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Application of He's variational iteration method to the estimation of diaphragm deflection in MEMS capacitive microphone

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ABSTRACT

In this paper, He's variational iteration method (VIM) is used to analyze the deflection of poly silicon diaphragm of Micro Electro Mechanical Systems (MEMS) capacitive microphone. The residual stresses in the material used to make the diaphragm change the vibrational characteristics of the microphone diaphragm and consequently influence the microphone's first resonant frequency, cutoff frequency and sensitivity. The most successful devices use poly silicon as a diaphragm material, because of its residual stress is controllable by high-temperature annealing after ion implantation by boron or phosphorous. External acoustic force causes to deflect the diaphragm of the structure and VIM is a powerful analytical method to predict the structural behavior and the microphone performance. Comparison of this new method with the previous approximate solution [1], is applied to assure us about the accuracy of solution.

1. Introduction

Microphones are transducers that convert acoustic energy into electrical energy. The microphones are widely used in voice communications, hearing aids, noise, and vibration control [2]. The silicon microphones have been based on the piezoelectric, piezoresistive and capacitive principles [3]. The capacitive microphones have been studied by many researchers because of their superior performances, e.g. high sensitivities, low power consumption, flat frequency responses in wide bandwidth, low noise level, stability and reliability [1]. There are mainly two branches in capacitive microphones – condenser microphone and electret microphones. Electret microphones consist of an electret material, which can store a permanent charge, eliminating the need for external DC biasing. Disadvantages of most electret microphones are the poor retention of electret charges, impossible to electrically regenerate any charges lost after their initial storage on the capacitor and incompatibility with IC process [4]. Condenser microphones consist of a variable gap capacitor. To operate, such microphones need to be biased with a DC voltage (to form a surface charge) [5,6]. The condenser microphone has demonstrated the highest achievable sensitivity and very low noise level. Different types of materials can be used for the fabrication of a diaphragm: silicon nitride, annealed poly silicon after ion implantation, polyamide, monocrystalline silicon, and so forth. The residual stresses in these films range from 110 MPa for silicon nitride thin films deposited by the plasma enhanced chemical vapor deposition (PECVD) method to 20 MPa for high-temperature annealed poly silicon thin film deposited by the low pressure chemical vapor deposition method (LPCVD) and ion implanted with phosphorous [7]. For the maximal acoustical sensitivity it is important to use low-stress material as a bending membrane (diaphragm). In a micromechanical component the area is inevitably small, one or two square millimeters. With the use of low-stress material, the bending membrane can be made very flexible [8]. Poly silicon is an alternative thin film for microphone diaphragm, which can be doped to make it electrically conductive. In general, as-deposited LPCVD poly silicon

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Nomenclature

LPCVD	low pressure chemical vapor deposition	L	linear operator
PECVD	plasma enhanced chemical vapor deposition	N	nonlinear operator
MEMS	micro electro mechanical system	$g(t)$	inhomogeneous term
VIM	variational iteration method	σ	residual stress of the diaphragm
W	diaphragm deflection	v	Poisson's ratio
D	flexural rigidity	t	diaphragm thickness
T	tensile force per unit length	E	Young's modulus of elasticity
∇^2	Laplacian operator	a	diaphragm width
∇^4	$\nabla^2(\nabla^2)$	f_{res}	first resonant frequency
t	time	τ	time
λ	Lagrangian factor		

thin films on silicon wafers show large residual stress (about 100 MPa), which makes less interesting for microphones for which high mechanical sensitivity is required. High-temperature annealing of a low pressure chemical vapor deposition (LPCVD) of poly silicon thin film that is ion implanted with phosphorous can confine the residual stress to as low as 20 MPa. Thus, low-stress poly silicon is a common choice for the diaphragm material [9]. The high-sensitivity microphone for the proposed acoustical sensor is the capacitive type and can be fabricated as a single structure using MEMS technology. The microphone is to be fabricated using a doped poly silicon diaphragm (Residual stress = 20 Mpa, Young's modulus = 1.6×10^{11} Pa, Poisson's ratio = 0.22) an air gap and a silicon nitride back plate with acoustical ports on silicon wafer, as shown in Fig. 1. The microphone diaphragm has a thickness of 0.8 μm, an area of 2.6 mm^2, an air gap of 3.0 μm and a 1.0 μm thick back plate. A 12.0 V DC bias voltage is provided between the diaphragm and the back plate. When biased oppositely, the diaphragm and the back plate constitute an air core parallel plate capacitor. When the acoustical wave strikes on the diaphragm, it causes the diaphragm to vibrate; accordingly that changes the capacitance due to changing air gap. The capacitance change causes a time varying current.

Many essential parameters obtained by partial differential equations which rose in real-world physical problems. Diaphragm deflection in MEMS capacitive microphone was one of them which estimated by approximate solution of related partial equation [1]. The solution of these electromagnetic field problems are often too complicated to be solved exactly. So many approaches are investigated to solve these problems. Recently, a new variational iteration method (VIM) is proposed by He [10–13]. VIM has many merits over classical approximate techniques which can solve nonlinear equations easily and accurately. This method is based on the use of Lagrange multipliers for identification of optimal values of parameters in a functional and cause a rapid convergent sequence is produced. The variational iteration method is suitable for finding the approximation of the solution without discretization of the problem [14] and has recently been applied to various engineering problems [15–17]. In this paper, we use VIM to consider diaphragm deflection of MEMS capacitive microphone. The rest of this paper is organized as follows: Section 2 explains related partial differential equation which deflection parameters are obtained from it. Section 3 describes the details of the proposed method. Sections 4 will analyze method to estimate diaphragm deflection behavior. Section 5 shows the simulation results. Finally, conclusions are presented in Section 6.

2. Diaphragm deflection in differential form

The performance of the microphone depends on the size, stress and deflection of the diaphragm. The diaphragm deflection W can be approximated by the following differential equation [1]:

$$-D\nabla^4 W + T\nabla^2 W = \rho \frac{\partial^2 W}{\partial^2 \tau} \tag{2-1}$$

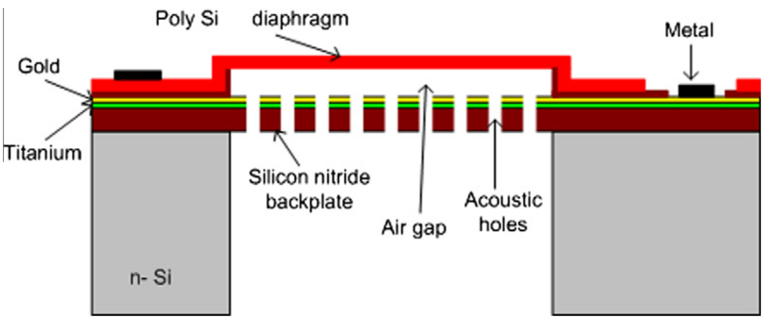

Fig. 1. Cross-sectional view of the micro-machined capacitive microphone.