Sensitive Element of Microaccelerometer on Surface Acoustic Waves for Measuremant of Superhigh Accelerations

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Abstract—**The article presents the main shortcomings of the sensitive element of the micromechanical accelerometer on surface acoustic waves, developed earlier at the Department of Laser Measuring and Navigation Systems ETU. Solutions for elimination of deficiencies are offered. The merits of the proposed design of a sensitive element for measuring super large accelerations are described. The strength of the materials and the design of the sensitive element was evaluated.**

I. Introduction

The last decades have been "golden" for devices based on microelectromechanical systems (MEMS): due to in-creased sales of mobile applications and gadgets, not only has the demand for quantity and quality increased, but the scope of such devices has expanded. According to reports from authoritative publications specializing in the analysis of the state and prospects for the development of the world market of innovative devices, the growth in sales of sensory devices will grow from $ 38 billion to $ 66 billion in 2021 – 12% in comparison with the previous year. In addition to the fact that sales volumes are growing and the market is constantly expanding and trying to offer the consumer a wider spectrum of devices, the vector of the proposed applications is also changing. There is a growing demand for MEMS for use in heavy industry and military technology. The main requirements provided by consumers of such directions are high-performance and quick-payback devices (inertial sensors, pressure sensors, etc.), which are expected to operate under extreme conditions: vibrating, shock-resistant sensors capable of operating in a wide temperature range with low power consumption.

The solution to this problem is seen in the development of solid-state microsensors on surface acoustic waves using the molecular kinetics of a solid. Of particular interest are acceleration sensors that make measurements during overloads up to 20000 g, which are easily realizable on quartz substrates due to the basic properties of surface acoustic waves.

Early, on the basis of the Department of Laser Measuring and Navigation Systems of St. Petersburg State Electrotechnical University "ETU", the following concept of a micromechanical accelerometer for surface acoustic waves was developed [1]. The sensitive MMA pendulum type is a console 1 of quartz ST-cut, rigidly fixed at one end and loaded with inertial mass (IM) on the other (Fig. 1). On the opposite surfaces of the SE, there are applied interdigital transducers (IDT) 2, which realize their own working frequency. To exclude the mutual synchronization of two self-excited oscillators 3, the fundamental frequencies of the single-cavity resonators and, placed on opposite sides of the console, are carried to some fixed frequency. Under the action of acceleration, the cantilever begins to bend, and the surfaces experience deformation of the "stretching-compression". Deformation of data is provided to mixer 4. The difference frequency at the output of the filter 5 is proportional to the acting acceleration, and the total frequency at the output of the filter 6 is used to reduce the destabilizing factors.

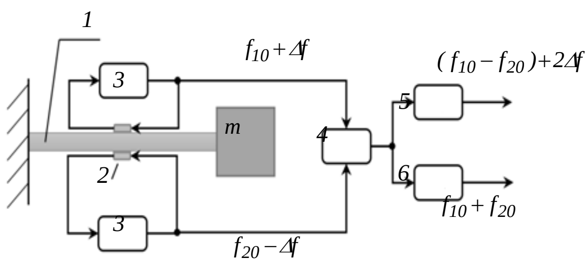
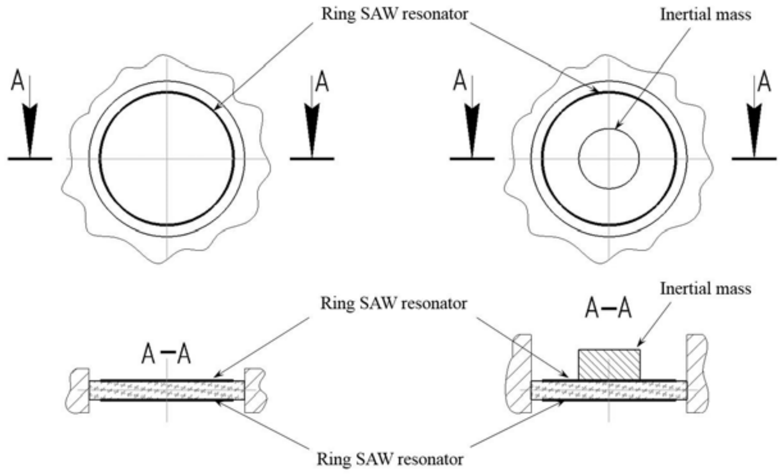


Fig.1. Structural diagram of the SAW accelerometer

One of the most important criteria determining the sensitivity of MMA on surfactants are relative deformations. The unevenness of the relative deformations leads to additional errors. In an effort to reduce these errors, a triangular form of the console was proposed, the relative deformations of which are uniform. A drawback of the construction of such SE's is the impossibility of using super-large accelerations for measuring.

To solve this problem, the SE – is proposed, a round plate rigidly fixed along the perimeter (Fig. 2, a). Ring-shaped IDT-resonators are located on opposite surfaces of the sensitive element. To increase the sensitivity, the plate can be loaded with inertial mass (Fig. 2, b).



a b

Fig.2. a. Sensitive element of a microaccelerometer on a surfactant of circular shape with a ring resonator; b. Sensitive element of a microaccelerometer on a SAW of a circular shape with a ring resonator and inertial mass in the center

SE due to the form and method of attachment solves several problems at once:

- is able to withstand and measure accelerations hundreds and thousands of times more g, compared with previous designs;
- provides a uniform distribution of stresses and relative deformations in the area of deposition of a SAW-resonator;
- the error is reduced due to low cross sensitivity.

II. Evaluation of the strength of a sensitive element of circular shape

To assess the strength, an analysis was made of the stress-strain state of SE. To describe the symmetrical bending, fixed around the perimeter and uniformly loaded round plate, apply polar coordinates [2]. If we take r – polar radius, and θ – polar angle as shown in Fig. 3, then the relationship between polar and Cartesian coordinates will be expressed by the equations:

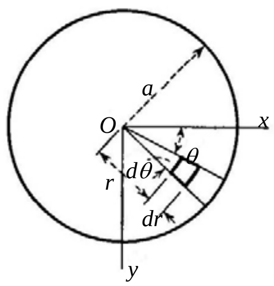


Fig.3

$$r^2 = x^2 + y^2 , \ \theta = arctg \frac{y}{x} ,$$

it follows that: $$\frac{\partial r}{\partial x} = \frac{x}{r} = cos\,\theta ,$$

$$\frac{\partial r}{\partial y} = \frac{y}{r} = sin\,\theta ,$$

$$\frac{\partial \theta}{\partial x} = -\frac{y}{r^2} = -\frac{sin\,\theta}{r} , \ \frac{\partial \theta}{\partial y} = \frac{x}{r^2} = \frac{cos\,\theta}{r} .$$

The differential equation for the curved surface of a transversely loaded plate in Cartesian coordinates takes the form:

$$\frac{\partial^4 \omega}{\partial x^4} + 2\frac{\partial^4 \omega}{\partial x^2 \partial y^2} + \frac{\partial^4 \omega}{\partial y^4} = \frac{q}{D} ,$$

where x, y, z – coordinates of the Cartesian coordinate system; ω – deflection of a plate; q – load intensity; D – bending stiffness of plate.

The differential equation of symmetric bending of a uniformly loaded circular plate in polar coordinates has the form:

$$\partial \Delta \omega = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} \right)\left(\frac{\partial^2 \omega}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \omega}{\partial \theta^2} \right) = \frac{q}{D}$$

If we take into account the load distribution, the boundary conditions and integrate the equation, we can obtain the expression for the maximum stress of the plate:

$$\sigma_{max} = \frac{3}{4}\frac{qR^2}{h^2}$$

where q – load intensity; R – plate radius; h – plate thickness.

Since MMA measures acceleration, the maximum voltage can be expressed using the following equations:

$$q = \frac{F}{S} , \ F = ma , \ m = \rho V ,$$

$$V = \pi R^2 h\,,\ S = \pi R^2\,,$$

where F – force; S – load area; m – mass of plate; a – acceleration; ρ – material density; V – plate volume.

The expression for the maximum voltage has the form:

$$\sigma_{max} = \frac{3}{4}\rho a \frac{R^2}{h}$$

It can be seen from the expression that the maximum stress depends on a and $\frac{R^2}{h}$.

Figure 4 shows the straight lines for sensitive elements of two types of materials SiO_2 ST-cut и $LiNbO^3$ cut YX-128°, showing the maximum stresses as a function of acceleration, so that each straight line will correspond to some particular value $\frac{R^2}{h}$.

When choosing the dimensions of the SE for a micromechanical accelerometer for surfactants, in the first place, it follows to build on the possibility of physics of the principle of construction on which it is realized. Surface acoustic waves have a weak penetrating power, about 3λ [3]. Assuming that the IDT will be located on both sides of the SE, the minimum thickness of the quartz element should be at least 7λ, where λ =7.29 µm, т.е $h_{min} \geq 50$ µm, or 0.05 mm. For lithium niobate this value will be $h_{min} \geq 64.5$ µm, or 0.0645 mm (where λ =9.19 µm). For a sensor of the size in $1cm^3$ it is necessary that the ratio be $\frac{R_{max}^2}{h_{min}} \leq 500$ - for quartz and $\frac{R_{max}^2}{h_{min}} \leq 400$ - for lithium niobate. Further, for a more graphic comparison, the relations: 25, 100, 200, 400.

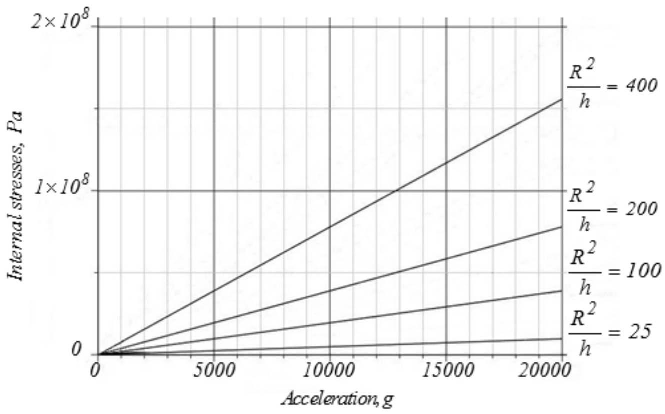


Fig.4, a. Graph of internal stresses of sensitive elements of quartz ST-cut for the proposed size relationships

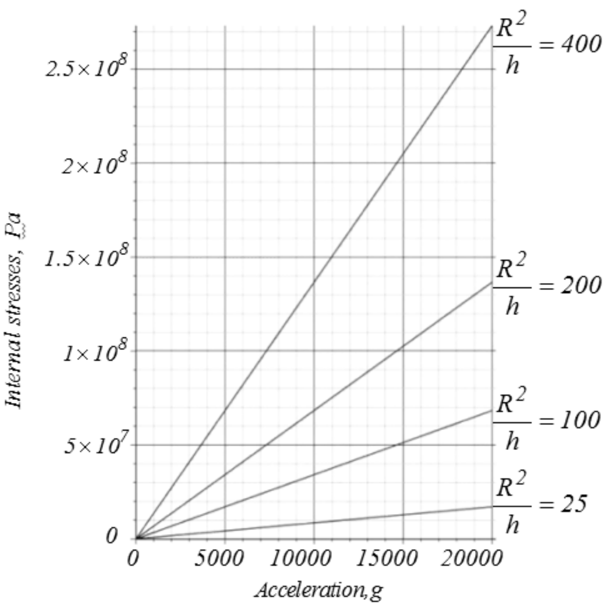


Fig.4, b. Graph of internal stresses of sensitive elements of lithium niobate YX-128º-cut for the proposed size relationships

To assess the sensor measurement range and the maximum overloads at which it can work, it is necessary to know the mechanical capabilities of the SE. In particular, the ultimate strength at the out-of-the-way, from which the SE is made. Under the ultimate strength is meant a tense state at which a qualitative change in the properties of the material occurs-a transition from one mechanical state to another, for brittle materials-this means destruction.

According to the classical theory of strength, there are five types of strength criterion for different materials, depending on their structure [4, 5, 6]. The theory of maximum normal stresses is suitable only for the strength analysis of brittle materials, and only for certain loading conditions. From this theory follows the condition of bending strength:

$$\sigma_{calc.}^{max} = [\sigma]$$

where σ – ultimate strength of material, $\sigma_{calc.}^{max}$ – calculated maximum stress. Evaluation of the strength in this particular case is simple. The strength test is to determine the magnitude of the maximum stresses and then compare them with the permissible values. Passed by the strength test are recognized elements that satisfy the condition of strength, i.e. the maximum stresses in which do not exceed the allowable ones. With a linear stress state, the limiting value of the only principal stress in this case can be determined directly from the experiment. Knowing the ultimate strength of the material, it is possible to estimate under what loads and dimensions of the sensor the sensor will remain operational and take this into account in further calculations. In order to determine the ultimate strength of materials, it was necessary to conduct static tests of quartz samples ST-cut and lithium niobate YX-128º.

III. Static testing of samples of quartz materials of ST-cut and lithium niobate YX-128°

On the basis of the Faculty of Mechanics and Mathematics of the St. Petersburg State University tests were carried out on quartz samples of ST-cut and lithium niobate YX-128º, in order to determine the maximum ultimate strength of the material SE [7], [8].

The tests were carried out using special equipment for evaluating the mechanical properties of materials and parts - INSTRON, the floor testing system series 5985 for large forces up to 600 kN, Fig. 5, a. These mechanical testing machines are widely used for testing tension and compression; however, they also test for bending, tearing, shearing, breaking and cyclic testing.

The method of testing specimens of bending material consists of the definition:

- bending strength;
- modulus of elasticity when loading a sample within the proportionality of deflection from the load;

Fig. 5, a. Experimental installation INSTRON 5985

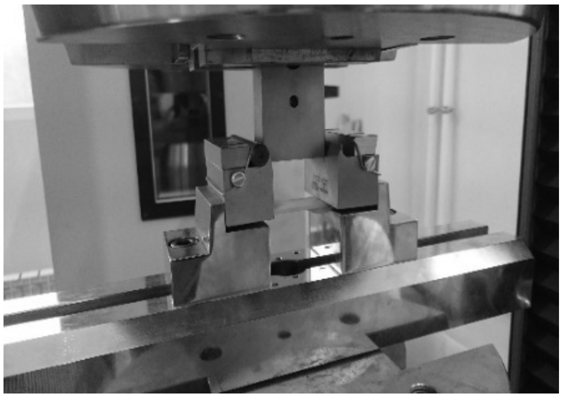


Fig.5, b. Method of fixing the plate on the equipment

- the dependence of the deflection on the load when the specimen is loaded down to failure.

The fixing scheme on the test bench corresponded to the proposed method of fixing the SE in the body of the microaccelerometer, and also to the fixing scheme for calculating the ultimate strength. The load simulated the effect of acceleration on the element.

Before the test, the INSTRON 5985 machine was fitted with clamps with clamps and parallelism of the supporting surfaces was ensured. The traverses provided the clamping strength of the clamps during testing and had a standard scale division of 1 mm, allowing the clamps to be mounted at a given distance, Fig. 5, b. Samples of quartz plates of ST-cut, with dimensions of 39.9 × 19.89 × 1.98 mm and lithium niobate of cut YX-128º, dimensions of 23.2 × 18.4 × 1.04 mm, were rigidly fixed by clamps in the experimental setup and were subjected to mechanical action in the form of a pressure "from top to bottom" by a uniformly distributed load, before the material was destroyed, Fig.6.

The testing machine made: bending loading with a given constant speed of movement of the active gripping 0.00165 mm/s and measuring the load with an error of not more than 0.5% of the measured value. Figure 7 shows the graphs of load dependencies versus time, as well as the moments when the test plates were destroyed.

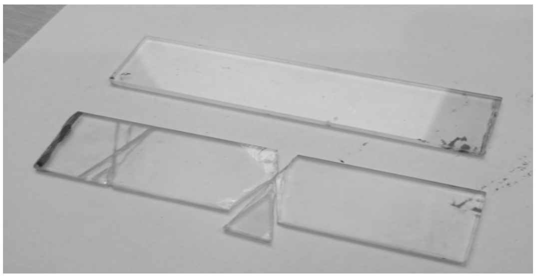


Fig.6. Samples of plates of ST-cut of quartz and lithium niobate of cut YX-128°

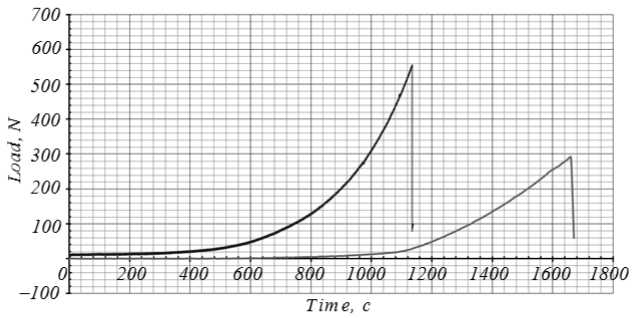


Fig.7. Graphs of the dependence of the load on time for quartz samples of the ST-cut (blue line) and lithium niobate of the YX-128 cut (red line).

To measure the deflections of the samples, built-in instruments were used that provided automatic recording of the "load-deflection", as well as digital indicators and deformation converters. The load and movement data were displayed on the computer screen during the experiments. Under the action of a load of 555 N, the sample of the quartz plate collapsed. A lithium niobate sample collapsed at a load of 290.8 N. At the end of the test, the data on the dependence of loads and displacements in time were obtained.

IV. Calculation of ultimate strength of quartz materials of ST-cut and lithium niobate YX-128°

Since the fixing scheme was non-standard, automatic output of the results of ultimate strength of the material was impossible. Therefore, according to the data known and obtained during the test (Table 1), calculations were made of the ultimate flexural strength of uniformly loaded rectangular plates: quartz ST-cut and lithium niobate YX-128° rigidly fixed at the edges [2], [7], [8]:

TABLE I. Material sample parameters

Parameter	Quartz ST-cut	Lithium niobate YX-128°
Elastic modulus, *E*[Pa]	$58\cdot10^9$	$170\cdot10^9$
Poisson's ratio, *ν*	0.23	0.25
The load at which the sample collapsed, *F*[N]	555	290.8
Length, *l*[mm]	39.9	23.2
Thickness, *h*[mm]	1.98	1.04
Width, *b*[mm]	19.89	18.4

$$q = \frac{F}{l \cdot a};$$

$$\sigma_1 = \frac{Eu^2}{3(1-\nu^2)}\left(\frac{h}{l}\right)^2;$$

$$\sigma_2 = \frac{q}{2}\left(\frac{l}{h}\right)^2 \psi_1(u);$$

$$\sigma_{max} = \sigma_1 + \sigma_2;$$

where σ_1 – tensile stress (Pa); σ_2 – maximum bending stress (Pa); σ – limiting voltage (Pa); E – elastic modulus (Pa); ν – Poisson's ratio; q – distributed load; l – length (cm); h – thickness (cm); a – width (cm) of the plate; F – load (N); u, $\psi_1(u)$ – intermediate values are calculated from the graphs.

Ultimate strength of quartz ST-cut is 141.8 MPa, and lithium niobate cut YX-128º - 106.8 MPa (Table 2) [7,8]. In the future, we can estimate the upper threshold of the dynamic range, focusing on the ultimate strength of the material. It should also be noted that when choosing the dimensions of the SE and following this correct evaluation of the maximum stresses, it is necessary to take into account the material safety margin, which is 30% of its limit.

TABLE II Ultimate strength of materials

Parameter	Quartz ST-cut	Lithium niobate YX-128°°
Ultimate strength, *σ* [MPa]	141.8	106.8

Figure 8 shows the relative dimensions of the SE, the maximum acceleration that they can withstand and the critical stresses caused in this case in the elements, according to the graph, it is also possible to estimate the upper limit of the range of the measured acceleration for each ratio of the size of the SE.

As a result, it can also be concluded that under equal conditions - acceleration overloads of 20000g, rigid fixing of SE around the perimeter - quartz, unlike lithium niobate, allows to realize in 1 cm^3 a greater number of variants of the size ratios. This suggests that quartz should be used more rationally, as a material for SE MMA on SAW, if the goal is the ability of the device to withstand large overloads and measure extreme accelerations.

V. Conclusion

In this article, estimates of the limiting capabilities of materials and structures of MMA sensitive elements on SAW are shown. Realized in this form, the SE allow the acceleration sensor to measure values of tens of thousands of g.

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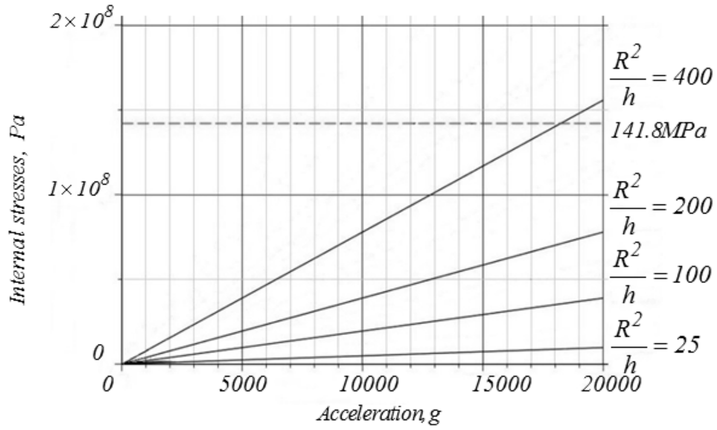

Fig. 8, a. Graph of internal stresses of sensitive elements of quartz ST-cut for the proposed size relationships

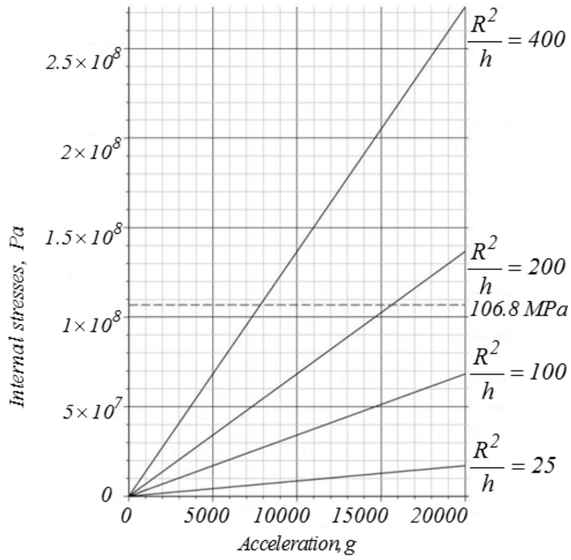

Fig. 8, b. Graph of internal stresses of sensitive elements of lithium niobate YX-128º-cut for the proposed size relationships

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