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Integrated Micro-Mechanical Tunneling Accelerometer

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Abstract

In this work the design of the integrated micromechanical linear accelerations sensor based on the tunnel effect is developed. The method of MEMS constructing using controlled self-assembly operations of mechanically stressed GaAs / InAs semiconductor layers is briefly described. The designed construction of the tunneling accelerometer was simulated in ANSYS CAD system, the obtained results of mathematical modeling satisfy the requirements for modern micromechanical accelerometers and allow using them for the further development of MEMS structures. The obtained data can be used to calculate the recommended parameters in the development of methods for designing velocity and linear accelerations tunneling sensors and for development of more accurate models of MEMS structures.

Keywords: MEMS, micromechanical accelerometer, design, sensor, mathematical simulation

INTRODUCTION

Micro- and nanomechanical devices are widely used in modern technical systems for various purposes: from household appliances (cameras, toys, mobile phones and tablets, etc.) to specialized (automotive, medical, industrial, navigation) [1 – 3].

One of the most actively developing area of microsystem technology is the development of devices capable to solving problems of trajectory analysis, motion parameters and dynamic characteristics of moving objects. Such devices include angular velocity and linear acceleration sensors, which belong to the class of microelectromechanical systems (MEMS).

This article presents the design of an integrated micromechanical sensor of linear accelerations based on the tunnel effect and method of its constructing using self-assembly operation based on controlled self-organization of mechanically stressed GaAs / InAs semiconductor layers. The static analysis results of the proposed tunnel accelerometer design obtained in ANSYS CAD are presented and confirm its compliance with the requirements for modern devices for registering linear accelerations.

PROBLEM STATEMENT

The important problem of microsystem technology is the creation of highly sensitive gyroscopes and accelerometers. Due to the high prevalence of these devices, the important scientific and engineering task is not only improvement of technical parameters (threshold sensitivity, nonlinearity, operating frequency range, etc.) but also other aspects, in particular, reduction of the finished product cost, increase of manufacturability, provision of the integral production together with the other MEMS components.

It is known that the most sensitive to displacement are accelerometers that used a tunnel current to register the distance between the electrodes. The characteristic values of the tunnel current are about 1 nA and voltage are about 0.1 V, while the distance between the electrodes is about 1 nm [4, 5]. In this case, tunnel accelerometers have important advantages: hypersensitivity caused by the fact that tunneling current is exponentially depends on the gap between the electrodes; the decrease in characteristic dimensions affects the sensitivity much less than in the traditional capacitive accelerometers (this is due to the small area of the sensitive region, i.e., the tunnel contact); signal processing schemes for tunnel accelerometers are usually simpler than those for capacitive accelerometers [6, 7].

DESIGN DESCRIPTION

Figure 1 shows the structure of the tunnel accelerometer, where 1 is the semi-insulating wafer, 2 is the base of the stationary electrode, 3 is the base of the electrostatic actuator, 4 is the movable electrode pad, 5 is the technological layer in the stationary electrode region, 6 is the technological layer in the electrostatic actuator region, 7 is the spring suspension, 8 is the contact area of the stationary electrode, 9 is the contact area of the electrostatic actuator, 10 is the contact area of the movable electrode, 11 is the proof mass, 12 is the fixed electrode, 13 is the fixed electrode of electrostatic actuator, 14 is the contact to movable electrode, 15 is the movable electrode of electrostatic actuator, 16 is the movable electrode (tip).

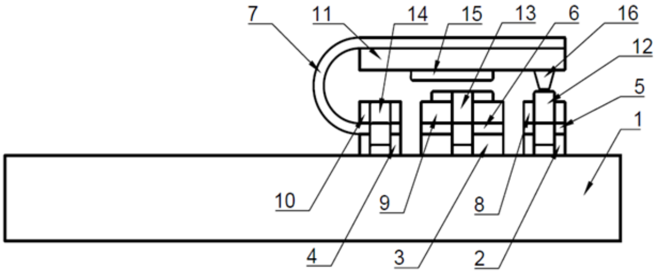

Figure 1 – Tunneling accelerometer structure

The motion transducer is a tunnel contact formed by the fixed electrode 12 and the movable electrode (tip) 16. The spring suspension is a J-shaped and it's a segment of a cylindrical shell witch one end is adjacent to the movable electrode pad 4 and rigidly fixed to the semi-insulating wafer and the another end is adjoined with the proof mass. The electrostatic actuator is formed by a stationary deflecting electrode 13 and a movable deflecting electrode 15.

The spring suspension 7 is formed using the Prinz technology [8, 9]. It is made from a two-layer material (as technological layers 6, 5) in such a way that the outer surface of the spring suspension is formed from InAs film, and the inner surface is formed from GaAs film. Because of the difference in the values of InAs and GaAs lattice constants (Δa / a = 7.2%), the resulting hetero film is mechanically stressed. So it bends when it is locally released from bonding to the wafer by controlled selective etching of the AlGaAs sacrificial layer (areas 4, 3, 2 also formed from this material) [10].

Thus, controlling the etching time, it is possible to control the process of strained InAs / GaAs layers self-organization and to get a tunnel gap between the fixed electrode 12 and the movable electrode 16. This method has several advantages over the traditional planar technology of forming micromechanical accelerometers. Firstly, manufacturability improves, since all operations are performed in a single technological process and there is no need for complex microassembly operations, which makes it possible to integral group processing methods using standard technological operations of GaAs technology. Secondly, there is the possibility of a precision formation of a tunnel contact with a gap about of a few nanometers. Thirdly, on the basis of this technology, it is also possible to manufacture integrated multi-axis accelerometers [10]. In addition, it is possible to include in the structure a functionally and technologically integrated calibration system and an accelerometer signal processing circuit.

The tunnel gap is formed by controlling the parameters of the etching operation of the sacrificial layer. In practice, deviations from the necessary gap dimensions can occur, due to the spread of the material parameters, external conditions, etc. To solve this problem, a calibration system including contacts 13, 15 is provided. When the appropriate voltage is applied, the position of the movable beam is changed due to electrostatic forces.

SIMULATION

To analyze working characteristic of the presented tunneling accelerometer, the macro file for ANSYS APDL was designed. This macro describing the sketch of the structure with physics and geometric parameters presented in Table 1.

Table 1 - Accelerometer design parameters

Parameter	Designation	Value	Units
Inner radius	R_i	0.35e-6	m
thickness of the inner film (GaAs)	H_i	0.02e-6	m
thickness of the outer film (InAs)	H_o	0.03e-6	m
Length of the movable beam	L_{im}	3.00e-6	m
Width of structure	W	1.00e-6	m
Thickness of inertial mass	H_{im}	0.06e-6	m
Fixed electrode thickness	H_e	0.06e-6	m
Tunnel gap	D_t	2.00e-9	m
Young's modulus of InAs	E_{InAs}	50.00e9	Pa
Poisson's ratio of InAs	μ_{InAs}	0.33	-
density of InAs	ρ_{InAs}	5.67e3	kg/m^3
Young's modulus of GaAs	E_{GaAs}	82.68e9	Pa
Poisson's ratio of GaAs	μ_{GaAs}	0.31	-
density of GaAs	ρ_{GaAs}	5.32e3	kg/m^3

At this stage of work, only mechanical modeling is carried out, so the model was somewhat simplified (see Figure 2). The model takes into account the two-layer structure of the spring suspension with the corresponding parameters of the layers.

A static analysis was performed; the results are shown in Figure 2 and in Table 2.

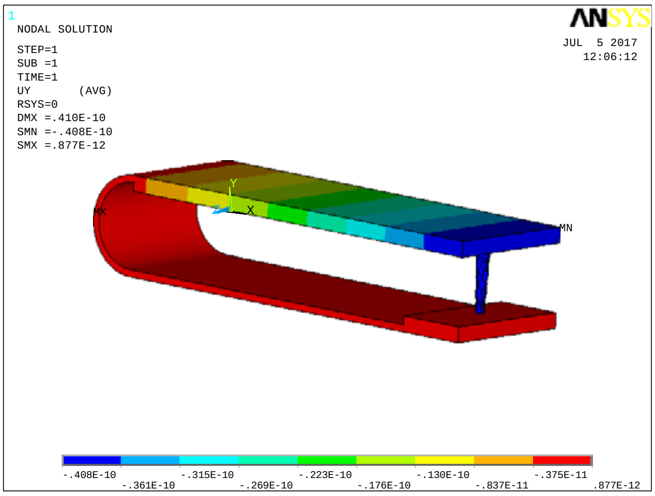

Figure 2 - Results of static analysis of the design.

An acceleration of 5 g is applied along the Y axis. The displacement of the movable electrode of the displacement transducer along the Y axis is $-0.408*10^{-10}$ m

Table 2 - Results of static analysis of the structure with acceleration of 5g.

Direction of 5g acceleration	The displacement along the X axis (m)	The displacement along the Y axis (m)	The displacement along the Z axis (m)
- X	$-0.772*10^{-13}$	$-0.698*10^{-11}$	$-0.703*10^{-14}$
X	$-0.635*10^{-13}$	$0.617*10^{-11}$	$-0.812*10^{-14}$
- Y	$0.252*10^{-11}$	$0.361*10^{-10}$	$-0.140*10^{-12}$
Y	$-0.336*10^{-11}$	$-0.408*10^{-10}$	$0.124*10^{-12}$
- Z	$-0.161*10^{-12}$	$-0.622*10^{-13}$	$-0.973*10^{-11}$
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From Table 2 it can be seen that the greatest displacement of the movable electrode arises from the application of acceleration along the axis perpendicular to the plane of the wafer, so the accelerometer is most sensitive to linear accelerations arising along the Y axis.

In [5], the dependence between the tunnel current (I), the voltage applied to the electrodes of the motion transducer (V), and the value of the tunnel gap (D_t) is illustrated by the following expression:

$$I \propto V \times e^{((const)(-Dt))}, \quad (1)$$

those, the tunnel current is linearly proportional to the applied voltage, and exponentially depends on the tunnel gap distance. Thus, the displacements shown in Table 2 are sufficient for detecting linear accelerations arising along the Y axis.

From the available data it is possible to calculate the sensitivity of the accelerometer (which can also be represented by the reciprocal value - k / m ratio) using this expression:

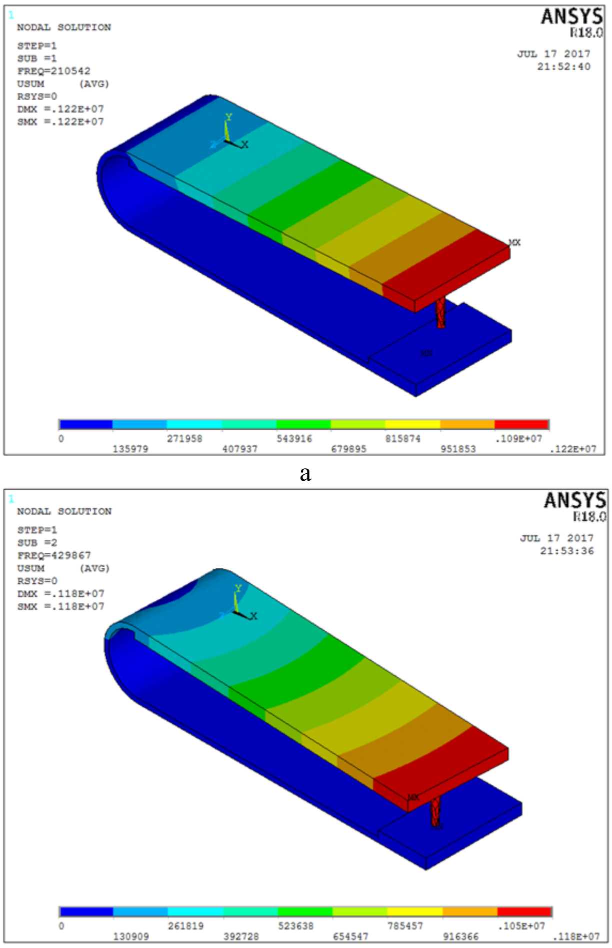
$$\frac{k}{m} = \frac{a}{z}, (2)$$

where k is the stiffness coefficient of the suspension, m is the mass of the proof mass, a is the acceleration, and z is the displacement of the proof mass. Thus, the k / m ratio will be 1.225e12 s^{-2}, and the sensitivity is 8.163e-13 s^2.

A modal analysis of the presented structure was carried out, the results for the first ten modes are presented in Table 3 and in Figure 3.

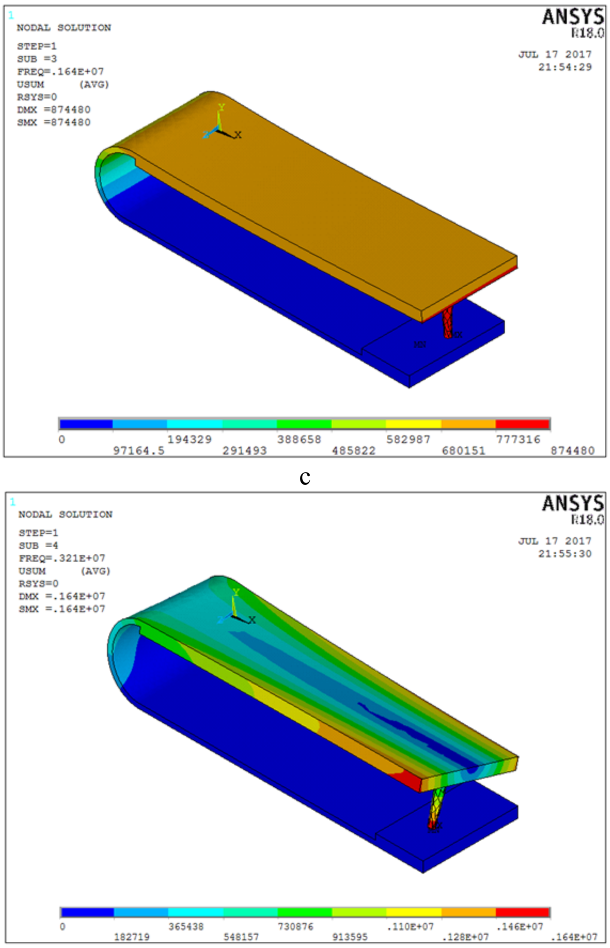
Table 3 - Results of modal analysis of the accelerometer construction.

Mode number	Natural oscillation frequency (Hz)
1	0.211e06
2	0.430e06
3	0.164e07
4	0.321e07
5	0.330e07
6	0.823e07
7	0.892e07
8	0.132e08
9	0.159e08
10	0.221e08



a

b



c

d

Figure 3 - Results of modal analysis of the accelerometer construction. A is the first mode; B is the second mode; C is the third mode; D is the fourth mode.

CONCLUSION

Thus, the obtained results make it possible to conclude that the proposed sensor elements can be constructed through controlled self-organization of GaAs / InAs strained layers, and also the possibility of using such structures for constructing integrated micromechanical accelerometers containing nanosized motion transducers based on the tunnel effect.

Achieving that will allow to reduce the mass-dimensional characteristics of sensors of inertial orientation and navigation systems, increase their functionality, provide high precision and expand their scope, including small-sized mobile objects.

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REFERENCES

[1] Berkeley, S. Sensor & actuator center. 2014 [Online]. Date view September 17, 2017 http://www-bsac.eecs.berkeley.edu/
[2] Konoplev, B.G., Lysenko, I.E. and Ezhova, O.A. “Criteria of equality of modal frequency of

[3] micromechanical gyroscopes- accelerometers sensitive elements", Modern Applied Science,2016; 10: 52-55
[4] Konoplev, B.G., Lysenko, I.E. and Ezhova, O.A. "Evolution Criteria Fingers Hardness Electrode MEMS Comb Converters", Bioscience. Biotechnology research Asia, 2015; 12(3). Date view September 17, 2017 http://www.biotech-asia.org/?p=3594>
[5] Konoplev B.G., Pristupchik N.K., Ryndin E.A. A Simulation Method for Displacement Transducers Based on the Tunnelling Effect. Vestnik Yuzhnogo Nauchnogo Tsentra, 2012; 8(4): 20–26
[6] Boyden E., El Rifai O., Hubert B., Karpman M., Roberts D. A High-Performance Tunneling Accelerometer. MIT Term Project Paper 6.777, Introduction to Microelectromechanical Systems, Spring 1999
[7] Dong H., Jiaa Y., Haoa Y., Shenb S. A Novel out-of-plane MEMS Tunneling Accelerometer. Sensors and Actuators A., 2005; 120: 360–364
[8] Chin Yong Huan, Haslina Jaafar and Nurul Amziah Md Yunus. Classification on MEMS Accelerometer and Device Application. Second International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE2014) (TAEECE), 2014, pp. 215 – 225.
[9] Prinz V.Ya. Precise semiconductor nanotubes and nanoshells fabricated on (110) and (111) Si and GaAs. Physica E., 2004; 23: 260-268.
[10] Mutilin, S.V., Vorobyova, ., Ju.S., Vorob'ev, A.B., Putyato, M.A. and Prinz, V.Ya. Curvature-tuned InAs-based shells containing two-dimensional electron gas. J. Phys. D: Appl. Phys., 2011; 44: 365104.
[11] Ryndin E.A., Pristupchik N.K. Integrated Micromechanical Tunneling Accelerometer Based on Driven Self-Assembly of Strained GaAs/InAs Layers. Izvestiya SFEDU. Engineering Sciences, 2009; 01: 129 – 134.