SOS strain gauge sensors for force and pressure transducers

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Abstract
A set of semiconductor force and pressure sensors developed on the basis of heteroepitaxial layers of silicon on sapphire (SOS) is briefly described. Physico-technological optimization of the SOS sensing elements makes it possible to create transducers for pressure measurement of cryogenic (down to 1 K), normal- and high-temperature (up to 350 °C) media without compensating elements and with a very small error due to temperature sensitivity, as well as radiation-resistant transducers.

Introduction

Silicon strain gauge sensors for measurements of mechanical parameters (mainly pressure, force or acceleration) are characterized by high sensitivity, reliability and the possibility of mass production with relatively high accuracy. However, the peculiarity of piezoresistance in semiconductors and p-n junction isolation in most widely used diffused silicon strain gauges lead, as a rule, to significant non-linearity, temperature dependence of the sensitivity and restricted operating temperature range of silicon sensors. Many different types of circuitry are used to compensate the errors that arise. As a result, the best silicon transducers have an accuracy of about 0.1-0.2%, but to achieve this individual adjustment is necessary, which makes their production more expensive.

A good illustration of silicon's possibilities as a material for integrated sensors used in different mechanical transducers is pressure and force sensors with sensing elements made of heteroepitaxial 'silicon-on-sapphire' (SOS) structures [1]. The evident advantage of SOS usage is a significant extension of the operating temperature range due to the absence of a p-n junction [2]. Besides, detailed research on SOS as a material for sensing elements in integrated sensors has shown that an optimum choice of the silicon layer's characteristics and the strain gauge circuitry topology allows the basic sensor errors (non-linearity and temperature sensitivity error) to be excluded and the circuit correction of these errors in the transducer to be greatly simplified or even unnecessary. Using SOS structures, we managed to produce pressure and force sensors operating in a wide temperature range (from -272 to +350 °C) with high accuracy. They are also stable to ionizing radiation.

Properties of SOS as a material for sensing elements

The choice of construction and production techniques for integrated sensors has always been based on the results of piezoresistance research in silicon, including diffused piezoresistors. We can mention here investigations of piezoresistive non-linearity [3] or the temperature dependence of the sensitivity at different doping levels [4] and its relation to the impurity distribution in piezoresistors [5]. But up to now we could only talk about more or less successful efforts to decrease error in diffused silicon sensors due to the choice of certain material properties rather than about full optimization of the piezoresistors' physical characteristics.

Detailed research on piezoresistance in SOS structures of p-type conductivity with $(001)_{Si}/(\bar{1}012)_{Al_2O_3}$ crystallographic orientation makes it possible to optimize the choice of the silicon layer's electrophysical characteristics, so that in certain cases the sensor errors practically disappear and thus the transducers do not need any circuitry error correction.

Measurements of piezoresistance non-linearity in p-SOS layers [6, 7] have shown that, in contrast to diffused silicon strain gauges [3], the dependence of the relative resistance change on deformation is parabolic for both longitudinal and transverse gauges:

$$\left(\frac{\Delta R}{R_0}\right)_{\parallel,\perp} = K^{(1)}_{\parallel,\perp}\varepsilon + K^{(2)}_{\parallel,\perp}\varepsilon^2 \qquad (1)$$

Here both coefficients $K_\parallel^{(2)}$ and $K_\perp^{(2)}$ are positive and for membrane pressure sensors are very close together in a wide temperature range (Fig. 1). The law (1) allows membrane pressure sensors to be constructed with linear output at high deformation level if the arrangement of the longitudinal and transverse gauges on the sensing element satisfies the condition $K_\parallel^{(2)}\varepsilon_\parallel^{(2)}= K_\perp^{(2)}\varepsilon_\perp^{(2)}$. A linear output is also achieved using gauges equally orientated relative to the membrane's characteristic deformation, and located in places with equal but opposite deformations.

Detailed investigations of the temperature dependence of resistivity and the basic elastoresistance coefficient m_{44} [8, 9] showed that at certain doping levels this dependence can be quite well approximated with an exponent in a wide temperature range (up to several hundreds of degrees):

$$\rho(T) = \rho_0 \exp(\alpha_\rho T) \qquad (2)$$

$$m_{44}(T) = m_{44}^0 \exp(\alpha_m T) \qquad (3)$$

Figure 2 shows typical experimental curves of $\rho(T)$ and $m_{44}(T)$ for p-SOS, and the boundaries of regions where eqns. (2) and (3) are valid are shown in Fig. 3(a). As α_ρ and α_m are equal to the differential temperature coefficients corresponding to ρ and m_{44} the fact of their being simultaneously constant was called the differential-temperature invariance of piezoresistivity (DTIP) [8]. The importance of the DTIP region in p-SOS is that, as can easily be shown [8], for sensors with a bridge circuit formed by two pairs of adjacent strain gauges R_1 and R_2 and fed by a constant-current source, the condition of temperature sensitivity stability is denned as

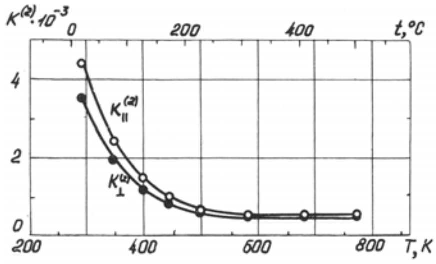

Fig. 1. Temperature dependence of second-order piezoresistance coefficients for radial $K_{\parallel}^{(2)}$ and tangential $K_{\perp}^{(2)}$ strain gauges on a membrane pressure sensor with SOS sensing element.

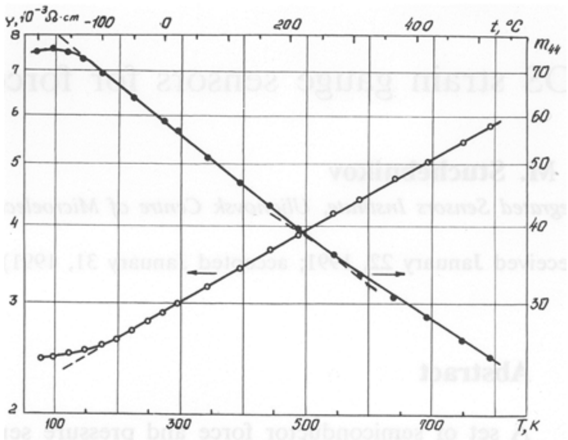

Fig. 2. Temperature dependence of resistivity ρ and elastoresistance coefficient m_{44} in p-SOS (p=5xl0[19] cm[-3]).

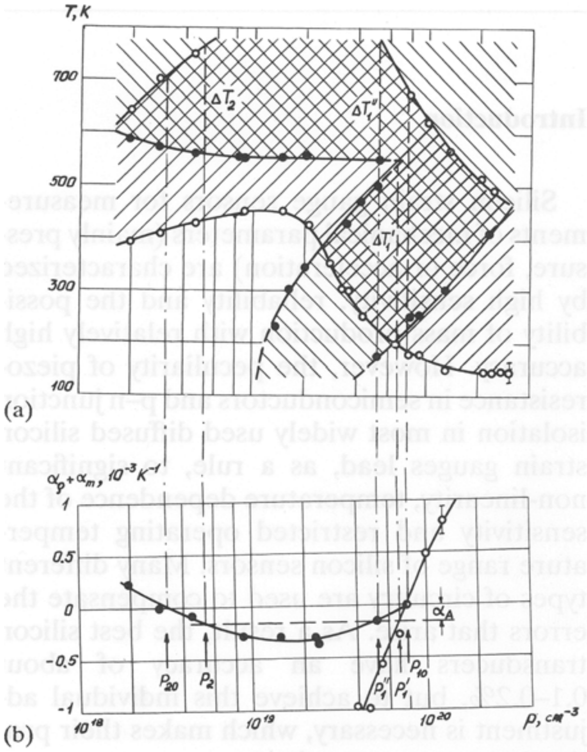

Fig. 3. (a) The boundaries of regions where α_ρ (○) or α_m (●) are constant. The DTIP region is cross-hatched. (b) Dependence of the sum $\alpha_\rho+\alpha_m$ on the hole concentration in p-SOS in the DTIP region.

$$\alpha_U = \alpha_R + \alpha_K + \alpha_A = 0 \tag{4}$$

where

$$\alpha_U = \frac{1}{U(T)}\frac{\partial U(T)}{\partial T} \tag{5}$$

is the temperature coefficient of the sensor sensitivity (TCSS),

$$\alpha_R = \frac{1}{R(T)}\frac{\partial R(T)}{\partial T} \tag{6}$$

is the temperature coefficient of the bridge resistance (TCR),

$$\alpha_K = \frac{1}{K(T)}\frac{\partial K(T)}{\partial T} \quad (7)$$

is the temperature coefficient of the strain gauge bridge sensitivity (TCS) and

$$\alpha_A = \frac{1}{A(T)}\frac{\partial A(T)}{\partial T} \quad (8)$$

is the temperature coefficient of elastic transformation (TCET).

Here the strain bridge sensitivity coefficient (gauge factor) is defined as

$$K = \frac{1}{2\varepsilon}\left(\frac{\Delta R_1}{R_0} - \frac{\Delta R_2}{R_0}\right) \quad (9)$$

where ε is the characteristic deformation of the sensing element related to the measured mechanical parameter II (force, pressure, etc.):

$$\varepsilon(T) = A(T)\Pi \quad (10)$$

For S0S layers with given orientation and membrane pressure sensors with radial and tangential Si strain gauges orientated along ⟨110⟩ crystallographic axes, $K=m_{44}$, so that $\alpha_K=\alpha_m$. Noting also that for Si $\alpha_R=\alpha_\rho$, we have condition (4) in the form

$$\alpha_\rho + \alpha_m = -\alpha_A \quad (11)$$

Figure 3(b) shows the dependence of the sum $\alpha_\rho+\alpha_m$ on the S0S layer's hole concentration p in the DTIP region. As can be seen, this sum becomes zero at $p=p_{10}$ and $p=p_{20}$, taking into account that $\alpha_A>0$, we can choose values p'_1, p''_1 and p_2 such that condition (11) is satisfied in corresponding temperature intervals $\Delta T_1'$, $\Delta T_1''$ and ΔT_2, and therefore dependence of the sensor sensitivity on temperature disappears. This property of p-SOS layers can be used for auto-compensation of the sensor sensitivity temperature error [10].

If the sensor bridge circuit is fed by a constant-voltage source, the sensor sensitivity temperature stability condition is

$$\alpha_K + \alpha_A = 0 \quad (12)$$

This condition is also fulfilled in sensors with SOS layers at a certain doping level, but in a low temperature range (less than -170 °C) [11].

SOS layers are characterized by high thermal compression due to the difference of the thermal expansion coefficients of silicon and sapphire [12]. As a result, practically all the properties of silicon strain gauges, formed as a mesa on a sapphire wafer (Si layer resistivity ρ, piezoresistive coefficients $K^{(1)}$ and $K^{(2)}$, TCR α_R and TCS α_K), depend on the strain gauge size, i.e., on the gauge's width b to layer thickness d ratio [6, 8, 13, 14]. At $b/d>50$ this dependence disappears. This property of SOS mesa gauges can also be used for correcting sensor errors [15].

Force and pressure sensors using SOS

Though SOS membrane sensing elements in pressure sensors can be similar in form to chemically etched Si membranes [16], the high chemical stability and hardness of sapphire make it preferable to use flat SOS sensing elements in mass produced sensors. Sapphire can be easily and firmly silver brazed to titanium [17]; as a result, some force and pressure sensor constructions were developed [1] in which standard flat sensing elements with dimensions 10 mm×10 mm×0.2 mm were used.

In a force sensor (Fig. 4(a)) the sensing element 1 is brazed to the surface of the metal diaphragm 2, made of titanium alloy in one piece with the base and the central lever 3. The base is welded to a housing 4. Electric leads from the sensing element are welded to collector 5. The cap 6 protects the leads and the sensing element. The strain-sensitive bridge (Fig. 4(b)) is topologically closed; the strain gauges are located at the inner edge of the lever [18] along the diaphragm diameter and orientated along the [110] axis of silicon. The force applied transverse to the lever's end bends the diaphragm; the gauges are strained and the bridge output signal appears. The adjacent arms of the bridge contain additional resistors, initially shunted with silicon strips. Tearing these strips in the sensor adjustment process allows the bridge to be balanced without changing the TCR of the gauges. The use of a closed bridge eliminates possible instability due to contact resistance.

In single-diaphragm pressure sensors (Fig. 5(a)) the sensing element 1 is brazed to the diaphragm 2 made as a whole with the base 3. The rigid centre 4 can be used to linearize the output. To increase the sensitivity, double-diaphragm sensors are used (Fig. 5(b)); in these the diaphragm 2 is stiffly connected by the rod 5 with a metal diaphragm 6 having a larger diameter. The strain gauges of the sensor's bridge circuit are located at the outer border of the diaphragm above the base [19]. The bridge is also topologically closed and has the elements of initial output balance.

The described force and pressure sensors are produced commercially; they are used in the set of 'Sapfir-22' pressure transmitters [20]. The operating temperature range for the sensors is -60-120 °C; some sensor characteristics are given in Table 1, accounting for the technological scatter of SOS parameters in full-scale production. The possibilities of DTIP for sensor temperature autocompensation are illustrated in Fig. 6(a), where typical temperature curves of sensor sensitivity are shown with a close to optimum SOS doping level. SOS sensors are highly stable: the change of operating characteristics for a pressure sensor over six months is less than the dead-weight tester error used for calibration (0.02-0.05%) [21].

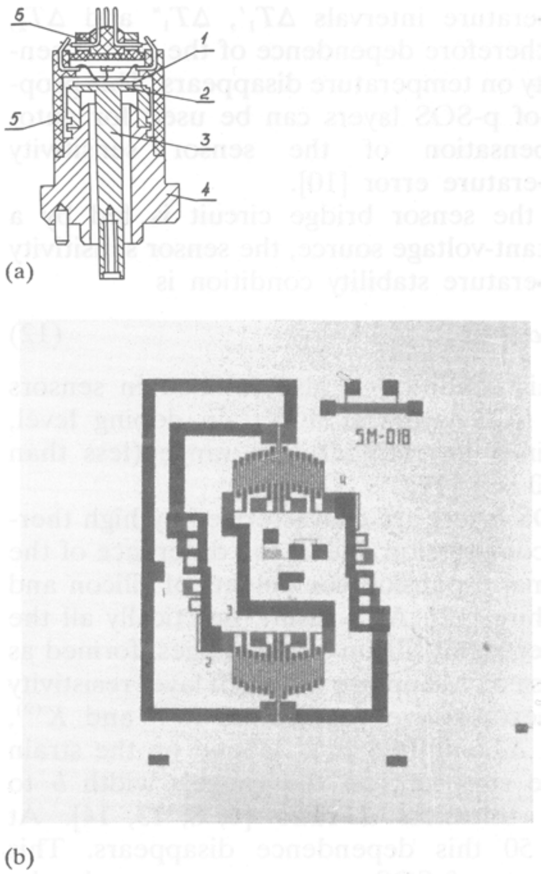

Fig. 4. (a) Force sensor with SOS sensing element brazed to titanium diaphragm. 1, SOS sensing element; 2, titanium diaphragm; 3, lever; 4, sensor housing; 5, collector; 6, cap. (b) Photo of the SOS sensing element for force sensor.

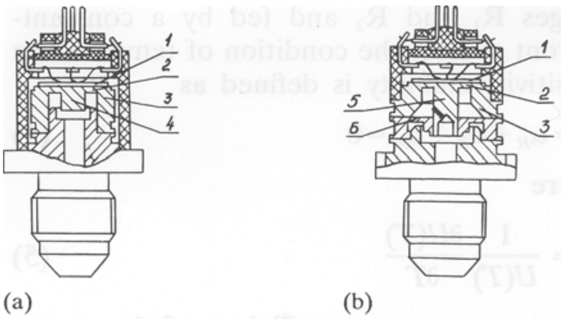

Fig. 5. (a) Pressure sensor with a single metal diaphragm. (b) Pressure sensor with two titanium diaphragms, stiffly connected by a rod. 1, SOS sensing element; 2, titanium diaphragm; 3, diaphragm's base; 4, rigid centre; 5, rod; 6, second titanium diaphragm.

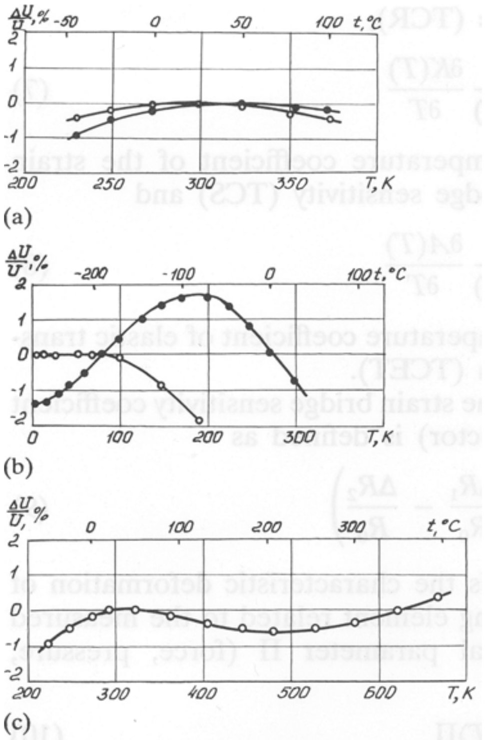

Fig. 6. Temperature dependence of span for pressure sensors with SOS sensing elements on titanium diaphragms, when the silicon doping level is close to optimum, for normal-temperature (a), low-temperature (b) and high-temperature (c) sensors.

Besides sensors operating in the climatic temperature range, SOS sensors were developed for operation at cryogenic temperatures (down to -272 °C), as well as at a high temperature of the medium measured (up to 350 °C) [22, 23]. The metrological characteristics of these pressure sensors are given in Table 1, and the possibilities of physico-technological autocompensation of the temperature sensitivity errors are shown in Fig. 6(b) and (c). Using low- and high-temperature pressure sensors, pressure transmitters for cryogenic and high-temperature media can be produced [24, 25]

TABLE 1. Some characteristics of SOS sensors

	Climatic-temperature sensors	Low-temperature sensors		High-temperature sensors
Ranges of measurement	0-2.5; 0-16; 0-200 MPa 0-5; 0-50 N	From 0-0.25 to 0-2.5 MPa		From 0-0.4 to 0-60 MPa
Input resistance, kohm	3.2±0.2	3.2 ±0.2	3.2 ±0.2	3.2 ±0.2
Current/voltage supply	2 mA	5 V	2 mA	2 mA
Offset, mV	±5	±5	±5	±5
Span, mV	250-350	80-130	80-130	80-130
Non-linearity, %	± (0.05-0.2)	±(0.05-0.2)	± (0.05-0.2)	± (0.05-0.2)
Hysteresis, %	<0.05	<0.05	<0.05	<0.05
Repeatability, %	<0.05	<0.05	<0.05	<0.05
Temperature range, °C	-60 to +120	-272 to -190	-272 to +50	±5 to ±350
Thermal zero shift, mV/10 °C	±(0.05-1)	±(0.05-1)	±(0.05-1)	± (0.05-1)
Thermal span change in the entire temperature range, %	1-3	0.2-0.5	4-6	2-5
Dimensions, mm	0 20X40	0 40x30	0 40x30	0 40x30

SOS structures for radiation-resistant sensors

The characteristics of SOS layers are poorly influenced by ionizing radiation; therefore radiation-resistant CMOS/SOS circuits have been developed [26]. These properties of SOS can be used for developing radiation-resistant pressure and force transducers, which are useful, e.g., for control systems in nuclear power stations.

Investigations of the influence of neutron and gamma radiation on the electrophysical characteristics of highly-doped p-type SOS layers [27-31] have shown that radiation changes mainly the resistivity of the Si layer and correspondingly the resistance and TCR and the silicon resistors. This change depends greatly on the layer's doping level: n° radiation up to a flux $\Phi=10^{16}$ cm^{-2} changes the resistivity of SOS layers three times for an initial hole concentration $p_0=10^{19}$ cm^{-3} and only ≈30% for $p_0=10^{20}$ cm-^{3}. With γ-radiation up to a dose $D=10^{10}R$ the resistivity change is about 6% for $p_0=5\times 10^{19}$ cm^{-3} and goes down to ≈0.5% for $p_0 = 2\times10^{20}$ cm^{-3}. At the same time such radiation does not practically affect the piezoresistance in highly doped p-SOS. The change of the elastoresistance coefficient m_{44} in layers with $p_0>5\times10^{19}$ cm^{-3} irradiated by neutrons to $\Phi\sim4.5\times10^{16}$ cm^{-2} does not exceed 2% and is within the measurement accuracy limits. In lower-doped p-SOS layers ($p_0\sim2\times10^{18}$ cm^{-3}) the m_{44} change is about 6%.

The described results show that SOS can be used to develop n°- and γ-radiation-resistant mechanical sensors. However, in this case the constant-current source supply of the bridge for temperature sensitivity error autocompensation cannot be used because the radiation-induced bridge resistance change will lead to a corresponding change of the bridge output. Better results are achieved by transition to a higher doping level (about 2×10^{20} cm^{-3}) and constant-voltage source supply; the resulting slight temperature dependence of the sensor sensitivity (of about 0.5%/10 °C) can be easily compensated in the transducer using known circuit techniques.

Conclusions

The results of investigations and the development of SOS integrated sensors for pressure and force measurement demonstrate the fact that the use of silicon as a material for mechanical sensors working in different, often extremely harsh conditions, is far from being complete. They also show the importance and efficiency of the physico-technological techniques for optimization of the sensor characteristics, which allow the quality of sensors and sensor-based transducers to be significantly increased and at the same time the cost of sensor manufacture to be reduced due to the decrease or even the avoidance of individual error correction of integrated transducers and transmitters.

Concerning the perspectives of SOS structures for integrated mechanical sensors, the described sensors with metallic elastic elements are preferable for crucial control systems where a pressure sensor should not be destroyed even after a failure, e.g., due to sudden overload. The SOS sensors will undoubtedly be more widely used after the development of chemical profiling technology (similar to that for silicon) and of low-temperature techniques for joining the SOS sensing element to sapphire or the ceramic parts of the sensor case. The somewhat higher cost of SOS structures compared to silicon has little effect on the transducer's cost, and at the same time the high chemical and thermal stability of sapphire allows the application area of silicon integrated sensors to be significantly extended.

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Biography

Vladimir M. Stuchebnikov, born in 1942, graduated from the physics department of Moscow State University in 1964. He received his master's degree in physics (radiative recombination in GaSb) in 1969, working at Moscow University, and a doctorate in technical science (strain gauge SOS sensors) in 1987, working at NIITeplopribor, Moscow. At present he is vice-director of the Integrated Sensors Institute in the Uljanovsk Centre of Microelectronics. His main field of work is semiconductor and film sensors.