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METHODS FOR INVESTIGATIONS AND TESTING

NEW TYPES OF RESISTANCE STRAIN GAUGES MADE OF SEMICONDUCTOR WHISKERS

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We created resistance strain gauges on the basis of threadlike semiconductor monocrystals of tellurium and selenium and investigated their deformation characteristics under uniaxial tension and compression (up to $\pm 2.6 \cdot 10^{-3}$) and hydrostatic pressure (up to $5 \cdot 10^{8}$ Pa). Their characteristics are compared with the parameters of resistance strain gauges made of p-type silicon. We developed electric contacts for selenium crystals and concluded that resistance strain gauges are promising for investigation of composite materials under triaxial compression.

At present, silicon monocrystals and mono- or polycrystal films of p-type (p-Si) are the undisputed leaders in semiconductor tensometry [1]. Threadlike micron-sized monocrystals with a perfect structure and high mechanical strength are regarded as a separate variety of them. On the basis of these monocrystals, many resistance strain gauges have been created, including small-based ones with a wide range of parameters [2, 3]. However, these resistance strain gauges have certain shortcomings. In particular, they have different sensitivities to tension and compression deformations, a long-term relaxation of resistance after unloading, and a weak sensitivity to deformation under hydrostatic pressure.

We tested whiskers of Te and Se semiconductors. Due to the high piezoresistance of monocrystalline tellurium [4], it is used in the case of all-round compression [5–7]. At the same time, selenium (especially, monocrystals) is little used in tensometry despite the fact that its piezoresistance is known [8] and mechanical gauges, i.e., Se–CdSe structures [9], have been created. Since the crystal structures of tellurium and selenium are similar and the forbidden gap of selenium is wider (~2 eV), we might expect the appearance of certain physical effects in this case.

We measure and analyze the deformation dependences

$$\frac{\Delta R}{R_0} = f(\varepsilon)$$

for tellurium whiskers, where R_0 is the resistance of a strainless resistance strain gauge and ΔR is the variation in the resistance under deformation of uniaxial tension or compression ε varying in the range $\pm 3 \cdot 10^{-3}$. In experiments, we used cantilever beams and special small-sized deformable devices. We glued gauges with a VL-931 glue according to a standard procedure.

We obtained that the coefficient of strain sensitivity

$$K = \frac{\Delta R}{R_0 \varepsilon}$$

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Table 1. **Strain Sensitivity of Tellurium Resistance Strain Gauges**

No.	$\rho = 9\,\text{M}\Omega\cdot\text{m}$	K^{*}/K^{**}
1	1	163/180
2	9	178/184
3	18	123/150
4	20	150/171

of tellurium crystals has constant and high values. The values of this coefficient for tension K^{*} and compression K^{**} are different. As for p-Si, these values are greater for compression deformation (see the data in Table 1 given for $\varepsilon = 1.9\cdot 10^{-3}$).

The coefficients of strain sensitivity are maximum for a specific resistance of crystals of $\rho = 9\,\text{M}\Omega\cdot\text{m}$ and $R_0 = 1000-1400\,\Omega$. The relative difference between the coefficients K for tension and compression is equal to 3.25%, while it is twice as mush under a lesser strain for p-Si resistance strain gauges ($\varepsilon = 5\cdot 10^{-4}$).

According to the deformation dependences of high-sensitive resistance strain gauges made of tellurium whiskers (specimen No. 2 in Table 1) for two types of deformation (Fig. 1), the relative change in resistance is equal to 40% for unilateral compression. In the process of unloading of a resistance strain gauge, the quantity $\Delta R/R_0$ becomes negative (down to 0.2%) due to a possible tension deformation. However, the resistance immediately relaxes to its initial value, contrary to the behavior of resistance strain gauges made of p-Si, for which relaxation continues for several minutes. The relative change in resistance of resistance strain gauges under hydrostatic pressure reaches 80%. The different configuration of point contacts on resistance strain gauges [symmetric (curve 3) and asymmetric (curve 4)] has, in fact, no effect on it. In general, dependences are exponential. However, for pressures $p \le 5$ MPa, they are well approximated by straight lines. Deviations from the linear behavior can be related to the complicated strain state (often, a specially created one) of a resistance strain gauge, i.e., to the appearance of additional components of the stress tensor. In addition to the longitudinal strain sensitivity (K_1), the transverse (K_2) and shear (K_{12}) strain sensitivities are distinguished. The longitudinal resistance of resistance strain gauges is presented in the form

$$\frac{\Delta R}{R_0} = K_1\varepsilon_1 + K_2\varepsilon_2 + K_{12}\varepsilon_{12} + (1+2\mu)\varepsilon_1,$$

where ε_1, ε_2, and ε_{12}, are longitudinal, transverse, and shear deformations in the plane where the resistance strain gauge is glued and μ is the Poisson ratio.

For glued resistance strain gauges, the transfer of deformation depends significantly on the thickness and properties of the glue layer. For the linear deformational characteristics of resistance strain gauges, it is easier to determine all these additional deformations than for nonlinear deformations.

To our mind, after removal of deformation, the relaxation of the resistance of resistance strain gauges is determined by the following factors:

— the influence of polarization effects in the “glue–surface of the resistance strain gauge” system;

— possible plastic deformation in subsurface layers of resistance strain gauges due to the shear components experimentally observed in whiskers of the system Si–Ge [10];

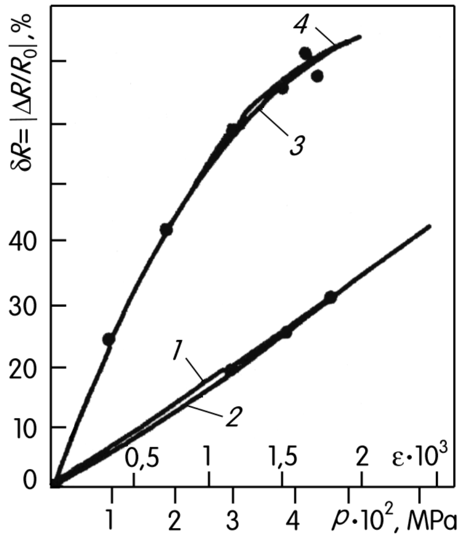

Fig. 1. Deformation characteristics of resistance strain gauges made of tellurium whiskers ($\rho = 9\ \mathrm{M\Omega \cdot m}$) for maximum strains $\varepsilon = 2.6 \cdot 10^{-3}$ and pressure $p = 500$ MPa: (1) and (2) uniaxial compression (loading and unloading), (3) and (4) hydrostatic pressure for symmetric and asymmetric contact.

— barrier effects in metal–semiconductor contacts (accumulation of charge), which lead to deviations of the voltage–current characteristics of contacts from the linear behavior and to the different resistances of resistance strain gauges for two polarities of the current.

In addition, nonuniform deformations can lead to conicity of a crystal, the appearance of defects, etc. Investigations showed that the second reason is decisive for resistance strain gauges made of *p*-Si, while, for tellurium and selenium resistance strain gauges, the third reason is the most important. As for the morphology and structure, selenium crystals are similar to tellurium crystals. They are trihedral needles and strips with a specific resistance of $0.3-1\ \mathrm{M\Omega \cdot m}$, *p*-type conductivity, and a resistance of $130-550\ \Omega$. Strain sensitivity is better for greater values of these parameters. The coefficients of strain sensitivity for compression deformations are greater than those for tension deformations. For example, $K^{**} \cong 130$ and $K^{*} \cong 110$. However, if the resistance of resistance strain gauges is measured for the polarity corresponding to greater resistance R_0, then the coefficients have other values, namely: $K^{**} \cong 140$ and $K^{*} \cong 90$ (in this case, the dependence on deformation is nonlinear).

The characteristics are linear in a small range of deformations ($\leq 5 \cdot 10^{-4}$) (Fig. 2). For larger deformations, the dependences deviate from straight lines up (compression) (curves 4′ and 5′) or down (tension) (curves 4 and 5). For tellurium resistance strain gauges, there is, in fact, no difference between characteristics for compression deformations (curves 2′ and 3′) for both polarities of the current. At the same time, tension increases the strain sensitivity of resistance strain gauges with greater resistance (curve 2) as compared with gauges with smaller resistance (curve 3). Dependences 1 and 1′ describe the deformation of silicon resistance strain gauges for tension and compression, respectively. A nonlinear behavior of the dependence

$$\frac{\Delta R}{R_0} = f(\varepsilon)$$

and a high strain sensitivity for compression deformation make the use of selenium resistance strain gauges promising. In our opinion, these phenomena are connected with the hydrostatic part of the stress tensor from the side of a glue and with the corresponding deformation [6, 8].

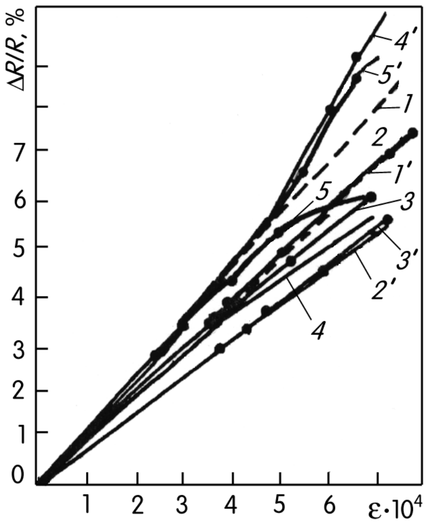

Fig. 2. Deformation characteristics $\Delta R/R_0 = f(\varepsilon)$ for resistance strain gauges made of various semiconductors: (1) and (1′) p-Si, (2), (3) and (2′), (3′) Te, and (4), (5) and (4′), (5′) Se.

Table 2. Coefficients of Strain Sensitivity at Various Temperatures

Resistance strain gauges	Temperature, °C			
	20	30	40	50
p-Si	117	115	112	110
Te	113	123	173	343
Se(2)	70	78	51	30

As the temperature increases from 20 to 60°C, the resistance of resistance strain gauges made of p-Si increases, while the resistance of tellurium and selenium resistance strain gauges decreases, which is typical of semiconductors with a given concentration of free charge carriers. The change in strain sensitivity with temperature is the least for resistance strain gauges made of p-Si. The strain sensitivity of tellurium and selenium resistance strain gauges increases and decreases, respectively (Table 2).

In the climatic temperature range, the relative change in the resistance of resistance strain gauges made of p-Si and selenium glued to an elastic element (change in the parameter $\Delta R/R_{20°C}$) varies within the range of several percent. For tellurium resistance strain gauges, this range is greater.

For silicon resistance strain gauges, the electric contacts, which were created by welding a platinum microwire (or a gold microwire for tellurium crystals), are rather well elaborated and studied [11, 12]. But for selenium microcrystals, we first tested them by welding microwires made of various materials.

The voltage–current characteristics of contacts (Fig. 3 and Table 3) are rather linear (up to currents $I_c \leq 5$ mA), despite the fact that the resistance of contact R_c is different for two directions of the current. The resistance of contacts is rather high (up to 5% of the resistance of the specimen), which does not entirely comply with the requirements for ohmic resistance and is greater than the resistance of contacts on resistance strain gauges made of p-Si and tellurium.

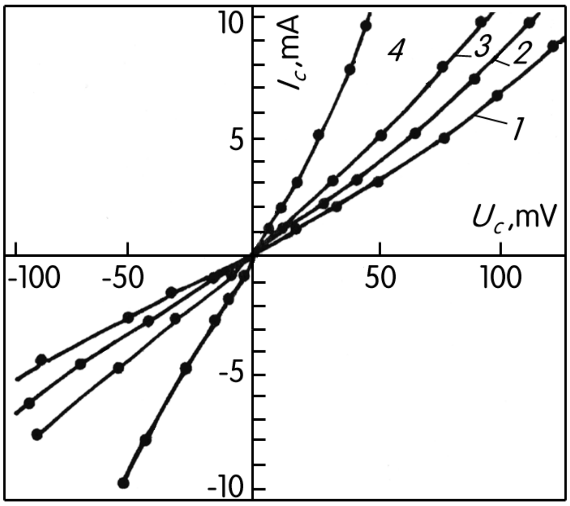

Fig. 3. Voltage–current characteristics of contacts to selenium crystals: (1) Au, ∅ 40 μm; (2) Au, ∅ 60 μm; (3) Pt, ∅ 40 μm; (4) Ag, ∅ 30 μm.

Table 3. Parameters of Contacts to Selenium Resistance Strain Gauges

Contact	Diameter of microwire, μm	$R_c\uparrow/R_c\downarrow$, Ω	$\Delta R_c/R_c \cdot 100\%$	Nonlinearity of voltage–current characteristics	
				direct branch	reverse branch
Au	40	16.9/18.8	11.2	1.7	1.1
Au	60	14.5/16.2	12.1	3.4	3.0
Pt	40	11.1/11.5	3.6	2.2	1.9
Ag	30	5.86/5.86	0.04	4.4	4.4

Direct and reverse resistances ($R_c\uparrow$ and $R_c\downarrow$) are determined by the relation

$$R_c = \frac{U_c}{I_c}$$

for the direct and reverse branches of voltage–current characteristics.

According to the requirements imposed on a metal–semiconductor contact, platinum is the best material among the tested metals on the basis of the condition $W_1 \le W_2$, where W_1 and W_2 are the work functions of electrons from a semiconductor and a metal, respectively. It is obvious that there appear chemical compounds (Ag_2Se) in welding a silver microwire that considerably change the structure of the contact and decrease the barrier height. The diameter of a microwire also has an influence on the parameters of the contacts. Its increase leads to decreasing R_c, which is related, first of all, to an increase in the power of an electric pulse on welding.

Thus, small-size resistance strain gauges made of tellurium and selenium can be regarded as promising for the investigation of structural materials under the action of bulk directed deformation.

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