MICROELECTROMECHANICAL ACCELERATION TRANSDUCER WITH A TUNNEL CURRENT SENSOR

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I. INTRODUCTION

Tunnel accelerometers are miniature and highly sensitive transducers with high resolution, which operation is based on the electron tunnelling effect. The following advantages are inherent to tunnel accelerometers:

– high manufacturability and repeatability (the use of well developed and controlled engineering processes allows obtaining products with desirable characteristics),

– microminiature and high functionality (manufacture of transducers, processing circuits and actuators within a single device allows creating finished systems of sufficiently high complexity in a miniature housing),

– high reliability and resistance to external impacts,

– low cost (integration of processing electronics in MEMS components allows avoiding additional connections and matching circuits).

Separately, it is necessary to note such advantage of tunnel accelerometers being untypical for other types of transducers as broad frequency transmission band with the availability of high sensitivity and resolution, precision accuracy of measurements. The above-listed advantages determine a broad spectrum of possible applications of tunnel accelerometers:

– automotive electronics (electronic stability control (ESC, ESP), electronically controlled suspension (ECS), antitheft alarm systems, sensor clusters),

– multimedia applications and portable devices (position detectors, systems for hard disk protection against damage, user interfaces),

– medical engineering (controlled medical probes, rehabilitation simulators, diagnostic systems, active prostheses),

– household appliances (transducers and control system for household appliances, their functional units),

– robot engineering (transducers and control system for kinematic parameters of manipulator movement),

– navigation systems,

– safety systems (seismic activity transducers, non-destructive testing systems, sensors of unauthorised penetration/influence upon the control object).

The above-listed advantages and a broad spectrum of possible applications of tunnel accelerometers determine the prospectiveness of works on design and development of this type of transducers.

II. PHYSICS OF THE EFFECT

With the distance Δz between the sensor needle and the inertial mass of about 1 nm, a potential barrier with the width of Δz is generated. The barrier height is determined by the values of electronic work function of the material of sensor needle φ_u and inertial mass φ_n. As it is supposed to manufacture the inertial mass and sensor needle from the same material, then the barrier height is $\varphi = \varphi_n = \varphi_u$. For a one-dimensional rectangular barrier, the probability of tunnelling W is determined by the formula $W = e^{-k \cdot \Delta z}$, where k is the constant of attenuation of the wave function in the barrier area ($k = \frac{2\sqrt{2m\varphi}}{\hbar}$), $m = 9{,}1 \cdot 10^{-31}\, kg$ is the electron mass, $\hbar = 1{,}054 \cdot 10^{-34}\, J \cdot s$. With application of the potential difference V between the sensor needle and the inertial mass, the tunnel current appears, which is mainly generated by electrons with the energy in the neighbourhood of Fermi levels [1]. In case of a low voltage value $(\varphi >> eV)$, the dependence of the tunnel current density upon the potential barrier width has the following form [2]:

$$j_t = \frac{e^2\sqrt{2m\varphi}}{4\pi^2\hbar(\Delta z)^2}\frac{V}{\Delta z}\exp\left(-2\sqrt{\frac{2m\varphi}{\hbar^2}}\Delta z\right) \qquad (1)$$

In formula (1) j_t is the tunnel current density, $e = 1{,}6 \cdot 10^{-19}\, C$ is the electron charge.

For high voltages $(\varphi << eV)$, the dependence of the tunnel current density upon the potential barrier width can be expressed by the Fowler-Nordheim for field emission of electrons to vacuum:

$$j_t = \frac{e^3 V^2}{16\pi^2 \hbar \varphi (\Delta z)^2} \exp\left(-\frac{4\sqrt{2m\varphi^3}}{3e\hbar V} \Delta z \right) \quad (2)$$

The exponential dependence of the tunnel current density upon the potential barrier width allows determining the movement of the inertial mass with respect to the sensor needle with a high accuracy.

III. SCHEMATIC CIRCUIT DIAGRAM OF THE TRANSDUCER

The tunnel accelerometer being developed, (fig.1) is a transducer of compensation type including inertial mass (2), cantilever (3), sensor needle (9).

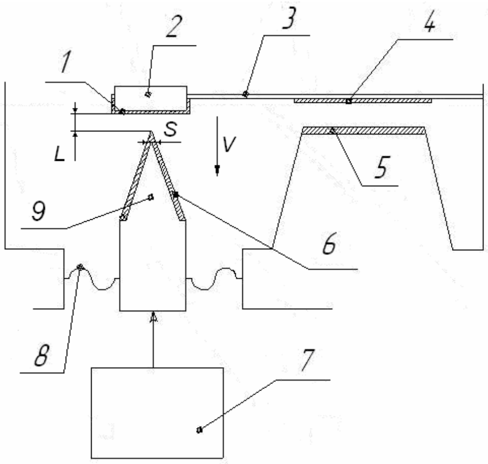

Fig. 1. Schematic circuit diagram
of the microelectromechanical acceleration transducer
with a tunnel current sensor

It is assumed that the transducer production will be carried out by means of silicon technology. Therefore, in order to fulfil the conditions of appearance of the tunnel effect the inertial mass (2) and the sensor needle are coated with a metallisation layer (1 and 6 respectively). The feedback is performed by elements 7 and 8. An advantage of the transducer being developed is its adaptivity to the input signal level. It is achieved by means of a capacitive feedback provided by metallisation layers 4 and 5.

In the cause of designing the accelerometer under consideration a resolution has been received № 2008126675/28(032572) of 27.11.2009 of issuing the patent for the invention of “Microelectromechanical Acceleration Ttransducer”.

On the whole, the accelerometer being developed is a double-circuit automatic control system. The first circuit provides the retrieval of information about the input signal value. The second circuit supports the value of distance between the sensor needle and the inertial mass within the permissible value rang. Such arrangement of the transducer provides a broad spectrum of its possible solutions.

The accuracy characteristics of the transducer are determined by the optimal character of selection of the following parameters (fig. 1):

– potential difference between the sensor needle and the inertial mass, V ,
– geometric dimensions of the sensor,
– optimal distance between the sensor needle and the inertial mass, Δz .

The significant influence upon the transducer accuracy is exerted by selection of the model for conversion of the tunnel current value into the value of sensor needle movement.

The production of the transducer being developed can be implemented at microelectronic industry enterprises in the town of Zelenograd (Moscow Region).

IV. EVALUATION OF THE TRANSDUCER SENSOR PARAMETERS

In selecting the input voltage value, it is necessary to take into account the dependence of the tunnel conductivity G upon the potential difference V between the sensor needle and the inertial mass, the accuracy of fulfilment of the conditions $\varphi >> eV$ or $\varphi << eV$. As the typical electronic work function is $\varphi \approx 4eV$, the most expedient is to select the input voltage value less than 1 V. If $\varphi > eV$, the dependence of G upon V is determined by the following expression [3]:

$$G \approx \gamma \sqrt{\varphi} \exp\left(-A\sqrt{\varphi}\right) \cdot \left(1 + 3\sigma \cdot V^2\right) \quad (3)$$

In formula (3) $\gamma = \frac{e\sqrt{2m}}{4\pi^2 \hbar^2}$, $A = 2\sqrt{\frac{2m}{\hbar^2}}$, $\sigma = \frac{(Ae)^2}{96\varphi(\Delta z)^2} - \frac{Ae^2}{32\Delta z \varphi^{3/2}}$. The dependence between the tunnel conductivity G and the potential difference в V obtained experimentally is shown in fig. 2. [4]

The typical voltage being applied to the probes of scanning tunnel microscopes is the voltage of about 0.3 V [4]

The curve of dependence of the tunnel current value j_t upon the distance Δz between the sensor needle and the inertial mass is given in fig. 3.

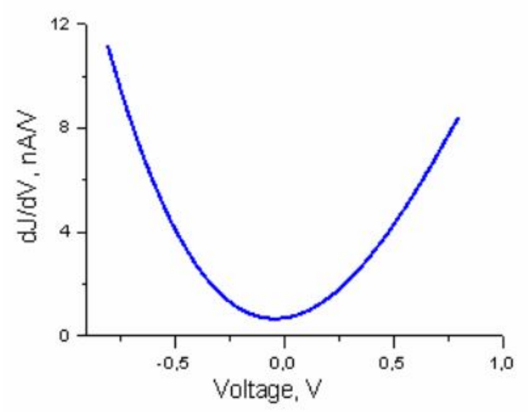

Fig. 2.Dependence between the tunnel conductivity G and potential difference V obtained experimentally

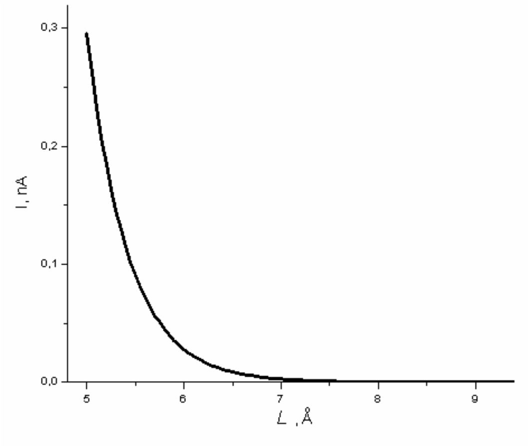

Fig. 3. Curve of dependence of the tunnel current value j_t upon the distance Δz between the sensor needle and the inertial mass

It has been determined experimentally that the optimal value of the distance between the sensor needle and the inertial mass for a transducer of compensation type is $\Delta z \approx 5{,}5\ \overset{0}{A}$ [2] From formula (1) (at $\varphi = 5{,}7\,eV$, $\Delta z \approx 5{,}5\ \overset{0}{A}$), it follows that more than 97% of tunnel current is passing through the layer of atoms being nearest to the needle surface. As the tunnel current value is $j_t = 0{,}1 \cdot 10^{-9} A$, then the minimal diameter of the needle is limited by the permissible current density. Given that the permissible current density for platinum is $2 \cdot 10^5\, A/cm^2$, the minimum diameter of the tunnel contact S is about 5 $\overset{0}{A}$.

V. CONCLUSION

The analysis of the possibility of using the electron tunnelling effect for implementation of the retrieval of information, the determination of peculiarities of the design, schematic circuit diagram of the transducer being under consideration and preliminary evaluation of the sensor parameters allow making the following conclusions:

1. The transducer being developed can find wide application in diverse branches of engineering - from automotive industry and household appliances to safety systems and positioning systems for moving objects.
2. Well-known and well developed technologies of the production of microstructure engineering can be used for production of the transducer.
3. Additional research of metrological characteristics of the sensor are required for evaluation of the prospects of use of the transducer being developed in automatic control and regulation systems.

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