## Nano-indentation and micro-compression tests on the measurement of mechanical properties on hyper-deformed surfaces

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The behavior of metallic surfaces represents an important issue in several industry fields, such as the scientific innovation or the economical development. One option to reduce some fabrication and materials costs is to induce specific mechanical properties to the material surfaces, in order to improve the service lifetime of materials in a significant way and relieve the complexity of different mechanical elements. In the industry there are several techniques which allow increasing the mechanical properties in the near-surface of materials, such as the mechanical surface treatments (impact-based, sliding-based): «Surface Mechanical Attrition Treatment, Intensive shot-peening, or Friction Stir Processing ».

In these kinds of procedures the material is exposed to repeated mechanical loadings, producing a severe plastic deformation in the near-surface, and then leading to a local refinement of the microstructure into the affected zone (Tribologically Transformed Surfaces - TTS). The microstructure's transformation is characterized by a progressive
increment of the grain size from the surface until the bulk material. These mechanically-induced surface nano-structures exhibit very interesting physical properties such as high hardness and better tribological properties over a few tens of microns.

Nowadays, it is well-known that the grain size gradient generated in the material induces an evolution on the mechanical properties in the impacted zone. However, a simple micro-hardness test is not quite enough to quantify precisely the variation of mechanical properties due to the heterogeneity of the transformed surface. Consequently it is difficult to quantify the increase in mechanical properties induced.

In our project, a methodology based on nano-indentation tests and in-situ micro-pillars compression tests on several model materials (Pure Iron, copper, austenitic stainless steel) will be presented. The main issue of this work is to assess and describe precisely the elastic-plastic behavior and the distribution of mechanical properties on deformed zones, produced on these model materials.

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## Stress Development and Void Evolution in Open TSVs

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Through silicon vias (TSVs) are components in three-dimensional integrated circuits responsible for the vertical connections inside the dies. Beside the traditionally used filled copper TSVs, a new approach is based on so-called open TSVs. In this technology the TSV is a hollow tungsten-plated cylinder rather than an entirely filled interconnect and it is connected by an aluminum ring on the top and at the bottom to the adjacent interconnect structures. Thereby an aluminum/tungsten interface is formed, which introduces an electromigration (EM) problem due to the highly different resistances against EM. To fully understand the EM degradation of this structure these interfaces have to be particularly addressed.

In this work, we present studies about the EM reliability of open TSVs by means of finite element method based simulation. The calculation of the material flux and the stress build up in the TSV is based on the three-dimensional EM model of Sarychev, a drift-diffusion model where the flux is driven by the concentration gradient, the stress gradient, and the electrical field representing the EM force. Furthermore, the Rosenberg-Ohring term to model the annihilation/generation of vacancies due to stress in the structure is employed. These equations are coupled to the Navier-Cauchy equations for solid mechanics through the inelastic strain due to vacancy flux and their generation/annihilation. When the condition for a void nucleation is fulfilled, a void is placed at the most probable position and its evolution is described by a phase field model.

The EM failure calculations are based on a two-step approach. In the first step the stress development of a void free structure is analyzed using only the Sarychev model. This analysis indicates the locations, where voids due to stress are most probably nucleated. It was found that these locations are close to the tungsten/aluminum interfaces as well as to the silicon-oxide/aluminum interfaces. This is due to the shrinking of the aluminum caused by EM, which does not occur in the tungsten or in the silicon-oxide. In the second step voids are placed in the high stress regions of the aluminum and their evolution is traced. The result of this simulation shows the development of the TSV's resistance in time. After a void is placed and allowed to grow with time, it is found that the resistance rises more than linearly because the growing void reduces the conducting cross section. Finally, an abrupt resistance jump is observed leading to an open circuit failure. Our findings are in good agreement with results of accelerated EM tests and give hints, where the most problematic regions for EM are.

## Stress Analysis in Open TSVs after Nanoindentation

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Three-dimensional technology is considered necessary to maintain integrated circuit performance on the path described by Moore's law. Several layers of different materials compose an open Through Silicon Via (TSV) structure. For the sake of the TSV's mechanical stability, it is important to understand and to predict the behaviour of each material subjected to an external force.

A possible mechanical characterization to study the physics of the stress development, cracking, and plasticity is the nanoindentation. This technique enables to study the stress development in each layer of a TSV and to assess the risk of cracking and delamination. It is one of the most common experimental tools to test the mechanical properties of materials. Nanoindentation is based on an interaction between the tip and the material. The tips can have different shapes and can be made of different materials.

In this work we have investigated nanoindentation in TSV structures by means of simulation. For our calculations we have considered a spherical diamond tip. During the nanoindentation, the tip penetrates into the TSV and applies a force onto the material, causing a deformation of the material. The comparison between the loading force and penetration depth allows obtaining information about the mechanical properties of the device.

We have investigated two different settings. First, the materials are considered only within the elastic limit and then, the simulations are extended beyond the limit of the plastic deformation.