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Underfill flow simulation based on lattice Boltzmann method

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ABSTRACT

Underfill process is carried out mainly to prevent interconnection failures caused by the mismatch of CTE between the die and the substrate in flip chip encapsulation. Owing to troubles in calculating the capillary force, i.e., result-based and interface reconstruction, the underfill flow cannot be well characterized by current simulation methods. In this paper, we present a mesoscale underfill simulation method based on three-dimensional LBM (lattice Boltzmann method) with D3Q19 velocity set and LBGK (lattice-Bhatnagar–Gross–Krook) evolution model. In this method, the GIPM (generalized interparticle-potential model) is first proposed to model the capillary flow, which can solve the fluid–fluid interaction and the solid–fluid interaction in a unified manner. A geometric model for underfill simulation is then developed. The solid wall is divided into three parts, i.e., the substrate, the die and the solder bump, and each part is allowed to have a different wettability by assigning a mesoscale interaction parameter. For verification purpose, three underfill cases, which are different in wall wettability, are examined. In each case, besides the experimental results, we also present numerical results predicted by a VOF multiphase method with CSF capillary model. The results show that the proposed method has a good performance in the underfill simulation.

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1. Introduction

Due to its high electrical performance and high interconnect density, flip chip technology has become a promising method in electronics packaging. However, the fatigue cracking and electrical failure, mainly caused by the mismatch of CTE (coefficient of thermal expansion) between the die, the substrate and solder bumps, restrict the usage of this technology. To prevent these potential failures and also to improve reliability of the interconnection system, underfill process is carried out [1]. Fig. 1 shows the classic capillary-driven underfill process. Encapsulant (a modified epoxy) is firstly dispensed along the periphery of one, two or three side(s) of the die, and then is filled into the gap by capillary action at a low speed. After the gap is filled up, the package is taken into an oven where the encapsulant is cured. It is important to note that the encapsulant can fill into the gap only with the help of capillary action. Hence, the fluid flow behavior in the gap, which will directly affect the reliability of the packages, depends on the capillary action.

In recent years, the underfill process has been studied and simulated based on macroscale finite methods, such as FEM [2–4], FVM [5–6], and FDM [7]. As the drive force, the calculation of capillary force is crucial in these macroscale simulations. In the existing study, the capillary action was treated as a force exerted on the melt-front interface (the free surface). The calculation models of the force can be classified into two types: the surface force model and the volume force model. In the surface force model, the surface tension force was considered as a surface force (pressure) according to the Laplace equation [8–11], and then was introduced in the solution as a pressure boundary on the melt-front. While in the volume force model, the surface tension force was considered as a volume force [7]. The basic concept of this model was the continuum surface force (CSF) model proposed by Brackbill [12]. In the CSF computational model, the surface tension force was converted into a form of volume force, which was proportional to the product of the interface gradient and the surface curvature. The volume force was then included in the momentum equation as an external force term.

In both models, the capillary force is related to the free surface curvature, thus the flow front tracking method need be coupled during the underfill simulation, as shown in Fig. 2. In each time step, the flow front was reconstructed first, and then the capillary force was calculated out using the interface information. After that, the force was exerted on the melt-front interface to drive the fluid flow. From the calculation process, the capillary force depended upon the interface rather than determining the interface. Therefore, that capillary force calculation is result-based, which cannot characterize the nature of the capillary process. Essentially, capillary force originates from the unbalanced molecular force at interface, and the interface is a result of the force. Furthermore, the interface reconstruction is approximated using an interface tracking method, such as the VOF method or the level set method. Unfortunately, this is always not so easy for the underfill simulation because of the complex gas/liquid/solid interface.

In order to evaluate the underfill flow process more objectively, and also to eliminate the capillary calculation troubles, a LBM (lattice

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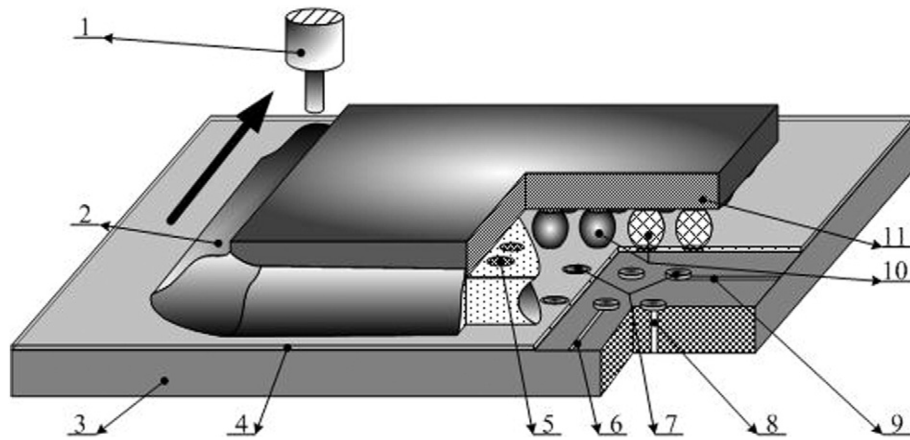

Fig. 1. The conventional underfill encapsulation process for one line dispensation: 1 dispenser; 2 encapsulant; 3 substrate; 4 solder mask; 5 under bump metallization (UBM); 6, 9 printed circuits; 7 solder pads; 8 through hole; 10 solder bumps; and 11 die.

Boltzmann method) based simulation method is established according to the multiphase IPM (interparticle-potential model). The IPM was first proposed by Shan and Chen [13–14] in 1993. The pseudo potential between mesoscale particles is introduced, and is used to characterize interactions between the fluid phases. The effective force of the k-th phase is calculated according to the gradient of the pairwise potential, and then the force is exerted on the mesoscale particles conversely by modifying the equilibrium velocity in the collision operator [15]. The force guarantees surface tension effects. Shan and Doolen [16] corrected the unphysical artifacts in Shan and Chen's IPM by modifying the equilibrium velocity and the common velocity. Martys and Chen [17] introduced solid–fluid interaction force (wall adhesion) into the IPM model by adding a wall effect. Benzi et al. [18] developed Martys and Chen's model by assigning the solid wall as a free density. The contact angles could be easily adjusted through changing the pseudo density. With the fluid–fluid interaction and solid–fluid interaction, the IPM has been successfully applied to study wetting and spreading [19], capillary filling [20–22], bubble deformation [23] and immiscible fluid displacement in porous media [24], but the IPM based underfill simulation method has not been reported yet.

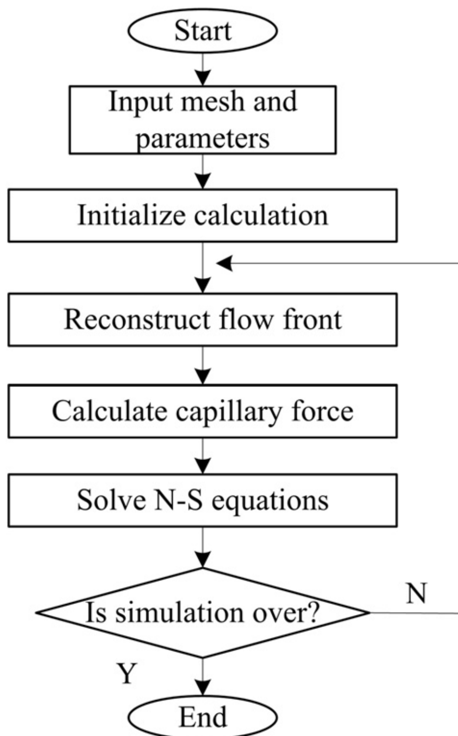

Fig. 2. Flow chart in the macroscale underfill simulation method.

In former models for underfill flow simulation, the capillary force was calculated from the free interface rather than determining the interface. Hence, that capillary force calculation was result-based, which could not characterize the nature of the capillary process. Essentially, capillary force originates from the unbalanced molecular force at interface, and the interface is a result of the force. In addition, the calculated capillary force was then exerted on the melt-front interface to drive the fluid flow, which causestrouble. Firstly, the calculated capillary force is a surface force, which cannot be added into the momentum equation directly to solve the problem. Secondly, the melt-front interface is approximated by a flow front tracking method, which might not be so accurate for the real capillary interface. However, the proposed mesoscale underfill simulation method is devoted to eliminate these troubles, and evaluate the underfill flow process more objectively. Unlike conventional models, the proposed simulation method is based on the mesoscale LBM. The fundamental idea of LBM is to solve a discretized Boltzmann equation on a lattice, where the fluid is modeled with mesoscale particle. It is known that there is microscopic interaction among molecules, and the capillary force is resulted from the unbalanced molecular force at interface. This interaction varies with distance and phase, which is the microscopic potential. Based on this physical nature, the potential between mesoscale particles is introduced into the LBM to characterize the interaction between the particles. The potential is different for different phase particles, and the same for same phase particles, thus the interfacial dynamics is natural implemented according to the interparticle potential. For the fluid–fluid interaction and the solid–fluid interaction, a unified calculation model is developed by setting a solid particle density. Furthermore, this method needs not to track interfaces, and complex interface is produced naturally according to the density distribution function.

In this paper, a mesoscale underfill simulation method is established based on three-dimensional LBM (D3Q19 velocity set and lattice-Bhatnagar–Gross–Krook evolution model). In this method, the GIPM (generalized interparticle-potential model) is first proposed to model the capillary flow, which can solve the fluid–fluid interaction and the solid–fluid interaction in a unified manner. In the GIPM, the improved IPM is used to model the fluid–fluid interaction. For the solid–fluid interaction, a solid particle that is close to a fluid particle is set to the wall material density, and then is treated as fluid particle during the calculation of inter-particle force. But the interparticle potential strength parameter is different with that for the fluid particle. Thus, the classic IPM model is developed as the GIPM. A geometric model for underfill simulation is developed accordingly. The solid wall is divided into three parts, i.e., the substrate wall, the die wall and the solder bump wall, and each part is allowed to have a different wettability by assigning a different mesoscale

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