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Development of a process modeling for residual stress assessment of multilayer thin film structure

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ABSTRACT

The mechanical behavior of Microelectromechanical systems (MEMS) devices is significantly influenced by fabrication processes conditions, deposition steps and geometry, e.g., processing temperature, thickness of thin film layers, deposition rate, etc. These processes under different deposition temperature will generate residual stress/strain in thin film layers, which will affect device sensing stability, accuracy and robustness, therefore, predicting and minimizing the residual stress become a critical issue on thin film devices design. This research develops a simulation methodology using finite element analysis (FEA) with process modeling technology to analyze the thermal stress/strain of thin films varying on different process procedures in a selected MEMS microphone device. In general, the residual stress/strain of multi-layers thin film is combined of intrinsic and thermal stresses, the thermal induced mechanical stress can be obtained using FEA but intrinsic stress which contains many uncertainties is very difficult to be defined. The residual stress in thin film layer on each processing procedure can be obtained from Stoney's equation. A comparison of the experiment and simulation results showed that the combined thermal induced stress and dislocation induced intrinsic stress in aluminum thin film will be rearranged after first annealing. The intrinsic stress, however, will affect the final residual stress when thickness of aluminum film is under 1 μm. The residual stress and the warpage of MEMS microphone are predicted by using processing modeling technology. The polysilicon will warp downward if the diaphragm is subjected to compressive stress. However, the polysilicon film will have much less warpage when intrinsic stress is positive.

1. Introduction

Microelectromechanical systems (MEMS) microphone (Fig. 1) has become one of the most popular technologies for electronic devices because of its small size and high integration. Although the fabrication process of MEMS is compatible with semiconductor, the residual stress and undesirable pre-deformation of thin films during deposition and etching process will lead to reliability and yield problems. In the past few decades, numerous researches have been widely discussed in MEMS technology, but few of them focused on process simulation. This study developed a methodology using finite element analysis (FEA) with process modeling technology to analyze the residual stress in a structure of capacitive MEMS microphone.

The residual stress of thin film is composed of thermal and intrinsic stresses [1]. The intrinsic stress, which is caused by deposition temperature, lattice mismatch, recrystallization and chemical reactions, etc., and is a process sensitive property, should be obtained from experiments. Extrinsic stress is applied to films mainly caused by coefficient of thermal expansion (CTE) mismatch and can also be called thermal stress which can be predicted using process modeling technique by element birth and element death in ANSYS®. In addition, extrinsic stress would also be caused by wafer chucking and wafer flatness

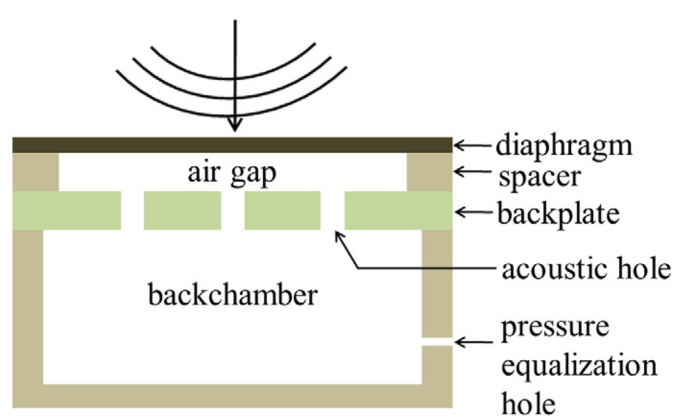

Fig. 1. The sketch of MEMS microphone.

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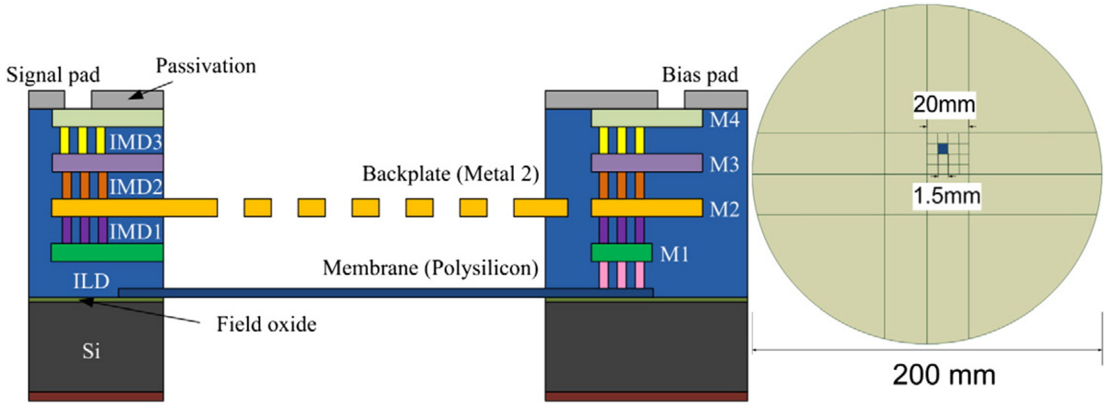

Fig. 2. Cross-section of 1P4M MEMS microphone.

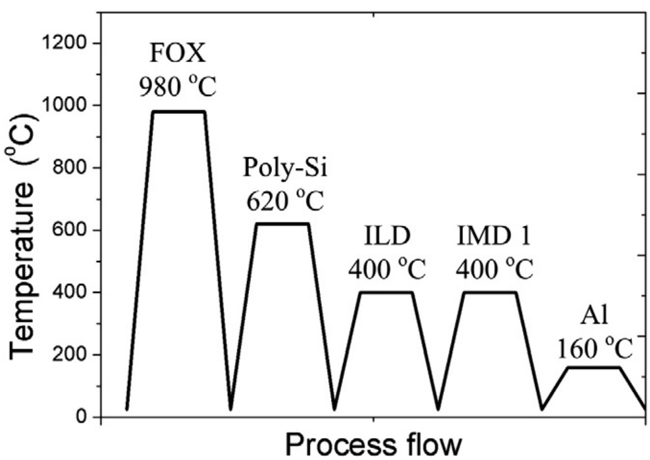

Fig. 3. The process flow of the multilayered structure.

variation [2]. The average residual stress of multilayered structure is determined from Stoney's experiment which measures the curvature on blanket wafer after each process. The experiment results indicated that the residual stress of thin films reduced and became stable after several thermal cycles. The residual stress can be measured by wafer curvature measurements and then the thermal stress subtracted from it to estimate the intrinsic component. Several authors have studied intrinsic stress in thin film [3–7], but few [8] discussed intrinsic effects in simulation.

For capacitive type MEMS microphone, the component consists of a flexible diaphragm and a rigid backplate with acoustic holes. These two electrode plates are separated by an air gap. This study analyzes the residual stresses of polysilicon diaphragm and aluminum backplate through experiment and numerical analysis. Polysilicon, the material of diaphragm, is often used in MEMS structure because it can be fabricated by thin film deposition process. For MEMS microphone, the polysilicon diaphragm would bend after etching process if it is subjected to compressive stress. This would make resonant frequency and microphone sensitivity far from the original design. The residual stress can be controlled by changing deposition and annealing temperatures [9–12]. Setting tensile film stress after etching process will let the microphone have better performance.

The objective of this work is to obtain the intrinsic stress of thin film and discuss the intrinsic effect on a microphone structure.

2. Theory and experiment

The first theoretical formula for the evaluation of stresses in a thin film on a thick substrate was developed by Stoney [13]. The effective residual stresses of aluminum and polysilicon thin films on silicon wafers have been determined by Stoney's equation, shown as below

$$\sigma_f = \frac{E_s t_s^2}{6(1-\nu_s)t_f}\left(\frac{1}{R}-\frac{1}{R_0}\right) \quad (1)$$

where σ_f is thin film stress; E_s and t_s are Young's modulus and thickness of substrate, respectively; ν_s is the Poisson's ratio; t_f is the film thickness; R_0 and R is the radius of curvature on the substrate before and after film deposition. It assumes that $t_s >> t_f$, the lateral dimensions of the film and substrate are significantly greater than the thickness, and the substrate is elastically isotropic. The above formula does not involve the material properties of the film, and the film stress was obtained by measuring the curvature before and after film deposit.

Table 1
Processing steps and fabrication parameters of the multilayered structure.

Procedure	1	2	3	4	5
Film	Field oxide (FOX)	Poly-Si	ILD	IMD	Al (TiN-AlSi1%Cu0.5%-TiN)
Process	Atmospheric pressure CVD	Low pressure CVD	PE TEOS	PE CVD	Sputter
Process temperature(°C)	980	620	400	400	25-160
Film thickness (μm)	0.39	0.2	0.85	1.0	0.495
Structure	Field Oxide Si	Poly Silicon Field Oxide Si	ILD Poly Silicon Field Oxide Si	IMD ILD Poly Silicon Field Oxide Si	Al IMD ILD Poly Silicon Field Oxide Si
Number of thermal cycle	2	2	1	1	3
Peak temperature(°C)	1,000	1,100	450	450	450