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GaSb whiskers in sensor electronics

***A.A.Druzhinin*[1,2], *I.I.Maryamova*[1], *O.P.Kutrakov*[1]**

[1]Department of Semiconductor Electronics, Lviv Polytechnic of National University, Ukraine
[2]International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland

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Piezoresistive properties of gallium antimonide whiskers grown from the vapour phase by chemical transport reaction were studied in the temperature range of −150÷+100°C. The possibility to create different piezoresistive mechanical sensors based on these microcrystals was shown. On the basis of *n*- and *p*-type GaSb whiskers the strain gauges were created with high sensitivity operating in the wide temperature range. Sensors of hydrostatic pressure up to 5000 bar based on the *n*-type GaSb whiskers with high sensitivity were developed, that allows to obtain the output signal to 700 mV (without amplification) at this pressure.
Keywords: Gallium antimonide, whisker, piezoresistance, sensor, stain gauge, hydrostatic pressure sensor.

Пьезорезистивные свойства нитевидных кристаллов антимонида галлия, выращенных из газовой фазы методом химических транспортных реакций, исследовались в диапазоне температур −150÷+100°C. Показана возможность создания различных пьезорезистивных сенсоров механических величин на основе этих микрокристаллов. Созданы тензорезисторы с высокой чувствительностью для работы в широком диапазоне температур на основе нитевидных кристаллов GaSb *n*- и *p*-типов. Были разработаны датчики гидростатического давления до 5000 бар на основе нитевидных кристаллов GaSb *n*-типа с высокой чувствительностью, что позволяет получить выходной сигнал до 700 мВ (без усиления) при этом давлении.

Ниткоподібні кристали GaSb для сенсорної електроніки. *А.О.Дружинін, І.Й.Мар'ямова, О.П.Кутраков*.
П'єзорезистивні властивості ниткоподібних кристалів антимоніду галію, вирощених з газової фази методом хімічних транспортних реакцій, досліджувалися у діапазоні температур −150÷+100°C. Показано можливість створення різних п'єзорезистивних сенсорів механічних величин на основі цих мікрокристалів. Створено тензорезистори з високою чутливістю для роботи у широкому діапазоні температур на основі ниткоподібних кристалів GaSb *n*- і *p*-типів. Розроблено датчики гідростатичного тиску до 5000 бар на основі ниткоподібних кристалів GaSb *n*-типу з високою чутливістю, що дозволяє отримати вихідний сигнал до 700 мВ (без підсилення) при цьому тиску.

1. Introduction

Nowadays, in sensor electronics silicon is a major material to create semiconductor piezoresistive mechanical sensors [1, 2]. On the basis of Si whiskers the various mechanical sensors were developed [3–7]. However, mechanical sensors on the basis of silicon sometimes could not satisfy all of the appearing requirements due to progress of new branches of science and technology. Therefore it is interesting to search and study other semiconductor materials for sensors, particularly A^3B^5 compounds.

Table 1. Piezoresistance of gallium antimonide.

Material	Impurity concentration at 20°C, cm^{-3}	Resistivity, Ohm·cm	$\pi \cdot 10^{-12}$ cm^2/dyn				m_{max}
			π_{11}	π_{12}	π_{44}	π_{max}	
n-type GaSb	$1.37 \cdot 10^{18}$	0,0040	−58.5	−55.7	−78	−108.6	−111
n-type GaSb	$4.6 \cdot 10^{18}$	0.0012	−38.4	−34.3	−89.3	−95.2	−97.6
p-type GaSb	$1 \cdot 10^{17}$	0.08	+5	−2.4	+87	+58	+58.7

The aim of this paper is to study gallium antimonide as a material to create piezoresistive mechanical sensors on its base. For this purpose we analyze the piezoresistance of GaSb crystals.

Piezoresistance coefficients π_{11}, π_{12}, and π_{44} for gallium antimonide from the experimental data are presented in Table 1 [8, 9]. Maximal values of the longitudinal piesoresistance π_{max} for GaSb in this Table were calculated. It could be noticed that the maximal piezoresistance of n- and p-type GaSb was observed in crystallographic direction [111]. Therefore the maximal longitudinal piezoresistance coefficient for GaSb was calculated by equation [10]

$$\pi_{\max} = \pi_{[111]} = \frac{1}{3}\pi_{11} + \frac{2}{3}(\pi_{12} + \pi_{44}), \quad (1)$$

and the maximal longitudinal elastoresistance coefficient was determined as

$$m_{\max} = m_{[111]} = \pi_{[111]} \cdot E_{[111]}, \quad (2)$$

where $E_{[111]}$ is the Young module for GaSb in [111] direction.

As observed in Table 1, n- and p-type GaSb crystals are characterized by high piezoresistance, which suggests the possibility to create the high sensitive piezoresistive sensors based on GaSb.

Besides it, n-type GaSb crystals have high sensitivity to the hydrostatic pressure [11, 12], that is determined as

$$K_h = \pi_{11} + 2\pi_{12} \quad (3)$$

and equals $K_h = 172.5 \cdot 10^{-12}$ cm^2/dyn for n-type GaSb with resistivity $\rho = 0.004$ Ohm·cm.

Therefore n-GaSb crystals could be successfully used to create the sensors of hydrostatic pressure on their basis.

2. Strain gauges based on GaSb whiskers

GaSb whiskers were grown by means of chemical transport reactions from the vapour phase in a closed system using iodine as a transport agent. Gallium and antimony in the stoichiometric proportion and iodine are loaded in a quartz ampulla. The evacuated ampulla was placed in a three-zone furnace. GaSb whiskers were grown at temperature 750–850°C in the dissolution zone and at 620–680°C in the crystallization zone. Grown GaSb whiskers were formed as triangular prisms elongated in crystallographic direction [111], which corresponded to the direction of maximal piezoresistance of n- and p-types GaSb.

GaSb crystals grown from the stoichiometric composition have hole conductivity, their resistivity is 0.05–0.15 Ohm·cm, while carrier concentration equals $5 \cdot 10^{16}$–$5 \cdot 10^{19}$ cm^{-3}. Doping of the crystals by Zn gives the possibility to obtain p-type GaSb whiskers with different resistivity in the range from 0.007 to 0.15 Ohm·cm. To obtain n-type GaSb whiskers the crystals were doped by Te.

To study piezoresistive properties of the GaSb whiskers, 4–6 mm long microcrystals with 20–40 μ width faces were selected. Contacts to the GaSb whiskers were created by welding the microwire fabricated from the contact material with the crystal. For the p-type whiskers the ohmic contacts were created with using Au-microwire with 30 μ diameter, as for the n-type crystals with Au-microwire doped by Te impurity was used.

The piezoresistive properties of the GaSb whiskers were studied in the wide range of strain ($\varepsilon = \pm 1.2 \cdot 10^{-3}$ rel.un.) and temperature −150÷+100°C. The n-type GaSb whiskers with resistivity of 0.002 – 0.004 Ohm·cm and the p-type crystals with resistivity of 0.007 – 0.15 Ohm·cm were investigated. Dependences of resistance for the GaSb whiskers with different resistivity, mounted on the steel beam vs applied uniaxial strain at the room temperature are shown in Fig. 1. As observed in Fig. 1, the dependences of resistance vs strain for the p-type GaSb whiskers have the best linear-

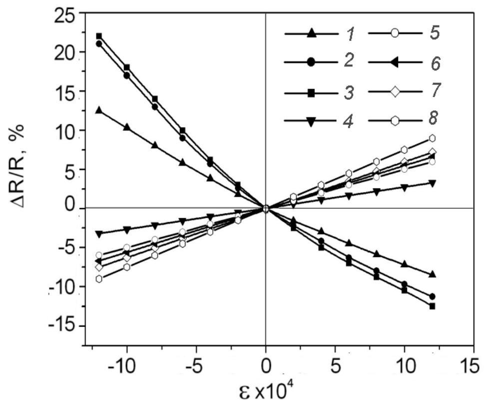

Fig. 1. Relative change of resistance vs strain for GaSb whiskers with different resistivity at 20°C:

1 — *n*-GaSb(Te), $\rho = 0.002$ Ohm·cm;

2 — *n*-GaSb(Te), $\rho = 0.0042$ Ohm·cm;

3 — *n*-GaSb(Te), $\rho = 0.0048$ Ohm·cm;

4 — *p*-GaSb(Zn), $\rho = 0.007$ Ohm·cm;

5 — *p*-GaSb(Zn), $\rho = 0.016$ Ohm·cm;

6 — *p*-GaSb(Zn), $\rho = 0.056$ Ohm·cm;

7 — *p*-GaSb(Zn), $\rho = 0.08$ Ohm·cm;

8 — *p*-GaSb(Zn), $\rho = 0.12$ Ohm·cm.

ity in comparison with the *n*-GaSb microcrystals. Gauge factor K for these crystals was calculated by equation

$$K = \frac{\Delta R(\varepsilon)}{R_0 \varepsilon}, \quad (4)$$

where R_0 — resistance of unstrained crystal; $\Delta R(\varepsilon)$ — change of a resistance under applied strain; ε — applied uniaxial strain.

Longitudinal gauge factor of the *p*-type GaSb whiskers is $K = +(26 \div 77.5)$ for the crystals with resistivity of 0.007 – 0.12 Ohm·cm. Obtained value $K = +61.4$ for the microcrystals with $\rho = 0.08$ Ohm·cm is in a good conformance with the longitudinal coefficient of elastoresistance $m_{[111]} = +58.7$, calculated from the longitudinal piezoresistance coefficient for the *p*-type GaSb bulk monocrystals with the same resistivity [9]. Transverse gauge factor for the *p*-GaSb whiskers is not more than 2.6 % from the value of the longitudinal gauge factor of these crystals.

The gauge factor of the *n*-type GaSb whiskers is more than for the *p*-type whiskers. The obtained value $K = -105$ (at $\varepsilon = +1 \cdot 10^{-3}$ rel.un.) for the *n*-type GaSb whiskers with resistivity $\rho = 0.0042$ Ohm·cm is well conformed with the value of $m_{[111]} = -111$ (see Table 1), calculated from the experimental data of piezoresistance for the *n*-GaSb bulk monocrystals with resistivity $\rho = 0.004$ Ohm·cm [8].

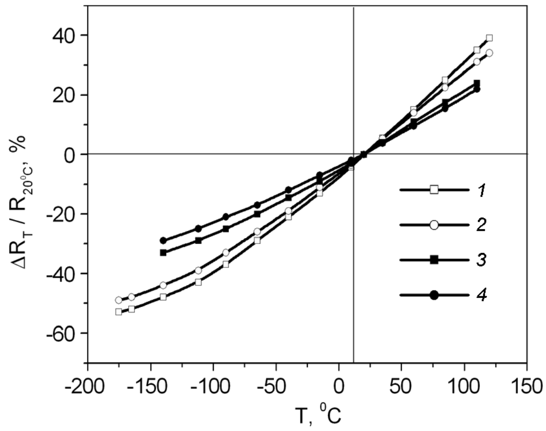

Fig. 2. Temperature dependences of relative change of resistance for *n*-type GaSb whiskers "free" (*1*, *2*) and mounted on steel (*3*, *4*): *1*, *3* — $\rho = 0.0038$ Ohm·cm; *2*, *4* — $\rho = 0.0023$ Ohm·cm.

Temperature dependences of resistance for "free" (unmounted) GaSb whiskers were studied in the temperature range of $-180 \div +100$°C. For the "free" Te doped *n*-type GaSb whiskers with resistivity $\rho = 0.002 - 0.004$ Ohm·cm in this temperature range, monotonic increase of the crystals' resistance with rise of the temperature was observed (Fig. 2). Temperature coefficient of resistance (TCR) for this crystals equals $+(0.33–0.36)\% \cdot \text{grad}^{-1}$ in the temperature range of $-150 \div +100$°C.

On the curves of the temperature dependence of resistance for the Zn doped *p*-type GaSb whiskers with resistivity $\rho = 0.03 - 0.15$ Ohm·cm was observed the minimum, which could be explained by transition from one mechanism of carriers scattering to another (Fig. 3 a,b). For heavily doped *p*-GaSb whiskers this minimum is absent (Fig. 3a, curve *3*). In the temperature range of $-50 \div +100$°C TCR for the Zn doped *p*-type GaSb whiskers with resistivity $\rho = 0.016 - 0.033$ Ohm·cm TCR equals $+(0.23 - 0.24)\% \cdot \text{grad}^{-1}$ and for whiskers with $\rho = 0.12 - 0.15$ Ohm·cm TCR $\leq 0.3\ \% \cdot \text{grad}^{-1}$.

After mounting the crystals on the steel (material of the spring elements) the GaSb crystals undergo the thermal strain arising

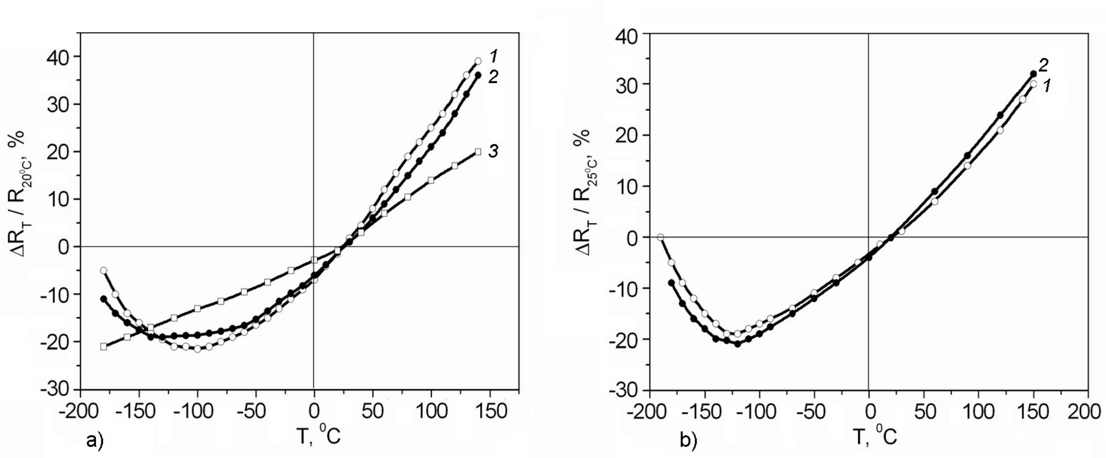

Fig. 3. Temperature dependence of relative change of resistance for p-type GaSb whiskers with different resistivity: a) *1* — 0.033 Ohm·cm; *2* — 0.0164 Ohm·cm; *3* — 0.007 Ohm·cm; b) *1* — 0.12 Ohm·cm; *2* — 0.15 Ohm·cm.

due to difference of the temperature expansion coefficient of the GaSb crystals (α_{GaSb} = $6.3 \cdot 10^{-6}$ %·grad^{-1} [13]) and the steel. This thermal strain ε_t could be estimated as [14]

$$\varepsilon_t(T) = \gamma \int_{T_0}^{T} \left[\alpha_S(T) - \alpha_C(T)\right] dT, \quad (5)$$

where α_S and α_C are the thermal expansion coefficients (TEC) of semiconductor and material of spring element (substrate) respectively, T_0 — the hardening temperature of adhesive used for mounting whiskers on spring element, factor γ characterize the strain transmission from the spring element to the crystal.

In our case the temperature expansion coefficient of GaSb is smaller than TEC of steel, $\varepsilon_t < 0$. Therefore the whisker, mounted on steel, undergoes the compressive strain ε_t. This strain causes the changes of resistance and temperature dependence of resistance for the GaSb whiskers, mounted on steel, in comparison with the free (unmounted) crystals. Temperature dependence of the n-type GaSb whiskers, mounted on steel, is smaller than for the free crystals (Fig. 2); at the same time for the p-type GaSb crystals this dependence is increasing. The temperature coefficient of resistance for the n-type GaSb whiskers with resistivity 0.002 – 0.004 Ohm·cm, mounted on steel, equals +(0.22 – 0.24) %·grad^{-1}.

For the p-type GaSb whiskers, a decrease of gauge factor when the temperature is raising in the range of −140÷+100°C was observed. For the crystals with resistivity 0.09 – 0.12 Ohm·cm the gauge factor changes according to the low $1/T$. However, as the charge carriers' concentration in the crystals increase, the temperature dependence of the gauge factor in this crystals decrease. Therefore the p-type GaSb (Zn) whiskers with resistivity of 0.01 – 0.08 Ohm·cm have the weaker temperature dependence of gauge factor $K = f(T)$ (Fig. 4, curve 1). For these crystals the temperature coefficient of gauge factor equals −(0.25 – 0.3) %·grad^{-1} in the temperature range of −140÷+80°C.

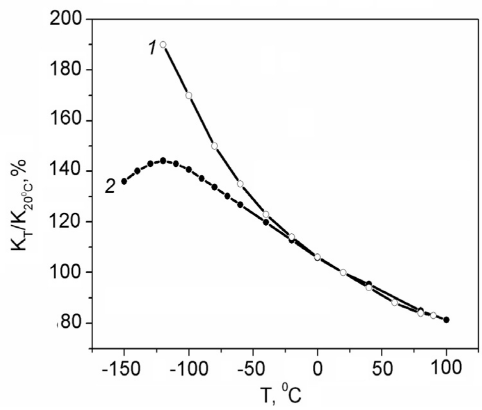

Fig. 4. Temperature dependences of gauge factor for GaSb whiskers: *1* — p-type with ρ = 0.03 Ohm·cm; *2* — n-type with ρ = 0.004 Ohm·cm.

The temperature dependence of gauge factor for the n-type GaSb whiskers has another characteristic. For these crystals at the low temperatures on the curve $K = f(T)$ it was observed the maximum (Fig. 4, curve *2*), that is in a good accordance with the tem-

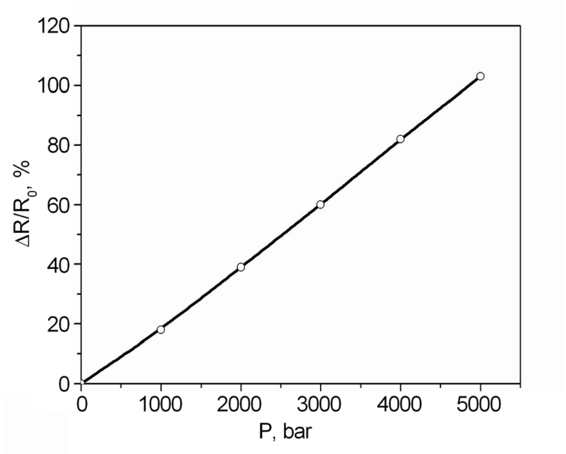

Fig. 5. Relative change of resistance vs hydrostatic pressure for n-type GaSb whiskers.

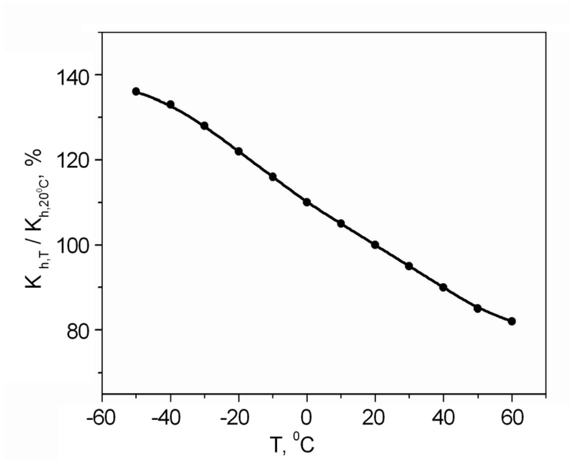

Fig. 6. Temperature dependence of hydrostatic pressure coefficient for n-type GaSb whiskers.

perature dependence of the longitudinal piezoresistance $\pi_{[111]}$ of the n-type GaSb [15].

The grown GaSb whiskers have the high mechanical strength due to their structural perfection, they hold out the uniaxial strain ~$(6-7)\cdot 10^{-3}$ rel.un. They also hold out more than 10^6 cycles of strain $\varepsilon = 5\cdot 10^{-4}$ rel.un. at dynamic tests.

Thus, the both n-type and p-type GaSb whiskers with [111] orientation grown by chemical transport reactions from the vapor phase, due to their morphology, size, excellent mechanical properties and high gauge factor could be used as active elements of semiconductor strain gauges operating in the wide temperature range (−160÷+100°C). Performance of the developed strain gauges is shown in Table 2.

3. *Hydrostatic pressure sensors based on GaSb whiskers.*

To measure pressures up to 1000 bar it is appropriate to use hydrostatic pressure sensors, which do not require the development of complicate construction with spring elements, because the pressure by help of the liquid is transmitted directly on the active element of the sensor.

To create such sensors the study of the n-type GaSb(Te) whiskers under hydrostatic pressure was carried out. Dependence of the n-type GaSb whiskers resistance vs hydrostatic pressure at the room temperature is presented in Fig. 5. As observed in Fig. 5, this dependence is linear in the studied pressure range up to 5000 bar. The coefficient of hydrostatic pressure K_h was determined by equation

$$K_h = \frac{1}{P}\frac{\Delta R(P)}{R_0}, \quad (6)$$

where P is hydrostatic pressure, R_0 — initial crystal resistance when $P = 0$, $\Delta R(P)$ — change of resistance under pressure.

The coefficient of hydrostatic pressure K_h for these crystals calculated from our experimental data equals $(16.5 \div 20.0)\cdot 10^{-5}$ bar^{-1} at 20°C, which is in a good agreement with

Table 2. Performance of strain gauges, based on GaSb whiskers

Parameter	Based on n–GaSb whiskers	Based on p–GaSb whiskers
Strain range, rel. un.	$\pm(1\cdot 10^{-5}... 10^{-3})$	$\pm(1\cdot 10^{-5}...1\cdot 10^{-3})$
Resistivity, Ohm·cm	0.002 ... 0.004	0.03 ... 0.08
Resistance at 20°C, Ohm	50 ... 120	200 ... 600
Gauge factor at 20°C	−95 ... −110	+50 ... +60
Temperature coefficient of resistance (TCR) of unmounted strain gauges, %·grad^{-1}	+(0.33...0.36) in range −150...+80°C	+(0.23...0.24) in range −100... +150°C
Operating temperature range, °C	−150...+100	−150...+100
Size, mm	(0.02 − 0.04)·(0.02 − 0.04)·(4 − 6)	

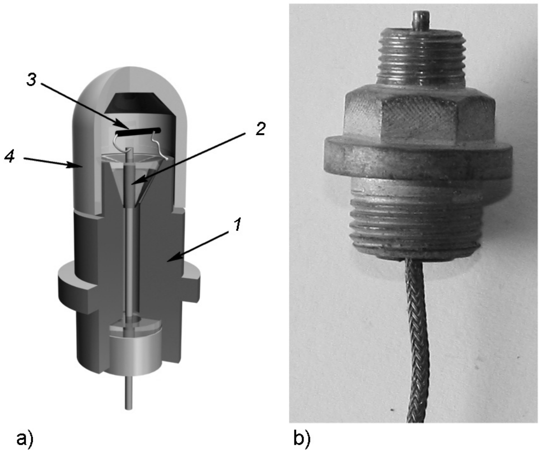

Fig. 7. Design (a) and view (b) of developed hydrostatic pressure sensor. *1* — housing, *2* — lead wire, *3* — GaSb crystal, *4* — protecting cap.

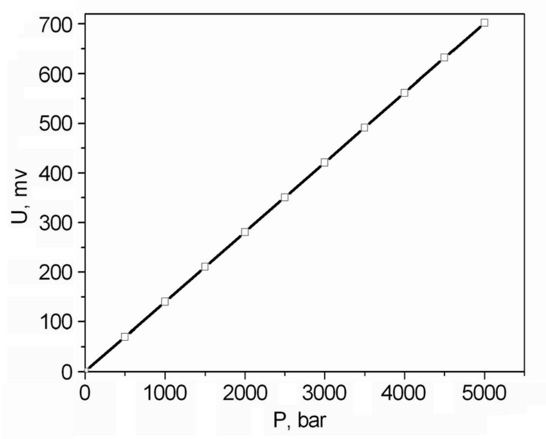

Fig. 8. Output of developed hydrostatic pressure sensor based on *n*-type GaSb whisker.

the value of K_h calculated from the piezoresistiance coefficients.

As temperature rise, the coefficient of hydrostatic pressure decreases (Fig. 6). In the temperature range of −60...+60°C, the temperature coefficient of K_h for *n*-type GaSb(Te) whiskers is −(0.4 – 0.5) %·grad^{-1}.

The design of the developed hydrostatic pressure sensor based on GaSb crystal [16] is presented in Fig. 7. The housing (1) of the sensor is filled with liquid that transmits the pressure directly on the crystal (3). The output signal vs applied pressure for the developed pressure sensor is shown in Fig. 8.

4. Conclusions

Our studies of GaSb whiskers, grown from the vapor phase by chemical transport reactions, give the light to the prospects for creating different piezoresistive mechanical sensors on their base.

GaSb whiskers are ideal material for active elements of strain gauges, due to their morphology, size, mechanical properties and high gauge factor. Developed strain gauges could operate in the wide temperature range of −150÷+100°C.

On the basis of *n*-type GaSb whiskers it was also developed the sensor to measure hydrostatic pressure up to 5000 bar. The advantages of such pressure sensor are the simplicity of its design, high sensitivity, which allows to obtain the output signal ~700 mV (without amplification) at 5000 bar and good metrological characteristics. Such sensors could be used to measure high and extremely high pressures in hydraulic systems, in chemical and oil industry.

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