, the imfluence of chemical reaction is included in the values of $\Delta G^*$ and $K_{eq}$ for solder wetting application. The impacts of process parameters, such as temperature profile, surface tension variation due to the types of fluxing agents and environmental gas, on $\Delta G^*$ and $K_{eq}$ are being investigated.

Wetting dynamics dependence on temperature profile was studied with isothermal wetting experiments at different temperature. If the temperature was higher than 210°C, the low residue flux, currently used in this experiment, evaporated before desired temperature. Therefore, isothermal experiments were performed only at 193°C and at 203°C. The contact angle relaxations at both temperatures were very slightly different from each other as shown in Figure 6. $K_{eq}$ at 203°C (6.88 x $10^{10}$) was little bit larger than $K_{eq}$ at 193°C (6.55 x $10^{10}$) because the driving force due to the imbalance of surface tension worked negatively with the temperature increase and the contact angle relaxations at both temperatures were almost same. More experimental investigation on $K_{eq}$ at various temperatures and with different surface tension environments should be performed to assess this dynamics model.

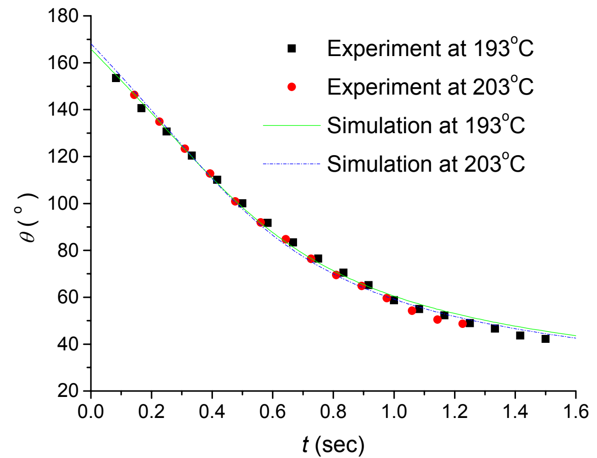


Figure 6: Contact angle vs. time at 193°C and at 203°C with molecular kinetics model with low residue flux

## Conclusions

A new analysis methodology to predict solder interconnect wetting was suggested and is under development by combining a wetting dynamics equation and Surface Evolver. As a first step for analysis methodology development, solder wetting dynamics was investigated. Based on governing physics defined, molecular kinetic dominant model and hydrodynamic models were selected and evaluated with experimental wetting data. Since molecular kinetic model showed very good agreement with solder wetting experiment, it is chosen as solder wetting dynamics model for this analysis methodology. Isothermal wetting tests at different temperatures were performed and more experimental study with various temperature and fluxing agents is ongoing to accommodate the impacts of process parameters.

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