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# Influence of Illumination and Temperature on Tenso Properties of Silicon with Nanoclusters of Manganese Atoms

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It is shown that the tensoproperties of silicon with nanoclusters of manganese atoms differ significantly from the tensoproperties of conventional semiconductors. Discovered has been found that an increase in temperature and illumination significantly increases the tenso sensitivity of the material. The results obtained are explained by the change in the energy spectrum of electrons both in nanoclusters of manganese atoms and in mini-zones formed by nanoclusters in such a material.

**Keywords:** pressure, tensoproperties, silicon, temperature, illumination.

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## 1. Introduction

Tensoelectric properties of solid-state materials mainly depend on the crystalline structure and interatomic bond type [1–4]. It is also necessary to consider the influence of external impacts — temperature, magnetic and electric field during measurement [5–7]. Study of pressure influence in imperfect crystals, in the bulk of which clusters of foreign atoms were formed specially, is of profound interest. On the other hand, such studies can reveal the mechanisms of cluster formation and their stability.

The object of research in this paper was single-crystal silicon, which is the main material in modern micro- and nanoelectronics. The authors of [8,9] developed a low-temperature technology for the making of impurity atom nanoclusters by the diffusion method [10,11] in the silicon bulk. Presence of impurity atom nanoclusters in the silicon lattice was confirmed by the EPR and AFM methods [12–14].

By now, various load cells having wide functional capabilities have been developed. It can be asserted that developers used all possible properties of semiconductor materials doped with various impurity atoms. Creation of high-sensitivity load cells requires new semiconductor materials [15] or new physical phenomena [16]. Study of the integrated influence of pressure, temperature and illumination on parameter change, in the first place, conductivity, is of profound scientific and practical interest for such materials [17,18].

## 2. Experimental procedure

The initial material was silicon of the $p$-type of conduction with specific resistance $\rho = 3\,\mathrm{Ohm}\cdot\mathrm{cm}$ (KDB-3), with oxygen concentration $N \sim 4 \cdot 10^{17}\,\mathrm{cm}^{-3}$. Manganese diffusion was performed in soldered-up ampules in the temperature range $T = 1050-1100^\circ\mathrm{C}$ for $t = 5-20\,\mathrm{min}$. After diffusion the plates were cooled in oil at the rate of $200^\circ\mathrm{C/s}$. Then the plates were polished to remove silicides and were etched in $\mathrm{HF} + \mathrm{HNO_3}$ [19].

The influence of pressure on the samples' parameters was studied using a specially created unit [20] that provided pressure in a local region of a sample to study its electrophysical properties at different temperatures (Fig. 1). This device provides results in a temperature range from room temperature to $100^\circ\mathrm{C}$. Pressure is created mechanically by pressing with the metal point of the probe. The unit provides uniaxial compression on a local region of the silicon surface with nanoclusters. At that, the surface area of the needle-shaped probe point and the force acting on it are taken into account. A photoresistor was used as an illumination sensor. This provided the lux-pascal characteristics.

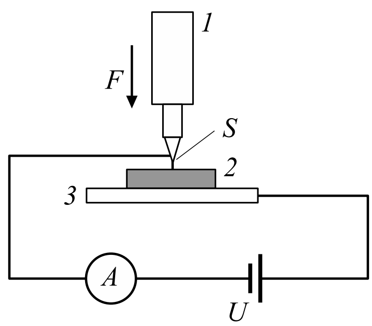


**Figure 1.** Design and electric diagram of a unit for measuring radial-point pressure on silicon surface: *1* — thin sharp-pointed probe, *2* — sample under study, *3* — flat surface of current-conducting material. $U$ — voltage, $S$ — surface area of thin sharp-pointed probe, $F$ — pressure force ($P = F/S$, $P$ — value of pressure on the sample).

## 3. Results and discussion

Influence of pressure from $5.16 \cdot 10^5$ to $7.74 \cdot 10^7$ Pa at 30, 40, 50, 70°C was studied. Voltage drop on the samples during measurement was equal to $U = 10$ V.

Table 1 gives the relative change of current depending on applied pressure at different temperatures, without illumination. Thereat, the study results show than tensosensitivity coefficient $\alpha$ upon a temperature increase in 2.3 times increases in more than 15 times.

Figure 2 shows the relative change of $I/I_o$ depending on pressure. It was established that the plot of relative change of current $I/I_o$ vs. pressure $P$ has two pronounced areas with a different tensosensitivity coefficient $\alpha_1$. A very high tensosensitivity ($\alpha_1 = 11.79$) is observed on the area where $P$ varies from $5 \cdot 10^5$ to $7 \cdot 10^7$ Pa. Tensosensitivity in the second pressure region $P = 2 \cdot 10^7 - 10^8$ Pa is lower ($\alpha_2 = 2.8$).

Very interesting results were obtained with illumination of the samples. It was found that tensosensitivity increases under illumination and reaches 15.43 (Table 2 and Fig. 3). However, it is known [21,22] that a reverse effect is observed in conventional semiconductor materials, i.e. illumination causes a decrease of tensosensitivity. This peculiarity of the studied samples means the creation of a new load cell class with a high sensitivity.

Tensosensitivity $\alpha$ varies from 2.02 to 10.8 in the temperature range of 30–70°C in darkness and from 5.6 to 11.79 in the temperature range of 30–70°C under 3000 lux illumination.

**Table 1.** Relative change of current under pressure influence at different temperatures in darkness

| $P$, Pa | $I/I_o$, ($T = 30°$C) | $I/I_o$, ($T = 40°$C) | $I/I_o$, ($T = 50°$C) | $I/I_o$, ($T = 70°$) |
|---|---|---|---|---|
| $5.16 \cdot 10^5$ | 1 | 1 | 1 | 1 |
| $1.29 \cdot 10^7$ | 3.16 | 4.06 | 6.56 | 8 |
| $2.58 \cdot 10^7$ | 3.44 | 4.8 | 8.33 | 10.16 |
| $3.87 \cdot 10^7$ | 3.55 | 5.14 | 9.21 | 11.33 |
| $5.16 \cdot 10^7$ | 3.62 | 5.39 | 9.83 | 12.62 |
| $6.45 \cdot 10^7$ | 3.7 | 5.59 | 10.53 | 13.7 |
| $7.74 \cdot 10^7$ | 3.75 | 5.75 | 11.13 | 14.62 |

**Table 2.** Relative change of current under pressure influence at different temperatures under 3000 lux illumination

| $P$, Pa | $I/I_o$, ($T = 30°$C) | $I/I_o$, ($T = 40°$C) | $I/I_o$, ($T = 50°$C) | $I/I_o$, ($T = 70°$C) |
|---|---|---|---|---|
| $5.16 \cdot 10^5$ | 1 | 1 | 1 | 1 |
| $1.29 \cdot 10^7$ | 4.97 | 5.35 | 6.61 | 8.25 |
| $2.58 \cdot 10^7$ | 6.99 | 7.88 | 8.83 | 10.59 |
| $3.87 \cdot 10^7$ | 7.75 | 8.95 | 10.01 | 11.86 |
| $5.16 \cdot 10^7$ | 8.63 | 9.8 | 10.88 | 13.25 |
| $6.45 \cdot 10^7$ | 9.39 | 10.69 | 12.03 | 14.44 |
| $7.74 \cdot 10^7$ | 9.89 | 11.34 | 12.7 | 15.43 |

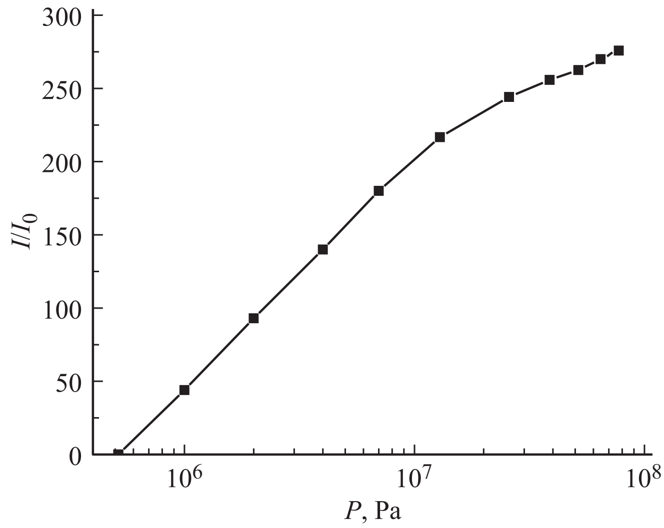


**Figure 2.** Relative change of current vs. pressure at room temperature (without illumination, at $U = 10$ V).

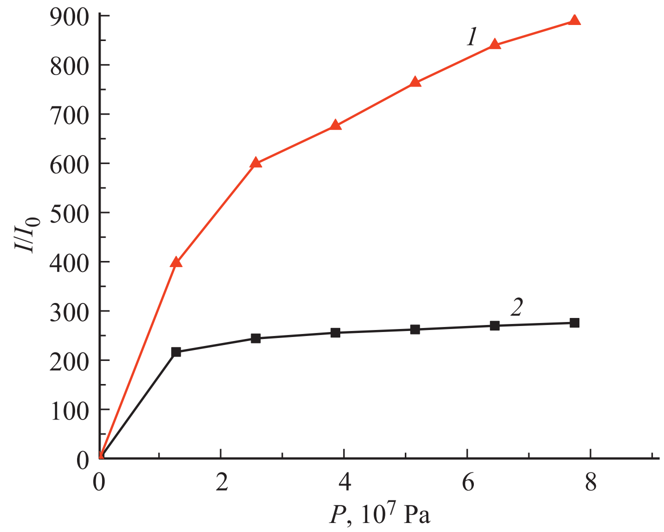


**Figure 3.** Ratio of tensoresistor currents vs. pressure at $U = 10$ V (*1* — with 3000 lux illumination, *2* — without illumination), at $T = 30°$.

Table 3 and Fig. 4 give coefficients $\alpha_1$ and $\alpha_2$ for load cells both in darkness and under illumination at different temperatures.

A peculiarity of the tensoproperties of the obtained samples is the significant temperature influence on tensosensitivity. As distinct from the results of [23,24], tensosensitivity does not decrease upon a temperature increase, but, on the contrary, increases significantly. Table 3 shows that tensosensitivity increases in $\sim 2.1$ times in the first region and in 2.01 times in the second one when temperature increases from 30 to 70°C.

**Table 3.** Tensosensitivity coefficient at different temperatures in darkness and under 3000 lux illumination

| Temperature | 30°C | 40°C | 50°C | 70°C |
|---|---|---|---|---|
| Without illumination | | | | |
| $\alpha_1$, $\mu$A/MPa | 2.02 | 3.36 | 6.97 | 10.8 |
| $\alpha_2$, $\mu$A/MPa | 0.11 | 0.36 | 1.14 | 2.46 |
| With illumination | | | | |
| $\alpha_1'$, $\mu$A/MPa | 5.6 | 6.72 | 9 | 11.79 |
| $\alpha_2'$, $\mu$A/MPa | 1.39 | 1.86 | 1.99 | 2.8 |

The obtained results show that silicon with nanoclusters really is a fundamentally new material for the making of high-sensitivity load cells. These properties of silicon with nanoclusters of manganese atoms are explained by the fact that nanoclusters act as multi-charge quantum dots which not only create a strong electric field around themselves [25,26], but also considerably affect the quantization of the electron energy spectrum in clusters [27–29]. Strong electric fields, generated by multi-charge clusters, cause space localization of conduction holes and, respectively, formation of energy mini-bands in the silicon band gap. This leads to a significant expansion of the energy state spectrum in such crystals [30].

Therefore, as distinct from conventional semiconductor materials tensosensitivity of which is directly associated with a band gap decrease, and which, respectively, have rather a low tensocoefficient, the whole energy spectrum in our material changes considerably under pressure. Thereat, a contribution from a change of ionization energy of impurity levels in nanoclusters and in mini-bands can be considerably greater [31,32] than the contribution defined by a change in $E_g$. It should be also noted that the material tensoproperties can be controlled by changing the level of nanoclusters' charge divisibility and the concentration of manganese atom nanoclusters in a lattice.

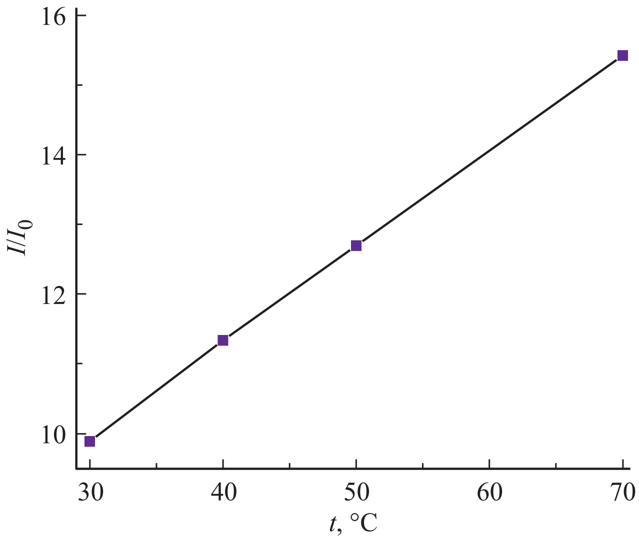


**Figure 4.** Ratio of tensoresistor currents vs. temperature at $U = 10$ V and pressure $P = 7.74 \cdot 10^7$ Pa (with 3000 lux illumination).

## 4. Conclusion

Tensoproperties of silicon with manganese atom nanoclusters differ considerably from those of conventional semiconductors. It was established that an increase of temperature and illumination significantly increases the material tensosensitivity. These results are explained by a change of the electrons' energy spectrum both in manganese atom nanoclusters and in the mini-zones formed by nanoclusters in such a material.

### Conflict of interest

The authors declare that they have no conflict of interest.

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