

# Coupled Simulation to Determine Across Wafer Variations for Electrical and Reliability Parameters of Through-Silicon Vias

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Three-dimensional (3D) integration of integrated circuits is a key challenge for the future evolution of semiconductor systems. Through silicon vias (TSV) are an integral component for interconnecting stacked circuits. For the fabrication of TSVs, a sequence of processing steps is required, including etching and deposition. Inevitable variations, for instance across the wafer or due to fluctuations of the equipment parameters, lead to variations of the fabricated structures, which in turn influence their properties, e.g. with respect to a TSV's electrical behavior or reliability. In this work, we demonstrate coupled equipment- and feature-scale process simulation and its application to layer deposition as part of a sequence for the fabrication of TSVs. The resulting structures are studied with respect to their electrical characteristics and reliability by means of finite element (FEM) simulations.

Part of the processing sequence studied is the plasma-enhanced chemical vapor deposition (PECVD) of a SiO<sub>2</sub> layer in a capacitively coupled plasma reactor. This work is mainly concerned with the resulting profile of the deposited SiO<sub>2</sub> layer and its variation across the wafer. To model the deposition process we assume that the adsorbed TEOS fragments are saturated on the surface and that the process is therefore governed by the local fluxes of oxygen ions and radicals [1]. Equipment modeling of a PECVD reactor containing argon and oxygen has been carried out using the Q-VT [2] software which is based on the plasma process simulator HPEM [3]. The most important species for the deposition process to be transferred to the feature-scale simulation are the oxygen radicals and O<sub>2</sub><sup>+</sup> ions. Fig. 1 shows the simulated reactor along with the concentration of the O<sub>2</sub><sup>+</sup> ions. Fig. 2 shows the fluxes of oxygen radicals and O<sub>2</sub><sup>+</sup> ions at the substrate versus the distance to the reactor center axis. These fluxes are provided as boundary condition for feature-scale modeling.

In order to simulate profile evolution on the feature scale, a phenomenological model [4] is employed which describes the local deposition rate as a composition of contributions from neutrals and ions. The model is implemented into the in-house tool DEP3D [5]. Due to the absence of actual rate and profile data, model calibration has been performed for the position on the center axis of the reactor (at 0.0 cm) using a typical feature-scale model parameter set obtained from literature [4]. The variations of the fluxes allow one to determine the variations of the feature-scale model parameters for various positions on the wafer and to simulate the resulting profile changes. An example for a simulated TSV geometry is shown in Fig. 3.

The simulated structures were provided to FEM simulation for electrical and reliability characterization using COMSOL Multiphysics 4.3a with an adaptation to include an electromigration model [6]. The variation of neutral and ion fluxes along the radial position, shown in Fig. 2, results in a variation in the deposited oxide thickness, which in turn, causes the TSV parasitic capacitance to depend on the TSV position on the wafer. This is shown in Fig. 4, where it becomes clear that the TSVs placed at locations exhibited to lower neutral and ion fluxes have an increased parasitic capacitance. The frequency dependence of the TSV capacitance can also be seen in Fig. 4, where the simulation is performed using a boron-doped bulk silicon (2.15·10<sup>15</sup> cm<sup>-3</sup>). The high-frequency parasitic capacitance does not vary significantly between the differently-located TSVs. This enables a small-signal analysis of the TSV, depicted as an LRC circuit, with an extracted resistance and inductance of approximately 400 mΩ and 4.3 pH, respectively.

Fig. 5 and Fig. 6 show the reliability performance of the TSV located at the center. A current of 1 A is applied, resulting in the current density distribution shown in Fig. 5. The aluminum, being the material where electromigration-induced failure is of highest concern, experiences a current density of approximately 1 MA/cm<sup>2</sup>. At this level, the electromigration-induced stress, after operating for an approximate 10 year period, is depicted in Fig. 6. A stress level of about 100 MPa is observed. This level does not vary with the TSV's location, because the stress level is affected by the movement of vacancies through the metal layers due to an applied current density and the observed variation of the oxide thickness is not large enough to significantly change the mechanical constraints of the aluminum line.

## Acknowledgement

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## References

- [1] G.B. Raupp, T.S. Cale, H.P.W. Hey, J. Vac. Sci. Technol. B 10 (1992) 37
- [2] Q-VT plasma processing simulator, release July 2013, Quantemol Ltd., London
- [3] M.J. Kushner, J. Phys. D: Appl. Phys. 42 (2009) 194013
- [4] C. Chan, J.P. McVittie, K.C. Saraswat, Proc. 9<sup>th</sup> Symp. Plasma Proc., ECS Proc. 92-18, p. 575
- [5] DEP3D, physical deposition simulator, release 0.6.0, Fraunhofer IISB, Erlangen, Germany, 2008
- [6] R. Orio, H. Ceric, S. Selberherr, Microelectronics Reliability 51 (2011) 1573

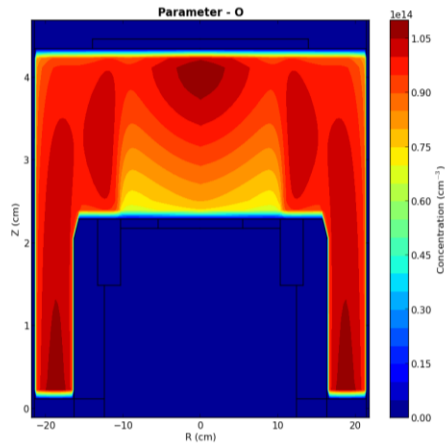


Figure 1: Equipment simulation result ( $O_2^+$  ions) for a PECVD reactor. The total mass flow and the pressure are 100 sccm and 40 mTorr, respectively, The electrical power (dual-frequency) is 200 W. The substrate is placed on top of the block in the center of the figure.

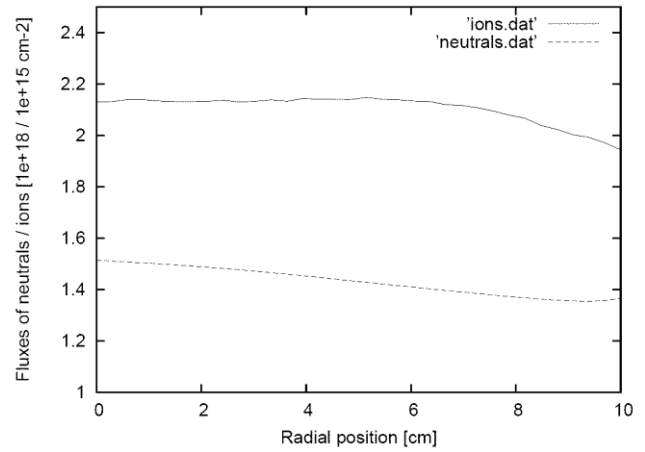


Figure 2: Fluxes of oxygen neutrals (radicals) and  $O_2^+$  ions at the substrate versus distance to the center axis for the equipment simulation shown in Fig. 1.

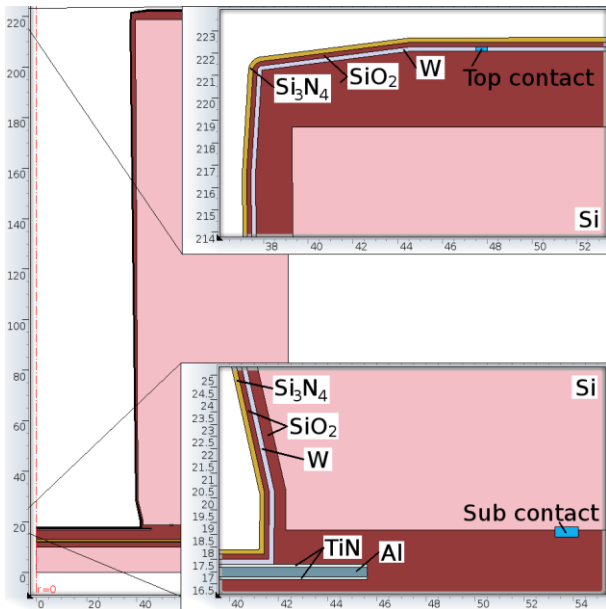


Figure 3: Simulated TSV structure. The left part shows one half of the via cross section, with close ups on the right. The changing thickness from top to bottom of the oxide layer between silicon and tungsten is clearly visible.

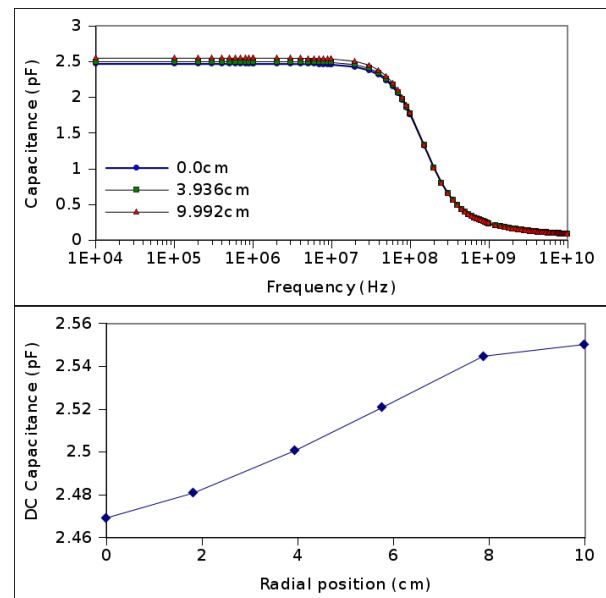


Figure 4: Simulated TSV capacitance between the *Top* contact and the *Sub* contact from Fig. 3. The top figure shows the frequency dependence of the capacitance. The bottom figure shows the radial position dependence of the capacitance at 0 Hz.

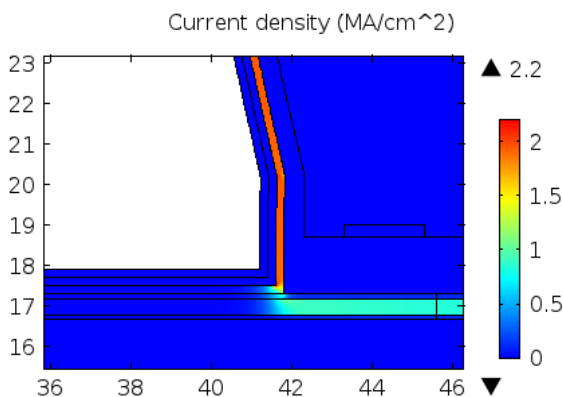


Figure 5: Simulation of the current density distribution, when a current of 1 A is applied to the TSV depicted in Fig. 3. The aluminum layer experiences a current density of approximately  $1 \text{ MA/cm}^2$ .

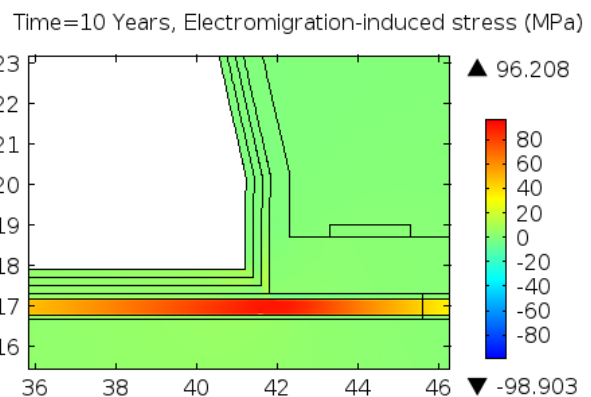


Figure 6: Electromigration-induced stress of the TSV depicted in Fig. 3 with a current density distribution from Fig. 5. After 10 years of operation, the aluminum layer experiences a stress of approximately 100 MPa.