FEA to Tackle Damage and Cracking Risks in BEoL Structures under Copper Wire Bonding Impact

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Abstract

With the recent increase in Gold (Au) wire cost Copper (Cu) wire becomes an attractive way to manage overall package cost. On the other hand, Copper wire bonding introduces much higher mechanical impact to underlying BEoL structures and actives because of the higher stiffness and lower ductility of Copper compared to Gold. These trends are accompanied by the application of new porous or nano-particle filled materials like low-k and ultra low-k materials for Back-end of Line (BEoL) layers of advanced CMOS technologies. As a result, higher delamination and cracking risks in BEoL structures underneath bonded areas represent an increasing challenge for the thermo-mechanical reliability requirements. To overcome the related reliability issues the authors performed a two level nonlinear FEM-simulation approach. Initially nonlinear axisymmetric modeling and simulation of the copper bonding process are coupled with a spatial simulation model of the whole BeoL and bond pad structure. Cracking and delamination risks are estimated by a surface based cohesive contact approach and the utilization of a crushing foam constitutive material model for ultra low-k materials.

1. Introduction

With the recent increase in Gold (Au) wire cost Copper (Cu) wire becomes an attractive way to manage overall package cost. Copper comes also with similar electrical properties. So, self inductance and self capacitance are nearly the same for Gold and Copper. Additionally, Copper wire has lower resistivity. On the other hand, Copper wire bonding introduces much higher mechanical impact to underlying BEoL structures and actives because of the higher stiffness and lower ductility of Copper compared to Gold. Moreover, the electronic industry pushes miniaturization and increases functional integration and in parallel drives the feature sizes down to the nanometer range – currently 28 nm, 20 nm and below. These trends are accompanied by the application of new porous or nano-particle filled materials like low-k and ultra low-k materials for Back-end of Line (BEoL) layers of advanced CMOS technologies. As a result, higher delamination and cracking risks in BEoL structures underneath bonded areas represent an increasing challenge for the thermo-mechanical reliability requirements. To tackle the related reliability issues the authors performed a two level nonlinear FEM-simulation approach because of the expected huge model sizes, feature size spreading, computing resources and stability issues. Instead of utilizing a submodelling approach were displacements will be transferred from a global model to a detailed local model the transfer of impact forces/stresses will be preferred. This allows utilizing those impact data from one specific wire bonding simulation for several distinct under bond structures. The intention is to start with nonlinear axisymmetric modeling and simulation of the copper bonding process which provides the transient surface stress data at the bonding interface. The transmission of these bonding impact data into a spatial simulation model of the whole BEoL- and bondpad-structure allows subsequently the nonlinear transient bonding impact simulation. It can be realized by specific User-subroutines for use within the FEM-code ABAQUS™. Ultrasonic impact and pull test loading steps complete the loading history. A lot of work is published in the literature of more than the last 10 years - exemplarily represented by [1]-[5] - where plane-strain, axisymmetric, 3D, quasistatic, dynamic, ultrasonic, transient nonlinear issues have been utilized but, nine times out of ten stresses, strains of accumulated plastic strains where evaluated knowing that localized singularities induce strong mesh density dependence or are altogether useless. Therefore, fracture mechanics and damage approaches are preferred for use, similar in fracture to [6] but, quiet different in damage modeling.

The cracking and delamination risk is investigated by a surface based cohesive contact approach which simulates here the initiation and propagation of damage and cracking in ultra low-k (ULK) regions along predefined crack paths. For testing reasons a crushable foam constitutive model is additionally used for the ULK materials inside the BEoL bond pad structure. Several BEoL design variations have been investigated and evaluated to give insights on the potential crack initiation sites within the BEoL stack and to estimate the risk of fracture during each process step.

2. The 2-Level Modeling Approach

In order to obtain the bonding forces on top of the bonding surface an axisymmetric model was established to simulate the pure bonding process without taking the ultrasonic vibrations into account. Basic information are the initial diameter of the bond wire, the shape of the free-air ball (FAB), the shape of the bond capillary, a smeared model of the underlying BEoL-stack, contact and friction between wire and capillary as well as at the bonding interface. Beside the given speed and displacement of the capillary also several boundary conditions and the constitutive behavior of all materials – also smeared properties – complete the simulation model – see Fig 1.

This highly nonlinear simulation model utilizes an adaptive re-meshing approach together with stabilization control options. As further steps of simulation the bond interface will be fixed and subsequently a cool down step and a pull test will be simulated by removing the capillary and pulling at the upper end of the bond wire. The postprocessor is then forced by a python script to pick out the necessary components of the stress tensor at the bond surface as a function of the distance r from center vs. time. A separate newly-created tool is reading these results and translating it to polynomial approximations σ (r,t). These results (polynomial coefficients, total time, order of the polynomial and the current bonding radius) will be stored for further utilization in spatial simulations.

The FE-code ABAQUS™/Explicit which is utilized here allows for introducing USER subroutines for several specialized subtasks. Here USER subroutines specify non-uniform distributed loads and prescribed nodal displacements conditions have been written and implemented. These subroutines take and apply the simulation results from axisymmetric bonding simulation and introduce ultrasonic vibration into the spatial simulation of the local transient stress distribution during bonding, ultrasonic and pull test. For this purpose the USER subroutines initially read in the data from the axisymmetric simulation step. They provide the necessary loading data for every element, node and integration time increment (within the current bonding contact radius) by interpolation in space and time.

In summary, 3 different BEoL bond pad stack parameterized model versions have been established – see Fig 3 and 4. With the intention of obtaining impressions about the cracking and delamination risks and associated critical locations a cohesive damage approach is used which utilizes the surface based cohesive behavior approach instead of a direct cohesive zone modeling (CZM - [7]) approach. Crack initiation and damage evolution parameters are taken from fracture mechanics experiments. Such cohesive contacts have been prepared within ULK-regions near its lower copper line plane to capture the possible damage region and also on top of the copper panel to capture delamination at the upper copper interface.

As some current ULK materials consist of nano-pores it seems near at hand that those materials could behave like metallic or polymeric foams. That's why, for testing reasons, a crushable foam constitutive model following [8] is applied. It reflects the enhanced ability of a foam material to deform in compression due to cell wall buckling/cracking processes (it is assumed that the resulting deformation is not recoverable instantaneously and can, thus, be idealized as being plastic for short duration events). The force vs. displacement curve reflects the force break down after exceeding the compressive strength, the subsequent ongoing pore compaction with a load level at the crushing strength and densification of the material with closed pores afterwards. In view of the fact that dedicated crushable foam material properties for ULK are not measured up to now some estimated values taken from fracture tests have been utilized for the present. So, the yield stress vs. plastic strain behavior is taken into account while volumetric hardening is assumed to take place – rate independent for the first time.

3 Results and Discussion

Following the intention of the designed modeling approach the axisymmetric global model had to be adapted first to the final bonding geometry found by cross sectioning (Fig 2, left). Therefore, the capillary movement, the FAB diameter and Copper plasticity properties are taken as variables. Repeated axisymmetric simulations with adapted parameters allowed for achieving a fitting geometry – see Fig 2. Subsequently, the 3D local FE-models were created and simulated with the help of the impact stresses at the bond interface (as previously described) by making use of the surface contact based cohesive approach and the crushable foam constitutive model for ULK.

The following results exemplarily demonstrate how the introduced damage and delamination modeling approaches work. Nano pore compression in ULK is represented by the accumulated plastic strain after bonding – see Fig 5 and Fig 8, in terms of the crushable foam constitutive model.

While no delamination at the upper copper plane material interface is observed under pure bonding impact, ongoing damage could be seen after a third of ultrasonic impact time - growing up to a level of 75 % at its end (Fig 6). Understandably, the highest damaging regions are located near the outermost boundary of the bonding region with regard to the ultrasonic vibration orientation. As a result of accumulated damage within the upper copper plane material interface after bonding and ultrasonic vibrations the delamination completes at the very beginning of the pull test. Accordingly, the middle area underneath the bond sticks together a bit longer (Fig 7).

The results of all models of under bump structures have been investigated and compared. Despite of some materal/damage property uncertainties, the simulation results show interesting insides into the damage processes underneath the bond area. Therefore, it is one goal of the ongoing research to enhance all modeling assumptions. Additionally, the accuracy of the utilized modeling approach will be reviewed by a complete 3D bonding model containing bond wire, FAB, capillary and bond pad structure as well as all loading conditions.

4. Summary

Copper wire bonding is an attractive way to manage overall package cost. But, Copper wire bonding introduces much higher mechanical impact to underlying Back-end of Line (BEoL) structures because of the higher stiffness and lower ductility of Copper compared to Gold. Additionally, the application of new ultra low-k materials for BEoL could lead to higher delamination and cracking risks. To tackle the related reliability issues the authors performed a two level nonlinear FEM-simulation approach. Initial nonlinear axisymmetric modeling and simulation of the copper bonding process is coupled with a 3D local simulation model of the underlying BEoL-structure. Cracking and delamination risks are investigated by a cohesive contact approach and by utilizing a crushable foam constitutive material model for ultra low-k materials. Even if some damage parameter taken into account are relatively uncertain, the simulation results show interesting insights into the damage processes underneath the bond area. The verification of the modeling assumptions as well of the enhancement of damage parameters are topics of ongoing research and should lead to a helpful tool supporting the development of robust under bump structures.

Acknowledgement

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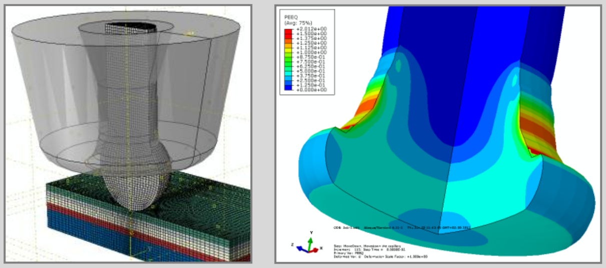
Fig 1 Axisymmetric model of the bonding process and accumulated plastic strains after bonding

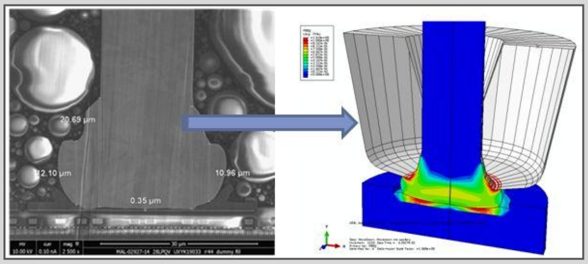

Fig. 2 Cross-section of a bond ball (left) and FE-model representation incl. capillary

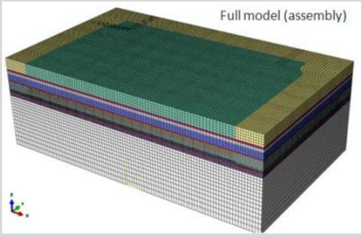

Fig. 3 Complete 3D local model

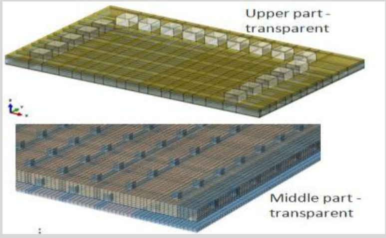

Fig. 4 Details of the 3D local model

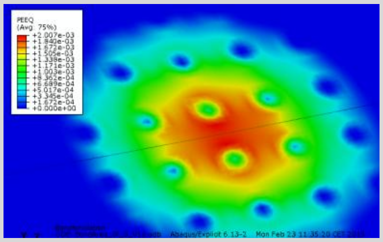
Fig. 5 ULK bonding pore compaction

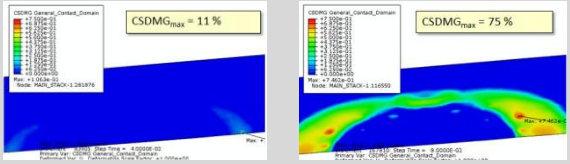

Fig. 6 Interface damage at start and end of ultrasonic

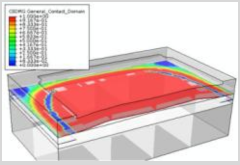
Fig. 7 Pull test debonding

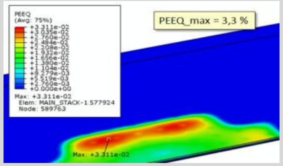

Fig. 8 ULK ultrasonic pore compaction