Comparison of finite element stress simulation with X-ray measurement for the aluminum conductors with different passivation topography

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Abstract

This paper evaluates the dependence of the thermal stresses of aluminum conductors and SiO_2 layers deposited by several different processes using the finite element method(FEM) and topography simulation. The results of topography simulation for four different deposition processes agree well with scanning electron microscopes and subsequent FEM stress simulations are compared with X-ray diffraction measurement data. Simulation results show that the different stresses are created in aluminum lines from different passivation processes. Especially, the stresses of aluminum lines decrease as the encapsulation of aluminum conductors by the oxide layer with void profiles decrease. Through this topography simulation followed by stress simulations for different deposition processes, we can systematically define the failure mechanisms of aluminum lines for various passivation processes.

1 Introduction

Today's VLSI technology requires multi-level metals and dense interconnection schemes, which can be realized by a suitable process to fill spaces between metal lines with a high aspect ratio without voids. The mechanical stresses generated by different thermal expansion between the aluminum and the SiO_2 layer must be controlled for immunity of the hillock formation and voids of metal lines. The formation and growth of voids from mechanical stresses of aluminum lines have been studied, especially in terms of the dependence of storage temperature, line width, topology, and thickness of a passivation layer[1]. In addition, the intrinsic stress of a passivation layer influences to the stresses in the aluminum lines. Previous work has reported the comparison of FEM stress simulation with X-ray diffraction measurement[2]. In this paper, we first reports the simulation results on the stresses of aluminum lines in several different deposition processes for a passivation layer that has different intrinsic stresses and different topographies including voids in the oxide layer.

To investigate the stress dependency of the aluminum on the passivation topography, an internally developed topography simulator is used to generate the void containing profiles for four deposition processes. In addition, the subsequent mechanical stress simulations are performed using ABAQUS for each profile obtained from those topography simulations. The results of topography simulation agree well with the vertical SEM micrographs and the stresses are also compared with X-ray measurements for all the deposition processes including the PECVD (plasma enhanced chemical vapor deposition), HDP (high density plasma) CVD and flowable oxide(FOX) by spin coating. Especially, aluminum lines which embedded void profiles in the dielectric layer have a lower stress than those processed by a void-free IMD process.

2 Topography simulation: details and results

In this work, we use an in-house topography simulator for investigating the oxide deposition process. This topography simulator has been integrated with a plasma equipment simulator based on the two dimensional hybrid model, HPEM(Hybrid Plasma Equipment Model), to obtain the density of each chemical and ion species[3,4]. Patterned aluminum lines were passivated by four deposition processes, HDPCVD oxide, two PECVD oxides using the SiH_4 source and the TEOS source, and FOX. These deposition processes are described by well-known surface reaction models[5].

Fig. 1 shows the results of profile simulation. The final profiles for different deposition processes match well with vertical SEM pictures. The PECVD oxides using the SiH_4 source and the TEOS source both create the voids between metal lines. On the other hands, FOX and HDPCVD oxides do not create voids. These simulation profiles with void structures are fed back to the finite element stress simulation. Thus, we can characterize the effect of the void profile of an IMD layer on the stress distribution of metal lines.

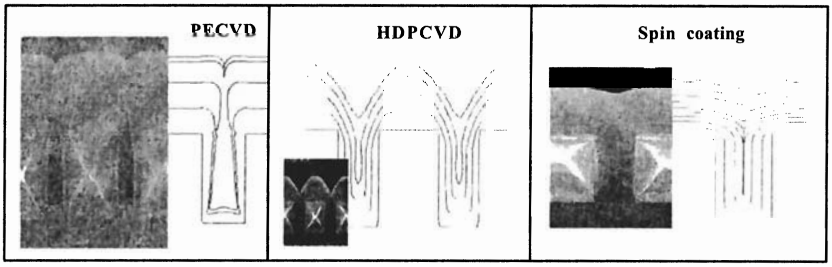

Fig. 1. Comparison between simulation profiles and SEM micrographs for different deposition processes of SiO_2

3 FEM stress simulation: details and results

We investigate the influence of the thermal stress distribution in a composite passivation layer with a real topography. ABAQUS· is used to model the stress distribution of the two dimensional profile obtained from topography simulation. We adopted the frozen view model, in which the maximum stress arising in the manufacturing process is usually evaluated during the temperature ramping down process. The stress simulation of a non-patterned wafer is performed to evaluate the material behavior according to the deposition process, and then the aluminum line passivated by SiO_2 is simulated to calculate the detailed stress distribution with respect to the pattern size and the passivation profile.

The stress simulation results of the non-patterned wafers are compared with the wafer warpage measurement, as shown in Fig. 2. We can extract the material behavior as a function of temperature for the different deposition processes. Fig-2(a) shows that different deposition processes and temperature cycles produce different intrinsic stresses and material behaviors of SiO_2 layers. The SiO_2 passivation layer of the patterned wafer must be described by the different modulus, thermal expansion coefficient, and viscous relaxation behavior to generate the experimental data. From these stress hysteresis simulations, we can describe the exact viscous relaxation effect and intrinsic stresses on the operating temperature. In addition, we simulated the non-passivated aluminum layer in the sputtered deposition process, as shown Fig. 2-(b). Especially, we can also describe the plastic deformation of the aluminum layer and extract the yield stresses for special deposition conditions.

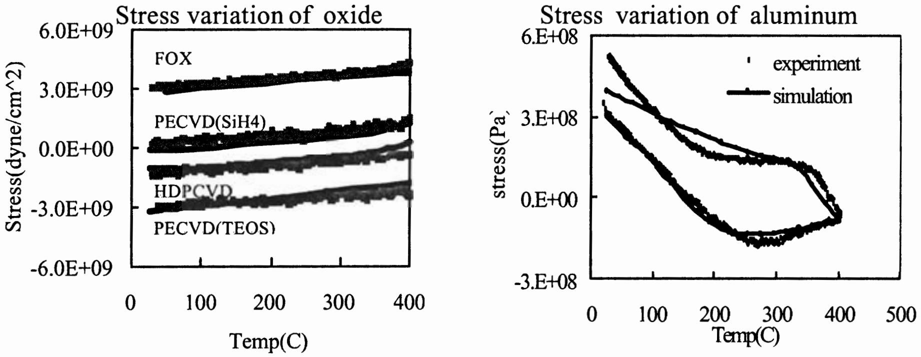

Fig. 2. Comparison of stress hysteresis simulation of a non-patterned wafer with the wafer warpage measurement.

We show the results of stress simulations starting from a real topography where Ti 30nm\Al 800nm\Ti 10nm\TiN 35nm metal stack is patterned and followed by four different passivation processes. Table 1. shows the comparison of FEM stress simulations to X-ray data that measure the residual stresses of the passivated metal lines, with monochromatic CuKa beam, at the 40kV 100mA beam condition. The most important result is that the trend of averaged tensile stress of an aluminum line from simulation correspond to the stresses from experiments according to the deposition process of the SiO_2 passivation layer.

Aluminum lines passivated by PECVD oxide using TEOS have a higher tensile stress, about 80MPa higher than that of the PECVD oxide using SiH_4. The differences of stresses in aluminum come only from the different intrinsic stresses of the SiO_2 layer. Some Researchers have argued that the high intrinsic compressive stress in the passivated layer is responsible for the high tensile stress in the metal[1]. However, simulation and experimental results show that the stresses of aluminum lines are dependent only on the intrinsic stresses of the SiO_2 layer. The different stresses between the PECVD and HDPCVD oxides are turned out to be originated from two reasons, intrinsic stresses and the existence of void profiles. In spite of low compressive intrinsic stresses of the HDPCVD oxide, stresses of aluminum passivated with the HDPCVD oxide has a high tensile stress, while that of PECVD passivation is relaxed by void profiles of SiO_2. Simulational stresses of aluminum passivated by the PECVD without void profiles has a higher tensile than that of the HDPCVD oxide. Thus, finite element stress modeling of aluminum must consider the void profiles in the passivation layer. In spite of voidless profile in the FOX layer, the stress relaxation of aluminum is due to the tensile intrinsic stresses and the large viscous relaxation properties of the FOX layer.

From this type of stress simulation with a real topography, we distinguish the evolution mechanism of thermal stresses for passivated aluminum lines with different deposition processes.

Table 1. Comparison of FEM stress modeling with X-ray measurement.

		PECVD (SiH4)	PECVD (TEOS)	FOX	HDPCVD (SiH4)	PECVD w/o void
XRD (MPa)	S_x	242	338	132	457	x
	S_y	98	197	89	363	x
FEM (MPa)	S_x	245	328	175	417	420
	S_y	198	275	111	258	355

4 Conclusions

We investigated the causes of stress differences in aluminum lines deposited by different processes. The level-set based topography simulator reproduced real topographies for different deposition process. Through the FEM stress simulation with the real topographies, we can systematically define why the deposition process of the passivation layer creates the different stresses and failures of aluminum lines.

Such a systematic FEM stress simulation with a real topography and intrinsic stresses is turned out to be useful in finding out the failure mechanism of integrated devices[6]

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