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Characterization of critical conditions for fracture during wafer testing by FEM and experiments

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ABSTRACT

In this work, we investigate finite element models of an imprinting scenario of a needle into a thin metallic film together with corresponding experiments in order to analyze the critical conditions that lead to brittle fracture in Back End Of Line (BEOL) bond pad stacks during wafer testing. We investigate the elastic-plastic material properties of the individual BEOL material layers and propose a plasticity law in terms of a **stress-strain curve for the aluminum layer**. Instrumented indentation testing is undertaken in order to reproduce the conditions that BEOL pad stacks are exposed to during wafer testing. Along with this, physical failure analysis reveals the dominant failure modes in the BEOL stack after indentation. We investigate the influence of silicon oxide and copper layers embedded below the first silicon oxide layer on failure. Finally, we provide an approach value for the **fracture strength of the silicon oxide** film that shows good agreement with previous literature data.

1. Introduction

Wafer testing is an essential step during integrated circuit manufacturing in order to verify the electrical performance of the circuits. During this process, metallic needles on a probe card, which are typically made out of Tungsten, contact the bond pads on the wafer mechanically. Electric signals are sent through these needles so as to verify the functionality of the corresponding circuits. In order to reduce the electric contact resistance between the needles and the contacted bond pad metallization layers, a minimum contact force is required. By contrast, the contact force may not exceed a maximum value since this would imply brittle cracking of the top SiO_2 (also referred to as “silicon oxide” or just “oxide” in this paper) layer underneath the pad metal. The brittle failure of SiO_2 layers is caused by over-critical tensile stresses that exceed its tensile strength and usually emerge due to layer bending. This was reported in several publications by means of experimental (see Refs. [1,2]) and simulation results (see Refs. [3,4]).

In general, the most dominant influence factors on oxide failure are probe needle geometry, chip structure (including numerous different layers) and overdrive, i.e., the vertical movement of the chuck, resulting in a vertical contact force between needle and metal pad. According to the experimental results shown in Ref. [1,2], the overdrive was the mainly relevant influence for cracks there. Another outcome of the experiments presented therein was that the risk of cracking got significantly reduced by lowering the pattern density of metallization in the metal layer directly embedded below the oxide and also in other metal layers beneath.

To date, the main standard methods used for the improvement of wafer testing have been based on trial-and-error experiments. However, only simulation methods based on Finite Element Modeling (FEM) are principally able to provide a physics-of-failure approach regarding fracture in complex three-dimensional realms of small microelectronic devices. In a reliability framework, FEM simulations alone are a meaningful means to obtain insight into dominant failure mechanisms. Knowledge of the critical values of mechanical stress and deformation in the chip layers relevant for fracture allows for obtaining quantitative information regarding the robustness of the chip structure during needle-pad interaction. This implies a tremendous potential of saving cost and resources by avoiding large test matrices. In Ref. [3] some previous approaches to wafer testing by means of FEM models are summarized.

When speaking about the robustness of BEOL structures during wafer testing (or wire bonding), the elastic-plastic properties of the pad layer such as the elastic modulus E and the hardness H, as well as the hardening behavior, should be considered first of all. Hardness is a measure for the mechanical resistance of a material against deformation

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by a compressive force exerted by an indenter. Thus, it provides an idea of the interaction of needle and pad layer as well as mechanical stress and deformations in the chip structure. In general, hardness is not an intrinsic material property but depends as well on the indenter and the imprint force [5]. Furthermore, hardness is related to the yield strength σ_y of a material by Tabor's formula [6]. In the case of most metals, where the ratio of σ_y/E is small, the relation $H = C^*\sigma_y$ applies with $C \approx 3$ [6].

Moreover, FE modeling relies on constitutive material laws represented in terms of stress-strain curves. The required model parameters, i.e., elastic modulus, yield strength, and hardening coefficients can be determined by experimental means. For example, instrumented indentation [7] does not only allow measuring the elastic modulus but also enables retrieving the yield strength via the hardness.

The first aim of this work was to find a good quantitative correlation between experiment and FE simulation. Once this was achieved, the second aim was to retrieve the critical conditions leading to BEOL failure during the wafer testing process from simulation results. Already in Ref. [3] a qualitative approach to different failure modes during wafer testing was developed, based on FEM. This work, by contrast, provides a quantitative physics-of-failure approach by means of two-dimensional axisymmetric and three-dimensional models built in ANSYS, together with the experimental results from instrumented indentation testing done at Infineon Technologies. The setup of the FE simulation model and the experimental background are explained in Section 2. The theory supporting the FE models is described in Section 3. Finally, the results are presented in Section 4: an initial analysis of the influence of different material properties on the characteristics of indentation load-displacement curves is provided in Section 4.1. In Section 4.2, a material law in terms of a stress-strain curve is derived in order to describe the elastoplastic behavior of an aluminum layer with copper content (AlCu). In Section 4.3, the critical forces leading to brittle oxide failure in a test chip structure are studied. In addition, we propose a value for the fracture strength of the oxide, based on a simulation approach. The main simulation results are discussed in Section 4.4, while Section 4.5 deals with a case study, where instrumented indentation was performed onto two different BEOL stack structures. This example illustrates the reduction of chip robustness when metal layers are embedded below the oxide layer. Eventually, we present the conclusions and prospective for future work in Section 5.

2. Simulation setup and experimental background

The FE simulation model of the wafer testing process presented in this work only considers one single probe needle tip and those chip layers that have relevant influence on the probability of brittle failure. In addition, the simulation results undergo a comparison to the outcomes of indentation testing. Instrumented indentation [7], being an ultra-precise and highly-resolving method, allows for accurate and reproducible experimental conditions regarding the application and measurement of load and displacement into surface. Thus, it enables similar conditions as present during wafer probing on BEOL pad stacks.

The experimental details of the BEOL layers and probe needles were provided by Infineon Dresden: maximum applied force to oxide fracture, layer thicknesses, material data, and the shape of the needle tip. For our FEM simulations we made the following basic assumptions:

- The probing needle applies load onto the BEOL pad stack in the vertical direction solely. This means that the influence of the scrub or horizontal displacement of the needle is discarded here.
- Frictionless contact is assumed between the needle and the pad. Refs. [5,8–11] already stated that changes in friction conditions do not lead to discernible differences in the numerical predictions of the load-penetration curves during micro-indentation testing. In Ref. [12], the authors stated: "The modeling results show that the effect of the friction coefficient on indentation testing is very little and can be ignored.". Following this approach, we have assumed frictionless contact. Nevertheless, in Refs. [13,14], a non-negligible effect of friction during indentation on load-displacement characteristics was detected. For completeness, an analysis of the effect of different friction coefficients ranging from 0 to 0.2 can be found in Appendix B.
- The effect of surface roughness during indentation has not been considered in this work. As stated in Refs. [15,16] the surface roughness of the layer in contact with the indenter affects the measured hardness and the displacement of the indenter. Nevertheless, for large indentation depths, that is, at least 20 times the roughness scale of the layer, the impact of roughness on the characteristics of the indentation imprint is negligible. As to this work, relevant indentation depths are in the range of one micrometer, and the above condition is fulfilled with roughness scales below 50 nm. Thus, neglecting the impact of roughness appears acceptable in our modeling.
- For modeling of needle probing and indentation, this work focusses on one single type of needle tip while putting an emphasis on the influence of critical load and material properties of the layers. The needle tip used here has a spherical shape with a diameter of 10 µm. It is modelled as a rigid solid, because its stiffness is much higher than that of the BEOL layers. Prevalent materials used for indentation tips and probing needles are diamond and tungsten, respectively, whose compliance is negligible as to that of aluminum or silicon oxide.

The boundary conditions for our FE simulation models are determined as follows (see Fig. 3):

- Fixed support for all outer boundaries of the chip structure except the uppermost one.
- Load is applied on the top surface of the needle downwards in vertical direction.
- The interfaces between individual layers are perfectly bonded. Assuming **bonded layers** in indentation scenarios is a common approach, as stated in Refs. [17–20], or in the Review article [10]. FEM models describing micro-pillar compression followed the same approach. For example, according Refs. [21,22], the assumption of perfect bonding at the interface of Al-SiC nanolaminates was proven feasible. Moreover, modeling delamination by means of cohesive zone models (cf. Ref. [23]) is beyond the scope of this work. In addition, the type of cracks observed during PFA (see Fig. 1) indicated that channeling cracks are more likely to occur than debonding or delamination.
- Two symmetry planes exist in the 3D models. Additional axisymmetric 2D models are equivalent to one of these planes, as indicated in Fig. 3.

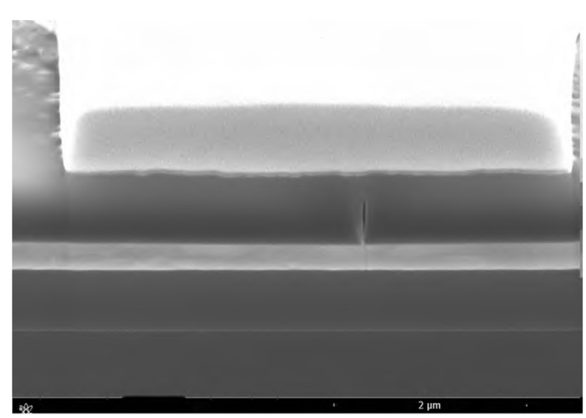

Fig. 1. Cross-section view of a crack in the oxide layer observed during FIB (Focused Ion Beam).